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A cost-benefit analysis of hydroponic wastewater treatment in Sweden

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Abstract

Wastewater treatment is an immensely important measure in order to reduce the stress that humans pose on their surrounding environment. As population grows and the detrimental effects of insufficient treatment becomes better understood, the demands on these processes increase. For Sweden, the Baltic Sea Action Plan manifest these increasing expectations, such as increasing demands on emission reduction of nitrogen and phosphorus. The present paper has sought to investigate the potential of hydroponic wastewater treatment plants as a technological step to meet set targets. A cost benefit analysis was performed using data from Fors wastewater treatment plant in Haninge in Sweden. Based on valuation studies, and reports from hydroponic wastewater treatment plants in Sweden and abroad, some conclusions were derived. The results show a positive net present value in favour of a hydroponic treatment plant in the base- and best case scenarios, but a negative in the worst case scenario. The sensitivity analysis shows that the results are sensitive to the quantity and valuation of emission of phosphorus and nitrogen. These results could with some adjustments be generalized to other municipalities and wastewater treatment plants in Sweden.

Keywords: Cost-Benefit Analysis, economics, eutrophication, Haninge, hydroponics, nutrient emissions, Sweden, wastewater treatment.

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1 Introduction

Insufficiently treated wastewater is one of the manmade cause of eutrophication in Sweden, due to the effluents high concentrations of nutrients, such as nitrogen and phosphorus (Naturvårdsverket, 2012, p. 295). The municipal wastewater treatment plants that are responsible for reducing such emissions are gradually facing higher pressure from an increasing population and higher expectations regarding efficiency and sustainability. In the Baltic Sea Action Plan, Sweden has been assigned to reduce nitrogen and phosphorus emissions by 28 000 tons and 290 tons respectively per year until 2021 (Naturvårdsverket, 2009, p. 16).

Treatment plants with a secondary treatment step that host hydroponically grown greenery is one of the technologies that could be the next step in meeting these increasing expectations. In a hydroponic wastewater treatment plant, organic plants grow in the wastewater flowing through large basins that are a part of the biological (secondary) treatment step. It is the second major step of a wastewater treatment plant, responsible for most of the nitrogen removal. This technology is henceforth be referred to as hydroponic wastewater treatment[1]. Different pilot studies have indicated that hydroponic wastewater treatment has some advantages compared to conventional methods, but there has yet had to be performed a complete economic evaluation of the net value of such an investment.

This paper seeks to fill that gap by performing a cost-benefit analysis, comparing the net present value (NPV) of a hydroponic wastewater treatment plant with a conventional plant of the activated sludge type[2]. That is a common type of wastewater treatment plant that consist of several different steps responsible for different parts of the treatment process. The analysis is limited to studying the Fors wastewater treatment plant (of activated sludge type) in Sweden as a base for this analysis. Data has been collected concerning the different costs and benefits associated with building a hydroponic treatment plant instead of a new conventional activated sludge plant, when replacing the current plant. The aim of this paper is to determine whether investment in a hydroponic WWTP in Fors is associated with a higher societal net present benefit than investing in a conventional activated sludge WWTP.

[1] There are other names for this, but in the academic literature, this is perhaps the most common.
[2] The name comes from the fact that produced sludge is recirculated into the system, but this is now common practice, and also not directly relevant for the current paper.

The results from the present study propose a few findings. Firstly, there is a positive net present benefit associated with building a hydroponic wastewater treatment plant in Fors. Secondly, further research into the valuation of nutrient emissions and damages connected to eutrophication is needed. Valuation of environmental damage from nutrient emission is an important aspect when performing an economic evaluation of technologies for treatment of wastewater. Thirdly, building a hydroponic plant in Fors could yield some non-monetized benefits in terms of research and development, since it would be the first one on a large scale in Sweden.

1.1 LITERATURE REVIEW

The literature on Cost-Benefit Analyses of wastewater treatment processes is still quite meagre, and of hydroponic wastewater treatment almost non-existent. Hence it is the hope that this paper can help cover a blank in the field. This section will present the most relevant articles in the field and their findings.

Shalaby et al. (2008) have studied a pilot low-tech hydroponic plant and found that it is less expensive than a conventional wastewater treatment plant.

Hernández-Sancho et al. (2010) calculated the economic and environmental costs and benefits of 43 municipal wastewater treatment plants in Spain. From this data, they computed shadow prices (implied costs of non-removal) for Nitrogen (N), Phosphorus (P), Suspended Solids (SS), Biological Oxygen Demand (BOD) and Chemical Oxygen Demand (COD), depending on the recipient water body. Molinos-Senante et al. (2011), in a similar context, estimated the environmental benefit of water re-use. There has been no similar study of Swedish wastewater treatment plants.

Norström (2005) wrote a dissertation on a pilot biological wastewater treatment system with a hydroponic middle step which was constructed at Överjärva Gård in Sweden. The hydroponic secondary treatment step was shown to be equally or more efficient than a conventional secondary treatment step with regards to pathogen, BOD and nitrogen removal. Some shortcomings of the system were also observed. Phosphorus removal was insufficient, and energy consumption and area use was greater than in a conventional treatment plant.

1.1.1 The knowledge gap

Shalaby et al. (2008) do not evaluate whether it would be possible to efficiently and consistently meet regulatory standards of treatment if employed at a larger scale. In contrast, this paper studies a centralized treatment facility, albeit a comparatively small one.

Neither Hernández-Sancho et al. (2010), nor Molinos-Senante et al. (2011), compare different technologies, but rather different plants using the same technology and none of them with a hydroponic secondary treatment step. The comparison made here thus contributes with a technologically comparative element.

Norström (2005) provided a lot of valuable data on the performance of hydroponic wastewater treatment in Sweden. However, the costs and benefits were not monetized and did not provide a net present value, as is attempted in this paper. Furthermore, the present paper studies the costs and benefits at a larger scale.

1.2 Wastewater treatment in Sweden

The treatment of wastewater has been applied in Sweden for the better part of the last century. Over the years, the demand for effectiveness of the treatment process has increased, requiring the development of more advanced plants and new technical solutions. When the water closet was first installed, the untreated wastewater was emitted directly into the closest water body. The first

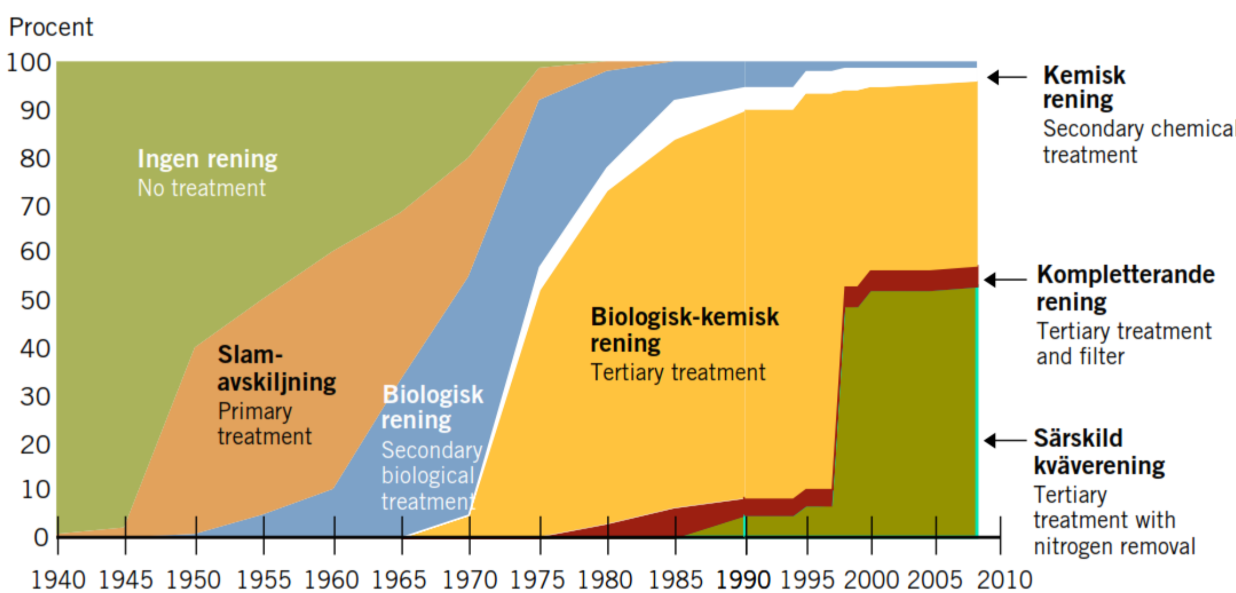

Figure 1 – Levels of treatment in Swedish wastewater treatment plants 1940-2008

(Naturvårdsverket, 2008a, p. 3)

treatment step to be introduced was the mechanical one, separating larger items from the effluent. In the 1960’s, a biological step was introduced to most wastewater treatment plants, removing organic material and nitrogen that is dissolved in the water. The third major development, the introduction of chemical treatment, the bulk of which was installed during the 70’s, mainly focuses on removing phosphorus from the effluent. Later on, additional modifications have been added to the chemical step in some plants, e.g. extra filtering or nitrogen removal, depending on the specific circumstances regarding the source of the wastewater and the recipient water body (Naturvårdsverket, 2008a, pp. 2–3). Apart from national initiatives, there are regulations and targets that Sweden has adopted in accordance with international agreements. Examples of these are the European Union (then EG) directive on wastewater treatment (91/271/EEG), and the Baltic Sea Action Plan of the Baltic Marine Environment Protection Commission.

