CHALMERS

Towards Sustainable Phosphorus Management

Material Flow Analysis of phosphorus in Gothenburg and
ways to establish nutrient recycling by improving the urban wastewater system

Master of Science Thesis in the Master's Programme Innovative and Sustainable Chemical Engineering

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ABSTRACT

All life forms require the nutrient phosphorus and it cannot be substituted by any other element. The global cycle of phosphorus is special among the major biogeochemical cycles, since it has no significant gaseous compounds and only closes every 10-100 million years. However, human activities, as application of mineral fertilizers, conversion of natural ecosystems to arable land and releases of untreated waste, intensify remarkably the phosphorus flows. The problems with linear flows of a limited resource leading to eutrophication of aquatic environments, for instance, have generated national environmental quality objectives for phosphorus in Sweden.

The main objective of this master thesis is to get a holistic overview of how phosphorus is moving through Gothenburg today, using Material Flow Analysis as method. The spatial system boundary is the municipality of Gothenburg and the temporal system boundary is the year of 2009. One way of dealing with the linear flows of phosphorus might be to develop the wastewater systems used in Gothenburg today. Possible changes in phosphorus flows, if kitchen grinders or urine-diverting toilets were installed in Gothenburg, are evaluated. In order to make the phosphorus management more sustainable, the linear flows have to be closed to a larger extent than today. One way towards this ambition is to emphasize other fertilizers than the mineral ones, like urine and low-contaminated sludge.

The MFA shows that the absolutely largest input of phosphorus to Gothenburg is via the food. The two large outputs of the same magnitude are the digested sludge from the wastewater treatment plant of Rya and the ashes from the waste-fuelled district heating power plant of Sävenäs. About 7% of the phosphorus input to Gothenburg continues into the aquatic environment. According to this study, urine diversion and separate collection of food seem prospective in order to decrease the phosphorus flows in digested sludge from the wastewater treatment plant, ashes and aquatic deposition. An additional advantage would be generation of recycled fertilizing products with good quality.

Keywords:

phosphorus, phosphorus cycle, Material Flow Analysis, nutrient recycling, environmental quality objectives, wastewater system, sludge, ashes, fertilizers, Gothenburg, urine diversion, kitchen grinders.

Mot en mer hållbar fosforhantering
Substansflödesanalys av fosfor i Göteborg och
sätt att uppnå näringsåtervinning genom att förbättra urbana avloppssystem
HELENA BORGESTEDT
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SAMMANFATTNING

Näringsämnet fosfor är nödvändigt för alla levande organismer och kan inte ersättas av något annat grundämne. Den globala fosforcykeln är speciell då den inte innehåller några gasformiga föreningar och sluts var 10-100 miljonte år. Användning av konstgödsel, omvandling av tidigare orörda ekosystem till odlingsmark och utsläpp av förorenat avfall är exempel på mänskliga aktiviteter som intensifierar fosforflöden. Problemet med att linjära flöden av denna begränsade resurs leder till övergödning av vattenmiljöer har genererat nationella miljömål i Sverige för fosfor.

Det huvudsakliga målet med detta examensarbete är att få en översikt av hur fosfor rör sig genom Göteborg idag med hjälp av substansflödesanalys. Den rumsliga systemgränsen är kommungränsen för Göteborg och den tidsmässiga avgränsningen är året 2009. Ett sätt att förbättra de linjära fosforflödena kan vara att utveckla de avloppssystem som idag används i Göteborg. Förändringarna som uppstår i fosforflödena vid installation av urinsorterande toaletter alternativt köksavfallskvarnar undersöks. Linjära flöden måste bli återcirkulerade i en högre utsträckning än idag ifall fosforhushållningen ska gå mot hållbarhet. Ett sätt att nå denna ambition är att lyfta fram andra gödselprodukter än konstgödsel, exempelvis urin och renare slam.

Flödesanalysen visar att det definitivt största inflödet av fosfor till Göteborg är via livsmedel. De två största fosforutflödena, båda i samma storleksordning, är rötat slam från Ryaverket och aska från sopförbränningsanläggningen Sävenäs. Cirka 7 % av den fosfor som flödar in i Göteborg fortsätter vidare ut i vattenmiljön. Enligt denna studie verkar urinsortering och separat insamling av matavfall vara goda lösningar för en framtid med mindre fosfor i slammet från Rya och i aska samt till vattenmiljön. En ytterligare fördel skulle vara erhållandet av hållbara gödselprodukter med god kvalitet.

Nyckelord:
fosfor, fosforcykel, substansflödesanalys, näringsåtervinning, miljömål, avloppssystem, slam, aska, gödselmedel, Göteborg, urinsortering, köksavfallskvarnar.

PREFACE

This master thesis has been carried out by Helena Borgestedt, master student in Aquatic and Environmental Engineering at Uppsala University, and Ingela Svanäng, master student in Bio- and Chemical Engineering at Chalmers University of Technology. It has been performed at the department of Civil and Environmental Engineering, Chalmers University of Technology. The thesis was initiated and supervised by Yuliya Kalmykova, Assistant Professor, Chalmers University of Technology. The subject reviewer of the master thesis was Håkan Jönsson, Professor, Swedish University of Agricultural Sciences.

The master thesis has in general been performed by the two authors together. In the background, Helena Borgestedt has looked into nutrients per se, while Ingela Svanäng has concentrated on the systems in which they move. The Material Flow Analysis is a collaborative work, where equal efforts have been put on collection of information and calculations. Helena has had a focus on systems with kitchen grinders and Ingela has focused on systems with urine diversion. The discussion is written and the conclusions are drawn jointly by the authors.

Thanks to Dr. Yuliya Kalmykova for supervision and that we got the chance to do this master thesis. Thanks to Dr. Håkan Jönsson for helpful comments and inputs during the process. Thanks to Robin Harder for warmly reading our drafts several times. We would also like to thank the professional persons that have contributed with important information to our work, among those, Lia Detterfelt and Peter Skruf, Renova, Pål Börjesson, the Faculty of Engineering at Lund University, Ann-Sofi Bergman, Arla Foods, Thomas Wennerberg and Martin Nilsson, Preem, Ann Mattsson, Gryaab, Frida Jones, SP, Robert Larsson, LRF and Fredrik Samuelsson, Brudbergets Jordprodukter.

Finally, we would like to express a special gratitude to each other for having a great time as colleagues. The support from our friends and families has been crucial to progress continuously during the spring of 2011.

Helena Borgestedt and Ingela Svanäng
Göteborg
September 2011

TABLE OF CONTENT

1. INTRODUCTION

A work towards sustainability includes quantification and understanding of nutrient flows. To establish nutrient recycling, the nutrient flows must be wisely managed. This management involves avoidance of dispersion of phosphorus into terrestrial and aquatic systems as well as minimization of the depletion of high quality phosphorus ores. Today, the recovery of nutrients in wastewater treatment plants, WWTPs, is debated. An environmental quality objective, concerning recycling of phosphorus in sewage, was adopted by the Swedish parliament and shows willingness to improve the current system. The objective to recycle 60% of the phosphorus from WWTPs back to productive land was stated to make the society more environmentally friendly. However, recovery at WWTPs is a downstream process and rather a treatment of symptom than a remedy. It would be desirable to implement an upstream process that minimizes the pollution of both water and nutrient fractions of the wastewater. The wastewater system is on the agenda in Gothenburg, since the capacity of the current centralized wastewater treatment plant is limited. It provides an opportunity to introduce an alternative wastewater system in order to provide the city with a better nutrient management. It was pointed out in a study by Liu et al. (2008) that a shift towards sustainability should probably be implemented as a natural part of the everyday life for the urban population rather than through a revolution. Therefore, it is time to start the work towards sustainable phosphorus management and to discuss the phosphorus flows as well as the future wastewater system in Gothenburg already today.

1.1 OBJECTIVES

The main goal of the project is to get a holistic overview of how phosphorus, and to some extent nitrogen, are moving through Gothenburg today. The spatial system boundary used in this thesis is the land area of the municipality of Gothenburg and the temporal system boundary is the year of 2009. The flows of phosphorus into, out from and within this system are to be quantified via a Material Flow Analysis and consequently discussed. Possible changes in the phosphorus flows, if kitchen grinders or urine diverting toilets were installed, with or without separate collection and recycling of blackwater, will be evaluated. The fertilizer products from the alternative systems will be compared, regarding quantity as well as quality. The environmental, technical and economic aspects of the alternative systems will be discussed. The flows will also be discussed in relation to relevant environmental quality objectives.

1.2 LIMITATIONS

It is important to realize that the work has three significant limitations. Firstly, only the flows of phosphorus are to be fully tracked and not the other important macronutrients. This is partly due to the fact that two of the Swedish environmental quality objectives put phosphorus in focus and partly due to certain interest in phosphorus in on-going research projects at Chalmers University of Technology. Secondly, the studied region is chiefly an urban area and accordingly, the agriculture that is a main actor in the phosphorus cycle will hardly be dealt with at all. One supporting argument to the choice of system is that phosphorus to a large extent ends up in the cities and needs to find new ways back to productive land. Thirdly, the aquatic parts of the municipality of Gothenburg are not included in the system.

1.3 STRUCTURE OF THE REPORT

The report has two main parts: the Material Flow Analysis of phosphorus in the municipality of Gothenburg, presented in chapter 4, and the investigation of alternative suitable wastewater systems for the municipality, presented in chapter 5. A theoretical background based on published literature is presented in chapter 2 in order to offer a solid background while discussing the results from the two main parts in chapter 6. Chapter 3 describes the methodology of a Material Flow Analysis. The conclusions are finally to be found in chapter 7.

2. BACKGROUND

This background section will introduce some basic knowledge about macronutrients, the global cycles of phosphorus and nitrogen and the fractions of wastewater. It will also give a brief introduction of the chosen system: Gothenburg, and its current wastewater system.

2.1 NUTRIENTS

Plants are living organisms, which besides water, carbon dioxide and oxygen, need several mineral nutrients. Some of these nutrients are required in larger amounts, more than one kilo per hectare and year; and are referred to as macronutrients, Table 1. Lack of those macronutrients will result in reduced plant growth and crop yields (White & Brown 2010). It does not matter if the nutrients are obtained from organic sources or inorganic, it is still the same mineral elements that are needed (Capon 2007).

The need for the macronutrients; nitrogen, phosphorus and potassium, always play an important role in commercial agriculture and food security. These three nutrients must often be supplied to productive soils, while sulphur often is naturally available in satisfying amounts (Dawson & Hilton 2011). However, the need of sulphur has increased as a result of reduced acid rains (Jönsson, pers. comm.). Fertilizers are applied on arable land with the purpose to increase the yield. As plants grow, the needed nutrients change in relative quantities, especially for nitrogen, phosphorus and potassium (Capon 2007).

Erosion is the main natural source for phosphorus and potassium, while the microbiological movement in organic material is important for the mineralization of nitrogen and sulphur. An important factor for plant availability of these nutrients is the pH-value in soils (SJV 2004).

Table 1. Average concentrations and uptake of macronutrients in plants (SJV 2004).

Macronutrient	Conc. in plant (µmol/g)	Amount needed (kg/ha*y)
Phosphorus	60	20-25
Nitrogen	1000	125-150
Potassium	250	125-150
Sulphur	30	0-20

2.1.1 MACRONUTRIENTS

The most important macronutrients are phosphorus, nitrogen, potassium and sulphur.

Phosphorus, P

All life forms require phosphorus and it cannot be substituted by any other element (Bondre 2011). The phosphorus plays an essential and unique role for the functions of the nucleic acids and in the cellular metabolism (Gilbert 2009). Phosphorus deficiency delays the growth of all plants, since it is needed for cell and root development. An increased amount of phosphorus is needed later on in the growing process to develop reproductive organs. Lack of phosphorus can cause pale plants or red stains. Surplus of phosphorus do not show symptoms, since the surplus binds to the soil particles (Båth 2003).

Inorganic phosphorus fertilizers are extracted from rock phosphate by using sulphuric acid (White & Brown 2010). Pure phosphorus is highly reactive and the nutrient exists therefore usually in the form of phosphate when exposed to air. In water, phosphorus can exist as free phosphate as well as bound in soluble organic compounds or in insoluble particles. These three forms together are normally referred to as “total phosphorus” (Thomson & Tracey 2005). In cultivated soils, phosphorus in inorganic forms is dominating and part of it is plant-available as phosphate ions (Båth 2003).

Nitrogen, N

Nitrogen is, as phosphorus, indispensible to life. Nitrogen is the fourth most common element in living tissues and a necessary component of proteins and nucleic acids, among others (Thomson & Tracey 2005). Nitrogen is needed for the protein synthesis and thus, the nitrogen supply is important for the protein yield of crops (Jönsson, pers. comm.). Shortage of plant-available nitrogen will cause the plant several problems, including reduced root development, weak stems and undeveloped leaves. Especially during the early stages of plant development, greater amounts of nitrogen are needed to contribute to the shoot development (Båth 2003).

The major reservoir of nitrogen is in the atmosphere, which to 78% consists of nitrogen gas. However, plants mostly take up nitrogen in its bioavailable inorganic forms: nitrate and ammonium. Nitrogen can also be present in soluble organic molecules, such as urea and amino acids. The forms of nitrogen that can be present in water: bioavailable inorganic nitrogen, soluble organic nitrogen and nitrogen in insoluble particles; are normally referred to as "total nitrogen" (Thomson & Tracey 2005). Nitrogen is found in different structures in the soil and the major part is bound in organic material. A smaller part is in the plant-available mineral forms, but some organic nitrogen can also be taken up by roots in nutrient-poor soils. Some plants can also assimilate fixed elementary nitrogen gas from the air by symbiosis with certain microorganisms (Båth 2003).

Potassium, K

Potassium is mined from ores (White & Brown 2010). In mineral soils, potassium is one of the most common macronutrients. In contrast to nitrogen and phosphorus, potassium is not included in any organic compounds, but it is found in minerals and is available in soils through erosion. Plant-available potassium is in the form of ions. Potassium is the most mobile macronutrient in plants and plays important roles in transport of other ions and the pH balance. Potassium is also important for synthesis of protein and starch. Lack of potassium can cause the plants to droop and increase the risk for fungal infections. Symptoms from surplus of potassium are rare (Båth 2003).

Sulphur, S

There are also ores of sulphur, but the main part of sulphur that is used today is a by-product from other industrial processes like for instance oil refining. Sulphur is the main resource for sulphuric acid, which is used by the industry to produce phosphorus and sulphur fertilizers (TSI 2011). 95-99% of the sulphur in arable soils is bound in organic material at the top layer and needs to be mineralized to become plant-available. Plants are provided with mineralized sulphur from the soil and the atmosphere. Sulphur is important for the protein structure in plants and lack of sulfate results in bleached areas on leafs, white petals and disturbed development of pods (SJV 2004).

2.1.2 THE GLOBAL CYCLES OF PHOSPHORUS AND NITROGEN

This section will exclusively deal with the global cycles of phosphorus and nitrogen, respectively. The environmental discussions pay most attention to these nutrients, although the cycles of potassium and sulphur also are crucial. Phosphorus and nitrogen are the two nutrients responsible for eutrophication, in other words, the nutrients that in excess levels are harmful for terrestrial and aquatic environments (Rockström et al. 2009).

During the last 10000 years, the Earth's environment has been unusually stable. This period is by geologists known as the Holocene and has allowed civilizations to arise and develop. The systems that keep Earth in this desirable Holocene state could be damaged by human activities that largely depend on fossil fuels and industrialized forms of agriculture. To meet the challenge of keeping the planet in the Holocene state, a framework with so-called planetary boundaries has been developed. The boundaries define the safe operating space for humanity and are related to the biophysical processes on Earth. For three processes – climate change, rate of biodiversity loss and interference with the nitrogen cycle – the boundaries are already exceeded. Among the processes that are approaching the safe limits, interference with the global phosphorus cycle is found (Rockström et al. 2009).

The anthropogenically intensified flows of nitrogen and phosphorus have reached levels that imply perturbations of the global cycles of these nutrients. Modern agriculture is a major cause of the disturbances mainly via the manufacturing of fertilizers and the cultivation of nitrogen fixating crops, such as peas and beans. Reactive nitrogen pollutes waterways and coastal zones, accumulates in soils and adds a number of gases to the atmosphere. Phosphorus makes most harm in aquatic environments. Almost half of the mined phosphorus ends up in the oceans, a rate of influx that is estimated to be eight times the natural processes. The planetary boundary for phosphorus is set to ten times the natural rate (Rockström et al. 2009). While Rockström et al. (2009) judge that the overall situation is still below the planetary boundary, another study that focuses on freshwater eutrophication states that the tolerable limit for phosphorus is already exceeded regarding this aspect (Carpenter & Bennett 2011). Worth mentioning is that the various planetary boundaries are tightly coupled and influence each other, which shall be kept in mind when the absolute values are discussed (Rockström et al. 2009).

Phosphorus

The global cycle of phosphorus, Figure 1, is special among the major biogeochemical cycles, since it has no significant gaseous compounds (Liu et al. 2008). The natural global cycle of the element is very slow; it closes only every 10-100 million years. However, human activities intensify the phosphorus flows. The intensification is mainly due to (Smil 2002):

- accelerated erosion and runoff caused by large-scale conversion of natural ecosystems to arable land,
- settlements and infrastructure for transportation,
- recycling of organic wastes to fields,
- releases of untreated, or insufficiently treated, urban and industrial wastes to streams and water bodies,
- application of inorganic fertilizers; and combustion of biomass and fossil fuels.

The finite and depleting nature of known global phosphate rock reserves requires attention. In 2010, the reserves of marketable phosphate rock were estimated by the US Geological Survey, USGS, as well as the International Fertilizer Development Center, IFDC. The estimation of USGS was 16000 Mton phosphate rock, and the estimation of IFDC was about four times higher, 60000 Mton phosphate rock. The main difference was in the assessment of the reserves in Morocco (Dawson & Hilton 2011). However, the USGS re-estimated remarkably the reserves to 65000 Mton in 2011. The total world production of phosphorus from phosphate rock today goes up to about 170 million ton per year (USGS 2011).

Nitrogen

Contrary to the phosphorus cycle, the lifecycle of nitrogen, Figure 2, can be measured in years or at most a century or two (Dawson & Hilton 2011). Additionally, a very important part of the processes with nitrogen occur when the element is in gaseous form. The anthropogenic impacts disturb on one hand the aquatic environment, on the other hand also significantly the atmosphere by emissions of the greenhouse gas nitrous oxide (Rockström et al. 2005). Three main causes of the global increase of reactive nitrogen that have been stated are listed below (Galloway et al. 2003):

- widespread cultivation of legumes and other nitrogen-fixating crops,
- combustion of fossil fuels,
- the Haber-Bosch process to industrially produce ammonia.

The finite and depleting nature of the fossil energy sources currently used in the production of ammonia for nitrogen fertilizers requires attention. The world total annual production of nitrogen, phosphorus and potash fertilizers together required 5850 PJ in 2008, equivalent to 1.1% of the total global energy use. The production of nitrogen fertilizers accounts for over 90% of the total energy input to the fertilizer production. The Haber Bosch process for the manufacture of ammonia is very energy-intensive and was, in 2000, responsible for 99% of the world nitrogen production, which was 85700 kton of nitrogen (Dawson & Hilton 2011).

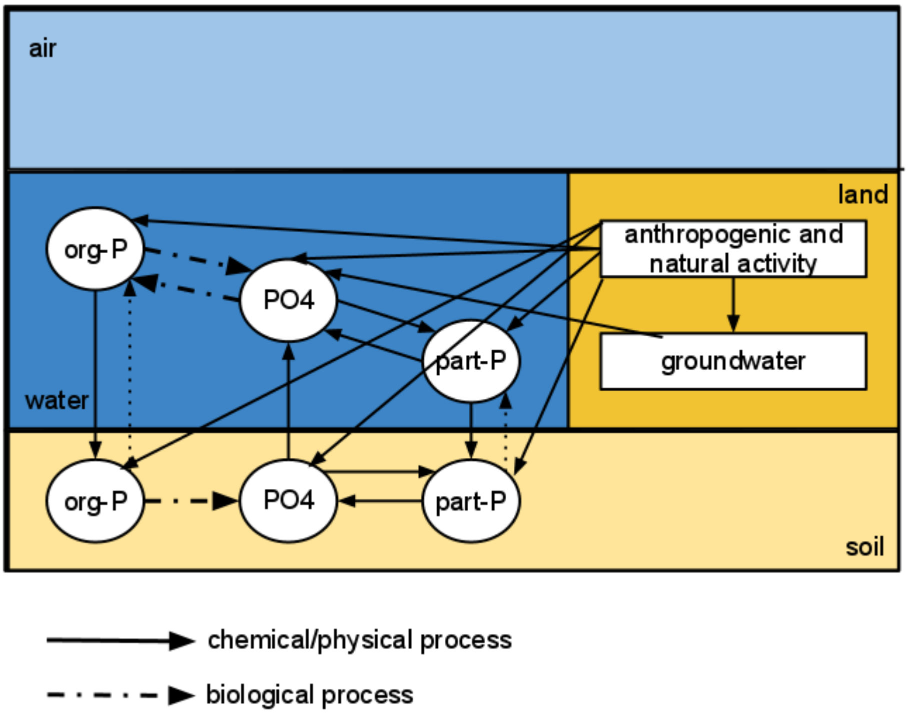

Figure 1. The global phosphorus cycle with fluxes between the biosphere, hydrosphere and lithosphere. Org-P is organic phosphorus in living and dead organisms and Part-P is phosphates absorbed to sediment particles. Inspired by Thomson & Tracey, 2005.

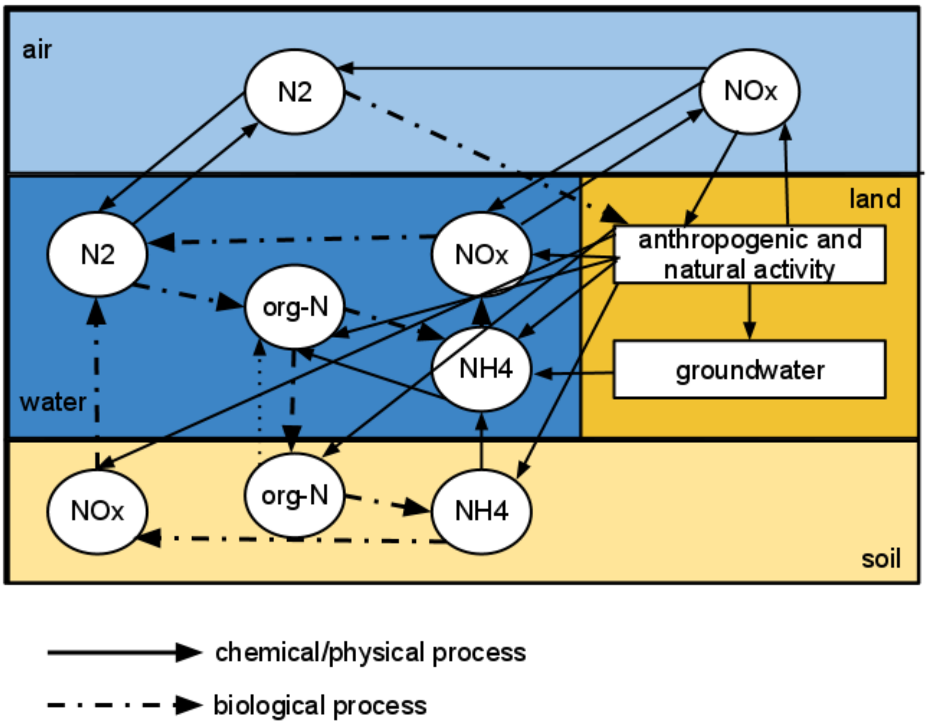

Figure 2. The global nitrogen cycle with fluxes between the atmosphere, biosphere, hydrosphere and lithosphere. Org-N is organic nitrogen in living and dead organisms. NOx in the atmosphere is nitrogen oxides as N_2O, NO and NO_2, while dissolved NOx is the ions nitrate and nitrite. Inspired by Thomson & Tracey, 2005.

