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van der Hoek, Jan Peter; de Fooij, Heleen; Struker, André

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Wastewater as a resource: strategies to recover resources from Amsterdam's wastewater

Jan Peter van der Hoek[1,2], Heleen de Fooij[3], André Struker[4]

[1]Waternet, Strategic Centre, Korte Ouderkerkerdijk 7, 1096 AC Amsterdam, The Netherlands, jan.peter.van.der.hoek@waternet.nl

[2]Delft University of Technology, Faculty of Civil Engineering and Geosciences, Stevinweg 1, 2628 CN Delft, The Netherlands, j.p.vanderhoek@tudelft.nl

[3]Waternet, Strategic Centre, Korte Ouderkerkerdijk 7, 1096 AC Amsterdam, The Netherlands, heleendefooij@gmail.com

[4]Waternet, Strategic Centre, Korte Ouderkerkerdijk 7, 1096 AC Amsterdam, The Netherlands, andre.struker@waternet.nl

Corresponding author:
Jan Peter van der Hoek, j.p.vanderhoek@tudelft.nl

Abstract

Resources are becoming scarce. Therefore, reuse of resources is becoming more and more attractive. Wastewater can be used as a resource, since it contains many resources like organic matter, phosphorus, nitrogen, heavy metals, thermal energy, etc. This study focused on the reuse of organic matter and phosphorus from Amsterdam's wastewater. There is a wide variety of possible alternatives, and the technical options are growing. The problem is not the availability of technology for resource recovery, but the lack of a planning and design methodology to identify and deploy the most sustainable solutions in a given context. To explore alternative, coherent and viable strategies regarding resource recovery from Amsterdam's wastewater chain, the development process of dynamic adaptive policy pathways was used. In the first phase a material flow analysis was made for Amsterdam's wastewater chain and analyzed for water, organic matter and phosphorus. In the second phase measures were identified and characterized. The characterization was based on criteria focusing on changes in material flows, recovered products and implementation horizon. For the Amsterdam case recovered products concerned alginic acid, bioplastic, cellulose, phosphorus and biogas. In the third phase the measures were combined into strategies, which are combinations of measures that focus on a specific goal of resource recovery. For the Amsterdam case this resulted in four strategies: a strategy focusing on production of alginic acid, a strategy focusing on production of bioplastics, a strategy focusing on recovery of cellulose, and a strategy focusing on recovery of phosphorus. Adaptive policymaking showed to be a good approach to deal with the wide variety of

possibilities and uncertainties. It resulted in a coherent policy as the resource recovery goals became clear, a flexible policy as the lock-in, no-regret and win-win measures could be identified, and an up-to-date policy as a periodic update is possible that will reveal new chances and risks.

Keywords

resource recovery – wastewater – adaptive policymaking – organic matter – phosphorus – biogas

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 is becoming more and more attractive.

Water, besides being a resource of its own, is a transport medium for resources. Materials, chemicals and energy are added to water by households and businesses, when they use drinking water and produce wastewater. Therefore, the urban water chain, and especially wastewater, has many opportunities to recover resources and close cycles. However, nowadays cities are not considered sustainable because they do not (re)use resources efficiently (Agudelo-Vera et al., 2012). Different approaches and models have been developed in which cities transform from consumers of goods and services and production of waste, into resilient cities that produce their own renewable energy and harvest their own internal resources. Venkatesh et al. (2014) developed a 'Dynamic Metabolism Model' to adopt a holistic system perspective to the analysis of metabolism and environmental impacts of resource flows in urban water and wastewater systems. Agudela-Vera et al. (2012) introduced the 'Urban Harvesting Concept' which includes urban metabolism and closing urban cycles by harvesting urban resources.

In all these conceptual models wastewater plays an important role. Water and wastewater system decisions have been traditionally driven by considerations of function, safety, and cost-benefit analysis (Guest et al., 2009). For a long time wastewater has been considered a human health concern and environmental hazard, but a paradigm shift is currently underway from an attitude that considers wastewater as a waste to be treated, to a proactive interest in recovering materials and energy from these streams (Puchongkawarin et al., 2015). Treated wastewater can be reused for various purposes to provide ecological benefits, reduce the demand of potable water and augment water supplies (Mo and Zhang, 2013). A transition in wastewater treatment plants towards reuse of wastewater derived resources is recognized as a promising solution to shift wastewater treatment from standard treatment to the current emphasis on sustainability (Wang et al., 2015). Although the recuperation and production of energy at sewage works is currently getting most attention, the resource recovery from wastewater and sludge should not be overlooked (Van Loosdrecht and Brdjanovic, 2014).

The importance to see wastewater as a resource is clear, but the question is where to focus on. There is a wide variety of possible alternatives, as the array of technical options grows. While water, energy and nutrient recovery (phosphorus and nitrogen) are known alternatives (Doyle and Parsons, 2002; Daigger, 2008; Daigger, 2009; McCarty et al., 2011; Sutton et al., 2011; Garcia-Belinchón et al., 2013; Lee et al., 2013; Puchongkawarin et al., 2015), other options are emerging, e.g. the recovery of cellulose fibers (Ruiken et al., 2013), biopolymers (Tamis et al., 2014), bioplastics (Kleerebezem and Van Loosdrecht, 2007) and protein (Matassa et al., 2015). The primary problem is not the availability of technology for resource recovery, but the lack of a social-technological planning and design methodology to identify and deploy the most sustainable solution in a given geographic and cultural context (Guest et al., 2009). According to Li et al. (2015) uncertainties about which techniques are most useful and how to combine them stands in the way of creating 'wastewater-resource factories'. Waternet, the water utility of Amsterdam and surroundings, struggles with this problem.

Waternet is responsible for the water management in and around Amsterdam. The activities of Waternet concern drinking water supply, sewerage, wastewater treatment, surface water management, control of the canals in Amsterdam and flood protection. The City of Amsterdam, one of two owners of Waternet, has formulated the ambition to develop further as the core city of an internationally competitive and sustainable European Metropolis (City of Amsterdam, 2010).

