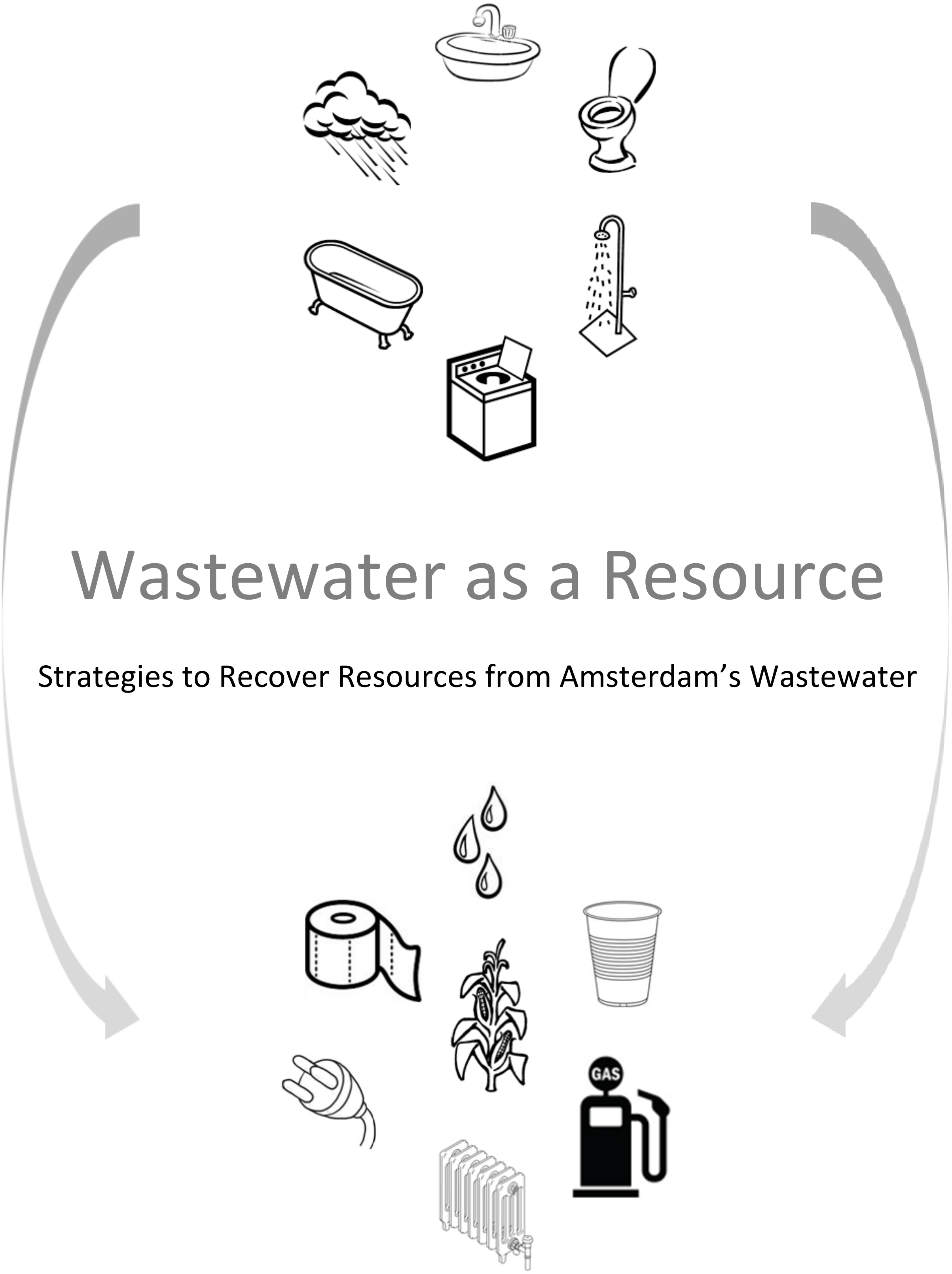

Wastewater as a Resource

Strategies to Recover Resources from Amsterdam’s Wastewater

MSc thesis in Civil Engineering and Management — Heleen de Fooij

Wastewater as a Resource: Strategies to Recover Resources from Amsterdam's Wastewater

MSc thesis in Civil Engineering and Management

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Preface

In this report I present my thesis concerning resource recovery from Amsterdam's wastewater chain. I conducted the research in cooperation with the University of Twente and Waternet, which performs all water related tasks for the City of Amsterdam and the Regional Water Authority Amstel, Gooi and Vecht.

My time at Waternet introduced me to the world of drinking-water and wastewater treatment; a relatively new topic to me. The graduation process opened my eyes to see a great sector where sustainability is high on the agenda. The fact that wastewater quality and the provision of essential resources, like phosphorus, are in the public interest was a great attraction to me. The whole time I kept wondering how things could be better or more sustainable. At one point I even found myself wondering whether it was more sustainable to use a pencil or a pen, which I thought was overdoing it!

I would like to thank my supervisors at Waternet: André Struker and Jan Peter van der Hoek. André, thank you for showing me around Waternet and the water sector and thank you for your enthusiastic guidance. Jan Peter, thank you for our meetings where we discussed both the wider topics of my study as well as the finer details. I would also like to thank all the other people at Waternet that were on some level involved in this research. Thank you for your sometimes almost philosophical contributions, for taking the time to explain technical issues and for your overall support.

Furthermore, I would like to thank my supervisors at the University of Twente: Arjen Hoekstra and Denie Augustijn. Thank you for your patience, for giving me elbow-room when I needed it and for discussing the fundamental parts of my research. Also, Denie, thank you for your detailed feedback and considerate guidance.

Finally, I thank my friends and family. Thank you for the talks, walks, parties, advice and support!

Heleen de Fooij

Amsterdam, January 8, 2015

Summary

Since resource recovery is a sustainable way to deal with resource scarcity, Waternet wants to recover resources from Amsterdam's water chain. Prior to this study, there was no overview of what resources are present in the wastewater chain, what measures exist to recover these resources and how these measures interact. Therefore, this study explored strategies regarding resource recovery from Amsterdam's wastewater to enable coherent and adaptable resource recovering policymaking.

Material flow analysis focused on water, organic matter and phosphorus and resulted in their flows through Amsterdam's wastewater chain. These material flows are presented in flow or Sankey diagrams. The diagrams show what resources are available, where they originate and which resources are currently recovered. Most of the organic matter and phosphorus is transferred into sludge, which is digested to produce biogas, and 16% of the phosphorus is recovered as struvite.

In the measure characterization phase of the research, nine criteria were used to evaluate the measures' impacts on resource recovery and to enable strategy development. Since the measures influence resource flows in the wastewater chain, they were organized based on their position in this chain. The criteria include changes to resource flows and resource recovery, the relative desirability or value of the recovered products and measures' implementation horizons. Per measure the criteria were presented in a spreadsheet for easy comparison.

The four strategies that were developed each focus on the maximum recovery of one product: alginic acid, bioplastics, cellulose or phosphorus. However, the strategies also include recovery of the other resources when this does not limit the production of the focus product. The importance of a measure for a strategy was qualified as significant, competing or optional. This overview led to conclusions about how strategies and measures are competing or complementary and what lock-ins, no-regret measures or win-win situations can arise by choosing a certain measure. This information, together with the measures' characteristics, enables the development of a coherent and adaptive resource recovering policy.

It is concluded from this research that bioplastic and alginic acid production are competing, but that the decision between these two measures can be postponed. Cellulose recovery is also competing with these two measures, but is a no-regret measure on the short term because bioplastic and alginic acid production are still under development and will most likely not be implemented before cellulose recovery reaches its return of investment. Furthermore, the three considered phosphorus recovering methods all have their own advantages and do not have significant disadvantages, so implementation of these is possible. Finally, thermal hydrolysis is a win-win situation since it increases biogas production and is probably also beneficial for alginic acid and struvite production. Thus, thermal hydrolysis is advised. Finally, it is advised, that for all measures additional research into investments and energy is done.

By considering interactions among measures, combining measures into strategies with specified goals and looking at measures' implementation horizons, lock-ins and no-regret measures can be anticipated and policy decisions can be made. Also, when the results of this study are updated and expanded as new information becomes available, opportunities can be seized and threats can be spotted early, which results in an up-to-date and coherent resource recovering policy.

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1. Introduction

Resources are becoming increasingly scarce (Fixen, 2009). Population and economic growth have led to a higher demand of resources, which puts more stress on resource supply and on the environment (Kennedy et al., 2007). Resource stocks are shrinking and resource extractions are negatively affecting the environment (Kennedy et al., 2007, Alfonso Pina and Pardo Martinez, 2014). Therefore, reuse of resources has become necessary and effective.

Water, besides being a resource of its own, is a transport medium for resources. Therefore, the urban water chain has many opportunities to recover resources and close cycles. Materials, chemicals and energy are added to water by households and businesses. Currently, these resources are often treated as waste and are lost for recovery. In Amsterdam, Waternet has the ambition to change this and to recover resources (Baars et al., 2010). This thesis provides strategies for Waternet to improve the sustainability of the wastewater part of the water chain (hereafter, wastewater chain) by resource recovery.

This chapter introduces the topic of resource recovery from Amsterdam’s wastewater chain. At first, background information on resource recovery is presented. Also, the goals of the research are defined in this section. In the second section research boundaries and restrictions are specified and the third section presents the methods that are used to reach the research goals.

1.1 Research goals

The City of Amsterdam and the Regional Water Authority Amstel, Gooi and Vecht aim at a transition from linear to circular resource use to deal with resource scarcity (Gemeente Amsterdam, 2010b, Klaversma, 2013). The cradle-to-cradle framework and the circular economy approach describe this transition in which waste(water) is an asset and a source for materials, chemicals and energy in new production processes, and not a liability and a source for costs (MBDC, 2012, Ellen MacArthur Foundation, 2012). With this in mind, Waternet, which performs all water related tasks for the City of Amsterdam and the Regional Water Authority Amstel, Gooi and Vecht, has expressed the vision to reuse all usable components in wastewater (Baars et al., 2010). This research project will explore how these goals can be achieved.

Thus, Waternet wants circular resource flows in Amsterdam’s water chain. Water in the water chain contains numerous resources, for example heat, phosphorus and cellulose. Some of these resources are currently recovered, but not according to a coherent policy. Decisions about recovering measures are made as opportunities arise. However, in this case, only the affected resource and the suggested measure are considered and interactions between measures and resources are easily neglected. Examples of such interactions are that cellulose recovery inhibits bioplastic production or that thermal hydrolysis is not only beneficial for alginic acid production, but also for biogas production and phosphorus recovery. Therefore, it is useful to consider resources and recovering measures in a coherent and holistic way.

Currently information is lacking to develop such a coherent policy. First of all, there is no overview of the resources in Amsterdam’s wastewater. Therefore, it is difficult to determine whether it is feasible and efficient to recover a certain resource. Furthermore, there is no overview of possible recovering methods. For example, it is necessary to know: what measures already exist and are expected to be developed; what resources these measures affect; where in the water chain they should be implemented; etc. and finally, how measures interact. Also, complex, dynamic and uncertain characteristics of the system and the measures need to be considered before a well-informed decision on a durable resource recovering policy can be made. The theory of adaptive policymaking explicitly considers these characteristics whilst recognizing that decisions have to be made. Therefore, in this research also flexibility and responsiveness of strategies are taken into account.

So, it is unclear what a coherent policy can be to recover resources from wastewater in Amsterdam. To develop such a policy it is essential to gain insight about resources in Amsterdam's wastewater, into the possible recovering measures and as to how these measures combine. Therefore, the following research goals are defined:

The main goal of this Master thesis project is to explore alternative, coherent and viable strategies regarding resource recovery in Amsterdam's wastewater chain with a focus on phosphorus and organic matter. In section 1.2 the choice for this focus is explained.

This research goal is split into three sub-goals:

A. To determine which resources are present in Amsterdam's wastewater, in which quantities they are present and where they are present *(material flow analysis)*
B. To identify and characterize different resource recovering measures and determine which ones are suitable to implement in Amsterdam *(measure characterization)*
C. To develop coherent strategies consisting of suitable resource recovering measures *(strategy development)*

1.2 Scope restrictions

Waternet aims to look for opportunities for win-win situations and wants to consider resources in- and outside the water chain. However, for reasons of practicality the scope of this research is restricted. This research explores how the resource flows can be viewed and how the opportunities for recovery can be considered by looking at organic matter and phosphorus in non-industrial wastewater. Also, only measures that can be implemented by 2040 are considered. These restrictions are explained in the paragraphs below.

The first restriction is that only resources in wastewater are considered. Measures that close resource cycles can be taken in different stages of the water chain, but in this research the drinking-water stage is excluded. So, for example, chemicals that are used in drinking-water production are not considered. Another example is that resource recovery from surface water is excluded from this research. Phosphorus from nonpoint sources can for example be removed from surface water using phosphorus sorbing materials (Buda et al., 2012). However, the boundaries of this research start at (drinking-) water use and end at wastewater treatment (see Figure 1).

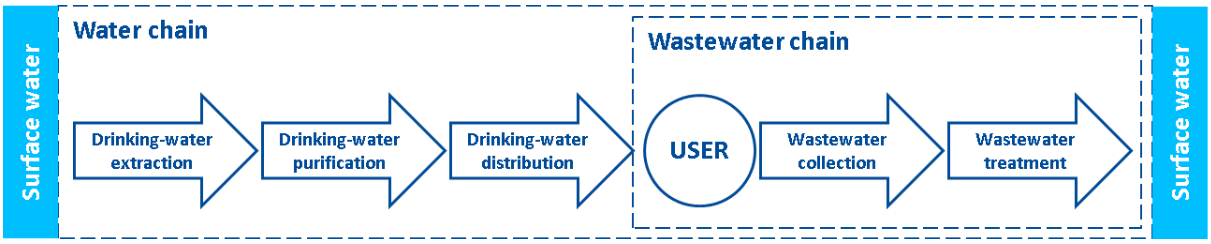

FIGURE 1 – WATER CHAIN VERSUS WASTEWATER CHAIN

The second restriction is that industrial water is excluded from this research. Industrial water is not looked at separately, because of restricted research time and the great differences between industries. Furthermore, in Amsterdam big industrial companies have their own treatment plants to remove their specific pollutants, so these resource flows are collected separately and can be looked at separately.

The third restriction is that only organic matter and phosphorus are considered. After a first analysis, organic matter and phosphorus were chosen as resources that are suitable to show the complexity of resource recovery. Phosphorus is especially interesting since scale is important: phosphorus recovery can be done in different sections of the wastewater chain. For example, phosphorus can be removed from separately collected urine at the beginning of the wastewater chain or from sludge ashes at the very end of the wastewater chain.

Organic matter is chosen because of the many different products that can be made from the organic matter in wastewater. These products all have pros and cons that make recovery more or less financially feasible, technically feasible, sustainable and circular. Also, since these products have the same organic matter as source, they are competing. Therefore, an assessment of products and recovery methods is an important step for the determination of future strategies and investments.

Other resources that were considered but excluded from the research are heat, nitrogen, heavy metals and pharmaceuticals (see Appendix B). A truly coherent and complete strategy would include these and other resources, but for reasons of practicality these are excluded. Examples of reasons why these resources were not selected over phosphorus and organic matter are their small quantities and low concentrations (e.g. heavy metals), no current recovering methods (e.g. pharmaceuticals) and no scarcity of the resource (e.g. nitrogen).

The fourth and final category of restrictions consists of the limited amount of criteria that are considered to characterize the resource recovering methods in this research. In this research the focus is on changes in material flows, recovered products and implementation horizons. However, more criteria are of influence when deciding upon a resource recovering policy. For example, financial considerations, like the costs of measures, the revenue from sold recovered products and the market conditions of these products, are excluded in this study.

1.3 Research methods

The research is split into three phases. In each of the phases a sub-goal is addressed. Phase A, material flow analysis, leads to insight in the presence of resources in various locations of the wastewater chain. Phase B, measure characterization, results in a list of resource recovering measures and their characteristics. Phase C, strategy development, results in strategies that describe how Amsterdam can move towards a more circular economy.

This research roughly follows the development process of dynamic adaptive policy pathways described by Haasnoot et al. (2013). This development process is divided into ten steps, of which in this research only the first six are conducted. Figure 2 is based on the ten steps of Haasnoot et al. (2013) and describes the phases in this research. The descriptions of the first six steps are somewhat different than the descriptions by Haasnoot et al. (2013). However, since steps 7 till 10 are not included in this research their names remain unaltered.

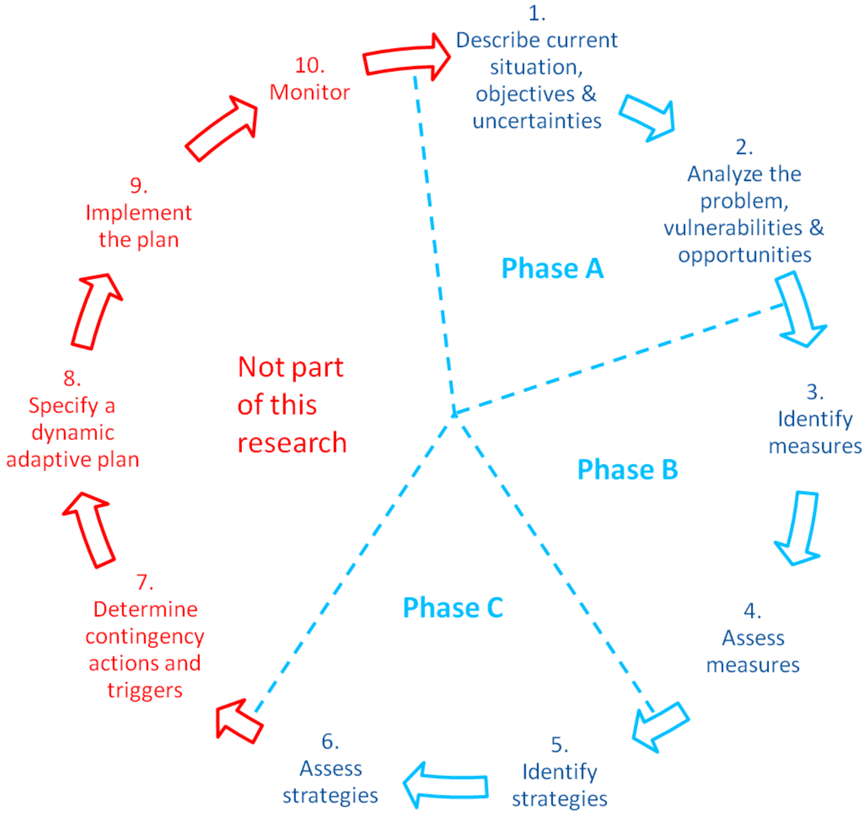

FIGURE 2 - METHOD DESCRIPTION (ADAPTED FROM HAASNOOT ET AL. (2013))

In the following three sections, the phases are explained. The sections describe the activities in the phases and how the results are presented in this thesis.

Phase A: Material flow analysis

Material flow analysis (MFA) describes and quantifies the material flows through a defined system (Chevre et al., 2013). In this research yearly material flows through Amsterdam's wastewater chain are analyzed (Alfonso Pina and Pardo Martinez, 2014). Since MFA is an indispensable first step for creating a system with increased resource efficiency and reduced losses (Cooper and Carliell-Marquet, 2013) and since quantification of the pathway of substances through the socioeconomic system is essential for the selection of appropriate measures to mitigate discharge of this substance (Yuan et al., 2011), MFA is chosen as the starting point for improvement of the resource circularity for Amsterdam's wastewater chain.

Prior to this research, the resources in Amsterdam's wastewater had not been presented in a structured way. Some resources were measured and measurements were documented, but they were scattered over many different reports. Therefore, the research starts with an analysis of Amsterdam's water chain and summarizing the resources in the wastewater.

In this phase, for different locations in the wastewater chain the quantities of resources were specified. This information was necessary to know what measures are possible and suitable to recover resources in Amsterdam. Since not all data were present for Amsterdam, assumptions were made to reach a more complete overview of resources. These assumptions were largely based on extrapolations of national data or data from similar cities to Amsterdam, e.g. in Western Europe or North America.

Since the location of resources in the water chain is so important, a spatial representation is essential. Therefore, Sankey diagrams are the chosen way for representing the resource flows (WordPress, 2014). Circle Economy (2013) already proved this type of diagram suitable for showing Amsterdam's "mass balance" and Blom et al. (2010) showed how well thermal energy in the water chain can be represented by Sankey diagrams. Similarly to Blom et al. the Sankey diagrams were made based on the location of the resources in the water chain.

Phase A resulted in the water flows, organic matter flows and phosphorus flows through Amsterdam's wastewater chain. As far as possible the Sankey diagrams include separate resource flows for different water uses and users. They also include how the wastewater is currently treated and where the resources end up in the current situation (e.g. in the air or in sludge). The overview of resource flows was used to determine the impacts of certain measures (Phase B) or strategies (Phase C) on the resource flows.

Phase B: Measure characterization

Besides an overview of resources, also an overview of possible recovering measures is necessary to develop resource recovering strategies. Therefore, in Phase B measures were identified and characterized.

In this research, measures are defined as plans or courses of action that change resource flows and/or recovery. Separate collection of urine is an example of a measure that changes the flows of the resources in urine and, thereby, also changes the recovery of phosphorus. The measures and their characteristics were summarized in one large spreadsheet (see Appendix H). For each of the measures the following questions are answered:

- How does the measure influence the material flows? So, how do the quantities of water, organic matter and phosphorus per location change by the measure?
- How much of which resource is recovered by the measure? How desirable is the recovered product?
- How far developed is the measure? Is the technology already proved at full scale or still in development?
- What changes and commitments are required for the measure? So, for example, is a change of legislation or behaviour required?
- When can the measure be implemented in Amsterdam?

Because some measures are competing, e.g. cellulose recovery limits bioplastic production, it is necessary to know what measures or recovered products are preferred over others. For this reason the concept of sustainability and several ways to appraise sustainability were studied. In the next paragraphs, the concepts of sustainability and the biomass value pyramid are introduced; for more information see Appendix A.

Since the United Nations define sustainable development as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (World Commission on Environment and Development, 1987, p. 15), limitation of resource use and increased resource reuse seems necessary to provide the extensive future generations with resources for their needs. In other words, a transition towards a circular economy, which is an economy in which the cradle to cradle concept of closing resource cycles by preventing use and reusing materials, seems necessary (MBDC, 2012, Ellen MacArthur Foundation, 2013).

With this in mind, optimal use of resources is essential. And since, the value of resources is determined by its application, the desirability of resource recovery is determined by the products made from these resources (Betaprocess bioenergy, n.d.). The biomass value pyramid shows what products are valued highest. The products that can be recovered by the measures in this research were placed in the framework of the value pyramid (see Figure 3). Even though phosphorus is not biomass, it is placed in the framework to make all products comparable. Phosphorus is placed in Category 3 since it is a fertilizer. For more information on the value pyramid see Appendix A.

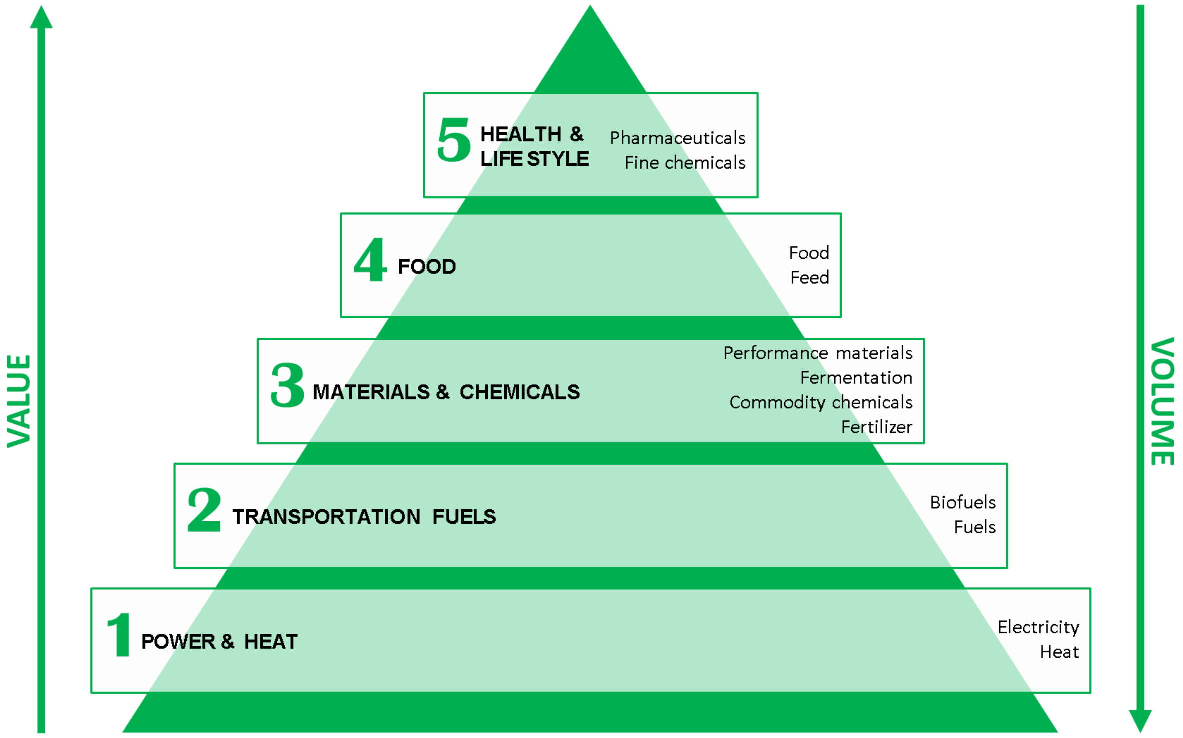

FIGURE 3 – VALUE PYRAMID (ADAPTED FROM BETAPROCESS BIOENERGY (N.D.))

Furthermore, since this research, among others, aims to help prevent lock-ins that inhibit use of measures because of made choices, innovative measures and measures that are still being tested are also considered. Many measures are established and proven, but possible future developments are explicitly considered to prepare for opportunities that may arise.

Phase C: Strategy development

The measures are combined into strategies, which are combinations of measures that focus on a specific goal of resource recovery. So, cohesion within a strategy is guaranteed by choosing a main focus and making sure that all measures in the strategy correspond with that focus. The four presented strategies are focussed on the maximum recovery of a specific product, namely, alginic acid, bioplastic, cellulose or phosphorus. These four products are chosen because these are valued rather similarly using the value pyramid and it is therefore not sufficient to only prioritize by value. Other characteristics of the products and strategies to recover them (e.g. how much can be produced or when production can start) need to be considered before a strategy can be chosen as preferable. Thus, each strategy aims to maximize production of one product. When measures do not compete with this main goal, they can also be part of the strategy to recover other resources in the wastewater stream according to the priorities in the value pyramid.

The strategies helped determine lock-ins, win-win situations and no-regret measures. Lock-ins are situations when by choosing one measure the option of implementing another measure is eliminated. A win-win situation can exist when a measure is beneficial for two goals. For example, thermal hydrolysis increases both biogas and struvite production. Finally, a no-regret measure is a measure that can be implemented in several strategies, so a strategic choice is not yet necessary; the measure is beneficial anyway.

In this report the results of “Phase A: Material flow analysis” are presented in Chapter 2, “Phase B: Measure characterization” results in Chapter 3 and “Phase C: Strategy development” leads to four strategies and a comparison of these strategies that are presented in Chapter 4. The results and the impacts of the restrictions and methods are discussed in Chapter 5 and Chapter 6 presents conclusions and recommendations for future research.

2. Amsterdam’s water chain and material flows

This chapter describes the main flows of three resources: water, organic matter and phosphorus. At first, the water chain is summarized to understand the water flows in Amsterdam and to know where the wastewater that arrives at the wastewater treatment plants (WWTPs) originates. For organic matter it is more difficult to determine its exact origins, therefore, the removal and recovery of organic matter from wastewater has the focus in the second section of this chapter. For phosphorus its origins are determined, but also the current treatment, removal and recovery of phosphorus are explained. Furthermore, it should be noted that for organic matter and phosphorus only the wastewater chain is presented and, thus, the resources in drinking-water (production and distribution) are excluded.

2.1 Amsterdam’s water chain

The water chain in Amsterdam is completely operated by Waternet. Waternet extracts drinking-water, purifies it and distributes it to businesses and households in Amsterdam. After use, the businesses and households discharge most of the water in the sewers. Besides this wastewater also part of Amsterdam’s storm water and some groundwater are transported via the sewers. Subsequently, the water is treated in two WWTPs (Amsterdam West and Westpoort) and discharged into surface water.