2.1.3 ENVIRONMENTAL QUALITY OBJECTIVES CONCERNING NUTRIENTS IN WASTEWATER

The Swedish parliament has adopted environmental quality objectives and among those, objectives about zero eutrophication and a good built environment are to be found. Both have interim targets for phosphorus, and those are; "*By 2010 Swedish waterborne anthropogenic emissions of phosphorus compounds into lakes, streams and coastal waters will have decreased by at least 20% from 1995 levels.*" and *"By 2015 at least 60% of phosphorus compounds present in wastewater will be recovered for use on productive land. At least half of this amount should be returned to arable land."* (Swedish Government 2005). The national environmental goals are in some regions also applied on local level. For instance, they are a part of the environmental policy of the municipality of Gothenburg (Göteborg Stad 2010).

The reason for the establishment of the interim targets above was the eutrophication problem when nutrients from sewage reach the watercourses. Furthermore, the environmental problems with phosphate rock mining and fertilizer production, in combination with problems of supply from the limited resource of available phosphate rock, played a significant role for the recover target. The Swedish Environmental Protection Agency, EPA, has stated that recycling of other nutrients, such as nitrogen, are also important in the long-run, but that the focus should be set on the recycling of phosphorus for the moment. However, the Federation of Swedish Farmers claimed that the interim target should not have been established for recycling of only one single nutrient, since macronutrients are closely related to each other (Swedish Government 2005).

A recently published report from the Swedish Energy Agency, SEA, underlines that the environmental interim target of phosphorus recycling does not counteract the use of sludge firstly in biogas production and then the remaining digested sludge as fertilizer product. In other words, the interests in biogas and in nutrient recycling are not contradictory but can develop collaterally. Furthermore, they claim that plans for waste and wastewater shall be coordinated in municipalities and deal with questions about both nutrient management and energy (SEA 2010).

In 2010, the region of Gothenburg presented a new waste management plan called A2020. It did not present any regional goals regarding the sludge and the recycling of phosphorus, but showed a will to do so in the next revision. On the other hand a goal concerning food waste and the recycling of nutrients within it has been proposed: *"At least 50% of the food waste from households, restaurants, communal kitchens and stores shall be managed in such way that plant nutrients can be capitalized. All separately collected food waste will be used in biogas production."*. One of the key performance indicators will show how big percentage of the phosphorus in mineral fertilizer that is actually substituted by recycled phosphorus from food waste (GR 2010). Food waste is also included in one of the interim targets of the national environmental quality objectives; *"By 2010 at least 35% of food waste from households, restaurants, caterers and retail premises will be recovered by means of biological treatment. This target relates to food waste separated at source for both home composting and centralized treatment."* (Swedish Government 2005).

2.1.4 TOWARDS A MORE SUSTAINABLE NUTRIENT USE

Phosphorus is one of the limiting plant nutrients and to increase agricultural yield, fertilizers are used in many countries due to a short supply of plant-available phosphorus in soils (Gilbert 2009). Today, about 90% of the worldwide demand for rock phosphate is for food production, mainly via mineral fertilizers. The production involves significant carbon emissions, radioactive by-products as well as heavy metals (Cordell 2009). The latter ones stay partly in the fertilizer product. In addition to reduced nutrient emissions to aquatic environments, a shift towards more recycling of nutrients could decrease the mining of phosphate rock, which would be good regarding both the limited availability and the environmental impacts.

The Swedish Energy Agency has calculated a theoretical market price of the nutrients in Swedish food waste and sewage sludge. By multiplying the current prices[1] for mineral fertilizers with the amount of nutrients in the food waste and sludge a value can be obtained. Today, food waste of a value of 130 million SEK is recycled and it has a potential to increase with another 95 million SEK from the fractions that are currently incinerated. Of the sewage sludge, 27 million SEK are recycled today and the remaining potential has a large market value of about 440 million SEK (SEA 2010). Even though these values are more guidelines than real prices, the importance of qualitatively better and quantitatively more products from wastewater systems is clear. In 2002, EPA judged that 15-20% of the phosphorus in mineral fertilizers used in Sweden could be substituted by phosphorus from sewage until 2015 (Swedish Government 2005).

Awareness of sustainability and the Swedish environmental quality objective have found the sludge from wastewater systems interesting as a nutrient source. Mineral fertilizer contains micropollutants, but so does also sludge. Sewage sludge contains micropollutants such as organic compounds, pharmaceutical residues, hormones, and heavy metals like for instance cadmium. In order to assure an acceptable quality of the sludge for farmland, the certification system ReVAQ has been created in Sweden.

The ReVAQ certification

ReVAQ[2] is a certification system for sewage sludge. To obtain the certificate, the Swedish WWTPs have to initially analyze 60 different micropollutants and make sure that they will not increase over time (ReVAQ 2011). Two important objectives of ReVAQ are to decrease the hazardous substances in the sludge to reach a sludge quality, which is acceptable to be spread on arable land as well as to get acceptance from the society (Malmqvist et al. 2006). An important aim for ReVAQ in their work towards sustainability is that the content of any non-essential element in the fertilized arable soil should not increase by more than 100% within 500 years (LRF 2011).

In Sweden, the application of sludge on farmland is increasing, but at the same time there are ongoing discussions concerning the risks of spreading sludge (Hoffman 2010). The Swedish food industry is restrictive, mainly for marketing reasons (Malmqvist et al. 2006). However, the regulations of spreading sludge in Sweden are stricter than the European Union sludge commission, 86/278/EEG (LRF 2011). In 2008, about 25% of the produced sewage sludge in Sweden was used as fertilizer in agriculture (Hoffman 2010).

The sewage sludge from the WWTP of Rya is certified by the ReVAQ since March 2009 (Svenskt Vatten 2011). In 2009, the amount that was hygienized and used on arable land was insignificant. So far, in 2011, about 10% of the sludge is being stored and is going to be used as fertilizer on arable land (Gryaab 2011d). This figure can be compared with figures from other European countries. The UK declared in 2004 that 64% of the sewage sludge was recycled to land, whereas in the Netherlands such recycling was, and still is, prohibited. Overall in the EU, less than 40% of the sewage sludge are used on arable land (Dawson & Hilton 2011).

[1] 9 SEK per kg N and 18 SEK per kg P

[2] Ren Växtnäring från Avlopp

2.2 WASTEWATER FRACTIONS

Wastewater is a collective name for different fractions of used water. These fractions have different origins and qualities. Four of the most common wastewater fractions in combined wastewater systems; blackwater, greywater, stormwater and industrial water, are presented further in this chapter. One kind of quality of the fractions is the content of nutrients in general and their plant-available forms in particular, Figure 3.

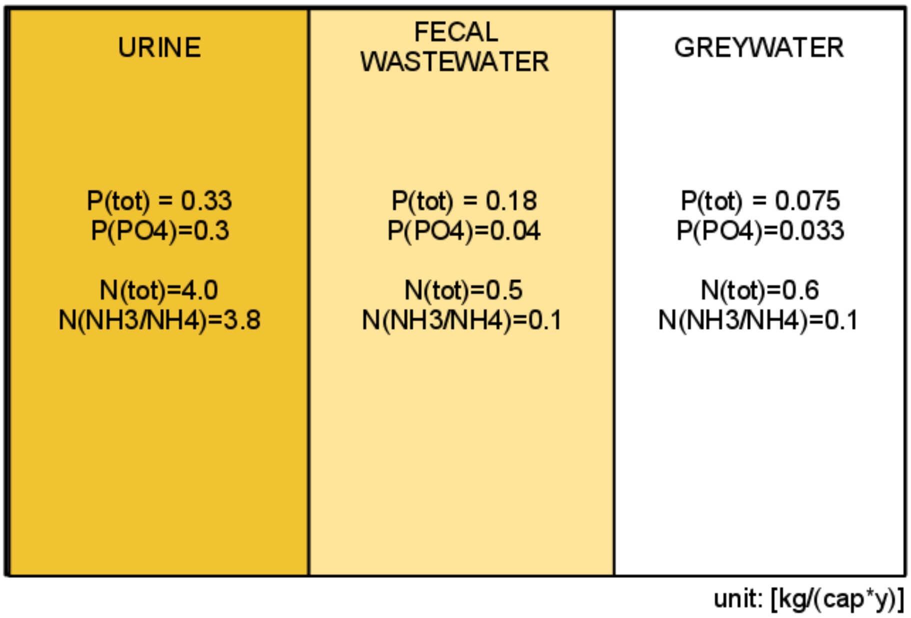

Figure 3. The content of total phosphorus and nitrogen, as well as, of their respective plant-available form (Jönsson et al. 2005, Jönsson, pers. comm.).

2.2.1 BLACKWATER

Blackwater is the common term for the wastewater from toilets. Blackwater consists of two fractions: urine and fecal wastewater.

Urine

Urine is the fraction of pure urine, possibly diluted with some flushing water. Total solids of urine show large variations and vary between 4-22 kg per person and year (Jönsson et al. 2005). 80-90% of the nitrogen, 50-80% of the phosphorus and 80-90% of the potassium consumed in food, are excreted in the urine. Urine contains about 4 kg of nitrogen, 0.33 kg of phosphorus and 1.1 kg of potassium per capita and year. All nutrients in urine are found in their water-soluble forms (Vinnerås 2001). The direct plant availability of phosphorus and nitrogen in urine is 91% and 95%, respectively, Figure 3 (Jönsson et al. 2005). Human urine contains ingested pharmaceuticals and hormones, which are to about 70% excreted in the urine with 50% of the ecotoxicological risk (Lienert et al. 2007). Only very small amounts of heavy metals are found in urine (Vinnerås 2001).

Fecal wastewater

Fecal wastewater contains feces and toilet paper. In waterborne systems, fecal wastewater includes flushing water. Total solids of feces are estimated to be about 11 kg of dry matter per person and year (Jönsson et al. 2005). 10-20% of the nitrogen, 20-50% of the phosphorus and 10-20% of the potassium consumed in food, is excreted in the feces. Almost all phosphorus and potassium, but only half of the nitrogen, are found in water-soluble forms (Vinnerås 2001). The direct plant availability of phosphorus and nitrogen in fecal wastewater is 22% and 20%, respectively, Figure 3 (Jönsson et al. 2005). Due to low uptake of consumed heavy metals, they will mainly be excreted in the feces (Vinnerås 2001). Fecal wastewater also contains ingested pharmaceuticals and hormones, which are to about 30% excreted in the feces with 50% of the ecotoxicological risk (Lienert et al. 2007).

2.2.2 Greywater

Greywater is the wastewater originating from dishwashing, laundry and bathing. Total solids content varies between 15-29 kg per person and year. The direct plant availability of phosphorus and nitrogen in greywater is 44% and 17%, respectively, Figure 3 (Jönsson et al. 2005). The main amount of heavy metals in household wastewater is found in greywater (Vinnerås 2001). Of the following metals, between 82-96% of the content in the total household wastewater is found in the greywater: cadmium, nickel, chrome, copper and lead (Jönsson et al. 2005). Furthermore, pollutants with origin in personal care and households products such as surfactants, fragrances and flavors, preservatives and biocides, are found in greywater (Hernandez 2010).

2.2.3 Stormwater

Stormwater is the water that has its origin in atmospheric precipitation and includes also the urban runoff from surfaces such as roads and roofs. A risk of micropollutants in the form of heavy metals, organic compounds and pesticides originating in vehicle traffic, metal leaching and horticulture is present (Lamprea & Ruban 2008).

2.2.4 Industrial water

Industrial water is the wastewater from industries. Due to strict regulations, industrial water is often pre-treated on-site before it is piped to a centralized wastewater treatment plant. Some industries do treat their wastewater to such an extent that they are allowed to emit it directly to the aquatic environment (Wennerberg, pers. comm.).

2.3 Current wastewater system in Gothenburg

Gothenburg is the second largest city in Sweden. In 2009, the municipality of Gothenburg had a population of 506730 inhabitants (SCB 2009). The total area of the municipality is 1029 km^2 of which 44% is land, while the rest mostly is made up by seawater (SCB 2011a). The area of arable land in the municipality of Gothenburg is 30.4 km^2, in other words only 7% of the land area (SJV 2009).

In the municipality of Gothenburg, an infrastructure built up during the last two centuries constitutes the urban water and wastewater system of the region. Most of the pipes combine the different wastewater fractions directly at their sources in a combined system, where no difference is made between water from households, industry and stormwater. This system was installed in the late 1950s and was argued to be the most practical and cheapest solution at that time. The pipes, with a total length of hundreds of kilometers, end up in the centralized wastewater treatment plant of Rya (Göteborg Stad 2007). In 2006, 99% of the inhabitants in the municipality of Gothenburg were connected to the centralized WWTP of Rya (Gryaab 2007).

2.3.1 The centralized wastewater treatment plant of Rya

The wastewater treatment is divided into three steps: mechanical, chemical and biological treatment. Thereafter, the remaining digested sludge from the anaerobic digestion can be either composted or hygienized through storage, depending on its final destination. The process steps are shown in Figure 4. In 2009, the wastewater treatment plant of Rya used totally 32.8 GWh of electrical energy and 13.7 GWh of heat energy. The same year, they produced 60.9 GWh of biogas as well as 162 GWh of heat via heat pumps (Gryaab 2009).

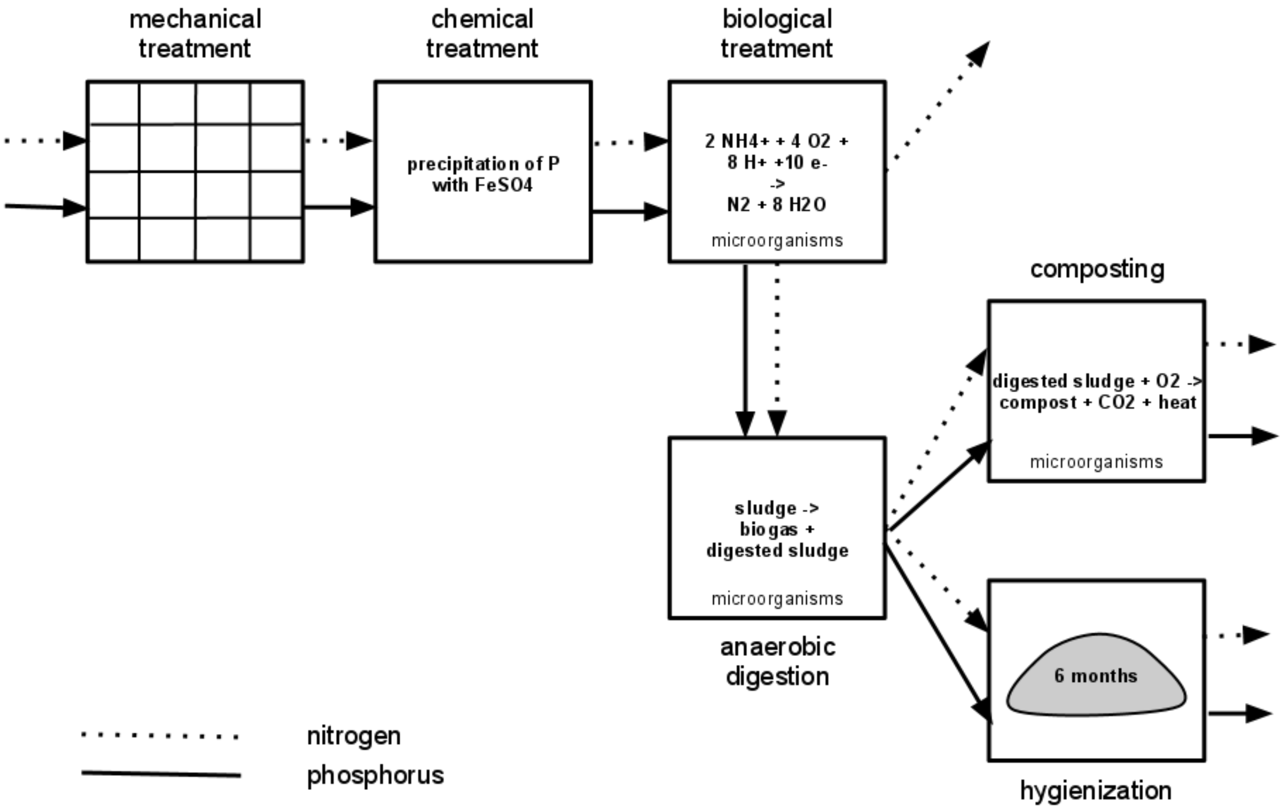

Figure 4. The flow chart of the WWTP of Rya with the major flows of nitrogen, carbon and phosphorus in focus (Gryaab 2009).

Mechanical treatment
The mechanical treatment aims to remove solid particles. Several kinds of equipment remove differently sized particles in sequential steps. Rya is equipped with coarse bar screens, sand trap, primary settling and disc filter (Gryaab 2011a).

Chemical treatment
The chemical treatment aims mainly to precipitate the phosphorus. The phosphorus is precipitated through addition of iron sulphate and the formed compounds get caught in the biological sludge and are removed from the water by sedimentation (Gryaab 2011a). In 2009, the iron sulphate consumption was in total 4626 ton (Gryaab 2009). The annual mean value for the total phosphorus aquatic emission from the WWTP of Rya should not exceed 0.4 mg P/l. In 2009, the emission was 0.3 mg P/l and below the limit (Gryaab 2010b).

Biological treatment
The biological treatment is performed by bacteria. Bacteria degrade the organic material and the nitrogen is converted in two main steps – nitrification (equations 1 and 2) followed by denitrification (equation 3) – to form nitrogen gas (Gryaab 2011a). The major amount of the nitrogen in wastewater both into and out from the WWTP is in the form of ammonia (Gryaab 2010b).

Nitrification, Part 1: $2\ NH_4^+ + 3\ O_2 \rightarrow 2\ NO_2^- + 4\ H^+ + 2\ H_2O$ (Eq. 1)

Nitrification, Part 2: $2\ NO_2^- + O_2 \rightarrow 2\ NO_3^-$ (Eq. 2)

Denitrification: $2\ NO_3^- + 10\ e^- + 12\ H^+ \rightarrow N_2 + 6\ H_2O$ (Eq. 3)

The environmental superior court has decided that the annual mean value for the total nitrogen aquatic emission from the WWTP of Rya should not exceed 10 mg N/l. In 2009, the emission was 13 mg N/l and above the limit. However, the WWTP of Rya has ongoing development of the plant to get below this limit (Gryaab 2010b).

Biogas production
Biogas is a product from an anaerobic process. The sludge is thickened before it enters a digester, where bacteria degrade the organic compounds of the sludge and produce the two main components of biogas, methane and carbon dioxide. The remaining liquid fraction is the digested sludge. To increase the biogas production at Rya, solid food waste is purchased and put into the anaerobic digester together with the sludge. The biogas is sold, upgraded and chiefly used as biofuel for vehicles (Gryaab 2011c).

Composting
Composting is an aerobic process, which can be used when the sludge has been thickened and digested. The major amount of the digested sludge from Rya is being composted and used as soil conditioner (Gryaab 2011b).

Hygienization
A small amount of the digested sludge from Rya is being hygienized by storage during 6 months. After storage, the sludge is accepted for agricultural use under the name of ReVAQ sludge. The operator of Rya plans to change to a hygienization process based on heat treatment instead of storage (Gryaab 2011b).

2.4 ALTERNATIVE WASTEWATER SYSTEMS

Many agree upon the fact that a change from end-of-pipe concepts in the sanitation technology towards more ecological closed-loop concepts is necessary. Nevertheless, the centralized system with a combined sewer system and a centralized wastewater treatment plant is the currently governing regime in Sweden and in many other industrialized countries. During the last decades, different approaches towards sustainability in the area have been launched. Some have been more successful than others, but still there is not yet a certain concept that is conquering the market. Among the promising technologies, kitchen grinders in households and urine diversion are to be found.

Since close to 100% of the phosphorus consumed in food is excreted, the wastewater fractions containing human excreta are becoming more and more interesting resources when nutrient recycling is emphasized. The urban phosphorus-rich wastewater fractions have no evidently good sink, since the urban agricultural production is small. A transition of urban wastewater systems implies a big challenge. However, it also offers a promising possibility to reuse nutrients in ecologically and economically efficient ways, if measures are managed to step-wisely be institutionalized into the economy and the society as a whole (Liu et al. 2008).

Diverted solutions have emerged and aim to separate nutrient-rich wastewater fractions from nutrient-poor wastewater fractions (Liu et al. 2008). Diversion in wastewater systems is of interest due to a couple of reasons. The recovery of nutrients in wastewater can be performed closer to the origin by collecting the nutrient-rich fraction separately and transport it to a special treatment plant. The consequence becomes that the nutrient recovery can be done from a more concentrated and less polluted fraction. The more concentrated and purer a fraction is, the easier the treatment of it should be (Meinzinger 2010).

Alternative wastewater systems can be centralized, semi-centralized or decentralized. The alternative ways of implementing the kitchen grinder and urine diversion systems will be presented in chapter 5. Also earlier studies will be mentioned there.

2.4.1 BLACKWATER DIVERSION

Blackwater diversion means that the toilet wastewater – urine, feces, toilet paper and flush water – is piped and treated separately from the rest of the wastewater fractions. Blackwater can be transported either by gravity or vacuum to a centralized or semi-centralized treatment site. Due to the fact that low dilution is desirable, vacuum or pour flush toilets are recommended (Meinzinger 2010). Blackwater is then treated aerobically by liquid composting, storage or ammonia treatment. Alternatively, it is treated anaerobically to produce biogas as an additional product. The anaerobic digestion process results in mineralization of nutrients in the digested sludge and particularly, nitrogen becomes more plant-available (Meinzinger 2010).

2.4.2 GRINDERS IN HOUSEHOLDS

The purpose with installation of kitchen grinders is to enrich the blackwater fraction in nutrients and subsequently diminish the nutrient content in solid waste. Phosphorus in household food waste typically goes to landfill (Dawson & Hilton 2011), via ashes from waste incineration in Gothenburg. This material could be readily recycled via a wastewater system, using kitchen grinders, possibly to municipal anaerobic digesters, and thence to agricultural land (Dawson & Hilton 2011). The optimal cycle of nutrients in food waste and blackwater by use of kitchen grinders is shown in Figure 5.

Kitchen grinders mince the food waste to small pieces together with cold water and direct the mix into the sewer system. They are installed under the kitchen sink and connected to the regular kitchen water pipe. There are two different types of kitchen grinders, one which works continuously when turning on a switch and one that works periodically when closing a lid. Both these types are used in Sweden, but the continuous one is used more often when dealing with bigger quantities of food waste. Kitchen grinders are constructed for most kinds of food waste and food processing residues, with the exception of hard bones, mussel shells, dough and larger amounts of grease (Stockholm Vatten 2008).

2.4.1 URINE DIVERSION

The option of urine diversion implies separate collection of 1% of the total volume of wastewater, but with a majority of the plant-available nutrients. Consequently, the nutrients can be obtained in a concentrated fraction (Meinzinger 2010). With urine diversion technology it is also possible to separately catch the feces and after hygienization use them as soil conditioner. A recovery potential of 40% of phosphorus has been estimated for urine diversion (Hultman et al. 2003), but the value should be higher if also the feces are returned to the soil. The optimal cycle of nutrients contained in urine, which are captured in urine diversion systems, is shown in Figure 6.