2 Theory of Cost-Benefit Analysis

The present paper performs a Cost-Benefit Analysis (CBA) of two types of wastewater treatment plants (WWTP), taking both direct expenses and cost savings into account, as well as some externalities.

The purpose of a CBA is to estimate whether a certain project or course of action provides a more positive net benefit from a societal perspective, compared to other options available. This is done by identifying all (significant) costs and benefits associated with the project, determine the direct physical impact of each property and then weigh them all together into one monetary value using different valuation methods. This section attempts to list the most important ethical foundations, advantages and disadvantages of using CBA in the present context and discuss how they are considered in the present paper. A brief discussion is held on these issues, for a more elaborate presentation, e.g. *see* Kriström & Bonta-Bergman (2013).

2.1 ETHICS OF CBA

Cost-Benefit analysis is an anthropocentric framework. It focuses on the costs and benefits borne by humans, measured in e.g. required work, used resources, produced goods or consumption value. This does not mean that the environment is disregarded, but nature, biodiversity and the climate only matter to the extent that it affects the wellbeing, revealed or stated, of human beings (Kriström & Bonta-Bergman, 2013, p. 11). No comprehensive discussion on moral philosophy is held in this paper, but this perspective is worth keeping in mind when assessing the results of any CBA. Furthermore, the idea of measuring the value of a certain project by the benefits it produces and the costs it induces is by definition based on consequentialist ethic philosophy, in contrast to e.g. virtue ethics. In other words this means that there is no value in doing a project that protects the environment unless it yields the intended outcome (ibid. 2013, pp. 11–12).

Compared to estimating the net profit of the actor, estimating the net benefit to society allows the inclusion of externalities into the computation. Because the costs of the externalities are not borne by neither the producer nor the consumer, it is not included in the market pricing of the good. Thus, from a societal perspective, it is insufficient to use the revenue determined by the market to estimate the total societal effect (ibid. 2013, p. 7). Additionally, when the benefit of a project is non-rivalry, such as broadcasting radio news, or having a national defense, it requires a societal perspective to determine the value of the good. If the good is excludable, people could be forced to pay a membership fee, but if this is not possible, then it is very difficult to use a market to determine the value of the good (ibid. 2013, p. 7). In this case, protecting the coastal areas from eutrophication is such a good. It can be enjoyed by everyone who visit the coastal region, and is only occasionally valued in market situations, e.g. the number of tourists visiting the archipelago depends on the cleanliness of the water.

The outcome of a CBA could contradict a common perception of what is morally right and wrong. For example, it could be found that investing in a project that violates someone's human rights is economically beneficial, or protecting someone's rights might not be. This risk does not discredit the method, but it warrants some caution when using the results for decision-making. Even though no such grave moral dilemmas is faced in this particular paper, the monetization of environmental impacts can sometimes yield controversial results. In the case of valuing the benefits of reducing emissions of nitrogen and phosphorus (reducing eutrophication), the conclusions could possibly contradict what politically set targets or what the populations or decision makers deem to be the "right thing to do".

Another possible disadvantage of CBA is that it favors technologies that are currently cheap, due to economics of scale or optimized production over time. Newer or less used technologies might be costly to adopt as the necessary components and competencies are less abundant. For a small project this does not matter much as the current costs of using a technology are the ones that will be relevant at the time and the project itself can be assumed to have very little effect on the overall market and prices of the components used. However, from society's perspective it might be beneficial if all small projects switched to the new technology/design. This way the components used for the new technology could be produced at a large scale, decreasing the price of a technology that in the long run is more effective. The implication for decision-makers is that sometimes a CBA of a specific small scale project might support a different conclusion than a CBA studying a national initiative for all similar projects. E.g. performing a CBA of a project that concerns all WWTPs in Sweden could get a different result than one where a similar project is considered for a single plant. The present analysis is trying to evaluate a single WWT plant.

2.2 TIME HORIZON AND TEMPORAL DISCOUNTING

There are several different ways that future consumption can be discounted. This paper use the most common approach of applying a constant discount rate. That is, giving each time period an exponentially decreasing weight compared to the initial time period[3]. There are important ethical considerations connected to discounting and the topic warrants a longer discussion than is feasible in this paper[4].

Social discounting is done based on certain assumptions. Firstly, there is an assumption that humans by nature are impatient, valuing (loss of) consumption today more than consumption in the future. This is also referred to as the *pure rate of time preference*. Secondly, every living person knows that he/she lives today, but there is always a risk (chance) of not being around when the future consumption (loss of consumption) will be enjoyed (suffered). In other words, future consumption is associated with uncertainty. A similar risk (chance), in a longer perspective, exists for a society. Thirdly, we expect there to be a real growth in the economy, yielding more consumption in the future. Along with the assumption of a decreasing marginal utility of consumption, this gives that a marginal unit of consumption will yield more utility today than in the future, after said growth has taken place.

When considering a long time frame, there is also reason to consider the concept of intergenerational equity. Is it really appropriate to take impatience of those living today into consideration if it will lead to downgrading the standard of living for future generations? This paper does not try to answer this questions, but it should be kept in mind when considering the results of the CBA.

3 Specification of project and identification of impacts

This section will firstly present the project that is evaluated, a hydroponic WWTP, and the baseline scenario that it is compared to, a conventional WWTP. This is followed by a list of the impacts what will be included in the CBA, together with the research that was carried out to identify them.

3.1 PROJECT SPECIFICATION

The two alternative projects that this paper seeks to evaluate and the difference between are presented below. The hydroponic wastewater treatment method is studied in terms of how it

[3] The social discount rate itself is constant, but due to accumulated effect over time, every time period is given less weight than the previous one.
[4] For some examples of further reading on the subject, *see* Beckerman & Hepburn (2007), Rabl (1996), Rambaud & Torrecillas(2005), Sáez & Requena (2007) and Weitzman (1998).

deviates from the conventional activated sludge type. I.e. the conventional activated sludge type serves as the counterfactual. The reason for this design of the study is twofold. Firstly, activated sludge WWTP is the most common type and thus relevant as a baseline scenario. Secondly, to some extent because it is very typical, there is detailed data available for its performance.

While there are many different designs possible for hydroponic wastewater treatment, the design of the project alternatives are chosen so that they are closely comparable in all but one section of the treatment process. This allows many factors to be held constant and make sure that it is the actual hydroponic step that is being evaluated. As presented below, the two WWTP designs only differ in the secondary (biological) treatment step.

3.1.1 SCOPE AND PROJECTIONS

The CBA of this paper is performed based on the context applying to Fors WWTP in the Swedish municipality of Haninge, south of Stockholm. The plant in Fors is planned to be reconstructed or replaced as it is approaching the end of its life, resulting in high level of maintenance and unsatisfying emission levels. There are different life expectancies stated for WWTPs. In a 2003 UN review of WWTP technologies, 50 years was suggested as the life expectancy of the sturdiest part of a plant (UN, 2003, p. 65). This corresponds with the plant in Fors that was built in 1964, making it 50 years old in 2014, which is now facing the need to be replaced. This paper thus use the estimate of 50 years as the life expectancy for a plant.

The current load corresponds to 11600 population equivalents (p.e.) and this is expected to increase to 20 000 p.e. by 2025 (Haninge Kommun, 2014b, p. 11), which is the maximum capacity of the current plant (Haninge Kommun, 2011, p. 4). For the base case, data from the current plant in Fors is used. The project alternatives is considered for the same size and capacity as the current WWTP in Fors (i.e. 20 000 p.e).

The effluent is discharged into Hågaån, which joins into Vitån and then leads the effluent water to Hårsfjärden in the southern Stockholm archipelago at Årsta havsbad (Haninge Kommun, 2014a, p. 3). The distance from the WWTP to the sea is less than 5 km. Data collected from the current plant of activated sludge type is used to construct two alternatives for a new plant.