Recently this ambition has been specified in the policy documents 'The Circular Metropolis Amsterdam 2014 – 2018' (City of Amsterdam, 2014a) and 'The Sustainability Agenda Amsterdam' (City of Amsterdam, 2014b). In these documents a choice is made for the Circular City concept as a way to achieve the ambition of Amsterdam to develop as a competitive and sustainable European Metropolis. Recovery of resources and materials is one of the main targets and operationalized in the roadmap 'Amsterdam Circular' (Circle Economy et al., 2015). The City of Amsterdam emphasizes that the transition towards a circular city is a shared quest for all stakeholders: companies, city government, inhabitants, research institutes and the financial sector. In this transition phase there is no clear market and thus no clear role for the city government as market regulator. The city government wants to play as a 'game changer' and facilitates involved stakeholders and tries to catalyze promising initiatives (City of Amsterdam, 2014a).

Waternet wants to contribute to the ambition of Amsterdam to develop as a sustainable European metropolis and to the transition towards a circular city by integration of water, energy and material flows (Van der Hoek et al., 2015). For this reason Waternet aims at recovering resources from

Amsterdam's wastewater. Some of these resources are currently recovered, e.g. 1000 tons/year struvite is recovered (Van der Hoek et al., 2015) and 13 million m^3/year biogas is produced (Van der Hoek, 2012a). However, these resources are recovered not according to a coherent policy. Decisions about recovering measures are made as opportunities arise. In that case, only the affected resource and the suggested measure are considered and interactions between measures and resources are easily neglected. 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. Firstly, there is no overview of the resources in Amsterdam's wastewater, which makes it difficult to determine whether it is feasible and efficient to recover a certain resource. Secondly, there is no overview of possible recovery methods and knowledge of how measures interact. Thirdly, external factors, such as new technologies, economic developments and market developments result in a complex, dynamic and uncertain situation, characterized by changing circumstances, where it is difficult to commit to short-term actions and establish a framework to guide future actions.

This study explores alternative, coherent and viable strategies regarding resource recovery in Amsterdam's wastewater chain. The research goals were:

1. to determine which resources are present in Amsterdam's wastewater, in which quantities they are present and where they are present;
2. to identify and characterize different resource recovery measures and determine which ones are suitable to implement in Amsterdam;
3. to develop coherent strategies consisting of suitable resource recovering measures.

2 Research Methods

2.1 Methodology

2.1.1 Adaptive policymaking

The idea of adaptive policymaking emerged at 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).

As shown in the introduction, the development of coherent strategies to recover resources from Amsterdam's wastewater is characterized by a wide variety of possible alternatives and many external factors, which may change over time due to technological, environmental, economic and market developments. A variety of relevant uncertainties and a variety of possible actions and measures thus impede this development process. There is no fixed policy or strategy, but yet decisions have to be made to achieve the goal of resource recovery from wastewater. Taking into account the similarities between the characteristics of the challenge to develop strategies to recover resources from Amsterdam's wastewater, and the characteristics of adaptive policy making, the research method applied roughly follows the development process of dynamic adaptive policy pathways as described by Haasnoot et al. (2013).

The development process as described by Haasnoot et al. (2013) is divided into ten steps, of which in this research only the first six are conducted. Figure 1 is based on the ten steps of Haasnoot et al. (2013) and describes three phases in this research: phase A, B and C. The descriptions of the first six steps are somewhat different from the descriptions by Haasnoot et al. (2013). Since steps 7 till 10 are not included in this research their names remain unaltered.

2.1.2 Phase A: Material flow analysis

Phase A comprises steps 1 and 2, and focuses on the description and analysis of the current situation and perceived problems. As the focus is on materials and material flows in the wastewater chain of Amsterdam, Material Flow Analysis (MFA) was used as tool in phase A. MFA describes and quantifies the material flows through a defined system (Chevre et al., 2013). 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 was chosen as the starting point for improvement of the resource circularity for Amsterdam's wastewater chain.

In this phase A, for different locations in the wastewater chain the quantities of resources were specified. This information was necessary to know which measures are possible and suitable to recover resources in Amsterdam. Data were obtained from year reports of Waternet. 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.

Sankey diagrams were chosen for representing the resource flows (WordPress, 2014).

2.1.3 Phase B: Measure characterization

Besides an overview of resources, also an overview of possible recovery measures is necessary to develop resource recovery strategies. Therefore, in phase B, which comprises steps 3 and 4, measures are identified and characterized. In this research, measures are defined as plans or courses of action that change resource flows and/or recovery. The measures were identified based on developments and initiatives that take place or may be considered in Amsterdam's wastewater chain (see section 2.2.2). To characterize and assess the measures, for each of the measures the following questions were answered:

- How does the measure influence the material flows?
- 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?
- Which changes and commitments are required for the measure? So, for example, is a change of legislation or behavior required?
- When can the measure be implemented in Amsterdam?

Because some measures are competing, it is necessary to know which measures or recovered products are preferred over others. In this research the biomass value pyramid, shown in Figure 2, was used as a tool to differentiate between recovered products (Betaprocess bioenergy, n.d.). The biomass value pyramid shows which products are valued the highest. The products which can be recovered by the measures in this research were placed in the framework of the value pyramid.

