Reality Check: Is stricter PFAS regulation a health win?

Health impact assessment of PFAS removal using granular activated carbon filtration

Parvathi Suresh Nair

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Final Thesis Report

by

Parvathi Suresh Nair

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Abstract

Per- and polyfluoroalkyl substances (PFAS) have remained persistent environmental contaminants since the 1950s, despite ongoing efforts to curb their production and find alternatives. Most health studies have focused on Perfluorooctanoic acid (PFOA) and Perfluorooctane sulphonic acid (PFOS), leaving limited data on other PFAS compounds in water. The European Union, particularly the Netherlands, has implemented stringent measures to control PFAS in drinking water due to their uncertain health impacts on humans. Recently, the Dutch Institute for Public Health and Environment (RIVM) proposed a new guideline of 4.4 ng PFOA equivalent (PEQ) per litre for PFAS in drinking water, a substantial reduction from the current European Drinking Water Directive standards of 100 ng/L for the sum of PFAS and 500 ng/L for total PFAS.

While improving drinking water quality is expected to have positive health outcomes, the advanced treatment technologies required to meet this new guideline can be harsh, potentially releasing emissions that may cause negative health effects. This research, centred on the Leiduin drinking water treatment plant operated by Waternet in the Netherlands, investigates whether the health benefits of the new guideline outweigh the potential harms caused by the treatment processes necessary to achieve it.

To explore this, the study first calculated the Disability-Adjusted Life Years (DALYs) lost due to PFAS exposure from drinking water at the current concentrations, exceeding the 4.4 ng PEQ/L guideline, using a literature review to link guidelines with PFAS health effects. The second step involved conducting a Life Cycle Assessment (LCA) of the treatment system at the Leiduin plant, focusing on the treatment steps necessary to meet the new guideline, and calculating the DALYs lost due to the environmental impact of achieving the 4.4 ng PEQ/L standard. These DALYs were then compared to assess whether adhering to the new guideline is justified in terms of health impacts.

The results indicate that the DALYs associated with the current and proposed guidelines fall within similar ranges, showing limited health benefits. Specifically, the health benefits (in DALYs) gained from implementing the new guideline range from 0.4 to 4 per year, while the DALYs lost due to the treatment technologies required at the Leiduin plant range from 1.55 to 3.25 per year for the population receiving drinking water from the Leiduin site, depending on the type of activated carbon used in the treatment process.

These findings suggest that the potential health benefits of stricter PFAS regulations in drinking water may be counterbalanced by the negative health impacts of the treatment technologies required to achieve these lower concentrations.

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List of Abbreviations

AE	Anion Exchange
APOS	Allocation at the point of substitution
$BMDL_{10}$	Benchmark Dose Lower Confidence Limit
CONTAM Panel	Panel on Contaminants in the Food Chain
DALYs	Disability-Adjusted Life Years
DWD	Drinking Water Directive
EBD	Environmental Burden of Disease
EFSA	European Food Safety Authority
EU	European Union
GAC	Granular Activated Carbon
GWP	Global Warming Potential
HBGV	Health Based Guidance Values
HH	Human Health
Hib	Haemophilus Influenzae
HPV	Human Papillomavirus
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
PEQ	PFOA equivalent
PFAS	Per and poly-fluoroalkyl substances
PFOA	Perfluorooctanoic acid
RIVM	The Dutch National Institute for Public Health and the Environment
RPF	Relative Potency Factors
RSF	Rapid Sand Filter
SSF	Slow Sand Filter
TDI	Tolerable Daily Intake
TWI	Tolerable Weekly Intake
WHO	World Health Organization
YLD	Years of Life with Disability
YLL	Years of Life Lost

Introduction

Per- and polyfluoroalkyl substances (PFAS) are a group of synthetic chemicals that have been widely used since their introduction in the 1950s. Known for their exceptional resistance to heat, oil, stains, grease, and water, PFAS have been integral in producing various consumer and industrial products. These substances are made of strong carbon chains (2 to 16 carbons in length) bonded to fluorine atoms [1], which make them highly resistant to environmental degradation [2].

Over the decades, more than 4700 PFAS chemicals have been developed and utilised [3]. From the 1950s to the early 2000s, PFAS were extensively manufactured, distributed, and incorporated into numerous products like paint, nonstick cookware etc [4]. This widespread usage has led to significant environmental contamination and human exposure. Despite the benefits of PFAS in enhancing product performance, their durability has resulted in them being dubbed ”forever chemicals,” due to their persistence in the environment [2].

In response to growing concerns about the environmental and health impacts of PFAS, major manufacturers have gradually phased out the production of certain long-chain PFAS compounds since the early 2000s. These efforts mark a critical step in reducing the release of these persistent chemicals into the environment. Perfluorooctanoic acid (PFOA) due to its usage in cookware, was one of the major targets of the early regulations. The European Union (EU) began regulating the compound in 2008 and finally banned it in 2020. The Stockholm Convention, a global health treaty between 186 countries, banned PFOA usage worldwide in 2020 [5].

PFOA and Perfluorooctane sulphonic acid (PFOS), the PFAS regulated the earliest worldwide, belong to the ”C8-chain” (8 carbons in the chain), making them more persistent and long-lasting in the environment. Manufacturers started using ”short-chain” (6 carbons or lower) [6] alternatives for these C8-chain substances. Though they were expected to be less hazardous, the reality was quite the opposite. Recent studies have found that shorter-chained PFAS can be as toxic to animal and human health as long-chained PFAS [1]. The Danish Environmental Protection Agency stated the presence of these short chains in human tissues can be worrying [1]. This leads to the worldwide call to regulate PFAS than to find substitutes that can be more harmful than the original compound.

The population encounters PFAS through food, drinking water, and house dust, resulting in its presence in the blood. While PFOS and PFOA have been linked to negative health outcomes, the effects of many other PFAS on human health remain yet to be studied [7]. Some communities, particularly those in contaminated areas, may experience higher levels of PFAS exposure. They bioaccumulate in the body and can take many years to be eliminated.

According to the European Food Safety Authority (EFSA), in 2018, food was a significant source of PFAS exposure. Food contributed to 67–84% of the median total PFOA intake and 88–99% for PFOS. Drinking water also contributes to PFAS intake, with median relative contributions varying between 0.57% and 0.68% for PFOS, and 9.1% and 11% for PFOA. These exposure pathways highlight the importance of monitoring and managing PFAS contamination in both food and water sources [8].

Exposure to persistent PFAS has been linked to several adverse health effects, including kidney and testicular cancer, ulcerative colitis, pregnancy and fertility problems, liver diseases, thyroid diseases, and elevated cholesterol levels. Additionally, prenatal exposure to PFAS has been associated with low birth weight, which can lead to higher risks of cardiovascular illness, respiratory disease, diabetes in adulthood, poor cognitive development, and reduced performance throughout a person’s lifespan [9].

PFAS exposure is also associated with immunotoxic effects, such as decreased antibody response to vaccination [10] which was used by EFSA as a basis to set a Health-Based Guidance Value (HBGV) for the Tolerable Weekly Intake (TWI) of 4.4 nanograms per kilogram of body weight per week [11]. The value referred to as EFSA-4, encompasses the sum of four PFAS: PFOS, PFOA, PFNA, and PFHxS [11].

The Dutch National Institute for Public Health and the Environment (RIVM) has extended the EFSA guidelines to include 23 PFAS compounds, referred to as PFAS-23 in the rest of the report, (mentioned in Table 1.1 found in drinking water), suggesting a nationwide guideline of 4.4 ng PEQ (PFOA equivalent)/L. However, the legacy of past usage continues to present significant remediation challenges [12].

Many drinking water treatment technologies are unable to remove PFAS from water effectively. Membrane filtration technologies like reverse osmosis are effective but are expensive and energy-intensive [13]. Activated carbon adsorption and ion exchange are widely used methods in drinking water treatment plants [14]. This paper will focus on activated carbon adsorption to remove PFAS from water. PFAS are a relatively new pollutant and research into their negative health impacts and the technologies to eliminate them from water is ongoing.

While the EU and the Netherlands have conducted extensive studies on the more common types of PFAS, regulating and restricting them, there is still a gap in knowledge about the viability of the newly suggested 4.4 ng PEQ/L limit [12]. Concerns remain regarding the health implications, the capacity of carbon adsorption systems, financial costs, and sustainability, especially for drinking water companies.

The main research question of this study is how the decrease in health risks due to lower PFAS exposure using Disability Adjusted Life Years (DALYs) as a tool compares against the associated negative health impacts of the required drinking water treatment technologies to reach the new guideline. This complex issue is not just a scientific or technical challenge but also an ethical one, demanding careful consideration of various moral and social dimensions.