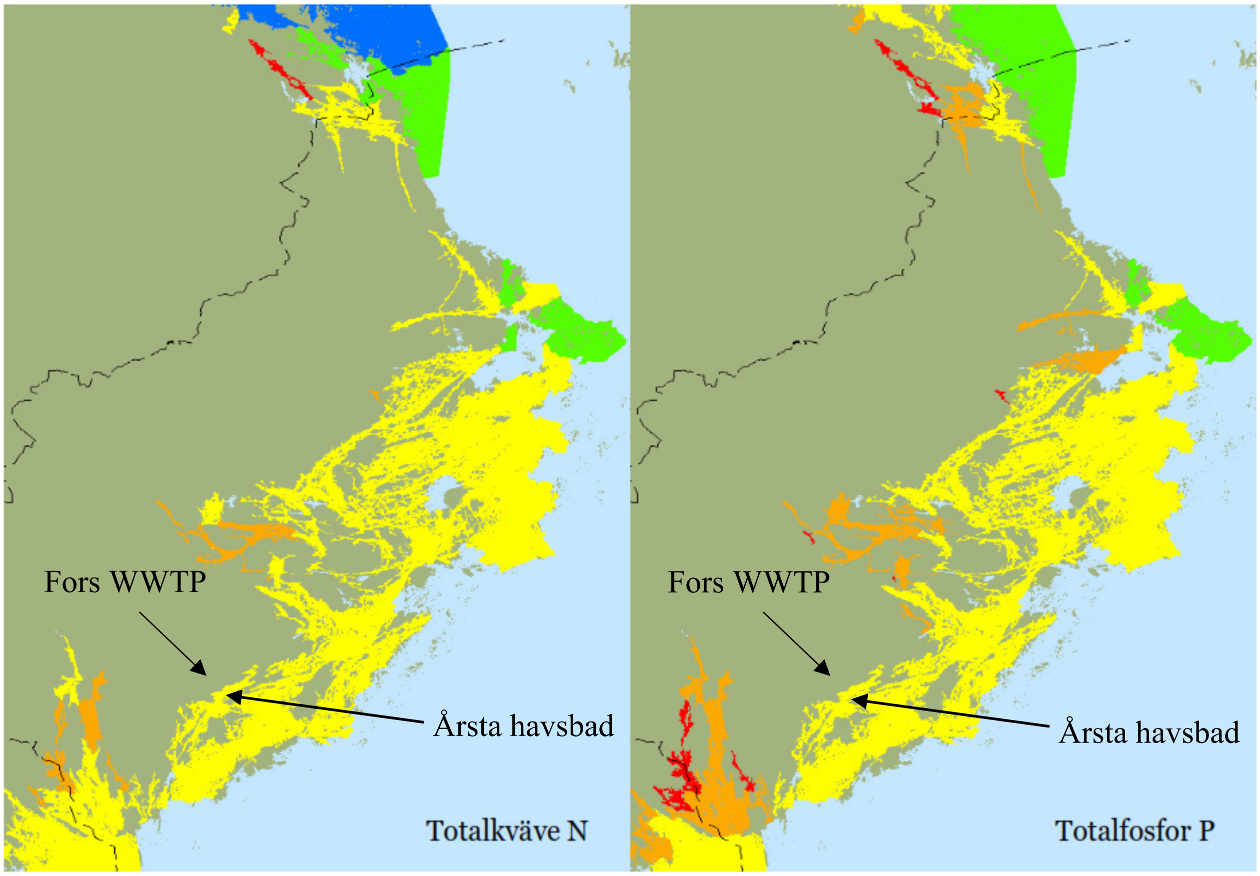

FIGURE 2 – ECOLOGICAL STATUS ON ACCOUNT OF NITROGEN AND PHOSPHORUS IN COASTAL AREAS OF STOCKHOLM COUNTY FROM MEASUREMENTS IN 2009-2011.
BLUE: BEST, GREEN: GOOD, YELLOW: MODERATE, ORANGE: UNSATISFACTORY, RED: BAD. MODIFIED (LOCATION POINTERS ADDED) FROM FIGURE IN REPORT PUBLISHED BY KOMMUNALFÖRBUNDET STOCKHOLMS LÄN (2013, p. 12).

3.1.2 ACTIVATED SLUDGE WWTP

The diagram in Figure 3 shows the typical steps in a conventional activated sludge WWTP[5]. The primary (mechanical) treatment mainly removes larger solid objects from the wastewater that could otherwise damage the rest of the WWTP, or that could risk clogging the system. This step, like many others in the plant, also include sedimentation of sludge. The secondary (biological) step contains microorganisms that nitrify and denitrify the wastewater in anaerobic and aerobic basin respectively. In the tertiary (bio-chemical) step, chemicals are added to precipitate phosphorus to enable it to be successfully removed from the effluent. This step in many cases also includes other proceedures that aim to further decrease nitrogen levels, filter out particles or disinfect the effluent, all depending on how sensitive the recipient is and if the water is intended

[5] In reality the system can be more complex, however this description is suitable for the purpose of showing the differences and similarities between the two projects, *see* Haninge Kommun (2014a, p. 4) for a detailed schematic diagram of the current plant in Fors.

to be reused. In Sweden it is common to have extra nitrogen removal, while the water is rarely reused[6] and thus does not require strict disinfection (Naturvårdsverket, 2008a, pp. 18–19). The activated sludge project alternative is based on the current plant in Fors with the current load and dimensions (*see* 3.1.1), but results are also computed for values reflecting a larger plant with a higher loading rate.

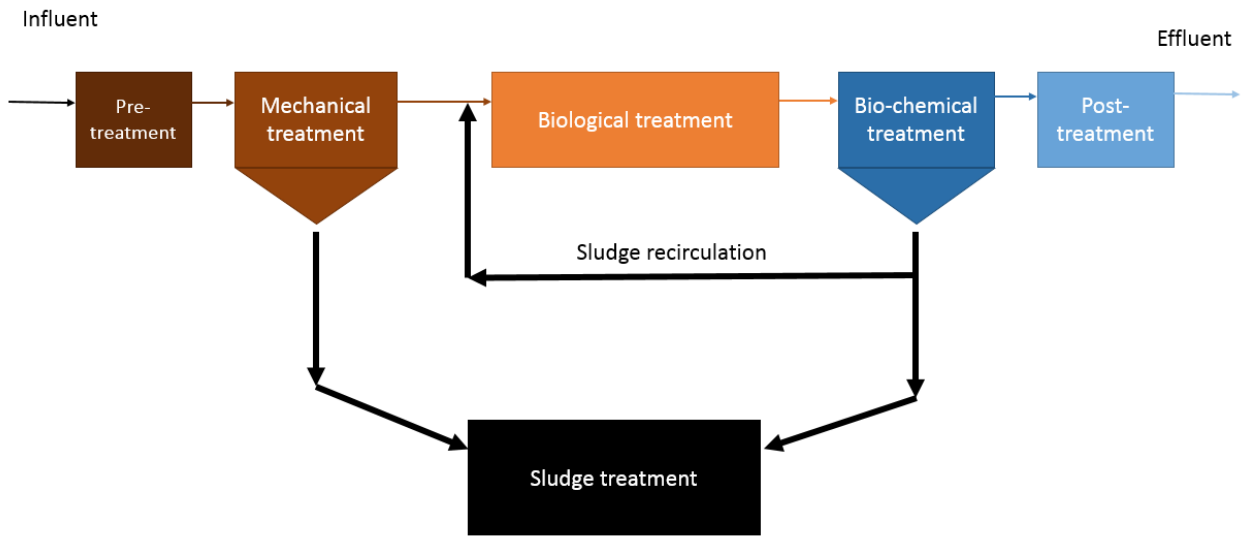

FIGURE 3 – SIMPLIFIED FLOW CHART OF THE ACTIVATED SLUDGE WASTEWATER TREATMENT PLANT ALTERNATIVE

3.1.3 HYDROPONIC WWTP

There are several parts of wastewater treatment that can be made in purely biological manner. The pilot plant in Överjärva Gård is one example of a completely biological WWTP, including having a hydroponic biological treatment plant. In this paper, however, the idea is to evaluate the hydroponic part of the plant alone. A design has thus been chosen where the difference between the two project alternatives lies solely in the secondary treatment step. The hydroponic WWTP has a greenhouse added on top of the biological treatment step, enhancing the conditions for growing plants in the basins. The plants themselves are held in place by a grid covering the basins and there are paths placed between them to provide staff with the possibility to tend to the plants while the plant is operating. The root system of the plants change the living conditions for the microorganisms in the basins, and thus affect their performance in nitrifying and denitrifying the wastewater flowing through the biological treatment step.

[6] The exception being some places on Gotland.

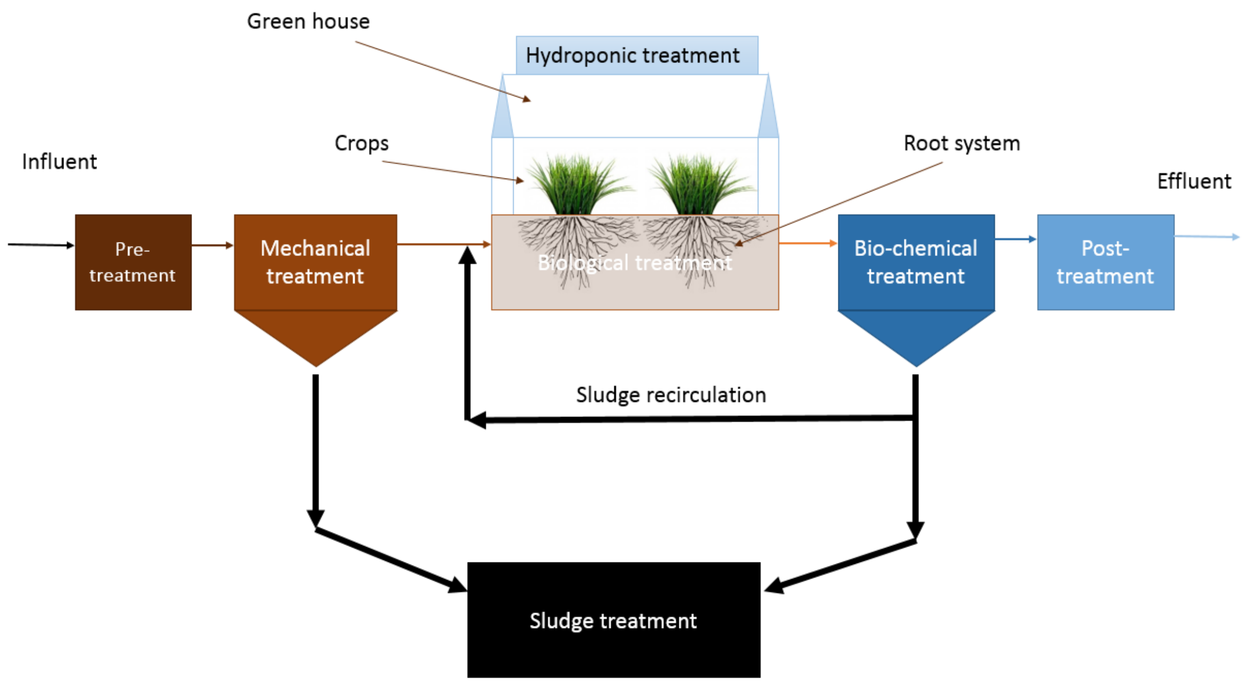

FIGURE 4 – SIMPLIFIED FLOW CHART OF THE HYDROPONIC WASTEWATER TREATMENT PLANT ALTERNATIVE

The plant diagram presented in Figure 4 has been structured in order to highlight the difference between the two project alternatives and does not necessarily represent exactly how such a plant would look in reality. E.g. one WWTP model called the Organica FCR has a series of consecutive basins in the biological treatment step, creating a range of habitats for different organisms, rather than having a single large basin as shown in the flow chart. However, the purpose of the biological treatment step is the same(Organica Water, 2012).