2.1.4 Phase C: Strategy development

Phase C focuses on the identification of strategies and the assessment of the strategies. A strategy is related to the mission and vison of an organization. A strategy encompasses actions, plans and measures, and makes choices between these, to realize the vision (Rampersad, 2002). In this case the vison of Waternet is to recover resources from Amsterdam's wastewater in order to contribute to the ambition of the City of Amsterdam to make the transition to a circular city. In this research strategies were defined as combinations of measures (derived from phase B) which focus on a specific goal of resource recovery. It was decided that each strategy had to aim at the maximization of a specific product. These products were selected based on experiences at Waternet or research at Waternet (see section 2.2.3) . Cohesion within a strategy was guaranteed by choosing this main focus and making sure that all measures in the strategy corresponded with that focus. Each strategy aimed at maximizing the recovery of one product. When measures, not part of a specific strategy, did not compete with the main goal of this specific strategy, they could also be part of this strategy to recover other resources in the wastewater stream according to the priorities in the value pyramid. The strategies were assessed by use of a strategy diagram. A strategy diagram shows the composition of each strategy and describes how each measure contributes to the strategy. This assessment enabled the identification of 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. 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.

2.2 Operationalization for Amsterdam's wastewater chain

2.2.1 Restrictions

Water utility Waternet covers the whole water chain in and around Amsterdam and looks for opportunities for resource recovery in the whole water chain. For practical reasons the scope of this research was restricted:

- Only resources in wastewater were considered. The boundaries used in this research are shown in Figure 3.
- Industrial wastewater was excluded from the research, as in Amsterdam big industrial companies have their own treatment plants to remove specific pollutants and these resource flows are collected separately.
- Only organic matter and phosphorus were considered. Organic matter was chosen because of the many 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. Phosphorus was chosen because Waternet already has experiences with phosphorus recovery (Bergmans et al., 2014; Van der Hoek et al., 2015) and because phosphorus recovery can be done in different sections of the wastewater chain. The different products and the different locations both show the complexity of resource recovery. Other resources that were considered but excluded from the research are nitrogen

because there is no scarcity of this resource, heavy metals because of the low quantities and concentrations, and pharmaceuticals because there are currently no recovery methods.

- Thermal energy recovery from wastewater was not selected as a resource product in this study. About 54% of the drinking water that is used in a household is heated and leaves the house at an average temperature of 27 ^{0}C: water from bathing and showers has a temperature of approximately 38-40 ^{0}C, tap water leaves the house at a temperature of 10-55 ^{0}C, and water from the dishwasher and washing machine has a temperature of approximately 40 ^{0}C (Roest et al., 2010). Hofman et al. (2011) estimate that 40% of the total energy losses in modern Dutch houses are represented by hot wastewater leaving the house. On a yearly base this implies a loss of 8 GJ/house (Van der Hoek, 2012a). However, thermal energy recovery from wastewater has several drawbacks (Elías-Maxil et al., 2014). Often there is a mismatch between supply and demand, both in time and location. To overcome this problem, thermal energy storage technologies may be applied, such as aquifer thermal energy storage. In addition, heat pumps are needed to transfer heat from a lower temperature to a higher temperature. Furthermore, biofilm development and deposits on the surface of the heat exchanger in the sewer lower the heat transfer and affects the hydraulic performance. These aspects were reasons for Waternet not to consider utilization of heat in the wastewater.
- Reuse of water was not taken into account in this study. Recently a strategic study was carried out into the most attractive raw water sources for drinking water production in the region of Amsterdam. Treated wastewater was one of the options, but was not chosen. For drinking water production the costs are too high, the public health risks are too high, and the social acceptance is too low (Rook et al., 2013). For industrial water production the costs of reuse are too high compared with an existing option: use of conventionally treated water (coagulation – sedimentation – filtration) from the river Rhine (Witteveen+Bos and Port of Amsterdam, 2004).
- A limited set of criteria were used to characterize the resource recovery measures. The focus was on changes in material flows, recovered products and implementation horizons. Financial considerations, like the costs of measures and the revenues from sold recovered products, and the market conditions of these products, were excluded.

2.2.2 Selected measures

In total 21 measures were selected that change the material flows in Amsterdam's wastewater chain. They change the available amounts of resources and/or change how much of these resources can be recovered. The 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 location is the sludge disposal. Table 1 shows the measures and includes short descriptions of the measures. The overview of measures 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. More detailed descriptions of the measures can be found in Supplementary Material 1.

2.2.3 Selected products

Five different products were considered that can be recovered from the wastewater. Table 2 summarizes these five products. Biogas and phosphorus were chosen as Waternet already has experiences with recovery of these products (Van der Hoek, 2012a; Van der Hoek et al., 2015; Bergmans et al., 2014). Cellulose was chosen as Waternet is carrying out research into cellulose recovery from wastewater (Ruiken et al., 2013). Bioplastic was chosen as polyhydroxyalkanoate (PHA) production from wastewater by microbial enrichment cultures and mixed microbial cultures is a promising option for biopolymer production (Tamis et al., 2014; Serafim et al., 2008). Aerobic granular sludge, as applied in the Nereda process (De Kreuk et al., 2005; De Kreuk et al., 2007) can be used for alginic acid production (Lin et al., 2010; Stowa, 2014).

2.2.4 Criteria

The measures were characterized using nine criteria, as shown in Table 3. These criteria focused on changes in material flows, recovered products and implementation horizons: the criteria describe how a measure changes material flows (water, organic matter and phosphorus: criteria 1-3) and resource recovery (organic matter and phosphorus: criteria 4-5), what the value of recovered products is (criterion 6), how uncertain a measure's development path is (criterion 7), how the measure depends on changes of behavior or actors outside Waternet (criterion 8) and when it can be expected to be implemented in Amsterdam (criterion 9).

3. Results and discussion

3.1 Amsterdam's water chain and material flows

Figure 4 shows the water flows in Amsterdam's water chain for 2013. In 2013 Waternet produced 57.2 million m^3 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 million m^3) and businesses (16.3 million m^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. It is assumed that approximately 2.5% of the water which 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 together with storm water and infiltrated ground water is transported via sewers to wastewater treatment plants (WWTPs). The total wastewater flow is 74.9 million m^3/year.