The primary objective of this research is to evaluate the overall health impact, expressed in terms of DALYs, of implementing the proposed drinking water limit of 4.4 ng PEQ/L for PFAS-23. The goal is to assess whether the reduction in DALYs due to lower PFAS exposure outweighs the negative health impacts, measured in DALYs, from the treatment technologies. These considerations have been translated into the following research question:

“How does the decrease in DALYs attributable to a lower PFAS exposure compare against the associated negative health impacts of granular activated carbon filtration, when PFAS-23 concentrations in drinking water are reduced to 4.4 ng PEQ/L in the Netherlands?”

To answer this question, the following steps will be taken:

1) Quantify the health gain by estimating the DALYs associated with reducing PFAS-23 concentrations in water to the 4.4 ng PEQ/L guideline.

2) Quantify the DALYs lost because of the impact of granular activated carbon filtration required to reduce the concentration according to the suggested limit of 4.4 ng PEQ/L using an LCA.

3) To compare these ranges and identify whether reducing the guideline is worth it in terms of DALYs.

The report is structured as follows: the first chapter provides the background of the research, including an explanation of the development of guidelines by DWD, EFSA, and RIVM, and how they are interconnected. The second chapter outlines the research methodology. Chapters three, four, and five present the results, discussion, and conclusion, respectively. Ethical considerations related to this research are addressed in the discussion chapter.

1
Background

1.1. PFAS limits

The European Drinking Water Directive

On January 12, 2021, the new European Drinking Water Directive (DWD) (Directive (EU) 2020/2184) came into force, setting updated standards for the quality of water intended for human consumption across member states. Among its provisions, the DWD introduced two parametric values specific to PFAS, marking a significant step in regulating these contaminants in drinking water.

The DWD establishes the minimum quality requirements for water intended for human consumption. In this DWD, PFAS are assessed as a group and evaluated based on two key parameters:
1) A parametric value of 100 ng/L for the “Sum of PFAS” which is a selection of twenty PFAS (PFAS-20) that are considered harmful in water intended for human consumption according to DWD. The EFSA-4 are also included in this list.
2) A parameter value of 500 ng/L for the “PFAS total”, the total of all PFAS, for which an analytical method remains to be determined [12].

On January 12, 2024, the European Commission issued technical guidance on analytical methods for monitoring ”total PFAS” or the ”sum of PFAS” in drinking water [15]. This guidance establishes parameters such as detection limits and sampling frequencies to ensure consistent monitoring across European member states. Under the European DWD, member states are mandated to adopt measures by January 12, 2026, to ensure that water intended for human consumption meets the specified parameter values for PFAS [12]. This directive aims to safeguard public health by regulating and reducing PFAS levels in drinking water.

From 2026 onwards, drinking water must undergo regular assessments to ensure compliance with the directive’s PFAS parameter values. If PFAS levels exceed these limits, measures should be implemented to remove them from drinking water sources. Moreover, data collected through monitoring efforts under the DWD will facilitate tracking and management of PFAS pollution in European water systems [12].

Understanding the study by Abraham et al.

The CONTAM Panel’s (Panel on Contaminants in the Food Chain) assessment highlighted that serum levels of PFAS are typically higher in breastfed children at 1 year of age compared to 5 years of age. The panel used a Benchmark Dose Lower Confidence Limit ($BMDL_{10}$) to estimate the daily intake by mothers that would result in a critical serum concentration in breastfed children at 1 year of age. These intake estimates were then utilized to derive HBGVs for specific PFAS compounds, including PFOA, PFNA, PFHxS, and PFOS [16]. These HBGVs were later translated into TWI values in Section 1.1.

HBGVs play a crucial role in regulatory frameworks by providing thresholds for safe exposure levels, particularly for vulnerable populations such as infants exposed to PFAS through breastfeeding. These values inform health risk assessments and guide policy decisions to mitigate PFAS exposure and protect public health [16].

Abraham et al.[10], examined the relationship between certain PFAS levels in infants’ blood and their antibody levels against diseases like Diphtheria, Tetanus, and Haemophilus influenzae type b (Hib). The study involved 101 infants born between 1997 and 1999 in Germany, of which 21 were primarily formula-fed, and 80 were breastfed for more than four months. For those breastfed, the median duration was about 7.4 months, considering both exclusive and partial breastfeeding.

Four PFAS types were measured in the blood of infants and their mothers: PFOS, PFOA, PFNA, and PFHxS. The key findings indicated that breastfed infants had higher PFAS levels in their blood compared to formula-fed infants, while mothers who breastfed had lower PFAS levels than mothers who did not breastfeed. This suggests a transfer of PFAS from mother to baby through breast milk, with PFOA being transferred more efficiently than PFOS, resulting in higher PFOA levels in infants.

The study also derived a BMDL_{10} increase of 17.5 ng/mL for the combined PFAS (PFOA, PFNA, PFOS, PFHxS), signifying the serum concentration below which adverse effects on antibody levels are unlikely. This threshold is critical in risk assessments, guiding regulatory decisions to limit exposure levels that could potentially affect immune responses in infants.

This research is crucial for understanding the transfer of PFAS through breastfeeding and its implications for infant health. It also plays a pivotal role in shaping drinking water standards, such as those recommended by EFSA, to ensure public safety in environments with PFAS contamination.

Updated PFAS limit by the European Food and Safety Authority

The EFSA derived a TWI of 4.4 ng/kg body weight per week for the sum of EFSA-4, which includes PFOS, PFOA, PFNA, and PFHxS. This TWI is based on a critical daily intake of 0.63 ng/kg body weight per day. The starting point for EFSA's assessment was a blood serum level of 17.5 ng/mL for the sum of EFSA-4 in children exposed through breastfeeding for 1 year [17]. Toxicokinetic models were used to convert the serum concentration into a weekly exposure level. Abraham et al [10] study indicates that concentrations above this level in blood serum could potentially impact children's immune function [10].

To determine safe long-term exposure levels for adults, EFSA considered the transfer of PFAS from food consumed by mothers to their blood serum, and subsequently through breast milk to the child's body and blood serum. This analysis used data on PFAS uptake and distribution in both the bodies of mother and child, ensuring that adult dietary intake levels do not elevate PFAS concentrations in breastfed infants to levels associated with adverse health effects [16].

EFSA chose a health-based limit for PFOS, PFOA, PFNA, and PFHxS. These PFAS were assessed as the sum because EFSA assumes that these four PFAS cause the same critical effect and because these are the main PFAS found in human blood. The EFSA-4 are not necessarily the relevant PFAS for other exposure pathways, environmental compartments, and policy frameworks. Current analytical methods detect about 10 to 20 different PFAS in soil, groundwater, surface water, and food. These other PFAS also contribute to the toxicity of the overall mixture to varying degrees. Therefore in practice, there is a need for methods to assess a broader group of PFAS than just the EFSA-4. Conversely, individual risk limits or standards may be needed in certain situations. For example, if the EFSA-4 do not all occur or have been measured. The PFAS parameter values in the new DWD are not aligned with the EFSA opinion on the risks of PFAS in food [12].

Concerns regarding EFSA-TWI

As mentioned above, EFSA-based TWI on Abraham et al. [10] which shows that PFAS found in the blood serum consists of 90% of these four PFAS. Only an association between PFOA and its effect on the immune system was found. The study used blood samples taken in the late 1990s. Other PFAS were analyzed but were not detected. However, EFSA does not exclude that this effect may also have been caused by the other three PFAS.

EFSA calculated the amount that adults should be allowed to ingest on a long-term daily basis without the blood serum of breastfed children exceeding the critical value for immune effects reached. EFSA assumes that at the serum concentration level, the four selected PFAS are each equally potent and their effects add up. EFSA-TWI depends on the ratio of PFOA and PFNA to PFOS and PFHxS. This means that the EFSA-TWI is theoretically only applicable to mixtures that have the same mixture ratio as the ratio in the study by Abraham et al. [10] on which EFSA-TWI is based [18].

EFSA additionally assumes that the four PFAS can cause immunotoxicity in equal proportions and are considered equipotent at the serum level. However, EFSA also assumes differences in toxicokinetics between PFOA and PFNA and PFOS and PFHxS which means that the external doses may not be equipotent. Nevertheless, EFSA recommends using the sum of the four PFAS without considering internal or external potency differences.

EFSA indicates that for immune effects, it has not been able to derive Relative Potency Factors (RPFs), the method used by RIVM (see below in Section 1.1), due to a lack of suitable studies and therefore adopts equipotentiality as a pragmatic choice.