The water flows in Amsterdam’s water chain for 2013 are summarized in the flowchart of Figure 4. The calculations of the values in the flowchart can be found in Appendix C. It should be noted that the values in Figure 4 are approximations based on measurements and global, regional or local averages. Furthermore, the values in Figure 4 are for 2013 and therefore only represent one year. However, most values do not change much per year. In the past four years influent originating in Amsterdam and arriving at its WWTPs ranged between 72.9 and 76.0 Mm^3 (Waternet, 2014b). Also, drinking-water use does not change much yearly. The weather, and thereby the amount of stormwater ending up at the WWTPs, does seem to impact the influent flows significantly.

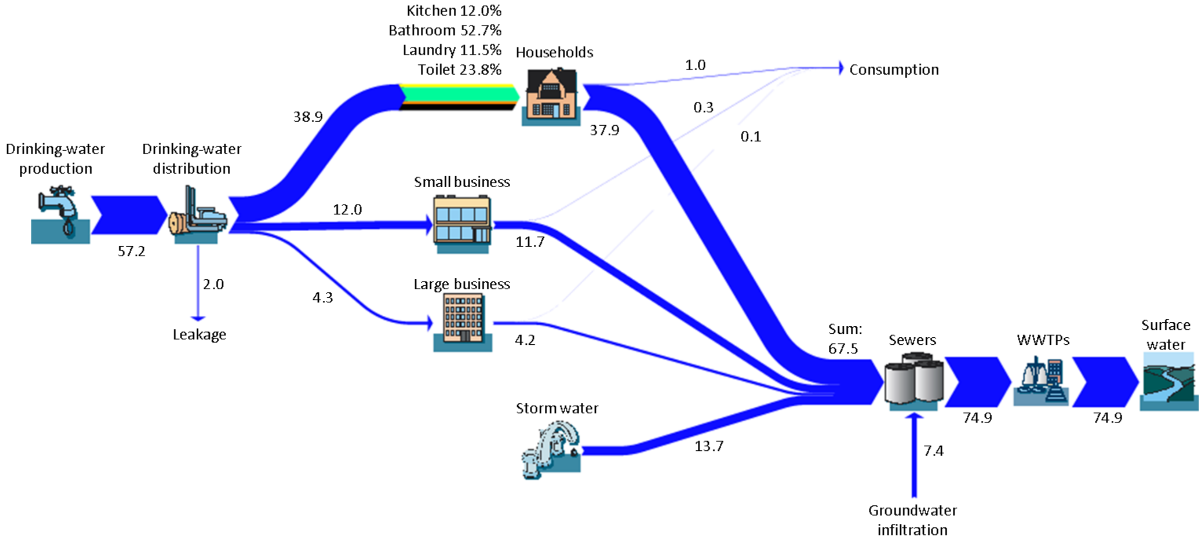

FIGURE 4 - AMSTERDAM’S WATER CHAIN 2013 [IN MILLION M^3]

In 2013 Waternet produced 57.2 million m^3 of drinking-water for distribution in Amsterdam. Part of this water is lost from the distribution network as leakage. The remainder is distributed to households (38.9 Mm^3) and businesses (16.3 Mm^3), of which 12.0 million m^3 is used in small businesses, like offices, hotels and restaurants, and 4.3 million m^3 is used in industry. Most of the household water use is for bathing. Of the average water use in Amsterdam of 133.5 L/p/day more than 60 L/p/day is used for showering (Foekema and Van Thiel, 2011). Other big water uses are toilet flushing and laundry (Roos, 2014, Waternet, 2014b).

It is assumed that approximately 2.5% of the water that is distributed to households and business is consumed and therefore is removed from the water chain. An example of water consumption is water that evaporates and is ‘lost’ to the atmosphere. The remaining 97.5% of the distributed water is used, but returns to the water chain and is transported via sewers to WWTPs.

In Amsterdam 75% of the surface is connected to separated sewers (Baars et al., 2010). The storm water in these areas is kept separately from the wastewater and is discharged to surface waters without treatment. However, 25% of the surface is connected to a combined sewer system. The precipitation in these areas either runs of directly to surface water or is transported through the sewers to the WWTPs. The contribution of storm water to the sewer flows in Amsterdam is estimated at 13.7 million m^3. Compared with the 53.8 million m^3 of household and business wastewater this is a significant amount.

The final source of Amsterdam’s treated wastewater is groundwater. Parts of the sewers in Amsterdam are under groundwater level since the groundwater level is relatively high to prevent collapse of the numerous wooden foundations. Consequently, when sewers are not completely watertight groundwater can infiltrate them. In Amsterdam, approximately 7.4 million m^3 of groundwater is transported to the WWTPs (Janse, 2012).

In calculations for annual reports of Waternet, the influent and effluent quantities for WWTPs are presumed to be equal. For simplicity, this presumption is adopted and the influent and effluent of the WWTPs in 2013 are 74.9 million m^3 (Waternet, 2014b).

2.2 Organic matter

Several materials are transported via the water chain. Organic matter is an example of a material group in wastewater. Organic matter is composed of organic compounds that have come from the remains of dead organisms like plants and animals and their waste products (Greenfacts, 2014). Organic compounds are formed mainly from carbon, hydrogen and other elements. Examples of organic compounds are cellulose, proteins, and carbohydrates. Organic matter ends up in the water chain via urine and faeces, as toilet paper, as food leftovers through cooking and dishwashing, etc. Figure 5 shows organic matter in Amsterdam’s wastewater chain. Appendix E shows the calculations for the values in this figure.

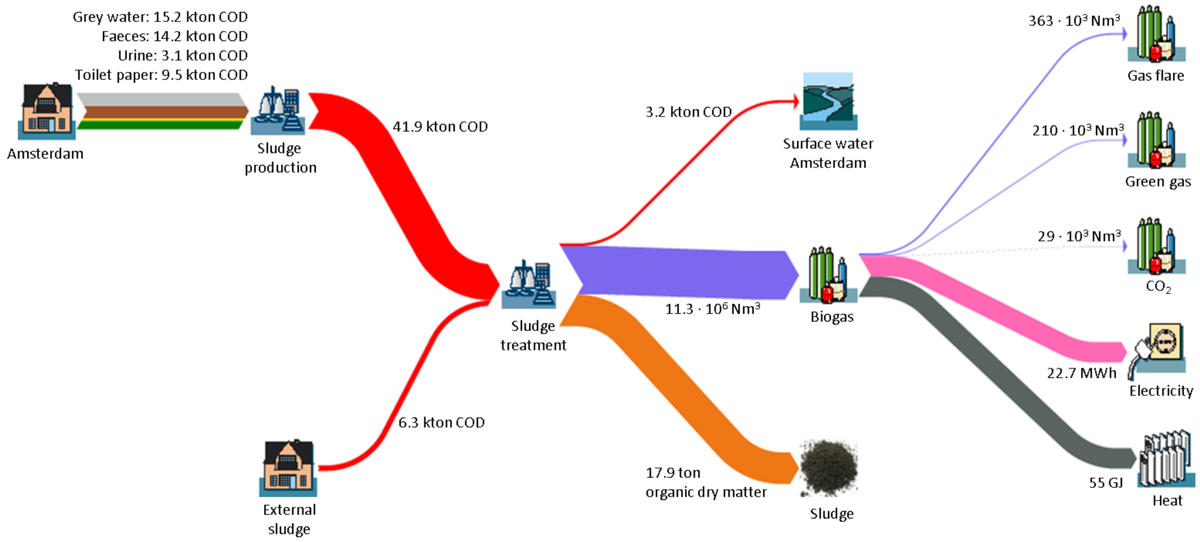

FIGURE 5 - ORGANIC MATTER IN AMSTERDAM'S WASTEWATER CHAIN 2013 (FOR CALCULATIONS SEE APPENDIX D)

The organic matter content in wastewater is measured as chemical oxygen demand (COD). In the determination of the COD most organic compounds are chemically oxidized. Then, the consumed amount of oxygen is calculated. In Amsterdam the total amount of organic matter in the wastewater is approximately 41.9 kton COD.

Organic matter originates in urine, faeces, toilet paper and grey water. Based on data from Kujawa-Roeleveld (2006) the distribution of these four sources is estimated. The biggest contributions to the COD of wastewater are from grey water (36%) and faeces (34%). Urine contributes 7% and the cellulose in toilet paper contributes 23%.

At WWTPs, most of the organic matter is removed from the wastewater as sludge. At the biggest WWTP of Amsterdam, WWTP Amsterdam West, sludge from a wider region is collected and treated. More information on how wastewater is treated at Amsterdam's WWTPs is presented in Appendix D.

At WWTP Amsterdam West sludge is currently treated using a mesophilic digester. After part of the water in the sludge has been removed the sludge is digested producing biogas. Part of the biogas cannot be used or stored directly and is therefore lost as gas flare. In 2013 gas flare was around 3% of the total biogas production. The rest of the biogas was upgraded to green gas, which has higher methane content than biogas and can therefore be used as a transportation fuel, or used for combined heat and power production.

Not all organic matter becomes biogas. The majority of the organic matter is not digested and remains in the sludge. After digestion the sludge is incinerated at the waste and energy company AEB. The residual heat of this incineration is used for district heating.

2.3 Phosphorus

Wastewater contains nutrients, such as phosphorus and nitrogen. These nutrients are present in human faeces and urine, in detergents in grey wastewater, etc. At present nutrients are removed from wastewater because high concentrations of nutrients can disturb the balance of nature in surface water leading to eutrophication and algal blooms. However, nutrients are also necessary and valuable. Phosphorus is an essential resource, since it is required for plant growth and food production (Cooper & Carliell-Marquet, 2013). Phosphorus recovery is especially interesting because phosphorus is a finite resource and phosphorus stocks are reducing.

Figure 6 shows the phosphorus in Amsterdam's wastewater. It is unknown how much of the phosphorus load at WWTPs originates at households and how much originates at businesses. Therefore, the assumption is made that the composition of household wastewater is comparable with the composition of business wastewater. Since small businesses, which make up more than 70% of businesses' water use, are mostly offices and hotel and catering industry, this assumption seems likely. Also a comparison between the composition of the wastewater at WWTP Amsterdam West and WWTP Westpoort, where most of the industrial wastewater is treated, supported this assumption.

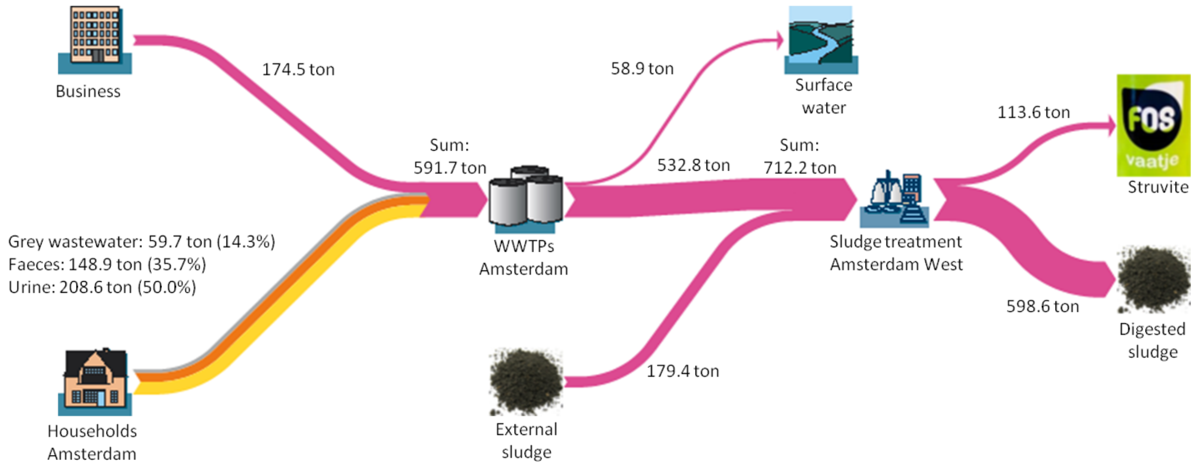

FIGURE 6 - PHOSPHORUS IN AMSTERDAM'S WASTEWATER CHAIN 2013 (FOR CALCULATIONS SEE APPENDIX D)

During primary water treatment and secondary or biological treatment most of the phosphorus ends up in the sludge. Only a small part remains in the water and is discharged to surface water. With the external sludge, from WWTPs outside Amsterdam, more phosphorus enters WWTP Amsterdam West. After sludge digestion, dissolved phosphorus in the sludge is precipitated using magnesium chloride in an installation called 'Fosvaatje'. In this way, currently around 16% of the phosphorus in sludge is recovered as struvite. The struvite is partially separated from the digested sludge and collected for use as fertilizer. For more information on struvite precipitation see Appendix F.12. The rest of the phosphorus remains in the sludge which is incinerated by AEB.

3. Potential measures and their effectiveness

The resources in wastewater can be recovered using different measures. This chapter describes measures and their characteristics. The characteristics or criteria for decision-making are described for each measure as if they were implemented in the current system. The effects of the measures are based on expected material flows in 2040.

3.1 Measures

The measures that are discussed in this chapter are measures that change the material flows in Amsterdam's wastewater chain. They change the available amounts of resources and/or they change how much of the resources can be recovered. These measures can take place at four different locations in the wastewater chain. The first location is the level of the water user: the households and businesses. The second location is the collection of wastewater or the sewer system. The third location is the WWTP and the fourth and final location that is considered is sludge disposal.

The overview of measures that is presented in this chapter is not complete; there are many more changes to the wastewater chain possible. The measures here are measures that are or could be considered in Amsterdam and are measures that show the wide variety of possibilities.

Figure 7 shows the measures in the order of the wastewater chain. The figure shows the possibilities of measure combinations. The measures that are currently implemented in Amsterdam are marked with a star. The advantage of looking at measures with respect to their location in the chain is that it shows dependencies. The measures influence the material flows, the water chain and measures that are 'downstream'. For example, the first measure at business level is separate urine collection. In this case the urine is not mixed with the wastewater. When this is implemented, two possibilities for urine treatment exist. One possibility is to treat the urine separately from the wastewater and sludge in a new to be installed urine treatment facility, which could nearly double the recovery of phosphorus from urine. The other possibility is to treat urine at a traditional WWTP, but adding it to the sludge instead of to the water to recover slightly more phosphorus than in the current situation. Whether or not these measures concerning urine collection and treatment are implemented, impacts the measures further 'downstream', like phosphorus recovery by struvite precipitation.

Table 1 includes short descriptions of the measures. More detailed descriptions of the measures including assumptions and calculations behind the criteria values can be found in Appendices F and H.

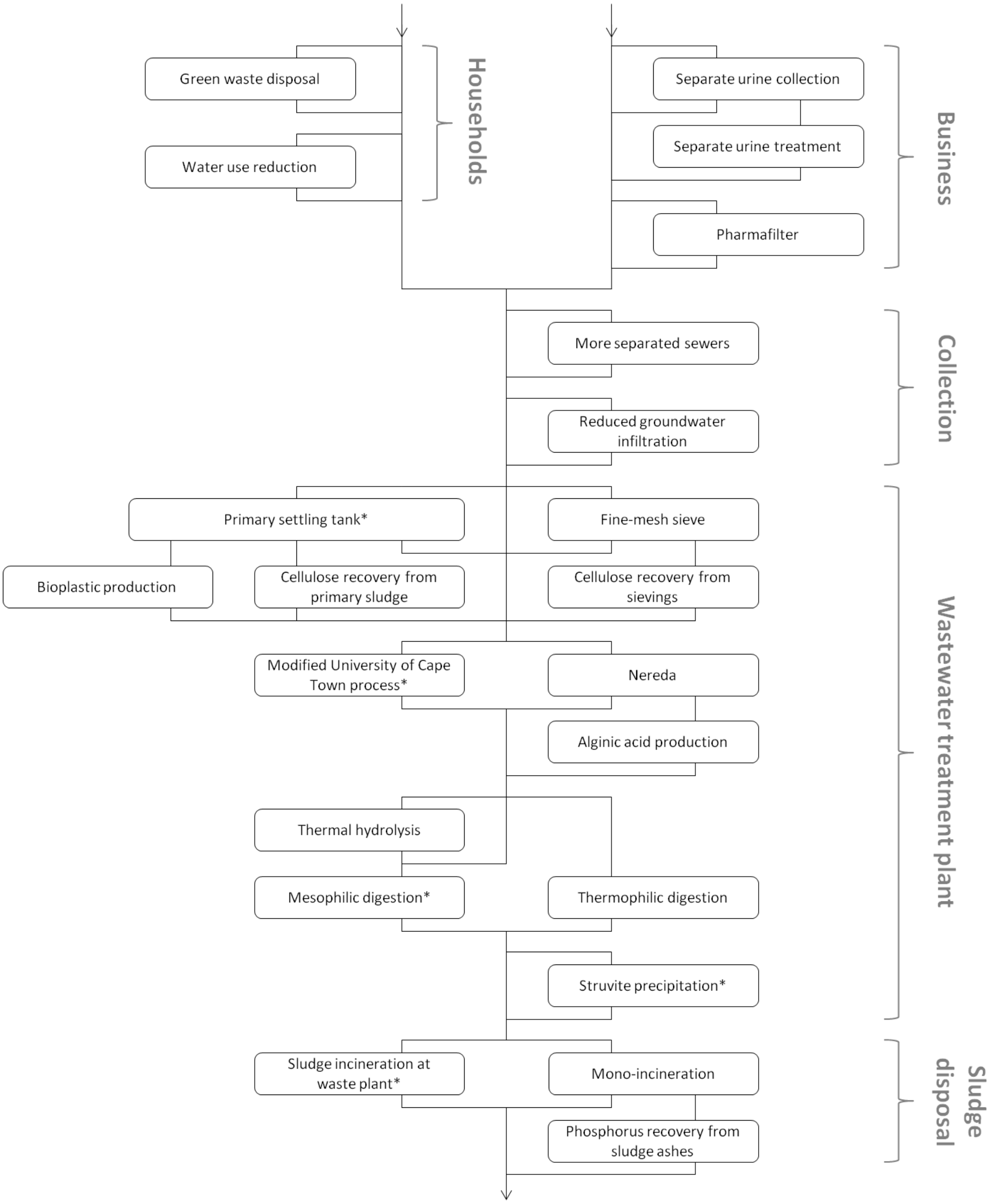

FIGURE 7 - MEASURES ROADMAP (* CURRENTLY PRESENT IN AMSTERDAM)

TABLE 1 – SHORT DESCRIPTIONS OF POSSIBLE MEASURES

Category	Measure	Description
Households	Green waste disposal	Waste disposal grinders are installed at households and/or businesses. Therefore, green waste is transported to the WWTPs.
	Water use reduction	Installation of water saving showers and toilets.
Business	Separate urine collection	Separate collection of the urine from larger hotels, offices and events. Treatment and recovery is done in the traditional way at the existing WWTP, but urine is inserted in the sludge treatment.
	Separate urine treatment	After separate urine collection, resource recovery is done at a separate urine treatment facility.
	Pharmafilter	Installation of Pharmafilter at hospitals and other care facilities.
Collection	More separated sewers	Combined sewers are replaced by separated sewers so less stormwater ends up at the WWTPs.
	Reduced groundwater infiltration	Old sewers are replaced by new ones resulting in less groundwater infiltration.
Wastewater treatment plant	Primary settling tank	Separation of primary sludge from the influent at WWTPs by settlement due to reduced flow velocities.
	Bioplastic production	Through fermentation (mixed or rich culture) the bioplastic PHA can be produced from (mainly primary) sludge.
	Cellulose recovery from primary sludge	After primary sludge is separated from the influent using a primary settling tank, cellulose is recovered from the sludge.
	Fine-mesh sieve & cellulose recovery from sievings	A fine-mesh sieve is used to separate larger particles, including cellulose fibres, from the influent.
	modified University of Cape Town process (mUCT)	Current biological treatment process that removes phosphorus and organic matter from the water and stores it (partially) in activated flocular sludge.
	Nereda	Biological treatment process that removes phosphorus and organic matter from the water and stores it (partially) in granular sludge.
	Alginic acid production	Alginic acid, a polysaccharide, can be produced from granular sludge.
	Thermal hydrolysis	Pre-treatment of sludge using heat and pressure that sterilizes sludge and makes it more biodegradable.
	Mesophilic digestion	Current sludge digestion at approximately 36°C and with a residence time of 20 days.
	Thermophilic digestion	Sludge digestion at approximately 55°C and with a residence time of at least 12 days.
	Struvite precipitation (‘Fosvaatje’)	By adding magnesium chloride to digested sludge, struvite precipitates. This struvite is separated from the sludge and thus phosphorus is recovered.
Sludge disposal	Sludge incineration at waste plant	Digested sludge is incinerated. Currently, sludge and solid waste are incinerated together (by AEB).
	Mono-incineration	Digested sludge is incinerated separately from solid waste to enable phosphorus recovery from sludge ashes.
	Phosphorus recovery from sludge ashes	Phosphorus in sludge ashes is precipitated using iron salts.

3.2 Criteria

Each of the measures is characterized using nine criteria (see Table 2). These criteria help determine to what extend the measures improve the circularity of Amsterdam's wastewater chain. The criteria describe how a measure changes material flows and resource recovery, how uncertain a measure's development paths is, how the measure depends on changes of behaviour or actors outside Waternet and when it can be expected to be implemented in Amsterdam.

TABLE 2 - CRITERIA USED TO CHARACTERIZE THE MEASURES

Criterion	Questions answered
Δ water	How are water flows changed by the measure? So, how do water use and/or wastewater production change due to this measure?
Δ organic matter	How are organic matter flows changed by the measure?
Δ phosphorus	How are phosphorus flows changed by the measure?
Recovery organic matter	What products are recovered from the organic matter and in which quantities?
Recovery phosphorus	What products are recovered from the phosphorus and in which quantities?
Value recovered products	What is the value of the recovered products using the value pyramid?
Development stage	At what stage of development is the measure? Possible answers are idea, lab phase, pilot phase, full scale testing and proven technology.
Dependencies	What changes and commitments are required for the measure? Who or what organizations are needed for success of this measure? Is a change of legislation or behaviour required?
Implementation horizon	From what moment onwards can the measure be operational in Amsterdam?

The measures discussed in this research all influence water, organic matter and/or phosphorus flows. Thereby, they change the resources that are or can be recovered. An example is the measure of green waste disposals. These grind green household waste enabling transportation of this organic matter using sewers. The extra organic matter arriving at the WWTP can be recovered using existing technology (e.g. mesophilic digestion) or new technology (e.g. fermentation to produce bioplastic). Water use of households will also increase when people start using these waste disposals. So, measures can change material flows and, thereby, change the amounts of potentially recovered products. Therefore, the first step of identifying the consequences for resource recovery is determination of the changed resource flows.

These changed or unchanged resource flows are then used to determine how resource recovery changes due to the measure. For measures that only change the resource flows and are no new recovering technology, only the quantities of recovered products change. For example, in case of the green waste grinders, the amounts of biogas, struvite and sludge that are produced will increase. For new technologies, the quantities of currently recovered products can change, but also new products, like bioplastic or alginic acid, can be made. For example, when a fine-mesh sieve is installed more cellulose and less sludge and biogas are produced. An overview of the products considered in this research is presented in Table 3. Concluding, the second step results in an overview of the (quantities of) recovered products.

TABLE 3 – DESCRIPTIONS OF PRODUCTS

Product	Description
Biogas	Biogas is a mixture of CH_4 and CO_2 that can be used to produce green gas and CO_2 and/or electricity and heat using combined heat and power technology.
Cellulose	Cellulose is the polysaccharide of which the fibres in toilet paper consist. The fibres can be used to produce building materials or paper products, but it can also be used to make bioplastic.
Bioplastic	Polyhydroxyalkanoates (PHAs), a type of bioplastic, can be produced from sludge.
Phosphorus	Phosphorus is a necessary nutrient for plant and human growth that can be recovered from wastewater.
Alginic acid	Alginic acid is a polysaccharide that can be used in the pharmaceutical or food industry and that can be recovered from granular sludge.

To know the desirability of a measure, it is also necessary to know the desirability of the product and, thus, the value, with regard to circularity and sustainability, of a product compared with other products. When the decision between a primary settling tank and a fine-mesh sieve has to be made it is, for example, necessary to know whether cellulose is a more desirable product than biogas and sludge. Ideally, it should be known how much cellulose should be recovered to compensate for a certain amount of biogas and sludge loss. The value or sustainability of a recovered product can be ranked using the value pyramid. Figure 8 shows how the products are ranked in this study. Products higher in the pyramid are valued higher and therefore preferred over products lower in the pyramid. So, this third step results in a summary of the values of the recovered products. More information on the value pyramid and the placement of products in it is presented in Appendix A.3.

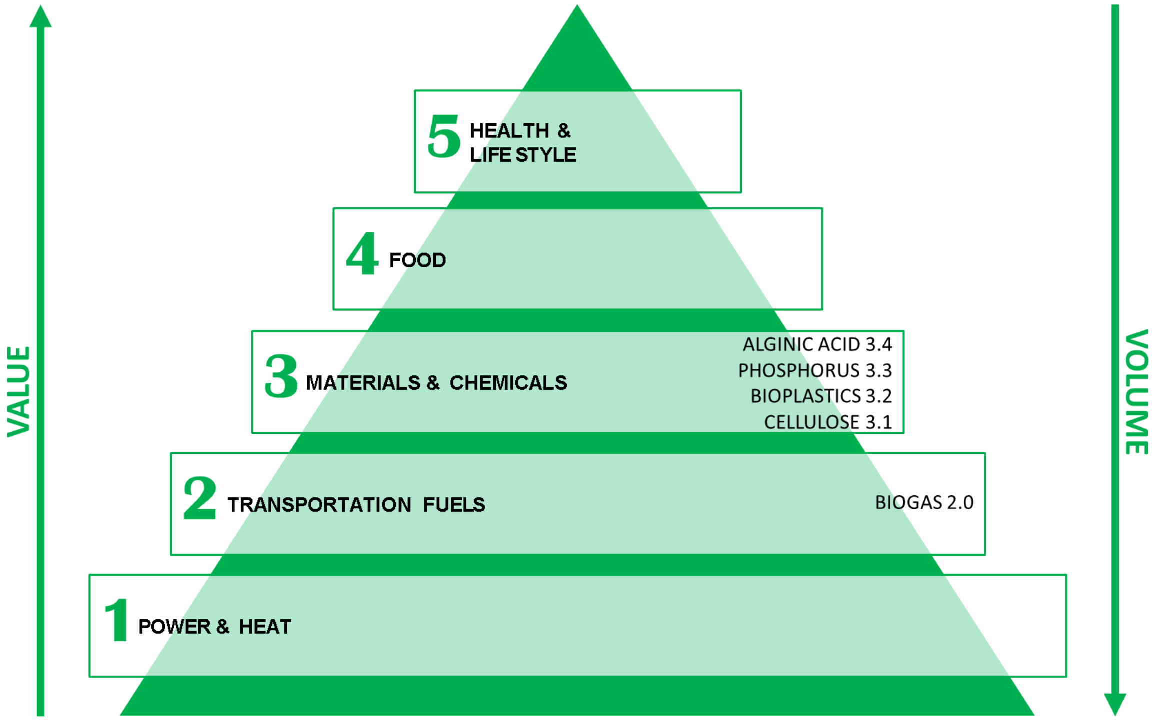

FIGURE 8 – VALUE PYRAMID (ADAPTED FROM BETAPROCESS BIOENERGY (N.D.))

In the fourth step, three criteria are chosen as indicators for the uncertainties in the implementation of the measures. The first is the development stage of the measure. Some measures exist for years and are fully tested. For these measures uncertainties are small and their effects can be reasonably well predicted. For other measures, however, their implementation and effects are more difficult to predict. For example, Waternet is currently participating in research into cellulose recovery from primary sludge. Lab tests indicate that primary sludge contains much cellulose and that this might be easily removed by a sieve, but this has not been tested at full scale. Not only the characteristics and effects of the measure are uncertain, but also the measure's place in the time frame. The second criterion that impacts implementation of measures consists of dependence on existing contracts, legislation, behaviour or infrastructure (e.g. for the way of sludge incineration to change, the current contract with AEB has to be changed). Because these dependencies influence the order in which decisions need to be made and also which measures can be combined at certain times in the future. The third and final implementation criterion is when a measure can be implemented in Amsterdam. This criterion is the result of the development stage of a measure, the dependencies of measures on external factors and possibly of the implementation horizon of other measures. For example, alginic acid production can only take place when a Nereda process is installed. Thus, the implementation of alginic acid will at the earliest be after Nereda was installed.

