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Evaluation of sustainability criteria for small-scale wastewater treatment facilities

Edvard Nordenskjöld

Abstract

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There are about 700,000 on-site sewage facilities (OSSFs) in Sweden, almost a quarter of which amount only to septic tanks for sludge collection and removal, with no form of post-treatment. All these OSSFs contribute about 10 % of the total anthropogenic phosphorus (P) load from Swedish coasts to the Baltic Sea. They also leak a considerable, but hard to quantify, amount of micropollutants (MPs). This is a large, diverse group of organic trace contaminants, including e.g., pharmaceuticals and detergents. The interests concerning OSSFs in Sweden have over time shifted from merely disposal issues, to health (removal of pathogens) and then further on to nutrient leakage.

In recent years there has been a growing interest in a more comprehensive sustainability perspective. In that spirit, during this thesis project, environmental (n=5) and socio-economic (n=5) criteria were assessed for three conceptualized, full-scale OSSFs. The evaluation was based on the efficiency of domestic wastewater treatment from a single household. These systems comprised conventional post-treatment, as well as extra capabilities for treating P and MPs. The evaluation was done with a multi-criteria analysis (MCA), the goal of which was to provide a proof-of-concept analysis of these treatment technologies in order to serve as decision-support at a national policy level.

The first of the decision options was a sandbed filter with Polonite® and Granular Activated Carbon (GAC) filters, for the adsorption of P and MPs, respectively. The second option was a reference package treatment system (PTSs), with flocculation chemicals for the precipitation of P, but nothing for the removal of MPs. The third solution was another PTSs, but with Polonite and GAC filters. The stakeholders chosen in this study were the Swedish Agency for Marine and Water Management (SwAM), a municipal regulator and a property owner. A total of 100 weight points were assigned to the 10 sustainability criteria. The minimum and maximum of these created a range for each criterion, which was multiplied with the grades 1-5 and added together.

The most sustainable alternative in this study was found to be the sandbed filter with 102-694 points (mid-range of 398), followed by the PTSs reference with 79-560 points (mid-range of 319.5) and the PTSs with filters with 82-500 points (mid-range of 291). The property owner put the highest weight on the economy, while SwAM put the highest weight on the environmental criteria, and the regulator on the social criteria. The sensitivity analysis indicated possible impact by changing the ranking position between the PTSs. This was deemed likeliest for the weight change of life-cycle costs and the grade change of the ease of compliance (legislative) criterion, but the highest ranking of the sandbed filter seemed hard to budge.

Keywords: On-site sewage facilities, phosphorus, micropollutants, multi-criteria analysis, precipitation, adsorption, full-scale, wastewater treatment

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Referat

Utvärdering av hållbarhetskriterier för småskaliga reningsverk
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Det finns ungefär 700,000 enskilda avlopp i Sverige, varav ca en fjärdedel endast består av trekammarbrunnar, eller liknande system, utan någon form av post-rening. Alla dessa enskilda avlopp belastar ungefär 10 % av den totala antropogena fosforn (P) från svenska kuster till Östersjön. Det sker också ett läckage av en betydande, men svår-kvantifierbar, mängd mikroföroreningar (MF). Detta är en stor, divers grupp av organiska spårföroreningar som t. ex inkluderar läkemedelsrester och tvättmedel. De övergripande intressena angående enskilda avlopp i Sverige har över tid skiftat från frågor gällande dess bortskaffande, till hälsa (avskiljning av smittämnen) och vidare till näringsläckage.

Under de senaste åren har det blivit ett växande intresse för ett mer omfattande hållbarhetsperspektiv. Under det här examensarbetet bedömdes miljö-kriterier (n=5) och socio-ekonomiska kriterier (n=5) för tre teoretiska, fullskaliga enskilda avlopp. Utvärderingen baserades på avloppsreningens effektivitet från ett enskilt hushåll. Dessa avloppssystem innefattade konventionell post-rening, såväl som ytterligare förmåga att behandla P och MF. Metoden som användes för utvärderingen var en multi-kriterie analys (MKA), vars mål var att förse en konceptuell analys av de här tre avloppssystemen med syfte att tjäna som beslutsstöd på en nationell policy-nivå.

Det första beslutsalternativet var en markbädd med Polonite® och granulärt aktivt kol (GAK) filter, för adsorption av P och MF. Det andra alternativet var ett referens minireningsverk (MRV) med fällningskemikalier för utfällning av P, men ingenting specifikt för avskiljning av MF från avloppsvattnet. Den tredje avloppslösningen var även den ett MRV, men med Polonite och GAK filter, som markbädden. Intressenterna som valdes i den här studien var Havs- och vattenmyndigheten (HaV), ett kommunalt miljökontor och en fastighetsbrukare. De 10 hållbarhetskriterierna fick var och en 100 viktpoäng tilldelade. De lägsta och högsta viktpoängen från de tre intressenterna skapade ett intervall för varje kriterie, vilket multiplicerades med betygen 1-5 och summerades.

Det mest hållbara alternativet i den här studien befanns vara markbädden med 102-694 poäng (mittvärde 398), följt av referens MRV med 79-560 poäng (mittvärde 319.5) och MRV med filter med 82-500 poäng (mittvärde 291). Fastighetsbrukaren tilldelade högst viktpoäng till ekonomin, medan HaV gjorde detsamma till miljökriterierna och miljökontoret till de sociala kriterierna. Känslighetsanalysen indikerade möjlig påverkan av de analyserade ändringarna genom att förändra den ovanstående rankingen mellan de båda MRV. Detta bedömdes vara troligast för viktändringen av livs-cykel kostnader och betygsändringen av kriteriet som avser lättheten att efterleva nutida och framtida (lagliga) krav, men den högsta rankingen av markbädden verkade svår att ändra på.

Nyckelord: Enskilda avlopp, fosfor, mikroföroreningar, multi-kriterie analys, utfällning, adsorption, fullskala, avloppsrening

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Preface

This Master's Thesis was performed within the Swedish RedMic research project – Novel Strategies to Reduce Diffuse Emissions of Micropollutants from On-Site Sewage Facilities – conducted by Umeå University (UMU), The Royal Institute of Technology (KTH), Stockholm University (SU) and The Swedish University of Agricultural Sciences (SLU) in 2013-2017, financed by The Swedish Research Council Formas.

I would like to thank Erik Kärrman (RISE Urban Water Management AB) for supervising this thesis study, as well as Wen Zhang, Berndt Björlenius, Gunno Renman (Department of Land and Water Resources Engineering, KTH) and Maria Sammeli (Ecofiltration AB) for providing support with calculations. Further, I thank Karin Wiberg for being the subject reviewer and Allan Rodhe for being the examiner in this thesis project.

I thank Sara Trulsson, Annika Nilsson and Misse Wester, in the RedMic project, for providing clarification and information about the social criteria. Lastly, I would like to thank Fredrick Regnell, Amanda Sievers (Master Students, Applied Industrial Ecology, KTH) and Sara Trulsson for participating in the workshop within this study, wherein they provided the perspective of important stakeholders concerning on-site sewage facilities in Sweden.

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Populärvetenskaplig sammanfattning

Utvärdering av hållbarhetskriterier för småskaliga reningsverk
Edvard Nordenskjöld

Enskilda avlopp definieras som tekniker för behandling av avloppsvatten för enskilda hushåll eller samfälligheter upp till 200-personekvivalenter (p.e.), avseende den förbrukade vattenmängden, enligt Havs- och vattenmyndigheten (HaV). Det sker en förbehandling av avloppsvattnet i slamavskiljare, vars syfte är att avskilja stora partiklar och sediment, snarare än att innefatta någon större rening. Ungefär en fjärdedel av de ca 700,000 enskilda avloppen i Sverige innefattar endast den här typen av förbehandlingar i trekammarbrunnar eller liknande system. Konventionell efterbehandling i Sverige består till ungefär hälften av markbaserad infiltration, som infiltrationsanläggningar och markbäddar, men även till ca 3 % av minireningsverk. Enskilda avlopp belastar ungefär 10 % av den totala fosfor mängden med ursprung från mänskliga aktiviteter, från svenska kuster till Östersjön, motsvarande en årlig belastning på 295 ton till grundvatten eller närmaste dike/rörledning.

Det sker också ett läckage av en betydande, men svår-kvantifierbar, mängd kemikalier som klassificeras som mikroföroreningar. Detta är en stor divers grupp av organiska föroreningar, förekommande i små halter, som t. ex inkluderar läkemedelsrester, tvättmedel och andra hushållskemikalier. De kan ha en toxisk effekt på vattenlevande organismer, men har hittills framförallt uppmärksammats vid kommunala reningsverk, och även det först nyligen. Historien om enskilda avlopp i Sverige handlade till en början bara om att avlägsna avloppsvattnet från boenden. Detta skiftade med tiden till de hälsofrågor som uppkom i samband med spridningen av orenat avloppsvatten till vattendrag, och den stora vikten av en fungerande rening av smittämnen från avloppsvattnet. Först efter detta var löst blev frågor gällande näringsläckagen från de enskilda avloppen en viktig fråga.

Under de senaste åren har det blivit ett växande intresse för ett mer omfattande hållbarhetsperspektiv, där alla de viktiga aspekterna för ett hållbart enskilt avlopp, såsom ekonomi, sociokultur och rening av avloppsvatten, tas i beaktande. Med tanke på denna ändring i fokus bedömdes under det här examensarbetet fem miljö-kriterier och fem socio-ekonomiska kriterier för tre teoretiskt ihopsatta enskilda avlopp ute i fält på en ospecificerad plats i Sverige. Denna utvärdering baserades på en litteraturstudie om avloppsreningens effektivitet, med förbrukad vattenmängd som kommer från ett enskilt hushåll. Data som analyserades kom från publicerad forskning inom området. Dessa avloppssystem innefattade konventionell för- och efterbehandling av avloppsvatten, såväl som ytterligare förmåga att rena vattnet från fosfor och mikroföroreningar. Den senare kapaciteten finns idag inte för enskilda avlopp i Sverige, varför data för den analysen kom från kommunala reningsverk, och extrapolerades till den småskaliga situationen i fält.

Metoden som användes var en multi-kriterie analys (MKA), som är ett verktyg för att utvärdera beslutsalternativ utifrån flera kriterier och att sammanväga detta. Det kan fungera utmärkt som ett beslutsstöd, men inte på en konsument-nivå i just det här fallet, då systemen är hopplockade och inte tillgängliga till fastighetsbrukare som konsumenter. MKA:n skulle istället kunna vara stöd på en nationell policy-nivå där myndigheter, som HaV och Naturvårdsverket, beslutar vilket avloppssystem som skulle få finansiellt eller lagligt stöd för ytterligare utveckling. Men metodens främsta mål var att tillhandahålla en analys som visar dess tillförlitlighet för det syftet, snarare än att resultaten i den här studien skulle vara direkt tillämpbara i det syftet.

Det första beslutsalternativet var en markbädd med Polonite® och granulärt aktivt kol (GAK) filter, för rening av fosfor och mikroföroreningar. Polonitets råmaterial är en kalkhaltig sedimentär bergart, men den har värmts upp kraftigt för att omvandla kalciumkarbonat till kalciumoxid, och därmed öka adsorptionskapaciteten av fosfor för materialet och uppfylla dess syfte som en fosforfälla. GAK består av mycket fina (granulära) kolpartiklar vars ursprung är från ett organiskt material med hög kolhalt, som en kokosnöt i den här studien. Även här har en kraftig uppvärmning ägt rum för att producera det granulära, fina kolpartiklarna som ökar adsorptionskapaciteten av mikroföroreningar. Det andra beslutsalternativet var ett minireningsverk med fällningskemikalier för utfällning av fosfor i stora saltföreningar i slammet, men ingenting specifikt för avskiljning av mikroföroreningar. Detta avloppssystem var menat att fungera som en referensanläggning, d.v.s. dess prestanda skulle få samma medelhöga betyg för alla kriterier så att de andra lösningarna kunde skalas och jämföras mot den. Det var önskvärt att jämföra prestandan av ett system som inte är avsedd att rena mikroföreningar mot ett som är det, då även den tredje avloppslösningen var ett minireningsverk med Polonite och GAK filter.

I MKA-metoden ingår, förutom en utvärdering av alla kriterier för var och en av de tre beslutsalternativen, även en viktning för desamma. Viktningen gjordes av viktiga intressenter inom ämnesområdet, i det här fallet gällande enskilda avlopp i Sverige. I den här studien rollspelades dessa av tre personer som hade kartlagt de viktigaste intressenterna för enskilda avlopp i Sverige, inom en diskussions-workshop. De var väl medvetna om ansvarsområdena och därmed indirekt vad som var viktigt för varje intressent. De tre intressenter som valdes i den här studien var Havs- och vattenmyndigheten (HaV), ett kommunalt miljökontor och en fastighetsbrukare. De 10 hållbarhetskriterierna fick således 100 viktpoäng tilldelade av var och en av dem. De lägsta och högsta viktpoängen från de tre intressenterna skapade ett intervall för varje kriterium, vilket multiplicerades med betygen 1-5, för varje system och kriterium. Dessa summerades ihop för var och en av beslutsalternativen. Därmed kunde en jämförelse göras mellan avloppslösningarnas intervall och mittvärde för att avgöra vilket system som skulle kunna anses mest hållbart, enligt den här beslutsstödjande metoden. En såkallad känslighetsanalys utfördes också för två betygsättningar och två tilldelade högsta viktpoäng. Det är en undersökning av hur stor påverkan på resultaten det skulle bli om dessa ändrades åt endera hållet.

Det mest hållbara alternativet i den här studien befanns vara markbädden med 102-694 poäng (mittvärde 398), följt av referens minireningsverket med 79-560 poäng (mittvärde 319.5) och sist minireningsverket med filter, med 82-500 poäng (mittvärde 291). Markbädden var billigast, men befanns ändå ha bra prestanda med reningen och de viktigare sociala kriterierna. Gällande viktning så tilldelade fastighetsägaren högst viktpoäng till ekonomin, medan HaV gjorde detsamma till miljökriterierna och miljökontoret till de sociala kriterierna. Känslighetsanalysen indikerade möjlig påverkan av de analyserade ändringarna genom att förändra den ovanstående rankingen mellan de båda minireningsverken. Detta bedömdes vara troligast för viktändringen av livs-cykel kostnader och betygsändringen av kriteriet som avser lättheten att efterleva nutida och framtida (lagliga) krav, men den högsta rankingen av markbädden verkade svår att ändra på. Resultatens största betydelse är att visa på MKA-metodens stora tillämplighet för att vara beslutsstöd på en nationell policy-nivå, snarare än att den här studiens resultat skulle användas på det viset. Framförallt behövs viktning med representanter från de reella intressenterna, även om en jämförelse med en tidigare studie visade på liknande viktning för miljökriterierna. Det ekonomiska kriteriet viktades högre i den här studien än i den tidigare, men de sociala kriterierna tillät inte en rättvis jämförelse.

Table of Contents

1. Introduction

Conventional post-treatment techniques for on-site sewage facilities (OSSFs) include, but are not limited to, soil filtration systems (SFSs), package treatment systems (PTSs) and source separation of sewage (SSS) (Zhang & Renman, 2016). SFSs include two distinct system designs: those with discharge to groundwater (GW) and those with discharge to surface water (SW) (Eveborn, 2013). Although PTSs is a variable group of OSSFs, virtually all fall into the latter design, releasing the wastewater to SW (SEPA, 1987). Three specific OSSFs, one SFSs and two PTSs, were evaluated in this thesis project for potential to remove pathogens, nutrients and micropollutants (MPs). To remove the two latter, add-on filters were inserted in the outlet of these OSSFs, creating a system better suited for the removal of phosphorus (P) and MPs than conventional treatment techniques. The analysis was carried out with a multi-criteria analysis (MCA), a method suited for a wide-ranging sustainability perspective including environmental, economic and social issues.

OSSFs are defined as treatment techniques for households and communities up to 200 person equivalents (p.e.) by the Swedish Agency for Marine and Water Management (SwAM) (SwAM, 2016). There are certain technical specifications and general advice (2006) from the Swedish Environmental Protection Agency (SEPA) concerning these that are more or less in use today. They have therefore been used for calculations in this report, with comparisons to their protection levels; normal and high. The technical specifications in their original text from 1987 was also organized and summarized into six short fact sheets in 2003, and were available in their current form in 2006 (SEPA, 1987, 2006d; a; b; c). However, a project is under way (projected end March 2017) by the Swedish Institute of Agricultural and Environmental Engineering (JTI), to establish new technical specifications for use in designing OSSFs (JTI, 2016). Also, a new legislature has been proposed by SwAM, for use as general advice in OSSFs (SwAM, 2016). Lastly, there has been attempts to update treatment stencils from SEPA's 2006 advice, with Swedish Environmental Emissions data, but even if these reflect the situation better, they have not yet been put into legislature (Ek et al., 2011).