Another main concern is that EFSA left out a large number of other PFAS due to the lack of information on the effects on the immune system. However, these PFAS contribute to external exposure that is unaccounted for in the EFSA guideline. Focusing on only EFSA-4 can lead to an underestimation of risk in situations that involve exposure to other PFAS as well [17].

The National Institute for Public Health and the Environment

The National Institute for Public Health and the Environment (RIVM) provide advice based on science and research to the Dutch Government to make beneficial and informed policies in the fields of public health and environment [19]. The RIVM has developed a new guideline for drinking water to reduce exposure to the public and the environment. The drinking water guideline value which was based on the EFSA-4 TWI, was derived from a health-based limit value in the form of a TDI (Tolerable Daily Intake). Based on the TDI, the maximum concentration allowed in drinking water without expected adverse effects on human health is then calculated [20].

The panel decided to use the daily intake of 0.63 ng/kg bw per day as the starting point and established a group tolerable weekly intake (TWI) of 70 x 0.63 = 4.4 ng/kg bw per week for the sum of PFOA, PFNA, PFHxS and PFOS. It was determined that no extra uncertainty factors were necessary since the $BMDL_{10}$ is derived from studies on infants, a group typically considered sensitive to immunotoxic chemicals. Moreover, a reduced response to vaccination is viewed as a risk factor for disease, not as a disease itself.

In the Netherlands, it is assumed that a seventy-kilogram adult drinks two litres of water daily. Based on the EFSA-TWI of 4.4 ng/kg body weight per week, the TDI is 0.63 ng/kg body weight per day. The contribution of drinking water to the TDI is set at 20% as a default by the WHO. This considers the possibility that people can also ingest a substance through other routes such as food, and a 20% contribution is considered a reasonable level of exposure through drinking water. Based on these values, the drinking water guideline for EFSA-4 becomes as given below:

0.63 (ng/kg body weight/day) x 70(kg) x 0.2/2 L = 4.4 ng/L

The diagram below shows the connection made from the guidelines of different organizations to reach the guideline of 4.4 ng/L.

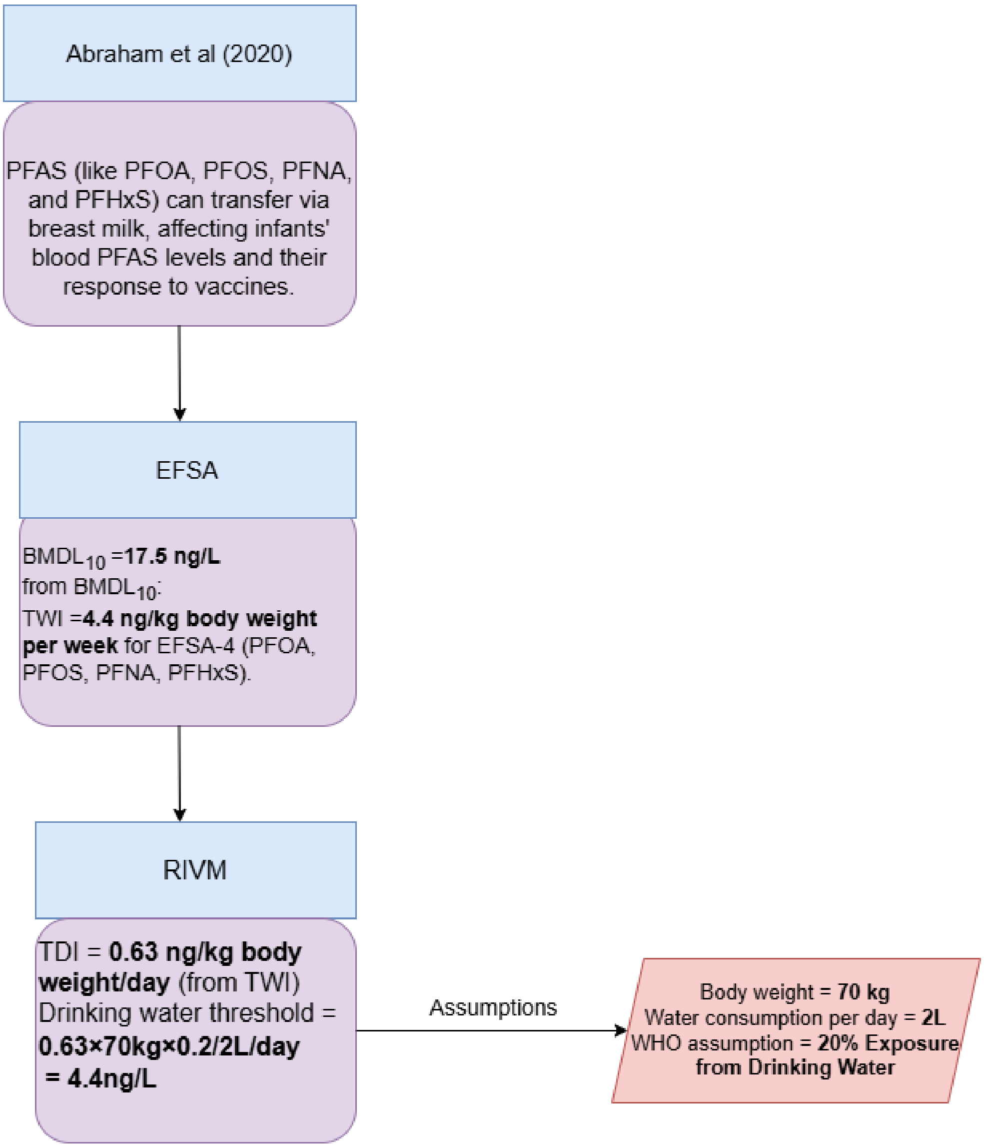

Figure 1.1: The different steps and the assumptions made to set the guideline of 4.4 ng/L.

RIVM used the EFSA opinion as a starting point and considered several options for assessing individual PFAS and PFAS mixtures based on the EFSA-TWI. Considering the concerns of EFSA-TWI, RIVM wanted to come up with a widely applicable method that:
1) Applies to the EFSA-4 as well as those that were not considered.
2) PFAS mixtures with different ratios and differences in potency between PFAS can be assessed.
RIVM chose RPFs as the option that best meets the above points. It is also conceptually simple and practically applicable [17].

In 2018, RIVM developed RPFs to assess the toxicity of individual PFAS relative to PFOA, expressed PEQ [20]. This approach uses PFOA as the index substance with an RPF of 1, based on the previous intensive studies done on the compound. The RPFs range between 0.001 and 10, indicating that individual PFAS can be up to 1000 times less or 10 times more toxic than PFOA. By multiplying the concentrations of individual PFAS by their RPFs, these concentrations can be converted into their PEQ concentrations.

Liver toxicity in rodents, manifested by liver hypertrophy (hepatocellular, centrilobular) and liver enlargement (absolute and relative liver weight), was selected as the critical effect for deriving RPFs for 23 PFAS compounds. For PFAS lacking experimental animal data on this endpoint, a read-across approach was used. Read-across is a technique for predicting the endpoint information for the target substance by using the data from the same endpoint of the source substance [21]. The assessed PFAS and their respective RPFs are detailed in Table 1.1 [12].

The RIVM guideline for PFAS is set at 4.4 ng/L PEQ using RPFs [20]. This value represents the sum of PFAS concentrations in a sample, expressed as equivalents of PFOA.

However, the RPF method has limitations. The RPFs are derived based on liver effects in rats, whereas EFSA's perspective is that immune effects cannot be reliably extrapolated from these liver-based RPFs [17]. EFSA notes the uncertainty regarding a common mechanism of action for immune and liver effects among PFAS. Additionally, RPFs do not account for potential differences in PFAS distribution between milk and serum.

Despite these drawbacks, RIVM contends that incorporating relative potencies of PFAS is more scientifically sound than assuming all PFAS have equal toxicity, as done by EFSA. While imperfect, the RPF approach is believed to provide a more accurate estimation of risk by considering potency variations among PFAS and allowing for the inclusion of multiple PFAS in risk calculations.