For each of the measures in Figure 7 and Table 1 the nine criteria are determined. The spreadsheet resulting from this is presented in Appendix H. Also the calculations behind the data in Appendix H are included in this appendix. Table 4 presents an example of the criteria for the measure where green waste is grinded and transported to WWTPs.

TABLE 4 – EXAMPLE OF CRITERIA FOR A MEASURE (GREEN WASTE DISPOSAL)

General information	Category	Households
	Measure	Green waste disposal
	Description	Waste disposal grinders are installed at households and/or businesses. Therefore, 30% of the green waste is transported to the WWTPs by 2040.
Material flows	Δ water	Extra water use is around 0.28 Mm^3/yr. This is 0.63% of the total water use by households and increases the wastewater flows to WWTPs by 0.33%.
	Δ organic matter	Around 11 kton of kitchen waste from Amsterdam will end up at the WWTPs. This is around 4.7 kton COD, which is an 8.6% increase of the COD transported to the sludge digester.
	Δ phosphorus	The kitchen waste contains around 28 ton P. This leads to a 4.0% increase of phosphorus from Amsterdam and an 3.1% increase of the phosphorus to the sludge digester.
Recovery	Recovery organic matter	The kitchen waste leads to an extra biogas production of 1,101,000 Nm^3/yr, which is an 8.6% increase.
	Recovery phosphorus	Phosphorus is recovered as struvite. Since the phosphorus to the digester increases with 3.1%, the struvite production also increases with 3.1%. This is an extra production of 4.1 ton P/yr.
Value pyramid	Value recovered products	8.6% increase of a value 2 product (biogas) and 3.1% increase of a value 3.3 product (phosphorus).
Implementation	Development stage	Idea to implement in Amsterdam; Proven technology in, for example, the United States
	Dependencies	It is currently illegal to put green waste in the sewers, so legislation has to be changed. Furthermore, water users/green waste producers need to change their behaviour of waste separation and need to install a green waste grinder.
	Implementation horizon	2018 (2 year legislation and research, 1 year implementation)

3.3 Comparison of measures

In this section the criteria per measure are discussed and the most striking differences are mentioned. Therefore, at first the recovering results of the different measures are compared and then the differences and similarities in the implementation of the measures are discussed.

3.3.1. Comparison based on resource recovery

To compare the resource recovery of the measures, the recovering products are summarized in Table 5. The calculations behind these numbers can be found in Appendix H. The material flows and recovered products of 2013 were first used to calculate the expected recovered products in 2040. This ‘ceteris paribus’ situation, or situation where the system undergoes no changes other than the assumed economic and population growth and some climatic changes, is used as the starting point for the calculations of the measures’ impacts. Appendix G shows how the ‘2040 ceteris paribus’ data are calculated.

TABLE 5 – CHANGES OF RESOURCE RECOVERING IMPACT PER MEASURE COMPARED WITH CETERIS PARIBUS IN 2040

Products	**Biogas**	**Cellulose**	**PHA**	**Phosphorus**	**Alginic acid**
unit	*10^6 Nm^3*	*kton*	*kton*	*ton*	*kton*
2013 Current situation	11	0	0	$1.1 \cdot 10^2$	0
2040 Ceteris paribus	12	0	0	$1.3 \cdot 10^2$	0
Measure					
Green waste disposal	1.1	0	0	4.1	0
Water use reduction	0	0	0	0.0	0
Separate urine collection	0.13	0	0	0.9	0
Separate urine treatment	0	0	0	8.5	0
Pharmafilter	3.5	0	0	-8.4	0
More separated sewers	0	0	0	0.0	0
Reduced groundwater infiltration	0	0	0	0.0	0
Primary settling tank	0	0	0	0.0	0
Bioplastic production	-3.3	0	0.47	>0.0	0
Cellulose recovery from primary sludge	-1.4	5.5	0	-1.0	0
Fine-mesh sieve & cellulose recovery	-2.1	7.9	0	-1.0	0
mUCT	0	0	0	0.0	0
Nereda	0.52	0	0	5.2	0
Alginic acid production	-1.4	0	0	5.2	9.5
Thermal hydrolysis	4.2	0	0	>0.0	0
Mesophilic digestion	0	0	0	0.0	0
Thermophilic digestion	2.4	0	0	>0.0	0
Struvite precipitation (‘Fosvaatje’)	0	0	0	0.0	0
Sludge incineration at waste plant	0	0	0	0.0	0
Mono-incineration	0	0	0	0.0	0
Phosphorus recovery from sludge ashes	0	0	0	$6.4 \cdot 10^2$	0

TABLE 6 - LEGEND OF TABLE 5

🟩	Large increase
🟩	Increase
🟨	No change
🟧	Decrease
🟥	Large decrease

Table 5 shows that only a few of the considered measures introduce new products: cellulose, bioplastic and alginic acid. Two of the measures, namely cellulose recovery from primary sludge and the fine-mesh sieve, recover cellulose. Since cellulose would otherwise end up in the sludge and would increase biogas production, these two measures decrease the biogas production. Furthermore, the measures also slightly decrease the struvite production from sludge. In the value pyramid cellulose is valued higher than biogas, so it can be argued that cellulose recovering measures have positive impact on the circularity and sustainability of the wastewater chain.

Phosphorus is valued higher than cellulose and since cellulose production also (slightly) decreases phosphorus recovery, this could be a reason not to implement cellulose recovering measures. This illustrates that decision makers need to choose how much reduction in biogas and struvite production can be compensated by cellulose production. Of course other arguments, like investment costs, sales revenues, required chemicals, etc., should also be considered, but the recovering performance of measures is certainly an important aspect in this choice.

There is only one measure that produces alginic acid. The combination of the Nereda biological treatment method and alginic acid production from the granular sludge can result in 9.5 kton alginic acid. Since alginic acid is an organic compound, the production of biogas from sludge is decreased when alginic acid is removed from the sludge. The extra phosphorus recovery as struvite is thanks to the Nereda process that removes more phosphorus from the wastewater into sludge. With regard to the value pyramid this measure should definitely be considered, since the production of a higher valued products, alginic acid and struvite, only reduces a lower valued product, biogas.

Furthermore, bioplastic production or PHA production also requires organic matter and therefore, the biogas production decreases when this measure is implemented. As was concluded for alginic acid, bioplastic production should be considered since it increases the production of higher valued products at the cost of lower valued products.

Finally, the other measures influence the production of recovered products that are at the moment already produced. These measures can, for example, be combined with the measures that recover new products to increase the production of these products. Chapter 4 presents strategies that combine measures to reach specified goals.

3.3.2. Comparison based on implementation

Besides the resource recovering capacities of measures, also the timing of measures is important when deciding a resource recovering policy. Some measures might not be the best in producing highly valued products, but they might be the best measures that are feasible at this moment in time. For example, cellulose is not the most highly valued product in the value pyramid, but the measures that recover cellulose are further developed than the measures that recover alginic acid or bioplastic. Therefore, it could be considered to recover cellulose until measures that produce higher valued resources reach full development. The decision whether one would invest in a measure that they will likely abandon when those other measures are proven technologies in this case largely depends on finances. Finances are excluded from this research, but one can imagine that when it takes a shorter period of time to recover the costs of cellulose recovery than it takes to develop the alternative measures, the choice for cellulose recovery can still be beneficial. Therefore, development stage, dependencies of external actors and implementation horizons are included in the criteria.

Table 7 presents a summary of the three criteria that influence the implementation of measures. In Appendix H these criteria are described in more detail, so see this appendix for the reasoning behind the information in Table 7.

It is concluded that three main factors should be considered when determining implementation horizons, namely the development stage of measures, the dependencies of measures on external actors and situations and dependencies between measures. In the next paragraphs these factors are discussed using examples from Table 7.

The first factor, presented in the third column of Table 7, is the development stage of the considered measure. In the case of alginic acid production, the development stage of the technology is highly uncertain resulting in high uncertainties in the implementation horizon. At the moment, it is known that alginic acid is present in granular sludge, but how it can be removed from the sludge, at what costs and with what purity is still very uncertain. Therefore, it is not only unclear when the technology will be fully proven, but it is also unclear whether the measure will ever be technically and financially feasible. In some cases, the development of a technology can be reasonably well predicted, but in other cases the timing of the end of development is highly uncertain. The consequence of this is that measures with unpredictable development paths require highly flexible implementation plans.

The second factor, presented in the fourth column of Table 7, is how a measure depends on external circumstances and actors. In the case of bioplastic production, for example, large quantities of sludge and fatty acids are required to make the production profitable. Production of bioplastic requires a complex factory that functions best at a bigger scale. Thus, for bioplastic from wastewater to be a success it would be beneficial to have more water authorities also use their sludge to produce bioplastic. Also, the marketing of the product would benefit from a bigger scale. So, for a water authority to implement bioplastic producing measures, it is dependent on other water authorities. Another example of a dependency on external factors is legislation. At the moment, green waste disposal via sewers is illegal. So, before water authorities can implement green waste disposals changes of legislation and, therefore, the support of politicians are required.

The third and final factor, presented in the fifth column of Table 7, is the implementation horizon based on the development stage, dependencies and the implementation horizon of other measures since some measures depend on others for their success. For example, for Nereda it is better not to have a primary settling tank, for alginic acid production Nereda is a prerequisite, phosphorus can only be recovered from sludge ashes when the sludge in incinerated separately, etc. Thus, when a measure can be implemented depends on when another measure is or can be implemented. So, it is unwise to remove the primary settling tank before you know when the Nereda process is installed and alginic acid production cannot start before this and, thus, implementation of alginic acid production should be matched with implementation of Nereda.

Concluding, it is wise to keep track of development paths of different alternative measures, the developments in the external factors that are important for successful implementation of measures and to consider the interdependencies of measures, when deciding upon a resource recovering strategy and plan.

TABLE 7 - IMPLEMENTATION INFORMATION PER MEASURE (SUMMARY OF APPENDIX H)

Category	Measure	Development stage	Dependencies	Implementation horizon
Households	Green waste disposal	Idea (NL); Proven (e.g. USA)	Legislation and user behaviour and investments.	2018
	Water use reduction	Proven	User behaviour and investments.	From 2015 onwards
Business	Separate urine collection	Pilot/full scale	Behaviour and investments at businesses.	From 2015 onwards
	Separate urine treatment	Pilot/full scale	N/A	After separate urine collection: 2016
	Pharmafilter	Full scale	Behaviour and investments at care facilities.	From 2015 onwards
Collection	More separated sewers	Proven	Investments in houses and road renovation.	Corresponding with (neighbourhood) renovation projects
	Reduced groundwater infiltration	Proven	N/A	From 2015 onwards
WWTP	Primary settling tank	Proven	N/A	Current system / possible replacement in 2035
	Bioplastic production	Lab	Additional sludge / fatty acids producers.	Between 2015 and 2030 and after full scale testing.
	Cellulose recovery from primary sludge	Lab	Market for recovered cellulose (and more suppliers).	2016
	Fine-mesh sieve & cellulose recovery from sievings	Pilot/full scale	Market for recovered cellulose (and more suppliers).	2016
	mUCT	Proven	N/A	Current system / possible replacement in 2035
	Nereda	Full scale/proven	N/A	2020/2035
	Alginic acid production	Idea/lab	Market for recovered alginic acid (and more suppliers).	After implementation of Nereda (2020/2035) and after full scale testing.
	Thermal hydrolysis	Proven	Possibly external sludge is required.	2016
	Mesophilic digestion	Proven	N/A	Current system / possible replacement (in 2035)
	Thermophilic digestion	Full scale	Possibly external sludge is required.	2016
	Struvite precipitation ('Fosvaatje')	Proven	Legislation.	Current system
Sludge disposal	Sludge incineration at waste plant	Proven	Cooperation with AEB	Current system
	Mono-incineration	Proven	Mono-incineration company (and cooperation with AEB).	2020
	Phosphorus recovery from sludge ashes	Lab	Ash processing company (and more suppliers of sludge ashes).	After mono-incineration (2020) and after full scale testing.

4. Four strategies for resource recovery in Amsterdam's wastewater chain

This chapter describes how measures can be combined in strategies and how strategies and measures can be complementary or mutually exclusive. The first section introduces the topic of adaptive policies. In the second section adaptive policymaking theory is used to develop four strategies for resource recovery from Amsterdam's wastewater. The third section presents these four strategies in more detail. And finally, the fourth section presents conclusions about the strategies and measures and summarizes how the strategy development method can be used to develop a coherent and adaptive resource recovering policy.

4.1 Adaptive policies

This section introduces adaptive policymaking. Adaptive policies consider the unpredictability of the future by making policies flexible and adaptable. Then, in the next sections of this chapter, this theory is used to develop strategies.

The idea of adaptive policymaking emerged in the beginning of the twentieth century, but the term 'adaptive policy' did not emerge until 1993 (Swanson et al., 2010). Adaptive policymaking was introduced to explicitly consider uncertainties and complex dynamics of problems being addressed in policymaking (Walker et al., 2001). Adaptive policies are different from the more common fixed or single static policies that are "crafted to operate within a certain range of conditions" (Swanson et al., 2010). These fixed policies have the disadvantages that they fail to exploit opportunities and that they ignore crucial vulnerabilities. Furthermore, they depend on critical assumptions that often fail to hold; resulting in policies with unintended impacts and that do not accomplish their goals (Walker et al., 2001, Swanson et al., 2010).

Adaptive policymaking recognizes that despite the complex, dynamic and uncertain systems it deals with, decisions need to be made (Swanson et al., 2010, Haasnoot et al., 2012). Putting off policy decisions is often undesirable because impacts may be significant when no action is taken, implementation of policy takes time and some strategies may no longer be feasible in the future (Haasnoot et al., 2012). Flexibility or responsiveness of policies preserves the policymaking structure since for many problems, uncertainties will become clearer over the course of time by new information (Walker et al., 2001). Thus, policies should anticipate and plan for the array of conditions that lay ahead (Swanson et al., 2010). So, identification of opportunities, no-regret actions, lock-ins and the timing of actions is necessary to show decision makers what choices they should make immediately and what choices they can postpone based on the long-term objectives (Haasnoot et al., 2013).

4.2 Strategy development

In this research four strategies are made and compared. Since the Regional Water Authority Amstel, Gooi and Vecht, the City of Amsterdam and Waternet have not yet developed specific goals regarding resource recovery from wastewater (see Appendix A.2) the strategies explore four different focus products. The strategies in this research all focus on the maximum production of one product. Strategy A focuses on alginic acid, Strategy B focuses on bioplastic, Strategy C focuses on cellulose and Strategy P focuses on phosphorus. Other resources than the focus product are also recovered in the strategy as long as they do not limit the recovery of the focus product. For these other resources the prioritization of the value pyramid (Figure 8) is used.

Table 8 summarizes the possible compositions of the four strategies; for every measure its compatibility with the strategies is presented. Some measures have a significant positive impact on a strategy's performance or they are essential for the strategy. These measures are marked with an "X". An example of an essential measure is the installation of the Nereda process for production of alginic acid, since alginic acid is produced from Nereda's granular sludge. On the contrary, other measures work against the aims of a strategy. In the example of alginic acid production: maximum alginic acid production takes place when granular sludge production is highest. Therefore, it is best not to install a primary settling tank or fine-mesh before the Nereda installation. Thus, these measures are marked with an "-". Finally, measures that are optional for a strategy are marked with an "O". These measures have no or a small impact on the main goals of the strategy. For example, measures that take place 'downstream' of the production of the focus product are optional.

TABLE 8 –STRATEGY DIAGRAM: POSSIBLE COMPOSITIONS OF STRATEGIES; "—" NEGATIVE INFLUENCE; "O" OPTIONAL; "X" SIGNIFICANT

Category	**Measure**	**Strategy**			
		A Alginic acid	**B Bioplastic**	**C Cellulose**	**P Phosphorus**
Households	Green waste disposal	X	X	X	X
	Water use reduction	O	O	O	O
Business	Separate urine collection	O	O	O	X
	Separate urine treatment	O	O	O	X
	Pharmafilter	O	O	O	O
Collection	More separated sewers	O	O	O	O
	Reduced groundwater infiltration	O	O	O	O
WWTP	Primary settling tank	-	X	X	O
	Bioplastic production	-	X	-	-
	Cellulose recovery from primary sludge	-	-	X	O
	Fine-mesh sieve & cellulose recovery	-	-	X	O
	modified University of Cape Town	-	O	O	O
	Nereda	X	O	O	O
	Alginic acid production	X	O	O	O
	Thermal hydrolysis	O	O	O	X
	Mesophilic digestion	O	O	O	O
	Thermophilic digestion	O	O	O	-
	Struvite precipitation ('Fosvaatje')	O	O	O	X
Sludge disposal	Sludge incineration at waste plant	O	O	O	-
	Mono incineration	O	O	O	X
	Phosphate recovery from sludge ashes	O	O	O	X

As mentioned in the previous section, to develop an adaptive plan it is important to know which measures lead to lock-ins and which measures can be considered no-regret or even win-win measures. Lock-ins are decisions that limit the number options that is possible after this decision. For example, when you would choose to produce bioplastic from primary sludge, you severely discourage cellulose recovery. So, measures that are mutually exclusive often lead to lock-ins. Lock-ins are visible in Table 8 when the labels of a measure differ per strategy. When a measure is significant (X) for one strategy and negative (-) for another, the decision for or against the measure will limit further choices. On the other hand, measures that do not limit the number of options after a decision was made are considered no-regret measures. An example of this is struvite precipitation. This measure can become less effective when more phosphorus is recovered earlier or later in the wastewater treatment process, but it will still have operational benefits that support the decision for its installation. No-regret measures can be recognized when all labels for a measure are significant (X) and optional (O) or when all labels are negative (-) and optional (O). Some measures can also be characterized as win-win measures. These measures are significant for more than one strategy. For example, thermal hydrolysis is (significantly) positive for alginic acid production, phosphorus recovery and biogas production.

In the next section the composition of each strategy is explained. Section 4.4 presents a comparison of the strategies and uses Table 8 and to show lock-ins and no-regret options. This information is presented so it can be used to develop a coherent and adaptive resource recovery policy.

4.3 The four strategies

In this section for each of the strategies its composition is described and summarized in a table. In each of these tables the measures that are included in the strategy are represented by ‘X’ and the measures that are excluded are marked by ‘-‘. Furthermore, for every measure the time when the measure could likely be implemented is presented in the last column of the composition table. This shows when the current situation is changed to the new situation. The table states ‘N/A’ (not applicable) when the measure is not implemented or when the measure is removed. The table states a year with the addition of ‘→’ when implementation is a gradual process. In other cases the table states a year or a range of years, possibly with additional explanation between brackets.

The difference between Table 8 and Tables 9, 10, 11 and 12 is that Table 8 is more flexible. In Table 8 the possible compositions of the strategies is presented and measures that do not greatly impact the resource recovering performance of a measure are marked optional. In this section, for each of the strategies an exact composition is presented: so, without optional measures. For each measure, a choice has been made whether or not it is part of the strategy. This way the composition of strategies is explained in more detail.

Strategy A: Maximization of alginic acid recovery

This strategy is based on the assumption that alginic acid is a recoverable resource from the granular sludge that is produced in the Nereda process. The strategy aims to recover as much alginic acid as possible. Additional resource recovering measures are also implemented in this strategy as long as they do not limit alginic acid recovery. The resources that are higher in the value pyramid of Figure 8 are preferred over resources lower in the pyramid. Therefore, after maximum alginic acid production the focus is on maximum phosphorus recovery, then bioplastic, then cellulose and finally biogas.

To maximize alginic acid production, granular sludge production should be maximized. Thereto, a maximum amount of organic matter should end up at the biological treatment step of the WWTPs. Measures that accomplish higher granular sludge production are green waste disposal and absence of primary treatment (e.g. primary settling tanks or fine-mesh sieves). Furthermore, Pharmafilter and separate treatment of urine have small negative effects on alginic acid production; therefore, they are less desirable.

Table 9 describes the composition of strategy A. Because alginic acid production is not yet possible and Nereda has to be installed first, the strategy is split up into two time periods. The first period is before Nereda is installed and alginic acid can be produced. The measures corresponding with this period prepare for the later maximum production of alginic acid. Then the second period describes the combination of measures that result in maximum alginic acid production. The implementation of measures is described in the last column of Table 9.

In Appendix H it is argued that Nereda will be functional either as soon as possible, which is after the decision has been made, the design is finished and the system is installed (around 2025), or when the WWTP is planned to be renewed (around 2035). Thus, the transfer between the two periods of strategy A will take place either around 2025 or around 2035.

TABLE 9 – COMPOSITION OF STRATEGY A: MAXIMIZATION OF ALGINIC ACID RECOVERY

Measure	**Current**	**Strategy A Before vs. after installation Nereda**		**Implementation**
Green waste disposal	-	X	X	2015 (after thermal hydrolysis)
Water use reduction or reuse	-	X	X	2015→
Separate urine collection	-	-	-	N/A
Separate urine treatment	-	-	-	N/A
Pharmafilter	-	-	-	N/A
More separated sewers	-	X	X	2015→
Reduced groundwater infiltration	-	X	X	2015→
Primary settling tank	X	X	-	N/A
Bioplastic production	-	-	-	N/A
Cellulose recovery from primary sludge	-	X	-	2015-2018
Fine-mesh sieve	-	-	-	N/A
modified University of Cape Town	X	X	-	N/A
Nereda	-	-	X	2025/2035
Alginic acid production	-	-	X	2025/2035 (after Nereda)
Thermal hydrolysis	-	X	X	2015
Mesophilic digestion	X	X	X	N/A
Thermophilic digestion	-	-	-	2015
Struvite precipitation (‘Fosvaatje’)	X	X	X	N/A
Sludge incineration at waste plant	X	-	-	N/A
Mono-incineration	-	X	X	2020 (after current contract)
Phosphate recovery from sludge ashes	-	X	X	2020 (after mono-incineration)

Strategy B: Maximization of bioplastic production

This strategy aims to produce as much bioplastic as possible. In this study, a specific type of bioplastic is considered, namely polyhydroxyalkanoates (PHAs). As with Strategy A, additional resource recovering measures are also implemented in this strategy as long as they do not limit bioplastic production. Also, the value pyramid is used to determine which additional recovering measures are preferred. Therefore, after maximum bioplastic production the focus is on maximum alginic acid recovery, then phosphorus, then cellulose and finally biogas production.

To maximize bioplastic acid production, primary sludge production should be maximized. In this research, two types of bioplastic production are considered and both require primary sludge to produce fatty acids. One type of bioplastic production, called rich culture, also uses a small amount of secondary sludge to create this rich culture. The bacteria in the rich culture then produce PHA from the fatty acids that are created through acidification of primary sludge. The other type of bioplastic production, called mixed culture, also uses the fatty acids from primary sludge. It however includes more use of secondary sludge, which results in higher PHA production, but has negative effects on the quality and use of chemicals. Concluding, PHA production requires primary sludge and some biologically produced secondary sludge. Since a primary settling tank or a fine-mesh sieve separate primary sludge from the influent, one of these measures is required. A primary settling tank is preferred, since it separates more organic matter from the influent. Another comment regarding the use of secondary sludge for bioplastics production is that it is unclear whether granular sludge from Nereda can also be used. However, for this research, it is assumed that granular sludge can also be used to produce fatty acids and PHA. (De Hart et al., 2014)

Measures that increase primary sludge production, and thereby the possibility to produce fatty acids as a carbon source for PHA, have a positive influence in this strategy. Thus, green waste disposal is advised. Since Pharmafilter has a small negative influence on primary sludge production and the organic matter in urine has no significant influence on primary sludge production, these are optional but left out of this strategy. The other household, business and collection measures only influence water flows and, therefore, do not influence PHA production. Since cellulose is an important component of primary sludge, the source for PHA production, no cellulose is recovered in this strategy.

The measures downstream of the PHA-production steps are optional: they do not influence PHA production. These downstream measures are, however, influenced by the PHA production measures. For example, since part of the organic matter is already used for PHA production, less sludge is available for biogas production. So, for these measures recovery of other products is normative. The production of alginic acid will be less than in strategy A, but it is still possible. Because primary sludge and some secondary sludge is used for PHA production, less granular sludge is produced and less alginic acid can be recovered. Furthermore, phosphorus recovery is maximized by struvite precipitation and recovery from sludge ashes.

TABLE 10 – COMPOSITION OF STRATEGY B: MAXIMIZATION OF BIOPLASTIC PRODUCTION

Measure	Current	Strategy B	Implementation
Green waste disposal	-	X	2015 (after thermal hydrolysis)
Water use reduction or reuse	-	X	2015→
Separate urine collection	-	-	N/A
Separate urine treatment	-	-	N/A
Pharmafilter	-	-	N/A
More separated sewers	-	X	2015→
Reduced groundwater infiltration	-	X	2015→
Primary settling tank	X	X	N/A
Bioplastic production	-	X	2020-2030 (a.s.a.p.)
Cellulose recovery from primary sludge	-	-	N/A
Fine-mesh sieve	-	-	N/A
modified University of Cape Town	X	-	N/A
Nereda	-	X	2025/2035
Alginic acid production	-	X	2025/2035 (after Nereda)
Thermal hydrolysis	-	X	2015
Mesophilic digestion	X	X	N/A
Thermophilic digestion	-	-	N/A
Struvite precipitation ('Fosvaatje')	X	X	N/A
Sludge incineration at waste plant	X	-	N/A
Mono-incineration	-	X	2020 (after current contract)
Phosphate recovery from sludge ashes	-	X	2020 (after mono-incineration)

Strategy C: Maximization of cellulose recovery

This strategy aims to recover as much cellulose as possible. Again, additional resource recovering measures are also implemented in this strategy as long as they do not limit cellulose recovery. Furthermore, the value pyramid is used to determine which additional recovering measures are preferred. Therefore, after maximum cellulose recovery the focus is on maximum alginic acid recovery, then phosphorus, then bioplastic and finally biogas production.

To maximize cellulose recovery, the amount of cellulose fibres in wastewater has to be maximal. Therefore, green waste disposal via sewers is part of this strategy. Pharmafilter has a small negative influence on cellulose recovery at the communal WWTP, but cellulose recovery at the Pharmafilter installation can be greater because other organic materials are also added to the wastewater. However, a barrier for cellulose recovery from 'Pharmafilter' wastewater is that the wastewater contains hospital waste and that the cellulose, therefore, would have to be decontaminated. For this study, we assume that cellulose recovery from Pharmafilter is not (yet) possible and that Pharmafilter has such a small impact that it can still be installed. Other household, business or collection measures do not influence the cellulose load of wastewater and are, therefore, optional.

At the WWTP cellulose can be removed from the influent or the primary sludge. The first option is to remove cellulose from the influent using a fine-mesh sieve: the sieving product is mostly cellulose. The second option is to remove cellulose from primary sludge. Therefore, a primary settling tank and a cellulose recovering technology (e.g. a fine-mesh sieve) are necessary. The advantage of this combination is that the hydraulic capacity of the sieve can be smaller since only the primary sludge has to pass the sieve. The calculations in Appendix H show that at the moment more cellulose would be recovered using a fine-mesh sieve instead of a primary settling tank. Therefore, this measure is included in this strategy. However, it is advised to review both options again in future, since both measures are still under development. The measures that lay 'downstream' of these options do not influence cellulose recovery and can, therefore, focus on the other products in the value pyramid.

In this strategy, the first priority after cellulose is alginic acid. Therefore, the Nereda process is installed and alginic acid is recovered from the granular sludge. Then bioplastic production is considered, but this requires primary sludge. Since most of the primary sludge is already recovered as cellulose, bioplastic production is not included in strategy C. After alginic acid is removed from the granular sludge, the remainder is digested to produce biogas, which can be upgraded to green gas. Since cellulose recovery does not impact phosphorus significantly, phosphorus can still be removed from the digested sludge using struvite precipitation. After mono-incineration of the digested sludge more phosphorus can be removed from the ashes.

