URBAN MINING FOR A CIRCULAR ECONOMY

A DYNAMIC MATERIAL FLOW ANALYSIS OF THE URBAN MINE OF THE DUTCH URBAN WATER CYCLE INFRASTRUCTURE

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‘SUSTAINABILITY WILL ONLY BECOME REALITY IF WE TREAT MATERIALS WITH THE AWE AND RESPECT THEY DESERVE AND DEVISE WAYS TO RECYCLE THEM OVER AND OVER’

– T.E. GRAEDEL (2011)

EXECUTIVE SUMMARY

Inherently related to the quadrupling of global population and the 20-fold increase of global economic output in the last century, is the increase of inputs of raw materials and energy into society and its corresponding outflows. In order to lower the volume of outflows and effectively control pollution, a reduction of raw material use throughout the economy is required. A shift from a linear to a circular economy plays an important role in achieving global climate goals. In a circular economy materials are kept in use for as long as possible so that the need for virgin materials is as little as possible.

From a perspective of a circular economy material stocks in urban areas can be considered as 'natural resources'. These in-use stocks can be described as the urban mine, a concept that is defined as the systematic reuse of anthropogenic materials from urban areas such as buildings and infrastructure for example. Although using the urban mine is desirable, knowledge about stocks and flows of the potential urban mines is limited. One of the infrastructure stocks that has not been assessed yet is the infrastructure of the urban water cycle in the Netherlands. The Dutch urban water cycle as assessed in this study consists of the drinking water production sites and supply network as managed by the 10 drinking water companies, the sewage network, gully pots and a large part of the sewage pumping stations as managed by the municipalities, and some of the sewage pumping stations, transportation pipelines and wastewater treatment plants as managed by the 21 water boards in the Netherlands.

In order to analyse the urban mine of the Dutch urban water cycle infrastructure, stock data was gathered about the current size and historic development of the different components of the urban water cycle infrastructure. Per component, the material composition and share is determined to calculate the total material stocks of the urban water cycle between 1950 and 2020.

The current stock of materials of the Dutch urban water cycle has a total mass of around 38Mton compared to a mass of 7.5Mton in 1950. The infrastructure component contributing most to this mass is the sewage network (59%), followed by the drinking water production plants (12%), wastewater treatment plants (12%), and supply network (9%). The material contributing most to the total mass of the urban water cycle infrastructure is concrete with 88%. Iron (4.2%), steel (4.4%), and asbestos cement (1.7%), have significant lower contributions, but even the materials with the lowest contributions, PVC with 1.1% and PE with 0.5%, still have a total mass of respectively 0.4Mton and 0.2Mton.

A dynamic Material Flow Analysis with a retrospective and prospective, bottom-up, stock-driven approach was conducted to analyse the development of stocks and flows of the Dutch urban water cycle until 2050. In order to analyse the stocks and flows between 2020 and 2050, different scenarios are used in which two driving forces are assumed to drive infrastructure changes of the urban water cycle: drinking water demand and the net construction of buildings. The scenarios are based on the Deltascenarios and translated into infrastructure stock changes until 2050 and used to analyse inflows and outflows of materials. The four scenarios are:

- DRUK – limited climate change, strong economic growth, low urbanization
- STOOM – rapid climate change, strong economic growth, high urbanization
- RUST – limited climate change, low economic growth, high urbanization
- WARM – rapid climate change, low economic growth, low urbanization

The material stocks of the supply network, sewage network, gully pots, and sewage pumping stations all increase until 2050 under all four scenarios due to the net construction of buildings. The number of drinking water production sites increases in scenario DRUK and STOOM because of exceedance of the current drinking water production capacity. The number of WWTPs and the corresponding pressurized pipelines do not change, since their capacity is not exceeded. The total stock of materials under scenario RUST and WARM is around 40Mton and increases to 44Mton in scenarios DRUK and 45Mton in STOOM.

It is however the outflow of materials that is most important for the potential of the urban mine of the Dutch urban water cycle infrastructure. Aside from the size of the outflow, the way the materials can re-enter the economy is also important. Inflows and outflows of materials were calculated with the Open software framework for Dynamic Material, a python model that can be used for conducting a dynamic Material Flow Analysis. The overall expansion of the stock of the urban water cycle infrastructure results in material inflows being higher than material outflows between 2020 and 2050 (except for asbestos cement). Inflows of materials are highest in scenario DRUK and STOOM, followed by scenarios RUST and WARM.

Based on interviews with drinking water companies and water boards, achieving circularity and reusing materials seems to be limited by (1) the high demand for raw materials which cannot be fully covered by the outflow of materials, (2) lack of responsibility regarding the waste collection and recycling, (3) perceived risks regarding the use of secondary materials, and (4) lack of awareness of the importance of reusing materials. Solutions for increasing material reuse are according to the interviewees: (1) increasing awareness among employees by showing them the value of secondary materials, (2) using the Environmental Cost Indicator

(MKI) in tenders to make sure new assets are made from more secondary and sustainable materials, and (3) setting up a marketplace for infrastructure materials.

The idea of a marketplace is not new however. It already exists in the form of a process related waste sharing platform (AquaMinerals) and a waste inventory platform (Circulair.biz), which could be extended with the sharing of infrastructure materials. Moreover, there seems to be some misconceptions about the reuse of recycle plastics in the drinking water supply network and about the concept of achieving circularity in general. Circularity does not have to be achieved within a drinking water company, municipality, or water board, but can also be achieved on a higher level.

To continue the development of knowledge about the urban mine of the urban water cycle, it is recommended to research exact material content that has reuse potential and investigate the size of the hibernating stocks to increase the accuracy of the stock and flow analysis. It is also recommended to use Geographic Information Systems for the visualization and managing of urban water cycle infrastructure data. Aside from knowledge of the size of stocks and flows, it is also important to know the location of where the materials of the Dutch urban water cycle become available at their end-of-life.

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INTRODUCTION

1 INTRODUCTION

During the last century the global population quadrupled and the global economic output measured in GDP grew more then 20-fold (Maddison, 2001). This is inherently related to an increase of inputs of raw materials and energy into society and the corresponding waste flows and emissions (Krausmann et al., 2009). The International Resource Panel and the Organization (IRP) for Economic Co-operation and Development (OECD) expect that the consumption of raw materials will double by 2060 compared to 2017 e.g. due to economic growth (IRP, 2019; OECD, 2019). It is thus expected that the extraction of resources will continue to increase and will lead to depletion of geological mines (van Berkel & Schoenaker, 2020). In order to lower the volume of final waste and effectively control pollution, a reduction of raw material use throughout the economy is required (IRP, 2019).

Achieving global climate goals and reduce the use of raw materials, a shift from a linear economy to a circular economy is needed in which environmental, economic, and social needs are still supported (Korhonen et al., 2018). A circular economy is described by the Ellen MacArthur Foundation (2013a) as "an industrial system that is restorative or regenerative by intention and design. It replaces the 'end-of-life' concept with restoration, and aims for elimination of wastes through designing of materials, products, systems, and business models", and is proposed as a promising solution for reducing the use of raw materials. Although the production phase is of great importance in a circular economy, the consumption phase is as important (Camacho-Otero et al., 2018). The importance of considering alternative options for the management of products, their materials, and their components at the end-of-life are already widely recognized according to UNEP (2017).

The idea behind a circular economy is thus that materials are kept in use as long as possible so that the need for virgin raw materials is as little as possible (Hanemaaijer et al., 2021a). The materials can re-enter the economy in various ways (Figure 1). As the diagram shows, there are two main cycles: a biological cycle and a technical cycle. In the biological cycle nutrients from biodegradable materials are returned to the Earth which allows the land to regenerate so the cycle can continue. The technical cycle describes the circulation of products through many different processes such as reuse, repair, remanufacture, and recycling. Materials are kept in use and serve as a material source and never become waste (Ellen MacArthur Foundation, 2013b). The "cradle-to-cradle" thinking can preserve the natural resources from scarcity and reduce the amount of waste disposal in landfills and the emissions from treatment (Cossu & Williams, 2015).

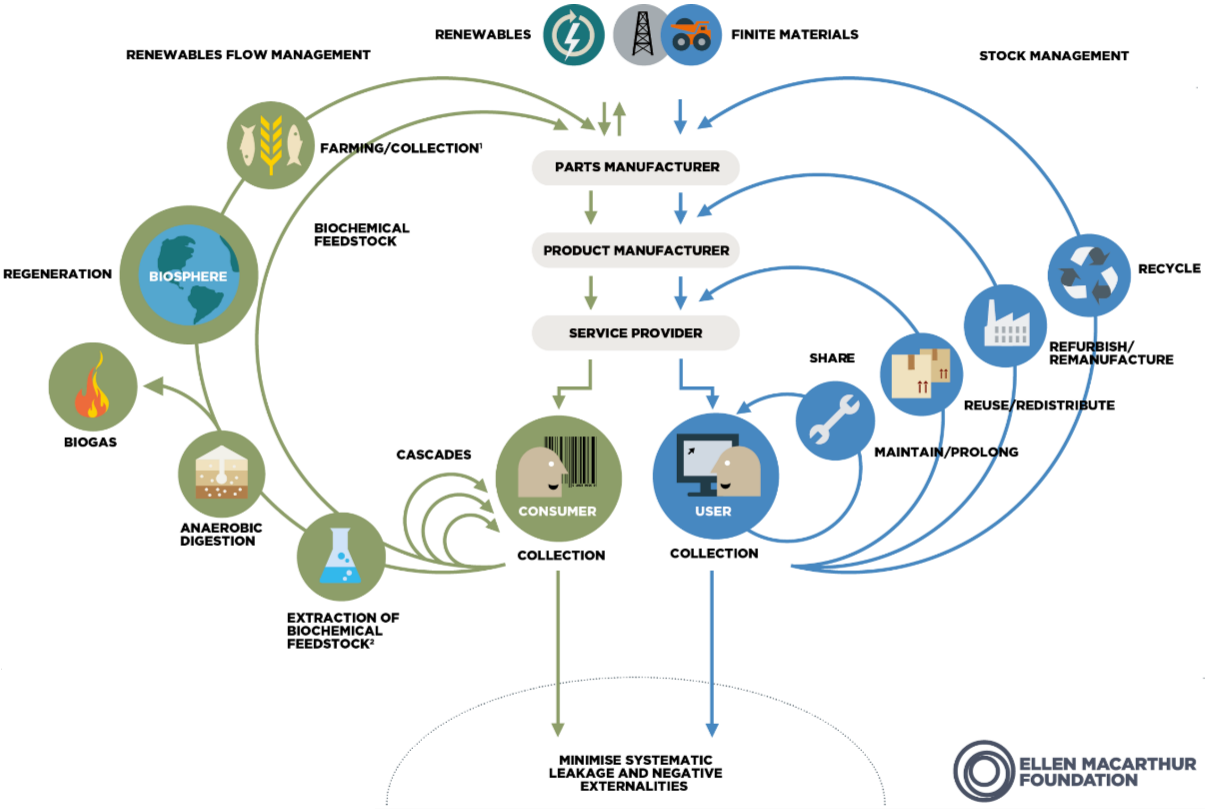


Figure 1. Butterfly diagram from the Ellen MacArthur Foundation (2019).

From the perspective of a circular economy, material stocks in urban areas can be considered as 'natural resources'. These in-use stocks have the ability to provide materials that would otherwise have been extracted from nature and are described as the 'urban mine' (Johansson et al., 2013; Ortlepp et al., 2015). Urban mining denotes the systematic reuse of anthropogenic materials from urban areas and is a circular economy strategy (Brunner, 2011). Large stocks of materials in society such as buildings, infrastructure, and waste stocks become available at their end-of-life and could partially replace the geological mine of raw materials (Brunner, 2011).

The urban mine has some fundamental differences compared to the geological mine. First of all, materials are still in-use, meaning that they are not yet available for mining. Furthermore, the urban mine is constantly replenished whereas geological mines are depleted (van Oorschot et al., 2020a).

1.1 PROBLEM DEFINITION & KNOWLEDGE GAP

Although using the urban mine is desirable, there are still barriers for the implementation of circular economy and urban mining activities (Bender & Bilotta, 2019). To facilitate urban mining more information is needed about the materials and substances in in-use stocks. We need to know the inflows of materials, the current stocks of materials, and the outflows of materials. Not only the quantity of those flows is important knowledge, but also when the materials become available (Brunner, 2011).

PBL, the national institute for strategic policy analysis in the fields of the environment, nature and spatial planning, is requested by the Dutch government to take the lead in a national research program aiming at evaluating and monitoring the transition towards a circular economy in the Netherlands (Hanemaaijer et al., 2021b). To support the Dutch circular economy policies, the Program on Monitoring and Evaluation Circular Economy 2019-2023 was set up. In the context of this program a few stocks are already assessed in the Netherlands: vehicles, the electricity system, electronics, residential and service buildings, electronic machines, and textiles (PBL, 2021; van Oorschot et al., 2020a, 2020b, 2021). The aim of this project is getting insights in stocks and materials available in the Dutch society, focusing on questions such as: When do these materials become available? What is the quality of these materials? What is the current destination of end-of-life materials? In order to get a more complete picture of the size of the Dutch urban mine, it is necessary to extend the beforementioned research with the assessment of other stocks.

One of the infrastructure stocks that has not yet been assessed is the infrastructure of the urban water cycle in the Netherlands. The urban water cycle and its infrastructure is a so called ‘top vital sector’, meaning it is fundamental to life and vital to households, industries, and government. Drinking water systems provide a critical health function and are essential to life, economic development, and growth. Since 2011, the Drinking Water Act, Drinking Water Decree, and Drinking Water Regulations are intended to ensure drinking water supply in a socially responsible manner (Veldkamp et al., 2019). These quality requirements as well as supply security ask for good quality infrastructure. Building and replacement of the infrastructure of the urban water cycle as well as improving the system requires currently large amounts of raw material inputs. Knowledge of the material stocks and flows of the urban water cycle infrastructure gives insights in the size of this urban mine. The following main research question and sub-research questions are defined:

What does the urban mine of the Dutch urban water cycle infrastructure look like until 2050 and how can it contribute to a circular economy?

Sub-RQ1 – What is the current size and material composition of the urban mine of the Dutch urban water cycle infrastructure?

Sub-RQ2 – How do material stocks and flows of the Dutch urban water cycle infrastructure develop until 2050?

Sub-RQ3 – How are the outflows of the Dutch urban water cycle infrastructure re-entering the economy and how can this be improved?

1.2 SCOPE OF THE STUDY

The water infrastructure in the Netherlands consists of many components. The focus of this study is on infrastructure in the Dutch urban water cycle. This includes the production of drinking water, supply of drinking water, transportation of wastewater and the treatment of wastewater. A more detailed explanation of the assessed components is presented in section 2.4.

1.3 OUTLINE

The report is structured as follows. The Dutch urban water sector is introduced in chapter 2, in which the assessed components for this study are presented as well. In chapter 3 the methodology is described, followed by the results in chapter 4. The results and methodology are discussed in chapter 5, followed by some recommendations in chapter 7. In chapter 8 a conclusion is given.

Dutch Water Sector

2 DUTCH WATER SECTOR

The Dutch water sector is characterized by the interplay of various organizations performing their duties at the regulatory and executive levels (Argento & van Helden, 2009). A distinction can be made between the water system and the water chain. Where the former entails the totality of groundwater and surface water and is regulated under legislation of the ministry of Transport, Public Works and Water Management, the latter comprises the pathway from drinking water supply to wastewater treatment and is regulated under the legislation for which the ministry of Housing, Spatial Planning and the Environment is responsible (Jong, 2007). The Dutch water chain consists of three main elements: (1) the drinking water production and supply, (2) the sewage system, and (3) wastewater treatment. It includes the abstraction and production of water, the distribution and usage of water, and the collection, transport and treatment of wastewater. Figure 2 presents the relations between the water chain, water system and the executive organizations. The three main elements of the Dutch water chain are explained in more detail in the next section.

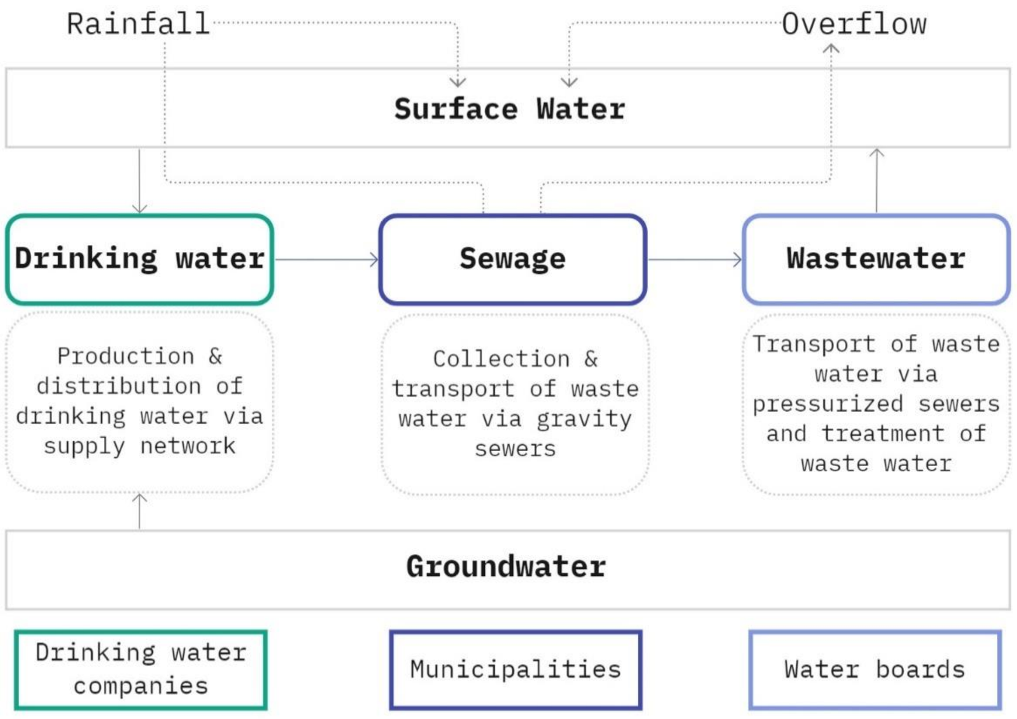


FIGURE 2. THE DUTCH WATER CHAIN AND MANAGING BOARDS BASED ON ARGENTO & VAN HELDEN (2009) AND JONG (2007).

2.1 DRINKING WATER

Since 2010, the Netherlands has ten drinking water companies. These drinking water companies are represented by Vewin – the national association of drinking water companies in the Netherlands (Vewin, 2019). Each drinking water company is obliged to provide drinking water 24/7 to a certain area in the Netherlands Figure 3. In order to supply water to their customers, the drinking water companies need to produce water and distribute it. Groundwater (two thirds) and surface water (one third) are the main sources for water abstraction. After following different purification and cleaning steps, drinking water is stored in so called clean water reservoirs. From the clean water reservoirs, drinking water is transported to the customers of the drinking water companies via different types of pipelines: (1) transport pipelines for the transportation of drinking water to various municipalities, (2) main pipelines that branch from the transportation pipeline into different neighbourhoods within a municipality, and (3) connection pipelines that connect the property of the customer to the main pipeline (Dunea, 2021).

FIGURE 3. SUPPLY AREAS OF THE TEN DRINKING WATER COMPANIES (VEWIN, 2019).

To meet the high quality regulations as described in the *Waterwet*, repairing and replacing pipelines is important. The maintenance of the abovementioned pipelines falls under the responsibility of the drinking water companies. Failure of drinking water pipelines are related to various pipe specific factors such as material, lifetime, diameter, length, but also by network specific factors such as soil type and weather conditions (Le Gat & Eisenbeis, n.d.).