In 2014, there were 691,000 OSSFs in Sweden, about 468,000 of which were used for permanent living. The annual load of these OSSFs was 295 tons of P and 3,066 tons of nitrogen (N), received by the GW surface or closest trench/pipeline. Reduction in transport of this load by soil retention happens, more so in the vadose zone than below the GW level, before treated effluent reaches the closest SW recipient (Olshammar et al., 2015). The 128,000 households in Sweden with only greywater effluent are not taken into account in this load since the nutrient concentration and wastewater volume is assumed to be low. As regards the black- and greywater treatment of the 625,000 households in Sweden with a toilet, 26 % were septic tanks lacking post-treatment, about 49% of the OSSFs were SFSs, 11 % were greywater systems with separate WC streams connected to collecting tanks (SSS) and 3 % were PTSs (Eveborn, 2013; Olshammar et al., 2015).

The main focus regarding OSSFs has shifted from merely disposal, to health issues and on to eutrophication issues. In recent years, there has been a growing interest in a more comprehensive sustainability perspective (Eveborn, 2013). This study will therefore assess the removal of P and MPs in OSSFs. While the separation of P in OSSFs (mainly SFSs) has been the focus of several recent studies (Eveborn et al., 2012), the same of MPs has not been the case, although municipal wastewater treatment plant (WWTPs) has gained recent research interest in effective treatment methods (Zhang & Renman, 2016). The interest in P is understandable considering the lack of knowledge of its retention in SFSs, its importance in eutrophying many coastal areas of the Baltic Sea, and its high separation requirement in SEPA's general advice (2006). This does not create ideal conditions for assessing if SFSs fulfils their requirement. Further, it does not allow evaluation on equal grounds of P separation between SFSs and PTSs (SEPA, 2006a; Eveborn et al., 2012).

Pathogens, bacteria and viruses in human faeces cause health hazards if transported to SW and GW recipients, whereby their removal in OSSFs is paramount. Microbiological monitoring for faecal indicator bacteria (coliforms, E.coli) in drinking water has been the major tool in managing the microbiological safety of drinking water over the last century (Hijnen et al., 2010). It is not N, but P, that is the limiting nutrient in many parts of the Baltic Sea environment. Furthermore, the N leakage from OSSFs in relation to the total diffuse N leaching is minimal, while the P leakage from OSSFs is considerable; about 10 %, of the entire anthropogenic load to the Baltic Sea from Swedish coasts (Eveborn, 2013). Therefore, this study focused on P removal in OSSFs from an eutrophication perspective, as well as the removal of MPs in OSSFs, as part of the RedMic project. MPs were further expounded upon, but not P since the information thus far expressed is sufficient for the purpose of this study. We also delved deeper into the design parameters important for SFSs, the performance of PTSs, and how the MCA method can be used generally, in the Background section. The synthesis of research in the MCA was done from the perspective of specific OSSFs, so the PTSs were chosen from extant commercial systems while the necessary dimensions of the SFSs were calculated (Method section).

1.1 Purpose and Objective

The purpose of this master thesis was to analyse the performance and sustainability of conceptualized, full-scale OSSFs with add-on filters (constituting systems), with regard to the treatment process of wastewater from a single household. The specific objective was to evaluate three different systems with a MCA, wherein the sustainability criteria were chosen and weighted and the system solutions were formulated and graded. Course students that had mapped out the responsibilities of stakeholders concerning OSSFs in Sweden provided the weighting perspective of the same within a discussion workshop. The grading was based on a synthesis of relevant research from the perspective of how the functional flow of the systems were conceived, which was the contaminant's path through the systems.

2. Background

2.1 Micropollutants

MPs consist of a vast and expanding collection of anthropogenic as well as natural substances, including e.g., pharmaceuticals and personal care products (PPCPs), steroid hormones, industrial chemicals, pesticides and many other emerging compounds. They often exist in water bodies at trace concentrations, at levels of ng L^{-1} to µg L^{-1} (Luo et al., 2014; Knopp et al., 2016). Consequently, the occurrence of MPs in freshwater sources is monitored worldwide. The impacts of these organic MPs on human and environmental health are presently unclear, but precautionary measures to avoid harmful effects are being implemented, such as end-of-pipe technical measures from point-sources to reduce MP discharge into the aquatic environment (Altmann et al., 2016).

There is as of today no requirement in Sweden that pharmaceuticals or other organic compounds shall be removed from wastewater. Selection of methods for removal of these organic substances has to be based on specific pharmaceuticals, and the level to which they have to be removed. It can be expected that future legislation will include other organic substances in addition to pharmaceuticals, as indicated by the watch list of the EU Water Framework Directive (Hörsing et al., 2014). Reduction of pharmaceuticals depends on the design and operation of the OSSFs, where good oxygenation and long residence time constitute favourable conditions for the reduction of most pharmaceutical substances. Those substances and OSSFs for which reduction is less efficient, are causing a substantial load of pharmaceuticals to the aquatic environment and GW. The risks of this load from OSSFs should be explored further, along with further analysis of reduction of pharmaceuticals in soil (Ejhed et al., 2012).

OSSFs have been evaluated for their capacities to remove nutrients (N, P) and suspended particles from domestic wastewater. OSSFs have been demonstrated to effectively remove microbial indicators from wastewater. However, there is insufficient knowledge on the occurrence and removal of organic contaminants such as PCBs, PPCPs, PFAs and PBDEs in OSSFs (Subedi et al., 2015). Swedish WWTPs are designed neither for degradation nor removal of pharmaceutical residues and other persistent organic pollutants (POPs). Powdered activated carbon (PAC) and ozonation are two methods commonly advocated, but filtration through granular activated carbon (GAC) is being studied more frequently. Advanced treatment is most often applied at the end of the treatment process, but examples can be found where ozonation and PAC/GAC has been integrated upstream in the treatment process (Cimbritz et al., 2016).

The design and implementation of OSSFs can vary widely, as well as MP occurrence between sources as a result of users served in an individual sewershed. MP concentrations are much more variable than traditional wastewater contaminants like dissolved organic carbon (DOC) and ammonia, even at a single location in a 24 h period (Teerlink et al., 2012). GAC has been used as a common measure for adsorbing water constituents to its surface in drinking water purification. However, GAC efficiency of MP removal might be significantly reduced by the presence of competing DOC in WWTP effluents (Altmann et al., 2014). This is signified by more and earlier MP breakthroughs occurring in GAC from an increase in background DOC (Kennedy et al., 2015). To solve this, placement of GAC filters after conventional OSSFs treatment is recommended, where DOC is commonly effectively degraded by microbes (SEPA, 1987).

2.2 On-site sewage facilities

The OSSFs discharging treated, domestic wastewater to GW include SFSs, e.g., infiltration systems, surface infiltration, reinforced infiltration, mound and infiltration well. The OSSFs discharging to SW include SFSs like sandbed filters, but also PTSs, that can treat the wastewater biologically or chemically. The conventional parts are comprised of a septic tank, a pumping well, the treatment facility itself, an outlet well, and a distribution well for the sandbed filter. The septic tank is situated first in order to remove sediment and large particles, normally containing a volume of 2.2 m^3 for a 5-p.e. household. An important consideration is that of pumping, which provides elevation to the treatment facility itself. It also dispatches the wastewater evenly to the facility over time, providing an even flow and treatment at the infiltration surface, with a microbial biofilm, and through the filter material (SEPA, 1987). The different component parts of the systems are depicted in Figure 1.

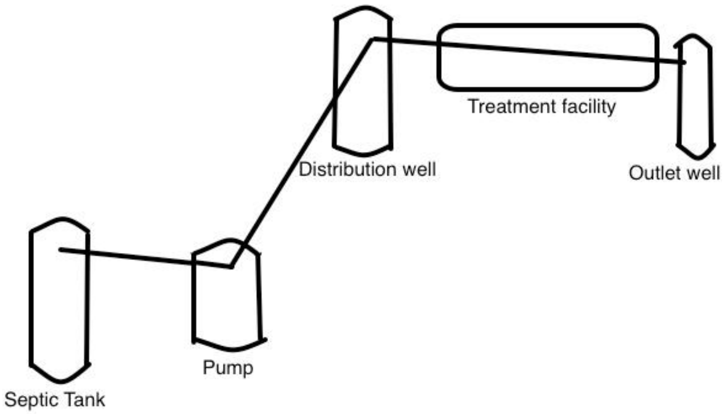

Figure 1. The generic component parts for an on-site sewage facility.

2.2.1 Sandbed filter

Most SFSs built in Sweden are gravity driven, often leading to a too deep placement under the ground level considering the risk of high GW level. This is opposite to the practice of placing the infiltration surface as shallow as possible, the facility thereby often being pump-driven, giving it greater height (Palm et al., 2012). The hydraulic longevity of SFSs is estimated to 30-40 years, but this is highly approximate. As long as the soil bed allows water to pass through, the biological function (including reduction of pathogens, biological oxygen demand (BOD) and N) is normally maintained. However, the chemical P-sorption process will decrease over time, mainly depending on the P load and the amount of soil available for the sorption process. In general, SFSs offers good sustainable use of resources and a sufficient protection for environment and health, as long as it is correctly situated and follows earlier SEPA recommendations (Palm et al., 2012).

In general, before construction of SFSs, a property owner might consider teaming up with neighbours, and determining its size for the number of connected households in his/her community or association. Concerning its placement, certain safety distances should be considered, nearby water sources being the most important one. The SFSs should be well downstream the withdrawal source as regards the GW stream, since the GW level is raised underneath the SFSs, but lowered underneath the source upon extraction, thereby risking reversing the direction of the GW current if the distance between the SFSs and the source is insufficient (SEPA, 2006b). Lastly, the terrain should be considered with placement, avoiding lowlands and too much inclination, leaving the middle of elevations with moderate tilt and the top of hills as the second best and best alternatives, respectively. The type of OSSFs and its configuration is mainly controlled by local soil- and GW conditions (SEPA, 1987, 2006b).

Soil samples are made, the purpose of which are to produce a particle size distribution curve for the local soil, comparing proportion of grains smaller than certain mesh with the same, containing requirement limits of the Swedish Geotechnical Society. It is good to avoid GW penetration into the facility, wherefore a distance of 1 m should be maintained between the bottom of the infiltration trench and the GW level during operation of the facility (SEPA, 2006c). The particle size distribution curve demonstrates the coarseness of the material and yields a recommended surface load and type of OSSFs, for example 5-6 cm d^{-1} for a sandbed filter. The fine material produces useful removal of contaminants and purification, but the coarse material provides high infiltration capacity. The coarser the material, the higher surface load is used because of higher infiltration capacity (SEPA, 1987, 2006c).

Within a sandbed filter, often about 2 m thick, there are drainage and diffusion pipes (Ø≈63 mm) along its length, with small holes (Ø≈8 mm) about 1 m apart, on their top and bottom, respectively. The diffusion pipes lies above the fine filter material, laterally discharging wastewater through this material. This is collected and discharged by the drainage pipes to the outlet well. The drainage pipes are situated underneath the filter material and about 1 m below the diffusion pipes. These two types of pipes should be of the same length and slope (≈0.5 %) within the treatment facility, and roughly above- and below one another for the purpose of collecting the wastewater, meaning they should be equal in number (SEPA, 1987).

The length of the diffusion and drainage pipes, L, are calculated according to equation 3, given by integrating equations 1 and 2:

$$L = \frac{A}{GP} \quad (1)$$

$$A = \frac{H}{B} \quad (2)$$

$$\rightarrow L = \frac{H}{BGP}, \quad (3)$$

Where
A is required total area at the horizontal infiltration surface [m^2],
G is total trench width at infiltration surface, recommended 1-2 m, where narrower width facilitates conduit to SW recipient, but thicker width reduces length and friction losses [m],
P is number of pipes, a maximum of five without a main distribution well,
H is water consumption per 5-p.e. household with WC, about 1000 L d^{-1} [m^3 d^{-1}],
B is maximal (infiltration) surface load for the filter material, for example 5 cm d^{-1} for foundry sand with trade name “Betongsand 0-8” [m d^{-1}] (SEPA, 1987, 2006c).

Other important functions are aeration of the soil bed to ensure BOD breakdown by the bacteria at the infiltration surface (where bacteria use other nutrients in the process), as well as de-sludging of the septic tank, normally performed once per year by the municipality, for OSSFs in Sweden (Palm et al., 2012). OSSFs have good ability to reduce bacteria and parasites, as well as viruses to a high degree, as they pass through their filter material that starts at the infiltration surface and continues laterally. Reduction of organic anthropogenic substances and pharmaceuticals could be expected to be at least as good in OSSFs as in municipal WWTPs (Gros et al., 2017). Recycling of nutrients is not a possibility with sandbed filters themselves, but could be achieved with add-on filters spread out on fields after use, with chemical precipitation or with SSS; for example blackwater or urine separation (Palm et al., 2012).

2.2.2 Tank-based package treatment systems

Manufacturers such as Flygt, Electrolux and Wallax installed the first PTSs in Sweden in the late 1960s. The first facilities were based on biological treatment with aeration or bio rotors, and active sludge. The modern PTSs with batch treatment and chemical precipitation of wastewater were launched in the late 1980s (County Administration Boards, 2009). The PTSs process varies with different suppliers, but usually includes chemical dosing, precipitation and aeration, like the SFSs. Screening for MPs, carried out in laboratories at the Swedish University of Agricultural Sciences (SLU) and Umeå University (UMU), revealed an average removal efficiency of 52.4 % for SFSs and 37.5% for PTSs (Zhang & Renman, 2016; Blum et al., 2017). It is challenging for municipalities to evaluate if the PTSs fulfil their requirements in a specific location regarding health and environmental protection. The CE certification, requiring third party testing of its treatment, impermeability and sustainability, aside from the manufacturer's own quality control, could be helpful in this regard (County Administration Boards, 2009).

Since 2005, there is a Swedish standard (SS EN 12566-3:2005) for testing of pre-fabricated and/or locally installed PTSs according to AC-class AC3, based on a European standard. Aside from lacking testing facilities of this standard in Sweden, thereby necessitating examination of PTSs in other Nordic countries or the PTSs country of origin, it is also hard to evaluate if the PTSs functions satisfactorily, even if approved EN-12566-3. Testing occurs in a laboratory, where the PTSs are loaded with municipal wastewater, therefore not resembling the wastewater the PTSs is required to treat full-scale. But above all, the PTSs is not exposed to climate, locally discrepant load or a lack of operational maintenance that is highly likely to influence its performance negatively. Lastly, the flocculation chemicals tested in the PTSs according to EN-12566-3 might be different than those used in the PTSs when it is finally launched into the Swedish market, resulting in dubious P reduction results (County Administration Boards, 2009).

According to the results of the 2009 study by three large County Administrative Boards in Sweden, in which 115 effluent water samples were taken for biological and chemical analysis on 24 different types of PTSs, the average BOD effluent was about 4.8 g BOD p^{-1} d^{-1}, just under 5.1 g BOD p^{-1} d^{-1}, which is the 2006 SEPA recommendation for high-level protection (Table 1). Further, the P effluent was about 0.8 g P p^{-1} d^{-1}, exceeding even the stringent normal-level protection (70%) of 0.6 g P p^{-1} d^{-1}, and the N effluent of 8.2 g N p^{-1} d^{-1} exceeded the high-level protection for N (Table 1). There is, however, no requirement for N at normal-level protection (SEPA, 2006a; County Administration Boards, 2009). The large sampling of every model for the different types of PTSs, and some of them being out of function in this study likely contributes to a picture of the true effluent load from PTSs in Sweden, despite the small number of different suppliers of PTSs. These results indicate a great sensitivity to disruptions in maintenance of many PTSs, and the conducted survey points to this being a common problem in Sweden, affecting the total PTSs load (County Administration Boards, 2009).

Table 1. High-level protection for on-site sewage facilities according to SEPA, 2006

	Reduction (%)	**Effluent [g p^{-1} d^{-1}]**
BOD	90	5.1
Tot-P	90	0.2
Tot-N	50	6.8

PTSs are normally constructed in order to reduce BOD, P and sometimes N as well. The reduction of pathogens is often poor if there is no processing unit installed for that purpose. SEPA's general advice gives no guidance as to when a requirement of post-treatment is justified, even though when a requirement is locally applied, it is often for the purpose of pathogen removal. Application of post-treatment requirement for PTSs is highly variable between municipalities due to a lack of guidance, which makes a description of the correct context for this requirement, along with appropriate technical solutions, considerably important in order to help manufacturers, suppliers and government authorities cooperate. Application of a requirement for post-treatment must nevertheless, as it is, be evaluated on a case-by-case basis. The post-treatment technical solution should have a documented positive function, and be adapted to the quality of the effluent water for the PTSs in question (Sylwan, 2011). For example, chemical precipitation occurs in the septic tank's sediment since the flocculation-dosing unit is situated to dispatch chemicals in the outlet conduit from the house into the septic tank, increasing its sediment production and required volume. (AB 4evergreen Solutions, 2016a). The P in the chemically precipitated sludge can thus be recycled to arable land after hygienisation, presuming the farming community accepts it. The flocculation-dosing unit could be used with both SFSs and PTSs (VA guide, 2016).