3.2 IDENTIFICATION OF IMPACTS

Data from expert sources and reports is used to determine which impacts are relevant to include in a cost benefit analysis of a wastewater treatment technology in general and those specifically relevant when analyzing a hydroponic wastewater treatment plant. Table 1 shows the impacts that were identified and the related data source.

Some of the mentioned sources are oral and written interviews with experts. Björn Oliviussion at Haningen Municipality (n.d.-f) has previous experience from pilot WWTP in Sweden with hydroponic treatment steps, one in Stensund and one at Överjärva Gård. These plants are not directly comparable to the plant design studied in this paper, but Oliviusson's experience provided some insights into the relevant impacts to consider. Furthermore, Oliviusson has made visits to hydroponic WWTP adapted by Organica Water in Budapest, further increasing his ability to help identify the relevant impacts to consider for the CBA. Anders Folke (n.d.-b) at Fors WWTP, has specific knowledge of the operations at Fors WWTP. His expertise thus was particularly useful in the quantification step of the CBA, but also held some insight into aspects that where important to the daily operations in general. A third correspondence was held with staff at Organica Water, Ágnes Juhász (n.d.-a) in particular. Their suggestions, both in correspondence and published material, was naturally focused on the differences between their type of WWTP and one of conventional (activated sludge) type.

TABLE 1 - DATA SOURCES FOR IDENFICATION OF IMPACTS

Impact	**Source(s)**	**Ground for inclusion**
Capital investment	Oliviusson (n.d.-f), Folke (n.d.-b), Organica Water (n.d.-a)	The hydroponic plant includes additional capital investment according to Oliviusson and Organica Water.
Labor requirement	Folke (n.d.-b), Organica Water (n.d.-a)	The hydroponic plant entails additional labor according to Organica Water.
Nutrient reuse	Oliviusson (n.d.-f)	Oliviusson mentioned the nutrient reuse as an important, but overlooked advantage of hydroponic WWTPs.
Gas production	Folke (n.d.-b)	Gas production is closely related to energy consumption and sludge treatment.
Oil use	Folke (n.d.-b)	Oil use is the main source of carbon emission from the plant.
Electricity consumption	Folke (n.d.-b), Organica Water (n.d.-a)	Decreased electricity consumption is mentioned by Organica Water as an important advantage of the hydroponic plant.
Phosphorus emission	Juhász (n.d.-a), Organica Water (n.d.-a)	Decreased phosphorus emission is mentioned by Organica Water as an important advantage of the hydroponic plant.
Nitrogen emission	Juhász (n.d.-a), Organica Water	Decreased nitrogen emission is

	(n.d.-a)	mentioned by Organica Water as an important advantage of the hydroponic plant.
Sludge production	Oliviusson (n.d.-f), Folke (n.d.-b), Organica Water (n.d.-a)	Decreased sludge production is mentioned by Organica Water as an important advantage of the hydroponic plant.
Odor Pollution	Oliviusson (n.d.-f), Organica Water (n.d.-a)	Oliviusson and Organica Water mentioned reduced Odor pollution as a very important benefit of hydroponic WWTPs.
Education and research	Oliviusson (n.d.-f)	

Previous cost estimates of wastewater treatment (Hernández-Sancho et al., 2010; Molinos-Senante et al., 2011) were also reviewed. In addition to some of the impact mentioned in Table 1, they included the value of treated effluent reclamation. Since treated wastewater is rarely reused in Sweden, this impact was not included.

The internal (financial) dimension is here defined as the costs and benefits that are borne by the owner of the plant, in the case of Fors WWTP this is Haninge Municipality's water and wastewater department. The external (societal) dimension is here defined as the costs and benefits to the broader society. Which individuals are included in the external dimension varies for respective aspects of the WWT process and this is discussed in relation to respective WWTP property below. Some of the externalities from wastewater treatment affect the immediate surrounding population (e.g. Odor Pollution), while other externalities have a global impact (e.g. GHG emissions).

Some of the aspects of wastewater treatment can be defined as costs, just as well as benefits. The treatment of wastewater is in itself of course connected with various benefits, most notably reduced eutrophication and removing harmful substances from the effluent. On the other hand the fact that the WWTP is emitting environmentally damaging substances and nutrients at all could be considered a cost. In this paper the conventional plant is used as the baseline and thus the result is presented as positive if the hydroponic alternative yields a more beneficial or less damaging/costly result.

4 Quantification and valuation

This chapter will present the costs and benefits that have been found to be the most important with regard to the two different WWT technologies. A CBA of WWT in general would benefit from including yet more aspects, e.g. construction and maintenance of sewage pipe networks, but this paper focus on aspects where the two technologies differ. This is most important for the purpose of this study.

4.1 DISCOUNT RATE

The discount rate that is used in the present analysis is 3,5% percent, as advised by the British HM Treasury (HM Treasury, 2003, pp. 97–98), and which has lately been employed by ASEK (2014, p. 9), a Swedish intersectoral working group addressing issues on the application of CBA in the transport sector[7]. These 3,5% corresponds to a pure rate of time preference of 1,5% and an expected growth rate of 2%. This discount rate is double the rate used by Nicholas Stern (2006) in the Stern Review who use a pure rate of time preference of 0,1% and a somewhat lower growth expectation. Still, 3,5% is lower than the 4 % discount rate that was recommended by the Swedish Environmental Protection Agency guidelines for water related environmental projects issued in 2008 (Naturvårdsverket, 2008b, p. 25).

4.2 IMPACTS

Below follows a description of the quantification and valuation of each impact. Each section include which quantities and values are used for the base case.

4.2.1 CAPITAL INVESTMENT

The main initial cost of investing in a new WWTP is the construction cost of the plant itself, including all on-site machinery and components. When estimating this cost there are a great deal of factors that one needs to take into consideration. Fortunately, the purpose of this study is to identify the difference in net present benefit between the two technologies and thus it is sufficient to identify the cost of the parts where the alternatives differ. The hydroponic WWTP project design in this paper is identical to the activated sludge WWTP, except for added sections in the biological treatment step. The costs for the conventional components apply to both alternatives and the difference between the two alternatives in terms of construction costs is thus due to the

[7] Although this is not exactly the same field as this CBA, it includes some similar environmental impacts and the working group contains experts from several sectors, including the Swedish Environmental protection agency.

added components in the hydroponic WWTP (*see* 3.1*)*. Since the extra components are added on top of the structure for the conventional activated sludge WWTP, it is assumed that the hydroponic WWTP would occupy the same amount of land as the conventional one would. The WWTP design presented by Organica Water is marketed as taking up less than half of the area used by a conventional activated sludge plant. However, because the land where Fors WWTP is located is not used for other purposes, the size of the plant is not considered have any significant impact on the results. Even if the area would be turned in farmland, the prices as of 2012 amounted to just above 5 SEK per square meter for farmland in mid-eastern parts of Sweden (Enhäll, 2013, p. 8).

Quantification[8]. Unfortunately, it has been difficult to come across a good estimate of the difference in the initial capital investment needed for a hydroponic plant and a conventional one respectively[9]. The best estimate of the capital investment is that for a plant with capacity to treat wastewater from 40 000 p.e. both the hydroponic and conventional design[10] falls within 150-200 Million Swedish Kronor (MSEK), as suggested by Oliviussion (n.d.-f). The current paper is making the comparison using the dimensions of the current plant in Fors, which is designed to be able to treat a load from half as many p.e. (*see* 3.1.1). Thus, the capital investment estimate has to be adjusted for the purpose of this analysis. Assuming that the capital investment cost is linearly proportional to the load capacity, the span would be 75 to 100 MSEK. This rough estimate would do for the construction cost of the conventional plant, but the estimate for the difference between the two projects would have to be more specific. Assuming that both alternatives indeed have an initial capital investment of between 75 and 100 MSEK, the construction cost of the hydroponic plant theoretically ranges from -25 MSEK to +25 MSEK compared to the conventional one. In a correspondence, Juhász suggested that the "Organica scope is approximately is (sic) 20% of a project" (n.d.-a). This would correspond to about 15-20 MSEK. 17,5 MSEK will be used for the base case scenario.

[8] Because the capital investment is measured in monetary value, this section will not include a valuation of the quantity.
[9] Haningen Municipality is not yet done with the procurement process and the quotes they have received are still classified at the time of writing.
[10] The span is indicated for four different alternatives, two of which are supposed to correspond to the project alternatives specified in this paper.

4.2.2 Labor requirements

There are many different kinds of expertise needed at a WWTP, but few tasks make up a full-time position. Since most parts of the two different project designs are identical, the difference in labor requirements are connected to the differences in the secondary (biological) treatment step. For the purpose of this analysis, the wage is assumed to include appropriate risk premiums for the people working at the plant.