In 2007, KWR Watercycle Research Institute researched the registration of failures at water companies and concluded that a uniform failure registration system would be beneficial. USTORE was set up in 2008 for water companies to register pipeline failures, but also to manage and analyse them (Moerman & Beuken, 2015). Next to failure registrations, the system also entails information about the length and material composition of pipelines and their geographic location. This system does not only show trends of failures related to for example pipe material, but it can also be used for risk analysis on the effect of failures on customers and the environment. This knowledge allows for well-informed decisions about the replacement of pipelines for example (KWR, 2022).

2.2 SEWAGE

Sewage includes the system of collecting wastewater and transporting it to soil, open water bodies (only rainwater) and wastewater treatment plants. The construction and maintenance of the gravity driven sewage system falls under the responsibility of municipalities. Unlike drinking water companies, collection, transportation and maintenance of the sewage system may be carried out by third parties, though the municipality remains accountable.

There are two types of sewer systems: gravity sewers and pressurized sewers. Gravity sewers have a difference in elevation. The energy resulting from this difference is used to transport both wastewater and rainwater. Within gravity sewers two types can be distinguished: (1) combined sewer systems where rainwater and wastewater are combined in the same pipe, and (2) separate sewer systems with two pipes: one for rainwater and one for wastewater. Pressurized sewers on the other hand are used in systems where gravity cannot transport wastewater and they rely on mechanical pumps or compressors to create pressure for the transportation of water. These pressurized sewers are managed by the water boards (section 2.3).

Concrete and plastic are the two main materials of which the sewage system is constructed (Oosterom et al., 2013). According to RIONED, the interest group for urban drainage concerns, municipalities manage around 150,000km of sewage pipelines (Stichting RIONED, 2010). The condition of these pipes is highly influenced by its age, the material it is made of, environmental circumstances, etc. (Mohammadi et al., 2020). Depending on these factors and the lifespan, pipes have to be repaired and replaced at some point (Oosterom et al., 2013).

2.3 WASTEWATER TREATMENT

Regional water boards ('*Waterschappen*') are decentralized government institutions in the field of water management. Water management includes the management of water defenses, management of quantity and quality of open water bodies, navigable waterways, and the treatment of urban wastewater. The infrastructure for the treatment of urban wastewater forms the third water infrastructure category for this research. The 21 water boards operate a total of 335 wastewater treatment plants (WWTPs) in the Netherlands (Figure 4) (Havekes et al., 2017). Although the municipalities are responsible for the gravity driven sewage network, the water boards manage the pressurized transportation pipelines. Besides the inclusion of the materials used in the RWZIs and pressurized pipelines, the water boards also manage the sewage pumping stations (Havekes et al., 2017).

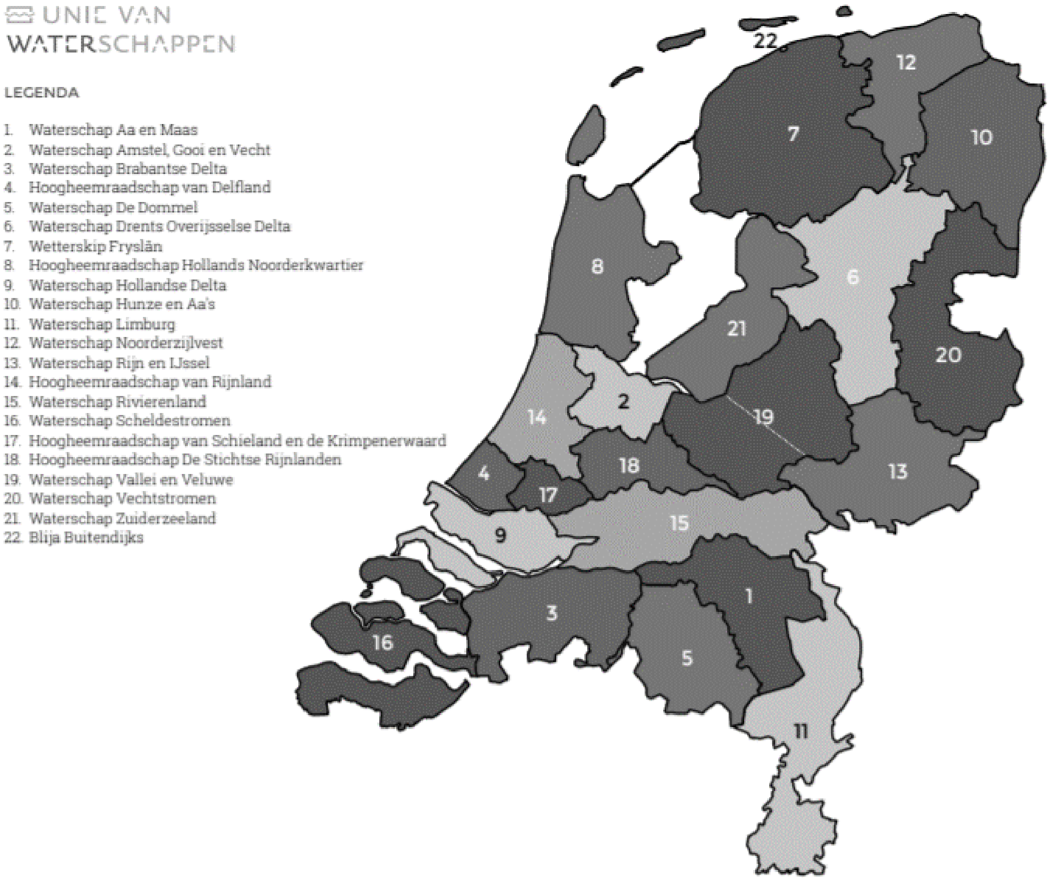


FIGURE 4. WATER BOARDS IN THE NETHERLANDS (HAVEKES ET AL., 2017).

2.4 COMPONENTS CONSIDERED IN THIS STUDY

The final outcome of a dynamic material flow analysis is the presentation of different material stocks and flows over time. The infrastructure of the Dutch water network consists of many different components, each with their own specific material content. In order to structure the search for stock data of the Dutch water infrastructure, the water sector is split up in different components. An overview of the drinking water sector and its different components is presented in Figure 5.

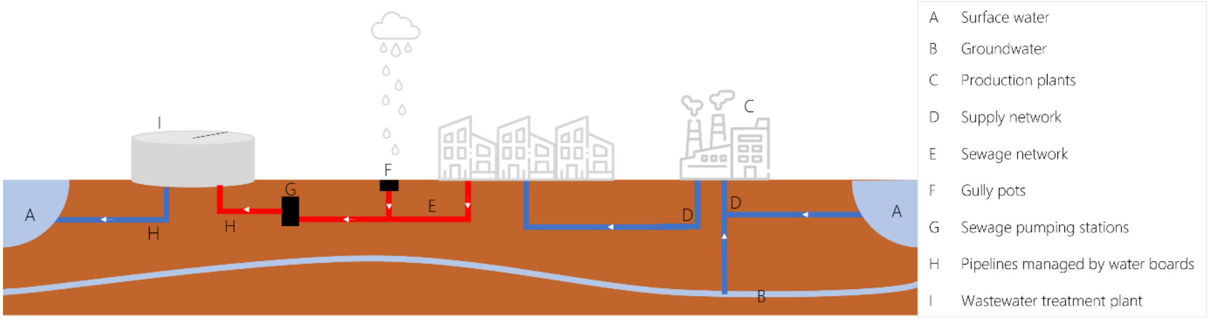


FIGURE 5. COMPONENTS OF THE DUTCH DRINKING WATER SECTOR.

The assessed stocks of this study are:

- The drinking water production plants
- The drinking water supply network
- The sewage grid
- The gully pots that are part of the sewage grid
- The sewage pumping stations
- The wastewater transportation pipelines managed by the water boards
- The wastewater treatment plants

These components are further on referred to as the *'Dutch urban water cycle infrastructure'* components.

METHODOLOGY

3 METHODOLOGY

In order to answer the sub-research questions and subsequently the main research question, several methods are used. Firstly, data is collected to determine the current size and material composition of the urban mine of the Dutch urban water cycle (sub-RQ1). The corresponding inflows and outflows of materials until 2050 are quantified with a dynamic Material Flow Analysis (sub-RQ2). Lastly, qualitative research is conducted to analyse the re-entering of urban water cycle infrastructure materials in the economy (sub-RQ3). In this chapter, the various methods are described in more detail.

3.1 CURRENT STOCKS AND MATERIAL COMPOSITION

Data on the current stocks and material shares of each of the urban water cycle components form the main types of data input for this study. First of all to be able to describe the current size and material composition of the Dutch urban water cycle and answering the first research question and secondly to be able to calculate material inflows and outflows with the dynamic Material Flow Analysis, which is described in section 3.2.

3.1.1 DRINKING WATER PRODUCTION PLANTS

The infrastructure of the drinking water production plants managed by the water companies consists of various elements. Depending on the source of the water (groundwater or surface water) different purification processes are needed. Each of the ten drinking water companies executes more or less the same purification steps for their production of drinking water (Veldkamp et al., 2019). It is assumed that since their production steps are comparable, the material use for their infrastructures is also similar. Ideally, one would use separate material compositions for different purification steps. However, due to the unavailability of published data for specific purification steps, only one average material composition is used for the calculations of the material content and stocks of the drinking water production plants.

STOCK DEVELOPMENT OF DRINKING WATER PRODUCTION PLANTS

The number of drinking water production plants between 1992 and 2019 is reported by RIVM as part of a research on agricultural practices and water quality in the Netherlands (Fraters et al., 2020). The number of production plants and the total volume of produced drinking water for those years are used to determine an average drinking water production volume per drinking water production plant. This average is used in combination with data from the Central Bureau of Statistics (CBS) on drinking water production volumes before 1992, to estimate the number of drinking water production plants between 1950 and 1992 (CBS, 2008).

MATERIAL COMPOSITION OF DRINKING WATER PRODUCTION PLANTS

Life Cycle Assessment (LCA) studies are used to extract specific material data for drinking water production plants. Many researchers neglect the construction phase of drinking water production plants due to their overall low environmental impact compared to the production phase. However, some LCA studies do mention material intensities of the construction phase of drinking water production plants per cubic meter of produced drinking water (Barjoveanu et al., 2019; Bonton et al., 2012; Friedrich, 2001; Igos et al., 2014; Ribera et al., 2013; Vince et al., 2008). The material intensities as reported in their studies vary a lot due to the different production capacities of the drinking water production plants they analysed. Data from Igos et al. (2014) was used because they analysed a drinking water production plant with a similar capacity as the average capacity of production plants in the Netherlands, which is 5 million cubic meters of produced drinking water per year.

CALCULATION OF MATERIAL STOCKS OF DRINKING WATER PRODUCTION PLANTS

The material content per drinking water production plant is presented in Table 1.

TABLE 1. MATERIAL COMPOSITION PER DRINKING WATER PRODUCTION PLANT.

Material	**Mass per production plant [ton]**
PVC	2.6E+00
Iron	1.8E+01
Steel	1.1E+02
Concrete	2.7E+04

The total material stock of drinking water production plants per material type is calculated with the following equation:

$$Material\ stock\ [ton] = Material\ content\ \left[\frac{ton}{plant}\right] * Number\ of\ plants$$

3.1.2 DRINKING WATER SUPPLY NETWORK

The drinking water supply network consists of pipelines from various materials with different diameters. Although the drinking water companies and Vewin publish annual statistics on the length of the supply network and its material composition, information about the exact material content per kilometer of pipeline is lacking.

STOCK DEVELOPMENT OF THE SUPPLY NETWORK

As mentioned before, the total length of the supply network managed by the drinking water companies is reported annually by Vewin (Vewin, 2020). In combination with a report by KWR (KWR 2018.012, *'Intelligent pigging: Inspectiebehoefte en technische randvoorwaarde',* (Beuken, 2018)) the number of kilometers per material are estimated to determine the development of the material stocks of the supply network between 1950 and 2020. A misalignment between Vewin and KWR regarding the analysed materials is overcome by merging some material categories (i.e. ductile iron and cast iron are merged to 'iron'). The categories of Vewin are leading in the merging of categories.

MATERIAL COMPOSITION OF THE SUPPLY NETWORK

The Joint Research Program (BTO) is a collective research effort between the drinking water companies and KWR to generate knowledge about water and different technologies (*Collectief Onderzoek Waterbedrijven | Drinkwater | BTO | KWR*, n.d.). One of the many subprograms of the BTO is thematic research to develop knowledge for drinking water companies specifically focusing on asset management decisions. Effective asset management requires data about the conditions of, in this case, the drinking water supply network. In order to meet the high quality requirements of the supply network, pipelines undergo many inspections. Although the analysis of different types of inspection techniques is not part of the scope of this study, many characteristics of the supply network are described in a report from BTO: *BTO 2016.013, 'Perspectief en randvoorwaarden voor de ontwikkeling en toepassing van autonome inspectierobots in waterleidingen'* (van Thienen et al., 2016).

The Dutch transport pipeline sector has been working via a system of standards recorded and reported by NEN (Stichting Koninklijk Nederlands Normalisatie Instituut). The NEN 3650 series 'Requirements for Pipeline Systems' reports all requirements for pipelines including the minimum wall thickness of transportation pipelines (NEN 3650-1:2020 en, 2020).

The share of diameters per pipeline material as reported in the reports from BTO and KWR, as well as the wall thicknesses as reported in the NEN 3650 series, are used to estimate an average material composition and content per kilometer of the drinking water supply network.

CALCULATION OF MATERIAL STOCKS OF THE SUPPLY NETWORK

For the calculation of the material content of the supply network, different calculation steps are required. For each material (PE, PVC, iron, steel, and asbestos cement) the length of the supply network made from that material is divided over different diameter categories and their wall thicknesses. The volume is then calculated according to the following equation:

$$Volume\ [m3] = (\pi * (outer\ radius[m])^2 * L[m]) - (\pi * (inner\ radius[m])^2 * L[m])$$

This calculated volume is then multiplied with the material density (kg/m3) to calculate the mass of the stock per material of the supply network. An overview of the pipeline lengths per material per diameter category, their wall thicknesses and material densities are presented in Appendix A as well as an example calculation.

The average material mass per kilometer of supply network is finally calculated by dividing the total material stock of a material by the total length of the supply network made from that material. This results in the following material contents as presented in Table 2. This can be interpreted as follows: if one kilometer of pipeline is completely made of PVC, its mass is 2.2 tons.

TABLE 2. MATERIAL MASS PER KILOMETER SUPPLY NETWORK MADE OF A CERTAIN MATERIAL.

Material	**Material content per km [ton]**
PE	3.8
PVC	2.2
Iron	14.6
Steel	48.9
Asbestos cement	9.3

3.1.3 SEWAGE NETWORK

As already mentioned in section 2.2, the sewage network is divided into two categories: (1) gravity sewers and (2) pressurized sewers. Stichting RIONED is an organization that publishes data about the Dutch sewage network. Their latest most detailed report with sewage network statistics is published in 2010 (Stichting RIONED, 2010). In this report they focus on the gravity sewage network and their material shares and length of the network for different diameter categories.

STOCK DEVELOPMENT OF THE SEWAGE NETWORK

The development of the length of the sewage network is determined by combining data from Stichting RIONED on the gravity sewers and data from KWR on pressurized sewers (Beuken, 2018; Stichting RIONED, 2010).

MATERIAL COMPOSITION OF THE SEWAGE NETWORK

The material composition and material content of the sewage network is determined by combining the information as given in the reports from Stichting RIONED, KWR, and online suppliers of sewer pipelines. According to the latter, concrete pipelines have a diameter between 250mm and 2000mm, resulting in the assumption that pipelines with diameters smaller than 250mm are made from other materials (Vereniging VPB, 2008). In the case of the gravity sewage network it is assumed that these pipelines are made from PVC. This assumption results in a PVC pipeline length of around 20,000km, which is also the length of the sewage network made from PVC as mentioned by Stichting RIONED (Stichting RIONED, 2010).

Although the length of the sewage network is known between 1950 and 2010, the material shares between 1960 and 2010 of the gravity sewage network are not publicly reported. Therefore assumption are made regarding the material shares of this part of the sewage network. In 1960, PVC was introduced as a material to transport wastewater because of its lighter weight and cheaper operational costs (Makris et al., 2020). It is thus assumed that the material share of PVC of the gravity sewage network is 0% in 1960 and 35% in 2010 (as reported by Stichting RIONED). The share of concrete decreases accordingly.

CALCULATION OF MATERIAL STOCKS OF THE SEWAGE NETWORK

The calculation of stocks of the sewage network is similar to the calculation of stock of the supply network (see subsection 3.1.2). An overview of the calculated material contents per kilometer sewage network is presented in Table 3.

Table 3. Material mass per kilometer supply network made of a certain material.

Material	**Material content per km [ton]**
PE	2.2
PVC	6.5
Iron	385.4
Steel	4.9
Concrete	74.5
Asbestos cement	73.1

Note that the difference in material mass per kilometer between the supply network and sewage network is caused by a difference in network length per material and diameter category.

3.1.4 GULLY POTS

The number of gully pots in the Netherlands is reported by Oosterom and Gastkemper (2012) and equals around 7 million. A gully pot serves as a catch basin for excess water from urban surfaces and is connected to the sewage network (Post, 2016). There are two main types of gully pots: (1) *straatkolken* and (2) *trottoirkolken*. The difference between the two is its location on the street and its grid. A *straatkolk* has a grid at street level whereas a *trottoirkolk* is higher and is connected to the sidewalk.

STOCK DEVELOPMENT OF GULLY POTS

There is no data publicly available on the number of gully pots in the Netherlands between 1950 and 2020. Therefore it is assumed that the number of gully pots is directly related to the length of the sewage network. Each kilometer of sewage network connects to 63 gully pots.

MATERIAL COMPOSITION OF GULLY POTS

Gully pots are most often made of around 150kg of concrete (the basin) and 35kg of iron (the grid). This is based on gully pot specifics from different online suppliers.

CALCULATION OF MATERIAL STOCKS OF GULLY POTS

The material stocks of gully pots are calculated with data input of material mass per gully pot and the number of gully pots. An overview of the material content per gully pot is presented in Table 4.

TABLE 4. MATERIAL COMPOSITION AND CONTENT PER GULLY POT.

Material	**Mass per gully pot [kg]**
Iron	35
Concrete	150

The total material stock of gully pots per material is calculated with the following equation:

$$Material\ stock\ [ton] = Material\ content\ \left[\frac{kg}{gully\ pot}\right] * \frac{Number\ of\ gully\ pots}{1000\ [kg/ton]}$$

3.1.5 SEWAGE PUMPING STATIONS

Although most of the wastewater in the Netherlands is transported via gravity sewage pipelines, there are points where the water has to reach higher levels. Sewage pumping stations are used to transport water to higher levels. According to Stichting RIONED there are currently 15,000 sewage pumping stations (Stichting RIONED, 2010).

Witteveen+Bos analysed the material flows in assets of the water boards as part of the research '*Circulair Assetmanagement Waterschappen*'. An analysis of the building materials of sewage pumping stations was also part of this study. Based on information given by the water boards, Witteveen+Bos gives an indication of the materials used in amongst other sewage pumping stations (Roelofs et al., 2022).

STOCK DEVELOPMENT OF SEWAGE PUMPING STATIONS

Similar to the number of gully pots, an average is used to determine the historic development of the number of sewage pumping stations in the Netherlands between 1950 and 2010. An average of 13.7 sewage pumping stations per 100km of sewage network is also reported by Stichting RIONED (Stichting RIONED, 2010).

MATERIAL COMPOSITION OF SEWAGE PUMPING STATIONS

The two main materials of sewage pumping stations are concrete (90%) and steel (10%). The total average assumed weight of a sewage pumping station is 87 tons.

CALCULATION OF MATERIAL STOCKS OF SEWAGE PUMPING STATIONS

An overview of the material content per sewage pumping station is presented in Table 5.

TABLE 5. MATERIAL COMPOSITION AND CONTENT PER SEWAGE PUMPING STATION.