Urine diversion is an upstream process. Urine is collected in urine-diverting toilets and thereafter transported by gravity in separate pipes to collection tanks, normally placed in the cellar or in the ground close to the houses. The goal is to obtain a fraction with a high concentration of phosphorus and a very low risk for disease transmission, with the purpose to use it as a highly potential crop fertilizer (Jönsson, pers. comm.). Additional benefits are the decreased nutrient load on the centralized wastewater treatment plants and the possibility to use simple treatment of urine only by storage (Meinzinger 2010).

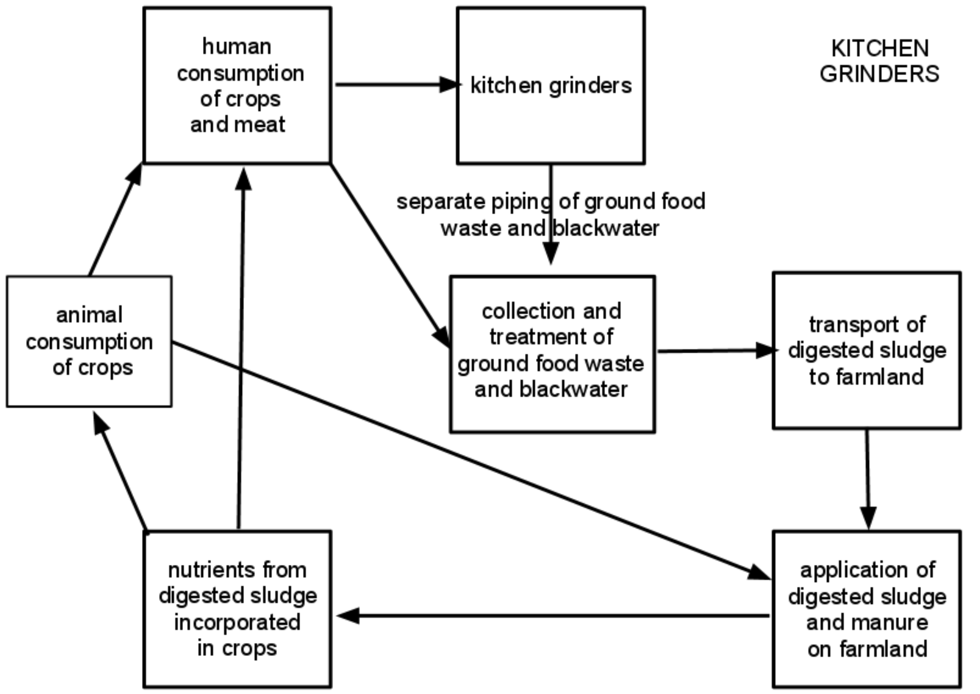

Figure 5. The cycle of the nutrients in food waste and blackwater if optimal use of kitchen grinders takes place.

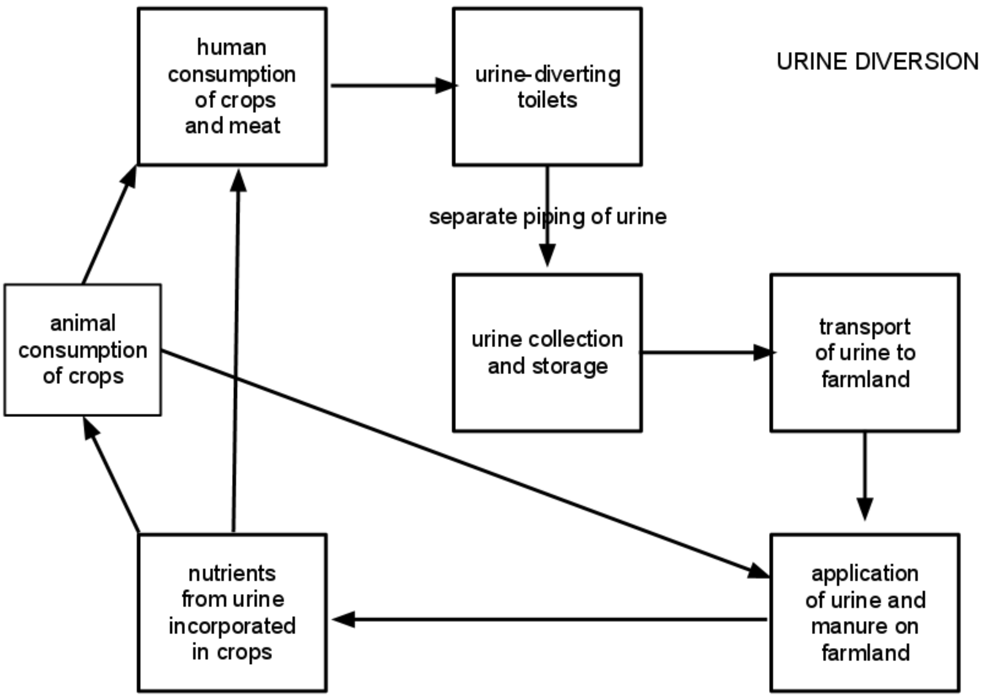

Figure 6. The cycle of the nutrients in urine if optimal urine diversion takes place.

3. METHODS

A concept called “urban metabolism” has been established and might be defined as the sum of all the technical and socioeconomic processes that occur in cities. These processes include those resulting in growth, production of energy and elimination of waste, among others. Urban metabolism is analyzed in terms of four fundamental flows: water, materials, energy and nutrients (Kennedy et al. 2007). In this project the phosphorus metabolism of Gothenburg city is mapped via a Material Flow Analysis, MFA.

Material Flow Analysis is a method to describe, investigate, and evaluate the metabolism of systems, natural as well as influenced by humans. By setting up mass balances for certain goods and substances of interest, the mass flow rates into and out from a well-defined system can be mapped and analyzed. The system boundaries must be defined both spatially and temporally. MFA is a way of tracking substances throughout a system, often in order to identify options to improve the sustainability by closing loops (Brunner & Rechberger 2004).

The methodology of MFA consists of five major steps (Brunner & Rechberger 2004):

1. Definition of the problem and of adequate goals.
2. Definition of the system (in space and time) including selection of substances, processes, goods and appropriate system boundaries.

   $$\sum_{k_I} \dot{m}_{input} = \sum_{k_O} \dot{m}_{output} + \dot{m}_{storage},$$

   where, $\dot{m}$ is the flow of goods, k_I is the number of input flows and k_O is the number of output flows.
3. Assessment of mass flows of goods and substance concentrations in these flows (i = goods, j = substances).

   $$\dot{X}_{ij} = \dot{m}_i * c_{ij} \,,$$

   where, $\dot{X}$ is the flow of a substance and c is the concentration of the substance in certain goods.
4. Calculations of substance flows and stocks and consideration of uncertainties.
5. Presentation of the results in an appropriate way to visualize conclusions and to facilitate implementation of goal-oriented decisions.

The data collection for the MFA in this thesis is based on literature studies, statistics and facts obtained via personal communication with professionals at the municipality, authorities, companies and organisations. No measurements have been done by the authors.

4. Material Flow Analysis of Phosphorus in Gothenburg

It has been stated that a prime requirement for rational management of all phosphorus resources is the better quantification of all flows and pathways: globally, regionally, nationally and locally (Dawson & Hilton 2011). The MFA that will be presented in this chapter is performed on a local scale. The spatial system boundary is the municipality of Gothenburg, not including the aquatic environment. The temporal system boundary is the year of 2009. Phosphorus is the substance in focus of this master thesis.

The potential contribution to increased nutrient recycling of the Swedish environmental target concerning phosphorus in sewage system will be analyzed by quantifying the phosphorus flows in Gothenburg. The objective is to see how much of the phosphorus input to the system that actually reaches sewage sludge. It is of interest for the municipality to invest in systems that can contribute to a significant change in phosphorus management and increase nutrient recycling. Therefore the quantities of various flows are important to know.

The food chain as well as the water and wastewater chain is in focus of the MFA. The food system is important due to relatively high concentration of phosphorus and high turnover rate via the daily consumption. The wastewater system is of certain interest, since it is the destination of a large amount of phosphorus, especially from the food chain. Another important aspect is the plant-available phosphorus, which is high in substrates and products in these two chains.

The phosphorus in forest products has only been regarded to the extent that it is annually incinerated. However, it should be mentioned that phosphorus is stored in buildings and other places where forest products are used inside the system. The phosphorus in toilet paper is not explicitly shown in the MFA, since it was calculated to contain less than 0.1 ton of phosphorus per year (Vinnerås 2001). The major part of all kind of food waste is included in the MFA, but still there is a risk that food waste from some food processing industries is not quantified. Such kind of food waste flows might be waste from fish processing, since Gothenburg is an important seaport, and from butcher shops, where phosphorus-rich bones and other kind of orts accumulate.

The concentration of phosphorus in plastics and textile products are low, and the phosphorus is also captured in these products during a longer time period (Sokka et al. 2004, Antikainen et al. 2005). Consequently, these goods are less significant in the specific flow analysis and have been assumed negligible in the MFA of Gothenburg. Additionally, it is noted that phosphorus is a component in many flame retardants used for furnishings and safety clothing (Gustafsson 2003) and phosphates are also used in treatment methods of metal surfaces (Skelack 2011) and thereby can reach the system. However, neither the content of phosphorus in flame retardants nor that used for metal surfaces is quantified. The use for surface treatment at Volvo might be significant, but at the same time, the phosphorus leaves Gothenburg with the cars.

The calculations for the different flows can be found in Appendix A and the uncertainties of them are presented in Appendix C. The values used in the MFA is presented in Table 14 and shown graphically in Figure 8 in the end of this chapter.

4.1 Input flows

The input flows are those flows that import phosphorus into the system over the system boundaries.

4.1.1 Atmospheric deposition

The amount of phosphorus that reaches the system by air is transported via precipitation. In Gothenburg the land area of the municipality is 44% of the total area, which is 1029 km^2 (SCB 2011a). In addition, the concentration of phosphorus in atmospheric wet deposition has been investigated in a study during the 1990s at several places in Sweden. The results showed that the content varies a lot during the year, but is generally lower at the west coast of Sweden than on the east coast, even though it rains more often on the west coast. According to this study, the average atmospheric deposition at a location close to Gothenburg is 0.058 kg phosphorus per hectare and year (Knulst 2001). This can be compared with the general values for Sweden, 0.06-0.3 kg phosphorus per hectare (SJV 1999). In 2009, the precipitation in Gothenburg was 855 millimeters, slightly higher than the average (SCB 2011c). The data on nitrogen was obtained from the Swedish Environmental Research Institute, which measured nitrate and ammonium content in precipitation at different locations in Sweden (IVL 2011).

Table 2. Atmospheric deposition of phosphorus. Values used for the calculations of an average inflow of phosphorus and nitrogen by precipitation. [[1](SCB 2011a), [2](Knulst 2001), [3](SCB 2011c), [4](IVL 2011)].

Information	Value	Unit
Area of the municipality of Gothenburg[1]	1029	km^2
Average yearly atmospheric deposition of phosphorus in Gothenburg[2]	5.8	$mg/(m^2*y)$
Annual precipitation in Gothenburg[3]	855	mm
Concentration of nitrate in precipitation[4]	0.36	mg/l
Concentration of ammonium in precipitation[4]	0.45	mg/l
Molar mass of nitrogen (N)	14.01	kg/kmol
Molar mass of nitrate (NO_3^-)	62.00	kg/kmol
Molar mass of ammonium (NH_4^+)	18.04	kg/kmol
Weight percentage of nitrogen in nitrate	22.60	wt%
Weight percentage of nitrogen in ammonium	77.66	wt%

The inflow of phosphorus to the land area of Gothenburg by precipitation is calculated, from the values in Table 2, to 3 ton per year. The corresponding value for nitrogen is 170 ton per year.

4.1.2 FOOD AND IMPORT OF WASTEWATER

Within the system, both humans and pets consume food. The term food also includes beverages in the MFA. The calculations on food consumption are based on the population of Gothenburg, as well as, an estimation of the number of dogs within the city. The import of wastewater is based on the population in the co-owning municipalities of Gryaab, Figure 7.

The food is assumed to be imported, since the food production within the urban system is very small. In the municipality, there are in total 3036 ha of arable land (SJV 2009). 684 of these hectares are used to cultivation of oat, wheat and barley (SJV 2009). The average yield of these cereals is 5 ton per ha (SCB 2010b). The average total phosphorus content in these cereals is 4 g per kg (SLU 2003). It results in a maximum phosphorus flow of 14 ton per year from the local agriculture, corresponding to less than 4% of the phosphorus in the total human food consumption. Additionally, the locally produced cereals are also used as feedstuff to livestock (Göteborg Stad 2010), which is further discussed in section 4.1.5.

Human consumption

The exact number of connected people from each municipality is unknown, so the calculations are made from the difference between the total number connected to Ryaverket, 649352 (Gryaab 2010b) and the population of Gothenburg, 506730 (SCB 2009). Since the proportion between connected women and men are unknown in the co-owning municipalities, the distribution of gender in Gothenburg: 1.0176 women to men; are used in all municipalities as a reasonable approximation.

According to a study, a woman consumes 1182 mg P/day and a man 1505 mg P/day in Malmö, Sweden (Welch et al. 2009). It is assumed that the inhabitants of Gothenburg have a similar food intake as the inhabitants of Malmö. A general assumption that has been found in the literature is 1-2 g of phosphorus per person and day (Brunner 2010). No consideration to different intake of children has been taken.

The input of phosphorus in the consumed food is calculated, from the values in Table 3, to 248 ton per year for the population of Gothenburg. The consumed food in the surrounding municipalities that are connected to the WWTP of Rya enter the system as blackwater and contribute with 72 ton of phosphorus per year.

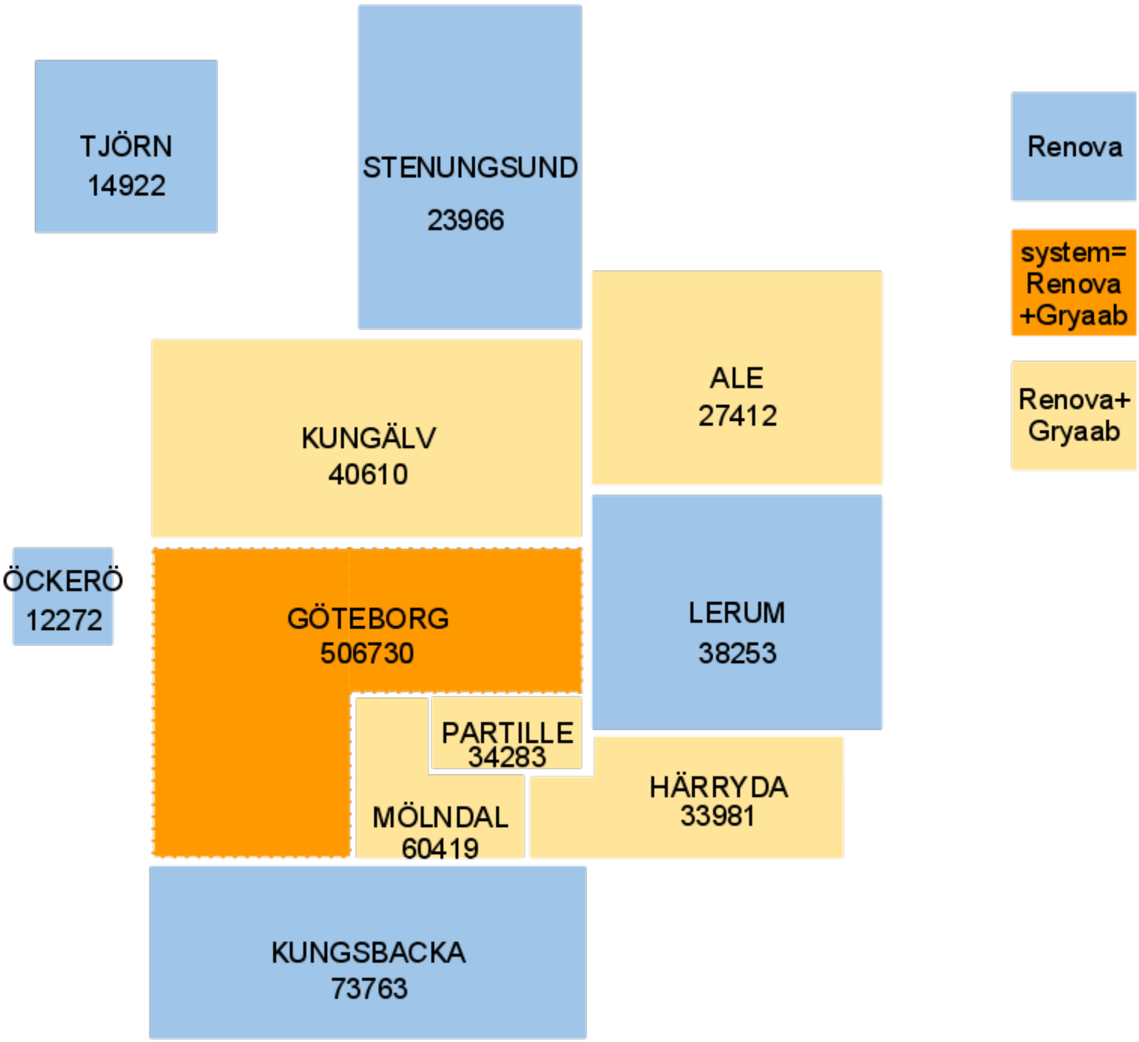

Figure 7. The municipalities that co-own the wastewater treatment company Gryaab and the waste treatment company Renova and their populations in 2009.

N-intake from food varies depending on diet, since the nitrogen comes from protein which contains about 16% nitrogen. An assumption made is a daily consumption of 90 g protein per capita and day (Abrahamson et al. 2006). The calculated values of nitrogen, based on the figures in Table 3, are comparable to values in another study, which used the N-consumption 5.4 kg nitrogen per capita and year (Schmid Neset et al. 2006). This assumption gives a flow of 2700 ton of nitrogen per year in Gothenburg and 780 ton of nitrogen per year in the surrounding municipalities, connected to Rya.

It is 1% of the population in Gothenburg that is not connected to the centralized WWTP of Rya, and has an on-site solution for wastewater treatment instead. This part of the population is assumed to live in the same manner as the rest regarding consumption and household habits. The 1% is then responsible for an input of 3 ton of P via the food, of which 2 ton P is consumed and 1 ton P is wasted.

The food that are consumed by the population of the system are taken into account by assuming that their yearly consumption takes place within the system. The consumption is regardless of place: household, school or workplace, restaurant et cetera, as long as it is inside the system boundaries. For sure, people in Gothenburg are not spending their entire life within the municipality, but a fair assumption is to assume that about the same amount of people that leaves enters. The current assumption allows the retail and restaurants, the public institutions as well as the households to be grouped into one common subsystem.

Table 3. Number of people connected to the WWTP of Rya and their consumption of phosphorus and nitrogen [[1](SCB 2009), [2](Gryaab 2007), [3](Gryaab 2010b), [4](Welch et al. 2009), [5](Abrahamsson et al. 2006)].

Information	Value	Unit
Population in Gothenburg 2009[1]	506730	cap
Women in Gothenburg 2009[1]	255570	cap
Men in Gothenburg 2009[1]	251160	cap
Percentage of population in Gothenburg connected to Rya[2]	99	%
Total population connected to Rya in 2009[3]	649352	cap
Phosphorus consumption by women[4]	1182	mg P/day
Phosphorus consumption by men[4]	1505	mg P/day
Protein consumption[5]	90	g/day
N content in protein[5]	16	%

Wastewater from food process industries

The food production industry, where raw material enters and products leave, must be mentioned alone. These flows do not significantly accumulate in the system, but are still flows of phosphorus that pass through the municipality of Gothenburg. In 2008, two food production companies, situated inside the system boundaries, were among the top-100 of employers in the region of Gothenburg (Business region Gothenburg 2009). The two businesses were the global dairy company Arla Foods AB and one of the leading Swedish bakeries, Pågen AB. In 2009, Arla Foods AB had an entering flow of phosphorus of 117 ton per year via the raw milk and an outgoing flow was 115 ton of phosphorus per year in manufactured dairy products, presented in Table 4. Consequently, the loss into the sewer system was about 2 ton of phosphorus per year (Bergman, pers. comm.). No data have been received from Pågen AB, but the loss is probably not larger than the one from Arla Foods AB due to the kind of products that Pågen AB is producing.

Table 4. Phosphorus that passes though the system via milk products processed at Arla Foods in Gothenburg in 2009. [[1](Bergman, pers. comm.), [2](Lindmark Månsson 2010)].

Information	Value	Unit
Amount of milk delivered to Arla Foods in Gothenburg in 2009[1]	116000	ton/y
Concentration of phosphorus in milk[2]	101	mg/100g
Amount of phosphorus lost to sewage from Arla Foods in Gothenburg in 2009[1]	2190	kg P/y

Pet consumption and waste

In 2004, the total numbers of dogs and of cats in Sweden were 950000 and 1600000, respectively (Manimalis 2004). Applied on Gothenburg, with 5.4% of the Swedish population (SCB 2011b), these numbers give an approximation of 51000 dogs and 86000 cats in the municipality, year 2009 (Manimalis 2004).

For dogs, there have been calculations of their average yearly waste, 120 kg feces per year (Wade 2011). A fair assumption should be to say that 75% of all dog owners pick up the excreta from their pet, and the rest leave it on the ground. The calculations, based on the values in Table 5, sum up to 4600 ton feces collected in plastic bags and 1500 ton left on the ground every year within the system. If the phosphorus concentration in dog feces is about the same as in human feces, about 0.5 wt% (Cordell et al. 2011), the yearly flows become 23 ton phosphorus collected and 8 ton phosphorus left on the ground. The collected feces go to the waste treatment plant and the rest into the soil. The phosphorus in urine is assumed to contain about 50% of the phosphorus in dog food. However, the urine containing 31 ton of phosphorus per year is entirely lost to the soil. No larger losses are assumed in the chain from import into the system to consumption, so the input of phosphorus in dog food is assumed to be 62 ton per year.

Table 5. Consumption and excretion of phosphorus from dogs in Sweden.
[[1](Manimalis 2004), [2](Wade 2011), [3](Cordell et al. 2011)].

Information	Value	Unit
Number of dogs in Sweden in 2004[1]	950000	dogs
Average yearly amount of feces from dogs[2]	120	kg/dog
Concentration of phosphorus in feces[3]	0.5	wt%
Number of cats in Sweden in 2004[1]	1600000	cats
Average daily food intake for cats	0.065	kg/day
Concentration of phosphorus in cat food	1	%

To get an approximation of how much food the cats in Gothenburg consume, an investigation at the local supermarket was performed. The average of five brands for a normal sized cat gave a daily food intake of 65 g, containing about 1% of phosphorus. These values results in a yearly input of 20 ton of phosphorus in cat food. No information about cat waste has been found. However, some general thought can be shared. Excreta from cats that are kept indoors can be assumed to go with the household waste and cats that are walking around outdoors put their waste directly on some kind of productive land. Assuming that 25% of the cat waste goes with the household waste to the WTP and 75% directly to soil, 5 ton phosphorus per year is heading to the WTP and 15 ton to the soil.

4.1.3 DETERGENTS FOR HOUSEHOLD USE

In 2009, the total population of Sweden was 9340682 inhabitants (SCB 2011b). Values for the use of detergents in households have been published and these are used to estimate the amount of phosphorus in greywater (SCA 2010). The greywater that goes from the surroundings into the system of Gothenburg with the destination of Rya will be regarded as an input flow.