Figure 5 shows organic matter in Amsterdam's wastewater chain for 2013. The organic matter content in wastewater is measured as chemical oxygen demand (COD). In Amsterdam the total amount of organic matter in wastewater is approximately 41.9 kton COD. Organic matter originates from 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. 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. Most of the biogas is used for combined heat and power production. 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 a higher methane content than biogas and can therefore be used as a transportation fuel.

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, which is located adjacent to WWTP Amsterdam West. The residual heat of this incineration is used for district heating.

Figure 6 shows the phosphorus in Amsterdam's wastewater. It is unknown how much of the phosphorus load at WWTPs originates from households and how much originates from businesses. Therefore, the assumption was 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 hotels and catering industry, this assumption seems likely. 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' (Van der Hoek et al., 2015). 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. The rest of the phosphorus remains in the sludge which is incinerated by the waste and energy company AEB.

3.2 Comparison of measures

All 21 measures (Table 1) were evaluated based on the nine criteria (Table 3). Supplementary Material 2 shows this evaluation in detail.

All measures influence water, organic matter and/or material flows (*criteria 1-3*). Thereby, they change the resources that are or can be recovered. An example is the measure of green waste disposals. These grinded green household wastes enable 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.

With respect to *criteria 4 and 5* (what products are recovered from the organic matter and phosphorus, and in which quantities), the effect of the 21 measures on the quantities of the five products that can be recovered from Amsterdam's wastewater (biogas, cellulose, bioplastic, phosphorus, alginic acid) are summarized in Table 4. The calculations behind these numbers can be found in Supplementary Material 2. Table 4 shows the current situation 2013 and the situation in 2040, assuming that the system does not undergo changes other than the assumed economic and population growth in Amsterdam, based on the Strategic Vision of Amsterdam 2040 (City of Amsterdam, 2010), Statistics Netherlands (CBS, 2014) and the statistics bureau of the Municipality of Amsterdam (Dienst Onderzoek en Statistiek, 2010), and some climate changes, based on climate change scenarios of the Royal Dutch Meteorological Institute (KNMI, 2014). This 'ceteris paribus' situation 2040 was the starting point for the calculations of the measures' impacts.

The value of the five recovered products (*criterion 6*) was ranked using the value pyramid (Figure 2). Products higher in the value pyramid are valued higher and therefore preferred over products lower in the pyramid. Biogas was ranked at level 2 (transportation fuels) as it may be converted into Green Gas and used as transportation fuel (Van der Hoek, 2012b). Cellulose, bioplastics, phosphorus and alginic acid were ranked at level 3 (materials & chemicals), while their value increased in this order in level three. Cellulose is the polysaccharide of which the fibers in toilet paper consist. The fibers can be used to produce building materials and paper products and, therefore, cellulose is placed at level 3, materials & chemicals. Cellulose is valued lower than bioplastic, phosphorus and alginic acid, because those three other products have closer links to level 4 (food) and 5 (health and lifestyle). Also traditional production of cellulose (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 at level 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, belongs at level 3. As phosphorus is necessary for food production (level 4) it is valued higher than cellulose and bioplastic. Furthermore, phosphorus stocks are decreasing and, therefore, alternative, more sustainable stocks 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 levels 4 and 5. So, even though alginic acid falls into the third level, it is valued highest within this level.

Table 4 shows that only a few of the considered measures introduce new products: cellulose, bioplastic (PHA) 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 a consequence of the Nereda process which 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 which are at the moment already produced (biogas and phosphorus as struvite). These measures can, for example, be combined with the measures that recover new products to increase the production of these products.

Besides the resource recovery capacities of measures, also the timing of measures is important when deciding to implement a resource recovery policy. Some measures may not be the best in producing highly valued products, but they may be the best measures that are feasible at this moment in time. Timing and implementation include the criteria development stage of a measure (*criterion 7*), the dependencies of measures on external actors and situations *(criterion 8*) and the implementation horizon (*criterion 9*). In Supplementary Material 2 these are described in detail for all measures.

The first factor to consider is the development stage of the measure (*criterion 7*). 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. Consequently, measures with unpredictable development paths require highly flexible implementation plans.

The second factor to consider is how a measure depends on external circumstances and actors (*criterion 8*). 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 in The Netherlands. So, before water authorities can implement green waste disposals changes of legislation and, therefore, the support of politicians are required.
The third factor to consider 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 is incinerated separately, etc. Thus, whether and when a measure can be implemented depends on whether and when another measure is or can be implemented. Continuing the previous examples, this implies that it is unwise to remove the primary settling tank before it is known when the Nereda process is installed, and alginic acid production cannot start before implementation of Nereda and, thus, implementation of alginic acid production should be matched with implementation of Nereda.

3.3 Resource recovery strategies

Based on the selected measures and their characterization, these measures were combined into four specific resource recovery strategies. The strategies were based on:

- Maximum recovery of one specific product: alginic acid, bioplastic, cellulose or phosphorus;
- Recovery of other resources than the focus product in the chosen strategy is allowed as long as it does not limit the recovery of the focus product. For these other resources the prioritization of the value pyramid (Figure 2) is used. Hence, biogas production is possible in the strategies, but is valued lower than alginic acid, bioplastic, cellulose or phosphorus production.

The four strategies are strategy A (focus on alginic acid), strategy B (focus on bioplastic), strategy C (focus on cellulose) and strategy P (focus on phosphorus). Measures can be complementary or mutually exclusive in the strategies. Table 5 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 sieves 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 impact 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.

To follow the principles of adaptive policymaking, as a tool to develop alternative, coherent and viable strategies regarding resource recovery in Amsterdam’s wastewater chain, 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 one 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 5 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 is 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. 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.

The most striking examples of competing measures, resulting in lock-ins, 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 costs 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 5 suggests conflicts with alginic acid and bioplastic production, cellulose recovery 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 recovery measures is postponed by one or two years because both measures are still under development. Concluding, cellulose recovery measures

can be implemented on 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 wastewater treatment process 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 through struvite precipitation are also encouraged, since recovery from urine 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 recovery 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 will depend 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.