Material	**Mass per sewage pumping station [ton]**
Steel	8.5
Concrete	78.4

The total material stock of sewage pumping stations per material is calculated with the following equation:

$$Material\ stock\ [ton] = Material\ content\ \left[\frac{ton}{pumping\ station}\right] * Number\ of\ pumping\ stations$$

3.1.6 PRESSURIZED SEWERS

The water boards manage a total of around 7200km of pressurized pipelines. Both Witteveen+Bos and KWR analysed the material contents of these pipelines (R. H. S. Beuken, 2018; Roelofs et al., 2022).

STOCK DEVELOPMENT OF PRESSURIZED SEWERS

The historic stock development of the pressurized pipelines is reported by KWR. According to them, the first pressurized pipeline was constructed in 1960. A linear development is assumed between 1960 and 2020 to estimate the length of pressurized pipelines in these years.

MATERIAL COMPOSITION OF PRESSURIZED SEWERS

The material content as reported by Witteveen+Bos is used for this study, since only limited data on the diameter shares is available. The main materials of sewage pumping stations are concrete, steel, and PVC material shares of respectively 60%, 30%, and 10%.

CALCULATION OF MATERIAL STOCKS OF PRESSURIZED SEWERS

The calculation of the material stocks of the pressurized sewers is less complex compared to the supply network and sewage network calculations. An overview of the material contents per material per kilometer is presented in Table 6.

TABLE 6. MATERIAL COMPOSITION AND CONTENT PER KILOMETER OF PRESSURIZED PIPELINE PER MATERIAL.

Material	**Mass per kilometer [ton]**
PVC	11
Steel	34
Concrete	67

The total material stock of pressurized pipelines per material is calculated with the following equation:

$$Material\ stock[ton] = Material\ content\ \left[\frac{ton}{kilometer}\right] * Number\ of\ kilometers$$

3.1.7 WASTEWATER TREATMENT PLANTS

There are currently 323 WWTPs that are used to treat wastewater in the Netherlands. Since the material content of a WWTP depends on the size and capacity of the plant, an average material content is used. The total material content is calculated by Witteveen+Bos as part of the project '*Circulair Assetmanagement Waterschappen*' based on data of six water boards that manage 64 WWTPs in total. The total material content of the WWTPs of the six water boards is dived by 64 to get an average material content per WWTP.

STOCK DEVELOPMENT OF WWTPS

The historic development of WWTPs between 1981 and 2019 is reported by CBS (CBS, 2022). Although there is not a lot of data publicly available on the number of WWTPs before 1981, Rijkswaterstaat published a report on the early days of wastewater treatment in the Netherlands (Lohuizen, 2006). In this report it is mentioned that in 1954 there were around 140 WWTPs. A second published article by RIZA (*Rijksinstituut voor Zuivering van Afvalwater*) reported the number of WWTPs in 1960, 1965, 1970, and 1973 (Heyn, 1974). These datapoints are used for the estimation of the number of WWTPs between 1950 and 1981.

MATERIAL COMPOSITION OF WWTPS

According to Witteveen+Bos, 1% of this weight is plastics, 7.5% is steel, 7.5% is iron, and 84% is concrete (Roelofs et al., 2022). The total average weight of one WWTP is around 15.5 tons.

CALCULATION OF MATERIAL STOCKS OF WWTPS

An overview of the material content per WWTP is presented in Table 7.

TABLE 7. MATERIAL COMPOSITION AND CONTENT PER WWTP.

Material	**Mass per WWTP [ton]**
PVC	1.6E+02
Steel	2.3E+03
Concrete	1.3E+04

The total material stock of WWTPs per material type is calculated with the following equation:

$$Material\ stock\ [ton] = Material\ content\ \left[\frac{ton}{WWTP}\right] * Number\ of\ WWTPs$$

3.2 MATERIAL STOCKS AND FLOWS UNTIL 2050

For the calculation of material inflows and outflows until 2050, a Material Flow Analysis (MFA) is conducted. An MFA is a method to analyse stocks and flows of different materials in a system that is defined in time and space (Brunner & Rechberger, 2016). Based on the mass-balance principle that is derived from the law of conservation of matter an MFA delivers information about accumulating stocks in a system and flows passing through a system (Brunner & Rechberger, 2016; van der Voet, 2002). There is large methodological variety within MFAs which is briefly discussed in the next subsection (Müller et al., 2014).

3.2.1 METHODOLOGICAL VARIETY OF MFAS

MFAs can be divided into static MFAs and dynamic MFA. A static MFA describes the flows and stocks of materials at a certain moment in time. With a static MFA, hotspots of material use are identified. A dynamic MFA model is an extension of a static MFA and takes into account the dynamics of a system (Brunner & Rechberger, 2016). Buildings and infrastructures last for a long time and cause a disconnection between the inflow and outflow of materials due to the existence of an 'in-use stock' (Hu, 2010). Analysing the change of stocks and flows of a system over time provides a quantitative estimate of these in-use stocks (Graedel, 2019). Historic development patterns of stocks and flows in combination with the lifetime of a material are not only used to track changes in the past, but can also be used to estimate the in-use stocks in the future.

Another way of distinguishing MFAs is by the way stocks are measured. In a top-down approach stock quantities are derived from the difference between the inflow and outflow. The bottom-up approach derives the stock quantities by summing up the materials that are present within a system at a certain time (Müller et al., 2014). Although both methods measure the total in-use stock, the top-down and bottom-up approach are fundamentally different. It is the availability of datasets that determine which method is used. When inflow and outflow time series datasets are available, a top-down approach is employed. However, since the stock quantity is estimated, this approach can be seen as less precise. On the other hand, the bottom-up approach derives stock quantities by counting all materials in-use, but is affected by uncertainties in terms of material content per unit counted. It is a trade-off that needs to be considered at all times during MFA research (Gerst & Graedel, 2008).

A third distinction is made between retrospective MFAs and prospective MFAs. Whereas the former analyses stocks and flows from the past, the latter looks into the future by using data extrapolation and different future material demand scenarios. Retrospective and prospective MFAs can be combined (Müller et al., 2014).

A fourth distinction is made between flow-driven MFAs and stock-driven MFAs. In a flow-driven model it is assumed that a material stock is driven by its inflow and outflow (Hu et al., 2010). Both inflow data and lifetime distribution data are used to calculate the outflow and stock of a material (Müller et al., 2014). For a flow-driven MFA, future inflows are explored as a function of socioeconomic factors and outflows are determined by a delay process or leaching process as described by van der Voet (2002) . In a stock-driven MFA the stock is the driver for the flows of materials. The in- and outflows of materials are calculated based on stock data and lifetime.

3.2.2 MFA METHODOLOGY FOR THIS STUDY

For this research a dynamic MFA with a retrospective and prospective, bottom-up, stock-driven approach is conducted to analyse the development of stocks and flows of the urban water cycle infrastructure in the Netherlands until 2050. Müller (2006) described stocks and flows exclusively in dependence on physical determinants and created a stock dynamics model (Figure 6). This conceptual outline created by Müller (2006) is applied to other stocks and materials as done by for example Bergsdal et al. (2007).

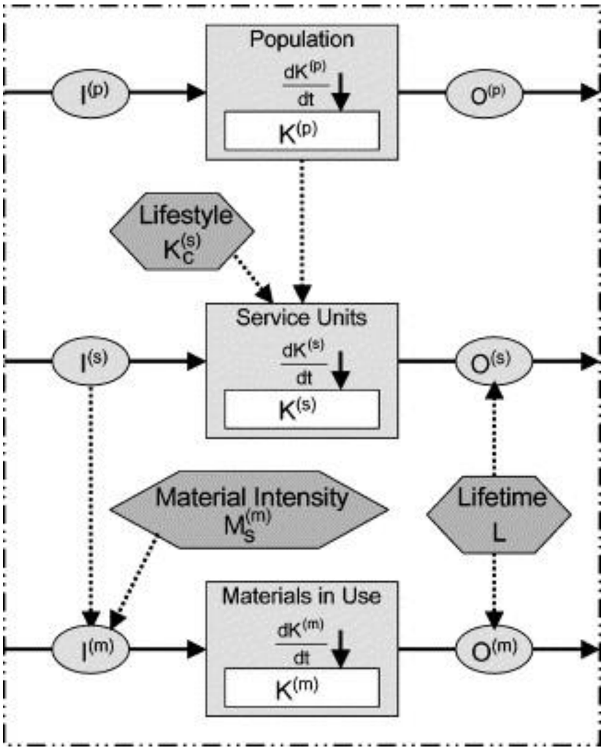


FIGURE 6. STOCK DYNAMICS MODEL FROM MÜLLER (2006).

A similar model is created for the urban water cycle infrastructure in the Netherlands (Figure 7). The in-use infrastructure stocks represent any of the seven components of this study. The model is discussed in more detail in the next subsection.

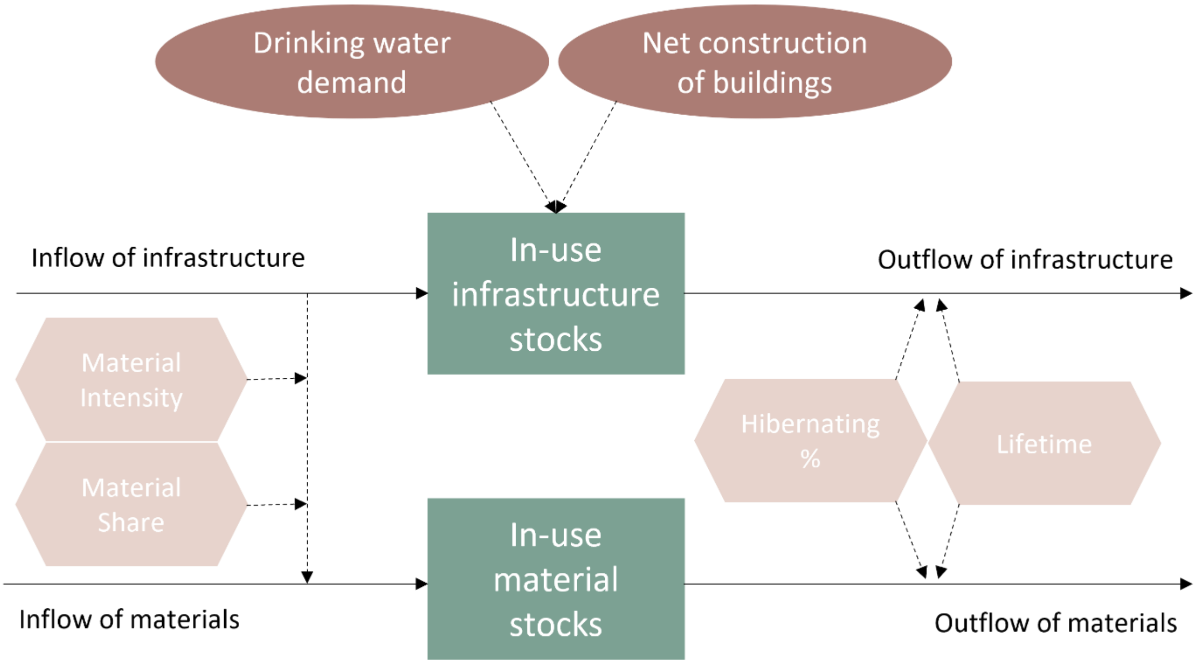


FIGURE 7. STOCK DYNAMICS MODEL FOR THE DUTCH URBAN WATER CYCLE INFRASTRUCTURE BASED ON THE MODEL FROM MÜLLER (2006).

STOCK DYNAMICS & EXTERNAL DRIVING FORCES

The model as presented in Figure 7 consists of a top part describing the infrastructure stocks and its inflows and outflows, and a bottom part describing the material stocks related to each infrastructure stock. The infrastructure stocks form the start of the dynamic modelling of stocks and flows of the Dutch urban water cycle infrastructure materials. The size of the infrastructure stocks is known between 1950 and 2020. The stock size between 2020 and 2050 is assumed to be mainly impacted by drinking water demand and the net construction of buildings. These driving forces form the basis of the scenarios that are used to explore the size of the urban water cycle infrastructure stocks between 2020 and 2050. These scenarios and the methodology for the prospective part of the dynamic MFA as conducted for this study are discussed in section 3.3.

CALCULATION OF FLOWS

The outflow of infrastructure is determined by the past input of infrastructure and its residence time in the economy (van der Voet, 2002). The lifetime represents this residence time and determines the size of the outflow per year. The modelling of stocks and flows can be done with a fixed lifespan, though it is often more appropriate to describe lifespans using a statistical distribution. The Weibull distribution is such a distribution and is widely used in reliability and survival analysis (Lai et al., 2006; Li, 2020). The Weibull distribution requires the input of a scale and shape parameter. Whereas the former represents the typical 'time-to-failure', the latter indicates whether the failure rate is increasing (>1), constant, or decreasing (<1) (Galar & Kumar, 2017). Another statistical distribution that is often used is the normal distribution. It describes a family of continuous probability distributions, all having a bell-shaped curve, but differing in their mean values and standard deviations (Ahsanullah et al., 2014). It is sometimes argued to be an inappropriate distribution for the modelling of lifetimes, because of the limit on the left side extends to negative infinity that results in the modelling of negative times-to-failure. However, as long as the mean is relatively high, this issue does not occur. One could also use the folded normal distribution, a distribution in which the probability mass on the left of x=0 is folded over to the right side (Ahsanullah et al., 2014).

The use of a specific distribution (i.e. the Weibull distribution or the normal distribution) often depends on availability of data. Since shape and scale parameters of the urban water cycle infrastructures could not be identified, a normally distributed lifetime was assumed with a standard deviation of 20% (Deetman, Personal Communication, 9 May 2022).

An overview of the assumed lifetimes per material per urban water cycle infrastructure component is presented in Table 8 (Beuken & Mesman, 2011; Ministerie van Verkeer en Waterstaat, 2009; Roelofs et al., 2022; van Diepenbeek & Creemers, 2012).

TABLE 8. ASSUMED AVERAGE LIFETIMES PER MATERIAL PER COMPONENT OF THE URBAN WATER CYCLE INFRASTRUCTURE.

Average LT [years]	**PE**	**PVC**	**Iron**	**Steel**	**Asbestos Cement**	**Concrete**
Production Locations	-	50	50	50	-	50
Supply Network	70	70	90	80	70	-
Sewage Network	70	70	90	80	70	100
Gully Pots	-	-	60	-	-	60
Pumping Stations	-	-	-	50	-	50
Pressurized pipelines	-	70	-	80	-	100
WWTPs	-	50	-	50	-	50

Hibernating percentages affect the size of the outflow as well. The hibernating stocks represent infrastructure stocks that reach their end-of-life in a certain year, but are not recovered and are thus not part of the outflow (Daigo et al., 2015). The inflow of infrastructure depends on changes in stock size and the outflow of infrastructure.

The inflows of materials and corresponding outflows are calculated with ODYM (Open software framework for Dynamic Material systems) (Pauliuk, n.d.). This model calculates relations between inflows, outflows and stocks.

TRANSLATION OF INFRASTRUCTURE STOCKS TO MATERIAL STOCKS

For the translation of infrastructure stocks to material stocks, two additional factors are included in the model: (1) material intensity and (2) material share. The material intensity represents the amount of material per infrastructure stock, i.e. the amount of material per drinking water production plant or the amount of material per kilometer of supply network. The material share represents the share of a material per infrastructure stock, i.e. the percentage of the supply network made from a certain material.

Apart from infrastructure changes due to changes in drinking water demand and the construction and demolition of buildings, material flows in the urban water cycle are determined by the material compositions of each of the components of the urban water cycle. It is assumed that the material compositions of the drinking water production locations, the WWTPs, the gully pots, and the sewage pumping stations do not change until 2050. The material compositions of the drinking water supply network, sewage grid, and transportation pipelines do change however.

Asbestos cement was a commonly used pipeline material in the 50s and 60s. Since 1993, the use of asbestos cement is prohibited by law, thus no new asbestos cement pipelines are constructed since then (Rijkswaterstaat, n.d.). However, research done by RIVM showed that the use of asbestos cement for water pipelines does not have consequences for public health, asbestos cement pipelines are not actively removed before reaching their end-of-life until now (Eysink et al., 2017). Since the end-of-life of many asbestos cement pipelines is reached now, water companies are becoming more active in replacing these pipelines. PE and PVC are most often used as replacements and it is assumed that the stock of asbestos cement by 2050 equals zero (Oasen, 2021). Furthermore, statistics of Vewin show a gradually decrease in iron use since 1950, which is for this study assumed to continue until 2050, based on the fact that pipelines made from PVC are becoming more and more popular due to their lower costs and lighter weight (Geudens & Kramer, 2022).

Regarding the other pipeline materials, it is assumed that once reaching their end-of life they are replaced by the same materials (Rasenberg, 2017). The vast majority of all other newly constructed pipelines will be made from plastics (PVC and PE) resulting in a steady increase of material share of PE and PVC (Veldkamp et al., 2019). An overview of the material shares in 2050 compared to 2020 is presented in Table 9. The percentages of 2020 are based on reported data by Vewin (Vewin, 2020). The percentages of 2050 are calculated based on the assumption that the share of asbestos cement decreases to 0% and is replaced by PE and PVC. Similar assumptions are made for the sewage network. The changes in material shares of the sewage network are presented in Table 10.

TABLE 9. MATERIAL SHARE CHANGES OF THE SUPPLY NETWORK.

Material	**2020**	**2050**
PE	8%	20%
PVC	55%	66%
Iron	7%	7%
Steel	7%	7%
Asbestos cement	23%	0%

TABLE 10. MATERIAL SHARE CHANGES OF THE SEWAGE NETWORK.

Material	**2020**	**2050**
PE	25%	25%
PVC	12%	13%
Iron	1%	1%
Steel	0%	0%
Asbestos cement	1%	0%
Concrete	61%	61%

3.3 SCENARIOS

The accuracy of exploring the size of the urban mine until 2050 depends highly on what the future looks like. Simply following historic trends may be incorrect, or not possible for all material stocks. The development of the urban water cycle infrastructure until 2050 is based on possible future developments that are described in scenarios without giving a probability of a scenario to actually happen. The scenarios used for this study are driven by two variables: (1) changes in drinking water demand and (2) changes in construction and demolition of buildings in the Netherlands. Both driving forces and their underlying scenarios as well as the assumptions that are made for this study are discussed. The basis of the scenarios used in this study are the Deltascenarios. The background of the Deltascenarios is first discussed in subsection 3.3.1, followed by in depth descriptions of the two main driving forces of changes in infrastructure in subsections 3.3.2 and 3.3.3. Changes in the Dutch urban water cycle infrastructure until 2050 under different scenarios are presented in subsection 3.3.4.

3.3.1 DELTASCENARIOS

There are many scenarios that can be used to investigate the future. The Deltascenarios are developed with the aim of exploring future developments and their impact and consequences for water management in the Netherlands. These Deltascenarios are a combination of the KNMI scenarios and the WLO scenarios.

The Royal Dutch Meteorological Institute (KNMI) is the Dutch national weather service. The KNMI developed future climate change scenarios for the Netherlands until 2050 and 2085 (van den Hurk et al., 2014). Their most updated version stems from 2014 and will be updated again in 2023. KNMI based their scenarios on the following information sources: (1) global climate models, (2) regional climate models for Europe, and (3) Dutch historic measurements series (Hurk et al., 2006). These information sources are translated into projections for sea level rise and wind change. Additionally, they are also analysed for their influences of global temperature and wind circulation change and their impact on climate in the Netherlands. These factors are finally translated into four different KNMI scenarios (van den Hurk et al., 2014).

The Centraal Planbureau and Planbureau voor de Leefomgeving analysed demographic and economic trends, as well as developments in the living environment. Two reference scenarios form the basis of the so called WLO scenarios: (1) WLO Hoog and (2) WLO Laag (Kool & Huizinga, 2015; Manders & Kool, 2015). In the WLO Hoog scenario there is a high economic growth of 2% per year with relative strong demographic developments. In the WLO Laag scenario there is a lower economic growth of 1% per year with limited demographic developments (Manders & Kool, 2015).