The input of phosphorus via detergents is calculated, from the values in Table 6, to 32 ton per year for the population of Gothenburg. The detergents used in the surrounding municipalities that are connected to the WWTP of Rya enter the system as greywater and contribute with 9.4 ton of phosphorus per year. The 1% of the population of Gothenburg that has small wastewater treatment is only responsible for a flow of 0.3 ton P via their household use of detergents. Content of nitrogen in detergents is assumed insignificant.

Table 6. Contribution of detergents to the concentration of phosphorus in greywater from households. [[1](SCB 2011b), [2](SCA 2010), [3](Göteborg Stad 2007), [4](Gryaab 2009)].

Information	Value	Unit
Population of the municipality of Gothenburg in 2009[1]	506730	cap
Amount of phosphates in dishwasher detergents for household use[2]	1431	ton/y
Amount of phosphates in laundry detergents for household use[2]	398	ton/y
Population of Sweden in 2009[1]	9340682	Cap
Molar mass of phosphorus (P)	30.97	kg/kmol
Molar mass of phosphate (PO_4^{3-})	94.97	kg/kmol
Weight percentage of phosphorus in phosphate	32.61	wt%
Percentage of the population of Gothenburg connected to the WWTP of Rya[3]	99	%
Total number of persons connected to the WWTP of Rya[4]	649352	Cap

4.1.4 PHOSPHORUS COMPOUNDS FOR INDUSTRIAL USE

Almost all industries in the municipality of Gothenburg are connected to the wastewater treatment plant of Rya. However, two refineries – Shell and Preem – do have their own treatment of wastewater. The water that is not recycled inside the refineries is emitted directly to the aquatic environment, which is also assumed to be the single outlet for phosphorus from the industries, except the sludge from the treatment plant. The output of phosphorus in the water from these refineries has been quantified, as mentioned in the section called "Aquatic deposition".

In 2010, the amount of produced sludge at Preem was 1081 ton. However, they had not quantified the phosphorus concentration of it (Wennerberg, pers. comm.). A reasonable assumption would be to say that the purification of water and precipitation of phosphorus into sludge do work with approximately the same efficiency as at Rya: about 10% of phosphorus is left in water and 90% goes into the sludge. Furthermore, the two refineries are assumed to deliver phosphorus in sludge in the same proportion to each others as they are emitting phosphorus to the aquatic environment, where Preem emits 0.2 ton phosphorus and Shell 0.8 ton phosphorus (Göteborg Stad 2010). If these assumptions are accepted, then Shell would deliver four times more than Preem in the sludge. Consequently, Preem annually delivers 2 ton and Shell delivers about 8 ton of phosphorus in the sludge.

The refineries in Gothenburg, Shell and Preem, are together annually producing liquefied petroleum gas, gasoline, jet fuel, diesel fuel and heating oil from about 10 million ton of crude oil (Preem 2011, Shell 2011). The input of phosphorus to the industries has not been quantified, but since crude oil contains no phosphorus (Nilsson, pers. comm.), the input is made up of detergents and other chemicals. An assumption that has been found reasonable in this Material Flow Analysis is to assume steady-state inside the refinery on an annual basis. The input to the system is then said to be equal to the output to the aquatic environment, namely 1 ton of phosphorus per year, plus the phosphorus that goes into the sludge. All together, the input estimation sums up to about 11 ton of phosphorus per year.

4.1.5 PHOSPHORUS TO AGRICULTURE

The amount of phosphorus that is spread via mineral fertilizers on arable land in the municipality of Gothenburg is calculated based on statistics. The area of arable land within the current system is 3036 ha (SJV 2009). Furthermore, the Swedish EPA has reported an average input of 7 kilogram of phosphorus from mineral fertilizers per hectare of Swedish arable land and year (EPA 2005). According to Swedish statistics, 24% of the smaller fields in the region are applied with 72 kg nitrogen via mineral fertilizers per hectare agricultural land and year (SCB 2010a). The calculated flows of phosphorus and nitrogen to urban agriculture via mineral fertilizers, based on the values in Table 7, are 21 and 52 ton per year, respectively.

Table 7. Phosphorus consumed by the agriculture in the municipality of Gothenburg due to use of commercial fertilizers and manure.
[[1](SJV 2009), [2](EPA 2005), [3](SCB 2010a), [4](LRF 2008), [5](Länsstyrelsen 2007), [6](SJV 2010a), [7](SJV 2007)].

Information	Value	Unit
Arable land in the municipality of Gothenburg[1]	3036	Ha
Cereals (wheat, barley, oat)[1]	684	Ha
Average input of mineral P fertilizers to arable land in Sweden in 2003[2]	7	kg P/(ha*y)
Average input of mineral N fertilizers to arable land in the Västra Götaland county[3]	72	kg N/(ha*y)
Average percentage of the small fields in the Västra Götaland county supplied by mineral N fertilizers[3]	24	%
Number of horses in Gothenburg in 2007[4]	2016	Horses
Annual amount of excreted phosphorus per horse[5]	13.7	kg P/y
Number of dairy cows in Gothenburg in 2009[6]	153	dairy cows
Annual amount of excreted phosphorus per dairy cow[7]	17	kg P/y
Number of beef cows in Gothenburg in 2009[6]	399	beef cows
Annual amount of excreted phosphorus per beef cow[7]	12	kg P/y
Number of heifers and bulls in Gothenburg in 2009[6]	343	heifers and bulls
Annual amount of excreted phosphorus per heifer/bull[7]	8	kg P/y
Number of calves in Gothenburg in 2009[6]	465	Calves
Annual amount of excreted phosphorus per calf[7]	3.1	kg P/y
Number of pigs in Gothenburg in 2009[6]	1147	Pigs
Annual amount of excreted phosphorus per pig[7]	2.5	kg P/y
Number of sheep in Gothenburg in 2009[6]	552	Sheep
Annual amount of excreted phosphorus per sheep[7]	1.5	kg P/y

In 2007, the number of horses in Gothenburg was 2016 (LRF 2008). A horse produces 25 kg of manure each day with a concentration of phosphorus of 0.15%, which equals 13.7 kg phosphorus per horse and year (Länsstyrelsen 2007). Some manure is transported away from the stables. The horse manure that is delivered to Renova is not incinerated, but sent further to a company called "Brudbergets Jordprodukter" and there composted (Renova, pers. comm.). Their products are for horticultural use and not returned to arable land. According to Brudberget, a yearly amount of 800-1000 m^3 with the weight of 400-500 kg per

m^3 and a concentration of 30-40% pure manure is delivered to them from Gothenburg, partly via Renova (Samuelsson, pers. comm.). It implies an output of maximum 0.3 ton phosphorus per year.

In 2010, the numbers of other kinds of livestock in Gothenburg were 153 dairy cows, 399 beef cows, 343 heifer and bulls, 465 calves, 1147 pigs and 552 sheep (SJV 2010a). Data are available for how much phosphorus each of these kinds excretes annually: 17 kg per dairy cow, 12 kg per beef cow, 8 kg per heifer and bull, 3.1 kg per calf, 2.5 kg per pig and finally, 1.5 kg per sheep (SJV 2007). It results in an annual phosphorus flow of 15 ton out from this livestock.

All together the livestock including horses make up a phosphorus flow of 43 ton per year via their manure. About 80% of the phosphorus consumed by cattle passes through their bodies in urine and feces (Wells 1998). If applying this number on the total livestock in Gothenburg, then 54 ton of phosphorus has to be contained in their feedstuff. The arable land in Gothenburg is more than enough to supply all livestock with feedstuff (Larsson, pers. comm.).

4.1.6 Import of combustible waste and net import of forest products

The waste-fuelled district heating power plant of Renova is an importer of combustible waste to the municipality of Gothenburg. The main reason is that the plant is co-owned by Gothenburg with another ten municipalities in the surroundings, Figure 7. It is also due to the fact that the capacity of the plant is large and to get as good use as possible of it, a large amount of waste must be combusted every year. Therefore, Renova also import combustible waste from Norway that would otherwise have been put directly on landfill (Bondeson 2011).

In 2009, Renova incinerated 453858 ton of combustible waste, of which 58% came from households. The total amount of imported waste from Norway was 44000 ton. If the rest of the combustible waste, which arrived from households to the plant of Sävenäs from its co-owning municipalities, was divided per each of the 359881 inhabitants (SCB 2009), then another 130500 ton was imported to the system (Renova 2009). Kretsloppskontoret, the municipal office working with sewage, waste and water, has analyzed the content of food waste as well as paper in the household waste. It was estimated that 39% of the household waste consisted of food and 17.5% of paper (Kretsloppskontoret 2011). The Swedish Waste Management has published percentages of food, paper and wood in business waste. They make up 22%, 27% and 17% of the business waste, respectively (SWM 2008). The concentration of phosphorus in dry matter of different kind of waste can be found in published literature. The concentration of phosphorus is 4 g P per kg dry matter, DM, biowaste, 0.24 g P per kg DM paper (Sokka et al. 2004) and 0.031 g P per kg DM wood (Barrelet et al. 2006). The dry matter of food waste is 35% (Sokka et al. 2004). For paper and wood, the dry matter is assumed 100%, which is high but acceptable since no better estimation was found.

The calculations, based on the values in Table 8, result in the following flows of phosphorus in waste: 202 ton of phosphorus in food waste, 23 ton in paper and 1 ton in wood. Of these flows, about 100 ton of phosphorus is imported via combustible waste from households into the system, mainly in the form of food waste. As has been estimated based on statistics, the food waste flow of phosphorus inside the system is 120 ton, section 4.3.1, and 28 ton goes via pet waste, section 4.1.2. For use inside the system, about 17 ton of phosphorus is imported via forest products, e.g. paper and wood, and then incinerated each year.

Table 8. Relevant information for the estimation of phosphorus content in imported waste [[1](Renova 2009), [2](Kretsloppskontoret 2011), [3](SWM 2008), [4](Sokka et al. 2004), [5](Barrelet et al. 2006)].

Information	Value	Unit
Total amount incoming waste[1]	453858	ton/y
Amount of imported incoming waste[1]	174500	ton/y
Percentage of household waste in incoming waste[1]	58	%
Percentage of biowaste in household waste[2]	39	%
Percentage of paper in household waste[2]	17.5	%
Percentage of biowaste in business waste[3]	22	%
Percentage of paper in business waste[3]	27	%
Percentage of wood in business waste[3]	17	%
Concentration of P in biowaste[4]	4	g P/kg DM
Concentration of P in paper[4]	0.24	g P/kg DM
Concentration of P in wood[5]	0.031	g P/kg DM
Dry matter of biowaste[4]	35	%
Dry matter of paper	100	%
Dry matter of wood	100	%

4.2 OUTPUT FLOWS

The output flows are those flows that export phosphorus out from the system over the system boundaries.

4.2.1 AQUATIC DEPOSITION

The aquatic deposition from different sources in the current system has been quantified by the environmental administration of the municipality of Gothenburg. In the report including the estimated values, the productive land in Gothenburg is said to be 8 100 ha and the two industries that are directly emitting phosphorus to the aquatic environment are the refineries Shell and Preem. Nitrogen is emitted from the same sources and in addition to the two refinieries, nitrogen is also released from the waste-fuelled heating power plant of Sävenäs (Göteborg Stad 2010). The total output of phosphorus to the aquatic environment, based on the values in Table 9, is 54.2 ton per year, and the corresponding value for nitrogen is 1877 ton per year.

Table 9. The aquatic deposition of phosphorus and nitrogen from the municipality of Gothenburg. Values calculated by the Environmental Administration of the municipality of Gothenburg (Göteborg Stad 2010).

Source	Amount of P	Amount of N	Unit
The WWTP of Rya	36	1560	ton /y
Leakage from agriculture	3.3	147	ton /y
Industries	1	72	ton /y
Stormwater	6	42	ton /y
Sewer overflow	4.1	26	ton /y
On-site wastewater treatment systems	3.8	30	ton /y

4.2.2 DIGESTED SLUDGE

Digested sludge after anaerobic digestion, is produced from the WWTP of Rya. In 2009, hardly any of it was returned to productive land. A tiny amount of the sludge was so-called ReVAQ-certified and could be used in agriculture. The rest of the sludge from the WWTP of Rya was composted and used for infrastructural purposes (Gryaab 2009). The amount of phosphorus in the digested sludge, 334 ton per year, is known from samples taken at the WWTP and makes up 90% of the phosphorus in the input flow (Gryaab 2010b). The amounts and destinations of the digested sludge from the WWTP of Rya are presented in Table 10. At the WWTP of Rya, 15-20% of the input nitrogen ends up in the digested sludge (Gryaab 2010b). This percentage corresponds to a yearly flow of 525 ton nitrogen. A comparative calculation, Appendix A, on how much nitrogen in digested sludge that comes from blackwater gives the value of 17%, which shows that the amount of consumed nitrogen is reasonable, if the nitrogen content in greywater and stormwater is low.

Table 10. Amount of and concentration in sludge produced in the WWTP of Rya in 2009 [[1](Gryaab 2009), [2](Gryaab 2010b)].

Information	Value	Unit
Digested sludge to composting[1]	43796	ton/y
Digested sludge to agriculture (REVAQ)[1]	840	ton/y
Digested sludge to disposal in Syrhåla cavern[1]	11	ton/y
Amount of phosphorus in the total amount of digested sludge produced in the WWTP of Rya in 2009[2]	334	ton P/y
Amount of nitrogen in the total amount of digested sludge produced in the WWTP of Rya in 2009[2]	525	ton N/y

4.2.3 ASHES TO DISPOSAL

As mentioned above, Renova incinerated 453858 tons of combustible waste in 2009 (Renova 2009) and all the phosphorous in this waste is assumed to end up in the ashes for disposal, since phosphorus never occurs in gas phase. In a project called VOKAB[3], twelve fuel samples from Renova were taken during one year and different inorganic substances were analyzed after incineration. The average content of phosphorus in those samples was 1.2 g/kg DM, with a median of 1.15 g/kg DM and a standard deviation of 0.61 mg/kg DM. The average water content in those samples was 36.3%, with a standard deviation of 5.33 percentiles (Claesson Jones 2010). The average content of phosphorus and water, respectively, is found in Table 11. Given that the amount of phosphorus going into the waste treatment plant is the same as the amount of phosphorus in the resulting ashes, these values give a total amount of phosphorus in ashes to disposal of 350 ton per year. Taken the two standard deviations into account this amount could

[3] "The pathway of inorganic elements from waste fuels in power boilers"

vary between 160 and 570 ton per year. This assumption states that no phosphorus is lost to the gas phase or other waste fractions from the plant, which is judged very reasonable. Worth mentioning is also that Renova has agreed upon this assumption and that they judged their current ash samples less scientifically reliable than the fuel samples of VOKAB (Detterfelt, pers. comm.).

Table 11. Amount of phosphorus in combustible waste that is processed to ashes at the WTP of Sävenäs (Claesson Jones 2010).

Information	Value	Standard Deviation	Unit
Average content of phosphorus in incinerated waste	1.2	0.61	g P/kg DM
Average water content in incinerated waste	36.3	5.33	wt-%

4.2.4 COMPOST FOR HORTICULTURAL USE

The organic waste that arrives to the treatment plant of Marieholm, owned by Renova, has mainly its origin in separately collected food waste from the households within the municipality of Gothenburg. Even though the food waste is combined with some brushwood during the composting process, the only figure for phosphorus that has been received from Renova is that one for the dry content of phosphorus in the incoming food waste (Skruf, pers. comm.). In the Material Flow Analysis, it has been estimated that almost no losses of phosphorus occur during the compost process. Therefore, the calculated value, based on the values in Table 12, has only been downward, which yielded 10 ton of phosphorus.

The sludge from Preem is sent to another waste treatment company, Stena Recycling (Wennerberg, pers. comm.). The sludge is being composted by them and the estimated amount of phosphorus within it is 10 ton per year, see section “Phosphorus compounds for industrial use”.

Worth mentioning is that the food waste is not going to be composted at Marieholm in the future. Instead the food waste is planned to be pretreated for biogas production in a new-built plant at the same site from the mid of year 2011. In the pretreatment step, the food waste will be ground and mixed to a slurry that can be transported to anaerobic digesters at other sites (Renova 2011).

Table 12. Amount of phosphorus in food waste processed to compost soil at the treatment plant of Marieholm (Skruf, pers. comm.).

Information	Value	Unit
Content of phosphorus in dry incoming food waste	0.24	%
Annual amount of incoming food waste	15000	ton/y
Dry matter of incoming food waste	30	%
Amount of phosphorus in compost from sludge from refineries	10	ton P/y

4.3 INTERNAL FLOWS

The internal flows are those flows that transport and/or transform phosphorus inside the system.

4.3.1 FOOD WASTE

Food waste is here defined as edible waste material or by-products generated in the production, processing, transportation, distribution and consumption of food. Before the food reaches human consumption there are several losses in the chain which results in that more food has to be produced than is actually consumed. According to a study, 5-10% of the food is wasted in the retail and during the distribution. In the households and public institutions the food wastage is between 20-35% (Skjöldebrand

2008). From these percentages a reasonable assumption is made that from the food coming into the borders of the municipality of Gothenburg, one third of the imported food never reaches the mouth of the consumers. The food wastage is counted as organic waste and is mostly an input into waste treatment plants, but some is also used for biogas production elsewhere. In 2009, the WWTP of Rya received 604 ton of external dry solid organic waste (Gryaab 2009). Together with the sludge, this organic waste was pumped into the anaerobic digesters to produce biogas. In 2010, a sample-taking on the received external organic waste was done at the WWTP of Rya and the calculated amount of received phosphorus was 3 ton (Gryaab 2010a).

The internal food waste flows of phosphorus and nitrogen in food waste have been calculated, based on the values in Table 13, to 121 and 1200 ton per year, respectively.

Table 13. Assumptions made for calculations of the food waste and its content of phosphorus and nitrogen in the municipality of Gothenburg [1](Gryaab 2010a).

Information	Amount of P	Amount of N	Unit
Human food consumption in Gothenburg	248	2660	ton/y
Estimated average percentage of food that is wasted during processing, trading and consumption	33.3	33.3	%
Amount of phosphorus in food waste processed at WWTP instead of WTP[1]	3	128	ton/y

4.3.2 STORAGE CAPACITY IN SOILS AND REUSE IN AGRICULTURE

The values for the storage capacity in soils for phosphorus and the reuse rate of the same nutrient in the municipality were hard to quantify. There are some farms in the municipality, although the urban areas are the dominating ones. According to the environmental administration of the municipality of Gothenburg, the main business for the farms in the city is horses (Göteborg Stad 2010). It is then assumed that a certain amount of phosphorus is recycled locally, for instance by returning manure to the fields where the animals later on will be grazing.

Additionally, there are quite many parks in Gothenburg, and it is highly probable that these are fertilized sometimes, in some kind of way. How much of the phosphorus that is on one hand applied, on the other hand stored in the soil, has not been explicitly estimated in this analysis. As mentioned before, one phosphorus input to soils is also the pet waste being left on the ground. The balancing that has been performed was to control that the sum of the inputs to the soil accords well with the outputs and that the difference between them looked like a reasonable storage capacity.

Table 14. Calculated flows used in the MFA, shown graphically in Figure 8.

Phosphorus flow	Value [ton/y]	Description
INPUT FLOWS		
Atmospheric deposition	3	Section 4.1.1.The P input via annual precipitation
Wastewater (food process industry)	2	Section 4.1.2. The P input via wastewater from Arla Foods AB.
Wastewater (5 co-owning municipalities of the WWTP of Rya)	82	Section 4.1.2 and 4.1.3. The P input via wastewater, both black- and greywater, from Ale, Härryda, Kungsälv, Mölndal and Partille.
Food (human and pets)	450	Section 4.1.2 and 4.3.1. The P input via food to the population of Gothenburg as well as the pets in the municipality.
Detergents (household use)	32	Section 4.1.3. The P input via detergents used in the households of Gothenburg.
P compounds (industrial use)	11	Section 4.1.4. The P input via detergents and chemicals to the two refineries in Gothenburg.
P to agriculture	21	Section 4.1.5. The P input via mineral fertilizers supplied to the arable land in Gothenburg.
Waste import (10 co-owning municipalities of the WTP of Sävenäs and from Norway)	100	Section 4.1.6. The P input via food waste, paper and wood waste from Ale, Härryda, Kungsbacka, Kungsälv, Lerum, Mölndal, Partille, Stenungsund, Tjörn, Öckerö and Norway.
Net import of forest products	17	Section 4.1.6. The P input via paper and wood that are annually incinerated at the WTP of Sävenäs.
OUTPUT FLOWS		
Digested sludge	330	Section 4.2.2. The P output via digested sludge from the WWTP of Rya.
Ashes	350	Section 4.2.3. The P output via fly ash and bottom ash at the WTP of Sävenäs, based on P-content in the incoming waste and the fact that P does not naturally occur in gas phase.
Compost	20	Section 4.2.4. The P output via compost produced at the treatment plant of Marieholm.
Aquatic deposition	54	Section 4.2.1. The P output via leakages from the activities in Gothenburg into aquatic environments.
INTERNAL FLOWS		
Food waste	120	Section 4.3.1. The P flow inside the system via the food waste produced by the population in Gothenburg.
Storage in soil and reuse in agriculture	-	Section 4.3.2 and 4.1.5. The P flow inside the system via manure and agricultural harvest.
Unspecified source of P	-	Introduction of Chapter 4. The balance over the WTP is not perfectly even and it means that some of the sources of P in the waste are underestimated or not quantified. Possible sources are small concentrations in plastics and textiles, flame retardants, lacquer as well as food waste from fish processing and butcher shops.

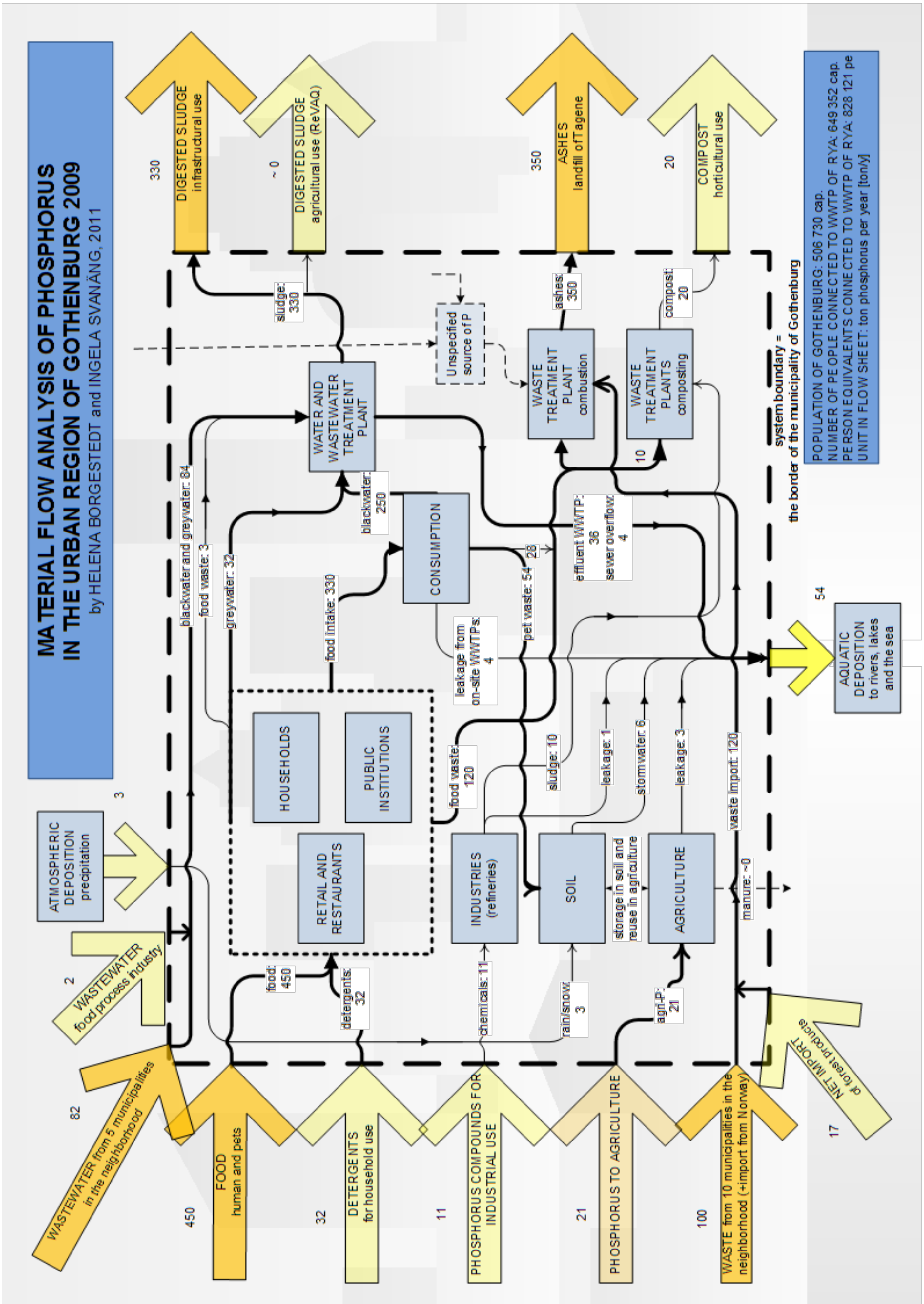

Figure 8. The MFA of phosphorus over the current system in Gothenburg, 2009.