2.2.3 Removal of bacteria, micropollutants and phosphorus

In general, viable bacteria populations show an immediate decline as a result of disinfectant exposure. But the conditions in a recipient stream could result in substantial recovery of the total bacterial community. The bacterial groups commonly used as indicators do not provide an accurate representation of the response of the bacterial community to disinfectant exposure and later recovery in the recipient (Blatchley et al., 2007). In a study out of Suzhou, China, qPCR and Q-RT-PCR methods were employed to investigate the species and proportion of pathogenic bacteria in secondary effluent. The most abundant, potentially pathogenic bacteria were affiliated with the genera of Clostridium, Arcobacter and Mycobacterium. 99.9 % of culturable E. coli and Salmonella were removed by UV disinfection at 60 MJ cm^{-2}. However, less than 90 % of culturable Mycobacterium was removed, and the removal efficiencies of viable Salmonella, E. coli and Mycobacterium were low. The study found that other advanced treatment processes were needed to ensure safe utilization of reclaimed water (Jing & Wang, 2016). For example, the alkaline mineral-based material Polonite® intended for filter wells in on-site wastewater treatments, performs better in removing indicator bacteria (E.coli and Enterococci), on average, than Sorbulite (Nilsson et al., 2013a), but not significantly better than blast furnace slag with regard to removal of Enterococci. The reduction in Enterococci increases with higher BOD content in wastewater, probably due to higher concentration of bacteria in that wastewater (Nilsson et al., 2013b). A safe drinking water guideline according to the World Health Organization (WHO) in terms of E.coli and thermo-tolerant coliform bacteria is if they are non-detectable in 100 ml water samples (WHO, 2011).

GAC filtration is commonly used in drinking water treatment to remove natural organic matter and MPs. Filtration rates and the granular material are also comparable to those of rapid sand filtration, but with longer contact times, lower back wash intensity, higher adsorption capacities for organic compounds and higher biofilm concentrations, indicating an elimination of microorganisms, by GAC, to some extent (Hijnen et al., 2010). Besides adsorption, the removal of particulate matter by filtration and biodegradation of organic substances in these filters has often been reported. The use of GAC as adsorbent for MP removal and filter medium for retention of solids in wastewater filtration represents an energy- and space saving option, but high DOC and suspended solids concentrations in the influent of the GAC material puts a lot of pressure on the filter and might result in backwashing and insufficient filtration efficiency (Altmann et al., 2016). For the purpose of sizing the filter weight, Aquacarb 207C 12X30, a coconut-based GAC, can be used (as in this study). Once it is saturated, it can be recycled by thermal reactivation to over 800 ^{o}C and reused (Chemviron Carbon, 2014). Larger GAC particles (less specific surface area) result in slower adsorption kinetics, since the latter are generally inversely proportional to the square of GAC particle diameter. Larger particles thus cause earlier MP breakthrough (Kennedy et al., 2015).

Polonite is produced in Poland from a calcareous sedimentary rock of Cretaceous age, naturally hardened with silica, but thermally treated to 900 ^{o}C so that a transformation occurs from calcium carbonate ($CaCO_3$) to calcium oxide (CaO). CaO, being more reactive than $CaCO_3$, enhances the P removal capacity of the material (Renman & Renman, 2010). Polonite is usually produced in similar grain fraction as the filter material in SFSs, often giving it about equal and satisfactory hydraulic properties (SEPA, 1987; Renman & Renman, 2010). Besides filtration, flocculation is an alternative for P removal, for example with the coagulants alum, ferric chloride and lime, all of whose P removal efficiency varied between 90 and 95 % over a period of 18 months in two WWTPs (Narasiah et al., 1994). This could be compared to an average PO_4 removal of 89 % after 92 weeks of operation, in a compact bed filter. Those column experiments demonstrated that a design volume of 1-2 kg of Polonite was the required amount for treating 1 m^3 of wastewater in on-site systems operating at target 90 % P mass removal, representing the load of domestic wastewater from one household per day. A filter has to contain sufficient material that a decline of P-sorption is minimised for a replacement interval, due to too much spent material (SEPA, 1987; Renman & Renman, 2010).

2.3 Multi-criteria analysis

MCA is a framework for evaluating decision options against multiple criteria. Numerous techniques for solving an MCA problem are available, weighted summation being one of them, and used in this study. While selection of the MCA technique is important, more emphasis might be needed on the initial structuring of the decision problem, which involves choosing criteria and decision options (Hajkowicz & Higgins, 2006). Advanced treatment processes such as reverse osmosis, ozonation, nanofiltration and adsorption are common industry-recommended processes for MP removal. However, natural systems such as constructed wetlands and riverbank filtration could also be efficient options for MP elimination from wastewater. In a study out of Saudi Arabia, a survey between two groups of participants including academics and industry representatives was conducted to assign weights for the criteria. The process rankings varied depending on the criteria and personal preferences (weights). The results suggested that the use of a hybrid treatment process, e.g., combining a natural system with an advanced treatment process, might provide benefits for MP removal. The MCA, as a decision support system, could be used as a screening tool for experimental planning or a feasibility study preceding the main treatment system selection and design. It can also be considered an aid in evaluating a multi-barrier approach to removing MPs (Sudhakaran et al., 2013).

3. Method

In order to apply the MCA framework in this subject area, the goal with the method and the specific system boundaries were formulated. The criteria were selected and the system alternatives formulated and conceptualized regarding their functional flow. The grading of environmental criteria was based on a synthesis of published research concerning the treatment process of wastewater in OSSFs and WWTPs. The socio-economic criteria were based on the size and function of the conceptualized OSSFs. Two students and a supervisor role-playing the stakeholders, within a joint discussion workshop, applied criteria weights based on their perspectives. The weights were compared to those of real stakeholders and a sensitivity analysis was conducted for the results of the final scores.

3.1 Goal and scope

The objective of this report was to use the MCA method in order to evaluate conceptualized, full-scale OSSFs. These have extra capabilities for removal of P and MPs. The goal, or the desired result, of this method was to provide a proof-of-concept analysis of conceptualized treatment technologies in order to serve as decision-support at a national policy level. This is as opposed to a consumer level, in that the MCA is meant for decisions earlier in the process, of what legislature and financing to apply for which OSSFs, in Sweden. The decision-makers given support from this particular MCA would not be property owners, whose choices are made from the available market, not conceptualized systems assembled from commercially available parts. The decision-makers would rather be SEPA, SwAM, County Administrations, regulators, and other government authorities.

3.1.1 Formulation of system boundaries

In order to limit the scope of this MCA, which is largely based on data from a literature study, the system boundaries was formulated as the treatment process of domestic wastewater in the OSSFs from a single household, excluding possible SSS within the same household, as well as an analysis of the environmental impact of the system over its lifetime with a life-cycle analysis (LCA) (Figure 2). However, the effluent load post-treatment from these OSSFs was compared to SEPA’s 2006 recommendation. An approximate lifetime of 40 years was used for these facilities, as outlined with some scepticism in (Palm et al., 2012). This was important for a part of the economic analysis, see the coming method section, Selection of sustainability criteria. The geographic location of the OSSFs was generic, in Sweden, not a specific location. But the treatment process for the facilities was assumed to be unaffected by similar systems, whereas the recipients were sensitive to high nutrient loads, thereby necessitating high-level protection according to SEPA’s 2006 recommendation (SEPA, 2006a).

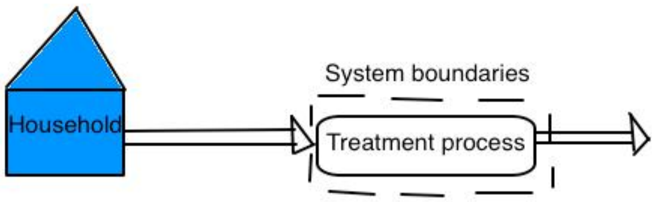

Figure 2. The system boundaries of this study as regards the on-site sewage facilities.

3.2 Selection of sustainability criteria

The sustainability criteria were selected from an assortment of preliminary criteria discussed in the RedMic project (Andersson, pers.comm. 2016). This was done in order to draw upon earlier work on highlighting important aspects of OSSFs. Some facets were removed from this original selection, with respect to the history of environmental concerns with OSSFs, other important environmental aspects, and with regard to if some social criteria could overlap with others. Then, the criteria were described anew by the author, to keep their characteristics separate and facilitate subsequent evaluation. These descriptions are shown in the results section, Selections of sustainability criteria, and the criteria themselves are enumerated in this section (Table 2).

Table 2. The sustainability criteria selected for evaluation in this study

Environmental aspects	Socio-economic aspects
1. Microbial risks	6. Life-cycle costs
2. Removal efficiency (RE) of eutrophying substances (ES)	7. User-friendliness
3. RE of MPs	8. Intrusiveness
4. Potential for recycling of nutrients	9. Ease of compliance
5. Energy use	10. Operation and maintenance

3.3 Formulation of system alternatives

The systems should be easily comparable, both in component parts and functional flow, which is the function of the different treatment steps in the system. Further, it was assumed that in addition to the high-level protection of SEPA's 2006 recommendation being in effect, so are requirements to treat MPs. This required a comparison of common OSSFs, but with extra capabilities to treat P and MPs. The former is already applied for sensitive areas, while the latter is used exclusively in WWTPs. There was also a need for a reference solution, in order to scale the evaluated grades of the systems. This reference solution should comprise extra capability to remove P, but not necessarily MPs, since it is desirable to evaluate if it is a worthwhile effort to install the extra MP removal capabilities. Since it is advantageous to discharge the treated wastewater to a SW recipient, this leaves the sandbed filter of the SFSs, as well as PTSs. The PTSs can remove P with precipitation, as they were first supplied in the late 1980s in Sweden, or with add-on filters, which is also true for SFSs. Two types of PTSs were conceptualized, one of which was a reference. Thus were the system solutions conceived (Table 3). The add-on filters in the system solutions are localized in the outlet well.

Table 3. The conventional part of the on-site sewage facilities, as well as their extra capability to remove phosphorus and micropollutants with add-on filters, along with the reference solution

	Conventional	Phosphorus	Micropollutants
System solution 1	Sandbed filter	Polonite	GAC
System solution 2	PTSs	Polonite	GAC
Reference solution	PTSs	Precipitation	-

3.3.1 Conceptualizing a theoretical sandbed filter system

When conceptualizing the sandbed filter, it was most important to calculate its infiltration surface area and to decide its height but also elevation relative to the soil surface. A pump provided many advantages aside from its cost; see the background section, On-site sewage facilities. However, there are solutions for managing if the facility or outlet well is located too deep, so the design can be adapted to local soil conditions. To calculate the infiltration surface, one might assume the one household condition as in the background section, Sandbed filter. With five drainage and diffusion pipes to reduce length while also avoiding a main distribution well, the calculated area is 4 m^2. In order to reduce friction losses along the pipe length, one might assume an infiltration trench width of 1.6 m, which is between 1 and 2 m. It might then be thick enough to reduce friction but also narrow enough to facilitate discharge to a SW recipient. This yields drainage and diffusion pipe lengths of 2.5 m, and since a normal height is 2 m, this gives a volume of approximately 8 m^3. It could be constructed partly or entirely as a mound above the soil surface.

When considering a functionality flow chart for the sandbed filter, one must contemplate what contaminants are mainly reduced from the wastewater in what part of the system. Table 3 is a good point of departure, since it can delineate the different stages of the treatment process. The wastewater enters the sandbed filter facility at the infiltration surface, where the diffusion pipes start and distribution pipes end (SEPA, 1987), and proceeding with appropriate inclination and flow to the far end of the 2.5 m pipe. At the infiltration surface, the microbes break down the organic matter, using nutrients like N and P, but functionally the main reduction is BOD. This part of the process is a kind of bottleneck, allowing the organic breakdown to occur, but afterwards the wastewater is laterally discharged through the small bottom holes and proceeds through the fine filter material. This constitutes a barrier to especially bacteria and parasites, but to a great degree to viruses as well, thereby creating hygienisation. This completes the wastewater treatment of the conventional part of the sandbed filter. Figure 3 depicts the functional flow of the sandbed filter with add-on filters. When the wastewater has been filtered through the fine filter material, it is collected by small holes at the top of the drainage pipes and driven on to the outlet well. There it is filtered through Polonite and GAC, where P, MP and bacteria are removed, see the background section, Removal of bacteria, micropollutants and phosphorus, and Figure 3. Nutrients such as BOD and N are also removed in these filters, but to a lesser degree and, especially in the case of BOD, the treatment occurs from lower influent concentration. As an amendment, a UV lamp is put into this conceptualized sandbed filter in order to disinfect pathogens and equalize between the alternatives, see the background section, Choosing tank-based package treatment systems below.

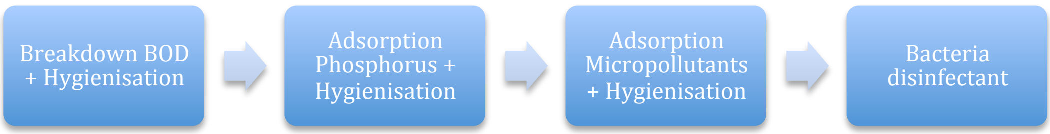

Figure 3. The functional flow of the sandbed filter with Polonite and GAC add-on filters, as well as disinfection of bacteria with a UV lamp.

3.3.2 Choosing tank-based package treatment systems

The point of departure for selecting the two PTSs was a market overview for OSSFs products, for the purpose of helping property owners know their alternatives for adopting new systems (VA guide & SwAM, 2016). This guide contained mostly PTSs, and two were chosen out of four known PTSs that already use Polonite, or where the alternative exists. One of these also had the option to use chemical flocculation agents, and naturally this was chosen to constitute the reference solution. The PTSs with Polonite was called “BIOP” (Svensk Avloppsrening, 2016a), while the PTSs reference with precipitation was called “Biorock”, described by the company as a “sandbed filter in a jar” (AB 4evergreen Solutions, 2016b). The functional flow of BIOP and Biorock was conceptualized mainly from its product sheet and descriptions of how it works, respectively (AB 4evergreen Solutions, 2016d; Svensk Avloppsrening, 2016b); see Figure 4 and Figure 5. As an amendment, a UV lamp is put into both these conceptualized PTSs in order to disinfect pathogens. According to the market overview mentioned above, BIOP had the cylindrical dimensions of 2.1 m diameter and 2.2 m height, corresponding to a volume of about 7.6 m^3. Likewise, Biorock had the effective rectangular dimensions of 1.5 m length and width, and 2 m height, corresponding to a volume of 4.5 m^3. Further, the market overview indicated that both PTSs could be installed above or below the soil surface, as desired (VA guide & SwAM, 2016). This could be important for evaluating some social criteria, considering that the sandbed filter considered here is conceptualized as a mound, partially or entirely above the soil surface.

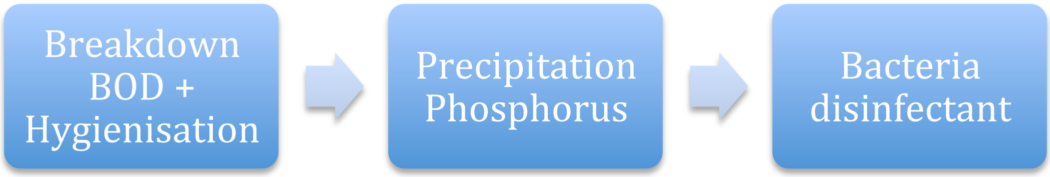

Figure 4. The functional flow of the package treatment system with precipitation of phosphorus, which is the reference solution Biorock. Package treatment systems often contain disinfection of bacteria with a UV lamp.

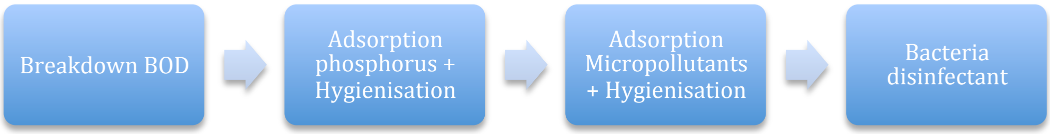

Figure 5. The functional flow of the package treatment system with Polonite and GAC, which is called BIOP. Package treatment systems often contain disinfection of bacteria with a UV lamp.