Table 1.1 below gives a list of PFAS-23 with their RPF values [12]

Table 1.1: The list of PFAS-23 with their RPF values [12]

	PFAS	PFAS abbreviation	RPF
1	Perfluorobutane sulphonic acid	PFBS	0.001
2	Perfluoropentane sulphonic acid	PFPeS	0.6
3	Perfluorohexane sulphonic acid	PFHxS	0.6
4	Perfluoroheptane sulphonic acid	PFHpS	2
5	Perfluorooctane sulphonic acid	PFOS	2
6	Perfluorodecane sulphonic acid	PFDS	2
7	Perfluoroundecane sulphonic acid	PFUnDS	NA
8	Perfluorododecane sulphonic acid	PFDoDS	NA
9	Perfluorotridecane sulphonic acid	PFTrDS	NA
10	Perfluorobutanoic acid	PFBA	0.05
11	Perfluoropentanoic acid	PFPeA	0.05
12	Perfluorohexanoic acid	PFHxA	0.01
13	Perfluoroheptanoic acid	PFHpA	1
14	Perfluorooctanoic acid	PFOA	1
15	Perfluorononanoic acid	PFNA	10
16	Perfluorodecanoic acid	PFDA	10
17	Perfluoroundecanoic acid	PFUnDA	4
18	Perfluorododecanoic acid	PFDoDA	3
19	Perfluorotridecanoic acid	PFTrDA	3
20	2,3,3,3-tetrafluor-2-(heptafluoropropoxy)propionic acid	GenX	0.06
21	Ammonium 4,8-dioxa-3H-perfluornonanoate	ADONA	0.03
22	1H,1H,2H,2H-perfluorooctanol	6:2 FTOH	0.02
23	1H,1H,2H,2H-perfluorocarbonol	8:2 FTOH	0.04

Table 1.1 includes all RPFs known to date that can be used for testing drinking water samples. For PFAS where RPFs cannot be directly derived due to insufficient data, RIVM extrapolates from related PFAS data to estimate the likely potency range, adopting the highest value for protective purposes. Branched PFAS, for which toxic potency data are scarce, are assumed to have equal potency to their linear counterparts, using the same RPF. Updates to the list of RPFs are anticipated as new data becomes available or if revisions are warranted based on emerging information [12].

Many PFAS in the environment lack RPFs due to a lack of liver toxicity data. Some of these substances degrade over time, transforming into other PFAS. For instance, perfluorooctane sulfonamide (PFOSA) degrades to form PFOS as a degradation product [17].

In addition to deriving an indicative drinking water guidance value, RIVM also made an indicative calculation of total exposure to the EFSA-4 from food and drinking water in the Netherlands. The total weekly intake of EFSA via food and drinking water combined in the Netherlands exceeds the EFSA-derived health threshold [17].

The contribution from food is greater than from drinking water, it is estimated that the average Dutch person ingests about 2% of EFSA-4 through drinking water if produced from groundwater and 17% if produced from surface water. In both cases, it is less than the 20% that is assumed in the derivation of the drinking water limits. This varies per person and location in the Netherlands, depending on individual consumption patterns and concentration of PFAS in local drinking water [17].

1.2. Human health risk assessment

DALYs are a temporal indicator which is the sum of the years lost due to premature mortality and the years of healthy life lost due to a disability caused by a specific disease in a population. Simply put, one DALY indicates the loss of one whole year of health [22].

DALY can be calculated using the formula given below:

$$DALY = YLD + YLL \tag{1.1}$$

where YLD is the *years lived with disability* and YLL is *years of life* lost prematurely due to the disease [22].

The equations for YLD and YLL and how they are used for calculation will be explained in Section 2.1. The life expectancy in the Netherlands in 2023 was 82.78 years which was used to do the calculations in the methodology. These equations will be used to calculate the DALYs for Diphtheria, Hib and Tetanus in the methodology. DALY is a health indicator that can be used in policy-related discussions [23]. It is a more comprehensive and standardised indicator that different organisations can use to compare several datasets.

Earlier Research quantifying health effects in DALYs

The study "Estimating the Burden of Disease Due to Lead, PFAS, Phthalates, Cadmium, Pyrethroids, and Bisphenol A Using HBM4EU Data [9]" uses biomonitoring data to estimate the DALYs associated with exposure to PFAS and other environmental pollutants. The application of biomonitoring data to estimate the disease burden helps contextualize the potential health effects of PFAS at a broader scale, providing a benchmark for comparing the health impacts which has been used in this thesis.

There are some indications of an effect of PFOA exposure on the kidneys resulting in increased uric acid concentrations in blood which may influence blood pressure [9]. According to the EFSA, there is no clear association between exposure to PFOS and PFOA and cardiovascular effects such as hypertension. However, the data in Table 1.2, based on research from Belgium, is assumed to be similar to data that would be available from the Netherlands due to similar lifestyles and contamination levels [9].

Table 1.2: DALYs per 1,000,000 persons due to exposure to PFOA and PFOS in Belgium in 2021, as found by Plass et al [9]

		Central Estimate	**Lower Estimate**	**Higher Estimate**
PFOA	Hypertension	89	28	158
	Small gestational age and IQ loss	284	0	553
PFOS	Hospitalization due to lower respiratory infections	8	2	12
	Total	381	30	723

This was the first step taken to analyze the problem based on the limited research linking PFAS exposure to human health. The diseases that have been linked to PFAS exposure in this study have limited scientific backing. They are just associated risks that may occur due to PFAS exposure.

DALYs from the National Immunization Report
In trying to understand the development of the EFSA and RIVM guidelines for PFAS contamination in drinking water, it was found that the guidelines were based on preventing a lower antibody response to Diphtheria, Tetanus, and Hib. This concept is used in the research to identify the DALYs related to PFAS exposure moving forward.

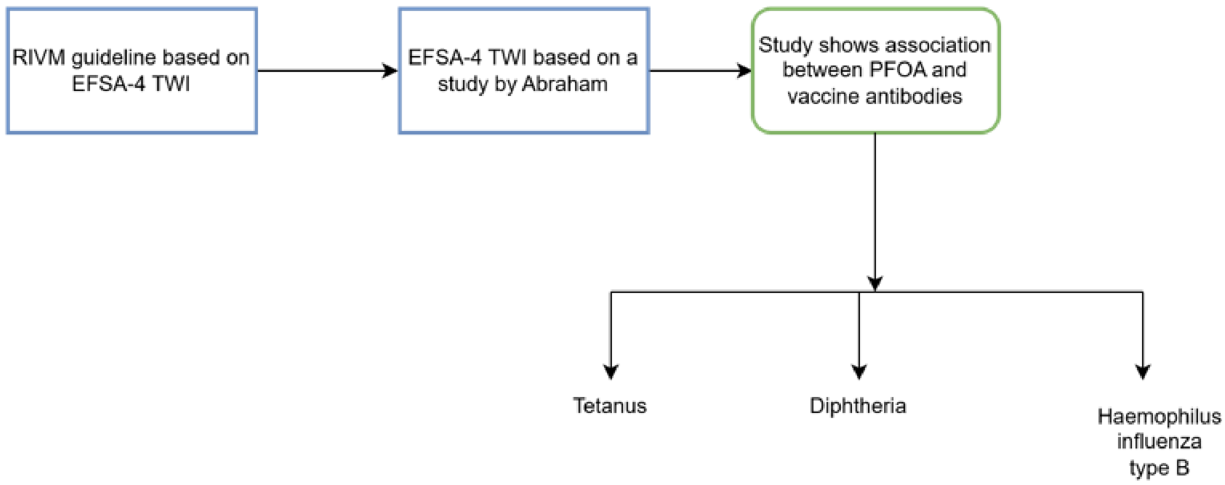

Figure 1.2: The link between the RIVM guideline to the three diseases used in the methodology of this research.

Vaccination of a large part of the population of the Netherlands against Diphtheria and Tetanus was introduced in 1952. Since December 2008, Hib has also been included in the vaccine program [24].

The RIVM maintains extensive records on mortality and hospitalisation cases caused by these diseases, documented annually in The National Immunization Report in the Netherlands [24] as mentioned in Appendix A.

1.3. Waternet

Waternet is a water company in charge of water management for the city of Amsterdam and is the regional water authority of Amstel, Gooi, and Vecht. [25]. The company provides the city of Amsterdam and some surrounding municipalities with drinking water (95 million m^3/year), of which 70% is produced at the Leiduin drinking water treatment plant [26] on which the case study for this research is conducted. Waternet estimates 141 L per person per day (L/p/d) consumption in Amsterdam; 9% higher than the national average of 128 L/p/d [27].

The company initially supplied drinking water from groundwater from dunes west of Amsterdam, which was extracted and provided after treatment. When the lowering of groundwater tables was confirmed, the dunes were recharged with pretreated water from the River Rhine over 55 km to maintain the hydrological balance in the dunes [28].