5. SCENARIOS WITH ALTERNATIVE WASTEWATER SYSTEMS IN GOTHENBURG

An increased recycling of nutrients from urban areas back to productive land is desirable for environmental as well as economic reasons. Since the Swedish environmental quality objective regarding recycling and reuse of phosphorus focuses on the wastewater system, the alternative scenarios mainly imply changes in this part. However, the alternative scenarios with kitchen grinders also explicitly deal with food waste, both in the centralized and semi-centralized scenarios. Even in the urine diverting scenario with a semi-centralized solution, the food waste might be included in the biogas production. As seen in the MFA for the current system, as much phosphorus as is found in the wastewater of Gothenburg, is captured in the ashes. Therefore, it is highly interesting to find solutions where the wastewater and waste systems convert and are both included. The holistic perspective is crucial if the nutrient cycles and the management of them ought to be improved. Arguments to analyze the future prospects for the wastewater systems already today, is the expected population growth in Gothenburg (GR 2010) and the attractiveness of planning and investing wisely for the future without rush.

5.1 CENTRALIZED VERSUS SEMI-CENTRALIZED SCENARIOS

The alternative wastewater systems might be centralized or semi-centralized. The centralized scenarios imply piping via the current piping system to a centralized wastewater treatment plant. The semi-centralized scenarios deal with collection of wastewater fractions on a local scale. The treatment can then take place either at the local collection site, for instance as in the case of urine storage, or at a site to which the substrate is transported by vehicles, for instance to a biogas plant. In all the alternative scenarios here, the greywater is piped to the centralized WWTP and the various ways of dealing with wastewater mainly refer to the blackwater and food waste fractions. A brief summary of the alternative scenarios is shown in Table 15 and Figure 9.

The authors have chosen biogas production as the treatment method of blackwater and food waste. The Swedish Energy Agency has stated that digested sludge from biogas production gives opportunities to better management of nutrients and decreases the need of phosphorus mining (SEA 2010). The Swedish Waste Management has emphasized the public welfare by producing energy in form of biogas from waste and wastewater. Biogas and digested sludge can contribute to nutrient recycling as well as reduced climate change (SWM 2011a). Furthermore, by-products from biogas production have a high plant availability of nutrients, which will be further discussed in section 5.3.3. An alternative to biogas production is composting and the advantage of this treatment method is easier local handling. On the other hand, compost soil is less interesting as fertilizer product, since the plant-available nitrogen content is low, shown in Table 21, and energy is lost instead of recovered. Furthermore, it has been emphasized that digestion of organic material with biogas production and nutrient recycling is much more resource efficient than composting (GR 2010). Flows can be transported in pipes either by gravity or vacuum, but this aspect is not taken into account in this master thesis due to the fact that the quantity and the quality of the nutrients are independent of the way of transportation.

Table 15. Four potential alternatives of new sanitation systems in Gothenburg.

	Kitchen Grinders	Urine Separation
Centralized	Grinder in every household. Blackwater, food waste and greywater in combined sewer to WWTP of Rya.	Separating toilet in every household and urine tank in every building. Fecal wastewater and greywater in combined sewer to WWTP of Rya.
Semi-centralized	Grinder in every household. Blackwater and food waste to special treatment plant for biogas production. Greywater in sewer to WWTP of Rya.	Separating toilet in every house hold and urine tank in every building. Fecal wastewater to special treatment plant for biogas production. Food waste might be added separately to the digester. Greywater in sewer to WWTP of Rya

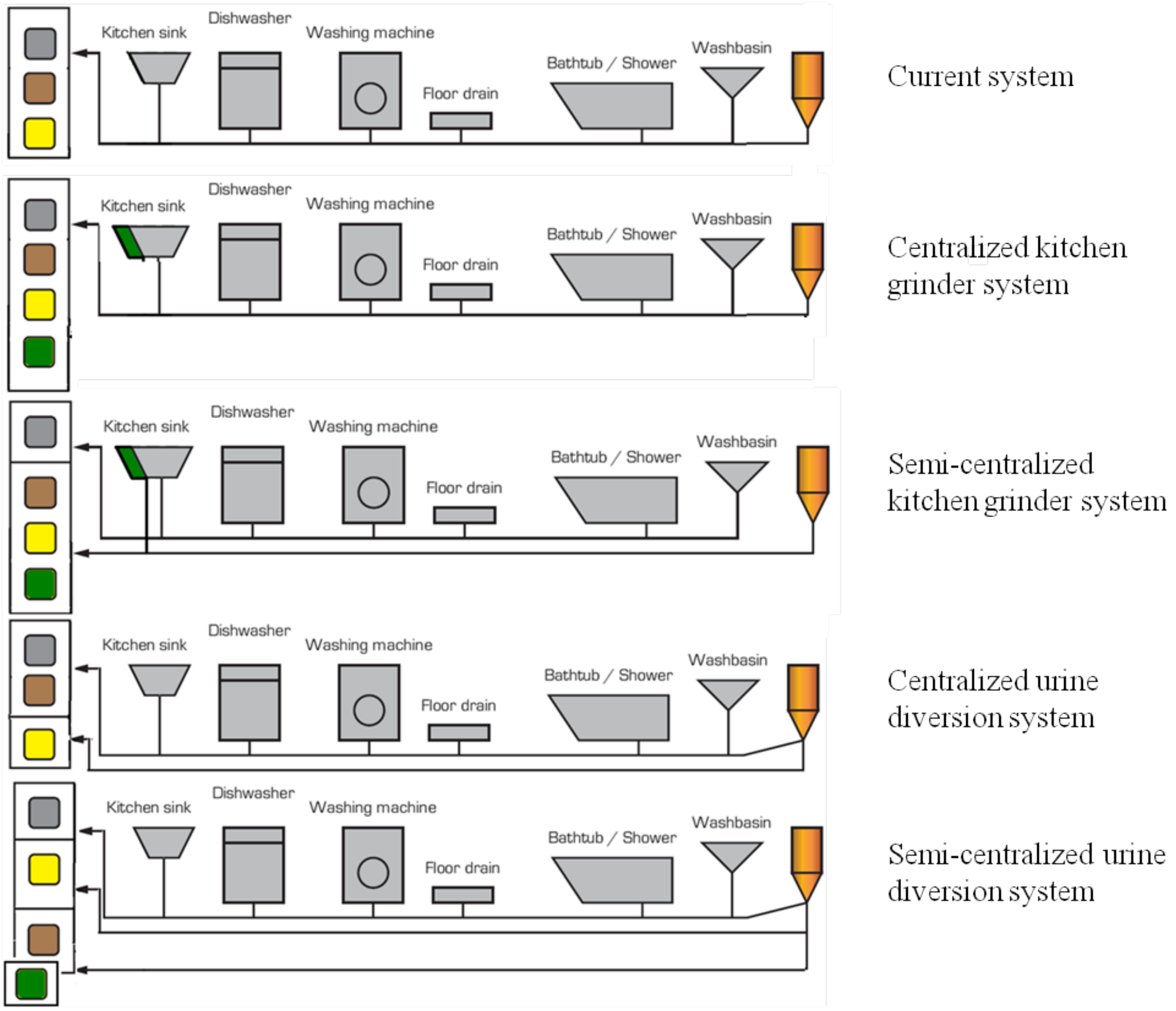

Figure 9. The current and alternative wastewater systems. In the two kitchen grinder scenarios, the kitchen grinder is symbolized by a green part of the kitchen sink and the orange symbol is the toilet. The grey box corresponds to greywater, the brown one to fecal wastewater, the yellow one to urine and the green box corresponds to food waste. (Harder pers. comm. [edited]).

In the scenarios with kitchen grinders, Figure 9, biogas and digested sludge are produced in larger amounts than today due to the addition of ground food waste. In the centralized scenario, the products are produced at the centralized WWTP of Rya. In the semi-centralized scenario, the products: biogas and BW+FW sludge[4]; are produced locally or at a new site to which the blackwater and ground food waste are transported after local collection. In the urine diversion scenarios, Figure 9, the fertilizer product is urine in both scenarios. In the semi-centralized scenario, biogas and BW+FW sludge are also produced. The BW+FW sludge is an additional fertilizer product. In the centralized scenario, biogas can still be produced at the centralized WWTP of Rya and is in this case produced from the combined wastewater fractions except urine. This WW sludge[5] can still be used, but contain less phosphorus than today when the urine is taken away.

5.1.1 Grinders in households in Gothenburg

The two scenarios with grinders in households have kitchen grinders installed in every household in the municipality of Gothenburg. The majority of the organic waste will no longer need separate collection as

[4] BW+FW sludge is digested sludge based on blackwater and food waste
[5] WW sludge is digested sludge based on all kind of wastewater from a combined sewer system

solid waste. It might also be expected that it becomes easier to separate the food waste from the rest of the solid waste if it just can be put in the sink and then ground into the sewer system. The greywater will continuously be piped to the centralized WWTP.

Centralized scenario
In this scenario the blackwater, food waste and greywater is collected in a combined sewer to the WWTP of Rya. No sewers in the municipality will be replaced. The pipes used today will be taking a higher load as a result from the organic waste from the grinders. Consequently, the flow will increase. In best case scenario approximately 80% of the food waste will be piped to the WWTP of Rya (Karlsson et al. 2008), the wastewater fraction will contain more nutrients than today. The nutrient-richer flow might imply that the centralized WWTP needs to improve and expand their treatment procedures. The biogas production will increase when more organic waste is transported to the plant.

Similar systems do exist. Kitchen grinders are common in North America, Japan and Australia, where they are implemented in centralized wastewater systems (Bolzonella et al. 2003). The highest number of grinders in Sweden is in the municipality of Surahammar (Stockholm Vatten 2008), where the grinders are connected to the original sewer system as well (Karlberg & Norin 1999).

Semi-centralized scenario
In the semi-centralized system there will be more material needed besides grinders for every household, since the blackwater is collected locally and treated at a special treatment plant. Local pipes for blackwater and organic waste need to be installed in each household and they will be connected to a separate sewer system. The blackwater and ground food waste will be transported to a special treatment plant, where it will be anaerobically digested to produce biogas. This means that the biological treatment process at the WWTP of Rya, in particular, will have a lot lighter burden than today.

A similar system has been tested in a small scale in Skogaberg, Gothenburg. It was set up for 130 new-built apartments, which got kitchen grinders installed with pipes for separated blackwater heading to a local treatment plant. Biogas was produced from the blackwater at a laboratory scale and showed a potential of producing approximately 90kW per person and year. The greywater was transported to the centralized WWTP of Rya (Karlsson et al. 2008).

5.1.2 URINE DIVERSION IN GOTHENBURG

The two scenarios with installation of urine diversion both imply the introduction of urine-diverting toilets and separate pipes as well as tanks for collection and storage of urine in the cellars or the ground close to the buildings. Furthermore, the greywater is, in the both scenarios, continued to be piped to the centralized WWTP.

Centralized scenario
In the centralized scenario the fecal wastewater is also piped to the centralized WWTP as in the current system. Consequently, the change between this new system and the current one is only the changed piping of urine. It is a small volume of liquid that is collected separately, but a large amount of nutrients. The flow to the centralized WWTP will remain almost constant, but the nutrient load on the same will diminish remarkably. The equipments that need to be installed are the new toilets, the tanks and the pipes between them. Additionally, a system for the emptying and transport of urine to farmland need to be developed. The centralized WWTP might possibly have the chance to reduce their treatment procedure due to smaller nutrient load.

Systems that are similar to this one do exist in both Germany and Sweden. Urine separation is taking place in the main office building of GTZ[6], Germany. The fecal wastewater and greywater are piped to a centralized WWTP. The urine is collected in tanks for storage in the bottom of the building and is planned

[6] Deutscher Gesellschaft für Technische Zusammenarbeit

to be used in agriculture after storage (SSA 2010). The Swedish municipality of Tanum has a water and sewage policy encouraging urine separation in all new buildings. The feces are most often sent by the normal sewage system and the urine is collected in separate containers for storage during six months before use as fertilizer on local farmland (Tanum 2008).

Semi-centralized scenario

In the semi-centralized scenario also the fecal wastewater is to be collected at site. The fecal wastewater is relatively viscous and a removal of this, from the pipes heading to the centralized WWTP, probably increases the velocity of the flow within them. Since the urine is aimed to be used in a different way from the fecal wastewater, the semi-centralized scenario needs installation of additional local pipes compared to the centralized scenario. The dimension of the pipe for fecal wastewater must be bigger than the one for urine, due to the various properties of the two liquids. Furthermore, the fecal wastewater must with this choice of diversion system be collected in separate tanks.

The local treatment of urine is the same as in the centralized scenario. The treatment of fecal wastewater includes, firstly, a biogas plant and then a process for the digested sludge. These processes might take place just where the wastewater is collected or at another site to which it is transported. Separately collected food waste might be added to the anaerobic digester as well. The centralized WWTP will be relieved from a lot of treatment load, if all toilet wastewater is treated elsewhere. The centralized WWTP could diminish its biological treatment to a large extent, since most of the nitrogen and a large part of the organic material never reach the centralized plant in this scenario. Also the use of chemicals in the chemical treatment step could diminish.

A similar system is the one in Gebers collective housing project, Orhem. It has urine-diverting toilets that pipe the urine to storage tanks under the houses. The feces are collected by gravity, but without flushing water, into plastic bins in the cellar. The greywater is led to a centralized WWTP. The urine is later on used as fertilizer and the feces are composted for future use as soil conditioner (GTZ 2005b).

5.2 MFA OF PHOSPHORUS FOR THE ALTERNATIVE SCENARIOS

When the material flow analyses of phosphorus have been set up for four hypothetical new wastewater systems, some general assumptions have been made. Those assumptions are listed below:

- No change in food habits,
- no change in habits of dishwashing, laundry and bathing,
- no change in industries,
- no change in atmospheric deposition,
- no change in agricultural management, and
- the new technology is only introduced within the system boundaries.

Thus, there are several flows that will be assumed to stay constant and those are listed in Table 16. The flows of phosphorus that will change and are of certain interest are those that potentially can be recycled and reused on productive land. Already today, the WW sludge from the centralized WWTP of Rya is to a certain extent returned. In the alternative scenarios, also urine and BW+FW sludge remaining from the biogas production are interesting fractions. Finally, it would be interesting to examine whether phosphorus can successfully be extracted from ashes, since the amount of phosphorus in ash is large in the system of Gothenburg.

Table 16. The current flows of phosphorus that are assumed unchanged in the alternative wastewater systems.

Flow of phosphorus	Value	Unit
Atmospheric deposition	3	ton/y
Food	450	ton/y
Detergents	32	ton/y
Phosphorus compounds for industrial use	11	ton/y
Phosphorus to agriculture	21	ton/y
Import of wastewater (households+industries)	84	ton/y
Import of waste	100	ton/y
Net import of forest products	17	ton/y

5.2.1 GRINDERS IN HOUSEHOLDS IN GOTHENBURG

The altered flows of phosphorus in the centralized and semi-centralized scenario, respectively, have been calculated. The calculations can be found in Appendix B.

Scenario with centralized kitchen grinder system

The installation of grinders implies that a large part of the food waste is diverted from the waste treatment plant to the wastewater treatment plant. A reasonable assumption of how big quantity of the food that actually can be ground is 80 wt% (Karlsson et al. 2008). Thus, the rest will still be treated at the waste treatment plants. Consequently, the amount of phosphorus in WW sludge will increase and the amount of phosphorus in ash decrease. If less food waste is collected and delivered to the waste treatment company, it is reasonable to say that the biological treatment, e.g. composting, is taken away.

Given that the WWTP can hold the same treatment efficiency; 90% of the phosphorus to the sludge and 10% to the aquatic environment, Appendix B. Since the total input of phosphorus will increase with kitchen grinders, both the flow of WW sludge and aquatic deposition will increase. Larger flows in the sewer system to the centralized wastewater treatment plant do at least not decrease the risk of sewer overflows. The risk of not enough treatment capacity is also immediate, but not taken into account in the calculations. The flows are presented in Table 17.

Table 17. The altered flows of phosphorus in the scenario with a centralized kitchen grinder system.

Flow of phosphorus	Current value	New value	Unit
Food waste to centralized wastewater treatment plant	3	100	ton/y
Food waste to waste treatment plant	121	24	ton/y
WW sludge	334	420	ton/y
Compost for horticultural use	20	10	ton/y
Ashes to disposal	350	263	ton/y
Aquatic deposition	54.2	65	ton/y

Scenario with semi-centralized kitchen grinder system
As for the centralized scenario, the semi-centralized system with kitchen grinders will divert phosphorus from the solid waste to the wastewater. What is new for this scenario is local collection of the separated and food-enriched blackwater flow as well as a special treatment plant for this fraction, where biogas will be produced and the phosphorus ends up in the BW+FW sludge. With a semi-centralized concept the burden on the centralized wastewater plant will decrease significantly and therefore also the risk of sewer overflows. The same treatment efficiency as in the previous scenario has been assumed. Since the input to the WWTP decreases, the phosphorus content in WW sludge and into the aquatic environment decreases as well. The flows are presented in Table 18.

Table 18. The altered flows of phosphorus in the scenario with a semi-centralized kitchen grinder system.

Flow of phosphorus	Current value	New value	Unit
Food waste to local wastewater treatment plant	0	100	ton/y
Food waste to waste treatment plant	121	24	ton/y
WW sludge	334	113	ton/y
Compost for horticultural use	20	10	ton/y
Ashes	350	263	ton/y
BW+FW sludge	0	345	ton/y
Aquatic deposition	54.2	27	ton/y

5.2.2 URINE DIVERSION IN GOTHENBURG

The altered flows of phosphorus in the centralized and semi-centralized scenario, respectively, have been calculated. The calculations can be found in Appendix B.

Scenario with centralized urine diversion system
The installation of urine diverting toilets will decrease the burden of phosphorus and nitrogen on the centralized wastewater treatment by collecting and treating the urine locally. It is estimated that 50% of the phosphorus in total wastewater is found in the urine and according to earlier experiences about 70% of expected amount of the nutrient can actually be caught in the diverted fraction (Vinnerås & Jönsson 2002). If less urine reaches the WWTP, less phosphorus goes into the sludge and the aquatic environment, given that the treatment efficiency is the same as before. The flows are presented in Table 19.

Table 19. The most important flows of phosphorus in the scenario with a centralized urine diversion system.

Flow of phosphorus	Current value	New value	Unit
Food waste to waste treatment plant	121	121	ton/y
Urine	0	98.1	ton/y
Fecal wastewater to centralized treatment plant	0	150	ton/y
WW sludge	334	245	ton/y
Compost for horticultural use	20	20	ton/y
Ashes to disposal	350	350	ton/y
Aquatic deposition	54.2	45	ton/y

Scenario with semi-centralized urine diversion system

For the semi-centralized scenario with urine diversion, also the fecal wastewater is collected locally. The fecal wastewater becomes BW+FW sludge during semi-centralized biogas production. Since the centralized treatment plant will receive much less phosphorus and nitrogen than before, sewer overflows should be avoided. The same treatment efficiency as in the previous scenario is assumed, and consequently, less phosphorus reaches the sludge and the aquatic environment. The flows are presented in Table 20.

If the food waste is collected separately, it can be added to the fecal wastewater in the biogas production. A reasonable assumption is to say that the same amount of food waste that can be ground, can be put in the digester. The redirection of food waste would diminish the content of phosphorus in ash with 97 ton and consequently increase the content of phosphorus in BW+FW sludge with the same amount.

Table 20. The most important flows of phosphorus in the scenario with a semi-centralized urine diversion system.

Flow of phosphorus	Current value	New value w/o FW	New value with FW	Unit
Food waste, FW, to waste treatment plant	121	121	24	ton/y
Urine	0	98.1	98.1	ton/y
Fecal wastewater, BW, to local treatment plant	0	150	0	ton/y
WW sludge	334	113	113	ton/y
BW+FW sludge	0	0	247	ton/y
Compost for horticultural use	20	20	10	ton/y
Ashes to disposal	350	350	263	ton/y
Aquatic deposition	54.2	27	27	ton/y

5.3 FERTILIZING POTENTIAL OF PRODUCTS FROM THE ALTERNATIVE SYSTEM

The quantity and quality of the fertilizer products, which can be obtained in alternative wastewater, will be analyzed in this section. The potential of alternative fertilizer products to substitute mineral fertilizers, and thereby decrease the phosphorus mining and eutrophication, is tempting.

The flows that change in the alternative scenarios presented in section 5.1 are quantified via MFA in section 5.2. In Figure 10, the output flows enriched in phosphorus are shown. The y-axis presents the quantity of the different flows and the order of the flows in the bars represents their quality based on plant availability. The best quality is found in the bottom, the urine, and the worst quality is in the top, the aquatic emission. The qualities will be further discussed in section 5.3.2. The aquatic emissions are decreasing with the semi-centralized solutions. The amount of phosphorus in ash decreases when the food waste is removed from the waste that is being incinerated and redirected to the wastewater system. The highest quality flow, the urine, is logically present in the urine diversion scenarios. The next best quality flow, the BW+FW sludge, is produced in all semi-centralized scenarios.