TABLE 11 – COMPOSITION OF STRATEGY C: MAXIMIZATION OF CELLULOSE RECOVERY

Measure	Current	Strategy C	Implementation
Green waste disposal	-	X	2015 (after thermal hydrolysis and/or cellulose recovery)
Water use reduction or reuse	-	X	2015→
Separate urine collection	-	X	2015→
Separate urine treatment	-	X	2015→
Pharmafilter	-	X	2015→
More separated sewers	-	X	2015→
Reduced groundwater infiltration	-	X	2015→
Primary settling tank	X	-	N/A
Bioplastic production	-	-	N/A
Cellulose recovery from primary sludge	-	-	N/A
Fine-mesh sieve	-	X	2016
modified University of Cape Town	X	-	N/A
Nereda	-	X	2025/2035
Alginic acid production	-	X	2025/2035 (after Nereda)
Thermal hydrolysis	-	X	2015
Mesophilic digestion	X	X	N/A
Thermophilic digestion	-	-	N/A
Struvite precipitation ('Fosvaatje')	X	X	N/A
Sludge incineration at waste plant	X	-	N/A
Mono-incineration	-	X	2020 (after current contract)
Phosphate recovery from sludge ashes	-	X	2020 (after mono-incineration)

Strategy P: Maximization of phosphorus recovery

This strategy aims to recover as much phosphorus as possible. Additional resource recovering measures are also implemented in this strategy as long as they do not limit cellulose recovery. The value pyramid is used to determine which additional recovering measures are preferred. Therefore, after maximum phosphorus recovery the focus is on maximum alginic acid recovery, then bioplastic, then cellulose and finally biogas production.

To maximize phosphorus recovery, the phosphorus load has to be large. Therefore, green waste disposal is beneficial for this strategy. Furthermore, three phosphorus recovering measures are included. The first is separate collection and treatment of urine, because separate treatment of urine recovers more phosphorus from the urine than with precipitation of digested sludge at the communal WWTP. The second measure is struvite precipitation. This measure is already installed at WWTP Amsterdam West and has large operational benefits. Therefore, it is included in the strategy. The third measure is phosphorus removal from sludge ashes. This measure has high removal efficiency.

As a note: it could be argued that struvite precipitation is unnecessary since the removal efficiency of phosphorus removal from sludge ashes is higher, but the struvite from precipitation is a very clean product and this measure has large operational benefits. Therefore, struvite precipitation is also included in this strategy.

Other measures that are implemented concern recovery of the other products in the value pyramid. So, alginic acid is recovered from granular sludge and biogas is produced from the sludge. Bioplastics are not produced since they require primary sludge, which is not produced because it limits alginic acid production. For the same reason no cellulose is recovered.

TABLE 12 – COMPOSITION OF STRATEGY P: MAXIMIZATION OF PHOSPHORUS RECOVERY

Measure	Current	Strategy P	Implementation
Green waste disposal	-	X	2015 (after thermal hydrolysis and/or thermophilic digestion)
Water use reduction or reuse	-	X	2015→
Separate urine collection	-	X	2015→
Separate urine treatment	-	X	2015→
Pharmafilter	-	X	2015→
More separated sewers	-	X	2015→
Reduced groundwater infiltration	-	X	2015→
Primary settling tank	X	-	N/A
Bioplastic production	-	-	N/A
Cellulose recovery from primary sludge	-	-	N/A
Fine-mesh sieve	-	-	N/A
modified University of Cape Town	X	-	N/A
Nereda	-	X	2025/2035
Alginic acid production	-	X	2025/2035 (after Nereda)
Thermal hydrolysis	-	X	2015
Mesophilic digestion	X	X	N/A
Thermophilic digestion	-	-	N/A
Struvite precipitation ('Fosvaatje')	X	X	N/A
Sludge incineration at waste plant	X	-	N/A
Mono-incineration	-	X	2020 (after current contract)
Phosphate recovery from sludge ashes	-	X	2020 (after mono-incineration)

4.4 From four strategies to one coherent plan

By describing for every strategy how different measures affect the main goals of the strategy (as was done in Table 8), strategies can be compared. This comparison can lead to conclusions regarding lock-ins or no-regret measures, which can be used to develop a coherent adaptive resource recovering policy.

The most striking examples of lock-in measures are alginic acid and bioplastic production. Since maximum alginic acid production requires maximum amounts of organic matter in the wastewater at the secondary treatment stage of a WWTP and maximum bioplastic production requires as much primary sludge as possible, maximum production of alginic acid and maximum production of bioplastic do not go together. However, it is possible to install both measures, when reduced production is acceptable. So, bioplastic and alginic acid production are not completely excluding each other, but other aspects like investment cost and market prices of the products become more important when one of the two measures is already installed and the other is considered.

Cellulose recovery is a no-regret measure on the short term. When the technologies for cellulose recovery from primary sludge or from the influent using a fine-mesh sieve have been perfected, cellulose can be recovered. Even though Table 8 suggests conflicts with alginic acid and bioplastic production, cellulose recovering measures can be implemented if they reach return of investment before the measures that produce alginic acid and bioplastic are fully developed. However, it is advised that the choice between the two cellulose recovering measures is postponed by one or two years because both measures are still under development. Concluding, cellulose recovering measures can be implemented in the short term, but in the long run the measures are probably removed to produce alginic acid or bioplastic.

Another no-regret measure is phosphorus recovery from sludge ashes. Even though this measure is still being developed and not all pros and cons of the measure are known, the measure has the advantage of being at the end of the line and is therefore not impacting other measures. Furthermore, phosphorus is a finite chemical, so circularity is more important for this product. Besides recovery from sludge ashes, recovery from urine and recovery from digested sludge are also encouraged, since recovery from urine (e.g. using the SaniPhos system) has a high efficiency and recovery from digested sludge, using the existing struvite precipitation system, has operational benefits and a pure product. A remark concerning combinations of phosphorus recovering measures is however that some measures require minimum phosphorus concentrations for them to be effective. So, before deciding to implement measures up-to-date information regarding these minimum phosphorus concentrations is needed.

The choice for some measures is dependent on the other chosen measures. Thermal hydrolysis could be an example of a win-win measure. Thermal hydrolysis might increase the amount of phosphorus that can be recovered by struvite precipitation and is probably also necessary for alginic acid production. Furthermore, thermal hydrolysis increases the production of biogas from sludge, which could be necessary when cellulose is removed from the sludge, which reduces the degradability of the sludge. So, thermal hydrolysis has many advantages for resource recovery, but the choices for other measures determine how effective thermal hydrolysis will be. Thus, the choice of other measures together with investment and operational costs, increased energy demand and other factors that are not explicitly considered in this research, determines whether thermal hydrolysis is a sustainable choice.

These lock-ins, no-regret measures and other similarities and differences between the strategies presented in Table 8 can be considered when developing a coherent and adaptive resource recovering policy. They show that some measures can be implemented without regrets later on and that other choices are more difficult to undo. Also, when the results of this study are updated and expanded as new information becomes available, opportunities can be seized and threats can be spotted early. Table 8 presents measures' interactions in a well-organized way. When this table is compared with the data in the measures and criteria spreadsheet, the possible order of measures and choices becomes clear. So, using this method to create a resource recovering policy helps develop an adaptive policy that functions well in a highly uncertain future.

5. Discussion

The scope restrictions, described in section 1.2, and other choices that were made in the process of this research have impacts on the conclusions. In this chapter, these impacts are summarized and clarified using examples.

A restriction that has impact on the research is the focus on organic matter and phosphorus in the wastewater part of the water chain. Thus, interactions with other resources, like pharmaceuticals, hormones, metals or nitrogen, are not considered. However, a fully coherent strategy would look at opportunities for win-win situations or risks of creating lock-ins for these materials too. An example of this is Pharmafilter. This measure has negative impacts on resource recovery at the WWTP, but has the possibility of more resource recovery locally and has the added bonus that it enables the removal of pharmaceuticals from hospital wastewater. So, Pharmafilter has positive impacts on resource recovery and wastewater treatment, but these lay outside the scope of this research and are thus not considered. Furthermore, the restriction to the wastewater chain has the effect that resource recovering measures in other parts of the water chain or water cycle are excluded from the research. Prevention of use measures and measures in the drinking-water or surface water part of the water cycle are left out.

Besides the focus on organic matter and phosphorus and the limitation to the wastewater chain, also the set horizon of 2040 limits the considered measures. Since wastewater treatment plants are built to last around 40 years, the sewer system in Amsterdam will take at least 100 years to replace and rigorous changes to the system require a longer transition period than the 25 years that are the scope of this research, larger system changes are not part of this research. An example of this is large scale decentralization of wastewater treatment. This is not considered because the current centralized system does not need replacing until 2035 and it is assumed that it will not be financially feasible to not use this system that is already in place. To still consider these system changes and to show what types of impacts can be expected of such measures, examples of decentralizing measures, like separate urine collection and treatment or Pharmafilter, were implemented on a smaller scale. Furthermore, this study could be expanded to include measures that require longer transition periods if Waternet would like to consider these for their resource recovering plans.

In addition to the fact that not all measures are considered, also some possibly important criteria are excluded from this research. For each measure its impact on the amounts of recovered resources, the value of these resources and the implementation horizon are considered, but when developing a resource recovering plan more factors are worthy of consideration. For example, the costs of implementation and operation of the measures need to be considered. Besides the costs of measures, also the revenue of measures is not considered here. From a financial perspective it is also needed to consider the possible revenue from the sales of recovered resources. Furthermore, different measures use different amounts of energy and chemicals. An example of this is phosphorus recovery from sludge ashes. This measure recovers much phosphorus, but it also requires many chemicals. This makes this measure less desirable because it decreases the overall sustainability of the measure. The consequences of including chemical use as a criterion could therefore result in exclusion of the measure and thereby change the composition of the resource recovering strategies. So, in this research not all criteria were included in the measures and criteria spreadsheet, but ideally they would be added before resource recovering plans are made.

Also, in the determination of the priorities in the value pyramid not all sustainability aspects of the resources were considered. One of these aspects is the relative sustainability of a production method because the decision to recover a resource from wastewater depends on how sustainable this recovering method is compared with the current production method. For example, when the production of alginic acid from seaweed can be controlled better, it might be more sustainable to produce alginic acid in this way. This leaves the organic matter in wastewater for the production of plastics, which are originally produced from oil and could be considered less sustainable. So, when the relative sustainability of production methods would also be considered the order of the resources in the value pyramid could change, which can largely impact the compositions of strategies and the conclusions of this research.

Furthermore, how the strategies were put together, impacts the conclusions considerably. For each strategy resource recovery is maximized for the highest valued product, than the second-highest product, than the third-highest product, etc. The result of this is that the production of one extra ton of bioplastic can be preferred over the production of 100 extra tonnes of cellulose. In reality, this would probably not be the case. As said in the previous paragraphs, the relative sustainability of the production method and financial criteria are required to make a resource recovering plan. These criteria can help decision makers determine how much of one product is more desirable than how much of another product. Therefore, it is advised to look at these criteria and present decision makers the choice between slightly more production of a higher valued product and significantly more production of a lower valued product.

Finally, even though future research is recommended to expand this research, it can be said that to deal with the complexity of developing a coherent resource recovering plan, simplifications of the system needed to be made. Not all measures and all criteria could be considered, but by simplifying the system important considerations regarding coherent resource recovery were unveiled. These considerations, conclusions and recommendation for future research can be found in the next chapter.

6. Conclusions and future research

6.1 Conclusions

Waternet aims for circular resource use by resource recovery. However, it was unclear what resources are present in the wastewater chain, what measures exist to recover these resources and how these measures interact, which made it impossible to create a coherent resource recovering policy for Amsterdam. Therefore, this study aimed to explore alternative coherent viable strategies regarding resource recovery in Amsterdam's wastewater chain, especially focussed on phosphorus and organic matter.

By performing a material flow analysis of the wastewater chain in Amsterdam, conclusions were drawn regarding organic matter and phosphorus flows. Organic matter mostly originates in households and small businesses and grey wastewater and faeces have the largest contributions in these. At wastewater treatment plants, most of this organic matter is transferred into sludge, which is partially digested to produce biogas. This biogas is converted into green gas or used for combined heat and power production. By knowing the organic matter flows to Amsterdam's wastewater treatment plant, the impact of possible contributions of other organic matter sources, like green waste disposal, could be calculated in the measure characterization phase.

More than 85% of the phosphorus in wastewater originates in faeces and urine. Around 90% of phosphorus is stored in sludge, of which 16% is recovered as struvite. The rest of the phosphorus ends up in the ashes of incinerated sludge. This material flow analysis showed that urine is the largest source of phosphorus in wastewater, which was used in the specification of the separate urine collection and treatment measures.

Since interactions of measures are important when measures are combined into strategies, the measures were organized based on their location in the wastewater chain. Upstream measures (e.g. at the water user) were considered, but also measures that influence wastewater collection or treatment and sludge disposal were taken into account. Upstream measures impact the material flows and thereby the downstream measures. For each of the measures nine criteria were summarized. These included changes to resource flows, changes to resource recovery, the relative desirability or value of the recovered products and the implementation horizons. Most measures only change the amount of resources recovered, but other measures also introduce the production of new products, like alginic acid, bioplastic or cellulose. The implementation horizon is important because in complex, dynamic and uncertain wastewater systems it is necessary to know what choices need to be made immediately and what choices can be postponed. For example, cellulose recovery can be implemented in 2015, but bioplastic production is still uncertain and can probably only be implemented by 2030.

Four strategies were developed each focussing on the maximum production of one product: alginate, bioplastic, cellulose or phosphorus. A strategy will also include recovery of the other resources when this does not limit the recovery of the focus product. The compositions of strategies were summarized in Table 8 to show what measures have a significant impact on a strategy, have a negative impact on a strategy or when a measure is optional for a strategy. This distinction shows the possible combinations of strategies and also provides insight into what measures are competing and what measures are complementary. Measures that are part of one strategy but not of another indicate a potential lock-in and measures that could be part of all strategies indicate a no-regret measure. This information together with the implementation horizons of measures, shows how measures can be combined and what decisions can be made immediately and which decisions can be postponed.

The most important conclusions are that bioplastic and alginic acid production are competing. Since bioplastic production requires primary sludge and alginic acid production requires secondary sludge, maximum production of these cannot be done simultaneously. Cellulose recovery is also competing with these two measures because it reduces the available amount of primary and secondary sludge. So, a choice for one of these three measures limits future options and therefore creates a lock-in. However, when the implementation horizons of these three measures are also considered a short term no-regret option is found. Since bioplastic and alginic acid production are still under development and will most likely not be implemented in Amsterdam for at least ten years and cellulose recovery is already possible, cellulose recovery could be implemented for a limited time. If return of investments for this cellulose recovering measure is reached before one of the competing measures can be implemented, this is a short term no-regret measure. So, by looking at interactions between measures and implementation horizons, the decision for cellulose recovery can be made now and it is not yet necessary to choose between bioplastic and alginic acid production.

Regarding phosphorus recovery the following conclusion is drawn: if financial criteria and chemical use do not raise serious objections for phosphorus recovery from sludge ashes and phosphorus concentrations in sludge ashes do not drop below a recoverable minimum, then this is a no-regret measure. Phosphorus recovery from urine and struvite precipitation can become less desirable measures when phosphorus is also removed at the end of the wastewater chain, but these two measures have other advantages that will encourage their implementation as well. Separate urine treatment has a high efficiency and struvite precipitation has operational benefits and a pure product. Thus, implementation of all three measures is possible.

Since it is measure that positively impacts organic matter and phosphorus recovery, thermal hydrolysis is a so-called win-win measure. This measure is probably necessary for alginic acid production, it increases biogas production from sludge and it will likely increase phosphorus recovery as struvite. So, because thermal hydrolysis has many advantages for resource recovery, the sustainability of the measure is determined by which of the other measures are implemented and by how, for example, energy use changes. Therefore, more research into these factors is advised.

By considering interactions among measures, combining measures into strategies with specified goals and looking at measures’ implementation horizons, lock-ins and no-regret measures can be anticipated and policy decisions can be made. Also, when the results of this study are updated and expanded as new information becomes available, opportunities can be seized and threats can be spotted early, which can lead to an up-to-date and coherent resource recovering policy.

6.2 Future research

Based on the discussion and conclusions this section describes recommendations for future research. These are both recommendations to improve or expand this study and recommendations to gain more fundamental insights into resource recovering measures.

As was mentioned in Chapter 5 the scope restrictions chosen for study also restrict the conclusions. Therefore, it is recommended to expand the scope and also consider measures outside the wastewater chain. Prevention of resource use measures are more sustainable than recovering measures because recovery always at least requires energy. By expanding the scope outside the wastewater chain, better suited measures could be found. Also, the focus on organic matter and phosphorus could be widened. By considering other materials, like pharmaceuticals or metals, valuable win-win measures could be found. Finally, more criteria could be considered. In the discussion it was mentioned that costs and benefits concerning money, energy and chemicals should be considered to compare measures and strategies.

Furthermore, it is recommended to assess the sustainability of recovered products and relative sustainability of alternative production methods, since the order in which products are placed in the value pyramid considerably impacts what strategy is preferred. Especially when other materials than organic matter and phosphorus are considered, it is advised to use a different prioritization of materials. This new prioritization can, together with a more complete overview of criteria help decision makers to create a coherent resource recovering plan.

Besides recommendations concerning expansion of this research, also some recommendations concerning resource recovering measures are presented here. At first, it is recommended to study how measures function when they are combined. For many measures their impact is considered in one system, but it is often unclear what the resource recovering efficiency is when it is used when it is combined with other measures. An example of this is the effect of changing the biological treatment process from mUCT to Nereda on the production of bioplastic. Furthermore, to better predict how measures respond to other changes in the system, it is recommended studying material flows more extensively. For example, when not only the incoming and outgoing material flows of WWTPs are known, but also the composition of the water and sludge between different measures at the WWTP, more exact information on the functioning of measures becomes available. Also, the results of research at one WWTP with one type of wastewater can be more easily transferred to another WWTP with different wastewater. Finally, better knowledge of material flows can also help to predict the impacts of measures outside the wastewater chain, like measures that reduce material flows by prevention of use.

References

AGENTSCHAP NL n.d. Bio-energie - Input. *In:* MINISTERIE VAN ECONOMISCHE ZAKEN, LANDBOUW EN INNOVATIE (ed.).

ALFONSO PINA, W. H. & PARDO MARTINEZ, C. I. 2014. Urban material flow analysis: an approach for Bogota, Colombia. *Ecological Indicators,* 42**,** 32-42.

BAARS, E., VAN ESCH, K. J., LODEWIJK, M. & SCHAART, N. 2010. Breed water: Plan gemeentelijke watertaken 2010-2015. Amsterdam, The Netherlands: Waternet.

BATELAAN, M. V., VAN DEN BERG, E. A., KOETSE, E., WORTEL, N. C., RIMMELZWAAN, J. & VELLINGA, S. 2013. Evaluation report Pharmafilter. Amersfoort: STOWA.

BERKHOF, D., DE BRUIN, B., KERSTHOLT, M., KRAAN, R., MISKA, V., PEETERS, T., VAN DER ROEST, H., VERSCHOOR, J., DE KREUK, M. & VAN LOOSDRECHT, M. 2010. Nereda pilotonderzoeken 2003-2010. Amersfoort: STOWA.

BERKHOF, D., KOORNNEEF, E. & JANUS, H. 2012. Thermische slibontsluiting: Pilot-onderzoek naar de mogelijkheden en randvoorwaarden. Amersfoort: STOWA.

BETAPROCESS BIOENERGY. n.d. *The value-pyramid* [Online]. Available: http://www.betaprocess.eu/the-value-pyramid.php [Accessed January 22 2014].

BEUMER, N. May 1, 2014 2014. *RE: Meeting with Waternet's asset manager sewerage.* Type to DE FOOIJ, H.

BIOBASED ECONOMY. n.d. *What is bio-based economy?* [Online]. Available: http://www.biobasedeconomy.nl/wat-is-biobased-economy/ [Accessed January 23 2014].

BISSCHOPS, I. & WEIJMA, J. 2013. Haalbaarheidsstudie urineopslag Heineken Music Hall. Wageningen: Lettinga Associates Foundation.

BLOM, J. J., TELKAMP, P., SUKKAR, G. F. J. & DE WIT, G. G. 2010. Energie in de waterketen. Amersfoort: STOWA.

BUDA, A. R., KOOPMANS, G. F., BRYANT, R. B. & CHARDON, W. J. 2012. Emerging technologies for removing nonpoint phosphorus from surface water and groundwater: introduction. *Journal of Environmental Quality,* 41**,** 621-627.

CADOS. 2014. *Hoe werkt een fijnzeef* [Online]. Available: http://www.cados.nl/cados/finescreen-fijnzeef/ [Accessed October 2 2014].

CBS. 2014. *Statline* [Online]. Available: http://statline.cbs.nl/StatWeb/?LA=nl [Accessed 12 February 2014].

CHEVRE, N., COUTU, S., MARGOT, J., KYI WYNN, H., BADER, H., SCHEIDEGGER, R. & ROSSI, L. 2013. Substance flow analysis as a tool for mitigating the impact of pharmaceuticals on the aquatic system. *Water Research,* 47**,** 2995-3005.

CIRCLE ECONOMY 2013. Circular Amsterdam - Opportunities and action points. Amsterdam, The Netherlands: City of Amsterdam & Circle Economy.

COOPER, J. & CARLIELL-MARQUET, C. 2013. A substance flow analysis of phosphorus in the UK food production and consumption system. *Resources, Conservation and Recycling,* 74**,** 82-100.

DE BRUIN, L. M. M., DE BRUIN, B., VAN DER ROEST, H., VAN BENTEM, A., BERKHOF, D., VAN DIJK, E., VAN GOOL, H., KRAAN, R., KRIJGSMAN, J., VAN DER KUIJ, R., VAN LOOSDRECHT, M., MEINEMA, K., MISKA, V., PRONK, M., VERSCHOOR, J. & WINKLER, M. 2013. Nereda(R) praktijkonderzoeken 2010-2012. Amersfoort: STOWA.

DE HART, N. R., BLUEMINK, E. D., GEILVOET, A. J. & KRAMER, J. F. 2014. Bioplastic uit slib: Verkenning naar PHA-productie uit zuiveringsslib. Amersfoort: STOWA.

DELTARES & TNO 2013. Huishoudelijk afvalwater: emissieschattingen diffuse bronnen. Rijkswaterstaat - Waterdienst.

DERKSEN, J. G. M., ROORDA, J. H. & SWART, D. 2007. Verg(h)ulde pillen: onderzoek naar emissie van geneesmiddelen uit ziekenhuizen. Utrecht: STOWA.

DIENST ONDERZOEK EN STATISTIEK 2010. Stadsdelen in cijfers 2010. Amsterdam: Gemeente Amsterdam.

DUTCH NATIONAL GOVERNMENT. 2013. *Wet milieubeheer* [Online]. Available: http://wetten.overheid.nl/BWBR0003245/Hoofdstuk10/Titel102/Artikel104/geldigheidsdatum_08-12-2013 [Accessed December 8 2013].

EHLERT, P. A. I., VAN DIJK, T. A. & OENEMA, O. 2013. Opname van struviet als categorie in het Uitvoeringsbesluit Meststoffenwet. Wageningen: Wettelijke Onderzoekstaken Natuur & Milieu.

ELLEN MACARTHUR FOUNDATION. 2012. *Towards the circular economy: Economic and business rationale for an accelerated transition: Executive summary* [Online]. Available: http://www.ellenmacarthurfoundation.org/business/reports/ce2012# [Accessed December 8 2013].

ELLEN MACARTHUR FOUNDATION. 2013. *Report Vol. 1 - 2012* [Online]. Available: http://www.ellenmacarthurfoundation.org/business/reports/ce2012# [Accessed December 8 2013].

FIXEN, P. E. 2009. World fertilizer nutrient reserves - A view to the future. *Better Crops,* 93**,** 8-11.

FOEKEMA, H. & VAN THIEL, L. 2011. Watergebruik thuis 2010. Amsterdam: TNS nipo.

GEMEENTE AMSTERDAM 2010a. Kwaliteit van leven in een compacte stad: Duurzaamheidsverslag Amsterdam 2009. *In:* BOUWTOEZICHT, D. M. E. (ed.). Amsterdam, The Netherlands: Gemeente Amsterdam.

GEMEENTE AMSTERDAM. 2010b. *Wat is Cradle to Cradle?* [Online]. Gemeente Amsterdam. Available: http://www.amsterdam.nl/gemeente/organisatie-diensten/dmb/doet-dmb/wat/advies-beleid/milieuadvies/projecten/cradle-to-cradle/ [Accessed November 20, 2013.

GEMEENTE AMSTERDAM 2011. Structuurvisie Amsterdam 2040: Economisch duurzaam en sterk. *In:* DIENST RUIMTELIJKE ORDENING (ed.). Amsterdam, The Netherlands.

GEMEENTE AMSTERDAM 2012. Amsterdamse kringlopen in beeld. *In:* DIENST RUIMTELIJKE ORDENING & STEDELIJKE WERKGROEP GRONDSTOFFEN (eds.). Amsterdam, The Netherlands.

GEMEENTE AMSTERDAM n.d. Amsterdam beslist duurzaam: Duurzaamheidsprogramma 2011/2014. Amsterdam, The Netherlands: Gemeente Amsterdam.

GREENFACTS. 2014. *Natural organic matter* [Online]. Available: http://www.greenfacts.org/glossary/mno/natural-organic-matter-NOM.htm [Accessed August 6 2014].

GROOT, C. & VAN DER WAAL, J. 2009. Notitie Definities, maatlatten en selectiecriteria bij gunning van klimaatneutrale nieuwbouw. Amsterdam: Dienst Milieu & Bouwtoezicht.

HAASNOOT, M., KWAKKEL, J. H., WALKER, W. E. & TER MAAT, J. 2013. Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world. *Global Environmental Change,* 23**,** 485-498.

HAASNOOT, M., MIDDELKOOP, H., OFFERMANS, A., VAN BEEK, E. & VAN DEURSEN, W. P. A. 2012. Exploring pathways for sustainable water management in river deltas in changing environment. *Climatic Change,* 115**,** 795-819.

JANSE, T. 2012. Analyse influentdebieten ter inschatting 'vreemd water' aanvoer. Waternet.

KENNEDY, C., CUDDIHY, J. & ENGEL-YAN, J. 2007. The changing metabolism of cities. *Journal of Industrial Ecology,* 11**,** 43-59.

KLAVERSMA, E. 2013. Transitie naar een circulaire economie - Advies hoe Waternet binnen haar eigen processen kan bijdragen. Amsterdam, The Netherlands: Waternet.

KLAVERSMA, E. 2014a. *RE: E-mail concerning calculations regarding changes WWTP due to water savings.* Type to DE FOOIJ, H.

KLAVERSMA, E. 2014b. Urine inzamelen en duurzaam verwerken. Amsterdam: Waternet.

KNMI. 2014a. *Jaaroverzicht neerslag en verdamping in Nederland (JONV)* [Online]. Available: http://www.knmi.nl/klimatologie/monv/ [Accessed 20 February 2014].

KNMI. 2014b. *KNMI'14 klimaatscenario's* [Online]. Available: http://www.klimaatscenarios.nl/kerncijfers/ [Accessed 15 October 2014].

KRAMER, F., VELDHOEN, A. & SMET, D. 2014. Haalbaarheid van thermofiele slibgisting in Nederland. Amersfoort: STOWA.

KUJAWA-ROELEVELD, K. & ZEEMAN, G. 2006. Anaerobic treatment in decentralised and source-separation-based sanitation concepts. *Reviews in Environmental Science and Bio/Technology,* 5**,** 115-139.

LANSINK, A. 2013. *Ladder van Lansink* [Online]. Available: http://www.adlansink.nl/?page_id=2 [Accessed December 12 2013].

LTO-NEDERLAND, ROYAL COSUN, UNIE VAN WATERSCHAPPEN, VEWIN & RESTSTOFFENUNIE, TWENCE AFVAL EN ENERGIE BV, VAN GANSEWINKEL, VION INGREDIENTS, NV SLIBVERWERKING NOORD-BRABANT, HVC, THERMPHOS INTERNATIONAL BV, ICL FERTILIZERS EUROPE, WAGENINGEN UR (UNIVERSITY & RESEARCH CENTRE), DELTARES, NUTRIËNTEN MANAGEMENT INSTITUUT (NMI), STAATSSECRETARIS VAN INFRASTRUCTUUR EN MILIEU, M. N. M. E. S. V. E. Z., LANDBOUW EN INNOVATIE,, BIORENEWABLES BUSINESS PLATFORM, INNOVATIENETWERK, WASTE, AQUA FOR ALL & NUTRIENT PLATFORM 2011. Ketenakkoord Fosfaatkringloop.

MARQUEZ LUZARDO, N. M. & VENSELAAR, J. 2012. Bio-based targeted chemical engineering education; role and impact of bio-based energy and resource development projects. *Procedia Engineering,* 42**,** 214-225.

MBDC 2012. Design for a Cradle to Cradle future.

MELS, A. 2005. Afvalwaterketen ontketend. Utrecht: STOWA.

MINISTERIE VAN LANDBOUW, NATUUR EN VOEDSELKWALITEIT 2007. Government vision on the Biobased economy for energy transition: 'Closing the chain'.