Combining the key figures of the KNMI scenarios and the WLO scenarios resulted in a total of four Deltascenarios: (1) DRUK, (2) STOOM, (3) RUST, and (4) WARM (Wolters et al., 2018a). The KNMI scenarios form the basis for the hydrological circumstances due to climate change and the WLO scenarios are used to analyse the impact of socioeconomic developments on space, land, and water. The scenarios are intended to outline a bandwidth (Figure 8) for developments regarding space, land, and water use. Although this figure is based on a report from 2012, it is included to visualize the idea of the Deltascenarios. Specifics regarding changes in the drinking water demand are based on reports by Deltares, KNMI, Plandbureau van de Leefomgeving, and Centraal Planbureau and discussed in the next subsection (Bruggeman & Dammers, 2013; Wolters et al., 2018a; Wolters et al., 2018b).

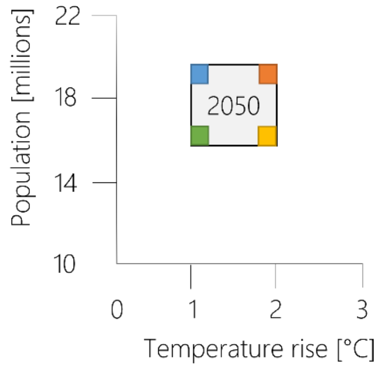


Figure 8. Bandwidth of scenarios, DRUK (blue), STOOM (red), RUST (green), WARM (yellow) (van der Greft et al., 2012).

3.3.2 Driving Force: Drinking Water Demand

The degree of climate change (limited or rapid) and degree of economic growth (high or low) are presented in Table 11 for each of the four Deltascenarios. The development of the drinking water demand until 2050 is determined by the resultant of demand-increasing and demand-decreasing developments for households and small businesses. Demand increasing developments are population growth, economic growth, water demand for personal hygiene, and demand decreasing developments are population decline, increase in efficiency of water supply, increase in efficiency of water-using household appliances and awareness (Wolters et al., 2018). Changes in drinking water demand is assumed to be one of the two main driving forces for changes in urban water cycle infrastructure.

Table 11. Degree of climate change, economic growth, changes in population and drinking water demand change for the Deltascenarios (Wolters et al., 2018).

	Climate Change	**Economic Growth**	**Population (2015-2050)**	**Drinking water demand change (2015-2050)**
DRUK	Limited	High	+ 0.5% per year	+ 10%
STOOM	Rapid	High	+ 0.5% per year	+ 40%
RUST	Limited	Low	- 0.4% per year	- 20%
WARM	Rapid	Low	- 0.4% per year	0%

The reference year used in the most recent Deltascenarios is 2015. In this year the total drinking water demand was 1081 million m^3, resulting in drinking water demand changes as presented in Table 12.

TABLE 12. ABSOLUTE DRINKING WATER DEMAND FOR 2020 AND 2050.

	Drinking water demand in 2015 *[million m^3 per year]*	**Drinking water demand in 2050** *[million m^3 per year]*
DRUK	1081	1189
STOOM		1513
RUST		865
WARM		1081

3.3.3 DRIVING FORCE: CONSTRUCTION & DEMOLITION

The second driving force for changes in urban water cycle infrastructure is the construction and demolition of buildings. Each new building requires new infrastructure. The more buildings are built in a specific area, the more drinking water supply pipelines and sewage pipelines are needed.

Although using an average of pipeline length per newly built building could be useful, geographic information on where these buildings are potentially constructed or demolished is of importance. The average transportation pipeline length differs per water company, municipality, and water authority due to a difference in geographic factors. A building constructed in a small municipality requires more pipeline materials compared to a building constructed in a large municipality as also mentioned by Vewin (Geudens & van Grootveld, 2017).

In a study done by van Oorschot et al., (2022) material stocks in buildings are analysed in 18 scenarios with the WLO Hoog and WLO Laag scenarios as a basis. For each of these two scenarios, construction and demolition data of buildings until 2050 is collected to investigate material flows. The data is gathered with Arc GIS Pro. The method is described in Appendix C. Construction and demolition data is divided in three different urbanization scenarios: (1) Dichtbij, (2) Verbonden, and (3) Ruim. For each of these scenarios (WLO Hoog and WLO Laag, and the urbanization scenarios) a division is made with three different material scenarios (van Oorschot et al., 2022). However, the subdivisions of material scenarios are not used in this study.

The urbanization scenarios Dichtbij, Verbonden, and Ruim are defined as follows. In scenario Dichtbij there is a high degree of inner-city construction and demolition in which low density buildings are replaced with high density buildings. Scenario Verbonden is similar to scenario

Dichtbij, except buildings are constructed close to public transportation services (van Oorschot et al., 2022). In scenario Ruim buildings are constructed outside existing built-up areas. In order to match these scenarios with the Deltascenarios, scenarios Dichtbij and Ruim are included, and scenario Verbonden is excluded since it is not linked to degrees of urbanization.

According to the key figures (Appendix B) of the Deltascenarios WLO Hoog is related to Deltascenarios DRUK and STOOM, in which scenario DRUK has a lower degree of urbanization with higher densities of urbanization compared to scenario STOOM (Wolters, Hunink, Delsman, de Lange, Schasfoort, van der Mark, et al., 2018). Therefore, scenario Ruim is considered as part of Deltascenario DRUK, and scenario Dichtbij with Deltascenario STOOM. The same applies to Deltascenarios RUST and WARM, where Deltascenario RUST considers more compact urbanization resulting in higher more high density buildings. It is therefore connected to scenario Dichtbij. Deltascenario WARM is assumed to be connected to scenario Ruim. An overview of is presented in Table 13.

It should be noted that although urbanization is part of the socio-economic factors of the Deltascenarios, it has not been taken into account for the calculations of future water demand (Hunink et al., 2018; Deltacommissaris, personal communication, 21 April 2022).

Table 13. Overview of urbanization scenarios in relation to the Deltascenarios.

Deltascenario	**Construction & Demolition Scenario**
DRUK	WLO Hoog & Ruim
STOOM	WLO Hoog & Dichtbij
RUST	WLO Laag & Dichtbij
WARM	WLO Laag & Ruim

Raster data as provided by van Oorschot (Personal Communication, 20 April 2022) is converted into point data in ArcGIS Pro. Boundaries of drinking water companies and municipalities are matched with construction and demolition data, resulting in a number of constructed and demolished buildings per area (either per drinking water company or per municipality). The total number of net constructed buildings for each scenario is presented in Table 14.

Table 14. Net constructed buildings per scenario.

Scenario	**Net constructed buildings**
DRUK	2.2E+06
STOOM	1,9E+06
RUST	0.8E+06
WARM	0.9E+06

3.3.4 INFRASTRUCTURE CHANGES

The last question that needs to be answered is how changes in drinking water demand and the net construction of buildings can be translated into changes in the urban water cycle infrastructure. In order to avoid double counting of newly constructed infrastructure, the seven components of the urban water cycle infrastructure of this study are split into two parts: (1) changes in urban water cycle infrastructure solely driving by drinking water demand changes, and (2) urban water cycle infrastructure changes that are solely driven by the net construction of buildings. It is assumed that the number of drinking water production plants and WWTPs is driven by changes in drinking water demand. Furthermore, changes in the total length of pressurized pipelines managed by the water boards depends on changes in the number of WWTPs. The net construction of buildings is assumed to drive changes in the length of both the drinking water supply network and the sewage network. The number of gully pots and sewage pumping stations depends on the length of the sewage network and is thus also driven by the net construction of buildings.

The choice to divide the urban water cycle infrastructure in two parts can be explained with an example. If water demand increases and more drinking water production plants are needed, this also means that more pipelines are needed to transport the water. However, at the same time, new drinking water supply pipelines are constructed, due to the net construction of buildings. This would results in some double counting of the total required construction of drinking water supply pipelines.

Changes in infrastructure are discussed per urban water cycle infrastructure component in the next subsections.

CHANGES IN DRINKING WATER PRODUCTION PLANTS

An overview of the factors influencing the drinking water production and reserves is presented in Figure 9. The reserve represents the amount of drinking water that could be available, but is currently not used. It is the difference between the normative production capacity and the necessary production capacity. The normative production capacity is determined by the minimum of licensed capacity, extraction capacity, and treatment capacity. The necessary production capacity is driven by the net drinking water demand, en-gross supply and delivery (drinking water supply contracts between neighboring drinking water production plants both within the Netherlands but also with drinking water companies in Belgium and Germany), losses during production and distribution, and the amount of drinking water stored as a buffer for unexpected water demand developments, droughts during summer, and forecasting errors.

If the reserve is <0, the normative capacity must thus grow by either increasing the extraction capacity, licensed capacity, or treatment capacity. The total licensed capacity in 2013 was 1255 million m^3 water of which 1183 million m^3 water could technically be extracted (Tangena, 2014). According to RIVM, this extraction capacity will decrease to around 1171 million m^3 in 2040. Assuming a linear trend, this means a decrease of extraction capacity of around 0.44 million m^3 per year, resulting in an extraction capacity of 1167 million m^3 in 2050 (Tangena, 2014). The decrease of extraction capacity is mainly caused by problems of the source itself, for example pollution. RIVM notes that this extraction capacity is large enough to cover for a drinking water demand of 1145 million m^3, but they also argue that although drinking water companies have enough production capacity to provide this amount of drinking water, only five companies have the capacity to also accommodate for sudden changes in drinking water demand (Tangena, 2014). This is due to the size of the reserves differing between the water companies (some water companies have very small reserves). RIVM states that an increase in the number of pumping stations and increase of treatment capacity and extraction capacity is needed to increase the normative production capacity.

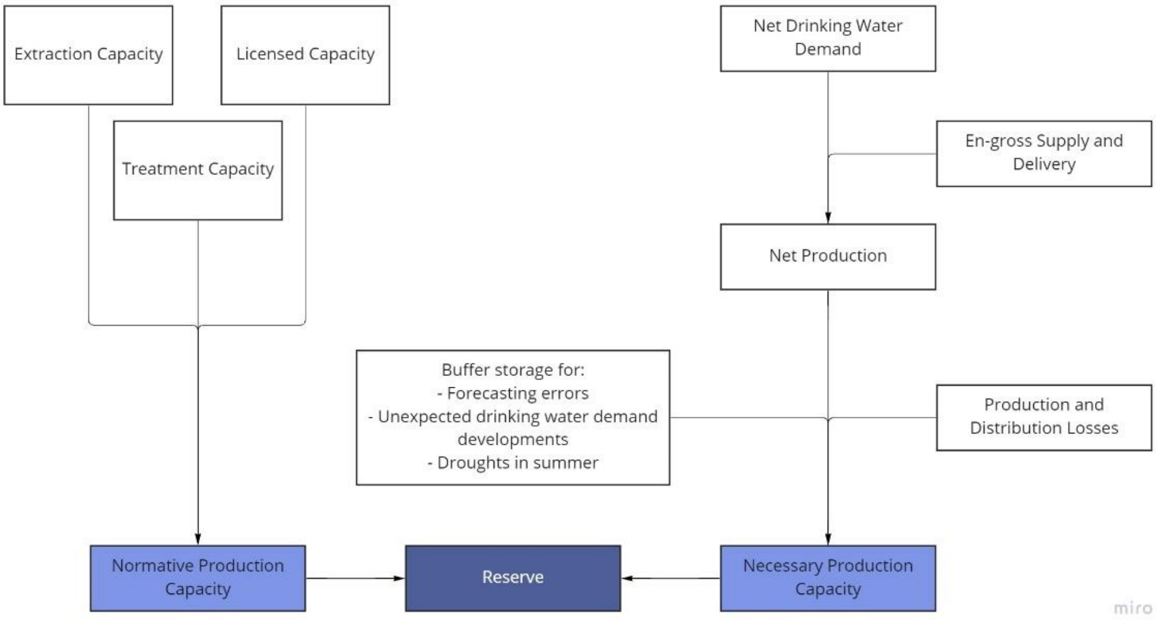


FIGURE 9. OVERVIEW OF FACTORS INFLUENCING DRINKING WATER PRODUCTION AND RESERVES (SCHEFFER & TVVL EXPERTGROEP, 2017).

At the request of Vewin, KWR also researched the drinking water demand and coverage in the Netherlands (Beuken & Vreeburg, 2015). The methods and results from KWR are similar to the study of RIVM, but KWR states that regional shortages will occur earlier compared to what

RIVM states. Furthermore, they state that the current non-operational reserve (the difference between the licensed capacity and the normative capacity, see Figure 9) might actually not be useable due to several restrictions. These restrictions entail for example pollution, salination, and dehydration of water extraction sources (van der Aa et al., 2015).

Although the estimated normative capacities as published by RIVM date from the year 2013, it is the most detailed data that could be found. It should however be noted that with more recent data, estimations of the number of production plants that should be constructed until 2050 might differ. Furthermore, it is assumed that the normative production capacity can be increased by the construction of drinking water production plants.

In scenarios RUST and WARM, there is no need for new infrastructure to meet the drinking water demand. Both estimated drinking water demands, respectively 865 and 1081 million m^3 are lower than the expected possible extraction of water in 2050 (1167 million m^3). The drinking water demand of scenarios DRUK and STOOM do exceed the extraction capacity. It is assumed that the 188 production plants from 2013 are able to produce a maximum of 1167 million m^3. This is an average of 6.2 million m^3 per production plant. The 1189 million m^3 estimated water demand in scenario DRUK thus requires a total number of 192 drinking water production plants. In the most extreme scenario, scenario STOOM, 244 production plants are required. This is a very large increase in production plants, but it should be noted that the drinking water demand also increases with 40%.

CHANGES IN WWTPS

An increase in drinking water demand results in an increase of wastewater as well. It is assumed that the capacity of WWTPs is sufficient to cover for both changes in drinking water demand, but also for increases in rainfall (CBS, 2022). It is thus assumed that in all scenarios, the number of WWTPs stabilizes until 2050. New technologies (for example fine screen technology) are constantly tested to either increase the capacity of WWTPs or decrease the total influent (KWR et al., 2017).

CHANGES IN PRESSURIZED PIPELINES

The pressurized pipelines managed by the water boards are connected to the sewage network to transport waste water to the treatment facilities. Since the number of WWTPs is assumed not to change until 2050, new pressurized pipelines to connect the sewage grid to new WWTPs is not needed, simply because there are no new WWTPs constructed. The net construction of buildings does not impact the length of pressurized pipelines. Where the supply network and sewage network are assumed to increase in length due to required connections of buildings with the main transportation pipelines of the supply network and sewage network, pressurized pipelines are not directly connected to buildings. Thus, with the construction of buildings there is no need for the construction of extra pressurized pipelines, assuming that the number of WWTPs stays the same.

Since it is assumed that the number of WWTPs is sufficient until 2050, it is also assumed that the length of pressurized pipelines does not have to increase or decrease.

CHANGES IN SUPPLY NETWORK

The average length of the supply network differs between drinking water companies. The average supply network length per building in the supply area of Waternet is for example 0.006 km, the average length per building in the supply area of Vitens is 0.019 km. This average is based on both connection pipelines and main transportation pipelines. An overview of the number of net constructed buildings per supply area per scenario is presented in Table 15. The average length per building is multiplied with the number of net constructed buildings to calculate the length of the supply network that needs to be constructed by 2050.

TABLE 15. NET CONSTRUCTED BUILDINGS AND AVERAGE PIPELINE LENGTH PER BUILDING PER DRINKING WATER COMPANY.

Water company	DRUK [net constructed buildings]	STOOM [net constructed buildings]	RUST [net constructed buildings]	WARM [net constructed buildings]	Average length per building [km]
Brabant Water	3.6E+05	2.7E+05	1.5E+05	2.0E+05	0.016
Dunea	1.9E+05	1.7E+05	0.7E+05	1.1E+05	0.008
Evides	2.0E+05	2.4E+05	1.4E+05	1.0E+05	0.013
Oasen	1.8E+05	1.3E+05	0.2E+05	0.4E+05	0.012
PWN	3.4E+05	2.5E+05	1.0E+05	1.3E+05	0.012
Vitens	6.4E+05	5.4E+05	2.2E+05	2.5E+05	0.019
Waterbedrijf Groningen	0.4E+05	0.3E+05	0.1E+05	0.1E+05	0.018
Waternet	1.2E+05	1.7E+05	0.8E+05	0.7E+05	0.006
WMD	0.3E+05	0.2E+05	0.5E+04	0.6E+04	0.026
WML	0.8E+05	0.6E+05	0.2E+05	0.3E+05	0.016

CHANGES IN SEWAGE NETWORK

Calculations for the extension of the sewage network by 2050 are similar to the calculation for the supply network. The average length of the sewage network per building is based on the size of the municipalities as published by Vewin (Oosterom & Hermans, 2013). An overview of the number of net constructed buildings per category of the size of the municipality is presented in Table 16. The average length per building is multiplied with the number of net constructed buildings to calculate the length of the sewage network that needs to be constructed by 2050.

TABLE 16. NET CONSTRUCTED BUILDINGS AND AVERAGE LENGTH PER BUILDING PER MUNICIPALITY SIZE CATEGORY.

Size of municipality [number of inhabitants]	DRUK [net constructed buildings]	STOOM [net constructed buildings]	RUST [net constructed buildings]	WARM [net constructed buildings]	Average length per building [km]
<10,000	75E+03	3.8E+03	1.7E+03	2.0E+03	0.15
10,000-20,000	2.5E+04	1.0E+04	0.3E+04	0.9E+04	0.15
20,000-50,000	7.4E+04	5.3E+04	1.3E+04	2.4E+04	0.15
50,000-100,000	4.4E+04	3.4E+04	1.3E+04	1.8E+04	0.13
>100,000	7.1E+04	9.0E+04	5.3E+04	4.2E+04	0.11

CHANGES IN NUMBER OF GULLY POTS AND SEWAGE PUMPING STATIONS

The number of gully pots and sewage pumping stations are related to the total length of the sewage network. An increase in the length of the sewage network results in an increase of the number of gully pots and sewage pumping stations. To each kilometre of sewage network, 63 gully pots are connected and 0.14 sewage pumping stations.

3.3.5 OVERVIEW OF INFRASTRUCTURE CHANGES

An overview of the changes in infrastructure of the urban water cycle due to changes in drinking water demand and construction and demolition of buildings is presented in Table 17. The infrastructure changes of the drinking water production locations, pressurized pipelines, and WWTPs are based on changes in drinking water demand as discussed in subsection 3.3.2. The infrastructure changes of the supply network, sewage grid, and transportation pipelines is based on construction and demolition of buildings as discussed in subsection 3.3.3. Changes in the number of sewage pumping stations and gully pots are based on changes in the length of the sewage grid.

Table 17. Overview of Dutch urban water cycle infrastructure changes until 2050.

Urban Water Cycle Component	**Current**	**Infrastructure changes**	
Drinking water production location	182	DRUK	6 extra production locations are built until 2050.
		STOOM	24 extra production locations are built until 2050
		RUST	0 extra production locations are built until 2050.
		WARM	0 extra production locations are built until 2050.
Wastewater treatment plants	317	DRUK	0 extra WWTPs are built until 2050.
		STOOM	0 extra WWTPs are built until 2050.
		RUST	0 extra WWTPs are built until 2050.
		WARM	0 extra WWTPs are built until 2050.
Supply network	120244 km	DRUK	31627 km of supply pipelines are constructed until 2050.
		STOOM	26592 km of supply pipelines are constructed until 2050.
		RUST	11533 km of supply pipelines are constructed until 2050.
		WARM	13256 km of supply pipelines are constructed until 2050.
Sewage grid	111162 km	DRUK	28686 km of sewage pipelines are constructed until 2050.
		STOOM	23934 km of sewage pipelines are constructed until 2050.
		RUST	9956 km of sewage pipelines are constructed until 2050.
		WARM	11960 km of sewage pipelines are constructed until 2050.
Pressurized pipelines	7158 km	DRUK	0 km of transportation pipelines are constructed until 2050.
		STOOM	0 km of transportation pipelines are constructed until 2050.
		RUST	0 km of transportation pipelines are constructed until 2050.
		WARM	0 km of transportation pipelines are constructed until 2050.
Sewage pumping stations	15300	DRUK	4934 extra stations based on the sewage grid until 2050.
		STOOM	4117 extra stations based on the sewage grid until 2050.
		RUST	1712 extra stations based on the sewage grid until 2050.
		WARM	2057 extra stations based on the sewage grid until 2050.
Gully pots	7000000	DRUK	2323566 extra gully pots based on the sewage grid until 2050.
		STOOM	1938654 extra gully pots based on the sewage grid until 2050.
		RUST	806436 extra gully pots based on the sewage grid until 2050.
		WARM	968760 extra gully pots based on the sewage grid until 2050.