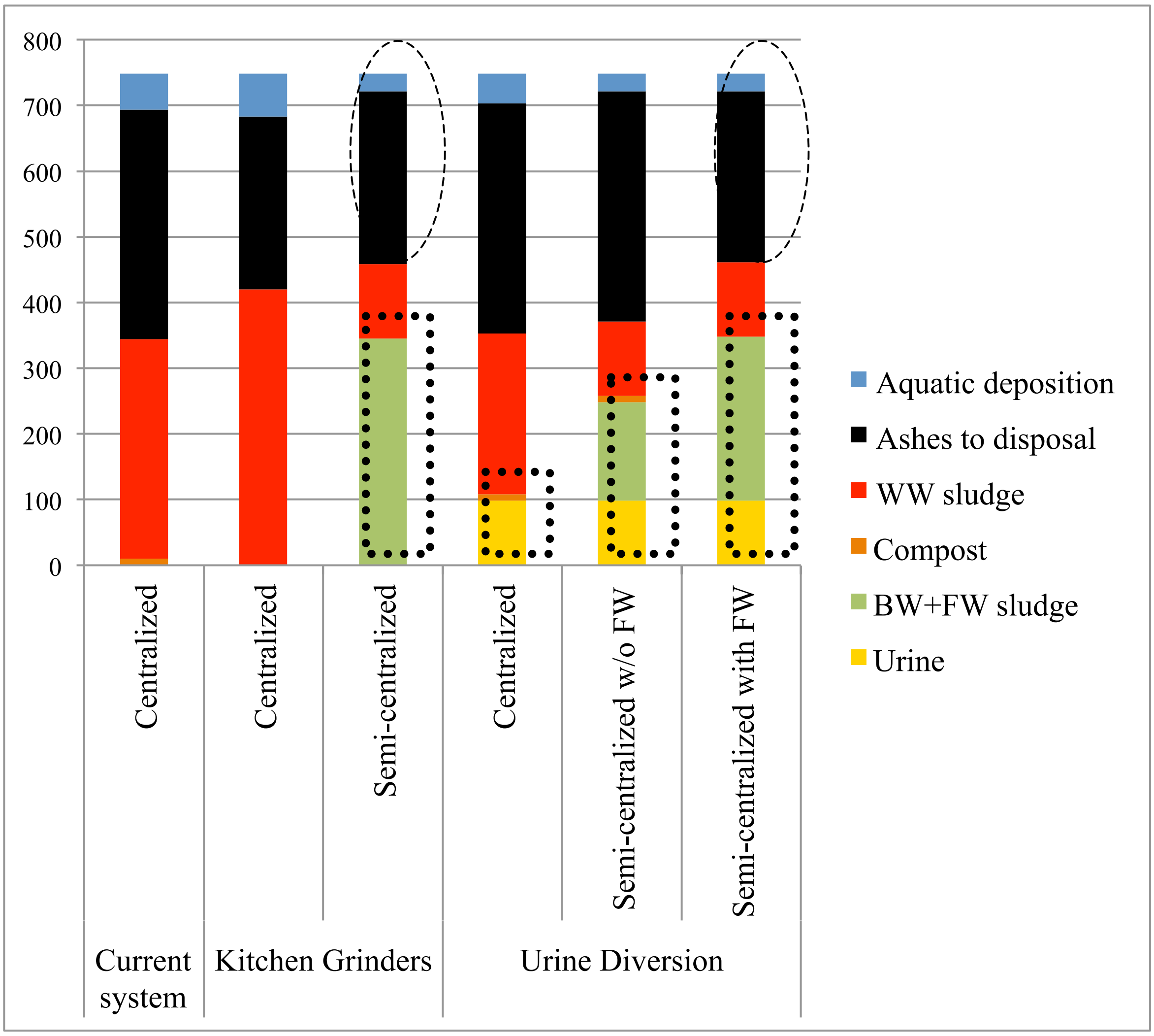

Figure 10. The output flows of phosphorus from the current and alternative scenarios. The quality of the flows is highest in the bottom and decrease the higher in the bar the flows are presented. The two wanted phosphorus flows are circumscribed by rectangles with dotted lines. The urine diversion systems offer the good fertilizer product urine. In all semi-centralized scenarios, digested sludge based on blackwater and food waste, with better quality than digested sludge from combined sewer system, is produced. When food waste is collected and treated separately from other fractions in the solid waste, the content of phosphorus in ashes decreases. The contents of phosphorus in ashes and in aquatic deposition are lowest in the semi-centralized scenarios marked with dotted circles.

5.3.1 QUANTITATIVE ASPECTS

The quantitative aspects that are dealt with in this section are firstly, the concentration of phosphorus in the fertilizer products from the various wastewater systems. Secondly, the absolute amounts, in other words the capacities, of these fertilizing flows are examined.

Concentration of phosphorus in fertilizing flows

As mentioned, a possible installation of kitchen grinders in Gothenburg will increase the content of phosphorus in the waste water. A study in Skogaberg, Gothenburg showed that the phosphorus content in the fraction with blackwater and ground food waste, produced by grinders, was four times higher and the nitrogen content was ten times higher than in the municipal combined wastewater (Karlsson et al. 2008). Also in the semi-centralized urine diversion scenario, when food waste is added afterwards to the fecal wastewater, the concentration of phosphorus should increase. Urine fertilizers are even more concentrated, since urine does not constitute more than 1% of the total volume of wastewater (Meinzinger 2010). In Table 21, the concentration of plant available phosphorus in various fertilizers is shown. As can be seen, urine is the most phosphorus- and nitrogenrich fertilizer except from mineral fertilizer.

Capacity of the fertilizer products

Regarding the urine flow, estimations of its potential has been done for Switzerland as well as the entire European Union, EU. About 37% of the nitrogen demand and 20% of the phosphorus demand, which is currently met by mineral fertilizers in Switzerland, could be replaced by urine (Larsen & Lienert 2007). Of the fertilizer consumption in the European Union, 12% of the nitrogen demand and 6% of the phosphorus demand could be met by nutrients recovered from urine. The smaller percentages for the EU are indicating that there currently is an excess supply of nutrients to arable land in the European agriculture (Maurer et al. 2003). The averaged value of phosphorus supply to arable land, used in the MFA, was 7 kg of phosphorus per hectare. Assuming that the urine produced per year in Gothenburg contains 98.1 ton of phosphorus and could be used to 100% as fertilizer, then about 14000 ha of arable land could be supplied. In 2009, the yield of wheat was about 5 ton per hectare in the county of Västra Götaland (SCB 2010b). This figure indicates that about 70000 ton of wheat could be produced from the urine fertilized fields. According to statistics, an inhabitant in Sweden consumes 80 kg of wheat per year (FAO 2010). Subsequently, the urine-fertilized wheat fields could supply all inhabitants in the co-owning municipalities of Renova, Figure 7, with their annual consumption of wheat.

5.3.2 QUALITATIVE ASPECTS

The qualitative aspects that are investigated in this section are first and foremost the plant availability of the nutrients in the fertilizer products from the various wastewater systems. Furthermore, the risk of micropollutants in the fertilizing fractions is emphasized.

Plant availability of phosphorus in fertilizer products

In Table 21, a comparison between mineral fertilizers and different alternative fertilizer products regarding the NPK-relation is shown. The mineral fertilizer chosen as reference is NPK 27-3-5, since it was the most sold fertilizer product in year 2008/2009 (SJV 2010b). The nitrogen and phosphorus values in the table below are the plant-available amounts, while all potassium is assumed to be plant-available.

Table 21. Concentration and NPK-relation of plant-available nutrients in different kind of fertilizers (wet matter) [[1](SJV 2010b), [2](Gryaab 2010b), [3] (Jönsson et al. 2005), [4](JTI 2006), [5](Winker et al. 2009)].

Type of fertilizer	Nitrogen (g/kg)	Phosphorus (g/kg)	Potassium (g/kg)	NPK-relation
Mineral fertilizer (NPK)[1]	270	30	50	**27-3-5**
WW sludge from Rya[2]	3.2	0.3	0.6	**21-2-4**
Urine[3]	6.87	0.54	1.6	**27-2-6**
FW sludge[4]	1.9	0.25	1.1	**20-2-9**
Compost[5]	**-**	-	-	**1-3-5**

Since the ambition is to decrease the use of commercial fertilizer, it is of crucial interest to have a large amount of plant-available nutrients in the fertilizer products obtained from the new scenarios. Depending on if the compounds are bound to carbon or are in mineral form, the plant availability of them differs. The products from the alternative systems: urine as well as blackwater and organic waste, have high potential as plant nutrient resources (Winker et al. 2009).

Commercial fertilizers are considered to have 100% plant availability of phosphorus, nitrogen and potassium (Jönsson, pers. comm.). A blackwater-based fertilizer product in the form of digested sludge contains all nutrients. Smaller losses of nitrogen occur during production of biogas, but on the other hand anaerobic digestion increases the mineralization of organic nitrogen (Winker et al. 2009). The study in Skogaberg, Gothenburg with kitchen grinders showed that 80% of the phosphorus was in the form of plant-available phosphates from the wastewater containing blackwater and ground food (Karlsson et al. 2008). In 2009, only 4% of the total phosphorus was considered plant available in the sewage sludge from the WWTP of Rya (Gryaab 2010b), Table 21. For potassium the plant availability is considered to be 100%. All ammonia, nitrate and nitrite in sewage sludge are plant-available, but a substantial amount of ammonia is lost during storage and spreading (Jönsson, pers. comm.). Plant availability of phosphorus in human urine is high: comparable with mineral fertilizers (Vinnerås & Jönsson 2002). Also all potassium and sulfur found in urine are plant-available (Jönsson, pers. comm.). In urine, at least 95% of the nitrogen is plant-available, but 5-10% is lost during storage and spreading on fields (Johansson et al. 2000). Experiments have shown that crop yields are more or less identical regardless of whether they have been treated with mineral fertilizer or urine (Peter-Frölich et al. 2007).

The different relationships between plant availability of nutrients in urine and blackwater have to be analyzed in the final product before spreading it. It is also impossible to state a specific proportion of macronutrients that are needed for plants, since all plants require different ones. For a successful usage of those "new" fertilizer products, they have to be adjusted to the current application techniques in agriculture.

Risk of micropollutants

Urine is close to free from toxic heavy metals (Vinnerås 2001). If urine is separately collected and used as fertilizer, the input of heavy metals in general, and the disputed cadmium in particular, to agriculture could be remarkably decreased compared to if sewage sludge or digested sludge from combined systems is spread (Remy & Jekel 2008). On the other hand, human urine contains ingested pharmaceuticals and hormones (Lienert et al. 2007). If these substances are polar and hardly biodegradable, they can be taken up by plants and thereafter enter the human food chain. The load of hormones and antibiotics in human urine is, however, much lower than the one in animal manure, that is commonly used as crop fertilizer today (Winker 2010). Furthermore, urine contains hardly any pathogens compared to blackwater, but the pathogens in blackwater can be eliminated by hygienization, e.g. addition of urea or ammonia (Winker et al. 2009).

The blackwater fraction is not as pure as the urine. In the semi-centralized scenario, it is separated from the greywater and thereby less polluted, since the main amount of heavy metals (Vinnerås 2001) and pollutants, with origin in personal care and households products, can be found in the household greywater (Hernandez 2010). The blackwater from the semi-centralized systems will also be free from all micropollutants from stormwater, which is loaded with heavy metals, organic compounds and pesticides originating in vehicle traffic, metal leaching and horticulture (Lamprea & Ruban 2008).

5.4 VARIOUS ASPECTS OF THE ALTERNATIVE SCENARIOS

Infrastructural changes for the future do have many aspects. This thesis mainly focuses on the nutrient management and how to deal with the phosphorus flows to make them more cyclic and sustainable. The analysis mainly concentrates on the fertilizing aspects, section 5.3. However, sustainability interconnects with several fields and to put the nutrient management in a more realistic context, also the environmental, technical and economic aspects from earlier published literature will be presented briefly.

5.4.1 ENVIRONMENTAL ASPECTS

A possible installation of an alternative wastewater system will affect the environment in Gothenburg in both positive and negative ways. There are several researchers to state that the specific choice of technology for diversion has large influence on the results and the environmental benefits of the certain technology (Larsen et al. 2009, Remy & Jekel 2008). Diversion systems are not per se more sustainable than the conventional systems currently used. One lifecycle assessment study, among several, indicated that a specific diversion system had the lowest impact regarding all indicators[7] except acidification (Remy & Jekel 2008).

Burden on aquatic environment

Input of phosphorus and nitrogen from wastewater plays a crucial role with regard to water resources and the risk of eutrophication in particular. Wastewater flows are normally large in densely populated regions. The recovery and recycling of nutrients in these flows are important on the way towards sustainability (Larsen & Lienert 2007). A urine diversion system would reduce the nutrient load to the WWTP of Rya and thereby possibly reduce the eutrophication in ground- and surface water (GTZ 2006). It would also diminish the load of pharmaceuticals and hormones on the aquatic environment by preventing these substances to reach the rest of the wastewater flows (Larsen & Lienert 2007).

The biological treatment is space-requiring and this aspect is then very significant for a centralized treatment plant with limited area. If the blackwater can be diverted away from the WWTP of Rya, the burden on the biological treatment could be much lighter due to reduced input of phosphorus and nitrogen as well as organic material. Probably, also the chemical treatment could be reduced and thereby the annual consumption of chemicals. The semi-centralized scenarios would imply such relief, while the centralized scenario with kitchen grinders would rather contribute in the opposite direction and negatively affect the aquatic environment. In the kitchen grinder project at Surahammar, no sewer overflows have appeared after the grinders were installed (Karlberg & Norin 1999). However, the WWTP of Rya has occasionally already today sewer overflows (SR 2011) and since kitchen grinders will increase the sewer loads and the risk of pipe blockages, the sewer overflows could increase as well. Furthermore, the pollution management at the WWTP of Rya can be simplified by implementing a semi-centralized system (Winker et al. 2009).

Energy

The energy consumption for new wastewater treatment systems should preferably be lowered compared to the current situation (Peter-Frölich et al. 2007). A model study has shown that processes for integrated treatment of urine and wastewater could be implemented to be much more energy-efficient and compact than the systems today. The conclusion of this study was, consequently, that the main advantage of urine separation is the savings in resources rather than the better effluent quality (Wilsenach & van Loosdrecht 2006). Other studies have underlined that in many cases, recovery of nutrients in urine is energetically more efficient than removal and new-production from natural resources (Jönsson 2002, Maurer et al. 2003).

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[7] cumulated energy demand; abiotic resource depletion, global warming and eutrophication potentials; freshwater aquatic, terrestrial and human toxicity potentials

In both the semi-centralized scenarios as well as in the centralized scenario with urine diversion, it will be additional transports of "products" compared to the current situation. Firstly, the urine is collected in tanks that must be emptied one or more times per year and transported to the site where it is to be spread on productive land. Secondly, the semi-centralized scenarios have fecal wastewater in combination with food waste to transport to the biogas plant and then further on to final users of biogas and digested sludge. The food waste that today is transported to Borås and Kristianstad, among others (Fahlgren 2011), could have reduced transport distances if the biogas plants are built more locally. For large flows and short transport distances of substrates and products from biogas production, pipes can be an alternative to vehicle transport. However, the texture of fecal wastewater and digested sludge makes the piping quickly difficult and more expensive than transport on road (SWM 2010). Even if transports are costly, actors are encouraged to cooperate and build common plants in order to reduce operating costs (SWM 2011a).

Material for manufacturing of grinders, toilets, pipes and tanks, as well as, transport and installation of material will cause a temporary larger energy use for all alternative systems. However, it has been shown that operation costs for well designed new sanitation systems are significantly lower than for the current ones, especially in combination with biogas, which in the long-term will be reinforced (Peter-Frölich et al. 2007).

In all the scenarios, except the centralized urine diversion system, the potential of biogas production is expected to increase since more organic waste is added to the process. Furthermore, a blackwater fraction with ground food waste could be readily recycled via a wastewater system to municipal anaerobic digesters, and thence to agricultural land (Dawson & Hilton 2011). An increased production of biogas is a source of income, since biogas is attractive on the market as renewable fuel. Recently, it was stated that:"*By using food waste, industrial waste and sewage sludge from WWTPs, we could supply all the buses in Sweden today with biogas as fuel*." [8] (Börjesson 2011). An increased recycling of digested sludge would also imply decreased mining of phosphorus ores. Energy is required in large amounts to produce nitrogen fertilizers (Winker et al. 2009), so there will be a lighter energy burden on the environment by using fertilizers produced in the alternative systems (Jönsson et al. 2005).

5.4.2 TECHNICAL ASPECTS

Both the scenarios with kitchen grinders and urine-diverting toilets imply installation of new techniques and material. New techniques are always more challenging than the well-known old ones. Even though new technology is accompanied by risks, there is also a belief in an increased easiness and efficiency. Furthermore, the new ideas aim to result in better environmental and economic effects, both in the short and long run.

Risk of sewer overflow and blockages

Kitchen grinders are banned by environmental laws in some European countries, including Austria, the Netherlands and Belgium. The concerns mentioned are that kitchen grinders could cause problems in sewers and wastewater treatment plants due to increased numbers of blockages, odor complaints and also the risk of increased pollution from sewer overflow (Thomas 2010).

In the scenario with urine diversion, blockages can occur in the piping from the urine-diverting toilets. Therefore, this piping needs some more maintenance than conventional piping. The blockages are results of fibres and other particles entering the piping system as well as chemical precipitation of struvite and calcium phosphates from the urine caused by the increased pH, which occurs when urea is degraded. As a precaution against blockage in the piping system, it is recommended that one liter of water is flushed down the toilet pipe once or twice a week as well as cleaning by caustic soda in the toilet about twice a year (Kvarnström et al. 2006).

[8] To supply all buses in Sweden today, 3.5 TWh biogas would be needed, but currently only 7% of them are supplied by gas (also including natural gas). Estimations state that 0.8 TWh from household waste, 1.1 TWh from industrial waste and increased production from wastewater treatment plants of 1 TWh could be obtained (Börjesson, pers. comm.).

Pipe diameters depend on which wastewater flow that is conducted within them, and to avoid metal leaching, plastic materials are advocated (Kvarnström et al. 2006). The more viscous a flow is the harder to transport it by pipes. The semi-centralized scenarios have short transport distances with pipes and then a transport system by vehicles for longer distances instead. The piping system in the house is driven by gravity. Alternative systems with vacuum do exist, but are not treated in this thesis.

Convenience of treatment method

One advantage of separated wastewater systems is the easier treatment of each fraction. Since the different wastewater fractions have different characteristics, as mentioned in section 2.2, a more specific treatment method can be chosen for each of them when they are separated. A urine fraction can be hygienized by storage (Kvarnström et al. 2006), ozone or UV light (Remy & Jekel 2008). For instance, ozonation that removes microorganisms would never work for an opaque combined wastewater fraction with a high turbidity. Furthermore, the greywater, stormwater and industrial wastewater can be easier treated at the centralized WWTP of Rya if the blackwater fraction is redirected. Probably, the biological treatment could be significantly reduced. The redirection of blackwater and consequently the reduced load on important process step would probably improve both treatment efficiency and effluent quality at the WWTP of Rya.

On the other hand, the digested sludge produced in biogas production must be treated in one way or another. The digested sludge contains phosphorus and nitrogen, but also large amounts of water. It is tempting to further process the digested sludge due to the low nutrient concentrations. However, the low concentration of nutrients also requires low input of resources if the process shall be economically viable. It has been stated that if the digested sludge can be used on farmlands in the surroundings to the production site, it is hard to find argument to thicken and further process the digested sludge even if the nutrient concentrations are low. If the digested sludge, however, is to be further processed, thickening by lime, stripping of ammonium and thereafter biological treatment of the residue seems like the most promising treatment procedure due to relatively low operating costs (SWM 2011b).

5.4.3 ECONOMIC ASPECTS

The economic feasibility plays a crucial role when talking about alternative solutions towards recirculation of nutrients from wastewater. It has been stated that phosphorus recovery cannot be motivated purely by the revenue from sale of phosphorus, and that: *"in order to imply phosphorus recovery, different actions must be introduced as development of more cost-effective strategies and technologies for phosphorus recovery, legal and regulatory requirements, and "green" taxes on phosphorus use and discharge."* (Hultman et al. 2003). The phosphorus recovery must be set in the context of other issues in the society and it has been said that: *"the difficult question is whether recovery of the resource phosphorus is worthwhile when economy and the consumption of other resources also are considered"*. It was underlined that, strictly economically, the recovery is not worthwhile, although several other aspects also need to be considered (Balmer 2004). As a suggestion, advantages such as improved environment, food security for households and safer handling of a waste flow from the household should be weighed against purely economic costs (Kvarnström et al. 2006). Also, a project in Berlin studied a residential area and concluded that the total project costs were not lower for new sanitary concepts than for conventional ones within a period of 50 years. The operational costs were lower for the new technologies, but offset by the installation costs (Peter-Frölich et al. 2007). When doing the economical investigation it is important to take into account that a new technology cannot fairly be compared to a well established one. The market price for the components needed by a new technology will probably decrease when its products are out on the broader market.

6. Discussion

The discussion will mainly focus on the Material Flow Analysis, the potential of the investigated alternative wastewater systems as well as the importance and power of the current environmental quality objectives. In the end of the chapter, also suggestions for further studies will be presented.

6.1 Material Flow Analysis

When performing a Material Flow Analysis, the system needs to be clearly specified both spatially and temporally. The authors of this master thesis chose the urban municipality of Gothenburg as spatial system. This choice implied an almost total ignorance of the effect of agriculture on the phosphorus cycle. Agriculture is a major actor in the anthropogenic cycle of phosphorus (Brunner 2010), which needs to be kept in mind when analyzing the results from a local urban study such as this one. The choice of Gothenburg also implied a study of a location that imports waste and wastewater from its surroundings. The reduced impact of agriculture and the increased impact of waste and wastewater import are also effects of choosing to work with a system on a local scale. For instance, if the county of Västra Götaland, to which Gothenburg belongs, or Sweden as a country had been studied instead, differences would have occurred (Sokka et al. 2004), since the proportion of agricultural land used for production, for instance, varies with the system scale.

The year 2009 was chosen mainly based on two arguments. Firstly, the data should be as up to date as possible. Secondly, the data should be as easily available as possible. The annual reports as well as the environmental reports from companies are normally not released before March/April the year later. Since this master thesis was started already in January 2011, year 2009 was judged as the best choice of temporal system boundary. However, what has to be mentioned is that 2009 differs in at least two ways compared to the current situation in 2011. First of all, the waste treatment company Renova imported a larger amount of combustible waste from outside of the co-owning municipalities than normally, due to reduced waste generation in the Gothenburg area caused by the financial crisis in 2008. Most of the waste came from Norway, where the alternative to incineration was judged less sustainable (Bondesson 2011). Furthermore, Renova has decided to invest in food waste treatment with biogas production instead of composting. Therefore, the compost flow from Renova in the MFA is actually already outdated.

A MFA must have a specific substance or goods to track. In this master thesis, a tracking of phosphorus has been performed while the accompanying flows of nitrogen only have been estimated to a certain extent. The main causes of the tracking of phosphorus is the underlying interest in the importance of the Swedish environmental quality objective concerning reuse of phosphorus in sewage sludge and the connection to other research projects at the department at which the thesis has been written. Since the most interesting reason to nutrient recycling must be the potential of substituting mineral fertilizers with recycled fertilizer products, a complete picture of the potential could only have been drawn if also the nitrogen and potassium flows were fully tracked. Now, the potential of recycled fertilizer products have to be discussed based on the phosphorus content as well as earlier published proportions of the three most important macronutrients in the output flows from the system instead.

When analyzing material flows in the same size as of phosphorus in this thesis, uncertainties are important to be aware of. No values have been measured by the authors themselves, so depending on the sources, the values differ in reliability. The specific flows and their uncertainty will be discussed further on and are summarized in Appendix C. However, the general tendencies in the current MFA and the order of magnitude for each flow are judged to be reliable. The overall balance is acceptable with only a marginal difference between the inflows and outflows. On the other hand, the balance over the WTP differs, which might be explained by underestimated internal flows of food waste, offal and bones, as well as of agricultural and horticultural waste. The underestimated input to the WTP is in Figure 8, shown as *"Unspecified source of P"*.