MOEDERS VOOR MOEDERS. 2014. *Wie is moeders voor moeders* [Online]. Available: http://www.moedersvoormoeders.nl/over-ons/34/wie-is-moeders-voor-moeders.html [Accessed October 2 2014].

MOL, S. & VERVERS, R. 2014. Haalbaarheidsstudie toepassing Pharmafilter bij AMC. Amsterdam: Waternet.

NORTH REFINERY. 2013. *Lansink's ladder* [Online]. Available: http://www.northrefinery.nl/english/vision/lansink%E2%80%99s-ladder.html [Accessed December 8 2013].

NOTENBOOM, G., VERGOUWEN, L., MORGENSCHWEIS, C., VAN SCHOLL, L. & POSTMA, R. 2013. Fosforhoudende producten uit de communale afvalwaterketen: Wet- en regelgeving, marktkansen, verwerkingsconcepten. Amersfoort: STOWA.

PINKSE, H. 2014. Projectidee: Cellulose uit primair slib. STOWA.

REIJKEN, C. October 30, 2014 2014. *RE: Meeting with Chris Reijken.* Type to DE FOOIJ, H.

REINIER DE GRAAF GASTHUIS. n.d. *Pharmafilter* [Online]. Available: http://reinierdegraaf.nl/algemeen/over-reinier-de-graaf/duurzaam-ziekenhuis/pharmafilter/ [Accessed January 21 2014].

ROOS, C. February 20 &21, 2014 2014. *RE: Communication via e-mail.* Type to DE FOOIJ, H.

RUIKEN, C. J., BREUER, G., KLAVERSMA, E., SANTIAGO, T. & VAN LOOSDRECHT, M. C. M. 2013. Sieving wastewater - Cellulose recovery, economic and energy evaluation. *Water Research,* 47**,** 43-48.

SAMUELS, A. 2013. Sustainable development: What is it? *Journal of Planning and Environment Law***,** 1374-1380.

SCHRAP, S. M., RIJS, G. B. J., BEEK, M. A., MAASKANT, J. F. N., STAEB, J., STROOMBERG, G. & TIESNITSCH, J. 2003. Humane en veterinaire geneesmiddelen in Nederlands oppervlaktewater en afvalwater. Lelystad: RIZA.

STICHTING H2O 2014. Thema Afvalwater. *H2O.* Den Haag: Stichting H2O.

STOWA. 2014. *Alginaat terugwinnen uit korrelslib* [Online]. Available: http://www.stowa.nl/projecten/Alginaat_terugwinnen_uit_korrelsib [Accessed August 13 2014].

STOWA, RIONED, S. & KWR 2012. Kennis om goede dingen goed te doen: Kennisagenda Waterketen en Stedelijk Waterbeheer.

SWANSON, D., BARG, S., TYLER, S., VENEMA, H., TOMAR, S., BHADWAL, S., NAIR, S., ROY, D. & DREXHAGE, J. 2010. Seven tools for creating adaptive policies. *Technological Forecasting & Social Change,* 77**,** 924-939.

SWART, B. 2008. Anders omgaan met huishoudelijk afvalwater II. Utrecht: STOWA.

SWINKELS, V. & CLOCQUET, R. 2010. Uitgerekend nul. Agentschap NL.

TONNEIJCK, F. 2008. Over bomen en buien. *Bomennieuws.*

TU DELFT n.d. Wastewater treatment: Lecture notes. TU Delft.

UNIE VAN WATERSCHAPPEN, INTERPROVINCIAAL OVERLEG, VEWIN, MINISTERIE VAN INFRASTRUCTUUR EN MILIEU & VERENIGING VAN NEDERLANDSE GEMEENTEN 2011. Bestuursakkoord Water.

UNITED NATIONS 1987. Our common future.

UNITED STATES CENSUS BUREAU. 2011. *2010 Census data* [Online]. Available: http://www.census.gov/content/dam/Census/programs-surveys/ahs/data/2011/h150-11.pdf [Accessed July 16 2014].

VAN BAAREN, M. 2010. Amsterdam waterbestendig. *Programma Amsterdam Waterbestendig.* Amsterdam, The Netherlands: Gemeente Amsterdam.

VAN DALE. 2013. *Gratis woordenboek* [Online]. Available: http://www.vandale.nl/opzoeken#.Up86gMTuKjw [Accessed December 4 2013].

VAN DER HOEK, J. P., STRUKER, A. & DANSCHUTTER, J. E. M. 2013. Amsterdam as a sustainable European metropolis: Integration of water, energy and material flows. *International Water Week (IWW) Conference " Integrated water solutions for a green economy".* Amsterdam, The Netherlands.

VAN KASTEREN, J. 2013. *Peking: papier hier* [Online]. Available: http://www.trouw.nl/tr/nl/5009/Archief/archief/article/detail/3455765/2013/06/10/Peking-Papier-hier.dhtml [Accessed January 21 2014].

VAN LIER, J. B., HEIJMAN, S. G. J., HUBERT, M. A. J. & HAGG, J. P. De watercyclus; daar zit wat in! 65ste vakantiecursus drinkwater en afvalwater, 2011 Delft. Delft University of Technology.

VAN MILL, G., VERHOEVEN, B. & RIJS, G. B. J. 2006. Monitoring geneesmiddelen en oestrogenen waterschap AA en Maas. Den Bosch: Waterschap Aa en Maas.

VAN VOORTHUIZEN, E., ZILVERENTANT, A. & IJPELAAR, G. 2013. Verkenning mogelijkheden 'grondstof rwzi'. Amersfoort: STOWA.

VERENIGING AFVALBEDRIJVEN 2010. Milieuverslag gft-afval 2009. 's Hertogenbosch.

VERGOUWEN, A. A. 2010. Fosfaat, van leegloop naar kringloop. Amersfoort: STOWA.

VEWIN 2013. Kerngegevens drinkwater 2012. Rijswijk.

WALKER, W. E., ADNAN RAHMAN, S. & CAVE, J. 2001. Adaptive policies, policy analysis, and policy-making. *European Journal of Operational Research,* 128**,** 282-289.

WATERNET 2010. Drinkwaterplan 2010-2015. Amsterdam, The Netherlands: Waternet.

WATERNET 2011. Schoon en veilig water: Publicatie afvalwater 2011. Amsterdam, The Netherlands: Waternet.

WATERNET 2013. Technisch jaarverslag afvalwater 2012.

WATERNET 2014a. Drinkwater: Jaaroverzicht statistiek 2013.

WATERNET 2014b. Technisch jaarverslag drinkwater en afvalwater 2013. Amsterdam: Waternet.

WATERNET n.d. Het draait om water: Watercyclusplan 2010-2015. Amsterdam, The Netherlands: Waternet.

WATERSCHAP AMSTEL, GOOI & VECHT 2010. Waterbeheerplan Waterschap Amstel, Gooi en Vecht 2010 - 2015. Amsterdam, The Netherlands: Waterschap Amstel, Gooi en Vecht.

WORDPRESS. 2014. *Sankey diagrams* [Online]. Available: http://www.sankey-diagrams.com/ [Accessed January 12 2014].

WORLD WATCH INSTITUTE. 2007. *Matters of scale - into the toilet* [Online]. Available: http://www.worldwatch.org/node/5142 [Accessed 17 March 2014].

YUAN, Z., SHI, J., WU, H., ZHANG, L. & BI, J. 2011. Understanding the anthropogenic phosphorus pathway with substance flow analysis at the city level. *Journal of Environmental Management,* 92**,** 2021-2028.

Appendices

Appendix A: Sustainability goals and principles

In this appendix the policies of Waternet, the Regional Water Authority Amstel, Gooi and Vecht and the City of Amsterdam concerning sustainability regarding energy, materials and chemicals are summarized. Therefore, first the concept of sustainability is defined and some general sustainability principles and concepts are introduced. Secondly, sustainability goals and visions for the Amsterdam Metropolitan Area (AMA) regarding energy and materials and chemicals are presented.

A.1 Sustainability

A.1.1 General definitions of sustainability

The terms sustainability and sustainable development have been defined in many different ways. A much used definition is from the United Nations (UN) report 'Our common future': "sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs". Furthermore, Sustainable development contains two key concepts: the concept of needs and the idea of limitations. The concept of needs implies that provision in the essential needs of in particular the world's poor is of overriding importance. The idea of limitations recognizes that the state of technology and social organization limit the environment's ability to meet present and future needs. The definition of the UN report focuses on the needs of all people on Earth and social equity between generations and within each generation. (United Nations, 1987)

Other definitions focus less on the human or societal aspects of sustainability. In most dictionaries only the environmental aspects of sustainability are mentioned. The Dutch dictionary Van Dale describes sustainable as "damaging/influencing the environment as little as possible, for example by using as few materials, chemicals and energy as possible" (Van Dale, 2013). The Longman dictionary of contemporary English also only recognizes the impact on the environment: "able to continue without causing damage to the environment" and their definition of the environment is "the air, water, and land on Earth, which can be harmed by man's activities". So the societal aspects of sustainability that are so important in the UN definition of sustainability are excluded from the dictionary's definitions.

Another observation that can be made regarding the term sustainability is that, besides the numerous definitions, almost all definitions are relatively vague and ambiguous. Samuels (2013) argues that the term sustainable is used frequently in policies and plans because of this ambiguity. Thereby, decision makers can state their intentions for sustainability while leaving considerable scope and flexibility for implementation. This freedom of interpretation has made it possible for many organisations to state their own sustainable goals and guidelines. In the next section the views of Waternet, the Regional Water Authority Amstel, Gooi and Vecht and the City of Amsterdam on sustainability are presented.

A.1.2 Sustainability in Amsterdam

In the Amsterdam Metropolitan Area (AMA) Waternet is responsible for the execution of the water related tasks of the Regional Water Authority Amstel, Gooi and Vecht and of the City of Amsterdam. Therefore, Waternet's interpretation of sustainability has to correspond with the interpretations of the Regional Water Authority and the City.

In the 'Sustainability Report Amsterdam 2009' the definition of sustainability is similar to the one of the United Nations: "In this report sustainable development is regarded as development that offers the present generation optimal quality of life without restricting the quality of life of future generations." In short, the City of Amsterdam defines sustainability as the quality of life in the future. (Gemeente Amsterdam, 2010a)

The focus on quality of life results in a definition that includes both societal and environmental aspects. However, in most other policy documents of the three organisations the focus is mainly on the environmental aspects of sustainability. It is remarkable that most policy documents do not define the concept of sustainability, but use the term frequently and in different contexts. In the next sections some examples of how the term sustainable/sustainability is used in policy documents for the AMA.

Some interpretations of sustainability recognize human or societal aspects. In the 'Bestuursakkoord Water 2011' the national , provincial and municipal governments, regional water authorities and water companies agreed to make common plans for knowledge development regarding the water chain and urban water management (Unie van Waterschappen et al., 2011). The interpretation of this agreement was done by three research organisations and they described sustainable water in the following way: "Sustainable water allows people, the environment and the economy to develop without hindering future generations" (STOWA et al., 2012).

Another example of societal sustainability in the interpretation of the UN can be found in the 'Water cycle plan 2010-2015'. In the document five points are mentioned as to how Waternet wants to become more sustainable. The first three points concern environmental aspects of sustainability, namely investment in sustainability and climate mitigation, reduction of CO_2-emissions and the goal for Waternet's operations to become climate neutral. The last two points focus on equity within a generation:

> Point 4: World Waternet focuses on good water provision and sanitation in a number of developing countries for which it wants to expand its activities in Africa. Thereby, we will contribute to the Millennium Development Goals.
>
> Point 5: The participation in World Waternet has grown from 12 fte in 2012 to 17 fte in 2014
>
> (Waternet, n.d.)

In other policy documents of Waternet, the regional water authority and the City of Amsterdam the focus is mainly on environmental aspects. Policies aiming to become more sustainable propose to use resources like raw materials, energy and water more effectively and to close cycles (Van der Hoek et al., 2013, Gemeente Amsterdam, 2012). Furthermore, anticipating on climate change and reduction of vulnerability are described as features of sustainability (Van Baaren, 2010, Baars et al., 2010).

A.1.3 Sustainability principles and concepts

In this section some sustainability principles and concepts are described. Some of these are explicitly included in policy documents for the AMA, others are implicitly mentioned. First the Ladder of Lansink, second the trias energetica, third cradle to cradle, and fourth the circular economy.

LADDER OF LANSINK

Since a debate regarding national budgets for 1980 Ad Lansink went deeper into the subject of waste management (Lansink, 2013). He determined bullet points for the main features of waste management. One of his statements was that waste separation at the source was better than separation afterwards. Furthermore, he states that reuse is better than recycling and that combustion while regaining resources was better than disposal of combustible waste. However, the very best way to deal with waste regarding Lansink was to prevent the waste. These ideas were converted into a hierarchical ladder with the most desirable ways of management at the top and the least desirable ways at the bottom (see Figure 9). According to Lansink all waste has to be processed at the highest level of the ladder (Klaversma, 2013).

FIGURE 9 – LADDER VAN LANSINK (NORTH REFINERY, 2013)

Lansink's notions were used in the Law for Environmental Management in which the following waste hierarchy is defined: a. Prevention; b. Preparation for reuse; c. Recycling; d. Other useful uses, among which energy recovery; e. Safe disposal (Dutch National Government, 2013). In this law points D and E in Lansink's ladder are combined. Both points are regarded as energy recovery.

TRIAS ENERGETICA

The City of Amsterdam uses the sustainability principle 'trias energetica', which according a sustainability programme report results in optimal CO_2 reduction (Gemeente Amsterdam, n.d.). With this principle three ways to reach sustainable energy supply are used simultaneously: energy saving, sustainable energy production, and more efficient use of fossil energy (Gemeente Amsterdam, n.d.). Thus, trias energetica focuses on energy efficiency and, similar to Lansink's ladder, it also focuses on prevention to improve the environment (Klaversma, 2013).

CRADLE TO CRADLE

All three water organisations in the AMA, Waternet, the regional water authority and the City of Amsterdam, mention the cradle to cradle framework on their websites or in policy documents. With this framework William McDonough and Dr. Michael Braungart want to discourage the notion that design causes problems that need to be solved and encourage the notion that design quality includes positive effects on economic, ecological and social health (MBDC, 2012). With the cradle to cradle framework sustainability is not only looked at as the goal to minimize the harm inflicted on our environment, but more so to optimize positive impacts (MBDC, 2012).

Instead of linear use of resources and energy, cradle to grave, the cradle to cradle framework suggests to close cycles. Using cradle to cradle principles in new designs enables full recovery of all materials, chemicals and energy (Gemeente Amsterdam, 2010b). New products are developed with consideration of future uses of its components. In theory this process of reusing materials is infinite (Gemeente Amsterdam, 2010b). Therefore, the cradle to cradle framework does not encourage prevention of use. It assumes that there is sufficient sustainable energy and that there are sufficient renewable materials available to continue with current consumption patterns (Klaversma, 2013). However, Klaversma (2013) states that, especially in the beginning of transition to an economy of closed cycles, sustainable energy and renewable materials are not yet available in sufficient quantities that prevention of energy and material use can be neglected.

CIRCULAR ECONOMY

A relatively new sustainability approach is the circular economy. In this approach focuses on economic opportunities that arise when the economy evolves from a “resource-constrained ‘take-make-dispose’ model towards one that is circular and re-generative” (Ellen MacArthur Foundation, 2012). The circular economy approach combines circular flows, similar to the cradle to cradle framework, with economy (Van der Hoek et al., 2013). “A circular economy is an economic and industrial system based on the recognition of reusability of products and materials and the recovering capacity of natural resources. It minimizes depreciation in the system and strives for appreciation in every link of the system” (Klaversma, 2013). A report by the Ellen MacArthur Foundation (2012) argues that this appreciation could result in net materials cost savings of 630 billion dollar per year towards 2025 in part of the European manufacturing sector. Thus, this approach focuses on the economic benefits that can arise from sustainable management.

The circular economy focuses on the following three aspects: to prevent depletion of natural resources; to phase out waste, greenhouse gas emission, and use of hazardous materials; and to completely convert to renewable and sustainable energy supply (Klaversma, 2013). So, it aims to prevent depletion but the circular economy approach does not acknowledge that energy or resource consumption must be prevented. Like the cradle to cradle framework, the circular economy approach states that with complete circularity consumption does not have to be restricted. However, Klaversma (2013), who was also cited in the cradle to cradle section, states that, especially in the beginning of transition to an economy of closed cycles, prevention of energy and material use cannot be neglected.

VALUE PYRAMID

It is widely accepted that fossil fuel reserves are shrinking and that a transition to a biomass based economy is necessary. The concept of a biobased economy comprises a wide field in which ‘green resources' are used to produce materials, chemicals, transportation fuels and energy (BioBased Economy, n.d.). Green resources are crops and residues from agriculture and the food industry.

Biomass consists of different components that, after separation, can be used in different ways (Ministerie van Landbouw, 2007). For example, some components can be used to produce fine chemicals; other components can be used to produce heat. In an un-separated form, biomass (residues) can easily be used for food, animal fodder, biogas fermentation and combustion applications (Ministerie van Landbouw, 2007). However, these uses do not present the highest possible economical or ecological values for all components.

The value of biomass, or green resources, is determined by its application (Betaprocess bioenergy, n.d.). Since different components of biomass have different applications, they also have different values. In a biobased economy components should be separated to reach the highest possible economic values (Betaprocess bioenergy, n.d.). The sum of the highest possible economic values of all biomass components can have a higher value for producers than if the entire product is used only for production of electricity or heat (Marquez Luzardo and Venselaar, 2012).

To show the different values of biomass applications, the Dutch Ministry of Agriculture, Nature and Food quality (2007) introduced the value pyramid (see Figure 10). According to this value pyramid, biomass should be used in different steps. First, biomass is used for the most economically interesting applications, after which the residue is used to the greatest extent possible (Marquez Luzardo and Venselaar, 2012).

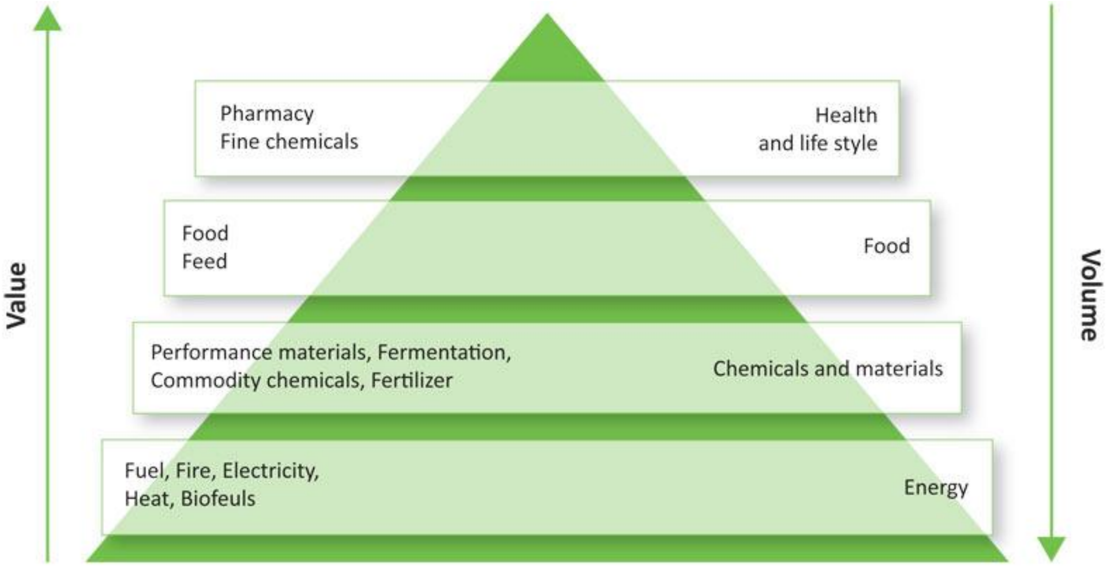

FIGURE 10 – BIOMASS VALUE PYRAMID (BETAPROCESS BIOENERGY (N.D.))

The step-by-step separation of biomass components is called biorefining. Biorefining means that the most valuable components of biomass are first isolated so they can be used for high-value products. Then, components that are used for products of a lower value in the pyramid are isolated. Finally, the residue is used to produce heat, the lowest value type of energy (Ministerie van Landbouw, 2007).

A.2 Goals and visions

The City of Amsterdam, the Regional Water Authority Amstel, Gooi en Vecht and Waternet have described their goals and visions for a sustainable Amsterdam Metropolitan Area (AMA) in numerous documents. In this section these goals and visions are enumerated. In the first part the distinct goals for the AMA are summarized. Not all goals for the AMA are defined as distinct or SMART, which stands for specific, measurable, attainable, relevant and time-bound, goals. Many are described in visions. Therefore, these visions are summarized in the second part of this section.

A.2.1 Distinct goals

The sustainability goals for the AMA are split into two subsections. The first section contains goals regarding energy and the second section contains goals regarding materials and chemicals.

ENERGY GOALS

The City of Amsterdam's main goals are to have a climate neutral municipal organization in 2015 and to reduce CO_2 emissions by 40% in 2025 and by 75% in 2040 (compared to 1990) (Gemeente Amsterdam, 2011, Van der Hoek et al., 2013). Furthermore, construction of new buildings has to be climate neutral from 2015 onwards (Gemeente Amsterdam, n.d., Gemeente Amsterdam, 2012). This includes both residential building and commercial and industrial building.

Waternet wants to become more sustainable in five ways. One of these can be regarded as a distinct energy goal. Waternet aims for its operations to be climate neutral in 2020 (Waternet, n.d.). With this goal it is important to mention that the term 'climate neutral' is debatable. The Dutch 'Reclame Code Commissie', consisting of independent representatives to prevent deception, decided that this term wrongfully suggests that the climate is not at all affected (Swinkels and Clocquet, 2010). Sometimes energy neutral or CO_2 neutral are used as synonyms for climate neutral. Energy neutral is defined by Swinkels and Clocquet (2010) as that the amount of energy that is consumed within the project boundaries has to be equal to the amount of sustainable energy produced within the project boundaries. The definition used by the City of Amsterdam's Environmental and Building Control Department is similar to this definition of energy neutral. It states that for newly built houses the energy demand for a building, which includes all energy for heating, cooling, tap water, and building bound energy use, has to be generated at site or exceptionally in close proximity of the building (Groot and Van der Waal, 2009). The definition excludes domestic energy use by the occupant, but Groot and Van der Waal (2009) expect that the definition will include this within 10 to 15 years.

Finally, Waternet has committed itself to the Climate Agreement of the Association of Regional Water Authorities (Dutch: Unie van Waterschappen). In this agreement targets for energy use and production were set. These targets apply to all the regional water authority's activities. Of the three energy targets Waternet already achieved two: 40% of the energy produced by Waternet is already sustainable (which had to be reached by 2020) and 100% of the energy used by Waternet is already sustainable. The third target, that still has to be met, is to become 30% more energy efficient by 2020 (compared to 2005). Waternet had reduced its energy use by 20% in 2011. (Waternet, 2011)

GOALS REGARDING MATERIALS AND CHEMICALS

In the category of materials and chemicals no specific goals for regaining resources are defined by the three water organizations in the AMA. All statements on materials and chemicals can be considered visions. The only goals that can be found are regarding drinking-water quality. Waternet aims to maintain the best score for the water quality index in the Netherlands: Waternet's standard for this index remains 0.018 or lower (Waternet, 2010). Furthermore, Waternet strives to remove more phosphate (P), nitrogen (N) and Chemical Oxygen Demand (COD) from the wastewater than the national average at the latest benchmark (Waternet, 2011). These goals concern water purification, but they do not focus on regaining materials or chemicals.

A.2.2 Visions

The sustainability visions are also split into two categories. Again, the first contains visions regarding energy and the second contains visions regarding materials and chemicals.

ENERGY VISIONS

The City of Amsterdam has the ambition to develop as a competitive and sustainable city (Van der Hoek et al., 2013). The cradle to cradle framework and the circular economy approach are used as basis for policy development (Gemeente Amsterdam, n.d., Gemeente Amsterdam, 2012). Therefore, the vision is to create closed cycles and initiatives to close cycles have already been taken by Waternet and the Waste & Energy Company (AEB) (Gemeente Amsterdam, 2012).

In several policy documents an impression of the future is given and methods to reach circularity are described. Some methods focus on prevention, even though that is excluded from the cradle to cradle and circular economy theories. Isolation, electrical cars and energy saving new technologies are mentioned as ways to reduce energy demand (Gemeente Amsterdam, 2012, Gemeente Amsterdam, n.d.). Other measures focus on energy recovery or sustainable energy production. Solar panels or wind energy are mentioned (Gemeente Amsterdam, n.d., Gemeente Amsterdam, 2012). However, most measures focus on energy recovery and sustainable energy production. Sewage treatment plants are described as energy factories where faeces and sludge are sources of energy (Waterschap Amstel, 2010, Gemeente Amsterdam, 2012). Sludge is fermented to produce gas, which is used as fuel for cars, and the remainder of the sludge is incinerated to produce heat or electricity (Waterschap Amstel, 2010, Gemeente Amsterdam, 2012). Furthermore, reuse of heat receives much attention. For instance, warm household wastewater, e.g. shower water, will be used as a source of heat within the household. On a smaller scale both heat and cold from industrial and domestic sources are planned to be stored in the ground (Gemeente Amsterdam, 2012, Gemeente Amsterdam, n.d., Gemeente Amsterdam, 2011). The earth is used as a source for heat in the winter and as a heat sink in the summer. The City of Amsterdam also wants to focus on district heating (Dutch: stadsverwarming) (Gemeente Amsterdam, 2012). The aim is to build a large continuous ring of district heating that is connected to power plants and sustainable energy sources.

VISIONS REGARDING MATERIALS AND CHEMICALS

As mentioned in the section on the energy visions, cradle to cradle and circular economy are used basis for policies in the AMA. The aim is to close cycles and use resources like raw materials effectively to prepare for a future with reduced availability of materials and chemicals (Van der Hoek et al., 2013, Gemeente Amsterdam, n.d.). The City of Amsterdam recognizes that the closing of cycles is mostly urgent because of this reduced availability of phosphate and other materials and chemicals (Gemeente Amsterdam, 2012).

By 2050 Waternet would like to reuse all usable components (minerals, energy and clean water) in wastewater (Baars et al., 2010). This ambitious vision is in line with the cradle to cradle framework and the circular economy approach. The Regional Water Authority Amstel, Gooi and Vecht also recognizes these theories as important, which is shown in its vision for 2027. In this vision wastewater flows are considered resources (Waterschap Amstel, 2010). The regional water authority would like to regain phosphate and reuse the effluent of water treatment plants. Furthermore, it would like to remove contaminants that hinder reuse or discharge to surface waters (Waterschap Amstel, 2010).

The City of Amsterdam describes a future with separate wastewater flows so the wastewater can be used effectively (Waterschap Amstel, 2010). Grey water, which includes residues from washing processes, and black water, which contains pathogens from toilets, are separated at household level. Grey water is purified to such a level that it can be used to flush toilets and perhaps so it can also be used to water plants in gardens. From black water phosphate, nitrogen and potassium are regained. From the remaining wastewater flow the remainders of medication and raw materials for bioplastics and the paper industry are regained. (Gemeente Amsterdam, 2012)

For many materials and chemicals the focus is currently on purification to prevent them to get into the environment. For example, remainders from medication and substance that influence hormones are removed from the water so they can do no harm, but they are not yet removed so they can be used again. Phosphate is an example of a substance that is already removed for reuse as well as for wastewater purification. In the next paragraph visions for phosphate are summarized.

The City of Amsterdam has described their most desirable future in 'Amsterdam's cycles described' (Dutch: Amsterdamse kringlopen in beeld) (Gemeente Amsterdam, 2012). The vision is that phosphate ore is no longer imported. Phosphate will only be imported through biomass. The phosphate cycle will be completely closed, because secondary phosphate is regained for the agricultural sector and fertilizer production. Phosphate is among others regained from domestical wastewater. Black water, containing faeces and urine, is treated locally and phosphate and other raw materials are regained. A first step towards a closed phosphate cycle has already been taken by signing the 'Green deal ketenakkoord Fosfaatkringloop' agreement (Gemeente Amsterdam, 2012). In this agreement twenty parties declare their ambitions to create a sustainable market for secondary phosphate within two years (LTO-Nederland et al., 2011). In this market, as much reusable phosphate as possible will be brought back into the phosphate cycle in an environmentally sound way.