The water, extracted from the dunes, is treated in the Leiduin plant. With an annual production capacity of 70 million m^3, this surface water treatment plant focuses on removing organics, hardness, pathogens, micropollutants, pesticides and nutrients. In The Netherlands, chlorine disinfection treatment is no longer acceptable because of the formation of disinfection by-products caused by chlorine and organics. Therefore, the pretreatment is carried out in Niuewgein, using River Rhine water and coagulation/sedimentation/filtration. Then this water is transported to the dune area west of Amsterdam for artificial recharge. The post-treatment process after aquifer recharge in the dune area consists of aeration, rapid sand filtration (RSF), ozonation (O_3), softening, granular activated carbon (GAC) filtration and slow sand filtration (SSF). The backwash water from the rapid sand and carbon filters is treated and returned to the aeration [28]. The flow chart is shown in the figure given below:

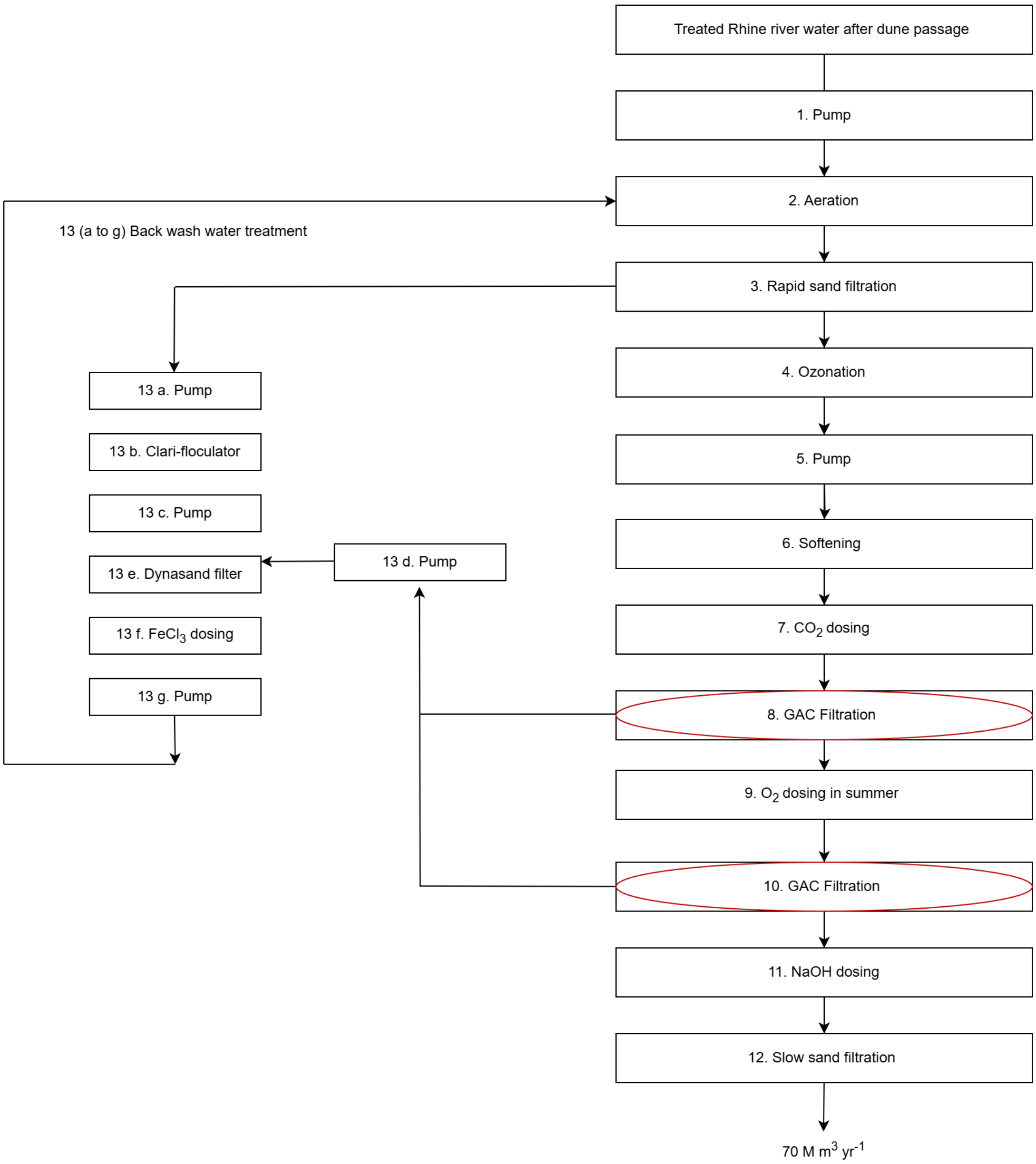

Figure 1.3: An overview of Leiduin's treatment scheme. The steps encircled in red are used for PFAS removal [28].

Waternet meets the legal requirements of the Dutch Drinking Water Act (100 ng/L). However, Waternet does not meet the guideline of 4.4 ng PEQ/L proposed by RIVM.

Several improvements and standardisations in treatment techniques have been implemented to get closer to the goal of 4.4 ng PEQ/L. In the drinking water treatment process, Waternet has activated carbon filters at its disposal to remove PFAS effectively. Activated carbon filters can adsorb organic compounds like PFAS and effectively remove them from water. The removal varies by substance and depends on the properties of each PFAS compound, such as functional group and molecular size. When a fresh activated carbon filter is used, almost all PFAS are removed but when it gets saturated over time, removal does not proceed well and the concentration of PFAS in effluent gradually increases [29].

In 2022, Waternet studied a reliable and comprehensive dataset of results at various points in the source, treatment, and drinking water. The activated carbon filters were placed between the rapid filters and the drinking water measurement point. At the last measurement point, the net effect of activated carbon filters could be found. The values in the table below are based on measurements of PFAS-20(excluding GenX and ADONA) concentrations in drinking water from 2022 [29].

Table 1.3: PFAS concentrations at different stages of the treatment in the Leiduin water treatment plant, including guideline values [29]

	ng PEQ/L	ng/L
Source (Lek Canal)	9.6	23.6
After dune passage	14.7	30.7
Drinking Water	10.0	29.2
Guideline values	4.4 (RIVM)	100 (DWR-standard)

The Leduin site has an average concentration of 10 ng PEQ/L of PFAS in drinking water because the source is surface water. This value is based on the samples taken in 2022 and it needs to be reduced to 4.4 ng PEQ/L to meet the future regulations proposed by RIVM [29].

Leiduin site - Using GAC for PFAS removal

Different treatment options have been examined to reduce the levels of PFAS in drinking water. Quiñones et al. [30] reviewed the effectiveness of various treatment processes in full-scale water treatment systems, including filtration, ozonation, coagulation/flocculation, and chlorination, for removing PFAS. The study found that all tested treatment combinations were largely ineffective, showing little to no reduction in PFAS levels [15]. Similar findings were reported by Appleman et al. [31], who also noted that other treatment methods, such as reverse osmosis, activated carbon, and anion exchange (AE), have demonstrated the ability to lower PFAS levels in drinking water [31].

GAC was chosen for the Leiduin site as this process step is already present at Leiduin since 1995. GAC is an organic carbon filtration media that removes organic contaminants from liquids and gases [32]. It is a treatment technology that also improves the taste and removes odour from water. It works through a process called ”physical adsorption”. The adsorptive quality is what makes it ideal for removing contaminants [33]. Adsorption is the accumulation of a substance in a solution onto a surface.

The degree of removal of PFAS from water depends on the time between reactivations of the activated carbon. Reactivation is the process of restoring the adsorbent capacity of the carbon [34] by burning off the adsorbed contaminants. During reactivations, a part of the carbon is burnt off and replenished by new carbon. So frequent reactivations can be attributed to a higher financial and environmental impact [34].

Due to the presence of PFAS in the surface water used as a raw water source, the reactivation needs to be shorter than under normal operations. The time between two reactivations used to be 3.3 years. In 2023, the time was calculated to be 1.5 years on average and in the future scenario of achieving 4.4 ng PEQ/L, it was estimated to be 0.5 years on average [34]. Based on the July 2023 report by A.M Motelica [29], in a future scenario where the guideline of 4.4 ng PEQ/L is met, the CO_2 impact for Leiduin is four times higher than the situation in 2023.

1.4. Life Cycle Assessment

Life Cycle Assessment (LCA) is a tool used to evaluate the environmental impacts throughout a product’s lifecycle, including water treatment technologies [35]. In recent years, LCAs have been applied to PFAS removal technologies, which are essential for mitigating harmful per- and polyfluoroalkyl substances in water.

LCA studies have primarily focused on the environmental burdens of processes like GAC, ion exchange, and reverse osmosis. These processes aim to reduce PFAS concentrations from contaminated water sources to safe drinking levels.