6.1.1 Input flows

Earlier published MFAs have agreed upon that the most important input of phosphorus to an urban region is the food supply to the population living there (Schmid Neset et al. 2010, Sörenby 2010, Tangsubkul et al. 2005, Faerge et al. 2001, Burström et al. 1997, Nilsson 1995). Also in this master thesis, the MFA shows that the largest phosphorus flow into the system is the food, about 60% of the total input. This is not surprising, since Gothenburg is a densely populated area, which requires large amounts of food and the opportunities to get locally produced food from the system are very limited, due to the small amount of arable land. Furthermore, the high content of phosphorus in food is expected, since plants require phosphorus during growth and embed it in their structures.

The phosphorus flow via consumed food is not interesting to discuss from a point a view that it should or could decrease, since the population in Gothenburg is likely to grow in the coming years. The administration of the municipality of Gothenburg has estimated a population of 592900 inhabitants in 2025 (GR 2010), which is an increase of 17% compared to year 2009. A population growth will result in a larger phosphorus flow via food, unless the phosphorus content in diets will decrease. However, the phosphorus flow in food waste should preferably diminish and thereby also the food input.

The assumption that people in Gothenburg consume similar amounts of phosphorus via the diet as the adult population of Malmö is made on the basis that those cities have a similar mixture of people and distribution of gender and nationalities. Additionally, the places are both urban areas. However, it can be questioned if the phosphorus intake used in the MFA should have taken the variances in phosphorus intake with age into account. For instance, children and old persons do probably consume a bit less phosphorus than the average adult. It should also be mentioned that the gender distribution has not been taken into account for nitrogen.

In the MFA of the current system, all food consumed in the region is assumed to be processed outside the boundaries. This is an approximation, since some of the food processing companies, Arla Foods AB and Pågen AB among others, are situated in the municipality of Gothenburg. However, it is difficult to estimate the quantity of the phosphorus flows from food industries inside the system. The assumption that has been done, that all food produced inside the system is exported and then can be imported back for consumption, is mainly supported by the argument that the majority of all consumed food within the system is produced elsewhere. The loss from the dairy industry to the wastewater system is however taken into account.

The second largest input flow of phosphorus to the system is the imported waste from 10 surrounding municipalities as well as from Norway, about 15% of the total input. The value is uncertain, but still showing a reasonable tendency. The phosphorus content in the imported waste is based on statistics of the fractions of various waste in the household as well as business waste. There is no registration at the waste treatment plant of what kind of waste that is received as combustible waste as long as it is not classified as hazardous. The input of combustible waste to this system is abnormally high due to the hosting of a co-owned waste-fuelled heating power plant.

6.1.2 Output flows

In Sweden, the major flow of phosphorus in earlier published MFAs has been sewage sludge mainly heading to landfills (Nilsson 1995, Schmid Neset et al. 2010, Burström et al. 1997) as well as to compost for horticultural and infrastructural use (Sörenby 2010). Digested sludge, which is composted for infrastructural use, and ashes to disposal are by far the most significant output flows in the MFA performed in this master thesis. The digested sludge contains 330 ton of phosphorus and the ashes contain about 350 ton of phosphorus.

Several earlier studies have shown that the phosphorus from food consumption mainly ends up in wastewater. A MFA of the municipal wastewater and waste system in Finland has shown that about 0.9

kg of phosphorus per person and year is emitted to the wastewater and one person annually gives off 0.2 kg of phosphorus into solid waste (Sokka et al. 2004), which equals a ratio of 9 to 2. In this thesis, the corresponding values become 0.6 kg of phosphorus per person and year[9] via wastewater and 0.3 kg of phosphorus per person and year[10] via solid waste. The ratio would then be 2 to 1 which differs a bit from the earlier study. The difference in phosphorus concentration in wastewater might be explained, at least partly, by the fact that runoff from rural areas is included in the Finnish study and that phosphorus is still commonly used in detergents in Finland. Since agriculture is a main contributor to phosphorus emissions to watercourses, the increased value per capita is probably due to the agricultural runoff. The amount of phosphorus per capita in ashes is a bit higher in this thesis compared to the earlier study, which might be discussed. The statistics and the MFA tell that a significantly large amount of food waste is incinerated in Gothenburg. Since the capacity of the waste-fuelled heating power plant of Sävenäs is large, probably more organic waste is incinerated than at most other places, where it could be separated instead. All of the phosphorus in the ashes is not fully tracked to its origins. It is possible that some sources to phosphorus in combustible waste have been forgotten, but it is also a possibility that the measurements of the phosphorus concentrations in the ash are not that reliable. The amounts of combustible waste are enormous and since only twelve samples have been taken, the value should be regarded as relatively uncertain. Nevertheless, it is clear that a lot of the phosphorus entering Gothenburg ends up in the ashes and that the order of magnitude of the value should be respected.

The relative content of phosphorus in digested sludge and ashes might be considered when determining whether the focus of nutrient recovery should be put on sludge or also on ashes. Even though the content of phosphorus in ash is excessive for Gothenburg, it is important to put this flow in focus in this certain region. It becomes clear when MFAs of phosphorus flows are performed, that even if complete recycling of sewage and solid waste took place, it would not have the capacity to solve the phosphorus scarcity problem alone but it will surely have an impact on the need for imported fertilizers. Additional infrastructural systems than the wastewater treatment systems need accordingly revision and reformation if a sustainable development shall take place.

6.2 Alternative wastewater systems

From a nutrient management policy perspective, if there are viable measures to recover and reuse phosphate that can now be identified and implemented it is surely better to do so, irrespective of the rate at which reserves may be running out (Dawson & Hilton 2011). This master thesis examines two different wastewater system technologies in two scenarios each. Since the main driving force to examine these alternative systems has been to increase the recycling of nutrients in general and phosphorus in particular, they are evaluated and discussed mainly based on their potential of producing fertilizer products. Furthermore, the amount of phosphorus should be minimized in the bad quality flows, particularly in the aquatic deposition, but also in the ashes where phosphorus is still difficult to extract and less plant-available. Finally, the burden on the centralized WWTP of Rya should preferably be lighter and the alternative technology sustainable and easily operated.

6.2.1 Potential of alternative fertilizer products

In section 5.3, the qualities of fertilizer products from the various wastewater system scenarios were presented. The goal with a new alternative wastewater system is to obtain an outcome that can be acceptably recycled from urban areas to productive land. This outcome shall replace mineral fertilizers to as large extent as possible in order to reduce the phosphorus mining. The phosphorus-containing outcome should preferable have a composition of nitrogen, phosphorus and potassium that is similar to the powerful mineral fertilizers used in the agriculture today. Table 21 shows very good results for urine,

[9] About 370 ton of phosphorus in sewage sludge and about 650 000 inhabitants connected to the WWTP of Rya.
[10] About 260 ton of phosphorus in ashes and about 1 000 000 inhabitants served by the waste treatment company Renova.

based on the proportion between the three important macronutrients. Especially, the content of plant-available nitrogen is higher in urine compared to the other alternative fertilizer products.

Urine is close to free from toxic heavy metals, which are one of the most feared threats when spreading the currently produced WW sludge from centralized WWTPs with combined sewer system. On the other hand, urine contains ingested pharmaceuticals and hormones. To what extent that this pharmaceutical load does affect the soil and plants is still not fully understood, but what is known is that the animal manure spread today contains more hormones and antibiotics than human urine (Winker 2010). Additionally, the urine is today part of the WW sludge from centralized WWTPs, so the difference in pharmaceutical load to use WW sludge compared to use pure urine should probably not change qualitatively. Finally, the main content of pathogens from humans is excreted in the feces and not in the urine. However, the fecal wastewater contains fewer pollutants if it is separately collected than if it is combined with greywater and stormwater.

The main advantage of BW+FW sludge compared to the WW sludge from the WWTP of Rya is chiefly that the two kinds of digested sludge are based on more or less separated wastewater fractions, containing more or less micropollutants and nutrients. As can be seen in Table 21, the nutrient proportions and the nitrogen content in particular are much better for the FW digested sludge than for both the compost as well as the untreated food waste. The drawback with BW+FW sludge is that it is less concentrated than both urine and WW sludge.

6.2.2 WAYS TO DECREASE THE LOSSES OF PHOSPHORUS

In section 5.3, the quantities of phosphorus-containing output flows from the various wastewater system scenarios were presented. Figure 10 presents both the qualities and the quantities, and it can clearly be seen that the flow in which phosphorus is less welcome is in the aquatic deposition. This is due to the fact that phosphorus will be practically lost forever by entering the oceans and that it causes serious eutrophication (Dawson & Hilton 2011). Secondly, there are no well-established technologies to extract phosphorus from municipal solid waste ashes today. Therefore, it is reasonable to avoid capturing as large amounts of phosphorus as possible in the ashes. An additional argument for this avoidance is that the ashes today only are put on landfill after incineration, the least favored way of waste management according to the Waste Framework Directive of the EU (EU 2008).

The aquatic deposition does change by installing the alternative wastewater systems, presented in this thesis. The semi-centralized scenarios favor the environment by their decreased burden on the centralized WWTP of Rya as well as on the combined sewer system. As can be seen in Figure 10, the content of phosphorus in ashes diminishes when food waste is redirected from combustible solid waste to either the blackwater fraction, as in the scenarios with kitchen grinders, or directly to the anaerobic digester for fecal wastewater in the semi-centralized scenario with urine diversion. On the one hand, the food waste should be treated separately from other combustible solid waste, and on the other, it should preferably diminish. The latter statement will be further discussed in section 6.4.

In Figure 10, the same amount of phosphorus can be diverted away from the ashes in the both the semi-centralized kitchen grinder scenario and the semi-centralized urine-diverting scenario with food waste. However, the estimation that 80% of the phosphorus in the food waste can be ground is probably overestimated since bones and shells that are phosphorus-rich cannot be ground. Therefore, the semi-centralized urine-diverting scenario with food waste is probably the best choice regarding management of phosphorus in waste and wastewater systems.

6.2.3 Simple and sustainable technology is desirable

The purely technological aspects have not been studied in depth in this master thesis. However, the operation and maintenance of the systems, both the current one and the alternative ones, should in preference be easily handled. The diverting systems, all alternative ones except the centralized scenario with kitchen grinders, do decrease the treatment burden on the centralized WWTP of Rya. As the nutrient and organic loads diminish, the need of biological treatment at the WWTP diminishes rapidly as well. The more the fractions are separated, the easier the handling and treatment of them each is. For instance, separated nutrient-rich urine can be hygienized only by storage, which is impossible for the rest of the wastewater fractions.

It is of high importance that a technology, which is to be broadly implemented in the society, is easy to operate and to support with maintenance. As an example, the kitchen grinder or the urine-diverting toilet needs to work efficiently independently of the technological skills of the user. Since both the just mentioned equipments are used already today, there would probably not be any large problem to install them in Gothenburg. However, the questions concerning sewer system and transports are trickier to solve, since it is the way from toilet or sink to field that is the less experienced part. For sure, the keep-going of the current system would still be the easiest way out for another decade or two. The question is whether it would be simpler to install a new wastewater system already today with a quite generous time margin or if it is easier to wait until the deadline approaches. Of course, it must also be asked whether the wastewater system is the best infrastructural system to invest in, in order to improve the nutrient management in our society.

6.3 Environmental quality objectives

The Swedish environmental interim target regarding recycling of 60% of the phosphorus in wastewater to productive land in 2015, concerns the amount of phosphorus today caught in the WW sludge from the WWTP of Rya. Of the input of phosphorus to the municipality of Gothenburg, about 45% is leaving the system via the digested sludge. It implies that 200-330 ton of phosphorus in total can be recycled annually, if the set objective is reached. A recycling of 200 ton of phosphorus via reuse of wastewater implies a recycling of about 25% of the phosphorus that annually flows through Gothenburg. Even if the environmental target is reached, still a lot of phosphorus will be left non-recycled, especially caught in the ashes. Instead of improving the extraction technologies from sludge or ashes, diversion and less loss, particularly in the form of food waste, would favorably be encouraged. The two targets concerning recovery of food waste, mentioned in section 2.1.3, are steps in the right direction.

The eutrophication caused by phosphorus and nitrogen emissions has decreased as the society has become aware of the problem. However, the problem does still exist and the environmental quality objective in 2010 regarding eutrophication by phosphorus emissions was not reached. The goal was a decrease of at least 20% of Swedish waterborne anthropogenic emissions of phosphorus compounds into lakes, streams and coastal waters compared to in 1995, but the actual reduction was only 13% (EPA 2011). The aquatic deposition from the system of Gothenburg is low, however not zero and also higher than in many other Swedish cities (Jönsson, pers. comm.). Of the input of phosphorus to the system, about 7% leaves it via aquatic deposition. In earlier published MFA studies from Sydney and Bangkok, the major flows of phosphorus out from the system went directly to the aquatic environment (Faerge et al. 2001, Tangsubkul et al. 2005). It can be concluded that Swedish cities are a lot more active in the work against eutrophication than in the studied cities mentioned above. In 2009, the WWTP of Rya emitted phosphorus to the aquatic environment below the limit, but nitrogen above the limit. Diverting systems would probably enhance the work towards zero eutrophication, since they could decrease the nutrient load on the WWTP and allow the best treatment method for each wastewater fraction.

The choice of producing biogas in the alternative wastewater scenarios presented in this master thesis as well as the investment in biogas production instead of composting at the waste treatment company

Renova, are steps in the same direction. The new waste management plan for the region of Gothenburg, A2020, emphasizes the benefits of biogas production by their goal of treating all separately collected food waste, at least 50% of all food waste, via anaerobic digestion. The easiness of grinding food waste directly in the sink with kitchen grinders could probably help the work towards the goal to sort out food waste from the municipal solid waste. However, the fact that the most phosphorus-rich parts cannot be ground is contradictory. An argument for the semi-centralized urine diverting scenario would be fertilizer products of two good qualities: the concentrated and pure urine as well as the nutrient-enriched BW+FW sludge. The authors of this master thesis encourage the initiative taken by the region of Gothenburg to create a key performance indicator that will indicate how big percentage of the mineral phosphorus that is substituted by recycled phosphorus from food and toilet waste but it ought to be supplemented by a simliar indicator for nitrogen.

6.4 FURTHER STUDIES

The phosphorus content in ash is a large output flow in the MFA of Gothenburg. This fact definitely need more research in terms of analyzing more deeply the origins of the phosphorus in solid waste in order to prevent the nutrient to be caught in the ashes. First the source separating of the incoming waste should be improved, with the food waste going to anaerobic digestion. For phosphorus that anyway ends up in the ashes, it is of great interest to find methods to extract phosphorus from the ashes and learn how to obtain it as plant-available phosphorus. Such a technology is not yet in use, but would be of importance for the future and the work towards sustainable phosphorus management, given that a lot of phosphorus is continued to be incinerated and provided that the recovery method will be resource efficient.

In this report only a very short outlook of the economy was performed. The authors chose to keep this short on the basis that a well-planned, realistic and structured economic analysis needs more time and financial knowledge. To implement a new alternative wastewater system in the municipality of Gothenburg would be a costly activity, but in a detailed economic analysis it is important to keep in mind what potential incomes that will arise from the new system. It is also important to value the environmental benefits of changing the wastewater system.

An extended investigation of how to solve the questions about the transportation of products from the semi-centralized solutions would also be needed. Furthermore, the most sustainable way to environmentally, economically and technically construct and operate the treatment plants with biogas production needs to be found. For instance, the optimal density of such treatment plants for separated blackwater and food waste is interesting to analyze.

Loss of phosphorus from the human food chain must be minimized. This can be achieved by more efficient use in agriculture and reduced waste as well as by incentivizing recovery and reuse the whole way down to consumer level (Dawson & Hilton 2011). It would be of great interest to map the consumption patterns from which food waste to a large extent arise, but this is beyond the objectives of this thesis. However, from 1999 to 2009, the amount of household waste increased with 20% (SWM 2011c) in Sweden and it is shown in the flow calculations for the alternative scenarios in this thesis that a lot of food could be taken care of in better ways. According to the new waste management plan, it is ten times more efficient to prevent food waste than to produce biogas from it (GR 2010). It is a challenge to find out how to encourage the population to respect food as the valuable resource it really is. Such a change can only be achieved by changed habits among the population.

7. CONCLUSIONS

- The largest input flows of phosphorus to the system of Gothenburg are those of food and imported waste. They make up about 60% and 15%, respectively, of the total input. The importance of food was expected, but the significance of imported waste is abnormally high for Gothenburg compared to most other municipalities.
- About 45% of the phosphorus that goes into the system of Gothenburg ends up in the digested sewage sludge from the WWTP of Rya today.
- The content of phosphorus in the ashes produced at the waste-fuelled heating power plant of Sävenäs is in the same order as the digested sludge produced at the wastewater treatment plant of Rya. This distribution is unusual and indicates that the ashes and waste system also need to be highlighted in the nutrient management in Gothenburg.
- The Swedish environmental quality objective that concerns recycling of at least 60% of the phosphorus in wastewater back to productive land in 2015, only deals with about 25% of the total phosphorus coming into Gothenburg.
- About 7% of the phosphorus going out from the system is heading to the aquatic environment. However, this value should desirably go to zero, since phosphorus dispersed in seas causes serious eutrophication and is practically lost phosphorus.
- Among the alternative wastewater systems that have been analyzed, the semi-centralized one with urine diversion seems most prospective. The reasons for this assessment are less phosphorus captured in ashes heading to landfill, a lighter burden on the WWTP of Rya already working at high capacity and the possibility to co-produce energy in the high value form of biogas. Additionally, the semi-centralized alternative with urine-diverting toilets offers less polluted fertilizer products with good nutrient proportions to return to productive land. The fertilizer products are mainly in the form of urine, but also in the form of BW+FW sludge based on fecal wastewater and separately collected food waste. However, the costs of this wastewater system technology need to be further studied.

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APPENDIX A: CALCULATIONS TO THE MFA OF THE SYSTEM TODAY

Atmospheric deposition

$$Average\ amount\ of\ phosphorus\ in\ to\ the\ system\ by\ atmospheric\ deposition:$$
$$(44\ [\%] * 1029 * 10^6)\ [m^2] * \frac{5.8}{10^9}\left[\frac{ton}{(m^2 * y)}\right] = 2.6 \approx 3\ [\frac{ton\ P}{y}]$$
$$Average\ amount\ of\ nitrogen\ in\ to\ the\ system\ from\ nitrate\ by\ atmospheric\ deposition:$$
$$22.60[\%] * \frac{0.36}{10^7}\left[\frac{ton}{m^3}\right] * \frac{855}{10^2}[m] * (44\ [\%] * 1029 * 10^6)[m^2] = 32\ [\frac{ton\ N}{y}]$$
$$Average\ amount\ of\ nitrogen\ into\ the\ system\ from\ ammonium\ by\ atmospheric\ deposition:$$
$$77.66[\%] * \frac{0.45}{10^7}\left[\frac{ton}{m^3}\right] * \frac{855}{10^2}[m] * (44\ [\%] * 1029 * 10^6)[m^2] = 135\ [\frac{ton\ N}{y}]$$
$$Total\ amount\ of\ nitrogen\ in\ atmospheric\ deposition: 32 + 135 = 167 \approx 170\ [\frac{ton\ N}{y}]$$

Food

$$Phosphorus\ in\ maximum\ local\ food\ production:$$
$$684\ [ha] * 5\ \left[\frac{ton\ cereal}{ha * y}\right] * 0.004\ \left[\frac{ton\ P}{ton\ cereal}\right] = 14\ \left[\frac{ton\ P}{y}\right]$$

$$population\ in\ Gothenburg\ connected\ to\ the\ WWTP\ of\ Rya:$$
$$Total: 99[\%] * 506730\ [cap] = 501663[cap]$$
$$99[\%] * 255570[women] = 253014[women]$$
$$99[\%] * 251160[men] = 248648[men]$$
$$Percentage\ women: \frac{255570}{501663} = 50.44\ [\%]$$
$$Percentage\ men: \frac{251160}{501663} = 49.56\ [\%]$$
$$population\ connected, \boldsymbol{not}\ including\ Gothenburg\ municipal:$$
$$Total: 649352\ [cap] - 501663\ [cap] = 147689\ [cap]$$
$$50.44\ [\%] * 147689\ [women] = 74494[women],\ 49.56\ [\%] * 147689[men] = 73195[men]$$
$$Pintake\ for\ women: \frac{1182}{10^6}\left[\frac{kgP}{day}\right] * 365\ [days] = 0.43143\ [\frac{kgP}{yr}]$$
$$Pintake\ for\ men: \frac{1505}{10^6}[\frac{kgP}{day}] * 365\ [days] = 0.54933\ [\frac{kgP}{yr}]$$
$$Pconsumption\ in\ Gothenburg:$$
$$\frac{\left(0.43143\ [\frac{kgP}{yr}] * 253014[women]\right) + \left(0.54933\ [\frac{kgP}{yr}] * 248648[men]\right)}{99\%} = 248\ \left[\frac{tonP}{y}\right]$$
$$Pconsumption\ in\ surrounding\ 5\ municipals:$$
$$\left(0.43143\ [\frac{kgP}{yr}] * 74494[women]\right) + \left(0.54933\ [\frac{kgP}{yr}] * 73195[men]\right) = 72[\frac{ton\ P}{y}]$$
$$Nconsumption\ Gothenburg:$$
$$16[\%\ N\ i\ protein] * \frac{0.090}{10^3}\left[\frac{ton\ protein}{day * cap}\right] * 506730[cap] * 365\left[\frac{day}{y}\right] = 2663 \approx 2700\left[\frac{ton\ N}{y}\right]$$

$$Nconsumption\ surrounding\ municipalities:$$
$$16[\%\ N\ i\ protein] * \frac{0.090}{10^3}\left[\frac{ton\ protein}{day * cap}\right] * 147689[cap] * 365[\frac{day}{y}] = 776 \approx 780\left[\frac{ton\ N}{y}\right]$$

Food production industries

$$116000\left[\frac{ton\ milk}{y}\right] * 0.00101\left[\frac{ton\ P}{ton\ milk}\right] = 117\ \left[\frac{ton\ P}{y}\right]$$

Pet consumption and waste

$$\boldsymbol{Phosphorus\ in\ feces\ from\ dogs\ in\ municipality\ of\ Gothenburg:}$$
$$\mathbf{51000}\,[\boldsymbol{dogs}] * \mathbf{120}\,\left[\frac{\boldsymbol{kg}}{\boldsymbol{dog * y}}\right] * \mathbf{0.5}\,[\%\,\boldsymbol{P\ in\ feces}] = \mathbf{31}\,[\frac{\boldsymbol{ton\ P}}{\boldsymbol{y}}]$$
$$\boldsymbol{Phosphorus\ in\ feces\ to\ the\ WTP:}$$
$$\mathbf{75}\,[\%] * \mathbf{31}\,\left[\frac{\boldsymbol{ton\ P}}{\boldsymbol{y}}\right] = \mathbf{23}\,\left[\frac{\boldsymbol{ton\ P}}{\boldsymbol{y}}\right]$$
$$\boldsymbol{Phosphorus\ in\ feces\ left\ on\ the\ ground:}$$
$$\mathbf{25}\,[\%] * \mathbf{31}\,\left[\frac{\boldsymbol{ton\ P}}{\boldsymbol{y}}\right] = \mathbf{7.7}\,\left[\frac{\boldsymbol{ton\ P}}{\boldsymbol{y}}\right] \approx \mathbf{8}\,[\frac{\boldsymbol{ton\ P}}{\boldsymbol{y}}]$$
$$Phosphorus\ input\ via\ food\ for\ dogs\ per\ year\ in\ Gothenburg:$$
$$31\,[\frac{ton\ P\ feces}{y}] * \frac{1}{0.5}\left[\frac{ton\ P\ tot}{ton\ P\ feces}\right] = 62\left[\frac{ton\ P}{y}\right]$$

$$Phosphorus\ input\ via\ food\ for\ cats\ per\ year\ in\ Gothenburg:$$
$$86000\,[cat] * 0.065\left[\frac{kg\ food}{cat * day}\right] * 0.00001\left[\frac{ton\ P}{kg\ food}\right] * 365\left[\frac{day}{y}\right] = 20\left[\frac{ton\ P}{y}\right]$$
$$\boldsymbol{Phosphorus\ in\ cat\ waste\ to\ the\ WTP:}$$
$$\mathbf{25}\,[\%] * \mathbf{20}\,\left[\frac{\boldsymbol{ton\ P}}{\boldsymbol{y}}\right] = \mathbf{5}\,\left[\frac{\boldsymbol{ton\ P}}{\boldsymbol{y}}\right]$$
$$\boldsymbol{Phosphorus\ in\ cat\ waste\ left\ on\ the\ ground:}$$
$$\mathbf{75}\,[\%] * \mathbf{20}\,\left[\frac{\boldsymbol{ton\ P}}{\boldsymbol{y}}\right] = \mathbf{15}\,\left[\frac{\boldsymbol{ton\ P}}{\boldsymbol{y}}\right]$$