3.4 Uncertainty and sensitivity

In section 3.3 alternative, coherent and viable strategies have been defined to recover resources from Amsterdam's wastewater. Although the development process of dynamic adaptive policy pathways was used to cover the wide variety of possible alternatives and the many external factors, there are several uncertainties arising from social, political, technological, economic and climate changes which may affect the outcome of the strategy development process.

A major uncertainty is *technology development*. In section 3.3 it was already mentioned that the speed of technology development for alginic acid production and bioplastic production may influence the attractiveness of cellulose recovery. However, it is not only the speed of technology development, but also the occurrence of new technologies. As an example, single cell protein production from wastewater as recently suggested by Matassa et al. (2015) introduces a new product in addition to the five selected products considered in this study (section 2.2.3). This may change the strategies for resource recovery and thus the strategy diagram.

Another uncertainty is the trend towards *decentralized wastewater treatment*. In this study centralized wastewater treatment was assumed for Amsterdam. However, decentralized water systems are considered to be effective, beneficial and useful in a number of urban settings (Moglia et al., 2011). Hamburg Wasser, Hamburg's water supply and wastewater utility, is rethinking the way of wastewater management by implementing an integrated concept for decentralized wastewater treatment and energy production (Augustin et al., 2014; Skambraks et al., 2014). This concept is based on source separation of domestic wastewater flows and their efficient treatment and use. As mentioned by Daigger (2009), centralized and decentralized configurations show differences in behavior with respect to resource recovery. In Amsterdam, some small initiatives have been started with respect to decentralized sanitation and wastewater treatment. When implemented on al large scale, this will affect the strategies for resource recovery from Amsterdam's wastewater.

Legislation and social acceptance are also uncertainties which may affect the outcome of the strategy development process. Legislation as uncertainty has already been addressed in section 3.2 for green waste disposal in the sewer. Products recovered from wastewater may be contaminated and may contain pathogenic microorganisms. An extensive study (Ehlert et al., 2013) was necessary to implement changes in the Dutch Fertilizers Act to allow the use of struvite from wastewater as a fertilizer (Overheid.nl, 2016). Although the opportunities for substituting phosphorus recovered from wastewater treatment works in fertilizer markets are already known for many years (Gaterell et al., 2000), and Waternet started with struvite recovery experiments just after the start-up in 2006 of the full-scale wastewater treatment plant (Van Nieuwenhuijzen et al., 2009), the change in the Dutch fertilizer act only took place recently on January 1, 2016. Social acceptance as uncertainty is pointed at by Matassa et al. (2015). They state that a change of mindset needs to be achieved to make recovery of reactive nitrogen from waste and wastewater as microbial protein and use for animal feed and food purposes acceptable.

Finally, *economics and market conditions* introduce high uncertainties. Resource recovery from wastewater introduces financial benefits and costs in wastewater treatment schemes, which depend on specific situations and interact with many other variables. As an example, struvite recovery from the wastewater in Amsterdam shows to have a positive business case only because it reduces the maintenance costs of the wastewater treatment plant. In addition it results in a lower greenhouse gas emission (Van der Hoek et al., 2015). To make use of these benefits, first the Dutch Fertilzers Act had to be changed, otherwise the product struvite would not have any market potential. Especially market potential and market competition introduce uncertainties. Bioplastics have to compete with plastics originating from the petrochemical industry, which are available in high amounts at relatively low prizes. Thus, the market potential of bioplastics seems limited at the moment. The expectation for alginic acid is opposite. Alginates are produced from seaweeds, and the availability and costs of alginate seaweeds is beginning to be a concern of alginate producers. Higher costs have been driven by higher energy, chemicals and seaweed costs, reflecting seaweed shortages (Bixler and Porse, 2011). These market conditions may favor the production of alginic acid from wastewater.

4 Conclusions

This research developed alternative, coherent and viable strategies regarding resource recovery in Amsterdam's wastewater chain using a method of adaptive policymaking. The Amsterdam case shows that this method results in a coherent policy as the goals of research recovery are clear, in a flexible policy as the lock-ins, no-regrets and win-wins are clear, and in an up-to-date policy as a periodic update will reveal new chances and risks.

A material flow analysis is the basis for the development of the strategies, as it gives insights into the organic matter and phosphorus flows in the Amsterdam's wastewater chain. In the next step, the selection of measures to recover resources, the measures can be characterized by use of nine specific criteria, focusing on changes in material flows, recovered products and implementation horizons. The final step is to define specific strategies focusing on the recovery of a specific product. In the Amsterdam case these were alginic acid, bioplastic, cellulose or phosphorus. The use of a strategy diagram, which shows the composition of a strategy and describes how each measure contributes to the strategy, shows to be a very useful tool to distinguish between lock-in measures, no regret measures and win-win measures. These lock-in, no-regret and win-win measures have to 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. The strategy diagram presents measures' interactions in a well-organized way in which the possible order of measures and choices becomes clear.

The method of adaptive policy making also enables to update and expand a specific case when new information becomes available, implying that new opportunities can be seized and threats can be spotted early. So, using this method to create a resource recovering policy helps to develop an adaptive policy that functions well in a highly uncertain future.

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Captions of figures

Figure 1. The dynamic adaptive policy pathways approach (adapted from Haasnoot et al. (2013)).

Figure 2. Value pyramid (adapted from Betaprocess bioenergy (n.d.)).

Figure 3. Research boundaries: water chain versus wastewater chain.

Figure 4. Amsterdam's water chain 2013 (in million m^3).

Figure 5.Organic matter in Amsterdam's wastewater chain 2013 (in ton COD).