3.4 RE-ENTERING OF MATERIALS IN THE ECONOMY

Knowledge about the size of the urban mine, its material composition and time of availability is key for urban mining as part of the circular economy, but knowledge on how these materials (can) re-enter the economy is also crucial.

In order to gain knowledge about the re-entering of materials from the Dutch urban water cycle infrastructure in the economy, different water companies and water boards are contacted and interviewed. The aim of this qualitative research is to gain knowledge on what is currently happening with outflows of materials of the water companies and water boards and what is limiting them in reusing their own infrastructure materials. The insights from the interviews with drinking water companies and water boards is used to substantiate potential improvements that need to be made regarding the re-entering of the urban water cycle infrastructure materials in the economy.

RESULTS

4 RESULTS

4.1 CURRENT STOCK & STOCK DEVELOPMENT

For each of the components of the urban water cycle infrastructure, the in-use stock in the year 2020 is calculated based on the stock size, material share and material intensity (see section 3.1). The results are presented in Figure 10. The sewage network has the highest material mass and thus contributes most to the total mass of the urban water cycle infrastructure. Except for the supply network, concrete has the highest contribution to the total mass of each component. A more detailed view of the materials per infrastructure component besides concrete are shown in Figure 11.

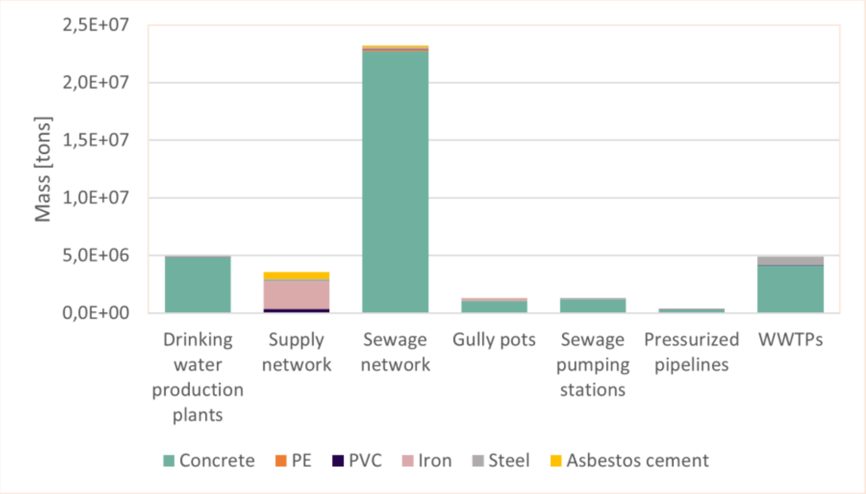


FIGURE 10. TOTAL MATERIAL STOCKS PER COMPONENT OF THE DUTCH URBAN WATER CYCLE INFRASTRUCTURE.

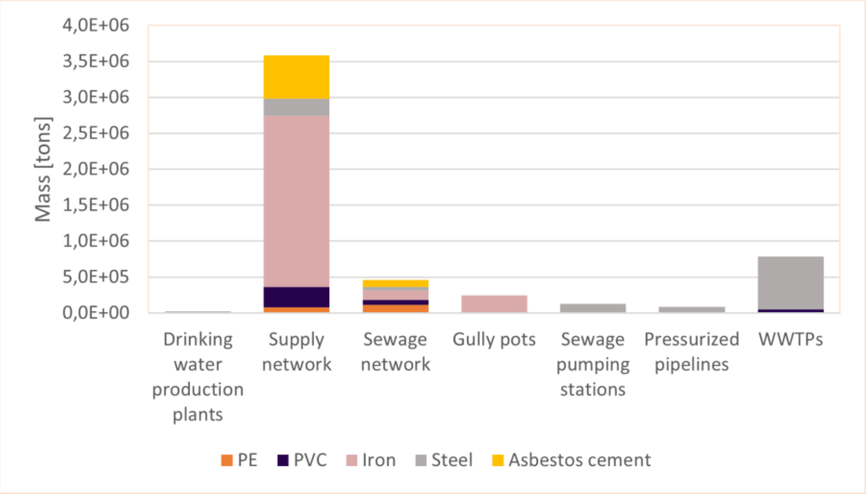


FIGURE 11. TOTAL MATERIAL STOCKS PER COMPONENT BESIDES CONCRETE OF THE DUTCH URBAN WATER CYCLE INFRASTRUCTURE.

One might question why the mass of the sewage network is significantly higher compared to the supply network, even though the lengths of the supply network and sewage network are more or less the same. Figure 12 shows the lengths of the pipelines (supply network, sewage network, and pressurized pipelines) and their material compositions. The two main material of the supply network is PVC and the main material of the sewage network is concrete. The higher mass of the sewage network is not only caused by the higher material density of concrete compared to PVC, but also by the pipeline diameters of these concrete pipelines compared to the PVC pipelines of the supply network. The concrete pipelines have larger diameters and wall thicknesses compared to the PVC pipelines, resulting in significantly higher material volumes. The higher volume of concrete is multiplied with a higher material density, resulting in a higher material mass compared to the material mass of PVC in the supply network. An overview of the differences can be found in Table 18.

Although the length of concrete pipelines in the sewage network is only slightly higher compared to the length of PVC pipelines in the supply network, the final mass is almost 80 times higher.

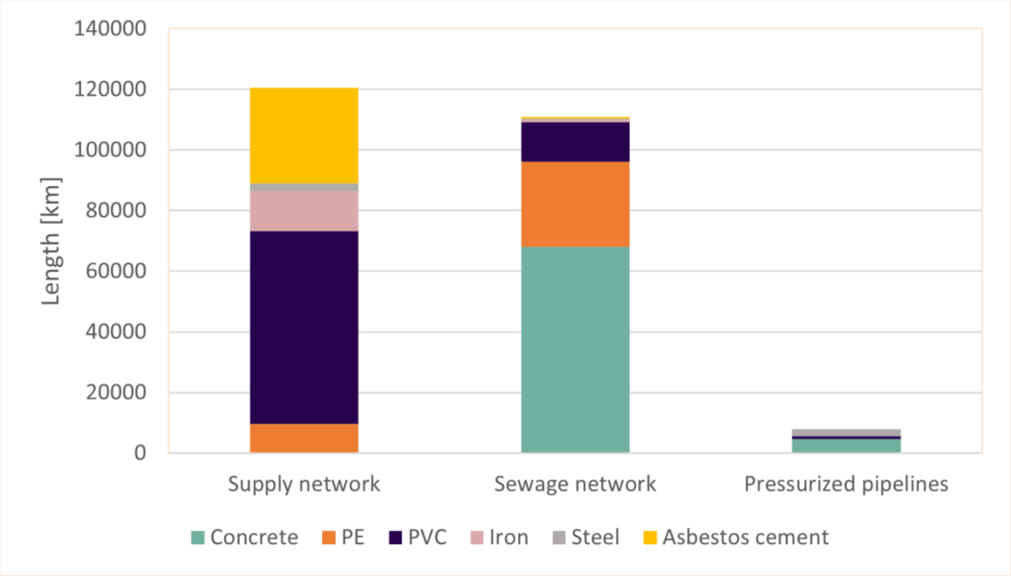


FIGURE 12. LENGTH OF SUPPLY NETWORK, SEWAGE NETWORK AND PRESSURIZED PIPELINES PER MATERIAL.

TABLE 18. EXAMPLE DIFFERENCES BETWEEN PVC IN SUPPLY NETWORK AND CONCRETE IN SEWAGE NETWORK.

	PVC in supply network	**Concrete in sewage network**
Length [km]	6.3E+04	6.8E+04
Volume [m^3]	2.2E+05	9.9E+06
Material density [kg/m^3]	1.3E+03	2.3E+03
Mass [ton]	2.9E+05	2.3E+07

4.1.1 HISTORIC STOCK DEVELOPMENT

The historic stock development of the mass of all materials of the Dutch urban water cycle infrastructure is presented in Figure 13. The stock development besides concrete is presented in Figure 14. The size of the urban water cycle infrastructure stock has almost six folded since 1950 and doubled in the last 50 years (1970-2020). This is most likely due to population growth, changes in drinking water demand and use, and the increasing number of buildings connected to the urban water cycle infrastructure. The total size of the current stock was around 38Mton in 2020. The material composition and the shares of materials of the urban water cycle infrastructure stock have changed between 1950 and 2020.

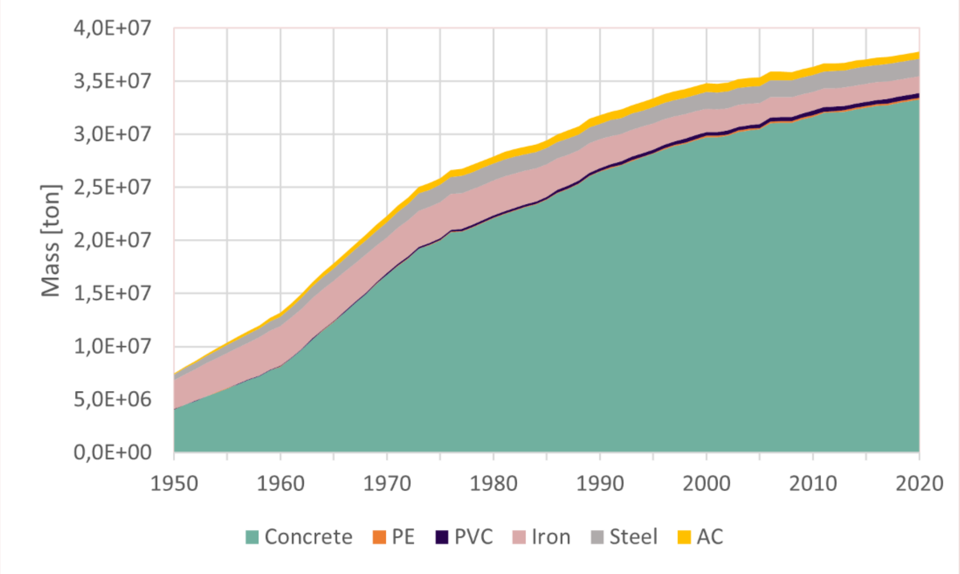


FIGURE 13. HISTORIC STOCK DEVELOPMENT OF THE DUTCH URBAN WATER CYCLE BETWEEN 1950 AND 2020.

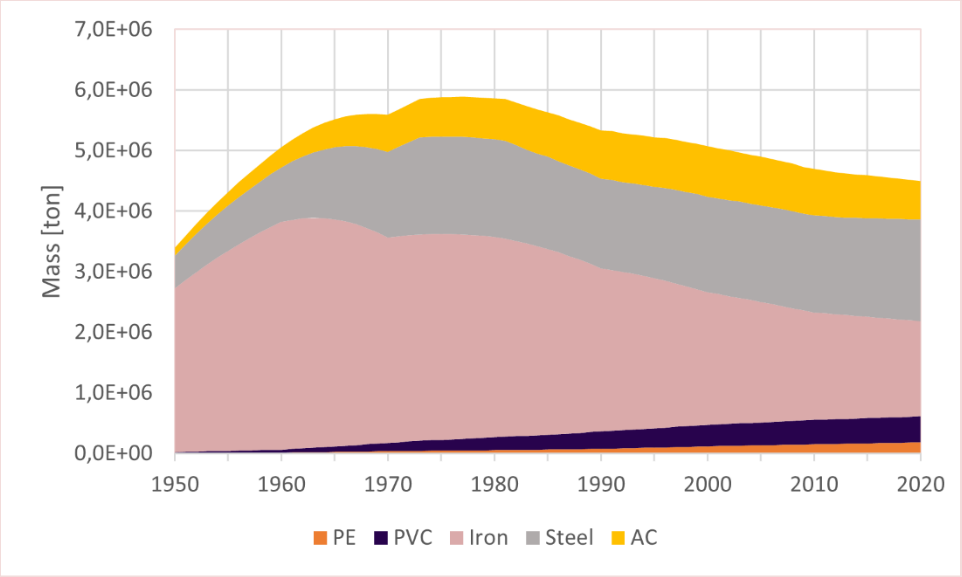


Figure 14. Historic stock development besides concrete of the Dutch urban water cycle between 1950 and 2020.

4.2 Stock Development until 2050

The stock changes as presented in Table 17 combined with material composition changes (Table 9 and

Table 10), are used as input for the modelling of the inflows and outflows of materials until 2050. Note that the scenarios outline a bandwidth of potential stock changes of the urban water cycle infrastructure and that these are not predictions of the future.

The stock changes per component as presented in Table 17 are assumed to linearly increase between 2020 and 2050. The stock changes of the materials per component until 2050 are presented in Figure 15 (note that the y axis scale differs per figure). The stocks of the drinking water production plants, the supply network, the sewage network, the gully pots, and the sewage pumping stations are all increasing for all four scenarios. The stocks of the pressurized pipelines, and the WWTPs do not change between 2020 and 2050 for any of the scenarios.

The stock changes for scenarios RUST and WARM are for all components almost similar. The stock changes for scenario STOOM are the highest, followed by the stock changes in scenario DRUK.

Relative and absolute stock changes of all materials are presented in Table 19. In 2020 4.2% of the total stock mass represented iron. In scenario DRUK, the mass percentage of iron increases to 4.5%, in scenario STOOM to 4.3%, and in scenario RUST and WARM to 4.4%. The material composition changes between 2020 and 2050 due to, amongst others, the replacement of asbestos cement and the construction of new infrastructure.

Table 19. Absolute and relative material stock changes between 2020 and 2050.

			DRUK		**STOOM**		**RUST**		**WARM**	
	2020 [ton]		**2050 [ton]**		**2050 [ton]**		**2050 [ton]**		**2050 [ton]**	
PE	1.8E+05	0.5%	3.9E+05	0.9%	3.8E+05	0.8%	3.4E+05	0.9%	3.4E+05	0.9%
PVC	4.3E+05	1.1%	6.1E+05	1.4%	5.9E+05	1.3%	5.4E+05	1.4%	5.4E+05	1.4%
Iron	1.6E+06	4.2%	2.0E+06	4.5%	1.9E+06	4.3%	1.7E+06	4.4%	1.8E+06	4.4%
Steel	1.7E+06	4.4%	1.9E+06	4.3%	1.9E+06	4.2%	1.8E+06	4.4%	1.8E+06	4.4%
Concrete	6.4E+05	88.1%	0.0E+00	89.0%	0.0E+00	89.3%	0.0E+00	89.0%	0.0E+00	89.0%
Asbestos cement	3.3E+07	1.7%	4.0E+07	0.0%	4.0E+07	0.0%	3.5E+07	0.0%	3.6E+07	0.0%

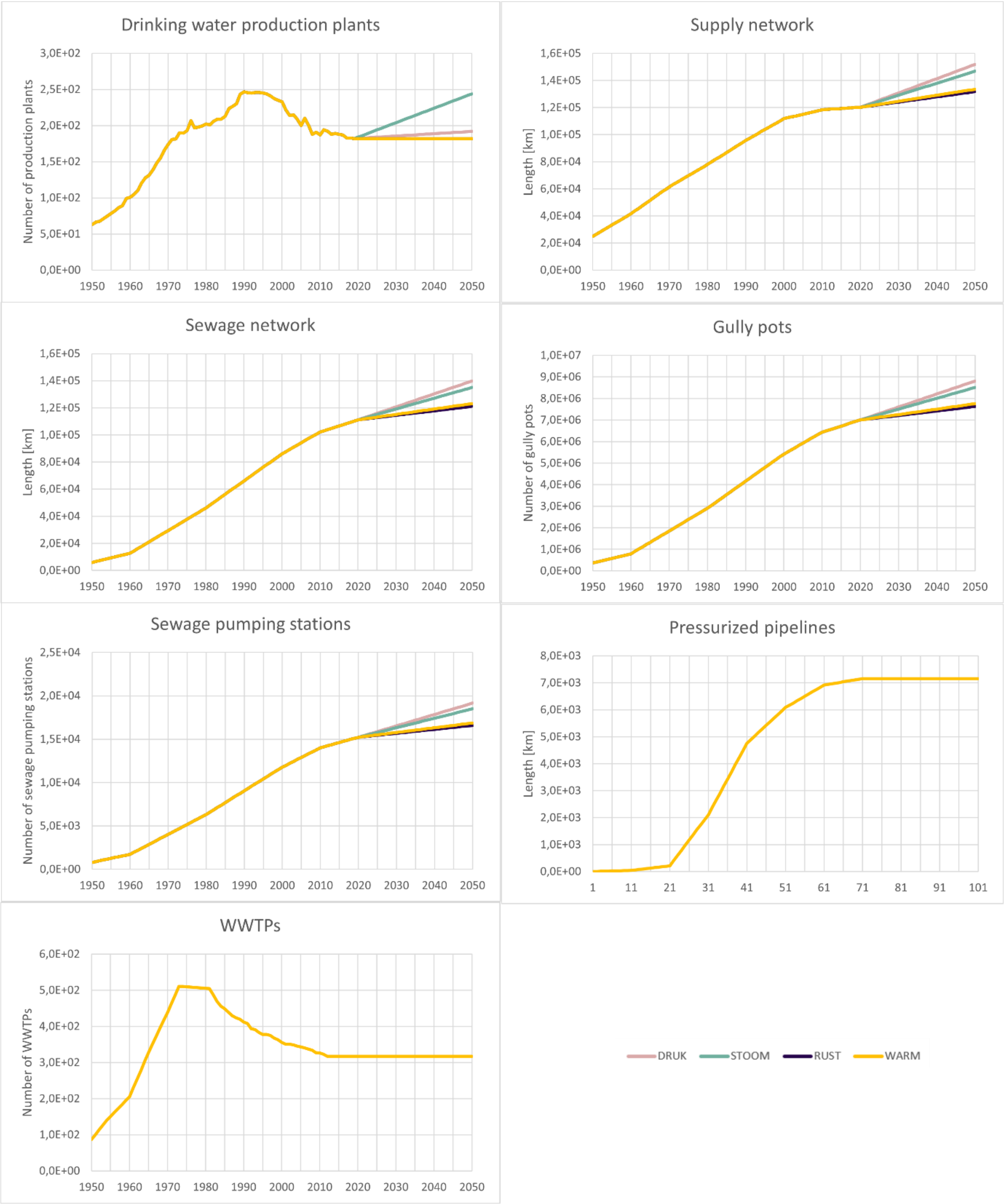


Figure 15. Stock changes per component of the Dutch urban water cycle infrastructure until 2050 under different scenarios.

4.3 MATERIAL INFLOWS & OUTFLOWS UNTIL 2050

For the presentation of the results, inflow and outflow data is aggregated per material (Figure 16). The figures thus represent the material in- and outflows of all components of the urban water cycle infrastructure together. First of all, it should be noted that the figures have different y-axis scales. Material masses cannot be compared one on one due to this scale difference. Furthermore, only one outflow is presented (and not per scenario) since the outflows per scenario for each of the materials are more or less the same size.