3.3.3 Removal of micropollutants and phosphorus, weight add-on filters

The weight of the add-on filters is important to avoid a breakthrough that severely hampers treatment efficiency due to spent filter material, as well as to determine the costs of this part of the systems. In order to determine the weight of GAC, the results of a column experiment by the Department of Land and Water Resources Engineering at the Royal Institute of Technology (KTH) was used, in which the DOC values and removal efficiency of certain filters during 12 weeks were measured. The five filter assortments that were used in this experiment were sand, lignite, Polonite & GAC, GAC and xylit. However, only GAC and xylit had high removal efficiency of DOC over the course of the experiment period, and as research about the removal efficiency of MPs with xylit was found lacking, only GAC was used for that purpose in this study. Polonite is studied here for the removal of P, even though its DOC removal efficiency is not insignificant. A replacement interval of two years for GAC yielded a filter capacity of about 119 g GAC m^{-3}, and thereby a necessary weight of 87 kg GAC, see Appendix A – Weight of add-on filters. In order to determine the weight of Polonite, treatment stencils and removal efficiencies of P from SEPA's technical specifications and 2006 general advice was used, as well as the same replacement interval of two years and an adsorption capacity of 1 % of the P load. The calculated total weight was 493 kg, approximately 500 kg, as seen in Appendix A – Weight of add-on filters.

3.4 Grading process

The overall methodology for grading the environmental criteria was calculations based on the functional flows and published research data. For microorganisms, nutrients and MPs, the process comprised of the gathering of data on the functional flow and different parts of the system, and calculating the final removal efficiency. Data was also obtained on the load of untreated wastewater for indicator pathogenic bacteria, P, N and BOD but not of MPs due to its variability of concentration. In this way, the effluent load or reduction of the treated wastewater was compared for the three system solutions. The energy use was obtained by calculating the annual electricity use of a typical pump for an assumed rise of elevation, unless this data was otherwise given in a product sheet. Furthermore, it was calculated by considering the energy use in production and transport of the add-on filters, which were used in the treatment process. However, this data was hard to find for the precipitation chemicals, see Appendix B – Economy and Energy. The nutrient recycling potential was evaluated by analysing it for the filters, on whose surface there is ample adsorption of most of the nutrients. The life-cycle costs were calculated from data of the main mechanical parts of the system. This was considered from the installation costs, as well as the annual costs over the lifetime of the OSSFs, in order to take into account the maintenance costs, see Appendix B – Economy and Energy. The social criteria were all evaluated based on the size and the inconvenience of the necessary actions to control and maintain treatment efficiency of the OSSFs. The criteria were thus assigned a grade of 1-5 (Table 4).

Table 4. The scale of grades and their definitions

Grades	**Definition**
1	Very poor
2	Poor
3	Neutral
4	Good
5	Excellent

A table for grading would look like Table 5, considering that the reference solution was scaled to 3 for each grade. Concerning the recycling of nutrients, the reference solution has capacity to achieve it when a farming community accepts the chemically precipitated sludge. If it was deemed a higher probability that the filter solutions were accepted to recycle nutrients than the reference solution, they were given a higher grade. The results of both filter solutions are shown in the Results section.

Table 5. The grades before the filter solutions are assigned, for each criterion

	Sandbed filter	**PTSs reference**	**PTSs with filters**
1. Microbial risks	-	3	-
2. RE of ES	-	3	-
3. RE of MPs	-	3	-
4. Potential for recycling of nutrients	-	3	-
5. Energy use	-	3	-
6. Life-cycle costs	-	3	-
7. User-friendliness	-	3	-
8. Intrusiveness	-	3	-
9. Ease of compliance	-	3	-
10. Operation and maintenance	-	3	-

3.5 Weighting process

In order to conduct a weighting of the criteria, a discussion workshop was arranged which included two KTH students and a supervisor, who was a participant in the RedMic project, and had interviewed property owners and municipal regulators. The contributors were in the process of conducting a project course in Applied Industrial Ecology, a KTH Master Programme. In that course they mapped out important stakeholders regarding OSSFs in Sweden, according to their responsibilities and perspectives. The three partakers were therefore able to role-play as a representative each of the most important of these stakeholders, namely a property owner, a generic municipal regulatory office and SwAM. From these perspectives, the role-players assigned 100 points to the 10 criteria individually, before the other participants. The minimum allowed allocated weight was 0.1 points and the maximum was therefore 99.1 points. These points were afterwards motivated, discussed and adjusted by all workshop partakers (Table 6). Other important stakeholders might have included SEPA, Statistics Sweden, Formas, The Swedish Chemicals Agency, The Swedish Water & Wastewater Association (SWWA), as well as entrepreneurs and suppliers of common OSSFs in Sweden (Andersson *et al.*, 2012).

Table 6. How the most important on-site sewage facility stakeholders assign the weights

	SwAM	**Property owner**	**Regulator**
1. Microbial risks	-	-	-
2. RE of ES	-	-	-
3. RE of MPs	-	-	-
4. Potential for recycling of nutrients	-	-	-
5. Energy use	-	-	-
6. Life-cycle costs	-	-	-
7. User-friendliness	-	-	-
8. Intrusiveness	-	-	-
9. Ease of compliance	-	-	-
10. Operation and maintenance	-	-	-

This process provided a minimum and a maximum weight out of the three choices (Table 7).

Table 7. The minimum and maximum assigned weights, creating a range (R_i) with indices i=1, 2, …

	Range (R_i)
1. Microbial risks	R_1
2. RE of ES	R_2
3. RE of MPs	R_3
4. Potential for recycling of nutrients	R_4
5. Energy use	R_5
6. Life-cycle costs	R_6
7. User-friendliness	R_7
8. Intrusiveness	R_8
9. Ease of compliance	R_9
10. Operation and maintenance	R_{10}

These created weight ranges (R_i), which were used to multiply with the grades (G) in order to obtain a summed-up final score for all the systems and criteria (Table 8).

Table 8. The final scores, obtained by multiplication of ranges with grades, for all the systems and criteria, with the summed-up final score for all on-site sewage facilities

	Sandbed filter	PTSs reference	PTSs with filters
1. Microbial risks	GR_1	GR_1	GR_1
2. RE of ES	GR_2	GR_2	GR_2
3. RE of MPs	GR_3	GR_3	GR_3
4. Potential for recycling of nutrients	GR_4	GR_4	GR_4
5. Energy use	GR_5	GR_5	GR_5
6. Life-cycle costs	GR_6	GR_6	GR_6
7. User-friendliness	GR_7	GR_7	GR_7
8. Intrusiveness	GR_8	GR_8	GR_8
9. Ease of compliance	GR_9	GR_9	GR_9
10. Operation and maintenance	GR_{10}	GR_{10}	GR_{10}
∑1-10. Final score	$\sum GR_i$	$\sum GR_i$	$\sum GR_i$

The weighting was greatly affected by the role-players knowledge, values and interests, and these were in all likelihood discrepant from those of actual stakeholders, even if the participants' knowledge in this area was elevated and an informal comparison was made with existent stakeholders at the workshop. However, an incongruity would be difficult to avoid, and in order to mitigate this, comparisons were made with studies that had used the weighting of real stakeholders, see the Discussion section. Also, a sensitivity analysis was conducted for the grades and weights that were deemed to affect the results most; see the section on Sensitivity analysis. Finally, one should keep in mind that this method is a proof-of-concept of decision-support at a policy level. It would need better decision options, perhaps additional criteria, and extra stakeholders, preferably real ones, in order to better serve as a decision-support. So before decisions are needed at a national policy level, this method could be used to greater effect if emphasis is put on initial structuring of the decision problem, see the background section, Multi-criteria analysis.

4. Results

4.1 Selections of sustainability criteria

As seen in the method section, Selection of sustainability criteria, the sustainability criteria were chosen from a collection of preliminary criteria in the Swedish RedMic project. The sustainability criteria were more precisely defined in this section, independently and anew by the author. This was done in order to delineate the methods by which the system solutions were graded, facilitate the weighting process and avoid misunderstandings with the participants in the discussion workshop.

4.1.1 Selections of environmental criteria

4.1.1.1 Microbial risks

This criterion defines how well the treatment facilities remove pathogenic bacteria and viruses from the wastewater. Both the barriers in the conventional part, the removal capacity of the add-on filters and that of other hygienisation strategies such as disinfection were evaluated.

4.1.1.2 Removal efficiency of eutrophying substances

This criterion expresses how well the system absorbs nutrients, specifically N, P and BOD, a large share of the latter being DOC. The removal capacity of the conventional part and the extra capacity of P was calculated from literature surveys and compared, with regard to N, P and BOD. The removal capacity of GAC was assumed to be negligent for these substances, in terms of load, when used to treat tertiary effluent, as occurs in this study.

4.1.1.3 Removal efficiency of micropollutants
This criterion delineates how well the system removes MPs on average, as one large disparate group. This data concerned the conventional parts as well as GAC, but the studies giving the average results did not, in all likelihood, concern the same group of MPs.

4.1.1.4 Potential for recycling of nutrients
Especially the capability to recycle P was evaluated since it constitutes a limited nutrient. An investigation of possible eco-toxic effect of recycling MPs in the process was not conducted. But processes to reuse spent material were considered.

4.1.1.5 Energy use
The energy use criterion included a calculation of how much energy [MJ; kWh] the systems use, whose expenditure originates partly from its pump. This provides a certain flux, pressure and especially elevation to the facility. But energy consumption also occurs indirectly from the add-on filters, which is why this energy use was included in the calculation.

4.1.2 Selections of socio-economic criteria

4.1.2.1 Life-cycle costs
This criterion comprise a calculation of how much the systems would cost for the one-time installation, as well as what this installation and maintenance would cost annually over the life-time of the facilities, for the property owners.

4.1.2.2 User-friendliness
This criterion designates how intricate it would be for the property owners to understand their responsibility for the facility functioning as intended. They need to know what specific actions need to be taken for controlling a proper function, for example sampling the treated effluent, that they might do it themselves or hire a service.

4.1.2.3 Intrusiveness
This criterion elucidates how large a space is needed for the facility, of the property owner's plot or land. This could have implications for rendering it difficult to avoid an intrusion upon a neighbour's plot, or to satisfy the required safety distances or distances that facilitate maintenance. Other aspects could be the noise or smell that the facility causes.

4.1.2.4 Ease of compliance
This criterion outlines the difficulty to know that the facility fulfils present legislation concerning its treated effluent. Crucially, the property owners need to be informed if there is new legislation coming in effect after the installation, whose requirement the OSSFs no longer fulfils.

4.1.2.5 Operation and maintenance
This criterion pertains to the difficulty of performing the specific actions that are needed to operate and maintain the facilities. The property owners can decide to accomplish this themselves or, as is almost universally the case, to use a service agreement. The latter case reflects the difficulty of the actions taken in the annual cost of the agreement. Either way, the inconveniences of the actions needed are evaluated, including sludge removal and the

replacement of filters or provisioning of chemicals. If these actions produce side effects, such as the creation of chemical by-products, this should be factored in.

4.2. Evaluating the system solutions

This section included the various literature results and calculations underlying the evaluations of half the criteria (mostly environmental), as well as the important considerations underlying the other half of the criteria (mostly social), for each of the OSSFs.

4.2.1 Sandbed filter

4.2.1.1 Evaluation of microbial risks

For comparison the indicator coliform bacteria was used. There is for example 6.34-log total coliform colony-forming units (cfu) per 100 ml septic tank effluent observed in a study in the US (Stacy et al., 2009). If this is assumed to be the total coliform bacteria concentration of the influent into the OSSFs in this study, the functional flow of the treatment process can be used to deduce the effluent of the respective OSSFs. The conventional part of the sandbed filter can reduce the coliform bacteria by about 99 % (2.0 log) (SEPA, 1987), which would leave about 4.34-log total coliform cfu $(100 \text{ ml})^{-1}$ in the sandbed filter effluent. Going along the functional flow to approximate for the effluent concentration, Polonite reduced coliform bacteria in column experiments at an average of 60 % (0.67 log) of E. coli, here approximated as coliform bacteria, for the duration of time until just before breakthrough (Nilsson et al., 2013a). This is similar to the full-scale situation considered here, in that Polonite is set to reach its limit of unspent material in two years, as a worst-case scenario for P adsorption capacity. Even if the material mostly traps P, this process seems to affect its adsorption of other nutrients and bacteria as well (Nilsson et al., 2013a). A 60 % removal would leave about 3.67-log total coliform cfu $(100 \text{ ml})^{-1}$ in the treated wastewater. In pilot plant (fresh and loaded) GAC filters with pre-treated SW at half the contact time of full-scale GAC-filters, the removal of E.coli ranged from 0.1-1.1 log reductions. This could be assumed as an approximately similar adsorption rate to coliform bacteria. It is not unreasonable, considering the limited contact time of that study, to assume the average of about 54 % (0.6 log) reduction in this full-scale situation (Hijnen et al., 2010). That would leave about 3.07-log total coliform cfu $(100 \text{ ml})^{-1}$ in the tertiary effluent. UV irradiation as a final disinfection step, in a WWTP in the greater Auckland New Zealand region, proved to reduce faecal coliforms by about 99.7 % (2.5 log) ((Jacangelo et al., 2003). The same effect here would reduce the effluent concentration to about 0.57-log total coliform cfu $(100 \text{ ml})^{-1}$, or about 3.7 cfu $(100\text{ml})^{-1}$. This treated wastewater could almost be considered safe since the guideline values for total coliform in 100 ml water samples is 0 cfu $(100 \text{ ml})^{-1}$ according to both the US EPA, Canadian Ministry of Health and the WHO (Rompré *et al.*, 2001).

4.2.1.2 Evaluation of removal efficiency of eutrophying substances

Concerning the total P (Tot-P) removal, the treated wastewater after sandbed filter contains approximately 1.500 g P p^{-1} d^{-1} compared to 2.040 g P p^{-1} d^{-1} in untreated wastewater. Polonite reduced this by 90 % to 0.150 g P p^{-1} d^{-1}. This is lower than 0.204 g P p^{-1} d^{-1}, or 90 % reduction, that is the high-level requirement in SEPA's 2006 recommendation (SEPA, 1987, 2006a), Appendix A – Weight of add-on filters. Concerning the total N (Tot-N) removal, the treated wastewater after the sandbed filter contains approximately 12 g N p^{-1} d^{-1}, compared to 13.6 g N p^{-1} d^{-1} in untreated wastewater (SEPA, 1987, 2006a). Polonite manages approximately 17.7 % reduction of total inorganic N (TIN), and assuming the same reduction for Tot-N, the load is reduced to about 9.9 g N p^{-1} d^{-1} (Nilsson et al., 2013a). This is higher than 6.8 g N p^{-1} d^{-1}, or 50 % reduction, that is the high-level requirement in SEPA's 2006 recommendation (SEPA, 2006a). It is reasonable to assume that a sandbed filter could itself approximately fulfil the high-level requirement of 90 % BOD reduction, reducing this load in untreated wastewater from 47.6 g BOD p^{-1} d^{-1} to 5.1 g BOD p^{-1} d^{-1} in treated wastewater. (SEPA, 1987, 2006a). Polonite would reduce this BOD load by a further 68 %, down to about 1.6 g BOD p^{-1} d^{-1} with new filter material, although this reduction would probably go down precipitously with time, since P adsorption over time results in less adsorption of other substances as well (PIA - Prüfinstitut für Abwassertechnik GmbH, 2015; Water facts, 2016).

4.2.1.3 Evaluation of removal efficiency of micropollutants

As stated in the background section, Micropollutants, MPs are a highly disparate group of pollutants representing a wide range of physico-chemical and biological properties. They are also variable in concentration and occurrence between localities. This also applies over time in the same OSSFs or WWTPs, since the usage varies. For the sandbed filter, the average removal efficiency of Swedish SFSs found in (Zhang & Renman, 2016) was 52.4 %, and this value was used in this study. It was detailed in the Micropollutants background section that DOC might have a competitive edge over many MPs when it comes to GAC adsorption. For example, of 30 studied MPs in five different SW, all of them led to GAC breakthrough after DOC (Kennedy et al., 2015).

SWWA has stated that Switzerland was the first country, in January 2016, to institute general requirements for different MPs, especially pharmaceuticals. This was after concluding that, although working to reduce MP usage upstream is crucial, it is probably insufficient to eliminate the negative effects of some substances that remain after conventional wastewater treatment. The requirements state that certain compounds according to a certain list should be removed by at least 80 %, indirectly leading to the removal of other persistent compounds, when the necessary technologies are instituted to meet the requirements. These are proposed as ozonation and PAC. But GAC filtration is also diligently studied (Cimbritz et al., 2016).