Quantification. The environmental report from Fors WWTP states that there are 8 people working at the department that the plant is run by. However, according to the then chief biologist and chemist at Fors WWTP, Anders Folke, the labor requirement for the plant itself is equivalent to about 1,3-1,7 fulltime employees (n.d.-e). Similarly to the capital investment costs, it is indeed the difference in labor needed to operate the two different project alternatives that is of interest. In a report from a hydroponic WWTP in Le Lude, France, the average workload was reported to be about 5 hours per day. In total, seven different tasks are mentioned (Organica Water, 2011, p. 7). The average of 5 hours per day amounts to 1250 hours per year. The only task that is specified in terms of time consumption is two weeks "maintenance of the botanical garden", two times per year (Organica Water, 2011, p. 7). Assuming these being full-time weeks for one person, it would amount to 160 hours per year. That is, 1090 hours used for other tasks than the annual garden maintenance. Assuming that the other six tasks each take up a sixth of the remaining hours, this leaves just over 180 hours per year per task. Only one of these tasks, daily gardening, can be considered to be directly connected to the plants in the biological treatment step associated with a hydroponic WWTP (Organica Water, 2011, p. 7). Based on the above mentioned estimates, the annual maintenance of the botanical garden and the daily gardening would amount to 340 hours per year.

The plant in Le Lude was serving 6000 p.e. at the time of the report, roughly half of the load currently treated at Fors WWTP. Assuming a linear relationship between workload and the load received by the WWTP, the sum of the workload connected to the hydroponic treatment would be 680 hours per year at a plant subjected the current load rate at Fors. This estimate of the difference in workload between the two alternatives is used in the present analysis.

Valuation. The exact cost of labor for Fors WWTP have not been acquired and thus a template wage cost is used. A 2008 Labor Cost Survey by Statistics Sweden (SCB, 2012) found the average cost per working hour for WWTP staff to be 282 SEK, corresponding to 295 SEK in 2013.

4.2.3 Sludge production

Sludge is a byproduct of wastewater treatment. The sludge is treated in a digestions chamber resulting in the production of sludge gas (*see* 4.2.4). The sludge is tested and then supplied as fertilization to local farmers by a contracted company.

Quantification. Currently, the sludge production at Fors amounts to 1450 metric tons per year (Haninge Kommun, 2014a, p. 12). According to material from Organica Water, a hydroponic plant of their design produces 30% less sludge than an activated sludge plant of comparable capacity (Organica Water, 2012). Norström did too find a lower sludge production at the Överjärva gård pilot plant (Norström, 2005, p. 35), but since the plant was a lot smaller and the reduction in sludge was not precisely measured, it gives no suggestion as to how big the reduction was.

Valuation. According to Oliviusson and Folke, the cost of contracting a company to take care of the produced sludge currently costs the municipality 500 SEK per metric tonne of sludge (n.d.-b, n.d.-f). This value is used in the analysis.

4.2.4 Gas and oil

Wastewater treatment plants use energy for machinery and heating. The plant in Fors uses its own produced sludge gas (i.e. biogas) for heating the digestion chamber, heating oil for heating the digestion chamber when the sludge gas supply is low, and electricity for running plant machinery and components. Electricity consumption is addressed in a separate section.

Quantification. The current amount of sludge gas produced at Fors amounted to 110 000 m^3 during 2013 (Haninge Kommun, 2014a, p. 13). This value is used for the baseline. According to Andreas Carlsson at Stockholm Vatten, The magnitude of the production of sludge gas depends on the amount of sludge digested in the chamber (n.d.-c). Because the sludge production is reported to be lower in the hydroponic plant, the same is expected for the production of sludge gas. Assuming a linear relationship, the expected sludge gas production volume for the hydroponic WWTP is 30% lower than the baseline (*see* 4.2.3), i.e. 33 000 m^3 less gas produced.

The digestion chamber requires a certain temperature to operate efficiently, a temporary or lasting shortage in sludge gas to heat the chamber has to be compensated by using heating oil, according to Carlsson (n.d.-b). Maintaining the assumption that the hydroponic plant produces less sludge gas, an increase in the use of heating oil to keep a sufficient temperature in the digestion chamber could be necessary. However, assuming that the amount of heating needed in the digestion chamber is proportional to the volume of sludge that it is designed for, a smaller chamber suited for a lower sludge production could be constructed. Theoretically, this would avoid the gas deficiency from decreased sludge production. The base case thus considers the heating oil consumption to be about the same for both project alternatives. Fors WWTP is currently using 6 cubic meters of heating oil per year.

Valuation. Burning oil for heating has both internal and external costs. The internal cost is the price of buying heating oil. The average price listed for 2013 by the Swedish Petroleum and Bio-fuel Institute was 10 623 SEK per cubic meter oil (SPBI, 2014a). Arguably, this externality is already internalized into the market price through Sweden's CO_2 taxes. I.e. this price is here considered to be the total cost (price + externality) of heating oil consumption. The following section presents the motivation.

The external costs consist of the environmental damages caused by GHG emissions from the burning of the oil. The amount of carbon dioxide equivalents (CO_2e) emitted from burning heating oil is 0,32 tonne CO_2e per MWh and there are 10 MWh per m^3 oil. This gives 3,2 tonnes of CO_2 per m^3 oil. According to the Swedish Petroleum & Biofuel Institute (SPBI, 2014b), the carbon tax on heating oil amounted to 3093 SEK/m^3 oil in 2013[11]. Using the conversion rate above, this would result in an effective CO_2e tax of 969 SEK per tonne of CO_2 emitted from burning heating oil. So, how does this compare to the environmental cost of CO_2 emissions? In a survey of 211 Social Cost of Carbon (SCC) estimates, SCC estimates were found to vary greatly. The median SCC among studies using a pure rate of time preference of 1%[12] was found to be 172 SEK per CO_2e (Tol, 2008, p. 3). This pure rate of time preference was the one closest to the one

[11] There is also an energy tax of 817 SEK/m^3 oil, but this is not based on, nor made to account for, carbon GHG emissions.
[12] This is not to be confused with a discount rate, which includes other aspects than pure rate of time preference (*see* 2.2).

assumed in this paper[13] (i.e. 1.5%, *see* 4.1). Assuming that this value is anywhere close to the "true" SCC, the Swedish effective tax on carbon emissions from the burning of heating oil covers the damages caused by the emissions.

Excess gas is flared (burnt) in order to avoid emission of methane, since it has more adverse effects than corresponding amount of coal in the form of CO_2-emissions. All of the produced sludge gas is thus burned, either for heating or by flaring. The resulting emissions are not subjected to carbon tax as the emission is a part of a natural carbon cycle. Thus, the emissions is here considered an externality. Unlike the GHG emissions from burning heating oil it has not been internalized into any other expenses. The SCC of 172 SEK per CO_2e from the above mentioned survey by Tol (2008) is used in the present analysis.

4.2.5 Electricity consumption

The electricity used at the plant is necessary to keep the plant running. The current annual electricity consumption at Fors WWTP is 800 MWh (Haninge Kommun, 2014a). This value is used for the activated sludge WWTP alternative.

Quantification. There are two counteracting factors effecting the estimated annual electricity consumption of the hydroponic WWTP alternative. Firstly, according to Organica Water the bulk of the electricity consumption goes into keeping the aerators running that pump air into the biological treatment step. This is verified by Anders Folke at Fors WWTP (n.d.-e). Organica Water states that the electricity consumption can be reduced by as much as 30% because most of the biomass in tanks being aerated is attached to the biofilm, rather than being suspended in the water. This allows the water to be supplied with oxygen much more efficiently and thus requires less activity from the blowers (Organica Water, 2014e). A 30% decrease from the current level at Fors WWTP would correspond to 240 MWh less electricity consumption per year.

Secondly, the Swedish winter climate may affect the need for heating and lighting. The facilities need to be warm and light enough for plants and organisms to stay alive. According to Oliviusson (n.d.-f), the water temperature can be expect to stay between 6-18 degrees depending on outdoor temperature. This could help regulate the temperature in the root systems and stems of the plants. Apart from having a decent temperature, the plant's need for sunlight might not be met during the

[13] Ideal would have been to perform a survey specifically for this paper, but this would be too time consuming considering the scope

darkest months of the year. Norström computed that theoretically, keeping the minimum required lighting (400 lux) and heating (10 degrees) for the plants to survive in the greenhouse part of a hydroponic wastewater treatment plant in the Stockholm area would be associated with an electricity consumption of roughly 75 kWh per m^2 (Norström, 2005, p. 17).

Data from case studies of plants in Etyek and Telki in Hungary, and Shenzhen in China, may serve as indicators of the greenhouse size. The size data is presented as ”footprint” of the whole plant, i.e. the are physically covered by the plant. Given the design of the Organica FCR plant presented by the company (Organica Water, 2012), a visual estimate would be that about 80% of the area of the whole plant is made up by the greenhouse. The plant size (area) to treatment capacity ratio for the three WWT plants range from 325-570 (average of 442) m^2 per m^3/day capacity (Organica Water, 2014b, 2014c, 2014d). Assuming that the greenhouse area makes up 80% of the area taken up by the plant, the average ratio from the three cases can be recomputed to about 354 m^2 greenhouse per 1000 m^3/day capacity of the plant. The WWTP in Fors has a dimensioned capacity of 8160 m^3/day. Based on these very rough estimates the greenhouse electricity consumption of a hydroponic plant with the dimensions of the current Fors plant would reach about 217 MWh per year.