A study by Rahman et al.[36] reviewed the effectiveness and environmental implications of various PFAS removal processes [36]. They found that GAC adsorption is widely used due to its effectiveness in removing longer-chain PFAS. However, the production and reactivation of activated carbon significantly contribute to environmental impacts because of high energy consumption and associated emissions [36].

In particular, GAC treatment can be energy-intensive due to the periodic need for carbon reactivation, which contributes significantly to greenhouse gas emissions.

The LCA in this research is conducted using SimaPro software, utilizing the Ecoinvent 3 database. The functional unit is defined as 1 cubic meter (m^3) of treated water, providing a standardized basis for assessing environmental impacts per unit of water treated.

2 Methodology

Fig. 2.1 explains the methodology followed to address the research question. The approach is divided into two main sections. The first section quantifies the DALYs lost due to exposure to PFAS from drinking water, specifically associated with the three diseases outlined in Chapter 1. The second section evaluates the DALYs lost due to the impact of water treatment technology that will be used to get the required future guideline of 4.4 ng PEQ/L at the Leiduin drinking water treatment plant of Waternet.

By comparing these DALYs, the research aims to determine whether reducing the guideline to 4.4 ng PEQ/L benefits human health. The comparison to tolerable targets is also key for decision-making.

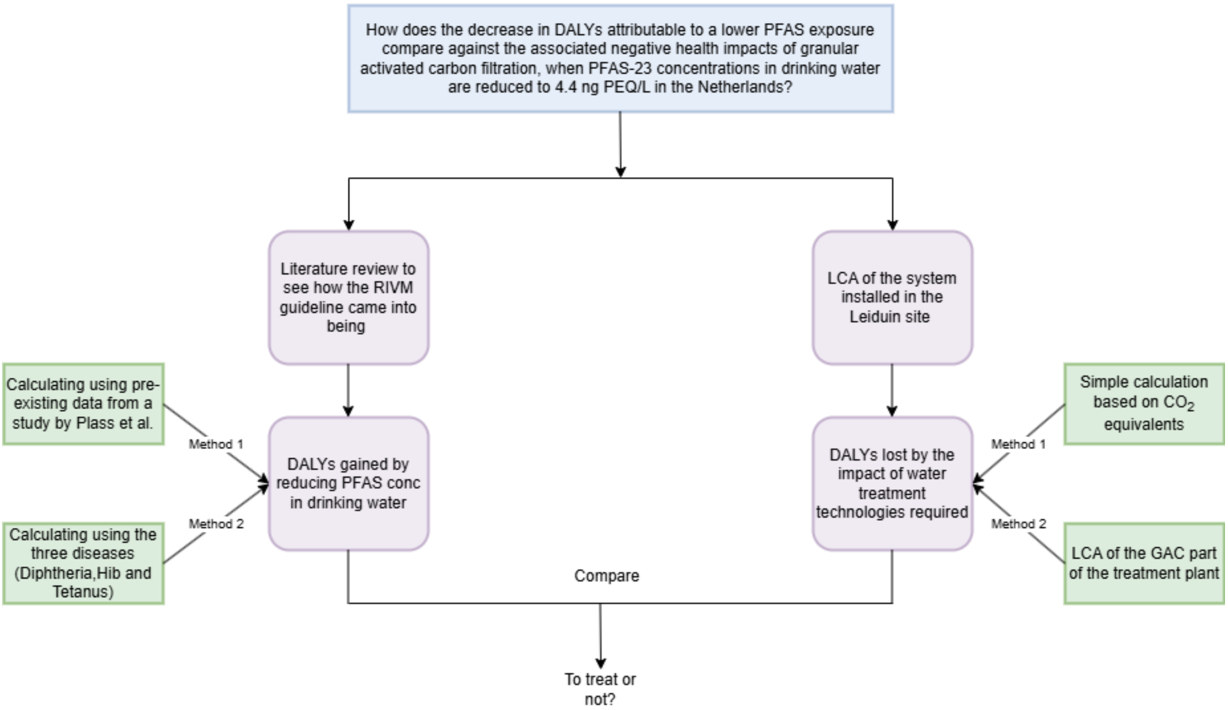

Figure 2.1: A flowchart to describe the methodology followed to answer the research questions

2.1. Health Impacts of Reduced PFAS Concentration

Estimation Method 1 - Using the Plass et al. study

Using the data available from Plass et al. [9] which was mentioned in Table 1.2, the DALYs related to health impacts and DALYs lost due to water treatment at Leiduin were calculated by using the steps mentioned below:

$$R_p = 1 - \frac{P_c}{C_c} \tag{2.1}$$

where removed PFAS (R_p) is the fraction of PFAS removed from the drinking water, and P_c is the prospective concentration of 4.4 ng PEQ/L after updating the treatment system. C_c is the current PFAS concentration in the produced drinking water at the Leiduin site which is 10 ng PEQ/L.

R_p was calculated to be 56% from Eq. (2.1). The fraction of PFAS exposure that may come from drinking water as stated by WHO is 20%. The equation below used these values to find the DALYs due to reduced PFAS exposure.

$$D_r = R_p \times P_{dw} \times DALY_{pl} \tag{2.2}$$

where D_r is the DALYs reduced by removing PFAS, R_p is the percentage of PFAS removed by the treatment system calculated from Eq. (2.1),P_{dw} is the WHO limit of PFAS that may come from drinking water and $DALY_{pl}$ is the total DALYs from PFAS based on Plass et al. [9] which is given in the table below. The values in the table below are the sum of DALYs per 1,000,000 persons for three suggested effects caused by PFAS exposure mentioned in Table 1.2 for lower, central and upper values respectively. The lower, central and upper values are taken from people in Belgium.

Table 2.1: The DALYs estimated using data from Belgium in 2021, as reported by Plass et al. [9]

	Total DALYs due to PFAS exposure per 1,000,000 people in 2021
Lower	30
Central	381
Upper	723

Assumptions made:
-The Plass et al. study [9] is based on data from Belgium. It is assumed that the data from the Netherlands would be similar.
-The data from the Plass et al. [9] study is from 2021 while the rest of the data used in this report is from 2023. While this does not cause a big change, it is something to be noted.
- The WHO limit for PFAS exposure from drinking water is 20%. In reality, it may differ based on person and location, but this WHO limit has been used for the calculation in this study.

Estimation Method 2 - DALYS for the three aforementioned diseases specific to the Netherlands:
As mentioned in Section 1.2, DALYs can be mathematically represented as shown below:

$$DALY = YLD + YLL \tag{2.3}$$

where YLD indicates the years lived with disability and YLL describes the years of life lost prematurely due to the disease [23].

$$YLD = I \times L \times DW \tag{2.4}$$

where I is the incidence rate, L is the average duration of the disability given in years and DW is the Disability Weight [23].

$$YLL = N \times L_e \tag{2.5}$$

where N is the number of deaths due to the disease and L_e is the life expectancy at the age of death [23].

The study conducted by Abraham et al. [10] explored the impact of PFAS exposure on the antibody response in infants against Diphtheria, Tetanus, and Hib. These three diseases were chosen as the focus of this research because the findings of Abraham et al. [10] were instrumental in forming the EFSA guidelines, which in turn were used by the RIVM to establish the 4.4 ng PEQ/L guideline.

To calculate the DALYs per 100,000 people for Diphtheria, Hib, and Tetanus, the relevant values were substituted into the formulas, as detailed in the table below. Even though most of these values have multiple decimal places, they are calculated based on assumptions.

Table 2.2: YLL and YLD values per 100,000 people per year

Diseases	I	L	DW			YLD			N	L_e	YLL
			Lower	Central	Upper	Lower	Central	Upper			
Diphtheria	0.08 [37]	0.003 [38]	0.04 [38]	0.05 [38]	0.06 [38]	0.000009	0.000012	0.000014	0.004 [39]	82.78 [40]	0.33
Hib	0.39 [24]	0.02 [41]	0.58 [41]	0.66 [41]	0.73 [41]	0.0042	0.0048	0.0053	0.02 [24]	82.78 [42]	1.61
Tetanus	0.03 [43]	0.07 [44]	0.38 [44]	0.42 [44]	0.48 [44]	0.00079	0.00088	0.00100	0.002 [45]	22.78 [45]	0.03

Assumptions made

- The data used in this table is for the general public. No assumptions were made specifically for the vaccinated public at this stage.
- Unlike Hib, the I values for Diphtheria and Tetanus were sourced from the WHO website instead of RIVM. RIVM didn't provide explicit incidence values for these two diseases in 2023. However, they matched the number of cases from RIVM with those on the WHO website after cross-referencing. Therefore, the incidence values are assumed to be the same as what RIVM would have calculated.
- The L and DW values for the three diseases were based on the symptomatic infection. It can differ if a person's health outcome is more severe or fatal. The values in the table assume that the patients are not facing life-threatening versions of these diseases.
- The N values of the diseases are not specific to the Netherlands.
- The L_e is generalised for the entire population of the Netherlands and is not specific to any gender. For Diphtheria and Hib, L_e is set at 82.78 years, the average lifespan of Dutch citizens. This value is based on the observation that even though there have not been any recent cases of death because of these diseases, in the past Diphtheria and Hib mortality rates were highest among children under five. For Tetanus, L_e the global average age of death is 60 years. The L_e has been adjusted to incorporate these factors.