Detergents for household use

$$Amount\ of\ phosphorus\ in\ greywater\ due\ to\ use\ of\ detergents\ in\ households\ within\ the\ system:$$
$$\frac{\left((1431 + 398)[\frac{ton}{y}] * 32.61[wt\%]\right) * (506730[cap])}{9340682[cap]} = 32.4\,[\frac{ton\ P}{y}] \approx 32\,[\frac{ton\ P}{y}]$$
$$Amount\ of\ phosphorus\ in\ greywater\ due\ to\ use\ of\ detergents\ in\ households$$
$$outside\ the\ system\ but\ connected\ to\ the\ WWTP\ of\ Rya:$$
$$\left((1431 + 398)[\frac{ton}{y}] * 32.61[wt\%]\right) * \left(\frac{649352[cap] - (506730[cap] * 99[\%])}{9340682[cap]}\right) = 9.4\left[\frac{ton\ P}{y}\right] \approx 9\,[\frac{ton\ P}{y}]$$

Phosphorus compounds for industrial use

$$Amount\ of\ phosphorus\ that\ stays\ in\ water\ after\ purification\ at\ Rya:$$
$$\frac{36\,[\frac{ton\ P\ to\ aquatic\ deposition\ from\ Rya}{y}]}{(334 + 36)\,[total\ ton\ P\ to\ Rya]} = 9.7\,[\%] \approx 10\,[\%]$$

$$Amount\ of\ phosphorus\ in\ biosludge\ from\ Preem: \frac{0.2\,[aquatic\ depostion\ \frac{ton\ P}{y}]}{9.7\,[\%]} = 2.06\,[\frac{ton\ P}{y}]$$

$$Amount\ of\ phosphorus\ in\ biosludge\ from\ Shell: 2.06\,\left[\frac{ton\ P}{y}\right] * 4 = 8.24\,[\frac{ton\ P}{y}]$$

$$Estimated\ input\ of\ phosphorus\ to\ industries: 0.2 + 0.8 + 2.06 + 8.24 = 11.3\,\left[\frac{ton\ P}{y}\right] \approx 11\,[\frac{ton\ P}{y}]$$

Phosphorus to agriculture

$$Amount\ of\ phosphorus\ consumed\ by\ agriculture\ due\ to\ mineral\ fertilizers:$$
$$3036\ [ha] * 7\ \left[\frac{kg}{ha}\right] = 21\ [\frac{ton\ P}{y}]$$

$$Amount\ of\ nitrogen\ consumed\ by\ agriculture\ due\ to\ mineral\ fertilizers:$$
$$3036\ [ha] * 24\ [\%] * 72\ \left[\frac{kg}{ha}\right] = 52\ \left[\frac{ton\ N}{y}\right]$$

$$Phosphorus\ flow\ via\ horse\ manure\ per\ year\ in\ Gothenburg:$$
$$2016\ [horse] *\ 0.0137\ \left[\frac{ton\ P\ in\ manure}{horse * y}\right] = 28\ \left[\frac{ton\ P}{yr}\right]$$

$$Phosphorus\ output\ via\ livestock\ manure\ to\ Brudbergets\ Jordprodukter:$$
$$1000\ \left[\frac{m^3\ manure\ and\ litter}{y}\right] * 500\ \left[\frac{kg}{m^3}\right] * 0.4 \left[\frac{kg\ manure}{kg\ manure\ and\ litter}\right] * 0.0000015[\frac{ton\ P}{ton\ manure}] = 0.3\ [\frac{ton\ P}{y}]$$

$$Phosphorus\ flow\ via\ dairy\ cow\ manure\ per\ year\ in\ Gothenburg:$$
$$153\ [dairy\ cow] * 0.017\ \left[\frac{tonP}{dairy\ cow * y}\right] = 2.6\ [\frac{ton\ P}{y}]$$

$$Phosphorus\ flow\ via\ beef\ cow\ manure\ per\ year\ in\ Gothenburg:$$
$$399\ [beef\ cow] * 0.012\ \left[\frac{tonP}{beef\ cow * y}\right] = 4.8\ [\frac{ton\ P}{y}]$$

$$Phosphorus\ flow\ via\ heifer\ and\ bull\ manure\ per\ year\ in\ Gothenburg:$$
$$343\ [heifer\ and\ bull] * 0.008\ \left[\frac{ton\ P}{heifer\ and\ bull * y}\right] = 2.7\ [\frac{ton\ P}{y}]$$

$$Phosphorus\ flow\ via\ calf\ manure\ per\ year\ in\ Gothenburg: 465\ [calf] * 0.0031 \left[\frac{tonP}{calf * y}\right] = 1.4\ [\frac{ton\ P}{y}]$$

$$Phosphorus\ flow\ via\ pig\ manure\ per\ year\ in\ Gothenburg: 1147\ [pig] * 0.0025\ \left[\frac{tonP}{pig * y}\right] = 2.9\ [\frac{ton\ P}{y}]$$

$$Phosphorus\ flow\ via\ sheep\ manure\ per\ year\ in\ Gothenburg: 552[sheep] * 0.0015\ \left[\frac{tonP}{sheep * y}\right] = 0.8\ [\frac{ton\ P}{y}]$$

$$Total\ phosphorus\ flow\ in\ livestock\ manure: 28 + 2.6 + 4.8 + 2.7 + 1.4 + 2.9 + 0.8 = 43\ [\frac{ton\ P}{y}]$$

$$Total\ phosphorus\ flow\ via\ livestock\ feedstuff: \frac{43\ [\frac{ton\ P}{y}]}{0.8\ [\frac{ton\ P\ manure}{ton\ P\ feedstuff}]} = 54\ \left[\frac{ton\ P}{y}\right]$$

Import of combustible waste

$$\boldsymbol{Amount\ of\ household\ waste\ of\ incoming\ waste\ to\ WTP}: \mathbf{58}\ [\%] * \mathbf{453858}\ \left[\frac{\mathbf{ton}}{\mathbf{y}}\right] = \mathbf{263238}\ [\frac{\mathbf{ton}}{\mathbf{y}}]$$

$$\boldsymbol{Amount\ of\ business\ waste\ of\ incoming\ waste\ to\ WTP}: \mathbf{42}\ [\%] * \mathbf{453858}\ \left[\frac{\mathbf{ton}}{\mathbf{y}}\right] = \mathbf{190620}\ \left[\frac{\mathbf{ton}}{\mathbf{y}}\right]$$

$$\boldsymbol{Total\ amount\ of\ incoming\ biowaste}:$$
$$(\mathbf{39}\ [\%] * \mathbf{263238}\ \left[\frac{\mathbf{ton}}{\mathbf{y}}\right]) + (\mathbf{22}\ [\%] * \mathbf{190620}\ \left[\frac{\mathbf{ton}}{\mathbf{y}}\right]) = \mathbf{144599}\ \left[\frac{\mathbf{ton}}{\mathbf{y}}\right]$$

$$Amount\ of\ phophorus\ in\ incoming\ biowaste:$$
$$144599\ \left[\frac{ton}{y}\right] * 35\ [\%\ dryness] * 0.004\ \left[\frac{kg\ P}{kg\ DM}\right] = 202\ [\frac{ton\ P}{y}]$$

$$\boldsymbol{Total\ amount\ of\ incoming\ paperwaste}:$$
$$(\mathbf{17.5}\ [\%] * \mathbf{263238}\ \left[\frac{\mathbf{ton}}{\mathbf{y}}\right]) + (\mathbf{27}[\%] * \mathbf{190620}\ \left[\frac{\mathbf{ton}}{\mathbf{y}}\right]) = \mathbf{97534}\ \left[\frac{\mathbf{ton}}{\mathbf{y}}\right]$$

$$Amount\ of\ phophorus\ in\ incoming\ paperwaste:$$
$$97534\ \left[\frac{ton}{y}\right] * 100\ [\%\ dryness] * 0.00024\ [\frac{kg\ P}{kg\ DM}] = 23\ [\frac{ton\ P}{y}]$$

$$\boldsymbol{Total\ amount\ of\ incoming\ woodwaste}:$$
$$(\mathbf{17}\ [\%] * \mathbf{190620}\ \left[\frac{\mathbf{ton}}{\mathbf{y}}\right]) = \mathbf{32405}\ \left[\frac{\mathbf{ton}}{\mathbf{y}}\right]$$
$$Amount\ of\ phophorus\ in\ incoming\ woodwaste:$$
$$32405\ \left[\frac{ton}{y}\right] * 100\ [\%\ dryness] * 0.000031\ \left[\frac{kg\ P}{kg\ DM}\right] = 1\ [\frac{ton\ P}{y}]$$

$$Amount\ of\ phosphorus\ in\ incoming\ pet\ waste:\ 23 + 5 = 28\ \left[\frac{ton\ P}{y}\right]$$

$$Total\ amount\ of\ phophorus\ in\ incoming\ waste\ to\ WTP: 202 + 23 + 1 + 28 = 254\ \left[\frac{ton\ P}{y}\right]$$

$$Import\ of\ phosphorus\ in\ combustible\ waste:$$
$$174500\ \left[\frac{ton}{y}\right] * \left(\left(39[\%] * 35[\%\ dryness] * 0.004\ \left[\frac{kg\ P}{kg\ DM}\right]\right)\right.$$
$$\left. + \left(17.5\ [\%] * 100\ [\%\ dryness] * 0.00024\ [\frac{kg\ P}{kg\ DM}]\right)\right) = 103 \approx 100\ ton\ P\ imported$$

Net import of forest products

$$Amount\ of\ phosphorus\ in\ paper\ via\ import\ of\ combustible\ waste:$$

$$174500\ \left[\frac{ton}{y}\right] * \left(17.5\ [\%] * 100\ [\%\ dryness] * 0.00024\ [\frac{kg\ P}{kg\ DM}]\right) = 7\ \left[\frac{ton\ P}{y}\right]$$

$$Net\ import\ of\ annually\ incinerated\ paper\ and\ wood\ to\ the\ system: 23 + 1 - 7 = 17\left[\frac{ton\ P}{y}\right]$$

Digested sludge

$$Amount\ of\ N\ in\ WW\ sludge\ from\ BW: \frac{525[\frac{ton\ N}{y}]}{0.9 * ((2663 * 0.99) + 776)[\frac{ton\ N\ in\ BW}{y}]} = 17[\%]$$

Ashes to disposal

$$phosphorus\ in\ combustible\ waste: 1.2\ \left[\frac{g\ P}{kg\ DM}\right] * 452858\left[\frac{ton}{y}\right] * (100 - 36.3)[\%] = 346\ \approx 350\ \left[\frac{ton\ P}{y}\right]$$
$$with\ standard\ deviation\ considered:$$
$$minimum: (1.2 - 0.61)\left[\frac{g\ P}{kg\ DM}\right] * 452858\left[\frac{ton}{y}\right] * \left(100 - (36.3 + 5.33)\right)[\%] = 156\ \approx 160\ \left[\frac{ton\ P}{y}\right]$$
$$maximum: (1.2 + 0.61)\left[\frac{g\ P}{kg\ DM}\right] * 452858\left[\frac{ton}{y}\right] * (100 - (36.3 - 5.33))[\%] = 566\ \approx 570\ \left[\frac{ton\ P}{y}\right]$$

Compost for horticultural use

$$Amount\ of\ phosphorus\ in\ compost\ at\ Marieholm:$$
$$30[\%] * 15000\left[\frac{ton}{y}\right] * 0.24[\%] = 10.8\ \approx 10\ [\frac{ton\ P}{y}]$$

Food waste

$$total\ amount\ of\ phosphorus\ content\ in\ food\ reaching\ the\ system = X\ [\frac{ton\ P}{y}]$$

$$amount\ of\ phosphorus\ \ in\ human\ consumption\colon \frac{2}{3} * X = 248\ [\frac{\text{ton P}}{\text{y}}]$$

$$\rightarrow X = 372\ [\frac{ton\ P}{y}]$$

$$total\ food\ waste = 372 - 248 = 124\ [\frac{ton\ P}{y}]$$

$$food\ waste\ to\ the\ WTP\colon 124 - 3 = 121\ [\frac{ton\ P}{y}]$$

$$total\ amount\ of\ nitrogen\ content\ in\ food\ reaching\ the\ system = Y\ [\frac{ton\ N}{y}]$$

$$amount\ of\ nitrogen\ \ in\ human\ consumption\colon \frac{2}{3} * Y = 2660\ [\frac{ton\ N}{y}]$$

$$\rightarrow Y = 3990\ [\frac{ton\ N}{y}]$$

$$total\ food\ waste = 3990 - 2660 = 1330\ [\frac{ton\ N}{y}]$$

$$food\ waste\ to\ the\ WTP\colon 1330 - 128 = 1202 \approx 1200\ [\frac{ton\ N}{y}]$$

APPENDIX B: CALCULATIONS TO THE MFAS WITH ALTERNATIVE WASTEWATER SYSTEMS

Scenario with centralized kitchen grinder system

$$Food\ waste, FW, to\ centralized\ WWTP: 121 * 0.8 + 3 = \mathbf{100}\ \left[\frac{tonP}{y}\right]$$

$$FW\ to\ waste\ treatment\ plant: 121 - (100 - 3) = \mathbf{24}\ \left[\frac{tonP}{y}\right]$$

$$Compost\ for\ horicultural\ use: 20 - 10 = \mathbf{10}\ \left[\frac{tonP}{y}\right]$$

$$Ashes\ to\ disposal: 350 - ((100 - 3) - 10) = \mathbf{263}\ \left[\frac{tonP}{y}\right]$$

$$Current\ percentage\ heading\ to\ aquatic\ environments\ from\ WWTP\ effluent:$$

$$\frac{36}{36 + 334}\left[\frac{ton\ P}{ton\ P}\right] = 0.0973\ \approx 10\%$$

$$Current\ percentage\ heading\ to\ digested\ sludge: \frac{334}{36 + 334}\left[\frac{ton\ P}{ton\ P}\right] = 0.903\ \approx 90\%$$

In the alternative scenarios the same proportion between digested sludge and aquatic deposition is assumed.

$$New\ estimated\ value\ of\ total\ output\ (WW\ sludge + aq. dep.): 431 + 36 = 467\left[\frac{ton\ P}{y}\right]$$

$$WW\ sludge: 0.9 * 467 = \mathbf{420}\left[\frac{ton\ P}{y}\right]$$

$$aquatic\ deposition\ from\ WWTP\ effluent: 0.1 * 420 = 47\left[\frac{ton\ P}{y}\right]$$

$$total\ aquatic\ deposition: 54.2 + (47 - 36) = \mathbf{65}\left[\frac{ton\ P}{y}\right]$$

Scenario with semi-centralized kitchen grinder system

$$FW\ to\ centralized\ WWTP: 121 * 0.8 + 3 = \mathbf{100}\left[\frac{tonP}{y}\right]$$

$$FW\ to\ waste\ treatment\ plant: 121 - (100 - 3) = \mathbf{24}\left[\frac{tonP}{y}\right]$$

$$Compost\ for\ horicultural\ use: 20 - 10 = \mathbf{10}\left[\frac{tonP}{y}\right]$$

$$Ashes\ to\ disposal: 350 - ((100 - 3) - 10) = \mathbf{263}\left[\frac{tonP}{y}\right]$$

$$Blackwater, BW, +FW\ sludge: 248 + (100 - 3) = \mathbf{345}\left[\frac{tonP}{y}\right]$$

$$Current\ percentage\ heading\ to\ aquatic\ environments\ from\ WWTP\ effluent:$$

$$\frac{36}{36 + 334}\left[\frac{ton\ P}{ton\ P}\right] = 0.0973\ \approx 10\%$$

$$Current\ percentage\ heading\ to\ digested\ sludge: \frac{334}{36 + 334}\left[\frac{ton\ P}{ton\ P}\right] = 0.903\ \approx 90\%$$

In the alternative scenarios the same proportion between digested sludge and aquatic deposition is assumed.

$$New\ estimated\ value\ of\ total\ output(WW\ sludge + aq. dep.): 90.1 + 36 = 126\left[\frac{ton\ P}{y}\right]$$

$$WW\ sludge: 0.9 * 126 = \mathbf{113}\left[\frac{ton\ P}{y}\right]$$

$$aquatic\ deposition\ from\ WWTP\ effluent: 0.1 * 126 = 13\left[\frac{ton\ P}{y}\right]$$

$$total\ aquatic\ deposition: 50.1 + (13 - 36) = \mathbf{27}\left[\frac{ton\ P}{y}\right]$$

Scenario with centralized urine diverting system

$$Urine: 0.5 * 0.7 * (248 + 32.4) = \mathbf{98.1} \left[\frac{tonP}{y}\right]$$

$$Faecal\ wastewater: 248 - 98.1 = \mathbf{150} \left[\frac{tonP}{y}\right]$$

$$Current\ percentage\ heading\ to\ aquatic\ environments\ from\ WWTP\ effluent: \frac{36}{36 + 334}\left[\frac{ton\ P}{ton\ P}\right] = 0.0973 \approx 10\%$$

$$Current\ percentage\ heading\ to\ digested\ sludge: \frac{334}{36 + 334}\left[\frac{ton\ P}{ton\ P}\right] = 0.903 \approx 90\%$$

In the alternative scenarios the same proportion between digested sludge and aquatic deposition is assumed.

$$New\ estimated\ value\ of\ total\ output (WW\ sludge + aq.dep.): 236 + 36 = 272 \left[\frac{ton\ P}{y}\right]$$

$$WW\ sludge: 0.9 * 272 = \mathbf{245} \left[\frac{ton\ P}{y}\right]$$

$$aquatic\ deposition\ from\ WWTP\ effluent: 0.1 * 272 = 27 \left[\frac{ton\ P}{y}\right]$$

$$total\ aquatic\ deposition: 54.2 + (27 - 36) = \mathbf{45} \left[\frac{ton\ P}{y}\right]$$

Scenario with semi-centralized urine diversion system

$$Urine: 0.5 * 0.7 * (248 + 32.4) = \mathbf{98.1} \left[\frac{tonP}{y}\right]$$

$$Faecal\ wastewater\ (called\ BW(+FW)\ sludge\ in\ Fig. 10): 248 - 98.1 = \mathbf{150} \left[\frac{tonP}{y}\right]$$

$$Current\ percentage\ heading\ to\ aquatic\ environments\ from\ WWTP\ effluent: \frac{36}{36 + 334}\left[\frac{ton\ P}{ton\ P}\right] = 0.0973 \approx 10\%$$

$$Current\ percentage\ heading\ to\ digested\ sludge: \frac{334}{36 + 334}\left[\frac{ton\ P}{ton\ P}\right] = 0.903 \approx 90\%$$

In the alternative scenarios the same proportion between digested sludge and aquatic deposition is assumed.

$$New\ estimated\ value\ of\ total\ output (WW\ sludge + aq.dep.): 90.1 + 36 = 126 \left[\frac{ton\ P}{y}\right]$$

$$WW\ sludge: 0.9 * 126 = \mathbf{113} \left[\frac{ton\ P}{y}\right]$$

$$aquatic\ deposition\ from\ WWTP\ effluent: 0.1 * 126 = 13 \left[\frac{ton\ P}{y}\right]$$

$$total\ aquatic\ deposition: 50.1 + (13 - 36) = \mathbf{27} \left[\frac{ton\ P}{y}\right]$$

If food waste is separately collected and added to the semi-centralized anaerobic digester, then:

$$Compost\ for\ horticultural\ use: 20 - 10 = 10 \left[\frac{ton\ P}{y}\right]$$

$$Ashes\ to\ disposal: 350 - (97 - 10) = 263 \left[\frac{ton\ P}{y}\right]$$

$$BW + FW\ digested\ sludge: 150 + 97 = 247 \left[\frac{ton\ P}{y}\right]$$

APPENDIX C: UNCERTAINTIES IN THE CALCULATED VALUES OF THE MFA

All values has been given two significant figures, except those smaller than 10 ton of phosphorus per year, which only have been given one significant figure. The number of significant figures might be discussed, and could perhaps have been more related to the estimated uncertainty.

Flow definition	Yearly amount of phosphorus [ton P/y]	Yearly flow of nitrogen [ton N/y]	Source of value	Uncertainty of the nutrient flow(s) [scale 1-5, with 5 the most certain]
Aquatic deposition	54	1900	Measured value in published data (Göteborg Stad 2010).	5
Digested sludge	330	530	Measured value in published data (Gryaab 2009, Gryaab 2010b).	5
Compost for horticultural use	20	-	Measured value in published data (Skruf, pers. comm., Wennerberg, pers. comm., Renova 2011).	4
Detergents in household use	32	-	Calculated value based on statistics (SCB 2011b, SCA 2010, Göteborg Stad 2007, Gryaab 2009).	4
Food	370+80=450 (human+pets)	2700 (human)	Calculated value based on published scientific data (SCB 2009, Gryaab 2007, Gryaab 2010b, Welch et al. 2009, Brunner 2010, Abrahamson et al. 2006, Schmid Neset et al. 2006, SCB 2011b, Manimalis 2004, Wade 2011, Cordell et al. 2011).	4
Import of wastewater	72	780	Calculated value based on published scientific data (Business region Gothenburg 2009, Bergman, pers. comm., Lindmark Månsson 2010).	4
Atmospheric deposition	3	170	Calculated value based on statistics (SCB2011a, Knulst 2011, SJV 1999, SCB 2011c, IVL2011).	3
Food waste	120	1200	Estimated value, partly based on statistics (Skjöldebrand 2008, Gryaab 2009, Gryaab 2010a).	3
Phosphorus compounds for industrial use	11	-	Estimated value, partly based on statistics (Wennerberg, pers. comm., Göteborg Stad 2010).	3
Phosphorus to agriculture	21	52	Calculated value based on statistics (EPA 2005, SCB 2010a , SJV 2009)	3

Ashes to disposal	350	-	Calculated value based on published measurements (Claesson Jones 2010, Renova 2009)	2
Import of combustible waste	100	-	Calculated value based on statistics (Renova 2009, Kretsloppskontoret 2011, SWM 2008, Sokka et al.. 2004, Barrelet et al. 2006).	2
Net import of forest products	17	-	Calculated value based on statistics (Renova 2009, Kretsloppskontoret 2011, SWM 2008, Sokka et al. 2004, Barrelet et al. 2006).	2
Pet waste	62+20=82 (dogs+cats)	-	Estimated value, partly based on statistics (SCB 2011b, Manimalis 2004, Wade 2011, Cordell et al. 2011).	2
Storage capacity in soil and reuse in agriculture	-	-	Not measured or estimated.	1