Figure 6. Phosphorus in Amsterdam's wastewater chain 2013 (in ton P)

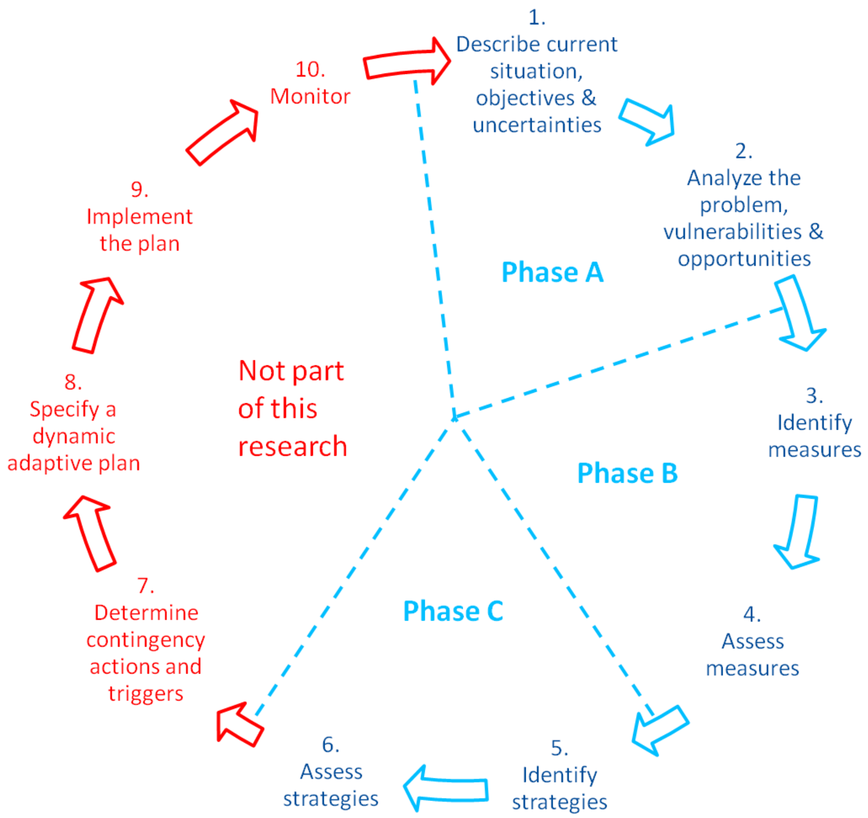


Figure 1. The dynamic adaptive policy pathways approach (adapted from Haasnoot et al. (2013)).

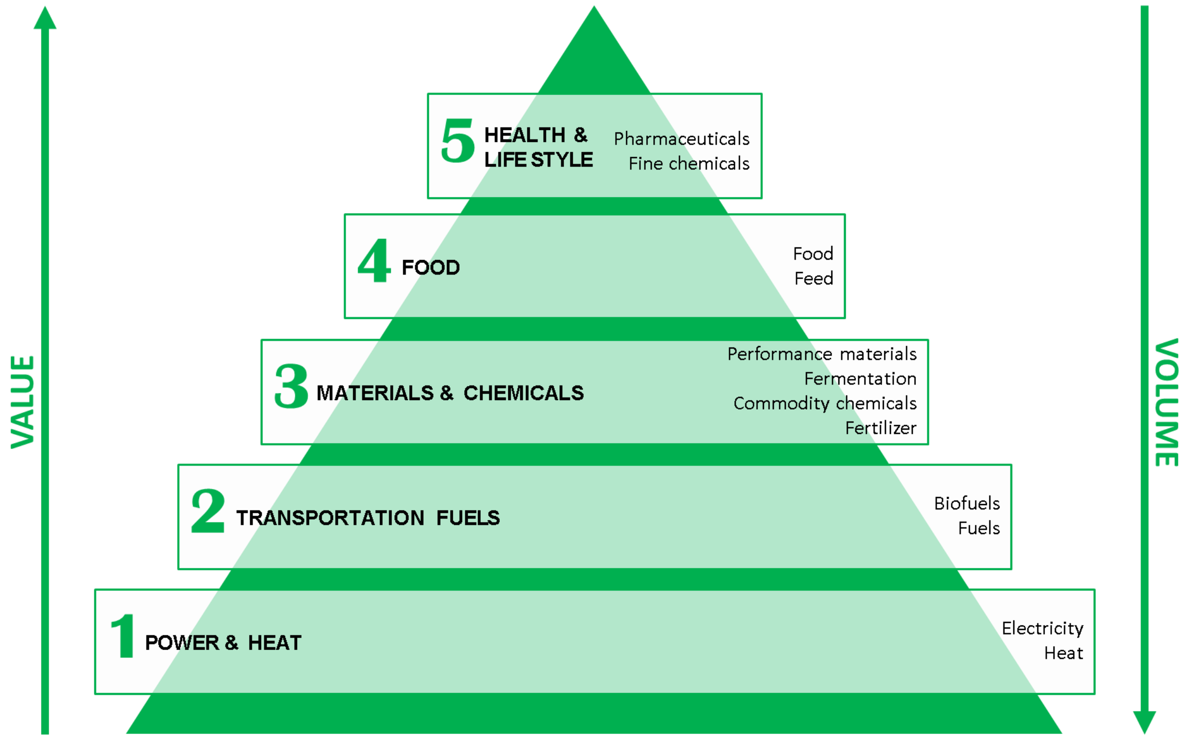
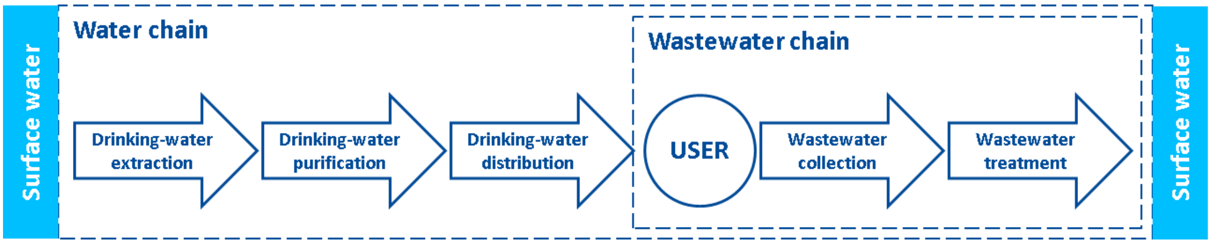


Figure 2. Value pyramid (adapted from Betaprocess bioenergy (n.d.)).