A.3 Application of the value pyramid in this research

In this research measures are compared that impact the production of alginic acid, phosphorus, bioplastic, cellulose and biogas. To determine which measures are preferred over others, a prioritization of the desirability of the products is established. The value pyramid is used to rank the products from most desirable to least desirable. This section of Appendix A describes how the products are ranked and why some products are valued higher than others (see Figure 11).

Since this research only focuses on organic matter and phosphorus, only products related to this are ranked in the value pyramid. However, in another research it is of course possible to include other products. It should be noted that the ranking of products is largely subjective and, therefore, the ranking will be different depending on who makes it. The way in which this method can be used, however, remains the same.

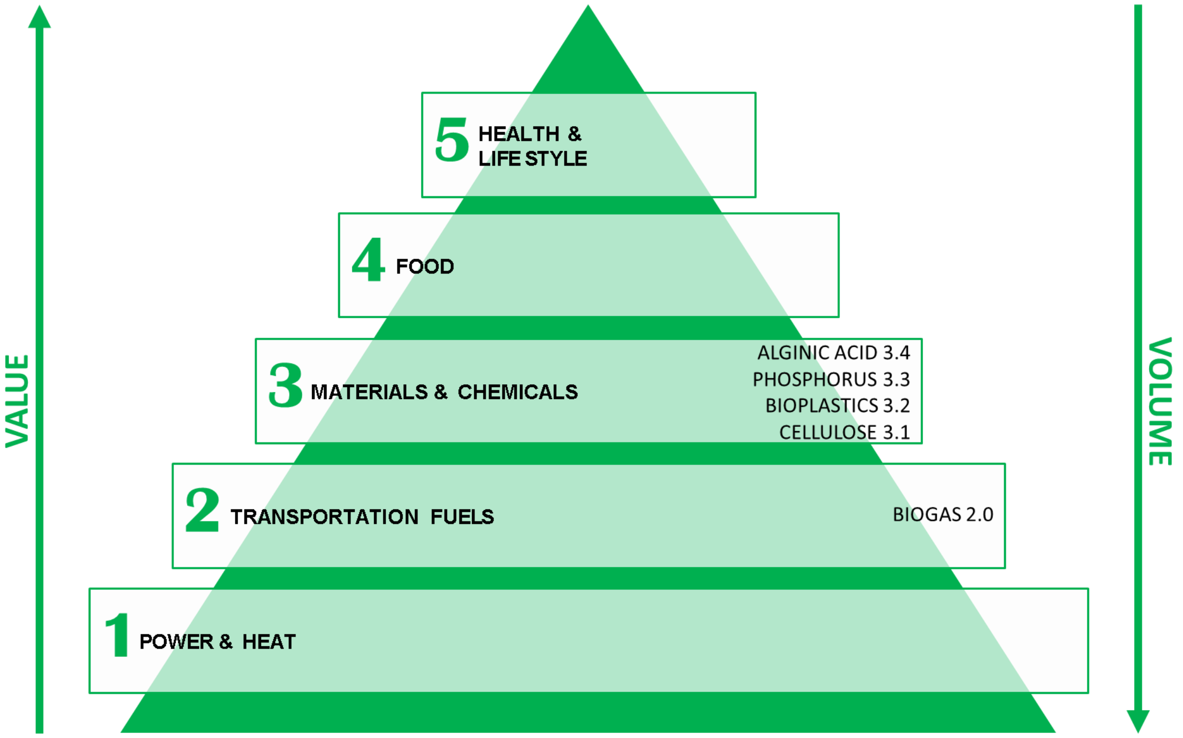

FIGURE 11 – VALUE PYRAMID (ADAPTED FROM BETAPROCESS BIOENERGY (N.D.))

The lowest valued product is biogas. Biogas is currently produced by sludge digestion. Biogas consists of methane and carbon dioxide and can be used to produce green gas (which has higher methane content), carbon dioxide and/or electricity and heat using combined heat and power technology. From the products that are considered this is valued the lowest. Biogas is placed in category 2: transportation fuels, since it can be used to make green gas. Biogas can also be used to produce power and heat, which belong in category 1. Biogas itself is, however, placed in category 2 due to its highest possible use. A remark with this is that from a value perspective, biogas can best be used to produce green gas and not to produce heat and power.

The other four considered products, cellulose, bioplastic, phosphorus and alginic acid, are placed in category 3: materials and chemicals. In the next paragraphs these products are described and compared. The comparison is made to rank the products within the category.

Cellulose is the polysaccharide of which the fibres in toilet paper consist. The fibres can be used to produce building materials and paper products and, therefore, cellulose is placed in category 3, materials and chemicals. Cellulose is valued lower than bioplastic, phosphorus and alginic acid, because those three other products have closer links to categories 4: food and 5: health and lifestyle. Also, traditional production of cellulose, so production not from wastewater, is a renewable process. Since cellulose is traditionally produced from wood.

Because bioplastic is also a material, it is also placed in category 3. Like cellulose, bioplastic also has no close links to food and health and lifestyle. However, because the traditional resources for plastic are fossil fuels, bioplastic is valued higher than cellulose. Since fossil fuel stocks are decreasing, traditional oil based plastic production is not assessed sustainable.

The nutrient phosphorus is a chemical and therefore, falls in category 3. But because phosphorus is necessary for food production (category 4) it is valued higher than cellulose and bioplastic. Furthermore, phosphorus stocks are decreasing and, therefore, alternative, more sustainable are desirable.

Finally, alginic acid is valued highest. This polysaccharide can be used in the pharmaceutical or food industry and it thus has close links with both categories 4 and 5. So, even though alginic acid falls into the third category, it is valued highest within this category.

Appendix B: Exploration of resources in Amsterdam’s water chain

This exploration of resources in Amsterdam’s water chain was done for the years 2009-2012. After the focus resources were chosen, the material flows were calculated for 2013.

B.1 Organic matter

Chemical and biochemical oxygen demand

Chemical and biochemical oxygen demand (COD and BOD) are measures for the organic substances in the wastewater. Organic compounds are formed mainly from carbon, hydrogen and other elements. Examples of carbons in domestic wastewater are carbohydrates, fats, proteins and urea, which is present in urine. In the determination of the COD most organic compounds are chemically oxidised using potassium dichromate as an oxidizing agent. The consumed amount of oxygen is calculated by comparing the difference between the added amount of potassium dichromate and the remains.

In the determination of the BOD bacteria oxidize biochemical oxidizable elements. The BOD is determined by comparing the oxygen content before and after oxidation. The BOD test takes 5 days at a water temperature of 20°C. Not all biochemical oxidizable elements are completely oxidized in this experiment. Therefore, the BOD value is lower than the COD. Even though the BOD does not represent all oxidizable components, it is a better measure for the concentration of (aerobic) biodegradable components that decomposed by aerobic micro-organisms.

The BOD/COD ratio can be used as an indication of biological treatability of wastewater. TU Delft (2008) mentions that a ratio of 2 or less shows aerobic treatability of wastewater, whereas a ratio of more than 2.5 indicates less treatable wastewater. In Amsterdam the average ratio for the period 2009-2012 was 2.3. The removal percentage of organic matter however still high; even though water treatment in Amsterdam is only biological and not chemical.

Table 34 shows the COD and BOD values for the influent and effluent at Amsterdam’s WWTPs. Due to recirculation of wastewater from dewatering processes in which also sludge of WWTPs from outside Amsterdam is dewatered, the values for WWTP Amsterdam West’s effluent are actually slightly lower.

TABLE 13 – CHEMICAL AND BIOCHEMICAL OXYGEN DEMAND IN AMSTERDAM’S WASTEWATER

2009-2012	**Influent WWTPs** [ton/year]	**Effluent WWTPs** [ton/year]	**Removal** [%]
Chemical oxygen demand (COD)	40,041	2,582	93.6
Biochemical oxygen demand (BOD)	17,193	219	98.7
Ratio BOD/COD	2.33		

For resource recovering and removal of organic matter also concentrations are important. Therefore, the concentrations of BOD and COD for both Amsterdam WWTPs are presented in Table 14.

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TABLE 14 – COD AND BOD CONCENTRATIONS IN WWTP INFLUENT

2009-2012	WWTP Amsterdam West	WWTP Westpoort	Amsterdam
COD load [kg/year]	29,682,778	10,357,744	40,040,522
Average COD concentration [g/L]	0.519	0.678	0.553
BOD load [kg/year]	12,544,394	4,649,015	17,193,410
Average BOD concentration [g/L]	0.219	0.304	0.237

Cellulose

Not much research has been done regarding cellulose in wastewater. Cellulose fibres are present in toilet paper. Ruiken et al. (2013) tested cellulose recovery with fine sieves at the Waternet WWTP in Blaricum. They found that fine sieves remove approximately 40 to 50% of suspended solids and that about 80% of the sieving product was cellulose. If these percentages are combined with the suspended solids data of Amsterdam's WWTPs the cellulose content of Amsterdam's wastewater is between 6010 and 7512 ton/year or 7.7 and 9.7 kg/p/year.

When the cellulose load is calculated based on toilet paper consumption slightly higher values are found. A toilet paper consumption of 7.7 as was found in the earlier calculations seems to be too low an estimate and the 15 kg/p/year Van Kasteren (2013) mentions seems too high. It is most likely that about 10 kg/p/year of cellulose ends up in the wastewater.

TABLE 15 – TOILET PAPER CONSUMPTION (WORLD WATCH INSTITUTE, 2007)

	Toilet paper use [kg/p/year]	Total use Amsterdam [ton/year]	Toilet paper as percentage of suspended solids [%]
Minimum range Ruiken et al. (2013)	10	7787	41.5
Stowa (2013)	10.8	8410	44.8
Average range Ruiken et al. (2013)	11.5	8955	47.7
Maximum range Ruiken et al. (2013)	13	10123	53.9
World watch institute (2007)	13.8	10746	57.2
Trouw (2013)	15	11681	62.2

B.2 Phosphorus

Waternet measures the phosphorus load of influent at WWTPs. For WWTPs Amsterdam West and Westpoort these loads are presented in the table below.

TABLE 16 – OVERVIEW PHOSPHATE INFLUENT WWTPS (WATERNET, 2013)

2009-2012	P-tot influent [kg/year]	Factor [-]	P-tot influent Amsterdam [kg/year]
WWTP Amsterdam West	455,460	0.94	428,133
WWTP Westpoort	193,575	0.77	149,052
Total	649,035		
		Influent WWTPs:	577,185

The total inflowing amount of phosphorus is 577 ton P per year. The phosphorus is removed from the wastewater in sludge. The total amount of phosphorus in the effluent that is attributed to Amsterdam from WWTP Westpoort is 9,865 kg per year. The rest of the phosphorus, 139,181 kg/year is transported via primary and secondary sludge to WWTP Amsterdam West.

TABLE 17 - OVERVIEW PHOSPHATE EFFLUENT WWTPS (WATERNET, 2013)

2009-2012	**P-tot effluent** [kg/year]	**Factor** [-]	**P-tot effluent Amsterdam** [kg/year]
WWTP Amsterdam West	40,540*	0.94	38,107*
WWTP Westpoort	12,811	0.77	9,865
Total	53,351		
		Effluent WWTPs:	47,972*

The phosphorus flows at WWTP Amsterdam West are however much more difficult to model. Due to recirculation of wastewater at the WWTP and due to additions of sludge from other WWTPs it is difficult to attribute phosphorus at this WWTP to the City of Amsterdam. Therefore, the phosphorus amounts in Table 10 are marked with asterisks. Determination of the origin of the phosphorus in the effluent requires extensive calculations that are not performed at this moment. Perhaps later when the consequences of measures at WWTPs need to be known these calculations will be performed.

Overview origin phosphates at households

The Foundation for Applied Water Research (Dutch: Stichting toegepast onderzoek waterbeheer, Stowa) has published a report that describes the results from a workshop concerning the future of phosphorus and water (Vergouwen, 2010). The workshop focused on moving towards circularity. In this report some data on the origin of phosphates. Most phosphate enters the water chain via black wastewater: more than 80% of phosphates enter the water chain via urine or faeces. Some of the numbers presented in the report are summarized in the table below. The data were presented for the whole of the Netherlands, but these are transformed into data for Amsterdam using inhabitant ratios.

TABLE 18 – ORIGIN OF PHOSPHATES AT HOUSEHOLDS

	P-content in urine/faeces [ton/year]	**Food intake** [ton /year]	**Calculated using ratios** [ton /year]
Urine	340.7 - 851.7	277.4	288.6 (50.0%)
Faeces	243.3 - 632.7	204.4	206.1 (35.7%)
Grey wastewater	19.5 - 111.9	N/A	82.5 (14.3%)
Total	*603.5-1596.3*	*(incomplete) 481.8*	*577.2 (100%)*

When this data is combined with the data concerning household water use it can be calculated that 85.7% of phosphorus is flushed with 23.8% of the drinking- water use by households. This 494.7 kg of phosphorus is transported in 8.8 Mm^3 of water, which is 12.2% of the wastewater arriving at the WWTPs. The removal percentage of phosphorus for Amsterdam is 92%, so this can be nearly achieved by separately collecting black wastewater. When urine would be collected separately the wastewater would contain 50% less phosphorus. The separated urine flow then contains 50% of phosphorus in 0.6% of the water usually treated at Amsterdam's WWTPs, namely 0.4 Mm^3.

B.3 Nitrogen

Nitrogen is present in wastewater in various forms: organically bound nitrogen, like proteins, and inorganic nitrogen, like ammonia (NH_3) or ammonium (NH_4^+). The organically bound nitrogen content can be determined using the Kjeldahl method. This quantity is also known as Kjeldahl-nitrogen (N-Kj). However, this is not a measure for all nitrogen in the wastewater. In the oxidation of ammonium also nitrate (NO_3^-) and nitrite (NO_2^-) form. Therefore, the total quantity of nitrogen (N-tot) measures both N-Kj and nitrate and nitrite. The classification of types of nitrogen is summarizes in Table 19. (TU Delft, n.d.)

TABLE 19 – CLASSIFICATION OF NITROGEN INTO N-KJ AND N-TOT

	Kjeldahl-nitrogen (N-Kj)	**Total nitrogen (N-tot)**
Organically bound nitrogen (e.g. proteins or amino acids)	●	●
Ammonia (NH_3) **& ammonium** (NH_4^+)	●	●
Nitrate (NO_3^-) **& nitrite** (NO_2^-)		●
Nitrogen gas (N_2)		

Waternet measures the nitrogen load of influent at WWTPs. For WWTPs Amsterdam West and Westpoort these loads are presented in the table below. For the influent N-Kj and N-tot are the same. This means that no nitrate or nitrite is measured.

TABLE 20 – OVERVIEW NITROGEN IN INFLUENT WWTPS

2009-2012	**N influent** [kg/year]	**Factor** [-]	**N influent Amsterdam** [kg/year]
WWTP Amsterdam West	3,407,990	0.94	3,203,510
WWTP Westpoort	1,215,254	0.77	935,746
Total	4,623,244		
		Influent WWTPs:	4,139,256

The total inflowing amount of nitrogen is 4,139 ton N per year. The total outflowing amount of nitrogen that is attributed to Amsterdam from WWTP Westpoort is 96,812 kg per year. The rest of the nitrogen either transported via primary and secondary sludge to WWTP Amsterdam West or has left the WWTP as nitrogen gas (N_2).

TABLE 21 - OVERVIEW NITROGEN IN EFFLUENT WWTPS

2009-2012	**N-tot effluent** [kg/year]	**N-Kj effluent**	**Factor** [-]	**N-tot effluent Amsterdam** [kg/year]	**N-Kj effluent Amsterdam**
WWTP Amsterdam West	472,576*	168,244*	0.94	444,222*	158,149*
WWTP Westpoort	125,730	49,862	0.77	96,812	38,394
Total	598,306	218,106			
			Influent WWTPs:	541,034	196,543

The nitrogen flows at WWTP Amsterdam West are however much more difficult to model. Due to recirculation of wastewater at the WWTP and due to additions of sludge from other WWTPs it is difficult to attribute nitrogen at this WWTP to the City of Amsterdam. Therefore, the nitrogen amounts in Table 10 are marked with asterisks. Determination of the origin of the nitrogen in the effluent requires more data and extensive calculations that are not performed at this moment. Perhaps later when the consequences of measures at WWTPs need to be known these calculations will be performed.

Overview origin of nitrogen at households

Most of the nitrogen that arrives at the WWTPs originates from household wastewater. Humans excrete nitrogen via urine and faeces. Also detergents and organic matter contain nitrogen. In Table 22 a summary of the origin of nitrogen according to different authors is presented. Swart (2008) presents two studies that differentiate nitrogen discharge of households into discharge via urine, via faeces and via grey water. Urine and faeces contain more than 90% of the nitrogen in household wastewater. As with phosphates, nitrogen in urine and faeces is highly concentrated. When urine and faeces were collected separately 91-97% nitrogen reduction could be achieved while only reducing the amount of wastewater by 0.6%. Black water, here defined as urine, faeces and the water that is used to flush toilets, carriers more than 90% of nitrogen while only involving 12.2% of all wastewater.

TABLE 22 – ORIGIN OF NITROGEN AT HOUSEHOLDS

	N-content [ton/year]	**N-content** [%]	**N-content (chosen)** [ton/year]
Urine	3126-3129	11-12	476 (11.5%)
Faeces	426	80-85	3415 (82.5%)
Grey water	125-358	3-9	248 (6.0%)
Total	*3667-3911*	*100*	*4139 (100%)*
Other data	*2844-3911*		

The row 'other data' in Table 22 presents the range of the N-content of household wastewater according to Netherlands Statistics (CBS), TU Delft and TNO & Deltares (CBS, 2014, TU Delft, n.d., Deltares and TNO, 2013). Some of these values are based on daily or yearly loads per person, like the TU Delft approximation of 10 g/p/day, other values are based on registration of emissions, like the CBS data.

B.4 Metals

Wastewater contains heavy metals. For example, these can enter the sewer system via storm water. Metal on roofs, on roads or in water pipes can end up at WWTPs. Table 23 shows at what concentrations metals are found in Amsterdam's wastewater.

TABLE 23 - HEAVY METALS AT AMSTERDAM'S WWTPS

	Metals in sludge			**Metals in effluent**			**Total**
	[kg/year]	[%]	[mg/kgds]*	[kg/year]	[%]	[g/L]*	[kg/year]
Arsenic	126	69.9	8.9	54	30.1	0.74	180
Cadmium	13	74.9	1.0	4	25.1	0.06	18
Chrome	450	94.5	31.8	26	5.5	0.36	476
Copper	7,986	96.1	564.8	323	3.9	4.45	8,309
Mercury	15	95.2	1.1	1	4.8	0.01	16
Lead	1,772	99.2	125.3	15	0.8	0.20	1,787
Nickel	329	64.5	23.3	181	35.5	2.50	510
Zinc	14,971	85.4	1058.9	2,561	14.6	35.33	17,532
Total	*25,663*	*89.0*		*3,165*	*11.0*		*28,827*

* The concentrations are calculated by dividing the load by total quantity of sludge or effluent. Therefore, these concentrations are no time averaged concentrations as would be found by measurements.

Most of the metals that are present in urban wastewater leave the WWTPs via sludge. After digestion, the sludge contains high concentrations of heavy metals. In Amsterdam no additional treatment is done to remove more metals from the effluent. By sedimentation of sludge enough heavy metals are removed to discharge the effluent into surface waters.

For arsenic and mercury concentrations in drinking-water are also measured since these metals are highly toxic. For arsenic the maximum concentration that was measured in 2012 is 2.6 µg/L and the average concentration was 1.0 µg/L. This results in 55.1 kg of arsenic that enters the wastewater via drinking-water per year. This is nearly one third of the total load. For mercury all measurements found concentrations < 0.02 µg/L. Therefore, the maximum load of mercury in the Amsterdam's drinking-water is 1.1 kg/year. So, at most 7% of the mercury in wastewater can be attributed to drinking-water.

B.5 Pharmaceuticals

The amount of pharmaceuticals in wastewater can be determined using measurements or using emissions per person. In Table 24 measurements of two sources are summarized.

The first is Schrap et al. (2003). They measured 101 pharmaceuticals in 15 pharmaceutical groups. For these pharmaceuticals the minimum measurements were smaller than the detection levels. However, the maximum concentrations could be detected and these were multiplied by the effluent quantity of Amsterdam's WWTPs.

The second source for pharmaceuticals measurements is Van Mill et al. (2006) via Derksen et al. (2007). They monitored pharmaceuticals and oestrogens for the Regional Water Authority Aa and Maas. The concentrations they measured are multiplied by the effluent quantity of Amsterdam's WWTPs to reach the pharmaceuticals loads for the influent and effluent.

TABLE 24 – PHARMACEUTICAL LOADS AT AMSTERDAM'S WWTPS

Source:	(Schrap et al., 2003)		Van Mill et al. (2006) via Derksen et al. (2007)		
	Number of measured substances	**Maximum load WWTPs** [kg/year]	**Amount of measured substances**	**Load influent WWTPs** [kg/year]	**Load effluent WWTPs** [kg/year]
Antibiotics	51	318.9	4*	79.0	40.6
Antiparasitic agents	1	1.1	-		
Coccidiostats	3	3.0	-		
Analgesics	11	1,159.5	3	534.1	92.8
X-ray dye / contrast medium	10	797.2	5	1,484.2	365.3
Cholesterol-lowering agents	7	558.0	-		
Beta-blockers	7	130.4	-		
Anticonsulvants	2	144.9	1	31.9	37.0**
Anesthetics	1	4.6	1	12.3	10.9
Total	93	3,117.7	14*	2,141.5	546.4

* Not all measurements were for both influent and effluent

** Loads are calculated based on concentrations and the influent/effluent quantities of WWTPs in Amsterdam. In Amsterdam influent and effluent are assumed the same for practicality. Therefore, when effluent concentrations are larger than influent concentrations, the load can increase. Where it is more likely that the load is equal or smaller and the effluent flow is smaller.

Van Voorthuizen et al. (2013) also presented a metoprolol, a beta-blocker, concentration of 2.7 µg/L in wastewater. This would mean a load of 196 kg/year in Amsterdam. Derksen et al. (2007) presented some emission data of three pharmaceuticals. Carbamazapine is an anticonsulvant, diclofenac is an analgetic and bezafibrate is a cholesterol-lowering agent. These pharmaceuticals were also measured by Van Mill et al. (2006) and are therefore presented side-by-side in Table 25.

TABLE 25 – COMPARISON EMISSION DATA AND WASTEWATER MEASUREMENTS OF THREE PHARMACEUTICALS

	Derksen et al. (2007)		Van Mill et al. (2006) via Derksen et al. (2007)	
	Emission [mg/p/year]	**Load** [kg/year]	**Load influent** [kg/year]	**Load effluent** [kg/year]
Carbamazepine	65.1	50.7	31.9	37.0
Diclofenac	51.0	39.7	26.8	31.2
Bezafibrate	9.0	7.0	33.3	8.7

B.6 Other resources

Potassium

Mels (2005) present an average potassium concentration in Dutch wastewater of 14 mg/L. When this is multiplied by the wastewater inflows at Amsterdam's WWTPs the yearly load for Amsterdam is approximately 1015 tons.

Sulphur

Van Voorthuizen et al. (2013) present sulphate (SO_4^{2-}) concentrations of between 20 and 35 mg SO_4 -S/L in Dutch wastewater. For Amsterdam, using the average influent over 2009-2012, this would be 1449 to 2537 ton SO_4-S/year.

Waternet's measurements of drinking-water present sulphate concentrations of between 3 mg/L and 44 mg/L with an average concentration of 23 mg/L. When this average concentration is multiplied by the amount of drinking-water that is distributed in Amsterdam a total sulphate load of 1323 tons per year is found.

Van Voorthuizen et al. (2013) state that the sulphate in wastewater is already present in drinking-water. This can also be concluded from the calculations above. Roughly between 50 and 90 percent of sulphate in wastewater was also present in drinking-water.

Appendix C: Calculation of Amsterdam's water chain

As an example of water flows in Amsterdam's water chain, some rough values are presented for the year 2013. However, differences between years can be quite large; deviations of 10 to 20% are common. In the overview the year 2013 is chosen as it is the most recent year for which drinking-water production and wastewater treatment data is available.

C.1 Drinking-water production and distribution

In 2013 of the total yearly production of 86.5 Mm^3, 18.1 Mm^3 was produced for other waterworks like Dunea and PWN. Of the remaining production 56.3 Mm^3 was supplied in Amsterdam. In the large drink-water distribution network about 2 Mm^3 of this was lost due to leakages in the pipes, 16.3 Mm^3 was distributed to businesses and 38.9 Mm^3 to households. These data are presented in the Annual overview of drinking-water statistics 2013 (Waternet, 2014a). Cobus Roos, data-analyst at Waternet, provided information on how much water was distributed in Amsterdam. (See Table 26)

TABLE 26 – OVERVIEW DRINKING-WATER PRODUCTION AND DISTRIBUTION

		Water quantity [Mm^3]
Total production	86.5	
Distribution to Waternet area	68.4	
Distribution to Amsterdam	57.2	
- **Consumers**		38.9
- **Business (big users)**		4.3
- **Business (small users)**		12.0
- **Leakage**		2.0

C.2 Overview of household water use

Many different studies looked at how much water is used by households and how this water is used (Foekema and Van Thiel, 2011, Swart, 2008, Vewin, 2013). Concluding, for the Netherlands values between 120 and 137 litres per person per day are found. Statistics Netherlands (CBS) presents yearly data on water usage by consumers and industry: on average in the period 2009-2011 consumers used 129.6 l/p/day (CBS, 2014). Foekema and Van Thiel (2011) present water usage data based on socio-demographic characteristics: for example age, household size, sex, region and ethnicity. The quantities that are used in this study and that are presented below are average values for three big cities in the Netherlands: Amsterdam, Rotterdam and The Hague. These values, total usage is 130.4 l/p/day, correspond roughly with the drinking-water use in Amsterdam, 133.5 l/p/day (Roos, 2014) and the CBS-data, 129.6 l/p/day. A disadvantage of the data from Foekema and Van Thiel (2011) is that the most recent year for which they present their findings is 2010.

The biggest difference between the average household water use in The Netherlands and in the three big cities is water use for showering. In the big cities people shower more frequently and also longer (Foekema and Van Thiel, 2011).

Table 27 shows the average household water use for The Netherlands, the three big cities and for Amsterdam. The data for The Netherlands and three big cities is bases on a study by Foekema and Van Thiel (2011). The total water use per person in Amsterdam is provided by Roos (2014) and the distribution of the household water use is calculated using the distribution of the three big cities.

TABLE 27 – HOUSEHOLD WATER USE (FOEKEMA AND VAN THIEL, 2011, ROOS, 2014)

	The Netherlands		**Amsterdam, Rotterdam & The Hague**		**Amsterdam**	
	[l/p/day]	[%]	[l/p/day]	[%]	[l/p/day]	[m^3/yr]
Shower	48.6	40.5	61.2	46.9	62.7	18.3
Toilet flushing	33.7	28.1	31.0	23.8	31.7	9.3
Laundry	15.4	12.8	15.0	11.5	15.4	4.5
Dish washing	6.1	5.1	6.0	4.6	6.1	1.8
Bath	2.8	2.3	2.7	2.1	2.8	0.8
Kitchen sink	5.3	4.4	6.3	4.8	6.4	1.9
Food preparation	1.4	1.2	1.3	1.0	1.3	0.4
Coffee & tea	1.2	1.0	1.4	1.1	1.4	0.4
Drinking	0.6	0.5	0.7	0.5	0.7	0.2
Bathroom sink	5.0	4.2	4.8	3.7	4.9	1.4
Total	*120.1*	*100.0*	*130.4*	*100.0*	*133.5*	*38.9*

C.3 Foreign wastewater

Sewers transporting wastewater are not completely closed. Some sewers are cracked allowing for water to flow out or in. In Amsterdam many of the sewers are (partially) below groundwater levels. In this case groundwater can infiltrate into the sewers increasing the amount of wastewater arriving at WWTPs. Theo Janse, researcher at Waternet, studied the origin of wastewater for each of the WWTPs operated by Waternet (Janse, 2012). The method he used was a time series analysis. Janse compared daily influent data at WWTP with precipitation data and groundwater flows and levels. Table 28 shows the findings of the study. Jansen mentioned that the results are quite uncertain and deviations should be expected.