It is not unreasonable to assume it could meet these requirements since GAC and PAC both could yield comparable MP removal for many compounds at similar carbon usage rates, but GAC achieves considerably higher biodegradable MP removal (Altmann et al., 2016). Without considering individual MP compounds, the GAC filter was supposed to separate an average of 80 % of all MP compounds, which there is good cause for (Altmann et al., 2016). This is still less than the above 90 % DOC removal of GAC for the first 12 weeks of the column experiment, but DOC adsorption is often higher than MP adsorption; see the background section, Micropollutants, and the method section, Removal of micropollutants and phosphorus, weight add-on filters. The MP removal of 80 % is in addition to the 52.4 %, typical for at least some SFSs in Sweden (Zhang & Renman, 2016). This indicates 90.5 % RE of MPs in this case.

4.2.1.4 Evaluation of potential for recycling of nutrients

Polonite can be used to recycle nutrients. When approximately 6-8 tons were applied per hectare of a wheat crop field, the amendment did not affect soil physical and sorption properties, but the rate was negligent as a P source for wheat in that soil (Cucarella et al., 2012). However, when Polonite had likewise been saturated with P after wastewater treatment, and again tested as fertilizers, but in a pot experiment, it induced the highest yield of barley per unit of amendment. This was higher than Filtra P and wollastonite, due to higher P content; also leading to slightly increased soil pH and decreased hydrolytic acidity (Cucarella et al., 2007), thus reducing Al toxicity risks and decreasing metal uptake in amended soils, especially Mn uptake (Cucarella et al., 2009).

Although nutrients can hardly be recycled from GAC, spent GAC (sGAC) itself can be recycled for drinking water treatment via pulverizing, as low-cost MP adsorbents. However, a decreased surface area and the induced surface acidic groups on the pulverized sGAC contributed to lower uptake, in a study in the Journal of Environmental Management. But the pulverized sGAC was less susceptible to adsorption competition due to its negatively charged surface that can repulse the accessibility of the co-present organic matter, suggesting the reusability of drinking water sGAC for MP adsorption in treated wastewater (Hu et al., 2015). This alternative for lower cost is in addition to thermal reactivation, as seen in the background section, Removal of bacteria, micropollutants and phosphorus.

4.2.1.5 Evaluation of energy use

Apart from the electricity usage with the pump, about 40 kWh yr^{-1}, as seen in Appendix B – Economy and Energy, there is the additional energy use concerning GAC to observe, due to its production, rather than the approximately null energy use at the OSSFs, at least that is the case with PAC at WWTPs (Cimbritz et al., 2016). The cumulative energy demand (CED) for the manufacturing of GAC for three investigated municipal WWTPs with GAC filtration was 1.78 kWh m^{-3} for a dosage of 45 g GAC m^{-3} treated wastewater, including 0.01 kWh_{el} m^{-3} energy demand at the WWTPs, and 1.77 kWh m^{-3} energy demand beyond the WWTPs, called primary energy demand (PED) (Mousel et al., 2017). This could be assumed to be the case for the studied full-scale OSSFs with 119 g GAC m^{-3}. This would, assuming linear relationship between dosage and energy demand, correspond to about 4.71 kWh m^{-3} of treated wastewater. Assuming a water consumption of 1 m^3 per household, that corresponds to about 1.72 MWh yr^{-1}, for a total of 1.76 MWh yr^{-1}, with the pump.

Since GAC used in MP removal requires regeneration or replacement (Bui et al., 2016), its energy use is considered whereas Polonite could be recycled to the soil. However, the reuse of GAC could reduce the energy use by half compared to fresh GAC, though not always with the same MP adsorption. There exists a great potential for optimization of CED by enhancing the performance of GAC filters, leading to lower dosages used. Also, GAC made from renewable material has not yet been optimized for MP removal, but could be (Mousel et al., 2017). This would probably signify a higher specific surface area; see the background section, Removal of bacteria, micropollutants and phosphorus. Only energy use regarding the treatment process was analysed, see system boundaries in the method section, Formulation of system boundaries, signifying the pump and the filter energy use. In contrast, total energy use in Sweden 2013 was about 565 TWh (Swedish Energy Agency, 2015). A short summation of most environmental criteria results for the sandbed filter is depicted in Table 9 and Table 10.

Table 9. The results of the environmental criteria that depict effluent load for the sandbed filter with Polonite and GAC. The effluent loads of phosphorus, nitrogen and BOD are compared with SEPA's 2006 general advice, high-level requirement. The septic tank effluent (facility influent) is assumed to be 6.34-log total coliforms cfu $(100\ ml)^{-1}$ that was observed in a study in the US (Stacy *et al.*, 2009)

	Sandbed filter	**SEPA's 2006 general advice**
1. Microbial risks [cfu $(100\ ml)^{-1}$]	0.57-log total coliform	-
2a. RE of P [g p^{-1} d^{-1}]	0.15	0.20
2b. RE of N [g p^{-1} d^{-1}]	9.9	6.8
2c. RE of BOD [g p^{-1} d^{-1}]	1.6	5.1

Table 10. The results of the environmental criteria that depict proportion of MP influent that is reduced through the facility, as well as the energy expenditure throughout the facility, for the sandbed filter

	Sandbed filter
3. RE of MPs [% reduction]	90.5
5. Energy use [kWh yr^{-1}]	1,760

4.2.1.6 Evaluation of socio-economic criteria
For a calculation of the installation investment as well as the annual cost for the lifetime of the sandbed filter, considering all its components, see Appendix B – Economy and Energy. For the social criteria, the most important considerations are that the sandbed filter is a mound, indicating that it could be bulky on a plot. However, its size is similar to both PTSs considered, neither of its filters require handling of chemical by-products (Bui et al., 2016; Ecofiltration, 2016c), and Polonite can reduce odour (Ecofiltration, 2016b). Its only maintenance consists of sludge removal once per year and replacing of filter media once every two years (background section Sandbed filter); (method section Removal of micropollutants and phosphorus, weight add-on filters).

4.2.2 Package treatment system – reference

4.2.2.1 Evaluation of microbial risks
6.34-log total coliform cfu $(100\ ml)^{-1}$ is again assumed to be the total coliform bacteria concentration of the influent into the OSSFs in this study, see the results section, Sandbed filter. As the Biorock functions like a sandbed filter, it could be assumed to remove coliforms, that are analysed here as an indicator bacteria, just as well as the sandbed filter functionally in the conventional part (AB 4evergreen Solutions, 2016d). This would signify that the coliforms are once again reduced by 99 %, or 2-log total coliform cfu $(100\ ml)^{-1}$, see the above results section, Sandbed filter. Functionally there are no more barriers or filters in the reference system after the conventional part. However, this system could also be assumed to employ UV irradiation as a final disinfection step (AB 4evergreen Solutions, 2016b), which would reduce the influent by 2.5 log (99.7 %) (Jacangelo et al., 2003). This would indicate just about 1.84-log total coliform cfu $(100\ ml)^{-1}$, or 69.2 cfu $(100\ ml)^{-1}$, remaining in the treated secondary effluent of this conceptual PTSs. This treated wastewater could not be considered safe, see the aforementioned results section, Sandbed filter.

4.2.2.2 Evaluation of removal efficiency of eutrophying substances
According to 4evergreen's CE-certified and EN-12566-3 test fallouts, the following results were obtained, for which scepticism is warranted if proper annual maintenance is neglected, including sludge removal (background section Sandbed filter) and refilling of chemicals. The system would cease to treat P entirely if chemicals were missing (VA guide, 2016). See the background section, Tank-based package treatment systems, for the importance of proper maintenance. For P, there is a 97.5 % reduction down to about 51 mg P p^{-1} d^{-1}, lower than the 90 % reduction of SEPA's 2006 high-level requirement to 204 mg P p^{-1} d^{-1}, as well as the 150 mg P p^{-1} d^{-1} of the posited sandbed filter. For N, there is a 67.5 % reduction down to about 4.4 g N p^{-1} d^{-1}, lower than the 50 % reduction, high-level requirement to 6.8 g N p^{-1} d^{-1}, as well as the 9.9 g N p^{-1} d^{-1} load of the theorized sandbed filter. For BOD, there is a 98 % reduction to about 0.95 g BOD p^{-1} d^{-1}, certainly lower than the 90 % reduction, high-level requirement to 5.1 g BOD p^{-1} d^{-1}, as well as the approximate 1.63 g BOD p^{-1} d^{-1} load, of the conceptualized sandbed filter (SEPA, 2006a; AB 4evergreen Solutions, 2016b).

4.2.2.3 Evaluation of removal efficiency of micropollutants

The PTSs reference does not contain any GAC filter, meaning that the only MP removal efficiency that can be expected is that which is typical of commercial PTSs, since the reference is indeed entirely commercially available from a single company (AB 4evergreen Solutions, 2016c). An average number of MP removal efficiency for PTSs used in this study was 37.5 %, and was assumed here (Zhang & Renman, 2016).

4.2.2.4 Evaluation of potential for recycling of nutrients

There is a certain potential to recycle flocculated sludge, see the background section, Tank-based package treatment systems. The potential for acceptance of the farming community for Polonite filter is judged as greater than the precipitated sludge, whereby the filter system solutions might get a better grade than this reference.

4.2.2.5 Evaluation of energy use

The energy use from the reference system will be principally from the pump, since it lacks filters, especially those that are not recycled, and the chemical dosing unit uses less than 1 kWh/year (VA guide, 2016). Therefore, the energy use was assumed to be about 40 kWh/year, with the same pumping station as with the sandbed filter, for easy comparison. A short summary of most environmental criteria results for the PTSs reference is depicted in Table 11 and Table 12.

Table 11. The results of the environmental criteria that depict effluent load for the reference package treatment system. The effluent load of phosphorus, nitrogen and BOD are compared with SEPA's 2006 general advice, high-level requirement. The septic tank effluent (facility influent) is assumed to be 6.34-log total coliforms cfu $(100 \text{ ml})^{-1}$ that was observed in a study in the US (Stacy *et al.*, 2009)

	PTSs reference	SEPA's 2006 general advice
1. Microbial risks [cfu $(100 \text{ ml})^{-1}$]	1.84-log total coliform	-
2a. RE of P [g p^{-1} d^{-1}]	0.05	0.20
2b. RE of N [g p^{-1} d^{-1}]	4.4	6.8
2c. RE of BOD [g p^{-1} d^{-1}]	0.95	5.1

Table 12. The results of the environmental criteria that depict proportion of MP influent that is reduced through the facility, as well as the energy expenditure throughout the facility, for the reference package treatment system

	PTSs reference
3. RE of MPs [% reduction]	37.5
5. Energy use [kWh yr^{-1}]	40.5

4.2.2.6 Evaluation of socio-economic criteria

For a calculation of the installation investment as well as the annual cost for the lifetime of the PTSs reference, considering its most important components, see Appendix A – Weight of add-on filters. For the social criteria, the most important considerations are that the PTSs reference can, depending on the local topography, be dug down in the ground, indicating that it need not be bulky on a plot. Its size is similar to both the other systems considered, and refilling of chemicals is required each year. This activity is similar but slightly more demanding than the replacement of two filters every other year, considering its higher frequency. It is probable that no handling of chemical by-products is required, since chemical by-products from precipitation end up in the septic tank and are thereby removed with the sludge each year. There is a greater amount of precipitated sludge, but that is factored into the cost of the municipal service agreement.

4.2.3 Package treatment system – with filters

4.2.3.1 Evaluation of microbial risks

There is no exact data on BIOP's removal efficiency of microbes for itself, other than that it is above 90 % (Svensk Avloppsrening, 2016b). Since it does not seem like there is any other microbial barrier but that of Polonite in the commercially available facility (Svensk Avloppsrening, 2016a), this would indicate inadequate hygienisation considering the diminishing microbial removal of Polonite once it approaches breakthrough, and that its average removal of E.coli (coliform bacteria) from fresh material until that time was 60 % (Nilsson et al., 2013a). If we were to assume that there is UV irradiation for BIOP, as there was for Biorock, this could reduce the coliform bacterial load by 2.5-log total coliform cfu (100 ml)$^{-1}$ (Jacangelo et al., 2003). Polonite and GAC would then further reduce this load by about 1.27-log total coliform cfu (100 ml)$^{-1}$, see the results section, Sandbed filter. The total reduction would then be 3.77-log total coliform cfu (100 ml)$^{-1}$, which would leave 2.57-log total coliform cfu (100 ml)$^{-1}$, or about 372 cfu (100ml)$^{-1}$, if the same influent as above were assumed. This treated wastewater could not be considered safe, see the results sections, Sandbed filter and Package treatment system – reference.

4.2.3.2 Evaluation of removal efficiency of eutrophying substances

According to Bioptech's CE-certified and EN-12566-6:2013 test outcomes, the following results were obtained, for which scepticism is warranted if proper maintenance is neglected, see the background section, Tank-based package treatment systems. There is a 93 % reduction of Tot-P, which would mean a 0.14 g P p^{-1} d^{-1} effluent load, compared to the 2.04 g P p^{-1} d^{-1} influent load. This treatment efficiency is higher than the sandbed filter and SEPA's 2006 high-level requirement, with effluent loads of 0.15 & 0.20 g P p^{-1} d^{-1} respectively, but lower than the PTSs reference, with an effluent load of 0.05 g P p^{-1} d^{-1}. There is a 53 % reduction of N, signifying an effluent load of about 6.4 g N p^{-1} d^{-1}, compared to the 13.6 g N p^{-1} d^{-1} influent load. This treatment efficiency is higher than the sandbed filter and SEPA's 2006 high-level requirement, with effluent loads of 9.9 & 6.8 g N p^{-1} d^{-1} respectively, but lower than the PTSs reference with an effluent load of 4.4 g N p^{-1} d^{-1}. There is a 92 % reduction of BOD, which would mean a 4.8 g BOD p^{-1} d^{-1} effluent load, compared to the 47.6 g BOD p^{-1} d^{-1} influent load. This treatment efficiency is higher than SEPA's 2006 high-level requirement, with an effluent load of 5.1 g BOD p^{-1} d^{-1}, but lower than the PTSs reference and the sandbed filter, with effluent loads of 0.95 & 1.6 g BOD p^{-1} d^{-1}, respectively (SEPA, 2006a; Norén, 2011).

4.2.3.3 Evaluation of removal efficiency of micropollutants

The RE of MPs was once again calculated from a generic influent concentration, meaning that the reduction itself was compared instead of the effluent concentrations. The average reduction of MPs was 37.5 % for PTSs (Zhang & Renman, 2016) and 80 % for GAC, see the results section for the Sandbed filter, Evaluation of removal efficiency of micropollutants. This amounts to a RE of MPs of 87.5 %.

4.2.3.4 Evaluation of potential for recycling of nutrients

This PTSs has the same potential for recycling of nutrients as the sandbed filter, considering that it consists of the same filters. This potential stem from Polonite, see the results section for the Sandbed filter, Evaluation of potential for recycling of nutrients.

4.2.3.5 Evaluation of energy use

This PTSs has approximately the same energy use as the sandbed filter, since it contains a pump and a GAC filter, which would be 1,760 kWh yr^{-1}, see Appendix B – Economy and

Energy and the results section for the Sandbed filter, Evaluation of energy use. However, according to the mentioned market overview for OSSFs products, the annual electricity use for just the commercial system itself (without the GAC filter) was 73 kWh yr^{-1} (VA guide & SwAM, 2016). Further, according to BIOP's general information page, BIOP contains no pump or other moving parts, and the electricity use is merely intended to impel the air compressor that furnishes the bio rods with oxygen (Svensk Avloppsrening, 2016c). From this we infer that the electricity use from the market overview cited above does not include a pump, which the conceptualized BIOP in this study does make use of. This is in order to facilitate comparison, so the local soil conditions are assumed to demand it. If the electricity use for the GAC filter, air compressor and the general pumping station used in this study are added, an electricity use of around 1,830 kWh yr^{-1} is obtained. A short summary of most environmental criteria results for the PTSs with filters is depicted in Table 13 and Table 14. A short summary of most environmental criteria results that were calculated, for all the OSSFs, is portrayed in Table 15.