Valuation. The internal cost of electricity is the market price charged by the supplier. The external costs are connected to GHG emissions in the electricity production. Similarly to a cost estimate study of wastewater treatment in the Stockholm area by Swedish consultancy firm SWECO (2013), a template value of 1 SEK per kWh is used for internal energy price. The use of electricity is not connected with any direct externality, but the production of energy is. The social cost of electricity production can be measured in different ways. Since the considered project is relatively small, and cannot be assumed to effect the overall structure of the energy production, this paper uses an estimate of the impact of the current marginal electricity production. In Sweden, marginal electricity is produced with coal power resulting in approximately 700 grams of CO_2e per kWh (Elforsk, 2006).

4.2.6 Phosphorus and nitrogen emission

The main purpose of a wastewater treatment plant is to remove substances from the wastewater that is considered harmful to the environment, before releasing the effluent into the recipient water body. The emission of phosphorus and nitrogen increases the risk of eutrophication, and thus it is associated with an environmental cost. This is strictly an externality to the WWTP operation and it has no direct impact on the income or expenses. However, WWT plants in Sweden are subjected to certain regulations with regard to concentrations and/or total amount of certain elements in the effluent over the course of a year. E.g. SNFS 1994:7 regulates that a plant of Fors ARV's size should release an effluent with no more than a 15 mg/l concentration of total nitrogen (Statens Naturvårdsverks författningssamling, 1994).

Quantification. The amount of nutrients in the effluent is measured regularly at Fors WWTP and the annual results are presented in an environmental report. These figures are used to determine the expected emission level for the conventional plant. Wastewater treatment technology has improved since the plant in Fors was built in 1964, and although several upgrades have been made over the years, it is likely that a new plant could be more effective than the current one. However, as is shown below, the estimates for the hydroponic plant are based on relative differences, not absolut. Thus using the current values for Fors will suffice for comparative purposes.

The average total annual emissions of nitrogen and phosphorus 2011-2013 were 27 and 0,285 tonnes respectively (Haninge Kommun, 2011, p. 10, 2014a, p. 10). According to Organica Water, a hydroponic plant of their design emitts 50% less nitrogen and phosphorus than a comparable conventional plant, or put differently, can reduce the same amount of nitrogen and oxygen using a plant half the size (Organica Water, 2012, 2014a). This is used as the expected difference between the conventional and the hydroponic plant.

Valuation. The value of reducing emissions (abatement) is here determined indirectly by using estimates of environmental improvement in the recipient. These estimates are collected from valuation studies using Benefit Transfer (BT). In a report published by the Swedish Environmental Protection Agency, recommendations were given with regards to transfer values from one context to another. They recommend unit value transfer (using a single point value estimate for all quantities) rather than value function transfer (using a function where value depends on quantity), as it requires a lot less resources and the difference in validity is not substantial enough to motivate the extra effort required (Håkansson, 2013, p. 304). There are studies that have shown that the difference in transfer error between unit value transfer and value function transfer can be significant (Brouwer, 2000, p. 140). Despite those findings, this paper makes use of unit value transfer because of the reasons mentioned in the abovementioned report from the Swedish Environmental Protection Agency, regarding time and resource requirements.

There are several valuation studies made with regard to water quality in Sweden. They vary in many regards and certain considerations have to be taken into account when choosing which studies and values to use. In 2009, a survey of 11 different studies valuing water quality in Sweden was performed with the aim of making a guideline for valuing water quality. From these, 5 were selected, all of which studied eutrophication, and had sufficiently specified methodology and results in order to be comparable to each other. This included studies that used both Contingent Valuation Method (CVM) and Travel Cost Method (TCM), leading to some of them including non-use value and some only use-value of better water quality due to less eutrophication. From these studies, best estimates of 31 SEK per kg nitrogen abatement and 1023 SEK per kg phosphorus abatement were established (Kinell, Söderqvist, & Hasselström, 2009, pp. 43–50).

4.2.7 Nutrient reuse

Wastewater contains nutrients. These nutrients cause eutrophication if emitted in too high concentrations (*see* 4.2.6). However, the nutrients can too hold economic value if collected and used for growing valuable plants, such as crops for biodiesel or ornamental plants. Today, a kind of nutrient reuse is done at Fors WWTP by distributing treated sludge from the plant to local farmers through a private contractor. This does not yield any income to the plant, and the municipality is paying for this service. It holds some environmental benefits compared to other types of disposal, but as this practice is assumed to be employed in the future too (regardless of which plant will be built to replace Fors WWTP), it does not impact the present analysis. The hydroponic plant, however, includes another type of nutrient recycling. Plants growing in the WWTP would have to absorb nutrients from the wastewater and cause them to be reused rather than emitted through the effluent or as sludge. Consequently, eutrophication from nutrients in the effluent would be reduced and sludge volume could potentially also be reduced as presented in previous sections (*see* 4.2.3 and 4.2.6). Here the focus is on the direct intrinsic costs and benefits of the nutrient reuse itself.

In this analysis, there is not considered to be any direct costs of the plants reusing nutrients, meaning that compared to a situation where the plants function in the hydroponic WWTP are replaced by a non-living substitute[14] there are no extra costs, apart from those connected with extra labor mentioned in previous section. The increased workload due to caretaking of the plants, and other associated tasks to keep them alive, has already been addressed. Assuming that it is possible to grow valuable crops in the greenhouse of the hydroponic WWTP, the reused nutrients can be valued as an input in the crop production. The direct value of nutrient reuse, leaving the improved degree of purification aside for the time being, can be judged from the value of fertilizers/nutrient solutions that it could substitute. In reality, there would have to be put in place a mechanism that allows this potential value to be reaped, but this issue is not addressed in this paper.

Quantification. The reuse of nutrients is valued using the value of the nutrients that are taken up by the plants, perceived as input factors into plant production. The amount of nutrients taken up by the plants is assumed to be equivalent to the difference between the amount of nutrients emitted by the respective project alternatives (*see* 4.2.6 on nitrogen and phosphorus emissions). Assuming that the difference between the two project alternatives in terms of emitted nutrients represents the nutrient uptake of the plants ignores that they might differ in concentration of nutrients in the sludge. This would mean that the difference in emissions between the two projects is not only representing the nutrient reuse.

Valuation. The Swedish Board of Agriculture has developed standardized values for the most common nutrients in fertilizers nitrogen (N) and phosphorus (P), when used as input into agricultural production. The values recommended for 2014 are 9 SEK/kgN and 20 SEK/kgP (Albertsson, 2014, p. 26) and are used for the base scenario.

4.2.8 Odor pollution

Odor pollution can be a nuisance to residents and businesses that are located close to a WWTP.

Quantification. According to Organica Water, the odor affected area around the WWTP is reduced by over 90% by covering the secondary treatment step with a greenhouse as in the Organica design used a model for the current analysis (Organica Water, 2012). E.g. Oliviusson (n.d.-f) informed that a plant in Hungary was able to reduce its buffer limit from 350 meters from the plant, to 50 meters. If the same difference would be assumed to exist between the two project

[14] I.e. some kind of synthetic material reassembling the plants root systems that would too provide a good habitat for micro-organisms, giving the same benefits in terms of improved treatment, but would not recycle nutrients.

alternatives in this paper, it would theoretically correspond to over 50 hectares[15] of new land that could be sold or rented out for commercial or residential purposes.

Valuation. Oliviusson (n.d.-f), as well as real estate agent Therese Norén at SkandiaMäklarna (n.d.-d) working in the surrounding area, have asserted that odor from Fors WWTP does not have a detrimental effect as it is located in an sparsely populated area. The value of reducing odor pollution is thus seen as having next to zero value in this particular context. This conclusion could of course be contended if one considers the population growth expectations presented by Haninge municipality (*see* 3.1.1). This growth might change the intended land use in the future. These are however mere speculations and since there, as of now, are no plans to populate the area. The odor pollution is given a zero-value.

[15] This is assuming a squared buffer zone around a plant larger than 20 x 20 meters, with no other surrounding obstructions preventing the area to be constructed.

5 Results and sensitivity analysis

This chapter will first present a summary of the included components of the CBA, their associated net costs or net benefits, and their real present values. It then proceeds to present some tests of the results sensitivity to changes in certain parameters. Unless otherwise noted, the time frame is 50 years for the total value and the social discount rate used is 3,5% (*see* 3.1.1 and 4.1).

5.1 BASE CASE SCENARIO

Using the values presented in the previous chapter, the hydroponic plant is associated with a net present benefit of about 2,2 MSEK. Table 2 shows the quantities and unit values, presented in thousand SEK, used for computing the net present benefit. The quantity is the difference between the two alternatives, i.e. $Hydroponic - Conventional$. A negative number signifies that the hydroponic plant use/produce less than the conventional plant. The unit value is negative when the use/production is associated with a cost, and positive when the use/production is associated with a benefit.