2.2. Impacts of Leiduin Treatment Plant

This section compares two distinct scenarios for the Leiduin drinking water treatment plant: one with the treatment technologies used to maintain the current concentration of 10 ng PEQ/L (the "2023 scenario") and one with enhanced PFAS removal treatment technologies for the stringent guidelines of 4.4 ng PEQ/L. The 2023 scenario involves GAC reactivation every 1.5 years, while the 4.4 ng PEQ/L scenario requires reactivation every 0.5 years.

Estimation Method 1 - Calculated based on increased CO_2 emissions

Waternet calculated that the implementation of the new guideline for PFAS removal at the Leiduin water treatment site would result in an increase of 5 kton CO_{2eq}/year [20] of emissions. However, according to A. Motelica [34], this estimate may be slightly lower. These increased emissions are directly tied to the enhanced treatment processes required to meet the new PFAS guideline of 4.4 ng PEQ/L, which leads to an inadvertent rise in CO_2 emissions. Since CO_2 emissions contribute to global warming and other environmental health risks, this increase also impacts public health, which can be expressed in terms of DALYs lost.

To quantify the health burden associated with the increased CO_2 emissions, the equation below was used.

$$D_{wt} = R_{CO_2} \times V_w \tag{2.6}$$

where D_{wt} is the DALYs lost per year due to treatment,R_{CO_2} is the range of CO_2 in DALYs/kg and V_w is the calculated value from Waternet in kton CO_{2eq}/year.This helps in understanding the public health implications of Waternet's emissions.

The R_{CO_2} is a conversion factor used to translate the environmental burden of CO_2 emissions into human health impacts. It was derived from the study by Eckelman et al. [46], which links global warming, due to CO_2 emissions, to human health risks such as respiratory diseases, heat stress, and other climate change-related ailments. R_{CO_2} represents the amount of DALYs lost per kilogram of CO_2 emitted and offers a way to express the long-term health consequences of increased greenhouse gas emissions [46].

Assumptions made

- R_{CO_2} used for this calculation is not based on the Netherlands.
- This method only considers the health impacts of increased CO_2 emissions, ignoring the potential health impacts from other stages of the water treatment process.
-These emissions are not specific to the GAC part of the water treatment plant but rather the overall process. This could potentially overestimate the actual health burden directly related to PFAS removal and carbon reactivation.

Estimation Method 2 - Life Cycle Assessment

Given the limitations of relying solely on CO_2 emissions for estimating DALYs shown in 2.2, an LCA offers a more comprehensive way to quantify the broader health impacts associated with the Leiduin drinking water treatment plant.

The goal of the LCA is to understand and find the total impact of PFAS from drinking water in the Leiduin treatment plant from a life cycle perspective. The scope is narrowed to steps meant for removing the PFAS-23 in drinking water. The Leiduin treatment plant is assessed for the scenario with carbon filtration at a low reactivation frequency.

The functional unit of an LCA related to drinking water is taken as $1m^3$ of drinking water produced per year. The system boundaries define which unit processes are related to the product or process under study and should be considered in the LCA [47].

A cradle-to-gate analysis was performed. The construction and dismantling of the infrastructure of the production plant and abstraction wells (pipes, pumps, buildings, reservoirs, etc.) were left out of this project's scope. Their impact per functional unit is assumed to be small because of their long functionality time. This assumption has been used in other drinking water production LCAs [48].

This study focuses on the flow of water, activated carbon, use of chemicals and electricity as shown in the figure below:

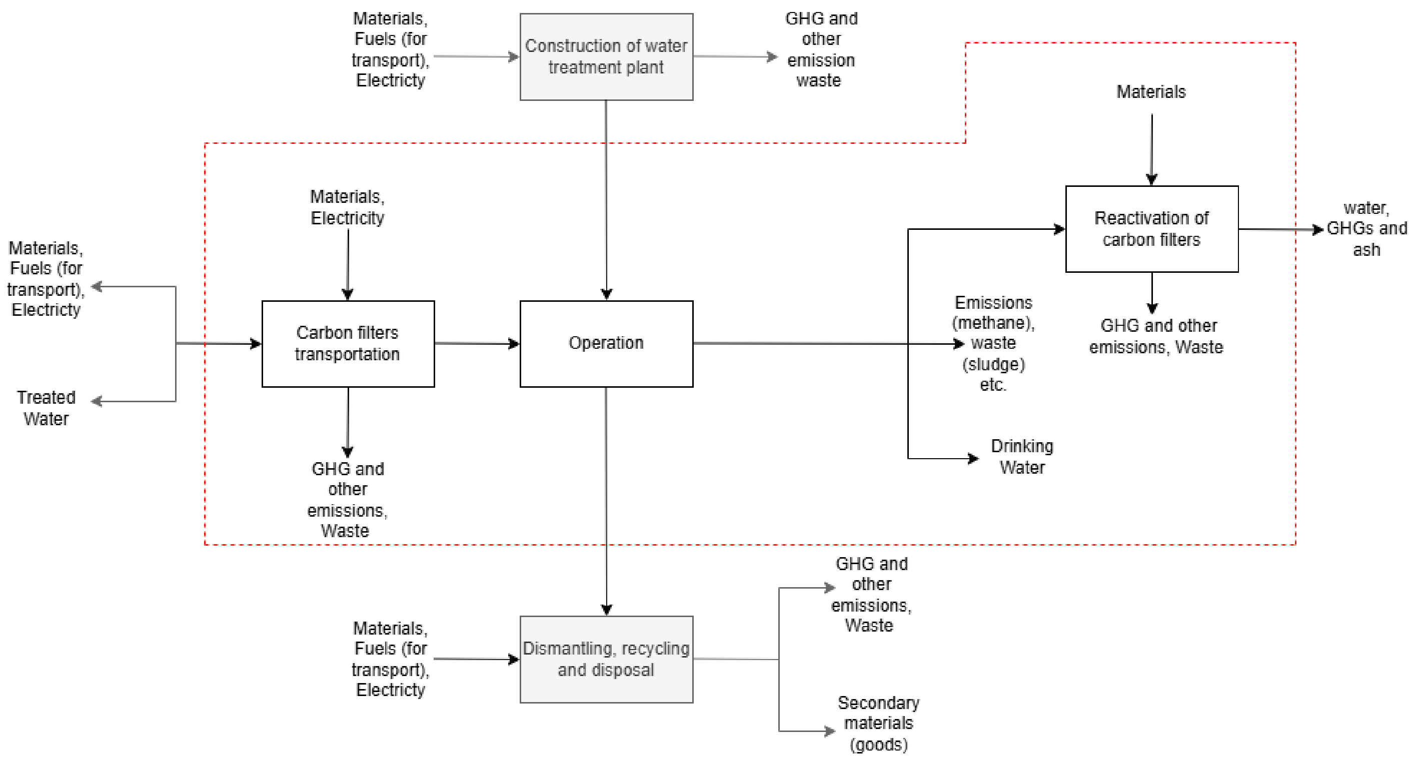

Figure 2.2: The system boundary assumptions made in this LCA [48]. The greyed-out processes are out of the project's scope.

The second step of LCA is the inventory phase. All input and output data collected in the inventory phase are normalised to the functional unit. The input and output data include using materials and energy and releases to air, land and water associated with the processes [47].

In this LCA, two scenarios are taken to compare the emissions from the system. Emissions are based on the current scenario in 2023 (with reactivation every 1.5 years) and a future scenario where the PFAS concentration in water will be reduced to 4.4 ng PEQ/L (with reactivations every 0.5 years). These scenarios will be compared to identify the DALYs solely based on the GAC treatment emissions needed to achieve the new guidelines.

The values considered in this system have been found in the literature and conversations with Waternet. Table 2.3 has the parameters inputted into Simapro to evaluate the total emissions from the treatment system.