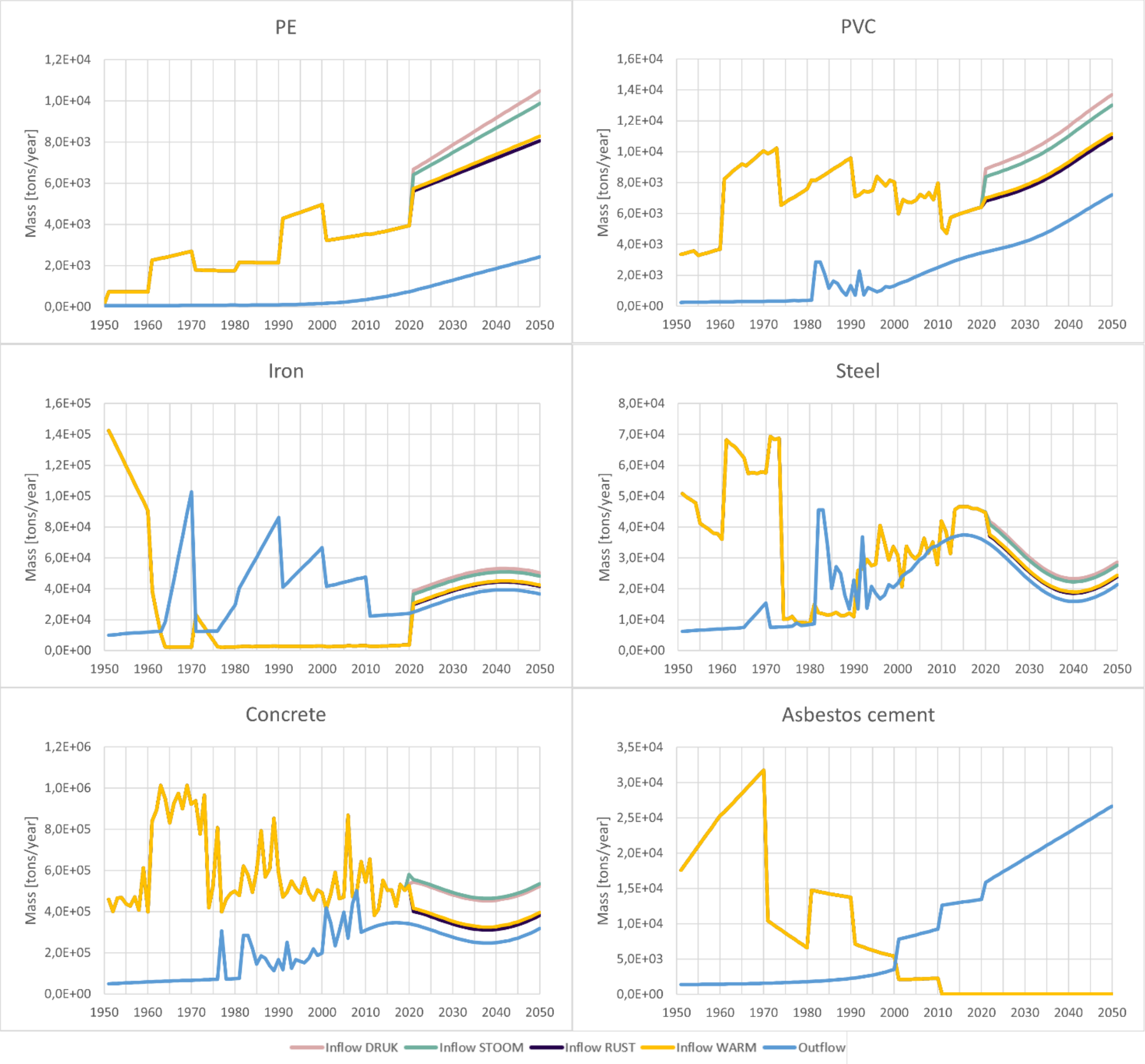


FIGURE 16. MATERIAL INFLOWS AND OUTFLOW BETWEEN 2020 AND 2050 UNDER DIFFERENT SCENARIOS.

The inflow of PE as a material has overall been increasing. Since PE is only assumed to be used as a material in the supply network and sewage network, its inflow is dependent on the stock developments and material share changes in the supply network and sewage network. As presented in Table, the share of PE is increasing until 2050.

Similar observations can be made for PVC, however PVC is not only a material used in the supply network and sewage network, but also the drinking water production plants, pressurized pipelines and WWTPs. Although the use of PVC increases in the supply network and sewage network until 2050, the stock changes of the drinking water production plants, pressurized pipelines and WWTPs cause the overall decrease of PVC inflow between 1970 and 2020. After 2020, the inflow of PVC is increasing for all scenarios due to the increase of number or drinking water production plants, supply network length and sewage network length.

Iron is used as a material in drinking water production plants, the supply network, the sewage network, and in gully pots. A first observation is the rapid decrease of iron inflow between 1950 and 1970. Although both the number of drinking water production plants and gully pots increased during this period, the share of iron in the supply decreased rapidly due to the increased use of asbestos cement, PVC, and PE. Since the total mass of iron in the supply network is significantly higher than the total mass of iron in the drinking water production plants, gully pots, and sewage network, a decrease in iron use in the supply network results in an overall outflow of iron. The inflows of iron for the drinking water production plants, gully pots and sewage network become invisible due to the large outflow of iron from the supply network. This is why the outflow of iron is higher than the inflow between 1960 and 2020. After 2020, the inflow of iron increases again, due to the stabilization of iron share in the supply network, and the overall increase of stocks of the drinking water production locations, supply network, sewage network, and gully pots for all four scenarios.

The total inflow of steel is higher than the outflow until around 1970. The inflow drops between 1970 and 1975. Between 1980 and 1990 the outflows are even higher than the inflows. This has most likely to do with the decrease of WWTPs in that period, resulting in an outflow of materials from the demolished WWTPs. After 1990 the inflow of steel is again higher than the outflow. After 1990 the steel share in the supply network increases which results in an increasing inflow of steel in the supply network, and thus also an overall increase of the size of the steel inflow.

The graph for concrete shows that the inflow of concrete is always higher than the outflow between 1950 and 2050. The largest contributor to the stock size of concrete is the sewage network. The ever growing length of the sewage network between 1950 and 2050 and more or less stabilized share of concrete, results in a continuous demand for concrete for the sewage network. Since the sewage network is the largest contributor to the total stock of concrete, small decreases in the number of drinking water production plants and WWTPs are not resulting in an outflow being higher than the inflow, unlike for example the flows of iron and steel.

A last interesting insight are the flows of asbestos cement. The ban of asbestos cement in the Netherlands around 1993 results in higher outflow of asbestos cement than inflows after 2000. If all asbestos cement pipelines are replaced by the year 2050, the material flows of asbestos cement will look like the flows from the asbestos cement graph in Figure 16. One might expect and inflow of 0 tons/year starting in the year 1993. However, there are still asbestos cement inflows between 1993 and 2010, which is in practice not possible. This is caused by certain modelling choices such as the chosen lifespan distribution, and the general fact that using a model is not always a perfect representation of real life.

4.4 HIBERNATING STOCK

As explained in subsection 3.2.2, the hibernating stock is one of the system dynamics that impacts the size of the outflow. An increase in hibernating stocks results in lower material outflows. Exact data on the size of the hibernating stock of the Dutch urban water cycle infrastructure components could not be found. As part of the nation-wide programme '*Nederland Circulair!*' Circle Economy and MVO Nederland (Bardout et al., 2017) published a report on the reuse of underground cables and pipelines. They mentioned 10,000 km of supply network and 2,000 km of sewage network being out-of-use and 2,000 km. This represents around 8% of the supply network and 2% of the sewage network. Analysing different hibernating stock percentages shows the effect of hibernating stocks on material outflows. The higher the hibernating percentage, the lower the outflow of material, and the less material can re-enter the economy as a secondary material if the hibernating stock is not recovered.

Although the material composition of the out-of-use pipelines is not mentioned, it is assumed that the majority is made of asbestos cement. The removal of old pipelines depends on the ability to get in to the ground. This has changed over time most likely due to the construction of buildings. A sensitivity analysis for different hibernating percentages for asbestos cement pipelines is presented in Figure 17.

Without hibernation, the outflow of asbestos cement in 2050 is around 22,500 tons. A hibernating percentage of 10% results in an outflow of 20,000 tons in 2050, and 17,500 tons if the hibernating percentage is 20%. If the hibernation percentage is indeed around 10%, this means that 2,500 tons of asbestos cement is not recovered compared to a scenario without any hibernation.

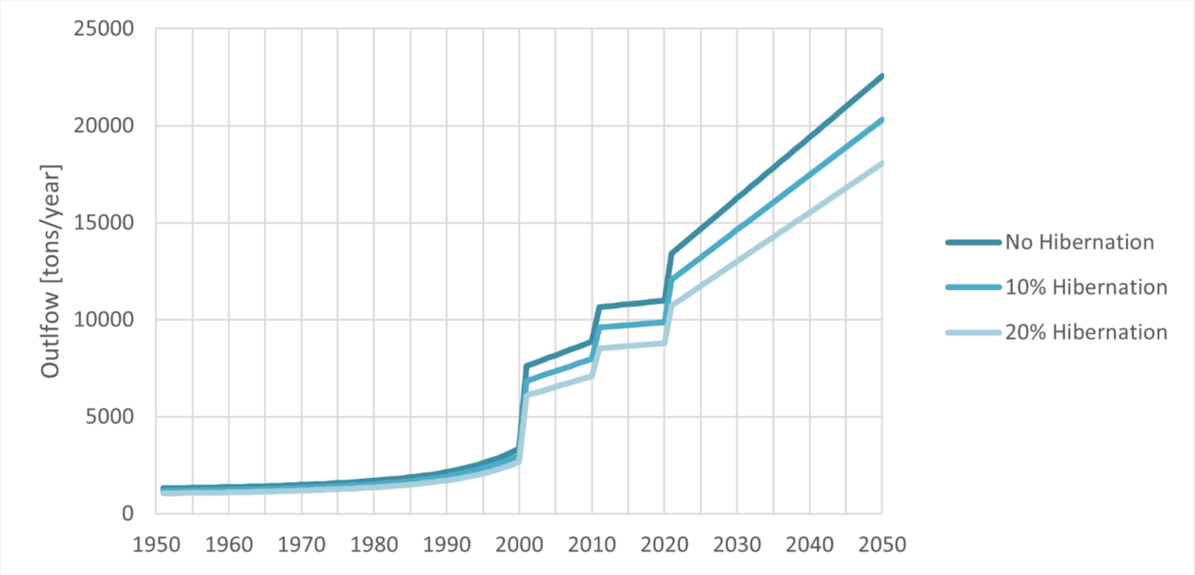


Figure 17. Sensitivity analysis of impact of different hibernation percentages on the outflow of asbestos cement.

4.5 RE-ENTERING OF MATERIALS IN THE ECONOMY

The potential of the urban mine of the urban water cycle infrastructure as a circular economy strategy depends on the re-entering of materials in the economy. Insights regarding the current reuse of materials by the drinking water companies and water boards are gained during interviews. The main insights from the interviews are discussed in the next subsections, followed by a last subsection with interpretation of the interview results.

4.5.1 INSIGHTS FROM INTERVIEWS

ANTHROPOGENIC MATERIAL USE

An interesting and important insight from the interviews with water companies and water boards is that there is currently still a high demand for raw materials. First of all, demand (inflow of materials) is currently higher than the outflow of materials. This is also confirmed by the prospective MFA results (section 4.3). This is inherently related to a continuous demand for raw materials. If the material demand is higher than the material outflow, reusing 100% of the material outflow is not sufficient to cover for the total material demand.

Furthermore, water boards, but also water companies come across a problem once their assets reach their end-of-life. In order to maintain production capacity or treatment capacity, new assets are first constructed before the old assets are demolished. Therefore it is impossible to directly reuse materials from the old asset in the new asset: materials cannot directly be reused within a water company, municipality, or water authority. This is seen as a limitation in becoming more circular.

RESPONSIBILITY

With the replacement of production plants, pipelines, pumps and treatment plants, a lot of material becomes available. These materials are separated, but often the water companies, municipalities, and water boards do not have a say in what exactly is happening with those materials. The management of waste outflows is outsourced to contractors who are responsible for taking care of all material outflows. Construction waste (including pipelines) is often collected by local waste companies and falls under the category of construction- and demolition waste.

According to one of the waste companies around 50% of the total waste of a drinking water company (excluding process related waste such as sludge) is recycled and used as secondary materials. It is however not specified how and where the recycled materials are used. The remaining 50% of waste is divided in waste to generate green energy (33%, energy generated from biogenic materials such as wood), waste to generate grey energy (16%, energy that is released during the incineration of residual waste), and residue (1%, ashes left from the incineration of residual waste).

Besides the lack of responsibility during demolition that withholds direct reuse of materials, the construction phase is as important in becoming circular. The circular ambition of the drinking water companies and water boards depends amongst other on the circular material use of their contractors. Therefore tenders play a crucial role as mentioned in some of the interviews. Circularity, specifically the use circular materials, is nowadays often implemented in tenders. Even the selection of the final contractor can be based on the contractors' level of circularity.

RISKS

Reusing components and recycled materials is according to the drinking water companies and water boards desirable, but not always possible or profitable. According to one of the drinking water companies using pipelines (partly) made of recycle plastics for the drinking water supply network is prohibited in the Dutch Drinking Water Act due to quality standards. Security of supply and drinking water quality are considered as the most important. The lack of knowledge about the quality of reused materials in, amongst others, the supply network results often in the use of raw materials instead of secondary materials according to some interviewees. They do not want to take the risk of reusing materials without having a quality guarantee.

Furthermore, as mentioned during some of the interviews, it is not only about the water quality risks, but also risks on the level of business. Investing money in extending the lifetime of equipment with a few years, without the guarantee of is working properly for those extra years, seems to be a bottleneck on a financial level.

SOCIAL ASPECT

A last main insight gained from the interview with the drinking water companies and water boards is that it is not necessarily the technical knowledge that is lacking regarding circularity and the reuse of materials. This is shown by the reuse of a fermentation tank as a sludge tank by one of the water boards, or the rewinding of sewage pumps and repairing lock gate mechanics before replacing them. It is more often the 'people side' where circularity achievements are obstructed. According to the drinking water companies and water boards, awareness of the importance of reusing materials is lacking, costs are perceived to be too high, and prove of success of using secondary materials are lacking for some.

4.5.2 SOLUTIONS BY INTERVIEWEES

AWARENESS

A few potential solutions were mentioned repeatedly during the interviews. First of all, creating awareness amongst the different stakeholders and convincing them to become more circular. This can be done by educating them about the advantages of reusing materials, giving them examples of successful implementation of secondary materials, and finding a way to lower the monetary risks that come with reusing materials and equipment. Creating a knowledge database, not only within a water company, municipality, or water board, but also amongst them. But it is not only about convincing people with a good story. Using data to prove that reusing materials is better than using raw materials may play a role. For example by making the use of the environmental cost indicator mandatory (see next subsection).

MKI

The environmental cost indicator (MKI) – a single-score indicating the monetary costs of the environmental impact of a material – during the tender process for the construction of new assets is more and more used to become more circular (Metabolic & SGS Search, 2017). It is a an already widely used indicator in the construction sector and is used to easily communicate environmental impacts of the use of a certain material.

Furthermore, becoming more flexible in terms of infrastructure is mentioned as an important aspect of becoming more sustainable and circular. To become future proof, water boards need to reduce annual costs, take on a more sustainable approach and improve the quality of treated wastewater all at the same time for example. This led to a concept called Verdygo: a modular, sustainable sewage treatment plant in which the technical equipment is designed in the form of transportable plug & play modules (Roelofs et al., 2022). In 2019, a new WWTP was build according to the Verdygo concept. In contrast to traditional construction methods with buried basins, a Verdygo built WWTP has aboveground basins that can be connected if needed. Upscaling or downscaling of the treatment facilities is therefore relatively easy and cost-effective (GWW, 2019).

REPORTING & REUSING MATERIALS

A final strategy for becoming more circular is the reporting of currently in-use materials of the water companies, municipalities, and water boards. While a material market place is mentioned as one of the solutions for the previous described problem of ‘building first, demolishing second’, one needs to know the type and quantity of materials present in all assets in order to gain knowledge about potential future material outflows. In this context, the use of material passports are mentioned multiple times. Although the research done by Witteveen+Bos gives a rough estimate of materials used in the assets of the water boards, it was mentioned that these estimates are sometimes based on blueprints from more than 50 years ago. For the successful setup of a marketplace, these material passports need to be updated.

4.6 ANALYSIS OF INTERVIEWS

Based on the insights from the interviews with the drinking water companies and water boards, some observations are made.

4.6.1 CIRCULARITY ACHIEVEMENTS

First of all, there seems to be large emphasis on becoming circular within a drinking water company or water board. The problem of constructing new assets first before the old one is demolished was mentioned multiple times. However, reusing your own materials is not a necessity for becoming circular. Reusing each other's materials is just as effective. In order to share waste materials among drinking water companies, water boards, municipalities, but basically among anyone taking part in our economy, sharing of data on the amounts of materials and quality becomes important. AquaMinerals was mentioned only a few times as important for circularity achievements of drinking water companies and water boards, despite them playing already a big role in material sharing.

AquaMinerals aims to actively provide services to create economic and sustainability value for current and future raw materials from the water cycle. Their focus is on drinking water sector residuals such as calcite pellets, carbon sludge, aluminum sludge, etc. and their potential to be reused in the economy (AquaMinerals, 2021). Some material streams can for example be used for agriculture and horticulture or bio digestion. Even the cement industry and the brick and concrete manufacturing industry can make use of residual streams of the drinking water sector. All drinking water companies are partners of AquaMinerals, but only four water boards are (AquaMinerals, 2021).

AquaMinerals currently only focuses on process related waste and not infrastructure related waste. However, their ability to report on residual waste and sharing knowledge on how these residues can be reused could potentially be further expanded to infrastructure waste. As an inspiration for this expansion can be Circulair.biz: a project set up by a consortium initiated by the province of South Holland (*Home | Circulaire Bedrijventerreinen Midden-Holland*, 2022). Similar to AquaMinerals they mapped waste flows of different business parks in the province of South Holland and with the help of a Pareto analysis, a selection is made of the most promising flows and their circularity potential. This is based on the number of logistic movements, financial value, and environmental impact. As an addition to the mapping of process related waste, construction and demolition waste is mapped as well.

4.6.2 RISKS

Another observation that can be made based on the interviews relates to the mentioned risks of reusing materials. First of all, any potential risks related to water quality when using secondary pipeline materials are overcome by the tests done by pipeline manufacturers and quality tests done by Kiwa, an institute originally founded for the testing of any item that comes in contact with our drinking water. Furthermore, the mentioning of the prohibition of secondary plastics in the supply network as claimed to be stated in the Drinkwaterwet is not true (*Drinkwaterwet*, 2009). This shows that not everyone is aware of what is and what is not possible regarding the reuse of materials.

Moreover, not having a guarantee for repaired equipment to work for a certain number of years was mentioned as a risk. However, a guarantee for a product to work for any number of years does not exist at all: failures can always occur, even for newly purchased equipment. The mentioning of this risk seems to be based on a financial risk. Unfortunately, like many other companies, the drinking water companies for example has a revenue model as part of their business model.

Discussion

5 DISCUSSION

5.1 DISCUSSION ON METHODOLOGY

The results of this study, specifically the use of a dynamic stock model to calculate inflows and outflows of materials until 2050, are dependent on the assumptions made for the stock dynamics and driving forces. These assumptions are made with the aim to imitate reality as closely as possible.

One of the assumptions that may have a large impact on the results is the chosen average lifetime of each component of the urban water cycle infrastructure. In order to analyse the effect of a chosen lifetime, a sensitivity analysis is conducted. The inflow and outflow graphs as analysed in the results chapter are an aggregation of all components per material. The flows of concrete are for example an aggregation of the concrete flows of the drinking water production plants, the sewage network, the gully pots, the sewage pumping stations, the pressurized pipelines and the WWTPs.