Results hydroponic plant

Conventional plant as baseline, all values given in thousand SEK

Property	**Unit**	**Annual Quantity**	**Unit value**	**Annual gross value**	**Total value**
Capital investment	MSEK	-	-1000	-	-17 500
Labor	hours	680	-0,28	-192	-4 690
Oil - Chamber heating	m^3	0	-10,6	0,00	0
Electricity - Heat & Light	MWh	217	-1,12	-243	-5 946
Electricity - Operation	MWh	-240	-1,12	269	6 576
Nutrient reuse - N	tonne	13,5	9,00	121,5	2 971
Nutrient reuse - P	tonne	0,14	20,0	2,85	70
Sludge production	tonne	-440	-0,50	220	5 374
Emission - N	tonne	-13,5	-34,3	419	11 309
Emission - P	tonne	-0,14	-1130	146	3 939
Gas Production	1000 m^3	-33	-0,13	4,43	108
TOTAL SUM				**175**	**2 213**

TABLE 2 - RESULTS OF THE BASE CASE SCENARIO

In these primary results, it is possible to make some general observations. Firstly, the two electricity posts roughly cancel each other out, with a slight positive net due to the quantity reduced in the operation, compared to lighting and heating. Secondly, because the heating oil used in the base case was assumed to be the same in the two project alternatives, it does to impact the results. Thirdly, the nutrient reuse of phosphorus has a very small NPV, despite being much more valuable per kg than nitrogen, simply because the quantity is minuscule. Fourthly, the reduced emissions of the same nutrients are of the same quantities, but here the difference in value between nitrogen and phosphorus are even bigger, and thus they both have an important impact on the results. Fifthly, the reduced sludge gas production, and the resulting reduction in GHG emission does not reach high enough quantities to affect the total outcome of the CBA. However, the hydroponic plants lower production of sludge has a quite big value in itself, surpassing the labor costs with a margin.

In short, the strictly internal costs and the strictly internal benefits (labor, energy and sludge) are similar in magnitude. This holds also when taking into account that about 10% of the cost per MWh electricity used is on account of the carbon emission from marginal electricity consumption (*see* 4.2.5). Based on this a proposition could be made that as the environmental improvements in terms of nutrient reuse and reduced nutrient emissions can match the capital investment costs, the hydroponic treatment plant is associated with a net present benefit, using the base case assumptions.

5.2 SENSITIVITY ANALYSIS

Data collection and valuation of non-marketed goods are subjected to a certain amount of uncertainty in any study, the present one is no exception. This section will attempt to argue for the different approaches that have been employed depending on the type of uncertainty, but more importantly it will offer transparent description to the reader. This paper employs an extreme case sensitivity analysis by defining a worst-case and best-case for each parameter. I.e. worst and best in the meaning that it would result in the lowest and highest expected net benefit for the hydroponic plant[16].

5.2.1.1 VALIDITY UNCERTAINTY

This CBA, like most, includes many different impacts to be estimated and valued. The wide arrange of values needed makes it necessary to rely on other studies and unit value transfer. These transferred values may not always fit the current CBA perfectly, and this gives rise to some uncertainty of the validity. In order to handle this uncertainty, the sensitivity analysis allows these

[16] Not to be confused with a normative assertion of what would be worst or best from a societal perspective, or for the decision-makers.

values to vary quite a bit between the worst-case and best-case scenarios. It is very difficult to know exactly what can be considered to be a good range for plausible errors. Unfortunately, unless there are several comparable studies made, the range chosen for the sensitivity analysis has to be arbitrary. It is very difficult to know the likelihood of the worst-case and best-case scenario respectively and this paper relies on transparency to counter uncertainty. When based on a single observed value, the worst and best case scenarios are given values that are +/- 10% for estimates that are considered highly reliable and +/- 25% for rough estimates. This approach is used for quantity and valuation data alike. If there are several valuation studies available, one value is chosen for the base case and alternative values are be selected for the worst and best case scenarios. This neither identifies nor removes the risk of value transfer errors, but it gives some indication of how large the impact of such errors could be.

5.2.1.2 DATA SOURCE BIAS

There is as of yet no large scale hydroponic WWTP in Sweden. The data for the hydroponic plant is thus estimated using reports from plants in other parts of the world that are in operation. For this particular design of hydroponic WWTP there is but one developer, Organica Water. The company that designs these plants thus authors the reports used and this warrants some caution when using the data as they have obvious incentives to put the results in the best light possible. The data collected from the producer is considered to be reliable, but in order to test what the results would be if these values turn out to be optimistic. The data that depends on the producing company is allowed to assume 40% less favorable value in the worst case scenario and 10% more favorable value in the best case scenario.

5.2.2 SENSITIVITY TO QUANTITY UNCERTAINTY

The quantities of capital investments, labor, heat & lighting and nutrient reuse are considered to be rough estimates and are given a 25% less (more) favorable value in the worst (best) case scenario. The quantities for sludge production, nutrient emissions and gas production (as it is based on the sludge production) are based on data from Organica Water and are given a 40% less favorable value in the worst case scenario and 10% more favorable in the best case scenario. Heating oil consumption is assumed to be the same for the two project alternatives in the base case, but in the worst case scenario, it is assumed to increase with 30% (same percentage as the decrease in sludge gas production).

Allowing the properties to assume their respective worst-case quantities has a rather dramatic effect on the total NPV of the analysis, as shown in Table 3. The costs associated with heating and lighting the greenhouse is almost double the savings from reduced electricity use by the blowers. The relationship between labor costs and the reduced sludge production is changed in a similar way. The internal (labor, energy and sludge) expenses by far exceed the internal savings in the worst-case scenario.

Sensitivity analysis - Quantity variation

Hydroponic plant base-case unit-values, all values given in thousand SEK

		Quantity			Net Present Value		
Property	**Unit**	**Worst**	**Base**	**Best**	**Worst**	**Base**	**Best**
Capital investment	MSEK	21,9	17,5	13,1	-21 875	-17 500	-13 125
Labor	hours	850	680	510	-5 862	-4 690	-3 517
Oil - Chamber heating	m^3	1,80	0,00	0,00	-468	0	0
Electricity - Heat & Light	MWh	271	217	163	-7 432	-5 946	-4 459
Electricity - Operation	MWh	-144	-240	-264	3 946	6 576	7 234
Nutrient reuse - N	tonne	6,08	13,50	18,56	1 337	2 971	4 086
Nutrient reuse - P	tonne	0,06	0,14	0,20	31	70	96
Sludge production	tonne	-264	-440	-483	3 224	5 374	5 912
Emission - N	tonne	-8,10	-13,50	-14,85	6 786	11 309	12 440
Emission - P	tonne	-0,09	-0,14	-0,16	2 364	3 939	4 333
Gas Production	1000 m^3	-19,8	-33,0	-36,3	65	108	119
SCENARIO SUM					**-17 884**	**2 213**	**13 118**

TABLE 3 - RESULTS USING WORST-, BASE- AND BEST-CASE QUANTITIES. VALUATION USING BASE-CASE VALUES.

The increased heating oil consumption in the worst-case scenario does not amount to a significant cost, mainly because of the low initial quantity. The difference between the total values of the scenarios is not due to any single wastewater treatment property, but rather due to changes in all of them. The worst-case scenario is much further from the base-case than the best case is. This has a lot to do with the fact that the quantity of many of the most important factors, such as electricity for operation, sludge production and emission levels, depend on data from the producer and have been treated as potentially biased in the sensitivity analysis (*see* 5.2.1.2).

5.2.3 SENSITIVITY TO VALUATION UNCERTAINTY

The valuation of labor and sludge production are considered to be reliable estimates and are given a 10% less (more) favorable value in the worst (best) case scenario. The valuation of nutrient reuse is considered to be rough estimates and is given a 25% less/more favorable value in respective scenario. The emissions of phosphorus, nitrogen and CO^2 (from flaring of sludge gas

& electricity production) have been given very different values depending on which study is used. The values for the worst and best case scenarios have been selected as presented below.

The intervals from the used survey of studies were found to be 11-211 SEK/kg and 382-6420 SEK/kg reduced emission of nitrogen and phosphorus respectively (Kinell et al., 2009, pp. 43–50). The best estimates from this survey are used for the base case in this CBA. Lower bounds of the intervals are used for the worst-case scenarios and the upper bound for the best-case scenario. Although these studies are the best available valuations of these emissions, there are reasons to believe that they are generally underestimating the costs. Using different methods and areas of study, the studies represented in the survey have estimated the willingness to pay for an improvement in sight depth by reducing eutrophication. However, decreased sight depth is but one of the consequences of eutrophication. Other impacts are oxygen depletion, loss of biodiversity (both sea life and aquatic plants) and loss of harvestable fish stocks. It is difficult to make any justifiable assessment of the value of these impacts without performing a larger study, but it is safe to say that these impacts have not been included in the valuation used for this analysis, unless the respondents have kept indirect damages associated with sight depth in mind when choosing their willingness to pay.

For SCC, alternative values from the previously mentioned survey by Tol (2008) is used. The median values 634 SEK per CO_2e for 0%, and 50 SEK per CO_2e for 3%, pure rate of time preference are tested (*see* 5.2.1.1 on contradicting valuation studies). The SCC is relevant for several aspects of the wastewater treatment process, but in the base case, the hydroponic project alternative has a lower total emission of CO_2e and thus the higher value is here associated with the best-case scenario and vice versa. This leads to the hydroponic plant performing "better" in the worst-case scenario than in the best case-scenario if only looking at the aspects where it emits more CO_2e than the conventional alternative. Another approach to avoid this would be to test each of these different aspects (e.g. gas vs heating oil) of wastewater treatment separately, but it is here deemed inappropriate to use different values for SCC in the same scenario.

Allowing the valuation to vary within the established plausible ranges has some notable implications on the results. As shown in Table 4, the internal dimension (labor, energy and sludge) is again fairly balanced in all scenarios.