TABLE 28 - CALCULATIONS DRY WEATHER FLOW, STORM WATER AND GROUNDWATER INFILTRATION FOR AMSTERDAM (JANSE, 2012)

	2009 [%]	**2010** [%]	**2011** [%]	**Average (2009-2011)** [%]	**2013 [Mm^3]**
WWTP Amsterdam West					60.3
- **Dry weather flow**	75.5	74.0	72.7	74	44.6
- **Storm water**	16.5	17.4	19.4	18	10.9
- **Groundwater infiltration**	8.0	8.6	7.9	8	4.8
WWTP Westpoort					14.6
- **Dry weather flow**	76.4	72.3	72.4	74	10.8
- **Storm water**	13.2	12.6	14.3	13	1.9
- **Groundwater infiltration**	10.4	15.1	13.3	13	1.9
Amsterdam					**74.9**
- **Dry weather flow**					**55.4**
- **Storm water**					**12.8**
- **Groundwater infiltration**					**6.7**

Based on the study of Janse and the effluents of Amsterdam's WWTPs dry weather flows, storm water flows and groundwater infiltration values are calculated (see Table 28). Due to uncertainties in the results of the study and the fact that Janse's study was performed for the years from 2009 to 2011 and the results are transferred to 2013, the resulting dry weather flow, storm water flow and groundwater infiltration values can be different.

The dry weather flow of 55.4 Mm^3 seems reasonable since 55.2 Mm^3 is distributed to households and businesses (see Drinking-water). In the next section the amount of storm water is discussed.

C.4 Storm water

The Royal Netherlands Meteorological Institute (KNMI) provides information regarding precipitation and evaporation. As is shown in Table 29 there was slightly more precipitation in 2013 compared to the average of 2009-2011, which is 910.2 mm. Rainfall was approximately 3% more than in the period 2009-2011.

TABLE 29 – PRECIPITATION AT MEASURING STATION AMSTERDAM (KNMI, 2014A)

	2009 [mm]	2010 [mm]	2011 [mm]	2012 [mm]	**2013** **[mm]**
Precipitation Amsterdam	861.9	942.2	926.6	1156.1	939.8

Of the total land surface of Amsterdam roughly 25% is connected to a combined sewer system and 75% is connected to a separated sewer system (Van Baaren, 2010). The rainfall falling in the area with a combined sewer system infiltrates into the ground, flows directly to surface water, evaporates and the remaining water ends up in the sewers. Therefore, how much water is transported in the sewers depends on the impervious surface in the area. Tonneijck (2008) states if 35 to 50% of the surface is impervious 30% of rainfall flows into the sewers and if 75 to 100% of the surface is impervious 55% of rainfall flows into the sewers (see Table 30).

TABLE 30 – STORM WATER IN DRY WEATHER SEWERS OR COMBINED SEWERS

	2009 [Mm^3]	2010 [Mm^3]	2011 [Mm^3]	2012 [Mm^3]	**2013** **[Mm^3]**
30% rainfall to sewers	10.7	11.7	11.5	14.3	11.6
55 % rainfall to sewers	19.6	21.4	21.0	26.3	21.3

The storm water quantity of 12.8 million m^3 found in the calculations of the foreign wastewater seems reasonable. For Amsterdam this would mean that 33% of the rainfall in the area with combined sewers is transported to the WWTPs.

C.5 Influent WWTPs

The influent at WWTPs is not registered in reports, because all removal performances need to be compared to the effluent quantity. Therefore, the value presented here is an average value of the effluent from the WWTPs Amsterdam West and Westpoort found in the Technical annual report wastewater 2013 (Waternet, 2014b). The actual influent will be larger than the measured effluent since water evaporates in the treatment process and water in screen waste, sand and sludge is transported separately and therefore is not measured as effluent but is part of the influent. At WWTP Amsterdam West the screen waste and grease is roughly 2500 ton in 2013. How much of this is water is unclear. The amount of digested sludge that is transported to AEB contains around 70,000 m3 of water. Furthermore, sludge from other WWTPs is transported to WWTP Amsterdam West for sludge treatment. This sludge contains water that partially contributes to the effluent of WWTP Amsterdam West because the digested sludge is dewatered there. Because the differences between the influents and effluents at WWTP are relatively small, the influent is assumed to be equal to the measures effluents.

Not all water that is treated at WWTPs Amsterdam West and Westpoort originates in Amsterdam. At WWTPs Amsterdam West and Westpoort roughly 94% and 77% respectively are attributed to the City of Amsterdam (Waternet, 2014b). Thus, the value presented as 'influent WWTPs' in the overview is the sum of 94% of the effluent of WWTP Amsterdam West and 77% of the effluent of WWTP Westpoort (see Table 31).

TABLE 31 – CALCULATION EFFLUENT WWTPS 2013

2013	**Effluent** [m^3]	**Factor** [-]	**Effluent Amsterdam** [m^3]
WWTP Amsterdam West	64,172,037	0.94	60,321,715
WWTP Westpoort	18,930,235	0.77	14,576,281
Total	83,102,272		**74,897,996**

In 2013 74.9 million m^3 of Amsterdam's wastewater ended up at WWTPs Amsterdam West and Westpoort. To put this number into perspective the effluents of the years 2010 till 2013 are presented in Table 32. It can be noticed that the effluents change, but that the range in the past four years is less than 4 million m^3 per year.

TABLE 32 – EFFLUENTS AMSTERDAM 2010-2013

	2013 [Mm^3]	**2012** [Mm^3]	**2011** [Mm^3]	**2010** [Mm^3]	***2010-2013*** *[Mm^3]*
WWTP Amsterdam West	60.3	60.2	58.3	57.4	*59.0*
WWTP Westpoort	14.6	15.8	14.6	15.6	*15.2*
Total Amsterdam	74.9	76.0	72.9	73.0	*74.2*

C.6 Dry weather flow, groundwater and storm water conclusion

TABLE 33 – SUMMARY OF WATER FLOWS IN AMSTERDAM'SWASTEWATER CHAIN

	Minimum [Mm^3]	**Maximum** [Mm^3]	**Chosen value** [Mm^3]
Dry weather flow	52.4	55.2	53.8
Groundwater infiltration	6.3	7.4	7.4
Storm water	11.6	21.3	13.7
Total influent WWTPs			***74.9***

Dry weather flow values: It is likely that not all distributed water ends up in the sewers. Part of the water evaporates, is used in gardening or is removed from the water chain in another way. Therefore it is assumed that between 95 and 100% of the supplied drinking-water flows into the sewers as dry weather flow.

Groundwater infiltration: When the minimum percentages for groundwater infiltration are used for WWTPs Amsterdam West and Westpoort, respectively 7.9 and 10.4%, a value of 6.3 Mm^3 is found. When the maximum percentages for groundwater infiltration are used for WWTPs Amsterdam West and Westpoort, respectively 8.6 and 15.1%, a value of 7.4 Mm^3 is found. In 2010 the rainfall was approximately the same as in 2013 therefore these groundwater infiltration percentages are used and the total infiltration of 7.4 million m^3 is found.

Storm water: How much precipitation ends up in the combined sewers is difficult to determine. Based on the study by Janse (2012) the contribution of storm water to the WWTPs influents is around 12.3 million m^3. Based on the storm water runoff percentages by Tonneijck (2008) values between 11.6 and 21.3 million m^3 are possible.

Because of the great differences in storm water estimates, this quantity is used to complete the overview. The storm water flow is calculated as the total influent WWTPs minus the dry weather flow and groundwater infiltration.

C.7 Effluent

As was mentioned at the calculation of the influents of the WWTPs the effluent and influent flows are considered equal for calculation purposes. The effluent is measured for each of Waternet's WWTPs and is calculated as in Table 31. The effluent of Amsterdam is 74.9 million m^3.

Appendix D: Wastewater treatment

Wastewater treatment in Amsterdam is performed at two WWTPs, namely Westpoort and Amsterdam West. Both WWTPs are located in the western harbour.

D.1 WWTP Westpoort

At WWTP Westpoort wastewater is treated from households in the west of Amsterdam and from the bigger businesses in the harbour. Primary treatment is done by bar screens, primary settling tanks and sludge screens. The bar screen have wide openings to remove large contaminations, like plastic bags and small branches. In the primary settling tank flow velocities are low causing settling of suspended particles. The suspended particles converged on the bottom of the tank from which it is removed to go through a sludge screen. This sludge screen removes relatively large contaminants. The primary sludge that results has only a few percent dry matter. The primary sludge is transported via pipes to the WWTP Amsterdam West. Figure 12 summarizes wastewater treatment at WWTP Westpoort.

After the primary treatment the wastewater is transferred to a series of biological treatment tanks (Figure 13). Together these form the modified University of Cape Town process. The sludge that accumulates in the clarifier, a secondary settling tank, is transported to the WWTP Amsterdam West for sludge treatment.

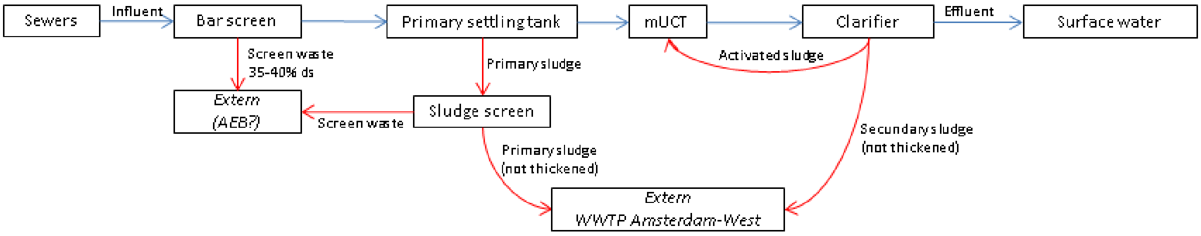

FIGURE 12 – WASTEWATER TREATMENT AT WWTP WESTPOORT

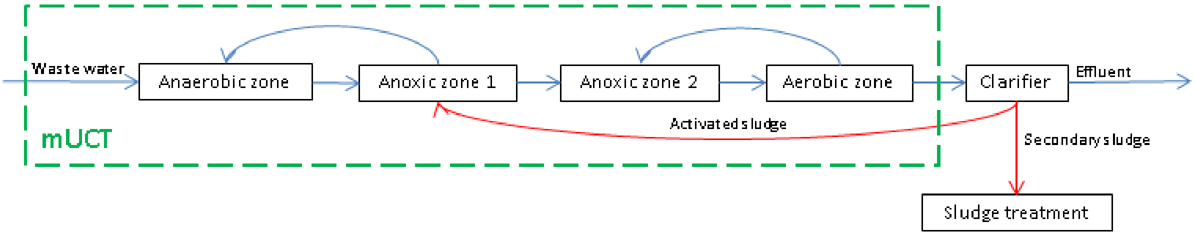

FIGURE 13 – MODIFIED UNIVERSITY OF CAPE TOWN PROCESS FOR BIOLOGICAL WASTEWATER TREATMENT

D.2 WWTP Amsterdam West

At WWTP Amsterdam West wastewater is treated from the rest of the households in Amsterdam and of small businesses. Wastewater treatment at Amsterdam West is the same as at Westpoort primary and secondary treatment consist of the same steps. The difference between the plants is the sludge treatment (see Figure 14).

At WWTP Amsterdam West the sludge of Amsterdam West and Westpoort is thickened. The primary and secondary sludge are kept separately during these steps. The primary sludge is thickened using gravity and the secondary sludge is thickened mechanically to achieve a dry matter content of 5-6%. Subsequently, the sludge of WWTP Amsterdam West, WWTP Westpoort and other WWTPs of

Waternet is digested. The digestion tank is an anoxic heated environment where bacteria break down longer organic molecules into smaller carbon molecules, namely carbon dioxide and methane. These gasses are than partially used to produce green gas, but mostly they are used to produce heat and cold. All these products, so the gasses and the heat and cold, are sold to other companies.

Besides the carbon dioxide and methane, sludge remains after digestion. This digested sludge is transferred to the struvite installation. This installation produces struvite, a phosphorus salt. After this step water is removed from the sludge one more time before the sludge is transported to AEB for incineration.

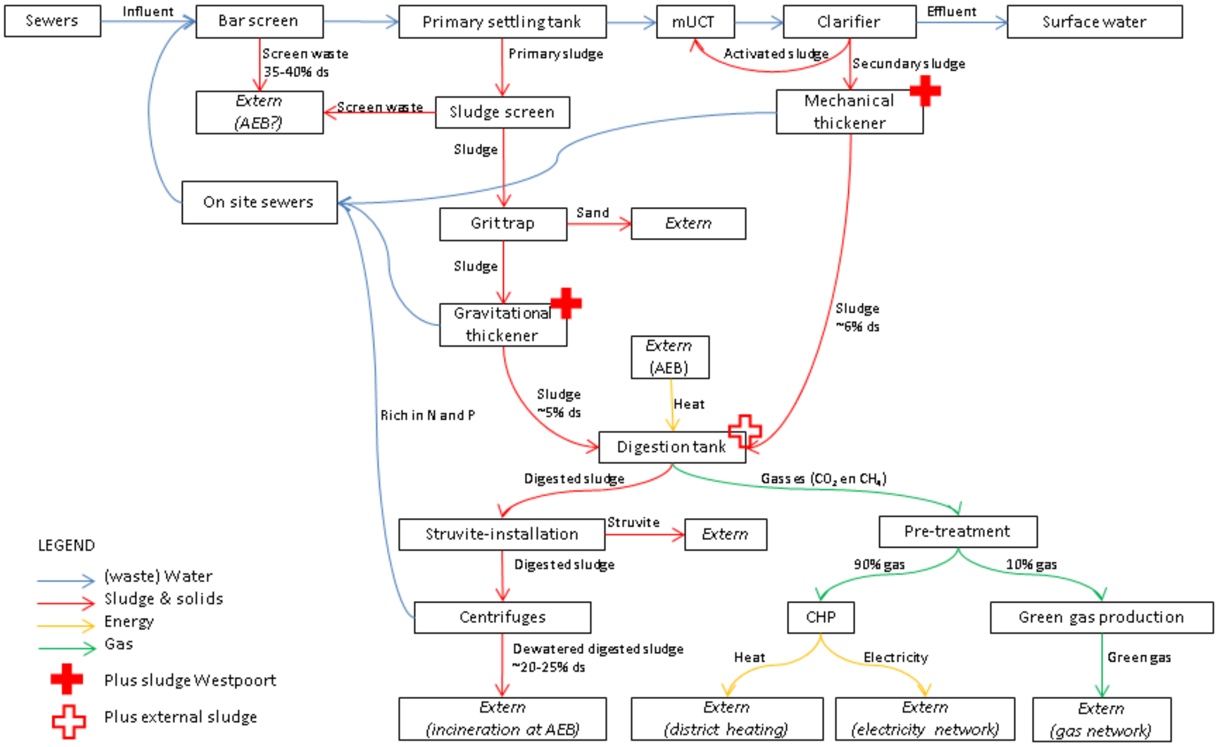

FIGURE 14 – WASTEWATER TREATMENT AT WWTP AMSTERDAM WEST

Appendix E: Calculations of resource flows

E.1 Organic matter

Chemical and biochemical oxygen demand influent

Chemical and biochemical oxygen demand (COD and BOD) are measures for the organic substances in the wastewater. Organic compounds are formed mainly from carbon, hydrogen and other elements. Examples of carbons in domestic wastewater are carbohydrates, fats, proteins and urea, which is present in urine. In the determination of the COD most organic compounds are chemically oxidised using potassium dichromate as an oxidizing agent. The consumed amount of oxygen is calculated by comparing the difference between the added amount of potassium dichromate and the remains.

In the determination of the BOD bacteria oxidize biochemical oxidizable elements. The BOD is determined by comparing the oxygen content before and after oxidation. The BOD test takes 5 days at a water temperature of 20°C. Not all biochemical oxidizable elements are completely oxidized in this experiment. Therefore, the BOD value is lower than the COD. Even though the BOD does not represent all oxidizable components, it is a better measure for the concentration of (aerobic) biodegradable components that decomposed by aerobic micro-organisms.

The BOD/COD ratio can be used as an indication of biological treatability of wastewater. TU Delft (2008) mentions that a ratio of 2 or less shows aerobic treatability of wastewater, whereas a ratio of more than 2.5 indicates less treatable wastewater. In Amsterdam the average ratio for the period 2009-2012 was 2.3. The removal percentage of organic matter however still high; even though water treatment in Amsterdam is only biological and not chemical.

Table 34 shows the COD and BOD values for the influent and effluent at Amsterdam's WWTPs. Due to recirculation of wastewater from dewatering processes in which also sludge of WWTPs from outside Amsterdam is dewatered, the values for WWTP Amsterdam West's effluent are actually slightly lower.

TABLE 34 – CHEMICAL AND BIOCHEMICAL OXYGEN DEMAND IN AMSTERDAM'S WASTEWATER

2013	**Influent WWTPs** [ton/year]	**Effluent WWTPs** [ton/year]	**Removal** [%]
Chemical oxygen demand (COD)	41,933	3,156	92.5
Biochemical oxygen demand (BOD)	18,533	334	98.2
Ratio BOD/COD	2.26		

As was done for the water flows, the influent quantities of COD are calculated using 77% of the influent load of WWTP Westpoort and 94% of the influent load of WWTP Amsterdam West.

Origin of organic matter in wastewater: cellulose

Not much research has been done regarding cellulose in wastewater. The fibres in toilet paper are cellulose, a polysaccharide. At Waternet's WWTP in Blaricum, Ruiken et al. (2013) tested cellulose recovery by using fine-mesh sieves. They found that fine sieves remove approximately 40 to 50% of suspended solids and that about 80% of the sieving product was cellulose. If these percentages are combined with the suspended solids data of Amsterdam's WWTPs removal of cellulose from Amsterdam's wastewater could be between 6133 and 7666 ton/year or 7.7 and 9.6 kg/p/year.

When the cellulose load is calculated based on toilet paper consumption slightly higher values are found. A toilet paper consumption of 7.7 kg/p/year as was found in the earlier calculations seems to be too low an estimate and the 15 kg/p/year Van Kasteren (2013) mentions seems too high. It is most likely that about 10 kg/p/year of cellulose end up in the wastewater. The Amsterdam population would then dispose of nearly 8,000 tonnes of cellulose each year. For the rest of the calculations it is assumed that the wastewater contains 10 kg of cellulose per person per year. A summary of other possible values is presented in Table 35.

TABLE 35 – TOILET PAPER CONSUMPTION

	Toilet paper use [kg/p/year]	Total use Amsterdam [ton/year]	Toilet paper as percentage of suspended solids [%]
Minimum from fine-mesh sieve	7.7	6,133	32.0
Maximum from fine-mesh sieve	9.6	7,666	40.0
Minimum range Ruiken et al. (2013)	10	7,993	41.7
Stowa (2013)	10.8	8,632	45.0
Average range Ruiken et al. (2013)	11.5	9,192	48.0
Maximum range Ruiken et al. (2013)	13	10,391	54.2
World watch institute (2007)	13.8	11,030	57.6
Trouw (2013)	15	11,989	62.6

To determine which part of the organic matter in the influent of Amsterdam's WWTPs is cellulose, the theoretical oxygen demand is calculated. Therefore the oxidization formula is constructed and the weight ratio of cellulose and oxygen is determined. The theoretical COD value is the required mass of oxygen to oxidize the cellulose.

$$6n\, O_2 + (C_6H_{10}O_5)_n \rightarrow 6nCO_2 + 5nH_2O$$

Since the molecular mass of O_2 is 31.998 u and of cellulose is 162.141 u, the weight ratio $O_2 : C_6H_{10}O_5$ is 191.988:162.141. Therefore, the 7,993 ton of cellulose in Amsterdam's household wastewater makes up 9,464 ton COD, which is 22.6% of the influent's total COD.

A remark with this has to be made. The COD of cellulose that is presented here is the theoretical COD and not the actual COD as would be determined using the COD test with potassium dichromate. The COD determined with the test would be lower since not all cellulose would oxidize within the test's time frame and under the test's conditions.

Origin of organic matter in wastewater: other household sources

Besides cellulose, the origin of COD is in urine, faeces and greywater. Kujawa-Roeleveld and Zeeman (2006) present data from several European sources (see Table 36). It is unclear in what category toilet paper is placed in this article, but it is assumed that is excluded from the overview since grey water is defined as "all wastewater other than toilet" (Kujawa-Roeleveld and Zeeman, 2006, p. 119). In Table 36 the total for Amsterdam is calculated by multiplying the daily personal loads with the amount of inhabitants in Amsterdam in 2013 and by the number of days per year. The data from toilet paper is based on the calculations in the last section. The total in Table 36 corresponds with the COD load found at the WWTPs of Amsterdam since that is around 42 kton. For representation in the Sankey diagram values are chosen that add up to the total in the influent.

TABLE 36 – ORIGIN OF COD (KUJAWA-ROELEVELD AND ZEEMAN, 2006)

	Urine	Faeces	Grey water	Toilet paper	Total
gram O_2/p/day	10-12	45.7-54.5	52	32.4	107.7-118.5
ton O_2/A'dam/yr	2,920-3,504	13,344-15,914	15,184	9,464	40,912-44,066
Chosen amounts [ton O_2]	3,119	14,166	15,184	9,464	41,933
Percentages [%]	7.4	33.8	36.2	22.6	100.0

E.2 Phosphorus

Overview origin Amsterdam's phosphorus

There are many different sources presenting many different values for phosphorus in household wastewater. In this section a few of these values and the chosen values for the rest of this research are presented.

In this research the amount of phosphorus in business wastewater, storm water and groundwater was not determined. The amount of phosphorus in groundwater is assumed to be negligible. The amount in storm water is also assumed to be zero, even though some studies mention that storm water includes phosphorus from atmospheric precipitation or other (organic) sources. Since the amount of phosphorus in the business wastewater is unknown but assumed to be significant, the amount of phosphorus in business wastewater is assumed to be equal to the amount in household wastewater. In the overview of Amsterdam's water chain it can be seen that the amount of business wastewater is 15.9 Mm^3 and the amount of household wastewater is 38.0 Mm^3. Using this 15.9/38.0 ratio, the amount of phosphorus attributed to businesses is 174.5 ton P and the amount of phosphorus attributed to households is 417.2 ton P. Due to the vast assumptions these values are very uncertain.

To determine the impact of recovering measures quantitatively it is also useful to know what the specific origin of the household wastewater is. The Foundation for Applied Water Research (Dutch: Stichting toegepast onderzoek waterbeheer, Stowa) has published several reports in which data for phosphorus content in wastewater are presented (e.g. Swart (2008) and Vergouwen (2010). These reports mostly use data from a study by Kujawa-Roeleveld and Zeeman (2006). This article presents a summary of the composition of wastewater in Europe. Thus, this article does not present specific data for the Netherlands or for Amsterdam, but it does give some indication of the amount of phosphorus from different origins. Some of the numbers presented in the report are summarized in the table below. The data were presented for the whole of the Netherlands, but these are transformed into data for Amsterdam using inhabitant ratios.

A disadvantage of using Sankey diagrams is that they only allow for one value per flow. Therefore, they do not show the uncertainties of values. Because Sankey diagrams are chosen for the representation of material flows one value for each flow had to be chosen. These values are based on Vergouwen (2010) and presented in the right column of Table 37.

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TABLE 37 – ORIGIN OF PHOSPHORUS AT HOUSEHOLDS

	(Kujawa-Roeleveld and Zeeman, 2006) **P-content in urine/faeces** [ton/year]	(Vergouwen, 2010) **Food intake** [ton /year]	(Vergouwen, 2010) **Calculated using ratios** [ton /year]	**Chosen values** [ton/year]
Urine	175.0-291.7	277.4	208.6 (50.0%)	208.6
Faeces	87.5-204.2	204.4	148.9 (35.7%)	148.9
Grey WW	87.5-145.9	N/A	59.7 (14.3%)	59.7
Kitchen WW	37.9-81.7			
Total	*388.0-723.5*	*(incomplete) 481.8*	*417.2 (100%)*	*417.2*

Phosphorus at the WWTPs

Waternet measures the phosphorus load of influent at WWTPs. For WWTPs Amsterdam West and Westpoort these loads are presented in Table 38.

TABLE 38 – OVERVIEW PHOSPHORUS INFLUENT WWTPS (WATERNET, 2014B)

2013	**P-tot influent** [kg/year]	**Factor** [-]	**P-tot influent Amsterdam** [kg/year]
WWTP Amsterdam West	483,990	0.94	454,951
WWTP Westpoort	177,653	0.77	136,762
Total	661,643		
		Influent WWTPs:	*591,743*

The total inflowing amount of phosphorus is 591.7 ton P per year. The phosphorus is removed from the wastewater in sludge. The total amount of phosphorus in the effluents that is attributed to Amsterdam from WWTP Westpoort is 8,071 kg per year. The difference between influent and effluent phosphorus, 128,691 kg P, is the amount of phosphorus in primary and secondary sludge that is transported to WWTP Amsterdam West.

TABLE 39 - OVERVIEW PHOSPHORUS EFFLUENT WWTPS (WATERNET, 2014B)

2013	**P-tot effluent** [kg/year]	**Factor** [-]	**P-tot effluent Amsterdam** [kg/year]
WWTP Amsterdam West	54,123*	0.94	50,876*
WWTP Westpoort	10,482	0.77	8,071
Total	64,605*		
		Effluent WWTPs:	58,947*

*The phosphorus flows at WWTP Amsterdam West are difficult to model. Due to recirculation of wastewater at the WWTP and due to additions of sludge from other WWTPs it is difficult to attribute phosphorus at this WWTP to the City of Amsterdam. Therefore, the phosphorus amounts in Table 39 are marked with asterisks.

The sludge from WWTP Amsterdam West, WWTP Westpoort and eight other WWTPs that are operated by Waternet is transported to WWTP Amsterdam for treatment. Here the sludge is digested and phosphate is recovered from the digested sludge using struvite precipitation. In total approximately 900 ton of struvite will be produced by the newly installed ‘Fosvaatje’, the struvite installation at WWTP Amsterdam West. Therefore, it is expected that 113.6 ton of the phosphorus will be produced in Amsterdam. This will likely also result in smaller phosphorus concentrations in the effluent of WWTP Amsterdam West, but this is neglected in these calculations. The assumption is made that the struvite production will only decrease the amount of phosphorus in the sludge.

For the calculations of the current phosphorus flows in Amsterdam, the amount of phosphorus in the sludge that is transported to AEB is calculated as the difference between the phosphorus going into the digestion tank and the phosphorus in struvite and effluents. The amount of phosphorus going into the digestion tanks is calculated using the amounts of sludge produced at the supplying WWTPs and the portion of this sludge that is digested at WWTP Amsterdam West. It should be noted that this results in an approximation of the phosphorus in sludge and that these are not exact measurements. The results from the phosphorus in sludge calculations are presented in Table 40. In total approximately 771.1 ton P is present in the sludge going to WWTP Amsterdam West's digester of which 591.7 ton P originates in Amsterdam and 179.4 ton P originates elsewhere.

TABLE 40 – PHOSPHORUS IN SLUDGE TO DIGESTER WWTP AMSTERDAM WEST (WATERNET, 2014B)

WWTP	Phosphorus to digester [kg P/year]		Phosphorus originating in Amsterdam [kg/year]
Amsterdam West	483,990		454,951
Westpoort	167,171		136,762
Amstelveen	29		-
Blaricum	16,169		-
Hilversum	31,390		-
Huizen	21,936		-
Loenen	3,248		-
Maarssen	7,692		-
Ronde Venen	17,885		-
Miscellaneous	19,467		-
Total	771,116		
		Total origin Amsterdam:	*591,743*
External origin	*179,373*		

The amount of phosphorus in the sludge going to AEB is than calculated by subtracting the struvite production (113.6 ton P) and the phosphorus in the effluent (58.9 ton P) from the amount of phosphorus going into the digester (771.1 ton P). This results in 598.6 ton P in the sludge going to AEB.

Appendix F: Measure descriptions

F.1 Green waste disposal

In Amsterdam the idea has risen to use the wastewater infrastructure to transport other types of waste than just wastewater. Amsterdam has the ambition to separately collect green waste and other types of solid waste. At the moment, however, only a small fraction of green waste is collected separately from other types of solid waste (Gemeente Amsterdam, 2012). Therefore, the valuable biomass in this waste is not used to its full potential. The combined waste is incinerated, but higher valued products than heat and power from incineration could be retrieved from the green waste if it was collected differently. Since transportation in the traditional way, via trucks, has thus far not been successful in all parts of Amsterdam, sewer transport could be a solution.

The green waste contains fibres and other types of biomass that could be recovered or used to produce, for instance, bio plastics and biogas. Since these recovering methods are also possible with wastewater a link between the two biomass flows could be valuable. Therefore, the idea is to transport grinded organic kitchen waste via the sewers. In the United States garbage disposal units are a common way to deal with green waste; roughly fifty percent of households have a unit installed (United States Census Bureau, 2011). So, this technology is already available. It is, however, unclear if Amsterdam's sewers are suitable for transportation of the grinded green waste. Concluding, this measure is still being developed and requires testing before it can be installed at a large scale.