Table 13. The results of the environmental criteria that depict effluent load for the package treatment system with filters. The effluent load of phosphorus, nitrogen and BOD are compared with SEPA's 2006 general advice, high-level requirement. The septic tank effluent (facility influent) is assumed to be 6.34-log total coliforms cfu $(100\ ml)^{-1}$ that was observed in a study in the US (Stacy *et al.*, 2009)

	PTSs with filters	**SEPA's 2006 general advice**
1. Microbial risks [cfu $(100\ ml)^{-1}$]	2.57-log total coliform	-
2a. RE of P [g p^{-1} d^{-1}]	0.14	0.20
2b. RE of N [g p^{-1} d^{-1}]	6.4	6.8
2c. RE of BOD [g p^{-1} d^{-1}]	4.8	5.1

Table 14. The results of the environmental criteria that depict proportion of MP influent that is reduced through the facility, as well as the energy expenditure throughout the facility, for the package treatment system with filters

	PTSs with filters
3. RE of MPs [% reduction]	87.5
5. Energy use [kWh yr^{-1}]	1,830

Table 15. The results of the calculated environmental criteria for all the on-site sewage facilities

	SFSs	**PTSs reference**	**PTSs with filters**
1. Microbial risks [cfu $(100\ ml)^{-1}$]	0.57-log total coliform	1.84-log total coliform	2.57-log total coliform
2a. Effluent load P: [g p^{-1} d^{-1}]	0.15	0.05	0.14
2b. Effluent load N: [g p^{-1} d^{-1}]	9.9	4.4	6.4
2c. Effluent load BOD: [g p^{-1} d^{-1}]	1.6	0.95	4.8
3. RE of MP (% reduction)	90.5	37.5	87.5
5. Energy use [kWh yr^{-1}]	1,760	40	1,830

4.2.3.6 Evaluation of socio-economic criteria

For a calculation of the installation investment as well as the annual cost for the lifetime of the PTSs with filters, considering its most important components, see Appendix B – Economy and Energy. For the social criteria, the PTSs with filters combines both of best worlds, with less-than-demanding maintenance of once-a-year normal-size sludge removal and every-other-year replacing of filters. It also is flexible in that it can be dug down in the soil, as the sandbed filter also can, but is not, as conceptualized in this study. This means the PTSs with filters might not be as bulky on a plot as the sandbed filter.

4.3 Results of grading

The systems were considered to be fairly equal in terms of pathogens (<400 cfu $(100\ ml)^{-1}$ effluent load) so all were assigned grade 3, as the reference system. For the removal of P, N and BOD, the filter systems were both deemed slightly worse than the reference system, assuming that maintenance is properly conducted, whereby they were both given grade 2. But since both contain a GAC filter that dramatically increases the removal of MPs, they were both given grade 5 for the RE of MPs. It was supposed that the farming community is much more likely to accept a saturated, dried-up Polonite (Ecofiltration, 2016b) than a mass of chemically precipitated sludge, whereby the filter systems were once again given grade 5 for recycling. But the reference was still given grade 3, since there is probability of an acceptance. For energy use, both filter systems were given grade 1, since the electricity consumption was considerably higher with the GAC filter than with the reference system that only used the standard pump. However, it is important to remember that the GAC energy use concerning its production nearly falls into the realm of a LCA, since the energy consumption at WWTPs, or probably for OSSFs, is low for activated carbon (Bui et al., 2016). The property owner, because of the service agreement for replacing the GAC filter every two years, pays for the cost of the energy use concerning the production and transport of GAC.

After the calculation of the installation investment as well as the annual cost for the lifetime of the systems, depicted in Appendix B – Economy and Energy, a linear relationship was adopted for grading the systems. This relationship had three reference points: grade 3 was the cost (62,264 SEK) of the PTSs reference, while grade 1 and 5 was the approximate cost of the most expensive (102,264 SEK) and cheapest (22,264 SEK) PTSs according to the market overview, respectively. This meant that two linear relationships were established, that between 3 and 5 for cheaper systems than the PTSs reference and that between 1 and 3 for more expensive systems than the PTSs reference, although their scale was the same; 40,000 SEK overall. In this way, grade 3.7 was attained for the cheaper sandbed filter, and grade 1.5 was obtained for the more expensive PTSs with filters. Concerning the criterion of user-friendliness, the conceptualized sandbed filter was deemed to facilitate water sampling since its outlet well would be comparatively elevated, thereby decreasing the cost of such a service, and making it easier to understand one's responsibilities. Also, the PTSs in general seem to be more dependent upon the stringent maintenance for upholding its function, see the background section, Tank-based package treatment systems. For the sandbed filter, even in the likely scenario of decreased chemical P-sorption over time (Palm et al., 2012), this would only improve the fertilizing quality of Polonite, with increased P saturation, assuming the P reduction stays at 90 %, see the results section for the Sandbed filter, Evaluation of potential for recycling of nutrients.

For intrusiveness, the sandbed filter is assumed to be a mound, increasing its bulkiness. This could be seen as the price for elevating the outlet well and facilitating sampling, and it is therefore given the grade 1 for intrusiveness. For ease of compliance, future legislation would probably be enforced concerning the treated effluent for OSSFs in general, regardless if the property owner chooses to achieve it with PTSs or SFSs. But especially more stringent legislation is easier to deal with if proper function can be ensured, and this is deemed easier for the sandbed filter, again concerning sampling. The results of the CE-certification is in itself hard to trust, and should be controlled with the bought PTSs at the desired location, in order to know what function should be upheld, if the test is satisfactory. For operation and maintenance, the sludge removal is cheaper for the non-reference systems since they produce less of it when it is not chemically flocculated. Also, the replacing of filters is only needed every other year, in contrast to every year for refilling of chemicals, and a negligence of filter service is less essential to secure a proper function than is the refilling of chemicals. Both these services are thereby deemed slightly less troublesome than those of the reference system, even if these actions are comprised in a service agreement. A summary of the assigned grades is portrayed in Table 16.

Table 16. The results of the assigned grades to the different on-site sewage facilities

	Sandbed filter	PTSs reference	PTSs with filters
1. Microbial risks	3	3	3
2. RE of ES	2	3	2
3. RE of MPs	5	3	5
4. Potential for recycling of nutrients	5	3	5
5. Energy use	1	3	1
6. Life-cycle costs	3.7	3	1.5
7. User-friendliness	5	3	4
8. Intrusiveness	1	3	3
9. Ease of compliance	4	3	3
10. Operation and maintenance	4	3	4

4.4 Results of weighting

Now it is time for a summary of the weighting allocation and the resulting range from the workshop (Table 17; Table 18). The participants made a great job of taking on their given perspective, but their knowledge of the evaluated grades might have affected the allocations. On the part of SwAM, their concern was with most of the environmental criteria, specifically those where OSSFs are known to have a certain effect or where they would have if the treatment function were impaired. One known effect is on eutrophication, where the OSSFs load is not insignificant, and where the recycling of nutrients could help alleviate the problem. The microbial risk is more of a past concern but still important to maintain proper functioning. The MP question is mostly a future concern since SwAM or SEPA has not yet put any requirement on its removal, so its relatively high weight would represent forward thinking on the part of SwAM. Energy use was given a low weight, likely from the perspective of low impact of OSSFs on the over-all energy consumption of a country or a municipality, and that there is no legislation concerning this criterion for OSSFs.

The socio-economic criteria that more closely reflected the immediate concern of the property owners were given low weights by SwAM, such as the cost, user-friendliness and intrusiveness. But the social criteria that more closely concerned the work of SwAM were given medium weights, like (legislative) ease of compliance and maintaining the treatment function. The regulators supervise the OSSFs in a municipality, whereby their perspective is somewhere between that of the legislators (SwAM) and property owners. The socio-economic questions that directly concern the property owners are more important for regulators than for legislators, since they supervise them and ensure it is satisfactory. This is seen in the high allocations for ease of compliance and operation and maintenance, but also for the slightly higher weights in cost, user-friendliness and intrusiveness. This reflects the different responsibilities of the legislators and the regulators, the former being environmental legislation for the whole country and the latter being the inspection of OSSFs in a municipality.

For a property owner, the overwhelming concern is with the investment cost of installing the OSSFs, hence its very high allocation. Another important perspective is that it is not their responsibility to ensure proper treatment function, hence the low weights for all environmental criteria. A relatively high allocation (of the remaining points) was given to user-friendliness, since there is a desire for the OSSFs to function with the least bit of trouble. In the low assignments to environmental criteria there is an assumption of smooth functioning, besides the aspect of it not being their responsibility. The environmental criteria would be a direct concern for the property owners if treatment were lacking, concerning drinking water, recreation and a requirement to ensure proper functioning. This is partly reflected in the slightly higher weight for microbial risks, since health concerns could directly affect property owners with private wells. Operation and maintenance is somewhat important for property owners, even with the almost universally used service agreements with the suppliers, considering that they are paying in order to not have to perform the actions themselves. This mostly concerns sludge removal and refilling of chemicals, while the filters are commonly not replaced, as they should, or at all. Intrusiveness and ease of compliance affects the property owners but are more the concern of legislators and regulators (Table 17; Table 18).

Table 17. The weights assigned by important on-site sewage facility stakeholders, each giving 100 points to 10 criteria

	SwAM	**Property owner**	**Regulator**
1. Microbial risks	13	2	12
2. RE of ES	18	0.1	12
3. RE of MPs	15	0.1	10
4. Potential for recycling of nutrients	15	0.1	10
5. Energy use	1	0.1	1
6. Life-cycle costs	7	79.6	10
7. User-friendliness	7	8	8
8. Intrusiveness	4	2	5
9. Ease of compliance	10	2	20
10. Operation and maintenance	10	6	12

Table 18. The results of minimum and maximum assigned weights from Table 17, creating a range (R)

	Range (R)
1. Microbial risks	2-13
2. RE of ES	0.1-18
3. RE of MPs	0.1-15
4. Potential for recycling of nutrients	0.1-15
5. Energy use	0.1-1
6. Life-cycle costs	7-79.6
7. User-friendliness	7-8
8. Intrusiveness	2-5
9. Ease of compliance	2-20
10. Operation and maintenance	6-12

If we multiply the grades in Table 16 with the weight ranges of Table 18, we obtain the scores for each criteria and system, and after summation, the respective final score for each system. This is depicted in Table 19. It signifies that within the set boundaries, calculations, literature data and reasoning of this study, the sandbed filter should be most highly invested in and supported by legislature, followed by one of the PTSs, depending on how important MP removal is for the decision-maker. This result in its entirety, including the grades and weights that lie behind it, as well as the chosen MCA method with weighted summation, is analysed in the Discussion section.

Table 19. The final scores for all the systems and criteria, with the summed-up final score for all on-site sewage facilities. The results indicate that the sandbed filter, within the boundary conditions of this study, is the best option for wastewater treatment, followed by the reference package treatment systems (PTSs) and the PTSs with filters

	Sandbed filter	PTSs reference	PTSs with filters
1. Microbial risks	6-39	6-39	6-39
2. RE of ES	0.2-36	0.3-54	0.2-36
3. RE of MPs	0.5-75	0.3-45	0.5-75
4. Potential for recycling of nutrients	0-5-75	0.3-45	0.5-75
5. Energy use	0.1-1	0.3-3	0.1-1
6. Life-cycle costs	25.9-294.5	21-238.8	10.5-119.4
7. User-friendliness	35-40	21-24	28-32
8. Intrusiveness	2-5	6-15	6-15
9. Ease of compliance	8-80	6-60	6-60
10. Operation and maintenance	24-48	18-36	24-48
∑1-10. Final score	102-694	79-560	82-500

If the final scores in Table 19 are taken at face value, the sandbed filter, as concerns the treatment process of wastewater from a single household, is the most sustainable option. The mid-range of the sandbed filter with 398 (102-694) would be followed by the PTSs reference of 319.5 (79-560) and the PTSs with filters of 291 (82-500). Therefore, the results indicated that the sustainability of the OSSFs should be ranked in that order. A sensitivity analysis was performed for these ranges in the Sensitivity analysis section.

4.5 Sensitivity analysis

A change in grades, because of an improved data set, or a modification in weights, because of an alteration in viewpoints or a gathering of more perspectives, would alter the results, perhaps drastically. This sensitivity analysis focused on how such an adjustment would change the above result, and possibly the ranking of the OSSFs, for the grade of two key criteria. These were the RE of eutrophying substances and ease of compliance. A change in maximum weights was also analysed in the same way for two key criteria, which were the RE of MPs and life-cycle costs. In general, the weights consisted of higher numbers than the grades and were therefore mathematically more important to the final score (Table 20). This is because the grades were assigned to each criterion and OSSFs on a range of 1-5 (Table 4), or for all criteria a range of 10-50 points and a mid-range of 30 points. In contrast, the weights were allocated to each criterion and OSSFs a range of 0.1-99.1 points, around an average of 10 points. In this case, 26.4 weights points were assigned at a minimum, to all the criteria, while 186.6 weight points were allotted at a maximum. This could be compared to the 30.0, 31.5 and 33.7 grade points assigned to the PTSs reference, PTSs with filters and sandbed filter, respectively (Table 20). This would indicate that if it were deemed essential to balance the importance of the grades and weights, only the minimum weights should be chosen. But this would indirectly give a lot of import to the viewpoint of the one who assigned most of the minimum weights. In this case the property owner allocated eight out of the ten minimum weights.

Table 20. Total allocated points for grading the three system solutions and for the minimum and maximum weight. The latter could be seen as an outlier in this context, as it is about 53 % larger than the rest of them put together

	Total allocated points for all criteria
Sandbed filter, grade	33.7
PTSs reference, grade	30
PTSs with filters, grade	31.5
Minimum weight	26.4
Maximum weight	186.6

The property owners assigned the maximum weight for the only economic criteria, SwAM allocated it for all environmental criteria except one shared by the regulator, and the regulator allotted it for all social criteria, except one shared by the property owner. This spread of maximum-delegated points is one good way to analyse what is essential to the stakeholders, see the Discussion section. It might be better to sacrifice perfect balance between the grades and the weights, in order to make use of the created range for determining the results. This could be with a simple statistical tool, such as the mid-range above. The recommendation of this author is to use the range in order to create the ranking, as was its purpose.

Now with awareness of the greater weight points compared to the grades, the next step is to proceed to the sensitivity analysis for four key criteria. The RE of MPs is a straightforward criterion in this study, thanks to the comparison being only between using the GAC filter and not using it, in the PTSs reference. The reason for this was because there was only solid research data on GAC, of all the filters. Furthermore, since the RE of MPs is an extremely new research area for OSSFs, even the by far most researched GAC filter was almost exclusively researched for WWTPs. Those results were assumed to function similarly in OSSFs as for WWTPs. It is possible to use more data on the removal of indicator MPs, especially if other carbon-based filters like xylit and lignite are compared with GAC. But for the purpose of this study, it was clear that the GAC filter solutions should receive higher grades compared to the non-GAC reference.

The RE of ES is in many aspects similar to the RE of MPs, except the weight for the former is on firmer ground because of SEPA's 2006 general advice, which can function legislatively on the leakage of nutrients. This means that the stakeholder responsible for environmental legislation on a national level, SwAM, is more likely to assign generous weight points to the RE of ES than the RE of MPs. It is the grades that are more uncertain for the RE of ES criterion, since CE-certification and old SEPA data were used for the PTSs and sandbed filter results, respectively. It might have been better to use research data from full-scale experiments that have operated and maintained different PTSs and sandbed filters with real-world treatment results, instead of treatment stencils. This is especially true for BOD and N, whereas P was at least verified to be able to maintain high removal efficiency in the literature, for column experiments. P was also the most limiting, important nutrient. The impact of changing grade for the RE of ES and changing weight for the RE of MPs is depicted in Table 21 and Table 22, respectively.

The grading of the ease of compliance is similarly on loose footing since there is no data to support it, as was the case with all the social criteria. It is rather a guess based on how the different system solutions are conceived, but all the OSSFs should manage changing legislation rather well, since they achieve present and likely future requirements. The weight is, on the other hand, on rather more secure footing, based on the varying responsibilities of the different stakeholders. Lastly, the grade of the life-cycle costs is rather certain, within the suppositions used in this study, but the weight has a large impact on the mid-range and maximum final score for the three OSSFs. The impact of changing grade for the ease of compliance and changing weight for life-cycle costs is depicted in Table 21 and Table 22, respectively.

Table 21. Sensitivity analysis for changing a unit grade point for removal efficiency of eutrophying substances and ease of compliance, or their impact on mid-range and final score range

Change in unit grade point, criteria	Concurrent alteration on final score range	Concurrent alteration of mid-range final score
RE of eutrophying substances	0.1-18	9.05
Ease of compliance	2-20	11

Table 21 demonstrates that a change in unit grade point would alter the mid-range final score by around 10 points for two key criteria, the RE of eutrophying substances and ease of compliance. This would potentially change the ranking between the PTSs alternatives, or bring the sandbed filter closer to them, although the latter is out of reach for the two PTSs, with just this change. Even though both PTSs are in a similar situation when it comes to present legislation, the PTSs with filters could be changed one unit grade point up, in anticipation of future requirements for MP removal. This would bring it to the same grade as the sandbed filter, and the distance of mid-range final score would be 17.5 instead of 28.5, to the PTSs reference. As for RE of eutrophying substances, the sandbed filter was at a disadvantage with the data, but as the criterion was compared, it might have been justified to bring the PTSs with filters to the same grade as the PTSs reference. This would potentially bring the mid-range score distance from 17.5 to 8.45, between the PTSs alternatives. The same analysis with weights is portrayed in Table 22.