Sensitivity analysis - Valuation variation Hydroponic plant base-case quantity, all values given in thousand SEK							
		Unit value			Net present value		
Property	**Unit**	**Worst**	**Base**	**Best**	**Worst**	**Base**	**Best**
Capital investment	MSEK	-1000	-1000	-1000	-17 500	-17 500	-17 500
Labor	hours	-0,31	-0,28	-0,25	-5 159	-4 690	-4 221
Oil - Chamber heating	m^3	-10,6	-10,6	-10,6	0	0	0
Electricity - Heat & Light	MWh	-1,04	-1,12	-1,44	-5 493	-5 946	-7 662
Electricity - Operation	MWh	-1,04	-1,12	-1,44	6 075	6 576	8 474
Nutrient reuse - N	tonne	6,75	9,00	11,25	2 229	2 971	3 714
Nutrient reuse - P	tonne	15,0	20,0	25,0	52	70	87
Sludge production	tonne	-0,45	-0,50	-0,55	4 837	5 374	5 912
Emission - N	tonne	-12,2	-34,3	-233,2	4 013	11 309	76 976
Emission - P	tonne	-422,1	-1130	-7094,0	1 471	3 939	24 722
Gas Production	1000 m^3	-0,04	-0,13	-0,49	31	108	399
SCENARIO SUM					**-9 443**	**2 213**	**90 901**

TABLE 4 – RESULTS USING BASE-CASE QUANTITIES. VALUATION USING WORST-, BASE- AND BEST-CASE VALUES.

The big impact on the NPV of the worst-case and best-case scenarios alike comes from the valuation of the nutrient emissions, simply because of the dramatic differences between the different estimates from the valuation studies. In terms of percentage, the reduction in gas production is impacted heavily by the different SCC estimates used, but because it is at such a low level, it has a very small impact on the overall results. The huge variation in valuation of emissions of nitrogen, however has a large impact. The variation in the valuation of phosphorus emissions is not as big in absolute terms, but it is still substantially bigger than the variations for the other properties.

5.2.4 SENSITIVITY TO SOCIAL DISCOUNT RATE

All of the wastewater treatment properties, except for the capital investment costs, are active from the completion of the plant itself until the time horizon (50 years, *see* 3.1.1). This makes the impact of a change in the discount rate rather predictable, as depicted in Table 5. The lower the discount rate, the higher the absolute numbers, especially for the best case scenario.

Sensitivity analysis - Social discount rate variation									
Net present values using scenario based quantity and valuation, all values given in thousand SEK									
	2,0%			3,5%			5,0%		
Property	**Worst**	**Base**	**Best**	**Worst**	**Base**	**Best**	**Worst**	**Base**	**Best**
Capital investment	-21 875	-17 500	-13 125	-21 875	-17 500	-13 125	-21 875	-17 500	-13 125
Labor	-8 549	-6 218	-4 197	-6 448	-4 690	-3 165	-5 077	-3 693	-2 492
Oil - Chamber heating	-620	0	0	-468	0	0	-368	0	0
Electricity - Heat & Light	-9 103	-7 883	-7 619	-6 866	-5 946	-5 747	-5 406	-4 682	-4 525
Electricity - Operation	4 832	8 719	12 359	3 645	6 576	9 322	2 870	5 178	7 340
Nutrient reuse - N	1 330	3 939	6 771	1 003	2 971	5 107	790	2 340	4 021
Nutrient reuse - P	31	92	159	24	70	120	19	55	94
Sludge production	3 848	7 125	8 621	2 902	5 374	6 503	2 285	4 231	5 120
Emission - N	3 192	14 994	112 261	2 408	11 309	84 673	1 896	8 905	66 670
Emission - P	1 170	5 223	36 055	883	3 939	27 194	695	3 102	21 412
Gas Production	25	144	582	19	108	439	15	85	346
SCENARIO SUM	**-25 719**	**8 635**	**151 867**	**-24 774**	**2 213**	**111 321**	**-24 158**	**-1 979**	**84 861**

TABLE 5 – RESULTS UNDER THREE DIFFERENT DISCOUNTING REGIMES USING WORST-, BASE AND BEST-CASE QUANTITIES. VALUATION USING WORST-, BASE AND BEST-CASE VALUES.

The relative importance of the different posts remains the same over different discount rates, except for the capital investment cost. It is not affected by the discount rate, and therefore becomes more important to the final result the less the future is values. If there were variations in which years the different costs and benefits were active, changing the discount rates would also change the relative importance of the other costs and benefits.

6 Discussion and conclusion

The aim of this paper has been to find out whether it would yield a net present benefit to invest in a hydroponic wastewater treatment plant rather than a conventional activated sludge plant when replacing the Fors wastewater treatment plant in Haninge. There was a need to make some simplifying assumptions and the data availability created some limitations and uncertainties. Despite these considerations, it seems that the results speaks in favor of a hydroponic WWTP. This is not a definitive answer regarding the advisability of the construction of a hydroponic plant at Fors as the worst case estimate is has a very negative NPV, but both the base case and the best case scenarios does show that it holds some potential.

An interesting observation to make regarding the results is that while the nutrient emission had a substantial impact on the NPV estimate, the value of the nutrient reuse itself has a comparatively small impact on the result. There is some caution warranted using this method of valuing the nutrient reuse in the hydroponic WWTP. Firstly, the values for the respective nutrients provided by the Swedish Board of Agriculture are made for valuating solid fertilizers, when used in soil-based agriculture, and can be applied in any desired combination and concentration. The nutrients in this case are flowing in a non-soil based plant production where the concentrations and composition of the nutrient content vary idiosyncratically. Secondly, the nutrient values are estimated for fertilizers that can be applied to any kind of crops, while e.g. food crops would not be legal to grow in the WWTP. Hence, it is possible that the actual value of these nutrients would be even less.

Apart from the main question of whether to invest in a hydroponic or a conventional plant, there are some other conclusions that can be drawn from the analysis. Firstly, following the findings of the base results, if the decision makers find the reduced emissions, nutrient reuse and the non-monetized values to be worth more than the capital investments, it is worth the investment. Thanks to these findings the decision may only require the decision makers to determine the value of these benefits, rather than performing an entire new CBA. Specifically for Haninge municipality, the main discussion should probably center on the valuation of the nutrient emissions and the educational value of the plant. Some governmental support and/or pressure (which one is a question about who is responsible for improving the water quality beyond direct regulations) could be necessary in order to avoid the externalities being given less weight than the direct expenditures to the municipality.

Secondly, a motivation for investing in the hydroponic treatment technology would be to use it as test facility to determine the exact quantities for the different properties in order to make decisions for other plants in the country. E.g. the Swedish Environmental Research Institute, the Royal Institute of Technology and Stockholm University have, when in contact with Oliviusson (n.d.-f), shown interest in a potential hydroponic WWTP in Haninge for research. This would, however, only be relevant from a national/societal perspective. For Haninge as a municipality this information would not yield any direct benefits, as they do not have any other plants where a new plant is planned to be built. In fact, most of the wastewater treatment is done by Henriksdals reningsverk. For Sweden in general, considering the commitment to the Baltic Sea Action Plan, there could be a certain value connected to getting a plant running that could test out the hydroponic plant as a technology for reaching the undertaken goals of reduction in nutrient emissions. This value would of course only apply to the first plant built. For any consecutive plants, the evaluation would have to be based on the observed performance of this first plant.

Thirdly, regardless of which scenario and discount rate are considered, the sensitivity analysis shows that the single most important property is the treatment itself, the reductions in emissions of nitrogen particularly. The currently available studies offer some guidance, but are omitting some of the effects of the emissions and should be complemented with new studies. Alternatively, a study could be made to find out the cost of reducing phosphorus and nitrogen emissions through other measures, in order to determine the most efficient way to meet the national targets for nutrient emissions.

Fourthly, as stated in the section on the ethics of CBA (*see* 2.1) it is an anthropocentric and consequentialist method. Democratic processes (in municipal government in this case) have to determine whether there are any reasons connected to other moral codes that demands or objects to the building of hydroponic plant rather than a conventional one. E.g. if it is considered morally right to try all possible means to improve the environment (even if it looks economically questionable). However, it should be noted that the evaluation method for the externalities (most importantly nutrient emissions) is based on the opinion of a sample of the effected part of the population and should to some extent take into account such sentiments, albeit in an imperfect way.

When using these results in another context, some caution is warranted. Going through the WWTP properties evaluated, three contextual parameters could be argued to be important to the net present benefit of the project, apart from the obvious price levels and wages. The first one is the surrounding area. In a densely populated area, other factors such as plant footprint and odor pollution might be important to the decision-making process. The roughly estimated 50 hectares of freed land could have substantial value depending on the prices of land in the area surrounding the plant. The second consideration is the climate in the area where the WWTP is located. The electricity use for heating and lighting is very context dependent. The fact that, in this case, it had a similar magnitude as the reduction from less use of blowers cannot be expected to hold in an area with lower winter temperatures and less light than the Stockholm area, where more heating and lighting could be needed. In a warmer area, the difference between the two electricity properties could instead be in favor of the hydroponic plant. The third contextual parameter would be how society values the damages of eutrophication. This could in turn depend on several different variables such as environmental awareness, current levels of eutrophication and other more urgent environmental issues.

One suggestion for further research is to focus on the value of reducing nutrient emissions as it is such an important factor for the results of the CBA. Furthermore, attempts should be made to find values for potential educational values and research as this remained non-monetized over the course of this paper. Finally, for comparison of different technologies a CBA of other hybrid or totally biological treatment systems, such as the one built at Överjärva gård, would be useful.

In terms of data collection, Sweden should increase efforts to collect data on performance and costs of wastewater treatment plant in order to enable scholars and decision-makers to make local or nationwide studies and evaluations to arrive at recommendations for local and national policy.

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