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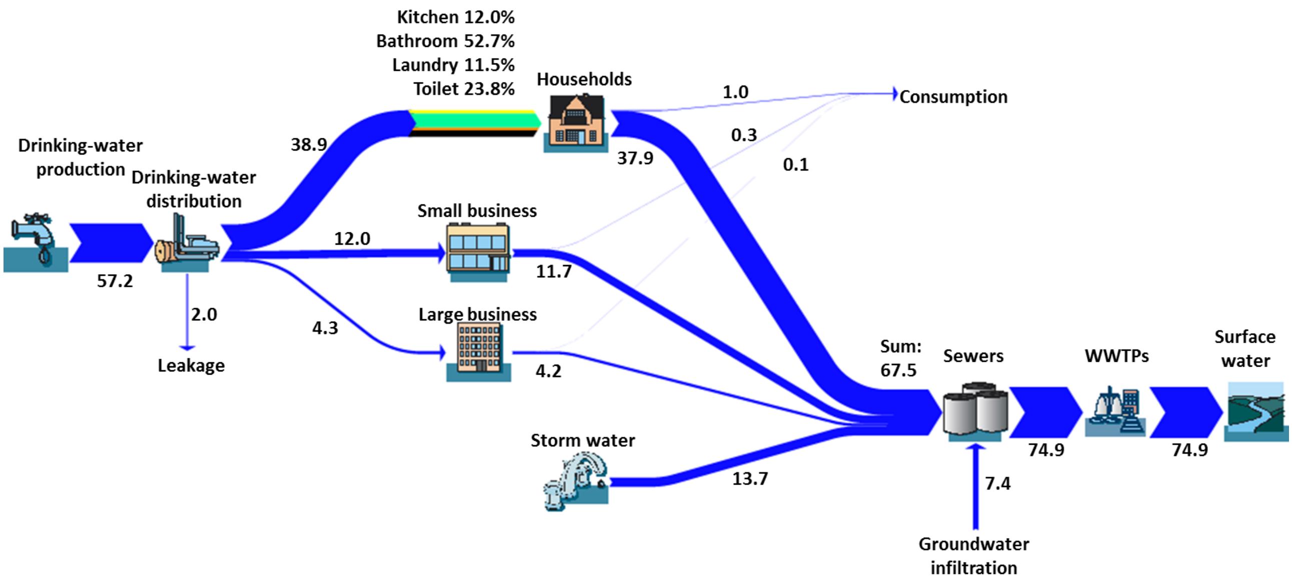

Figure 4. Amsterdam's water chain 2013 (in million m^3).

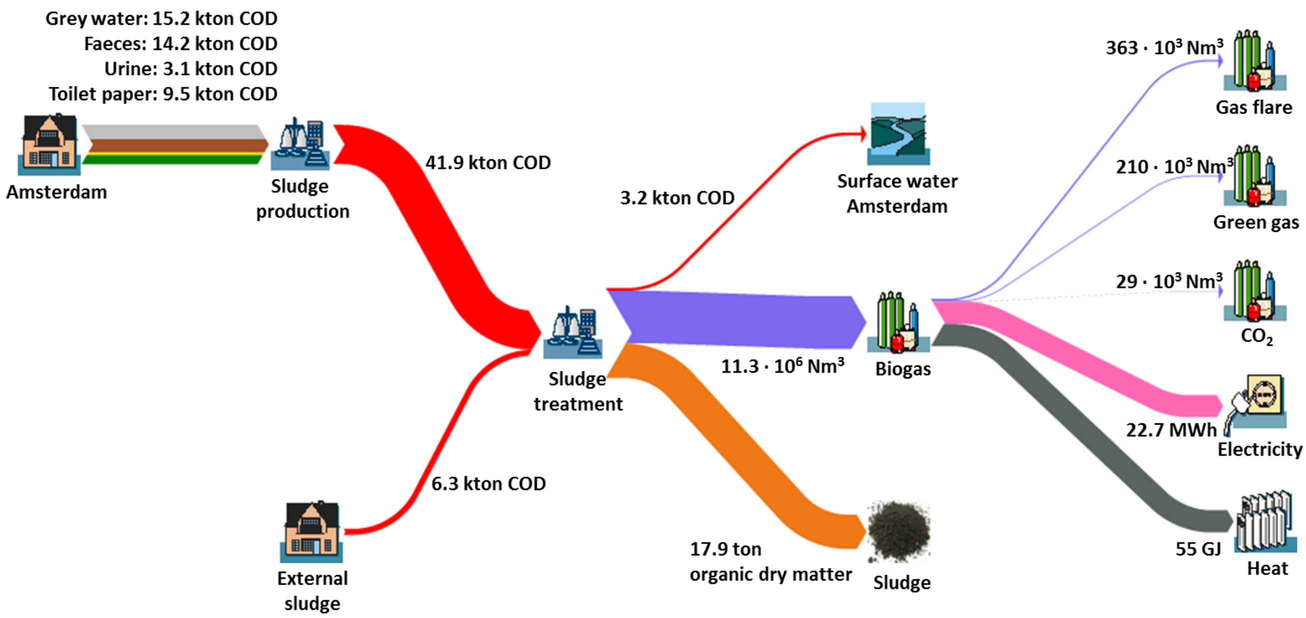

Figure 5.Organic matter in Amsterdam's wastewater chain 2013 (in ton COD).