Since the sewage network is the largest contributor to the concrete stock, a sensitivity analysis is performed for the lifetime of the sewage network. Concrete as a material for the sewage network is currently assumed to have an average lifetime of 100 years. The sensitivity analysis is performed by analysing the aggregated concrete inflows and outflows of scenario DRUK for the situation where the lifetime of concrete in the sewage network doubles (200 years) and the lifetime of the sewage network is halved (50 years) (Figure 18 and Figure 19). The lifetime of all other components containing concrete remain the same.

From the graphs below show that the longer the lifetime is, the lower the inflows and outflows are for each year. Where in the scenario with a lifetime of 50 years, materials are replaced every 50 years, materials are only replaced every 200 years in the scenario where the average lifetime is assumed to be 200 years. Although the stock increases the same amount per year for all lifetime scenarios, the material inflow needed for maintenance is significantly higher when the lifetime is shorter. This is because the outflow of materials is higher, since it is the outflow that is calculated based on the lifetime and the inflow being calculated based on changes in stock and outflow in that same year.

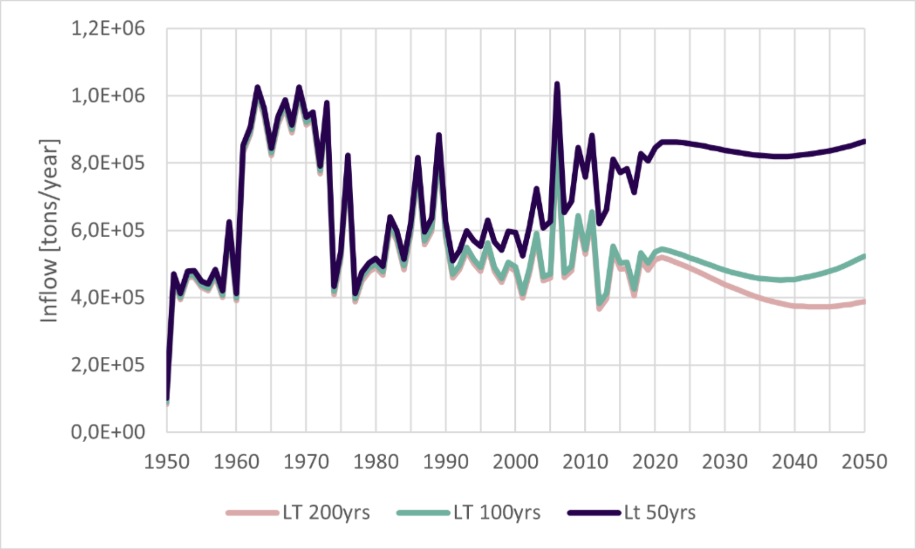


Figure 18. Total inflow of concrete for different lifetimes of concrete in the sewage network.

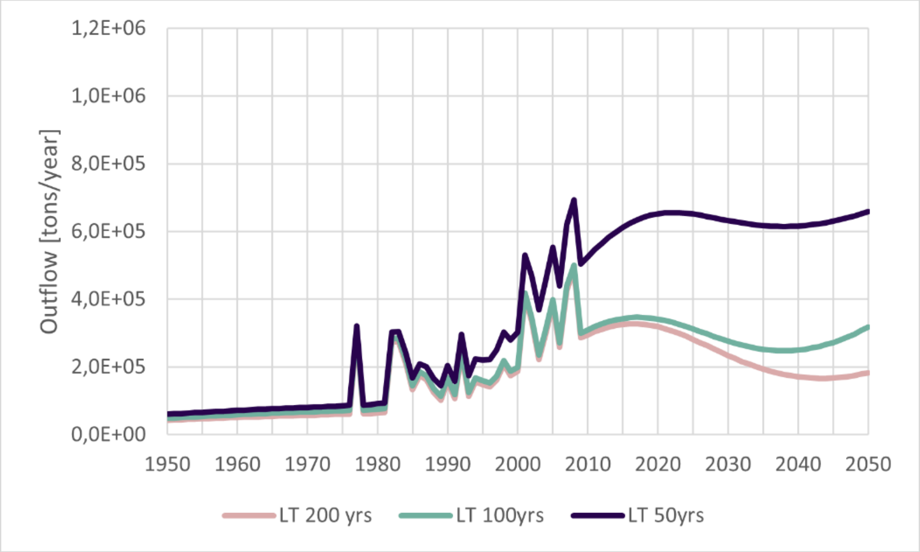


Figure 19. Total outflow of concrete for different lifetimes of concrete in the sewage network.

It should however be noted that for this sensitivity analysis the lifetime of the component with the highest contribution to the total stock has been analysed. The contribution of concrete from gully pots is for example way smaller. Analysing lifetime differences for gully pots results in less significant changes in inflows and outflows (Figure 20 and Figure 21).

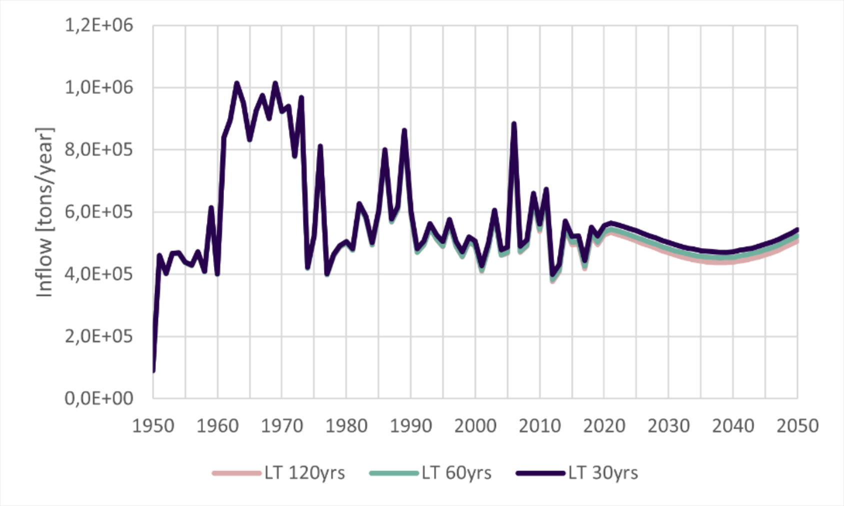


FIGURE 20. TOTAL INFLOW OF CONCRETE FOR DIFFERENT LIFETIMES OF GULLY POTS.

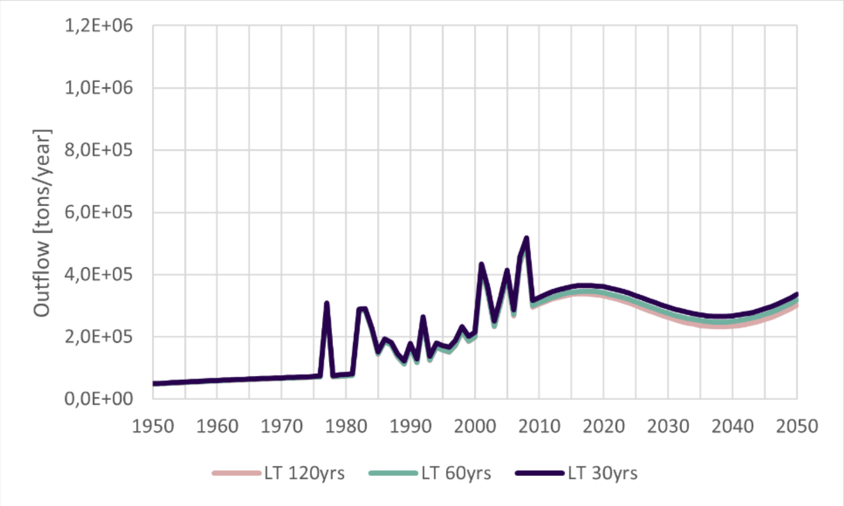


FIGURE 21. TOTAL OUTFLOW OF CONCRETE FOR DIFFERENT LIFETIMES OF GULLY POTS.

5.2 HISTORIC STOCK DEVELOPMENT AND CURRENT STOCK

This study only analyses material stocks and flows of seven components of the urban water cycle infrastructure. Due to lack of data, for example for the material composition and historic development of the number of overflows, no other assets are taken into account. The total mass and flows are thus only reflecting the urban water cycle infrastructure as defined in Dutch Water Sector.

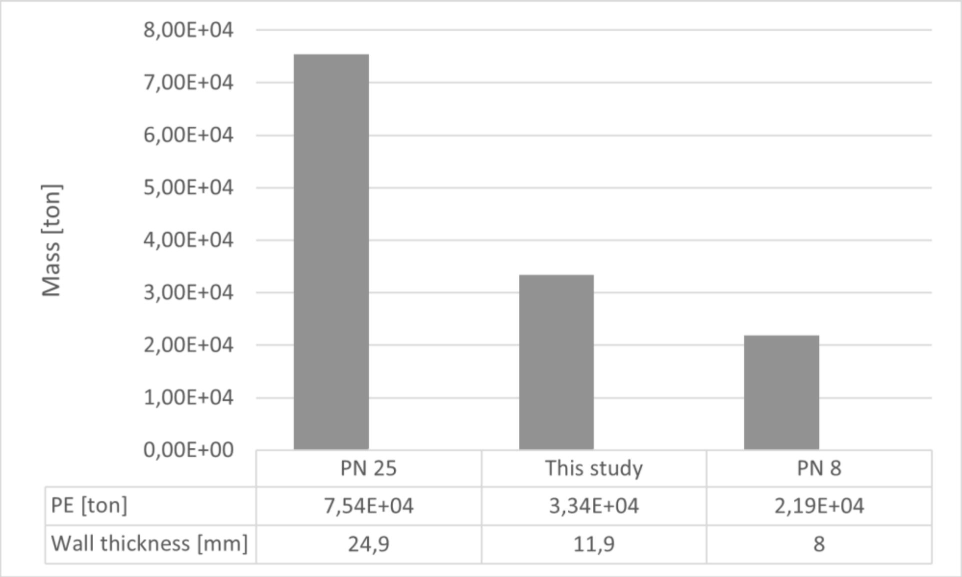
5.2.1 AGGREGATION OF MATERIAL CATEGORIES

In order to calculate the current stock and historic stock development some assumptions are made. The material compositions and shares of the supply network and the sewage network are based on average material volumes which are then multiplied with the material densities. First of all, ductile iron and cast iron are merged into one category. Although current stock data is available for both types of iron, historic development only mentioned the category iron (Geudens & Kramer, 2022). The impact of combining the two categories is most likely to not have a large effect on the total mass of the urban water cycle infrastructure since both material densities are the same. However, as a result the shares of ductile iron and cast iron in the material outflow is unknown. Vewin also used a category called 'other' for the supply network, which is assumed to be mostly steel based on yearly statistics of the water companies. However, there is also a small share of concrete in the supply network, but not enough historic data could be found to make valid assumptions for historic and future concrete shares. Concrete as a material is thus neglected for the supply network.

5.3 DIAMETERS AND WALL THICKNESSES

Moreover, assumptions are made for the average diameters of pipelines for each material. Although it is known that the drinking water companies and municipalities do have exact data on the wall thicknesses of their pipelines, they were not willing to share this data for this study. Therefore, the wall thicknesses as stated in NEN 3650 are used for the calculations of material volumes of pipelines. However, the wall thicknesses as presented in their table are not only related to the type of material of a pipeline and its diameter, but is also based on nominal pressure and induced stress. Since the nominal pressure (the maximum internal pressure that a pipe and its joints are capable of withstanding) is unknown, the median nominal pressure was taken and its corresponding minimum wall thicknesses. The question arises what the effect is of choosing a different wall thickness. To analyse this effect, a sensitivity analysis of the wall thickness of PE supply pipelines is conducted (Figure 22). For this analysis the wall thicknesses are taken that correspond the maximum reported nominal pressure and the minimum reported nominal pressure for PE supply pipelines with a diameter of 150mm.

The higher the nominal pressure, the higher the wall thicknesses and the higher the mass of PE pipelines with a diameter of 150mm in the supply network. If the wall thickness would be 4mm lower compared to what is assumed for this study, the mass of the 150mm PE pipelines decreases by a third. A doubling of the current assumed wall thickness results in double the mass of 150mm PE pipelines. Although PE is not the material with the highest contribution to the total mass of the urban water cycle infrastructure, this sensitivity analysis does show that the accuracy of the calculation of the material stocks an flows is highly dependent on the accuracy of the chosen wall thickness. This should be taken into account during the interpretation of the results and for future research. More detailed information on the exact wall thicknesses of pipelines would result most likely in a more accurate representation of the material masses of pipelines.



	PN 25	This study	PN 8
PE [ton]	7,54E+04	3,34E+04	2,19E+04
Wall thickness [mm]	24,9	11,9	8

Figure 22. Sensitivity analysis of impact of different wall thicknesses of PE pipelines in the supply network on the PE material mass of the supply network.

5.3.1 MATERIAL COMPOSITION

The material composition and shares of materials of the drinking water production plants are estimated based on an LCA study. This LCA study based their data on a drinking water production plants with a certain capacity. Although this capacity is in alignment with the average production capacity of all drinking water production plants in the Netherlands, there is not necessarily a one on one relation between the amount of infrastructure and production capacity. A drinking water production plant that produces twice as much drinking water per year, does not necessarily have twice as much infrastructure. However, since no specific data could be found on the exact production capacities of each drinking water production plant and only few LCA studies included the construction phase of drinking water production plants, the aforementioned assumptions were made.

The material composition data of the WWTPs and sewage pumping stations was directly taken from the Witteveen+Bos report that analysed the material contents of the assets of six water boards. A scaling factor was used to calculate the total material mass of all WWTPs and sewage pumping stations in the Netherlands. Additionally, it should be noted that it was mentioned during the interviews that the data as used in the Witteveen+Bos report is sometimes base on old building blueprints that may no longer be accurate for all WWTPs and sewage pumping stations. This stresses the urge for updated material passports.

5.4 Negative Inflow Correct

As mentioned in section 3.2, the python model used for this study includes an option to automatically correct for negative inflows of materials. For decreasing material stocks of for example the drinking water production plants between 1992 and 2019, negative inflows were calculated, which cannot exist in reality. These negative inflows are corrected for with the NegativeInflowCorrect command (Figure 23). This subsequently leads to different outflows (Figure 24). Apart from a difference in outflow size per year for some of the years, the sum of the concrete outflows from the drinking water production plants between 1950 and 2020 also changed (Table 20). When correcting the negative inflows of all components (if there are any), the total outflow of concrete between 1950 and 2050 increases with around 1.3 Mton in total, which is a bit more than 6% of the sum of outflows with a correction for negative inflows (see Table 20).

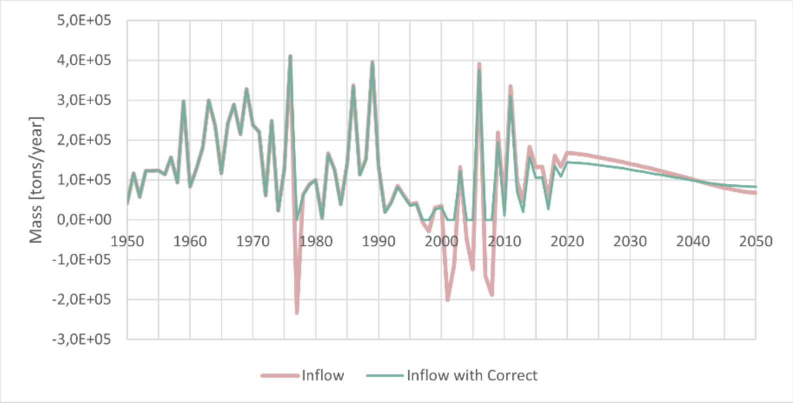


Figure 23. Inflow of concrete in drinking water production plants with and without using the NegativeInflowCorrect.

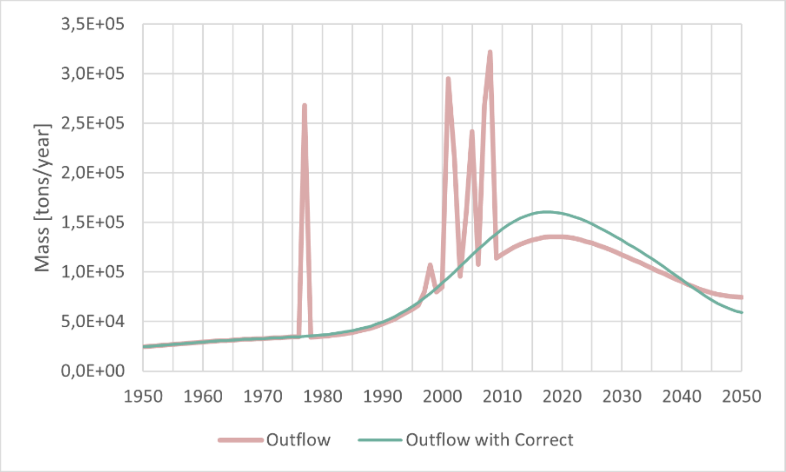


Figure 24. Outflow of concrete for drinking water production plants with and without using the NegativeInflowCorrect.

Table 20. Absolute and Relative impact of using the NegativeInflow Correct on the flows of concrete of the drinking water production plants and the total flows of concrete of the urban water cycle infrastructure.

	Without Negative Inflow Correct	**With Negative Inflow Correct**	**Change compared to Without Negative Inflow Correct**
Total inflow production plants	1.16E+07	1.21E+07	+ 4%
Total outflow production plants	8.12E+06	8.63E+06	+ 6%
Total inflow concrete	5.51E+07	5.65E+07	+ 2%
Total outflow concrete	1.97E+07	2.10E+07	+ 7%

5.5 SCENARIOS AND PROSPECTIVE ANALYSIS

The Deltascenarios were selected for their ability to show a bandwidth of future possibilities. Aside from the inclusion of the WLO Hoog and WLO Laag scenarios, the Deltascenarios also include climate change and its potential effects on drinking water demand, and rainfall. Therefore, the Deltascenarios can be seen as one driving force that summarizes different smaller driving forces (i.e. climate change as a driving force, economic growth as a driving force, etc.). However, this can also be seen as a limitation, since different driving forces are coupled instead of uncorrelated. Furthermore, although for example urbanization and agricultural area are mentioned in the Deltascenarios, they are not taken into account for the calculations of changes in drinking water demand. Where agricultural area is not seen as having a direct impact on drinking water demand (water with lower quality is used for land watering), urbanization is. This is why urbanization is analysed separately as a driving force and later combined with the Deltascenarios. Finally, where this study only takes into account the aforementioned driving forces, it does not mean that these are the only driving forces that impact changes in the urban water cycle infrastructure.

Furthermore, the scenarios are not predictions of the future. The actual future will most likely be somewhere in between these four scenarios, but could also lay outside of the presented bandwidth.

Regarding the translation of urbanization and drinking water demand into infrastructure changes, some assumptions were made. First of all, for the supply network and sewage network all apartments are assumed to be connected to the main pipelines per address. Whereas older apartment buildings are connected per building, newly constructed apartment buildings are often connected to every front door in the building. However, this assumption may lead to an overestimation of additional pipeline length. Another impactful assumption is that the number of WWTPs is assumed to be stable until 2050 based on their treatment capacities. However, water boards, but also drinking water companies, are continuously trying to improve their efficiency with new innovations. Despite innovations being taken into account in the Deltascenarios for the calculation of drinking water usage, innovations are not considered for the estimations of WWTPs and drinking water production plants. By the estimation of the number of drinking water production locations, geographic distribution of drinking water demand changes are not taken into account. However, according to the report from TVVL based on a study from RIVM, potential drinking water shortages are not equally distributed geographically (Scheffer & TVVL Expertgroep, 2017).

RECOMMENDATIONS

6 RECOMMENDATIONS

Based on the insights from this study some recommendations are formulated.