Table 22. Sensitivity analysis for altering the maximum weight by 5 points for removal efficiency of micropollutants and life-cycle costs, or their impact on maximum and mid-range final scores

Change in 5 maximum weight points, criteria	Concurrent alteration on maximum final score: SFSs, PTSs reference and PTSs	Concurrent alteration of mid-range final score: SFSs, PTSs reference and PTSs
RE of MPs	25, 15 and 25	12.5, 7.5 and 12.5
Life-cycle costs	18.5, 15 and 7.5	9.25, 7.5 and 3.75

Table 22 demonstrates what a change in 5 maximum weight points would mean for the maximum and mid-range final scores for the sandbed filter, PTSs reference and PTSs with filters, respectively. A change in 5 maximum points is more pertinent than a unit change for the maximum weight numbers, especially for life-cycle costs. This comparison would seem to show that the overall impact of a change in maximum weight points would have a greater impact on the RE of MPs grade than on life-cycle costs, but a change in life-cycle costs is more justified, because of its high number, than that big an alteration in the RE of MP weight. For every weight point lowered, the PTSs reference would win 2 points in RE of MPs over the filter solutions, but for every 5-point maximum weight lowered, the PTSs with filters would win 3.75 and 5.5 points over the PTSs reference and sandbed filter, respectively. Both these scenarios are likely, although the weights might be elevated as well, and this would have an impact on the maximum and mid-range final scores.

5. Discussion

The boundary conditions of this study was expressed in the method section, Formulation of system boundaries, but it was also necessary to set up further boundaries for each of the 10 sustainability criteria, in order to facilitate objective comparison and clearly delineate the criteria. This was mainly done with the formulation of the criteria, which could have been interpreted differently. Also, there were suppositions made, mainly for the purpose of performing detailed calculations, whose results might display more accuracy than is likely to be achieved in measurements. It was therefore important to provide an overview of the results, put them in a proper context and to interpret their meaning. For the microbial risks, as was first discussed in the background section, Removal of bacteria, micropollutants and phosphorus, the chosen indicator bacteria groups do not always provide an accurate view of the total bacterial community's response to UV disinfectants, nor its response and probable recovery in the recipient environment. The latter situation could be said to fall outside the system boundaries of this study.

The effect of the UV disinfection units on the coliform bacteria group, a standard indicator bacterium, was calculated. It was useful to estimate bacteria removal for one group, but it was good to know the limitations of this approach and understand that it introduces some uncertainty into the calculation. The hygienisation effect of the add-on filters is probably not overestimated in this study, considering that their data came from the average removal of coliform bacteria over the time from fresh material until just before breakthrough. It is initially much higher; then decreases precipitously and is at a minimum just before breakthrough. A higher uncertainty comes from SEPA's 1987 technical specifications of what amount of coliform pathogens a sandbed filter can adsorb, used for both the sandbed filter and the PTSs reference in these study results. The microbial reduction should be more deeply analysed if it is deemed a problem.

Regarding the removal efficiency of the important nutrients that have a eutrophying effect on coastal waters, this stands on more secure footing than the microbial reduction results. This was because both the influent load and the effluent concentration and volume (load) were well established for P, N and BOD. This was not the case for the microbial load, in the form of the indicator total coliform bacterial community, since it varies so much. The removal efficiency of eutrophying substances was presented in Table 15 for all OSSFs, with the data presented originally in each OSSFs in Table 9, Table 11 and Table 13. This was represented as an effluent load, instead of the more appropriate, for the name of the criteria, percentage reduction of the effluent compared to the influent. This was because the effluent load could be more easily translated to the eutrophication issue. For example, if all OSSFs in Sweden performed as well with regards to P as the worst performing OSSFs in this study, the sandbed filter, the P load from Swedish OSSFs would be reduced by over 87 % to less than 38 tons annually, compared to 295 tons. 295 tons is about 10 % of the total anthropogenic P load to the Baltic Sea from Swedish coasts, and the load from Swedish OSSFs; see the Introduction section.

The reduced load could instead be returned to the soil, fertilizing crop fields and meadows, see the results section for the Sandbed filter, Evaluation of potential for recycling of nutrients. Concerning the removal efficiencies of P and N, this study might have underestimated the conventional part of the sandbed filter with the SEPA data, at least compared to those SFSs (without filters for comparison) where the MP data came from (Zhang & Renman, 2016). There is justification to believe that the conventional part is capable of fulfilling the BOD requirements since this is the function of the conventional treatment facility. The removal efficiency for both PTSs might on the other hand be overestimated since the CE-certification results only sustain over time with proper maintenance and are trustworthy only if the same equipment is used both for the test and full-scale, see the background section, Tank-based package treatment systems.

Regarding the MP removal efficiency, it is clear that this environmental criterion suffers from the same problems as the microbial reduction criteria, but to an even greater degree. MPs are a large disparate group of compounds, so a number of indicator substances should be chosen for screening. Even then, the influent concentrations vary between regions, within the same region and community, as well as over time even within the same household, see the background section, Micropollutants. Since this study location is generic, for a single household and comprises a time horizon of the lifetime of the facilities, it is logical not to analyse the influent concentration regarding single compounds. Rather, it is useful to examine the MP reduction generally for a large enough sample of this compound group, and to understand the limitations and useful context of the data sources. The conventional MP reduction data came from eight SFSs and two PTSs in Sweden, and seven different types of MP: Fragrances, UV stabilisers, Food additives, Detergents, Plastic/rubber additives, Biocides and Pharmaceuticals (Zhang & Renman, 2016).

The GAC removal efficiency came from both the fact that good data shows it can remove many types of MP to 80 %, and that Switzerland has implemented a requirement to that effect for MPs, with ozonation and activated carbon as preferred, advanced treatment methods, see the results section for the Sandbed filter, Evaluation of removal efficiency of micropollutants. This removal efficiency greatly improves the MP performance of the non-reference systems compared to the PTSs reference (Table 15). It also was evaluated that this was to these systems' detriment in terms of energy use with the GAC production, at least for the grade (Table 16). It did not have such a large detrimental impact for the final score because of low assigned weights to energy use. This was because at the time of the workshop the only main energy consumption was that of the pump in the OSSFs. The energy use in production of GAC was added afterwards. If the 691,000 OSSFs in Sweden used GAC at the rate that is recommended for these studied systems, which was 1.72 MWh, it would constitute an energy use around 1.2 TWh, or about 0.2 % of Sweden's entire annual energy consumption in 2013, which was 565 TWh (Swedish Energy Agency, 2015). But there is great uncertainty in that the column experiment provided an understanding of only low quality material, for DOC that normally break through earlier than MP. But mostly, the numbers should be more closely compared and scrutinized as regards production and transport of GAC (Mousel et al., 2017).

For the life-cycle cost, the biggest supposition was that the systems were comprised of the specific sample parts that were suggested, and that the market overview determined approximately the most low-priced and most expensive PTSs. The sandbed filter had an advantage here, with a comparatively much more economical treatment facility in general (VA guide & SwAM, 2016). It was just as well that the annual cost of the facilities was not directly used for assigning grades, since it introduced more uncertainties, not the least of which is the set lifetime of the facilities and a constant interest rate over that time. There was, however, a clear proportional correlation between the one-time investment and the annual cost, since the former was the input in the formulas for the calculation of the latter. In other words, the annual cost would not have affected the grade considerably. For Polonite, the replacement cost for different intervals was provided by the major supplier to retailers and wholesalers (Ecofiltration, 2016a). For GAC, the cost was provided by a report that demonstrated the material cost (Creek & Davidson, 2000) and the weight from the column experiment, see Appendix A – Weight of add-on filters. For the economic calculations, see Appendix B – Economy and Energy.

With regard to the social criteria, there were two major differences between the systems. One was between the sandbed filter and both PTSs, in that the elevated position of the sandbed filter, as a mound, made it bulky on a plot and so it was detrimental to its intrusiveness, despite its similar size to both PTSs. However, it was evaluated to give the sandbed filter advantages both with user-friendliness and with ease of complying to current and future legislation, since it might be easier to control its function with improved effluent sampling. For operation and maintenance, the PTSs reference seemed to have the disadvantage to both other systems in that the precipitation chemicals had to be refilled every year, instead of every other year, like the filters. It was therefore evaluated as being more costly or troublesome to perform that action. Furthermore, if maintenance is not completed for the precipitation chemicals, the treatment will suffer greatly compared to the same situation for the filter systems.

The workshop was conducted with students who were well informed of the various roles performed by stakeholders involved in Swedish OSSFs. The three most important ones were chosen to provide their perspectives. These were determined to be SwAM as legislators and funders, a generic Swedish municipal regulatory office for inspecting OSSFs function, and a property owner, see the method section, Weighting process. It was a distinct limitation that the stakeholders themselves were not involved, but the participants knew the part the stakeholders play, and therefore arguably, their outlook, since one's responsibilities tend to influence what one values most. For comparison to real stakeholders in a MCA, one could use a previous master thesis study in the RedMic project. These various organisations put life-cycle costs at range 3-20, microbial risks at range 9-15, RE of ES & RE of MPs at ranges 9-20, while potential for recycling of nutrients and energy consumption received ranges 0-15 and 0-8, respectively. The socio-cultural criteria were differently described and enumerated than the social criteria in this study, so a comparison was problematic (Li, 2016). Therefore, of the economic and environmental criteria, the former was weighted higher and the latter generally quite alike in this study, compared to the previous master thesis study in RedMic.

Regarding the perspectives that were provided in this study, there are several manners to understand the outlooks and actions that the different stakeholders delivered. For instance, SwAM assigned the most weights to the environmental criteria, the regulators to the social criteria and the property owners to the economic criterion (Table 17). SwAM and the regulators are concerned with different aspects of legislation, the former with "larger" national legislation and fulfilling Sweden's environmental commitments, therefore the environmental criteria were imperative. For the municipal regulators, they inspect OSSFs function locally and so are more concerned with its function for the property owners, for example that there is proper maintenance and that the OSSFs complies with current and future legislation. The regulators are not especially interested in the environmental criteria, but not uninterested either, meaning they provide a kind of bridge between SwAM and the property owners.

The property owners are overwhelmingly attentive to the economic cost, especially of the large investment, but also of the service cost. This is logical, but the criteria might also have been rather narrowly defined, to only include this cost for the property owners, instead of including the sources and recipients of funds to and from SwAM and the regulators. This broader perspective should only have affected their weight and not the property owners, but it is an example of how the criterion's definition affected its weight, as it should. These definitions then constitute boundary conditions of this method. Another clear aspect that modifies the weighting results is the overall performance of the OSSFs with regard to the different criteria. This determines if a specific criterion is deemed a problem or not, and therefore their importance to the stakeholders.

For example, the energy consumption result at the time of the workshop was under 100 kWh/year for all OSSFs, which made everyone put this weight low. This complements the fact that there is no legislation for it concerning OSSFs. If the energy use in conjunction with the production and transport of GAC had been included, it might have affected the results. But as was shown above in this Discussion, it would not constitute a large impact on Sweden's energy supply even if all OSSFs adopted GAC. This is unlike the influence of the effluent concentration of P and MPs, see the Introduction and the background section, Micropollutants. So this new information should not affect the weighting results much, since each criterion and their grades should be put in its proper context.

Regarding the MCA, as seen in the background section, Multi-criteria analysis, the more significant aspects might be the structuring of the problem itself, including choice of criteria and decision options. This study certainly demonstrated their importance. The method, with which the decision options, or the OSSFs, were compared, might then have been less important. The weighted summation was very useful in that it provided a great opportunity to see the perspective of different stakeholders, and for them to see each other's viewpoint. Also, it was valuable to evaluate the different criteria by literature data and calculation. But the calculation exercise that provided the final scores should be seen mostly as a pedagogical support for making decisions, when put in the context of the assumptions and system boundaries of this study.

The MCA method is preferably applied to any decision-problem with real stakeholder representatives and not with role-players, even if the workshop participants were well versed in their perspective. This fact should be the greatest cause for treating the final results in this study, and their applicability for decision-support, with care. The above comparisons with Li (2016) adds some certainty that the weighting process in this study was comparable to real stakeholders at least for the environmental criteria, and these could therefore be better trusted. The same could not be said for the non-compared social criteria, whose weighting therefore should be treated with more scepticism. The range for life-cycle costs was higher in this study than in the compared one, and there is no way to determine what range is more correct. But the weighting in this study included the viewpoints from property owners, via conducted interviews. The previous study included a representative from each of the six representatives enumerated in (Andersson *et al.*, 2012), with no property owner. Considering the interviews, it is fairly certain that the property owners do consider the costs by far the most important, at least when a nearby recipient is not threatened by ill-functioning OSSFs. An assumption of good functioning and/or a non-sensitive recipient was therefore inherent in this weighting.

Other reasons to treat these results with care, besides the role-playing, might be the limited system boundaries of this study, seen in the method section, Formulation of system boundaries. These excluded a LCA for these systems, which in all likelihood would have included an analysis of emitted CO_2 for these OSSFs. This should prove negative for the filter systems, to balance the Polonite and GAC filters' positive effect on the treatment process. Further, several more actual stakeholders should be included to create a more comprehensive view. The grading of the social criteria was based on little more than guesses in this study, and this should be improved. Lastly, the removal of MPs is a very new field for OSSFs, and more filters than GAC should be included in order to perform an analysis of which one is the best, when further research is available.

All these considerations would lead to the conclusion that the greatest value of this study is in treating the MCA as a proof-of-concept method for decision-support at a national policy level. This means that even though the MCA method is applicable in that context, the specific grading and weighting processes in this study would need further improvements, as suggested in the above paragraph. There are very few MCA studies that have been applied to OSSFs, and these have typically not been as comprehensive as this one, with the inclusion of only environmental criteria, as for instance in (Sudhakaran *et al.*, 2013). An exception is (Li, 2016) and RedMic, and as more studies come forth in this topic, they may well disprove the results of this study. For now, this study is a solid summary of today's knowledge of MCA's applied to OSSFs, as well as the conventional and extra capability treatment of P and MPs in soil- and tank-based OSSFs. It also highlights the great insights and certainty that could be gained by applying the MCA method to decision-problems concerning OSSFs.

6. Conclusion

Within the boundary conditions and assumptions made in this study, it suggested that the sandbed filter was the most sustainable option, as concerns the treatment process of domestic wastewater from a single household. The sandbed filter obtained a range of 102-694 points, mid-range of 398, the PTSs reference a range of 79-560 points, mid-range of 319.5, and the PTSs with filters a range of 82-500 points, mid-range of 291. This alludes that of the three alternative OSSFs in this study, the sandbed filter should be supported with funding and legislature for its research and development. But there were reasons to treat these results with care, first and foremost because the stakeholders were role-played instead of being actual ones. The more sensible approach might be to view the MCA as a proof-of concept method at a national policy level.

In the sensitivity analysis, it was found that a change of grades for two key criteria, the RE of eutrophying substances and ease of compliance, had the potential to at least improve the average score ranking for the PTSs with filters, perhaps to the point of surpassing the reference PTSs. Further, a lowering of the maximum weight of RE of MPs would be to the detriment of the sandbed filter and the PTSs with filters while the same for life-cycle costs would be to the detriment of the former but success of the latter. A major reason for the result of the first ranking position, which seems hard to budge, was that the sandbed filter was the most economical, but was still not at a disadvantage with the environmental criteria, or the more highly weighted social criteria.

SwAM put the most emphasis on the environmental criteria, the regulator on the social criteria while the property owner put overwhelmingly the most weight on the economic criterion. This is reflected in the various responsibilities of the different stakeholders. SwAM is responsible for legislation on a national level and funding research in this field, and so is most focused on the treatment process, whereas the regulator inspects municipal OSSFs and ensures proper function at a local level. Lastly, the property owners are responsible first and foremost for installing well-functioning OSSFs at their property.

It is unlikely that the weight assignments were unaffected by the evaluated grades and performance of the OSSFs, signifying that the weights were allocated with awareness of if a criterion was deemed an overall problem, or largely solved. This is not necessarily a problem, but might be reasonable. The grades, more so than the weights, were affected by the specific definition and boundary of the criteria, since this concerned the calculations and reasoning directly, for example the calculation of coliform bacteria as a representation of the bacterial community. The MCA method used in this study could serve as proof-of-concept for evaluating the sustainability of different decision options, from a comprehensive sustainability perspective. This study depicted the benefits and insights that could be gleaned by using the MCA method for making decisions at a national policy level, if it is improved upon while still being aware of its limits when applied to a specific decision problem.