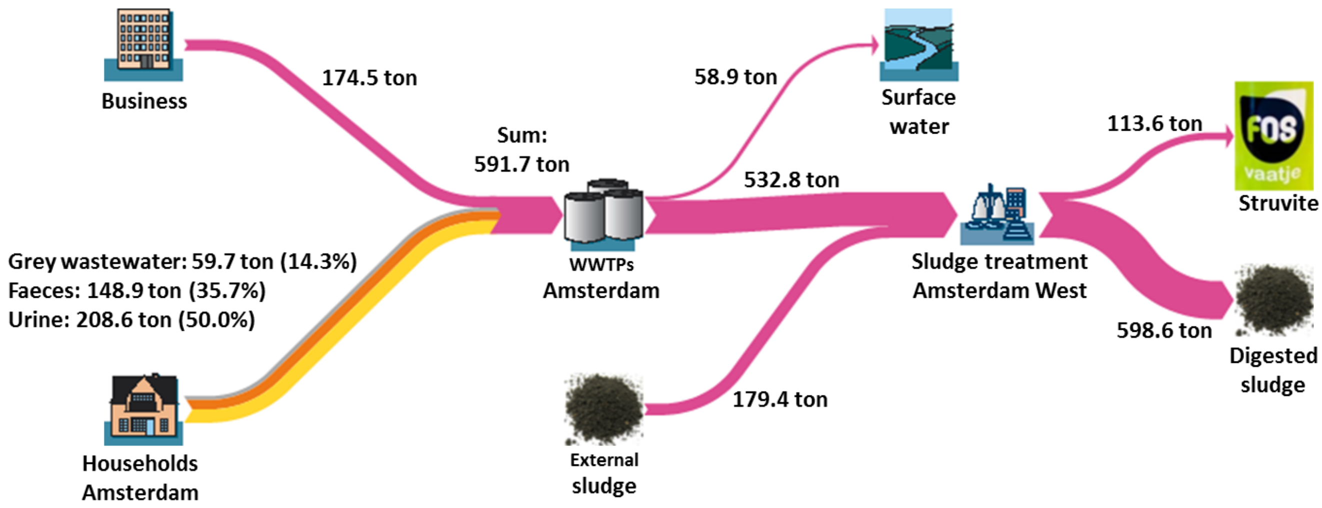

Figure 6. Phosphorus in Amsterdam’s wastewater chain 2013 (in ton P).

Table 1. Description of measures.

Category	Measure	Description
Households & Businesses	1. Green waste disposal	Waste disposal grinders are installed at households and/or businesses. Therefore, green waste is transported to the WWTPs.
	2. Water use reduction	Installation of water saving showers and toilets.
	3. 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.
	4. Separate urine treatment	After separate urine collection, resource recovery is done at a separate urine treatment facility.
	5. Pharmafilter	Installation of Pharmafilter at hospitals and other care facilities.
Collection	6. More separated sewers	Combined sewers are replaced by separated sewers so less stormwater ends up at the WWTPs.
	7. Reduced groundwater infiltration	Old sewers are replaced by new ones resulting in less groundwater infiltration.
Wastewater treatment plant	8. Primary settling tank	Separation of primary sludge from the influent at WWTPs by settlement due to reduced flow velocities.
	9. Bioplastic production	Through fermentation (mixed or rich culture) the bioplastic PHA can be produced from (mainly primary) sludge.
	10. Cellulose recovery from primary sludge	After primary sludge is separated from the influent using a primary settling tank, cellulose is recovered from the sludge.
	11. Fine-mesh sieve & cellulose recovery from sievings	A fine-mesh sieve is used to separate larger particles, including cellulose fibres, from the influent.
	12. 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.
	13. Nereda	Biological treatment process that removes phosphorus and organic matter from the water and stores it (partially) in granular sludge.
	14. Alginic acid production	Alginic acid, a polysaccharide, can be produced from granular sludge.
	15. Thermal hydrolysis	Pre-treatment of sludge using heat and pressure that sterilizes sludge and makes it more biodegradable.
	16. Mesophilic digestion	Current sludge digestion at approximately 36°C and with a residence time of 20 days.
	17. Thermophilic digestion	Sludge digestion at approximately 55°C and with a residence time of at least 12 days.
	18. 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	19. Sludge incineration at waste plant	Digested sludge is incinerated. Currently, sludge and solid waste are incinerated together (by AEB).
	20. Mono-incineration	Digested sludge is incinerated separately from solid waste to enable phosphorus recovery from sludge ashes.
	21. Phosphorus recovery from sludge ashes	Phosphorus in sludge ashes is precipitated using iron salts.

Table 2. Description 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 fibers in toilet paper consist. The fibers 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.

Table 3. Criteria to characterize the measures.

Criterion	Questions answered
1. Δ water	How are water flows changed by the measure? So, how do water use and/or wastewater production change due to this measure?
2. Δ organic matter	How are organic matter flows changed by the measure?
3. Δ phosphorus	How are phosphorus flows changed by the measure?
4. Recovery organic matter	What products are recovered from the organic matter and in which quantities?
5. Recovery phosphorus	What products are recovered from the phosphorus and in which quantities?
6. Value recovered products	What is the value of the recovered products using the value pyramid?
7. Development stage	At what stage of development is the measure? Possible answers are idea, lab phase, pilot phase, full scale testing and proven technology.
8. 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 behavior required?
9. Implementation horizon	From what moment onwards can the measure be operational in Amsterdam?

Table 4. Effect of measures on recovery of biogas, cellulose, PHA, phosphorous and alginic acid from Amsterdam's wastewater.

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

LEGEND

- Large increase
- Increase
- No change
- Decrease
- Large decrease

Table 5. Strategy diagram: possible composition of the four strategies; "– " negative influence; '0" optinal; "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	X	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