6.1 DUTCH WATER SECTOR

For the analysis of the Dutch urban water cycle infrastructure, seven components were included. However, some components such as overflows were left out due to lack of data. For a more complete analysis of the urban mining potential of the Dutch urban water cycle infrastructure, it is recommended to include as many components as possible, thus including overflows as well.

Furthermore, as presented in Chapter 2 the Dutch water sector is managed by a total of 10 drinking water companies, 344 municipalities, and 21 water boards. Smooth communication is key for optimal material exchange between these entities. It is thus recommended to look further in the relations of these entities and research how communication regarding material exchange can be optimized.

6.2 MATERIAL REUSE CONTENT

The potential of the urban mine requires quantification of material stocks and flows of a system, in this case the Dutch urban water cycle. As important as the quantification of materials, is the knowledge on how to reuse the materials in the economy. In order to gain knowledge on material reuse, more detailed information is required regarding the material stocks. Reusing materials depends on the current function of materials (i.e. used in a door or in a treatment basin). When demolishing a production or treatment plant, a door could probably be used directly in another building, whereas a treatment basin that is made from concrete that is poured directly at the location of a WWTP has to be pulverized and cannot be directly reused at another location. It is therefore recommended to analyse the components of the Dutch urban water cycle at a more detailed level and include as much information as possible on how much of the materials can actually be reused and in which way. Giving this knowledge to water companies, municipalities, and water boards may also stimulate them in becoming more circular, since all knowledge is available regarding their current material use and its potential as secondary materials.

6.3 HIBERNATING STOCK

The reuse of materials of the Dutch urban water cycle infrastructure depends not only on the size of the outflows, but also on the size of the hibernating stock. As show in *Results, Hibernating Stock* the hibernating percentage of materials in the supply network has a big impact on the size of the outflow of materials. During this study it was noted that water companies know the location of every pipeline and its status: in use or out of use. Unfortunately, they were unwilling to share this data due to their status as a vital sector. However, since hibernating stocks constitute resource reservoirs immediately accessible for recovery it is recommended to incentivize sharing data on hibernating stocks of the whole Dutch urban water cycle infrastructure. Whenever the hibernating stocks are identified, it is recommended to recover and reuse as much material as possible. Hibernating stocks do not fulfil any functions, but are a material source readily available.

6.4 GEOGRAPHIC INFORMATION SYSTEMS

Geographic Information Systems (GIS) were used for the gathering of construction and demolition data of buildings until 2050 as one of the driving forces in the scenarios for changes in the urban water cycle infrastructure.

Combining the use of material flow analysis and spatial analysis enables the spatial-temporal patterns of stocks and flows in the urban water cycle infrastructure. Spatial analysis can assist in the creation of dynamic and spatial models, data visualization and management, and examination of spatial-temporal process, drivers, and patterns. In the case of the Dutch urban water cycle infrastructure, GIS could be used for the visualization of material stocks of the urban water cycle in the Netherlands. Material accumulation hotspots could be identified and locations of hibernating stocks could be visualized. In order to reuse materials from outflows of the urban water cycle, one needs to know where these outflows occur.

The use of GIS for data visualization and in some cases for data gathering was obstructed by the unavailability of public data and time. Although data on the geographic locations of production plants and WWTPs was available, drinking water companies were not willing to share geographic data of their supply network. Not only geographic locations of the pipelines are part of their geographic datasets, but also exact diameters, materials, and status, which could have resulted in more accurate data on stocks of the supply network. Despite geographic data being publicly available for some municipalities and water boards, it is recommended to analyse geographic data of the 21 water boards and the 344 municipalities in the Netherlands.

However, geographic data would allow for visualizations and data management of material stocks and flows, and it is thus recommended to look further into the possibilities of using GIS in combination with MFA for the Dutch urban water cycle infrastructure.

CONCLUSION

7 CONCLUSION

The ever growing global raw material use and corresponding waste flows and their impact on the environment, asks for a different approach regarding material use. Achieving a circular economy in which materials are kept longer in use to reduce the demand for raw materials can be stimulated by making use of the so called urban mine: material stocks that are currently in use.

This research is conducted to expand knowledge on the size and material content of the urban mine in the Netherlands, specifically the urban mine of the Dutch urban water cycle infrastructure. By answering sub research questions on the current size of the material stocks, development stocks and flows until 2050, and the re-entering of materials in the economy, the main research as posed below is answered:

What does the urban mine of the Dutch urban water cycle infrastructure look like until 2050 and how can it contribute to a circular economy?

The size of the urban mine of the Dutch urban water cycle is currently around 38Mton an consists of PE (0.5%), PVC (1.1%), iron (4.2%), steel (4.4%), concrete (88.1%), and asbestos cement (1.7%). The component with the highest contribution to the total mass is the sewage network.

In order to know what the urban mine of the Dutch urban water cycle infrastructure looks like until 2050, different scenarios are formulated to investigate infrastructure changes in the future:

- DRUK – limited climate change and strong economic growth, low urbanization
- STOOM – rapid climate change and strong economic growth, high urbanization
- RUST – limited climate changes and low economic growth, high urbanization
- WARM – rapid climate change and low economic growth, low urbanization

The infrastructure changes are driven by changes in drinking water demand and the net construction of buildings in different areas in the Netherlands. The size of the material stocks of each component of the Dutch urban water cycle infrastructure is also based on changes in material share. Table 21 presents the main results of this study per scenario, which answers the first part of the main question: *What does the urban mine of the Dutch urban water cycle infrastructure look like until 2050?*

TABLE 21. MATERIAL COMPOSITION, MATERIAL SHARE, STOCK SIZE, AND CONTRIBUTION OF STOCKS SIZE PER COMPONENT OF THE DUTCH URBAN WATER CYCLE INFRASTRUCTURE IN 2020 AND 2050 UNDER DIFFERENT SCENARIOS.

		2020	**DRUK 2050**	**STOOM 2050**	**RUST 2050**	**WARM 2050**
Total stock size [Mton]		38	44	45	40	40
Material composition	*PE*	0.5%	0.9%	0.8%	0.9%	0.9%
	PVC	1.1%	1.4%	1.3%	1.4%	1.4%
	Iron	4.2%	4.5%	4.3%	4.4%	4.4%
	Steel	4.4%	4.3%	4.2%	4.4%	4.4%
	Concrete	88.1%	89.0%	89.3%	89.0%	89.0%
	AC	1.7%	0.0%	0.0%	0.0%	0.0%

The last part of the main research question is answered by gaining knowledge on the re-entering of material flows in the economy. Based on interviews with drinking water companies and water boards, achieving circularity and reusing materials seems to be limited by (1) the high demand for raw materials which cannot be fully covered by the outflow of materials, (2) lack of responsibility regarding the waste collection and recycling, (3) perceived risks regarding the use of secondary materials, and (4) lack of awareness of the importance of reusing materials. Solutions for increasing material reuse are according to the interviewees: (1) increasing awareness among employees by showing them the value of secondary materials, (2) using the Environmental Cost Indicator (MKI) in tenders to make sure new assets are made from more secondary and sustainable materials, and (3) setting up a marketplace for infrastructure materials.

The idea of a marketplace is not new however. Such a marketplace already exists in the form of a process related waste sharing platform (AquaMinerals) and a waste inventory platform (Circulair.biz). Instead of creating an entirely new marketplace for urban water cycle infrastructure, the currently existing platforms can be extended. Moreover, there seems to be misconceptions about the reuse of recycled plastics for the drinking water supply network and about the concept of achieving circularity in general. Circularity does not have to be achieved within a drinking water company, municipality, or water board, but can also be achieved at a higher level.

Although this study gives a head start in researching the urban mine of the Dutch urban water cycle infrastructure, some recommendations are proposed for further research. First of all, knowledge on the actual reusable content of the material stocks is required as well as more accurate data on the material content of each of the components of the urban water cycle infrastructure and their lifetimes. Furthermore, the hibernating stocks need to be researched, since this stock influences the size of the outflows of materials and forms a material source that could be recovered directly. Last but not least, it is recommended to analyse the material stocks and flows with Geographic Information Systems to also include a spatial aspect to the availability of materials of the Dutch urban water cycle infrastructure.

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9 APPENDIX A – MATERIAL CONTENT

9.1 MATERIAL CONTENT OF SUPPLY NETWORK

In order to calculate an average material content per km of supply network several input data is required. First, ten diameter categories were defined. Per diameter category (which is assumed to be the average diameter of all pipelines in that category), the length of the supply network made from a certain material is presented based on KWR data ().

TABLE 22. LENGTH OF SUPPLY NETWORK IN KILOMETERS PER DIAMETER CATEGORY PER MATERIAL.

	50 mm	150 mm	225 mm	275 mm	350 mm	500 mm	650 mm	900 mm	1150 mm	1300 mm
PE	2,367	5,866	343	207	371	282	100	10	1	0
PVC	15,446	38,279	3,397	1,244	2,513	1,871	409	90	0	0
Iron	2,746	6,804	1,298	619	784	509	280	83	5	0
Steel	169	418	111	89	152	306	542	274	242	84
Concrete	0	0	10	6	30	233	201	160	355	227
AC	6,669	16,527	2,247	797	1,441	1,504	538	108	4	0

A misalignment between KWR and Vewin on historic data resulted in the omission of concrete as a material of the supply network.

Each of these diameter categories has a specific wall thickness per material (Table 23).

TABLE 23. DIAMETER CATEGORIES OF THE SUPPLY NETWORK AND ASSUMED WALL THICKNESSES PER MATERIAL.

	50 mm	150 mm	225 mm	275 mm	350 mm	500 mm	650 mm	900 mm	1150 mm	1300 mm
PE	6.0	11.9	14.8	18.0	21.1	29.7	45.0	59.0	59.0	59.0
PVC	3.4	4.6	6.2	7.7	11.0	15.5	19.3	27.6	30.6	30.6
Iron	3.6	4.5	5.6	6.3	8.0	11.0	14.2	14.4	14.2	14.2
Steel	5.0	5.0	5.0	5.0	5.2	5.6	6.4	7.9	8.7	9.5
AC	10.0	13.0	16.0	17.0	23.0	32.0	48.0	60.0	64.0	64.0

The volume of a pipeline is calculated with the following formula:

$$Volume = (\pi * outer\ radius^2 * L) - (\pi * inner\ radius^2 * L)$$

Which can then be multiplied with the material density to calculate the material mass (Table 24).

Table 24. Material densities.

Material	Density [kg/m^3]
PE	940
PVC	1,300
Iron	7,300
Steel	7,860
Concrete	2,300
Asbestos cement	1,600

A calculation example is given for PE in Table 25.

Table 25. calculation example for calculating the material content of one km of PE of the supply network.

	50 mm	**150 mm**	**225 mm**	**275 mm**	**350 mm**	**500 mm**	**650 mm**	**900 mm**	**1150 mm**	**1300 mm**
Diameter [m]	0.05	0.15	0.225	0.275	0.350	0.500	0.650	0.900	1.15	1.3
Length [m]	2367 *10^3	5866 *10^3	343 *10^3	207 *10^3	371 *10^3	282 *10^3	100 *10^3	10 *10^3	1 *10^3	0 *10^3
Wall [m]	0.006	0.0119	0.0148	0.018	0.0211	0.0297	0.045	0.059	0.059	0.059
Inner Radius [m]	0.025	0.075	0.1125	0.138	0.175	0.250	0.325	0.450	0.575	0.65
Outer Radius [m]	0,031	0,0869	0,1273	0,1555	0,1961	0,2797	0,37	0,509	0,634	0,709
Volume pipeline [m3]	2,498	35,504	3,824	3,429	9,126	13,937	9,825	1,777	224	0
Material content [ton]	1,111	16,074	1,742	1,562	4,167	6,367	4,468	810	103	0

The average material content per km pipeline is then calculated by summing up all material contents and dividing it by the length of the PE network.

9.2 MATERIAL CONTENT OF SEWAGE NETWORK

Similar calculations are conducted for the material content of the sewage network. The length of the sewage network per material per average diameter is presented in Table 26.

TABLE 26. LENGTH OF THE SEWAGE NETWORK IN KILOMETERS PER DIAMETER CATEGORY PER MATERIAL.

	50 mm	**150 mm**	**225 mm**	**275 mm**	**350 mm**	**500 mm**	**650 mm**	**900 mm**	**1150 mm**	**1300 mm**
PE	1,749	816	103	30	20	30	4	3	0	0
PVC	16,994	7,930	5,688	2,813	2,393	2,477	0	0	0	0
Iron	0	0	264	113	113	678	339	377	188	188
Steel	0	0	0	0	0	1	1	1	1	2
Concrete	0	0	39	0	27,516	21,304	5,923	3,517	2,026	1,883
AC	0	0	233	350	467	1458	583	583	467	58

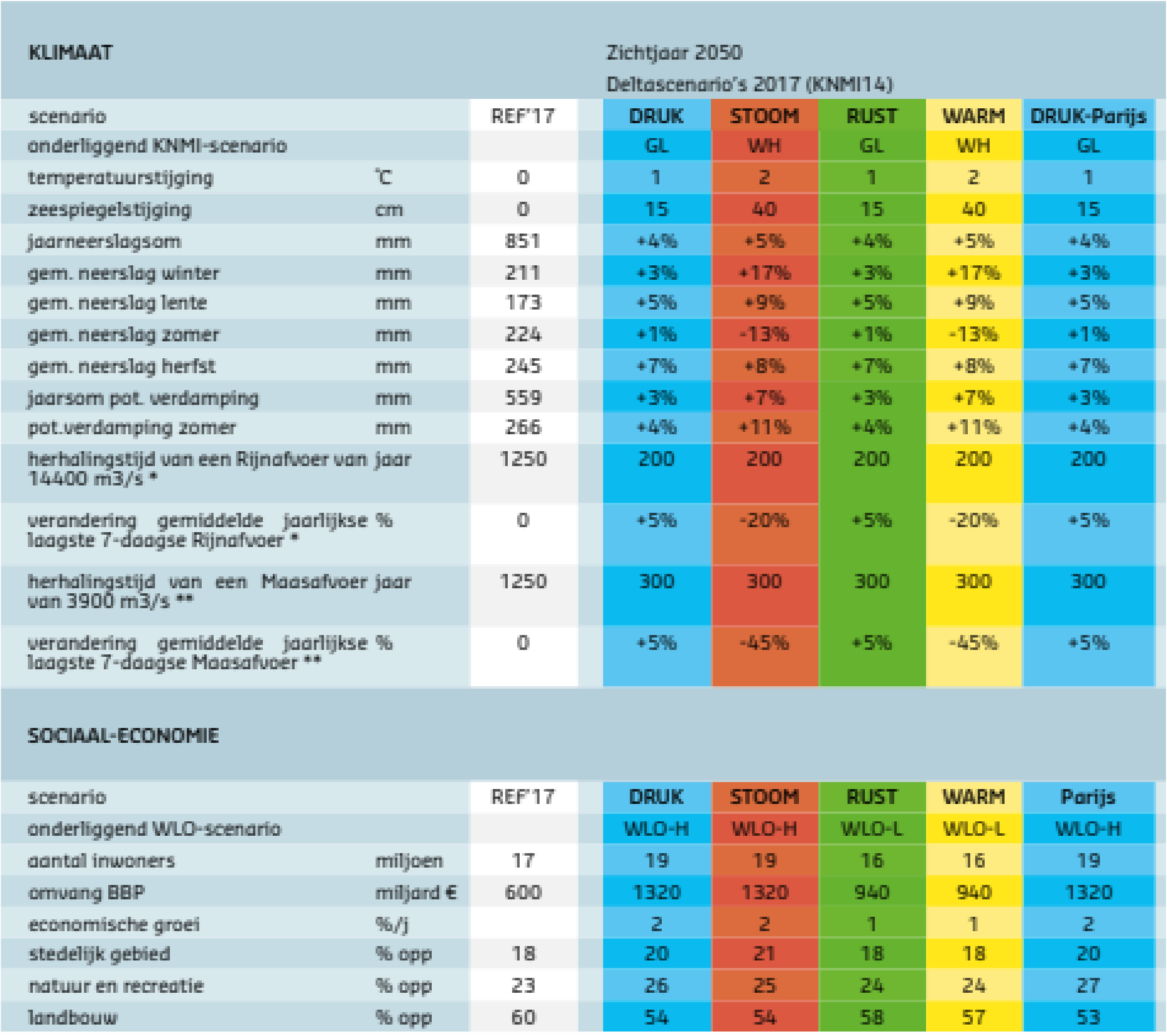
Similar wall thicknesses as the supply network are used for the sewage network (Table 23). The wall thicknesses of concrete are presented in Table 27.

TABLE 27. WALL THICKNESSES PER DIAMETER CATEGORY OF CONCRETE.

	50 mm	**150 mm**	**225 mm**	**275 mm**	**350 mm**	**500 mm**	**650 mm**	**900 mm**	**1150 mm**	**1300 mm**
Concrete	45	45	45	45	52,5	65	80	110	150	150

10 APPENDIX B - DELTASCENARIOS

Key figures of the Deltascenarios are presented in Figure 25.



KLIMAAT			Zichtjaar 2050 Deltascenario's 2017 (KNMI14)				
scenario		REF'17	**DRUK**	**STOOM**	**RUST**	**WARM**	**DRUK-Parijs**
onderliggend KNMI-scenario			GL	WH	GL	WH	GL
temperatuurstijging	℃	0	1	2	1	2	1
zeespiegelstijging	cm	0	15	40	15	40	15
jaarneerslagsom	mm	851	+4%	+5%	+4%	+5%	+4%
gem. neerslag winter	mm	211	+3%	+17%	+3%	+17%	+3%
gem. neerslag lente	mm	173	+5%	+9%	+5%	+9%	+5%
gem. neerslag zomer	mm	224	+1%	-13%	+1%	-13%	+1%
gem. neerslag herfst	mm	245	+7%	+8%	+7%	+8%	+7%
jaarsom pot. verdamping	mm	559	+3%	+7%	+3%	+7%	+3%
pot.verdamping zomer	mm	266	+4%	+11%	+4%	+11%	+4%
herhalingstijd van een Rijnafvoer van 14400 m3/s *	jaar	1250	200	200	200	200	200
verandering gemiddelde jaarlijkse laagste 7-daagse Rijnafvoer *	%	0	+5%	-20%	+5%	-20%	+5%
herhalingstijd van een Maasafvoer van 3900 m3/s **	jaar	1250	300	300	300	300	300
verandering gemiddelde jaarlijkse laagste 7-daagse Maasafvoer **	%	0	+5%	-45%	+5%	-45%	+5%
SOCIAAL-ECONOMIE							
scenario		REF'17	**DRUK**	**STOOM**	**RUST**	**WARM**	**Parijs**
onderliggend WLO-scenario			WLO-H	WLO-H	WLO-L	WLO-L	WLO-H
aantal inwoners	miljoen	17	19	19	16	16	19
omvang BBP	miljard €	600	1320	1320	940	940	1320
economische groei	%/j		2	2	1	1	2
stedelijk gebied	% opp	18	20	21	18	18	20
natuur en recreatie	% opp	23	26	25	24	24	27
landbouw	% opp	60	54	54	58	57	53

FIGURE 25. KEY FIGURES OF THE DELTASCENARIOS.

11 APPENDIX C – GIS DATA

Construction and demolition data of different scenarios until 2050 were provided as .tif files. The list below represents the different steps taken to derive the number of net constructed buildings.

1. .tif file has a raster layout. Tool ‘Int’ is used to convert each cell value of a raster to an integer by truncation.
2. Output of step 1 is converted to point data with the tool ’Raster to Point’.
3. Point data representing the number of buildings per type are spatially joined with municipalities and drinking water companies.
4. Each municipality or drinking water company has a value per building type for the number of buildings constructed in their area.
5. Steps are repeated for demolition of buildings.
6. All attribute tables are exported to Excel and the net construction of buildings is calculated by subtracting demolition data from construction data.

The result is an Excel file with the net constructed buildings per drinking water company or municipality.