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Appendix A – Weight of add-on filters

Theoretical weight of Polonite add-on filter

- [P] in wastewater, P [kg m^{-3}]: 0.0102 (SEPA, 2006a),
- Black- and greywater consumption per 5-p.e. household, H [m^3 d^{-1}]=1 (SEPA, 1987),
- Adsorption capacity of phosphorus, A=0.01 by supposition as the worst-case scenario (Ecofiltration, 2016b) & Sammeli, pers.comm. (2016),
- Remaining share of phosphorus load in wastewater after Sandbed Filter facility: $1.5\ g\ (p\ d)^{-1}\ (2.04\ g\ (p\ d)^{-1})^{-1} \approx 0.735$ (SEPA, 1987),
- The share of phosphorus load adsorbed to Polonite add-on filter, a supposition in terms of long-term removal=0.9 (Renman & Renman, 2010; Ecofiltration, 2016b),
- Recommended Polonite replacement interval, T [d]=2 yrs (Ecofiltration, 2016c),
- Polonite density, DP [kg m^{-3}]=730 (Ecofiltration, 2016b),
- Total current phosphorus load for 1 replacement interval=P_m [kg],
- Necessary Polonite weight=M_P [kg].

Full-scale calculation of Polonite weight

- $P_m\ [kg] = PHT = 0.0102\ \text{kg}\ m^{-3} \times 1\ m^3\ d^{-1} \times 2\ yrs \times 365.25\ \text{d}\ yrs^{-1} \approx 7.45\ kg,$
- [P] in wastewater, after sandbed filter≈0.735 P_m [kg],
- Adsorption to Polonite=0.900*0.735 P_m≈0.662 P_m [kg],
- $M_P[kg] = 0.662\ P_m A^{-1} = 0.662 \times 7.45\ \text{kg} \times 10^2 \approx \mathbf{493\ kg}$ (Sammeli, pers.comm. 2016).

Miscellaneous about Polonite add-on filter

- The surrounding cylindrical filter bag, B, has a diameter of 0.84 m and a height of 1.2 m. Its volume, $V_B[m^3] = Area \times height = \pi r^2 h = \pi \times (0.42m)^2 \times 1.20m \approx 0.665\ m^3 = \mathbf{665L}$ (Sammeli, pers.comm. 2016),
- The filter itself can, with a porosity of n_P=0.45 when entirely saturated, contain a volume of 280 L, indicating that its cylindrical dimensions VF might be, for example, 2 cm less in diameter and height than the cylindrical bag →$V_F = \pi \times (0.41m)^2 \times 1.18m \approx 0.623m^3 = \mathbf{623L} \approx 280\ \text{L}\ (0.45)^{-1}$ (Ecofiltration, 2016b),
- An hourly peak flow correlative to one household during a day, greater than the hourly average flow, is used for sizing the filter, as follows: $\mathbf{34}\ \text{L}\ (p\ h)^{-1} > 200\ \text{L}\ (p\ d)^{-1} \times 24^{-1} \text{d}\ h^{-1} \approx 8.33\ \text{L}\ (p\ h)^{-1}$. There is a need to retain a retention time of 1 hour for optimum treatment effect. The maximum number of person equivalents who could therefore strain this filter in peak flow would be: $PE = 280\ L\ (p\ h)^{-1}\ (34\ L\ (p\ h)^{-1})^{-1} \approx 8 > 5$ (Sammeli, pers.comm. 2016).

Theoretical weight of GAC add-on filter

- [TOC], U [g m^{-3}] ≈ 155 (Zhang, 2016b),
- Column water flux, V [m^3 d^{-1}] ≈ 7.1*10^{-4} (Zhang, 2016a),
- Assumed GAC replacement interval, T [d]=2 yrs (Ecofiltration, 2016c),
- Volume GAC [m^3], G=1*10^{-3} (Zhang, 2016a),
- Density of GAC, D [g m^{-3}]=4.6*10^5 (Chemviron Carbon, 2014),
- Total load of TOC during one replacement interval, U_m [g],
- Weight of GAC filter material used in the column experiment=M_{GAC} [g],

- S is the [TOC] after the sandbed filter, supposing that $BOD_7 \approx BOD_5$ and that the influent concentration is "very diluted". This corresponds to a maximum concentration of 100 mg L^{-1} and a TOD/BOD_5 ratio of 0.7. According to SEPA's (2006) treatment stencils, a concentration of 30 mg L^{-1} BOD_7 is obtained after a sandbed filter, yielding $S[TOC] = 0.7\times30 \text{ mg } L^{-1} = 21 \text{ mg } L^{-1} = \mathbf{21} \text{ g } m^{-3}$ (SEPA, 2006a; Water facts, 2016),
- H [m^3 d^{-1}]=1 (SEPA, 1987),
- Filter capacity=F [g GAC m^{-3}], describes the amount of material needed to add to the filter per unit volume of wastewater, signifying a lower quality if more filter material needs to be added,
- Necessary full-scale GAC weight=M_G [kg],
- Approximate full-scale GAC volume=V_G [m^3].

Full-scale calculation of GAC weight

$U_m\ [g] = UVT = 155 \text{ g } m^{-3}\times7.1\times10^{-4}m^3d^{-1}\times2\ yrs \times 365.25 \text{ d } yr^{-1} \approx 81.1\ g,$
$M_{GAC}\ [g\ GAC] = GD = 1\times10^{-3}m^3\times4.6\times10^5 \text{g GAC } m^{-3} = 460\ g\ GAC,$
$F[g] = SM_{GAC}(U_m)^{-1} = 21 \text{ g } m^{-3}\times460 \text{ g GAC } (81.1\ g)^{-1} \approx 119.1 \text{ g GAC } m^{-3},$
$M_G[kg] = FHT =$
$119.1 \text{ g GAC } m^{-3}\times1\ m^3\ d^{-1}\times2\ yrs\times365.25 \text{ d } yrs^{-1}\times10^{-3} \text{ kg GAC } (g\ GAC)^{-1} \approx$
$\mathbf{87\ kg\ GAC},$
$V_G[m^3] = M_GD^{-1} = 87 \text{ kg GAC } (460\ kg\ GAC\ m^{-3})^{-1} \approx 0.189\ m^3 = 189\ L.$

Control calculation – is there sufficient contact time at peak flow?

- Empty Bed Contact Time (EBCT), C_T=20 min (Bui et al., 2016),
- Peak flow, PF=34 L (p h)$^{-1}$,
- Flow during contact time, PS [L (p h)$^{-1}$]=$PF\times C_T$,
- Person equivalents per households=PE_H=5 p,
- Total volume passing the filter during contact time=PS_{Tot} [L],
- Necessary porosity, n_G V_G>PS_{Tot} [L].

$PS_{Tot} = PE_H\times PS = PE_H\times PF\times C_T = 5\ p\times34 \text{ L } (p\ h)^{-1}\times60^{-1}\text{h } min^{-1}\times20\ min \approx 56.7\ L.$
If the porosity, $n_G > \frac{PS_{Tot}}{V_G} = \frac{56.7\ L}{189\ L} \approx 0.30$. It is highly probable that the porosity is greater than this with a margin. The volume of GAC should be lower than this approximate one, meaning a greater porosity is needed, but the porosity should still be greater than that one (Clements, 2002).

For GAC-filtration it is recommended that an EBCT of 20-40 minutes be maintained, from the experience of Germany and Switzerland, which is why 20 minutes was used in the PS_{Tot} equation just above (Bui et al., 2016).

Appendix B – Economy and Energy

- NPV = Net Present Value,
- ANN = present value of annuity factor,
- r = long-term average rate = 0.03,
- n = economical lifespan = 40 years and 20 years,
- $ANN = \mathrm{r}(1-(1+r)^{-n})^{-1}$,
- $Annuity = NPV \times ANN$ (Aniander et al., 1998).

OSSFs 1: Sandbed filter including Polonite and GAC

One-time cost sandbed filter

1. Facility (including distribution well and outlet well)=7,995 kr (Avloppscenter, 2016). Operation and maintenance is commonly only in the form of sludge removal and replacement of filter (Avloppsguiden, 2016),
2. Septic tank (with pump): Black- and greywater 2.2 m3=15,500 kr (Din VVS-Butik, 2016b),
3. Pump station: (7,995+5,445+1,295+529) kr=15,264 kr (Din VVS-Butik, 2016a; c; d; e),

$\boldsymbol{Cost} =$
$1-3+double\ the\ annual\ cost\ of\ filters\ that\ are\ replaced\ every\ other\ year =$
$(7{,}995+15{,}500+15{,}264+7{,}900+2{,}220)\ kr \approx \mathbf{48{,}880}\ \boldsymbol{kr}$, as well as 15,264 SEK for another pumping station after 20 yrs.

Annual cost sandbed filter

1-2) $ANN = 0.03(1-(1+0.03)^{-40})^{-1} \approx 0.0433.$
3) $ANN = 0.03(1-(1+0.03)^{-20})^{-1} \approx 0.0672.$

1) $Annuity = 7{,}995\ SEK \times 0.0433 \approx 346\ SEK$,
2) $Annuity = 15{,}500\ SEK \times 0.0433 \approx 671\ SEK$,
3) $Annuity = 2 \times 15{,}264\ SEK \times 0.0672 \approx 2{,}052\ SEK$,
4) $Polonite\ (500\ kg) = 7{,}900\ \mathrm{SEK} \times 2^{-1} = 3{,}950\ SEK$ (Ecofiltration, 2016a),
5) $GAC\ (87\ kg) = 87\ \mathrm{kg} \times 1.25\ \mathrm{USD}\ lb^{-1} \times 9.259\ SEK\ USD^{-1} \times 2.205\ lb\ kg^{-1} \times 2^{-1} \approx 1{,}110\ SEK$ (Convert me; Valutaomvandlare; Creek & Davidson, 2000),
6) $Sludge\ emptying\ \&\ retrieval\ (2\ m^3) = (721+816)\ kr = 1{,}537\ kr$ (Värmdö Municipality, 2015),
7) $Pump = 0.8188\ \mathrm{SEK}\ kWh^{-1} \times 40.5\ kWh \approx 33\ SEK$ (Lerum energi, 2016), see energy calculation below for energy expenditure.

$\boldsymbol{Annual\ cost} = (346+671+2{,}052+3{,}950+1{,}110+1{,}537+33)\ SEK \approx \mathbf{9{,}700}\ \boldsymbol{SEK}.$

Energy calculation sandbed filter

Pumping after septic tank to the distribution well is sized so that the flow in each diffusion pipe is 0.1-0.2 L s^{-1}. The total volume dispatched at each pumping occasion should not exceed the total volume of all the cylindrical diffusion pipes (SEPA, 1987). If the individual pipe flow is set to 0.12 L s^{-1}, the total flow in the 5 pipes would be Q=0.6 L s^{-1}.

- $V_{flow} = \pi r^2 h = (0.0315\ m)^2 \times \pi \times 20\ m \approx 0.0624\ m^3 = 62.4\ L$→$t = V_{flow} Q^{-1} =$ 62.4 L $(0.6\ L\ s^{-1})^{-1} \approx 104\ s \times 60^{-1}$min $s^{-1} \approx 1.73\ min$→1.2 min=72 s good to avoid exceeding total diffusion pipe volume.

- Pumping effect, $P_{hydr}=\rho QgH$ [W=J s^{-1}=Nm s^{-1}],
- An assumed pumping elevation of H=2.5 m [Pa=N m^{-2}],
- Pumping flow=Q=0.6 L s^{-1} [m^3 s^{-1}],
- Acceleration due to gravity, g=9.81 m s^{-2},
- Density of water, ρ=1000 kg m^{-3},
- Input to specific pump, P_{in}=350 W
- Share of the hydraulic pump effect relative to input, $\eta = P_{hydr}(P_{in})^{-1} = \rho QgH(P_{in})^{-1} = 10^3 kg\ m^{-3} \times 0.6 \times 10^{-3} m^3 s^{-1} \times 9.81\ m\ s^{-2} \times 2.5\ m \times (350\ Nm\ s^{-1})^{-1} \approx 4.2$ %.

Suppose pumping for 1.5 min with shaft power (input)→$Energy\ [kWh] = 350\ W \times 1.2\ min = 0.350\ kW \times 0.02\ h = 0.007\ kWh.$

Refilling of the pumped volume:
$T = \mathrm{V}\ H^{-1} = 62.4\ \mathrm{L}\ (10^3\ L\ d^{-1} \times 24^{-1} d\ h^{-1} \times 60^{-1} h\ min^{-1})^{-1} \approx 89.8\ min$→One cycle ≈ (89.8+1.2) min=91 min≈1.52 h.

$Nr\ of\ cycles\ per\ year = 365.25\ \mathrm{d}\ yr^{-1} \times 24\ h\ d^{-1}(1.52\ h\ cycle^{-1})^{-1} \approx 5780$ cycles yr^{-1}.

Each cycle is 0.007 kWh→ $Energy = 5780$ cycles $yr^{-1} \times 0.007$ kWh $cycle^{-1} \approx \mathbf{40.5}\ \frac{\mathbf{kWh}}{\mathbf{year}}$.

OSSFs 2: Package treatment system with precipitation, reference solution

One-time cost PTSs 2 - reference

Installation cost is approximately 47,000 kr for 4evergreen Biorock. An estimated installation cost for the septic tank, the facility itself and the chemical-dosing unit therefore might be 20,000; 25,000 and 2,000 SEK respectively. They could all be put into one unit for cost calculations, if they are assumed to function for the life-time of the facility (VA guide & SwAM, 2016). The pumping station is chosen as the same one as above. The present value of the annuity factor, ANN, is the same since the facility and the pump is again assumed to function for 40 and 20 years, with an interest rate of 3 %. The chemical-dosing unit is assumed to operate at a negligent energy output (AB 4evergreen Solutions, 2016a).

$\boldsymbol{Cost} = 1 - 3 = (47{,}000 + 15264)kr = \mathbf{62{,}264\ kr}$, as well as 15,264 SEK for another pumping station after 20 yrs.

Annual cost PTSs 2 - reference

The operational maintenance for this facility is 2,500 SEK per year, of which 1,939 SEK is for sludge emptying and retrieval (3 m^3 septic tank; larger with chemical dosing), 33 SEK is for pumping electricity as above, and therefore 528 SEK is for the annual chemical dosing maintenance (Värmdö Municipality, 2015; VA guide & SwAM, 2016).

→1-2) $Annuity = 47{,}000\ SEK \times 0.0433 \approx 2035\ SEK$,
→3) $Annuity(pump) \approx 2052\ SEK$.

$\boldsymbol{Annual\ cost} = (2035 + 2052 + 2500)SEK = \mathbf{6587\ SEK}$.

OSSFs 3: Package treatment system including Polonite and GAC

One-time cost PTSs 3 - filters
Installation cost is approximately 52,000 SEK for BIOP ((59,900-7,900) SEK for Polonite) (VA guide & SwAM, 2016). The septic tank is assumed to be the same as OSSFs 1 above. The present value of the annuity factor, ANN, is the same since the facility and the pump is again assumed to function for 40 and 20 years, with an interest rate of 3 %. The facility and septic tank are assumed to function for the lifetime of the facility, while the pump is again assumed to function for half that time. The add-on filters are assumed to function in the same way as for OSSFs 1.

$\boldsymbol{Cost} =$
$1 - 3 + double\ the\ annual\ cost\ of\ filters\ that\ are\ replaced\ every\ other\ year =$
$(52{,}000 + 15{,}500 + 15{,}264 + 7{,}900 + 2{,}220)\ SEK = \mathbf{92{,}884}\ \boldsymbol{SEK}$, as well as 15,264 SEK for another pumping station after 20 yrs.

Annual cost PTSs 3 – filters

1) $Annuity = 52{,}000\ SEK \times 0.0433 \approx 2{,}252\ SEK$,
2) $Annuity = 15{,}500\ SEK \times 0.0433 \approx 671\ SEK$,
3) $Annuity(pump) \approx 2{,}052\ SEK$,
4) $Polonite\ (500\ kg) = 7{,}900$ SEK$\times 2^{-1} = 3{,}950\ SEK$ (Ecofiltration, 2016a),
5) $GAC\ (87\ kg) = 87$ kg$\times 1.25$ USD $lb^{-1} \times 9.259\ SEK\ USD^{-1} \times 2.205\ lb\ kg^{-1} \times 2^{-1} \approx 1{,}110\ SEK$ (Convert me; Valutaomvandlare; Creek & Davidson, 2000),
6) $Sludge\ emptying\ \&\ retrieval\ (3\ m^3) = (914 + 1{,}025)\ kr = 1{,}939\ kr$, as there are indications that a larger septic tank volume is needed, as in OSSFs 2 (Värmdö Municipality, 2015; Svensk Avloppsrening, 2016d),
7) $Pump = 0.8188$ SEK $kWh^{-1} \times 73\ kWh \approx 60\ SEK$ (Lerum energi, 2016; VA guide & SwAM, 2016).

The electricity usage was given in the guide, not calculated with the same pump since this indicates another pump. The electricity price is the same one as for OSSFs 1 and 2.

$\boldsymbol{Annual\ cost} = (2{,}252 + 671 + 2{,}052 + 3{,}950 + 1{,}110 + 1{,}939 + 60\ )SEK = \mathbf{12{,}034}\ \boldsymbol{SEK}.$