F.2 Water use reduction

At the moment an average person uses 133 litres of drinking-water per day. Most of this drinking-water is used, but not consumed and therefore enters the sewers as wastewater. In the past years innovations to reduce water use have become more commonly known. This measure does not consist of specific water reuse measures that reduce the amount of wastewater produced, but it consists of the general notion that wastewater quantities can reduce due to adaptations at household level. An example of such a measure is water saving shower heads. These shower heads can reduce water use for showering by more than 40% and water use for showering is around 50%. Thus, installing water saving shower heads instead of a traditional shower heads can reduce the water use of a household by 20%.

F.3 Separate urine collection (and treatment)

A general recovering principle is that recovery is more successful when concentrations are larger. Therefore, separation of resources or of wastewater flows can result in more effective resource recovery. The separate collection of urine is an example of this. Urine is a source of many resources and pollutants: for example 50% of phosphates, 82.5% of nitrogen, 80% of pharmaceuticals; while urine is only 1.5 litre of the total wastewater production of 130 litres per person per day. Therefore, separate collection (and treatment) of urine has high potential.

Leaf (2013) found that phosphorus recovery from urine is around 47% when it is mixed in with wastewater and treated at the WWTP. When urine is separately collected and added to the sludge just before the struvite installation, the recovering performance is slightly better, namely 52%. More phosphorus can be recovered in a separate urine treatment facility: Leaf (2013) found a recovery performance 95%.

Since separate collection of urine in existing building might be difficult due to required adaptations to toilets and infrastructure, this measure focuses on urine collection at events and event buildings. The Heineken Music Hall has special waterless urinals and thereby collects male urine without diluting it with much water (Klaversma, 2014b). At the moment, at most locations where urine is collected separately only male urine is collected. (Klaversma, 2014b) found that the event businesses around the Arena Boulevard in Amsterdam Southeast alone could collect 1310 m^3 per year. Another possible source of urine is the portable toilets at festivals. Finally, some pregnant women collect their urine so the hCG-hormone can be recovered for use in fertility treatments (Moeders voor moeders, 2014). Currently, this 1500 m^3/yr is treated by GMB, but this is no longer profitable for them so Waternet could take over this source (Klaversma, 2014b).

F.4 Pharmafilter®

Hospitals and other care institutes can install the Pharmafilter concept as a complete waste solution. In this concept hospital waste is grinded and transported via sewers and treated on location. Pharmafilter includes a bioreactor, membrane filtration, plural oxidation and activated carbon filtration. This process results in clean effluent and biogas (Reinier de Graaf Gasthuis, n.d.). Besides the successful water treatment, including the removal of most of the pharmaceuticals from the water, the economic viability is mainly due to logistical advantages (Batelaan et al., 2013). Hospital waste is not transported through the corridors of the hospitals, what takes time and poses hygienic risks, but the waste is grinded and transported with wastewater through the sewers (Batelaan et al., 2013). At the moment, Waternet is doing a feasibility study to explore implementation of the Pharmafilter concept at Academic Medical Centre hospital in the southeast of Amsterdam (Mol and Ververs, 2014).

F.5 More separated sewers

Around 75% of Amsterdam has a separated sewer system where storm water is collected separately from the dry weather flows. The remaining 25% has a combined sewer system. The two main reasons why this area does not have a separated system are that the old buildings in these areas are not suited for a combined system and that the storm water in the centre of Amsterdam is highly polluted (Beumer, 2014). However, some areas in Amsterdam are suitable for separated systems. Especially districts that are being renovated could get separated sewer systems, e.g. in Amsterdam North.

More separated sewers have the effect that less storm water runoff ends up at the WWTP. Since storm water contains less phosphorus and organic matter than average wastewater, resource concentrations go up when more storm water does not dilute wastewater. Higher concentrations result in higher resource removal or recovery. However, for the measure to actually result in a smaller WWTP legislation has to be changed. At the moment, water treatment performance is measured by effluent concentration and not by total load. Since this measure can increase the effluent concentration even though it decreases the total load, this measure can only be effective if water treatment performance would be measured as total load (Klaversma, 2014a).

F.6 Reduced groundwater infiltration

On average the sewers in Amsterdam are more than 27 years old (Waternet, 2014b). Some of the older sewers have leaks through which groundwater enters the sewer system. In Amsterdam groundwater levels are high, especially because many of the older buildings have wooden foundations that would rot when they are not under water. Therefore, many sewers are underneath the groundwater level resulting in groundwater infiltration when the sewers are not sealed properly.

Sewers can start too leak for three reasons. The first is that the seal of the pipes is deteriorated. Older sewers are linked using rope and wax, which do not last very long. The second is that sewer pipes can subside, which is especially common when groundwater levels are high. In Amsterdam, most sewers are founded, but leaks between pipes can still exist due to subsidence. The third and final reason for leaks is when the pipes themselves are leaking, e.g. through holes or cracks. This is very exceptional in Amsterdam. (Beumer, 2014)

The measure that is suggested here results in fewer leaks and therefore in less groundwater infiltration. When the older sewers are replaced, the new sewers are better founded and better linked (using rubber instead of rope and wax) the infiltration is reduced. At the moment, around 20 km of sewers are replaced each year. This is around 0.5% of all sewers in Amsterdam, which would mean that sewers need to last for 200 years. However, the sewers are designed for 40 years and in practice they remain in the ground for 60 years. This means that the sewers will need to be replaced at a higher pace in the next years. The goal is to double the yearly replacement to 40 km/yr. (Beumer, 2014)

This measure has similar effects as building more separated sewers. Groundwater has low concentrations of organic matter and nutrients and, therefore, also dilutes wastewater. When less groundwater infiltrates, removal and recovering performance will go up.

F.7 Primary treatment and recovery from primary sludge

In this study two types of primary treatment are considered, besides the standard (bar) screens and sand traps. The first is a settling tank that separates heavier particles from the influent. So, this separation technique is based on density. The second is a sieve that separates bigger particles and fibres from the influent. So, this technique is based on size. Both techniques can be combined with cellulose recovery.

At WWTPs, cellulose, a polysaccharide of which toilet paper consists, can be removed from sewage in two different ways. The first is by removing the cellulose from the sieving product of a fine-mesh sieve that is placed in the water line of treatment plant (Ruiken et al., 2013). The second is by removing the cellulose from the primary sludge that is separated from the wastewater using a settling tank (Pinkse, 2014).

F.7.1 Primary settling tank

At the moment the WWTPs Amsterdam West and Westpoort have settling tanks, also called sedimentation tanks. These separate the heavier particles from the influent. For example, in 2013 at WWTP Amsterdam West 28 percent of chemical oxygen demand (COD) and 26 percent of total suspended solids (TSS) in the influent was settled into primary sludge. At WWTP Westpoort these percentages were 21 and 50 percent respectively. (Waternet, 2014b)

F.7.2 Bioplastic production

Recently research has shown that bioplastics, especially polyhydroxyalkanoate (PHA), can be produced from wastewater sludge. Through fermentation volatile fatty acids (VFA) are produced from primary sludge. Then PHA accumulating microorganisms store PHA in their cells. In this process they use primary or secondary sludge as a carbon source. The PHA can be recovered from the cells via a chemical process. This product can be used as a raw material for bioplastics. The production of these bioplastics can be done at a large central location, so this does not have to be done by Waternet at the WWTP. (De Hart et al., 2014)

F.7.3 Fine-mesh sieve

Ruiken et al. (2013) researched the possibility of removing cellulose from wastewater using fine-mesh sieves. Fine-mesh sieves are an alternative for a sedimentation tank since they also remove suspended solids and fibres. A fine-mesh sieve is defined as a sieve with a mesh-size of 0.5 mm or smaller. At the WWTP Blaricum Waternet tested a fine-mesh sieve with a mesh-size of 0.35 mm. The sieve is usually placed after a coarse screen. The sieve is continuous and the screen moves taking the sieving product upwards where it is collected (see Figure 15).

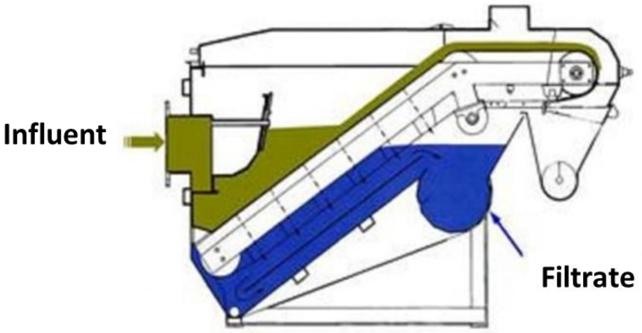

FIGURE 15 – CONTINUOUS SCREEN SIMILAR TO FINE-MESH SIEVE (CADOS, 2014)

F.8 Biological treatment

At the moment both WWTPs in Amsterdam treat wastewater biologically using the (modified) University of Cape Town process. However, recently a new type of biological wastewater treatment has been developed, Nereda. The biggest difference between the two types of treatment is that Nereda produces granular sludge instead of flocculent sludge, which creates the opportunity of recovery of alginic acid.

F.8.1 Modified University of Cape Town process

Appendix D describes the mUCT process that removes organic matter and nutrients from wastewater by a series of aerobic and anaerobic tanks. The mUCT results in flocculent sludge that is removed from the wastewater using a sedimentation tank. In Amsterdam this flocculent sludge is digested and then incinerated.

F.8.2 Nereda

At the end of the 1990’s researcher found that sludge could also form granules and from this knowledge a process of water treatment with these aerobic granules has been developed. From 2003 onwards pilot studies were done to test the new treatment method in practice at the WWTP in Epe. These tests were verified at two other WWTPs between 2007 and 2009. (Berkhof et al., 2010)

The way in which granular sludge is formed exactly is not yet known. Currently, research is being performed to find out what microorganisms play a part in the process. However, it is known that the following four preconditions play an important part in the Nereda process: hydraulic selection pressure, high initial substrate concentrations, selection of slowly growing organisms and high shear forces due to extensive mixing. (Berkhof et al., 2010, De Bruin et al., 2013)

In contrast to the continuous biological process of mUCT, Nereda is a batch process. So there are several parallel reactors that are filled in sequence. Below the four steps in the Nereda process are described (after Berkhof et al. (2010) and De Bruin et al. (2013)).

1. Filling/overflow. The high circular Nereda reactor is filled from the bottom. At the same time the treated water at the top of the tank flows into gutters. During this first phase there is no aeration, so this phase functions as the anaerobic phase for phosphate removal.
2. Aeration. Because of the aerobic conditions on the outside of the granules and the anaerobic conditions on the inside of the granules, nitrification and denitrification takes place during this phase. The aerobic steps of phosphate removal also take place in step 2.
3. Settlement. In this short phase the granules settle on the bottom of the reactor and the excess granules are removed from the reactor.
4. Anoxic phases. When the composition of the wastewater, the effluent requirements and the temperature require more nitrogen removal, the Nereda process can be expanded with anoxic phases before and after the aeration phase.

F.9 Alginic acid production

The material that makes the sludge of the Nereda process form granules is alginic acid. This polysaccharide has many different high end uses in, for example, the pharmaceutical and food industry. Therefore, the recovery of alginic acid has potential.

At the moment alginic acid production from granular sludge is being investigated by Stowa (Stowa, 2014). The potential of alginic acid was already explored by Van Voorthuizen et al. (2013) in a report on the possibility of WWTPs of becoming ‘resource factories’. This report stated that the production of alginic acid from sludge might require a thermal treatment, like thermal hydrolysis. Because the process of alginic acid production is still being developed it is difficult to determine whether consistent and safe alginic acid can be produced from wastewater, which is what the pharmaceutical and food industry will require of the product.

F.10 Thermal hydrolysis

Hydrolysis is the first step in anaerobic digestion. In this step, biopolymers in sludge are broken down into fatty acids, sugars and amino acids. Thermal hydrolysis is a variation on the standard hydrolysis, since this pre-treatment process for sludge and other complex organic matter disintegrates the organic matter by using high temperature (140-165 °C) and high pressure (4-8 bar) (Stichting H2O, 2014, Berkhof et al., 2010). The high temperature and pressure make undissolved components of sludge dissolved and thereby, better degradable components are released, which increases the biodegradability of sludge (Stichting H2O, 2014, Berkhof et al., 2012). Because the hydrolysis of slowly degradable macro molecules is the limiting process for the ultimate sludge degradation, the higher biodegradability results in higher biogas production in a shorter period of time (Berkhof et al., 2012). Thereby, thermal hydrolysis increases the capacity of the digester up to 300% (Stichting H2O, 2014). Furthermore, thermal hydrolysis increases the water removal efficiency of digested sludge and thus, decreases the costs for digested sludge incineration (Berkhof et al., 2012, Stichting H2O, 2014). A final advantage is that higher concentrations of nutrients exist in the reject water, which improves the possibilities of, for example, struvite precipitation (Berkhof et al., 2012). It should, however, be mentioned that the advantages of thermal hydrolysis depend highly on local circumstances (Berkhof et al., 2012).

F.11 Anaerobic digestion

Sewage sludge consists of a large fraction of decaying organic material and if this is not quickly processed it will start to acidify and distribute an unbearable odour (TU Delft, n.d.). Because of this and because sludge is a perfect environment for germs to grow, sludge is stabilized under oxygen free conditions (TU Delft, n.d.). This is called anaerobic digestion. In this research, two types of digestion are considered. The first is mesophilic digestion. In Amsterdam mesophilic digestion is the current method that stabilizes the sludge at a temperature of around 36°C (Waternet, 2014b). The second is thermophilic digestion, which could be considered in Amsterdam. Thermophilic digestion occurs at higher temperatures, namely around 55 °C (Kramer et al., 2014). These two types of anaerobic digestion are explained further in the next sections, but first anaerobic digestion in general is explained.

Anaerobic digestion consists of three steps (see Figure 16). These steps are carried out by various types of bacteria. The first step is hydrolysis. In this step the biopolymers in sludge are separated into smaller components, namely fatty acids, sugars and amino acids. This process occurs outside the bacteria cells by hydrolysis-enzymes and is relatively slow and incomplete since activated sludge consists of many complex slowly degradable components. The second step is acidification. This relatively quick step takes place inside cells of acidifying bacteria. The hydrolysis products are transformed into acetic acid, hydrogen and carbon dioxide. The third and final step of anaerobic digestion is methane formation. In this step methanogenic microorganisms transfer the end products of acidification into a mixture of methane and carbon dioxide. (TU Delft, n.d.)

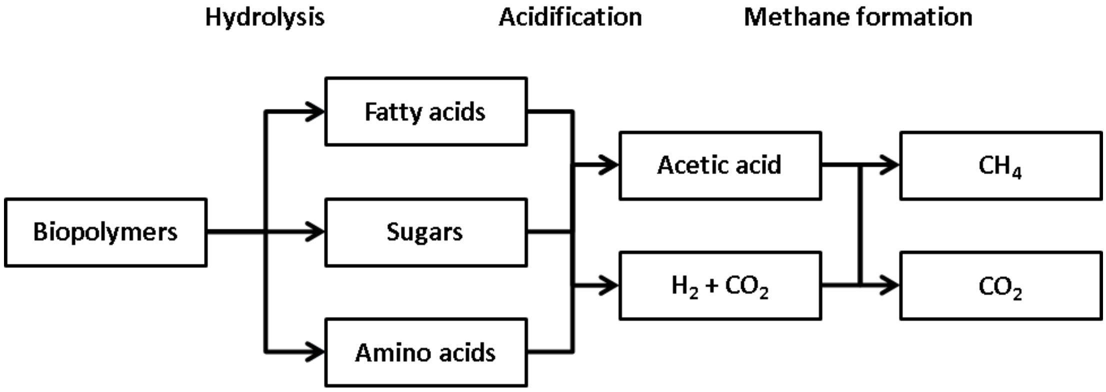

FIGURE 16 – ANAEROBIC DIGESTION (TU DELFT, N.D.)

F.11.1 Mesophilic digestion

Mesophilic digestion takes place at moderate temperatures of around 36 °C. In Amsterdam, sludge resides in one of three digestion tanks for twenty days. By doing this more than 30% of the dry matter, and more than 40% of the organic dry matter, is removed from the sludge. This dry matter is transformed into 11 million Nm^3 biogas. (Waternet, 2014b)

F.11.2 Thermophilic digestion

Thermophilic digestion takes place at higher temperatures of around 55 °C. Stowa (2014-23) performed a pilot study to compare the results of thermophilic digestion with mesophilic digestion. The biggest differences are that more organic matter is degraded, 51% instead of 45% with mesophilic digestion, and that more biogas is produced, 20% more than with mesophilic digestion. In Amsterdam, this would require more heating and possibly adaptation of the digestion tanks.

F.12 Struvite precipitation

At WWTP Amsterdam West phosphorus is recovered from digested sludge using an Airprex system. The system is called ‘Fosvaatje’. Phosphorus that is not bounded to the sludge can be recovered using struvite precipitation (Van Voorthuizen et al., 2013). Struvite is magnesium ammonium phosphate ($NH_4MgPO_4 \cdot 6H_2O$) that is produced by adding magnesium chloride to the digested sludge. The struvite, a salt, is than separated from the sludge by a sand trap. Struvite precipitation has four main advantages (Notenboom et al., 2013). The first is the production of struvite, which can be used as a fertilizer when legislation is changed. At the moment, struvite is considered waste because of its origin, but will most likely change soon (Ehlert et al., 2013). The second advantage is clogging of the pipes at the WWTP is reduced, since some struvite is usually produced in the pipes and this is prevented by the controlled struvite precipitation process. The third advantage is that the dewatering of the sludge improves and that thereby the costs of sludge incineration decrease. The fourth is that the reject water contains fewer nutrients and that thereby a smaller biological nutrient removal capacity is necessary.

It should be noted that it is also possible to precipitate struvite in the reject water (Notenboom et al., 2013). This option is not considered in this research since the Airprex system is already installed.

F.13 Sludge incineration

At the moment the digested sludge from WWTP Amsterdam West is incinerated together with household waste. However, to recover phosphorus from the sludge ashes the sludge ashes should not contain too much iron (Van Lier et al., 2011). Therefore, the sludge should be separately incinerated from household waste to enable phosphorus recovery from the sludge ashes.

F.13.1 Sludge incineration at waste plant

Currently, the digested sludge from WWTP Amsterdam West is incinerated at the Waste and Energy Company AEB, which is located next to the WWTP. The sludge is heated, which first removes the water from the sludge and then the sludge is incinerated. The heat that is produced by this process is used for combined heat and power production. At the moment, Waternet has a contract with AEB that ends in 2020, so until then the way of incineration is difficult to change.

F.13.2 Mono-incineration

For phosphorus recovery from sludge ashes separate incineration is required. This could either take place at AEB, but this may require adaptations at AEB. Another option is to incinerate the sludge at another location. This has the advantage that phosphorus recovery is made possible, but this has the disadvantage that the sludge has to be transported over larger distances. Currently mono-incineration is done in Dordrecht and Moerdijk, which are more than 100 km from WWTP Amsterdam West. And since the quantities are large, namely 87 kton sludge in 2013(Waternet, 2014b), this comes with high costs and large environmental impact.

F.14 Phosphorus recovery from sludge ashes

A prerequisite for phosphorus recovery from sludge ashes is that the sludge has to be incinerated separately from other waste; so-called mono-incineration. Notenboom et al. (2013) present two options for phosphorus recovery from sludge ashes. Both options are based on using a combination of sludge ashes and phosphorus ore to produce fertilizers and are still being developed. The first process is the Ecophos process, which uses only the fly ashes from sludge incineration. Hydrochloric acid is used to dissolve the ashes and ore to enable recovery of phosphoric acid, phosphate salts and other salts like iron chloride. Thus, this method also has negative environmental impact by using many chemicals. The second option is to use sludge ashes in the traditional fertilizer production process of ICL, a company with a factory in Amsterdam.

Appendix G: Calculations material flows 2040

The effects of the measures of Chapter 4 and the strategies of Chapter 5 are compared with the 'ceteris paribus' situation that is calculated for 2040. The material flows that are presented in the Sankey diagrams in Chapter 2 are transferred to 2040 based on prognoses for population, business and precipitation. Therefore, this appendix first describes these prognoses and then presents the material flows for 2040.

G.1 Prognoses 2040

The prognoses for population, business and precipitation are presented in Table 41. In the following section the derivation of these values is explained.

TABLE 41 – SUMMARY OF PROGNOSES FOR 2040

	2013	2040	Change [%]
Population Amsterdam	805,108	925,700	14.98
Population Netherlands	16,804,432	17,815,632	6.02
Business small			20.00
Business large			50.00
Business			27.91
Precipitation Amsterdam [mm]	939.8	944.2	0.47

G.1.1 Population prognoses

To calculate the material flows in 2040 two population growth values are needed. The first is for Amsterdam and the second is for the regions that also bring their wastewater or sludge to WWTP Amsterdam West.

For the population growth of Amsterdam two sources were found. The first was Statistics Netherlands (CBS, 2014). This source gives a prognosis for 2040 of 925,700 inhabitants. The second source was the statistics bureau of the Municipality of Amsterdam (Dienst Onderzoek en Statistiek, 2010). This source only presents prognoses for every five years till 2030. These prognoses are, however, older and therefore, the first estimates can be compared with actual inhabitant data. The prognosis for 2020 by the municipality is 796,793. This value was, however, already exceeded in 2013. Statistics Netherlands (CBS, 2014) states that on January 1st the population of Amsterdam was 799,278. Therefore, it is concluded that the municipality underestimates the population growth and the prognoses by Statistics Netherlands are used for population growth of Amsterdam.

Amsterdam's population in 2013 is calculated as the average of the values for January 1st 2013 and 2014. This results in 805,108 inhabitants in 2013. For 2040 Statistics Netherlands presents a prognosis of 925,700 inhabitants. Thus, the population is expected to grow by fifteen percent. (CBS, 2014)

For the areas outside Amsterdam the prognoses of Statistics Netherlands for the Netherlands are used. Again the value for 2013 is the average of January 1st 2013 and 2014. This results in 16,804,432 inhabitants. For 2040 the prognosis is 17,815,632 inhabitants (CBS, 2014). Concluding, population growth in the areas outside Amsterdam is expected to be six percent.

G.1.2 Business prognoses

It was hard to find data for the expected growth of business in Amsterdam. Therefore, the assumption is made that small business will grow just a bit more than the population of Amsterdam. Thus, a growth percentage of 20 percent is chosen.

Furthermore, it is assumed that large businesses will grow more than small businesses. One reason for this is the expected growth of goods transfer in Amsterdam's harbour. In 2011 the Municipality of Amsterdam presented a document stating an expected growth of goods transfer from 76 million tonnes in 2008 to 125 million tonnes in 2020 (Gemeente Amsterdam, 2011). When one assumes linear growth this would mean a growth of 31.5% between 2013 and 2020. This is used as an indicator for the growth of large businesses. The growth value of large business is chosen to be 50% between 2013 and 2040.

For some material flows no distinction is made between large and small business, therefore, a growth percentage of business as a whole is required as well. This percentage is calculated using the water use of both sectors. The resulting growth percentage for business is 27.9%.

G.1.3 Precipitation prognoses

The Royal Netherlands Meteorological Institute has recently updated its scenarios for precipitation in the Netherlands. The results of these scenarios are presented in Table 42.

TABLE 42 – PRECIPITATION SCENARIOS (KNMI, 2014B)

				Scenarios 2050				
		1981-2010	2013	GL	GH	WL	WH	Average
Netherlands	Growth percentage	0%		4%	2.50%	5.50%	5%	4%
	Precipitation [mm]	851	741	885	872	898	894	887
Amsterdam	Precipitation [mm]	912.5	939.8	949	935	963	958	951

The average of the scenarios is used to calculate the expected precipitation in 2040. In this calculation a linear growth is assumed between 1995 and 2050. The value that is found for 2040 is 944.2 mm. This would mean an increase of 0.47% between 2013 and 2040.

It should be noted that the precipitation of 2013 was relatively high compared with the average of 1981 and 2010. However, this does not result in problems, because the precipitation increase is only used to calculate groundwater infiltration and stormwater runoff. And therefore, the precipitation increase should be known between the actual precipitation in 2013 for which the groundwater infiltration and stormwater runoff are known.

G.2 Material flows 2040

The materials flows for 2040 are presented in Table 43. For each of the values in the Sankey diagrams in Chapter 2 the values for 2040 are given and in the last column of the table the way in which these values are determined is summarized.

TABLE 43 – MATERIAL FLOWS 2040

	Material flow	**2013**	**2040**	**Unit**	**How calculated?**
H_2O	Drinking-water production	57.2	68.0	Mm^3	Calculated based on distribution and leakage
	Drinking-water distribution	55.2	65.6	Mm^3	Sum of Drinking-water uses
	Leakage drinking-water infrastructure	2.0	2.4	Mm^3	Percentage of production

	Water use small businesses	12.0	14.4	Mm^3	Prognose small business
	Water use large businesses	4.3	6.5	Mm^3	Prognose large business
	Water use households	38.9	44.7	Mm^3	Prognose population A’dam
	- Bathroom	19.5	22.4	Mm^3	Prognose population A’dam
	- Kitchen & Drinking	55.1	63.3	Mm^3	Prognose population A’dam
	- Toilet	4.3	4.9	Mm^3	Prognose population A’dam
	- Laundry	38.9	44.7	Mm^3	Prognose population A’dam
	Consumption small businesses	0.3	0.4	Mm^3	Growth small businesses
	Consumption large businesses	0.1	0.2	Mm^3	Growth large businesses
	Consumption households	1.0	1.1	Mm^3	Prognose population A’dam
	WW production small businesses	11.7	14.0	Mm^3	Prognose small business
	WW production large businesses	4.2	6.3	Mm^3	Prognose large business
	WW production households	37.9	43.6	Mm^3	Prognose population A’dam
	Groundwater infiltration to WWTPs	7.4	7.4	Mm^3	Prognose precipitation
	Stormwater run-off to WWTPs	13.7	13.7	Mm^3	Prognose precipitation
	Influent WWTP	74.9	85.1	Mm^3	Calculated as sum of wastewater production and groundwater infiltration and stormwater runoff
	Effluent WWTP to surface water	74.9	85.1	Mm^3	Equal to influent
OM	COD A’dam grey water	15184	17458	ton	Prognose population A’dam
	COD A’dam faeces	14166	16288	ton	Prognose population A’dam
	COD A’dam urine	3119	3586	ton	Prognose population A’dam
	COD A’dam toilet paper	9464	10882	ton	Prognose population A’dam
	COD A’dam (total)	41933	48214	ton	Calculated as sum of grey wastewater, faeces, urine and toilet paper
	COD to sludge treatment (excl. A’dam)	6287	6665	ton	Prognose population NL
	COD to sludge treatment (total)	48220	54879	ton	Calculated as sum of COD A’dam and COD excl. A’dam to sludge treatment
	COD effluent	3156	3629	ton	Percentage of COD A’dam
	Dry matter to sludge incineration	26283	27865	ton	Ratio COD to sludge treatment
	Biogas production	11303	11983	1000 Nm^3	Ratio COD to sludge treatment
	Gas flare	363	385	1000 Nm^3	Ratio COD to sludge treatment
	Green gas production	210	223	1000 Nm^3	Ratio COD to sludge treatment
	CO_2	29	31	1000 Nm^3	Ratio COD to sludge treatment
	Electricity	22.7	24	MWh	Ratio COD to sludge treatment
	Heat	55	58	GJ	Ratio COD to sludge treatment
P	P business	174.5	223.2	ton	Calculated using water use and growth of small and large businesses
	P grey wastewater	59.7	68.6	ton	Prognose population A’dam
	P urine	208.6	239.8	ton	Prognose population A’dam
	P faeces	148.9	171.2	ton	Prognose population A’dam
	P A’dam	591.7	702.9	ton	Calculated as sum of businesses and households
	P to sludge treatment (excl. A’dam)	179.4	190.2	ton	Prognose population NL
	P to sludge treatment (total)	712.2	823.1	ton	Sum of sludges minus effluent
	P effluent	58.9	70.0	ton	Percentage of phosphorus in Amsterdam's wastewater
	P struvite production	113.6	131.6	ton	Percentage of phosphorus to sludge treatment
	P digested sludge to incineration	598.6	691.6	ton	Sludge to treatment minus effluent minus struvite

Appendix H: Measures & criteria spreadsheet

This is a digital appendix. The criteria per measure and the calculations behind these can be found in Appendix H.xlsx.