The values listed in Table 2.3 were input into Simapro for the 2023 scenario. The ReCiPe 2016 H/H method was selected for the LCA, as DALYs were the desired endpoint indicator for this research [49]. This method follows a Hierarchist (H) principle. The Hierarchist method was used because it is based on scientific consensus and policy-oriented approaches [49]. The inputs and outputs were adjusted to the functional unit, as shown in Fig. 2.3, converting the parameters to fit the required unit of 1 m^3 (=1000 kg). The infrastructure process and long-term emissions were excluded.

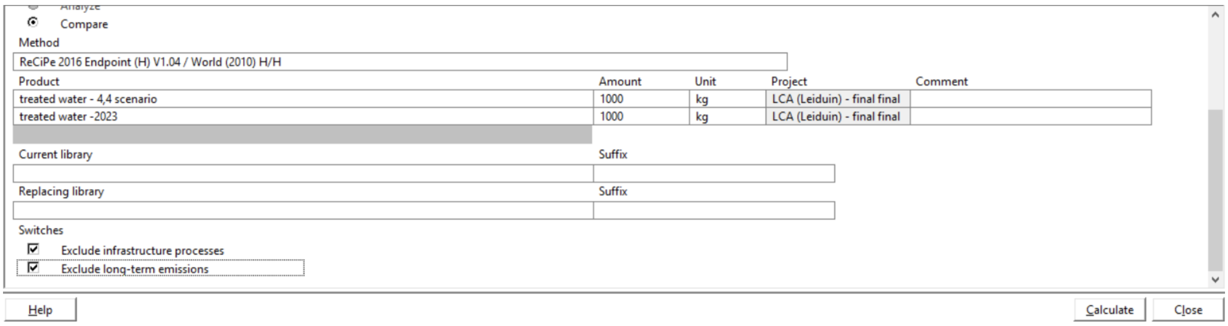

Figure 2.3: The user interface of the Simapro software shows how the functional unit was applied to the inputted values.

The input parameters below in Table 2.3 are specific to the values calculated in the Leiduin water treatment site for 2023 and Table 2.4 has estimated values for the future guideline of 4.4 ng PEQ/L. The attributional approach has been chosen since certain environmental impact has to be attached to certain products like tap water. This is done by using allocation at the point of substitution (APOS) which will be mentioned in the tables below. Table 2.3 and Table 2.4 were calculated for wood-based activated carbon, but the same values (specific to coal) were also applied to estimate the DALYs for coal-based activated carbon.

Table 2.3: Input parameters for the LCA of the Leiduin treatment process under the 2023 scenario in SimaPro with 1.5 years between reactivations

Inputs from technosphere: materials/fuels	**Amount**	**Unit**	**Source**	**Comments**
Tap water {Europe without Switzerland} market for | APOS, S	70,726,271	m^3	Waternet	Tap water is taken as the inflow because it passes through the treatment steps before reaching GAC and therefore will have the linked emissions.
Wood-based activated carbon	123	ton	Waternet	- Activated carbon new in 2023 (about 17% of the total activated carbon used in the year) - This process was made in Simapro based on data from [50] and is explained in Appendix B
Wood-based activated carbon- reactivated	716	ton	Waternet	- All the carbon is being reactivated (so the amount is the same as the output amount). - This process was also made in Simapro based on data from [50] and explained in Appendix B
Iron(III) chloride, without water, in 40% iron solution state {GLO} market for | APOS, S	5947.5	kg	Waternet	This value was added based on step 13f. as seen in the treatment process in Fig. 1.3.
Inputs from technosphere: electricity/heat	**Amount**	**Unit**	**Source**	**Comments**
Electricity, medium voltage {NL} market for | APOS, S	3,823,756	kWh	Waternet	This value is estimated by Waternet as the approximate usage of electricity specific to the GAC treatment.
Outputs to technosphere: Products and co-products	**Amount**	**Unit**	**Source**	**Comments**
Water outflow (after treatment)	70,653,937	m^3	Waternet	The water that is treated by the plant
Carbon reactivated	839	ton	Waternet	All the inputted carbon in 2023 was reactivated.
Emissions to air	**Amount**	**Unit**	**Source**	**Comments**
Carbon dioxide	123	ton	Assumption made to have a balanced material flow	17% of the carbon that has been outputted does not get reactivated. It is assumed to be emitted as carbon dioxide into the air.

The values below (in Table 2.4) are the ones inputted into Simapro for the future scenario of 4.4 ng PEQ/L with reactivation every 0.5 years.

Table 2.4: Input parameters for the LCA of the Leiduin treatment process under the 4.4 ng PEQ/L scenario in SimaPro with 0.5 years between reactivations.

Inputs from techno-sphere: materials/fuels	**Amount**	**Unit**	**Source**	**Comments**
Tap water {Europe without Switzerland} market for | APOS, S	70,726,271	m^3	Waternet	Tap water is taken as the inflow. The amount of treated water won't change with the implementation of the new guideline.
Wood-based activated carbon	507	ton	Waternet	- Activated carbon new in 2023 (about 17% of the total activated carbon used in the year) - This process was made in Simapro based on data from [50] and is explained in Appendix B
Wood-based activated carbon- reactivated	2,476	ton	Waternet	-All the carbon is being reactivated (so the amount is the same as the output amount). - This process was also made in Simapro based on data from [50] as shown in Appendix B
Iron(III) chloride, without water, in 40% iron solution state {GLO} market for | APOS, S	5947.5	kg	Waternet	This value is the same as the previous scenario. This is the value used to achieve 10 ng PEQ/L. I have assumed that the value would not change drastically to reach the 4.4 ng PEQ/L guideline
Inputs from techno-sphere: electricity/heat	**Amount**	**Unit**	**Source**	**Comments**
Electricity, medium voltage {NL} market for | APOS, S	3,823,756	kWh	Waternet	Same as the previous scenario. It is not expected that extra electricity is needed in case of more PFAS removal (assumptions based on calculations made by Waternet)
Outputs to techno-sphere: Products and co-products	**Amount**	**Unit**	**Source**	**Comments**
Water outflow (after treatment)	7,0653,937	m^3	Waternet	The water that is treated by the plant.
Carbon reactivated	2,983	ton	Waternet	All the inputted activated carbon was reactivated.
Emissions to air	**Amount**	**Unit**	**Source**	**Comments**
Carbon dioxide	507	ton	Assumption made to have a balanced material flow	17% of the carbon that has been outputted does not get reactivated. It is assumed to be emitted as carbon dioxide into the air.

Assumptions

- The backwash frequency does not change between the old and new processes which is why the ferric chloride doses remain the same in both scenarios. This is also the reason why the water inflow and outflow are assumed to be the same in both scenarios.
-The tap water input chosen for the LCA already contains emissions from GAC.
- Since both wood and coal-based activated and reactivated carbon have been inputted as a process in Simapro rather than using the activated carbon in the database, uncertainties prevail. The inputs have been modified to best suit the Netherlands based on the available sources on Simapro and are explained further in Appendix B.
- The assumption of 17% of the carbon being emitted as carbon dioxide into the air was only made for the wood-based activated carbon. This is because it was difficult to find literature about the emissions from wood-based GAC reactivation.
- There were studies about the production and reactivation of coal-based gac, so those emissions were used for creating the processes as shown in Table B.5 and Table B.8.

3
Results

3.1. Health Impacts of Reduced PFAS Concentration

Estimation Method 1 - Using data from the Plass et al. study
Based on the results of Eq. (2.1) and Eq. (2.2), the estimated reduced DALYs due to exposure to drinking water have been calculated as shown below.

Table 3.1: Estimated DALYs using data from Plass et al. to calculate the reduced DALYs specific to PFAS exposure from drinking water per year [9]

	Reduced DALYs due to exposure of PFAS from drinking water per 1,000,000 people in 2021
Lower	3.4
Central	42.7
Upper	81

Given that the Leiduin water consumers are approximately 1,000,000, the DALYs range from 3.4 per year at the lower limit to 81 per year at the upper limit, with a central value of 42.7 per year. This indicates the range of DALYs after considering the decrease due to the water treatment system.

Estimation Method 2 - DALYs for the three diseases specific to the Netherlands:
Using the data from Table 2.2, the DALYs per 100,000 people were calculated for Diphtheria, Hib, and Tetanus, as shown in the table below. The ranges per year are quite narrow, with Diphtheria between 0.331129 and 0.331134, Hib between 1.62 and 1.63, and Tetanus having the smallest range of 0.034 to 0.035. Values were reported to five decimal places to highlight the subtle variations in the estimated range.

Table 3.2: DALYs per 100,000 people from the three diseases per year (Diphtheria, Hib and Tetanus in 2023)

Disease	DALYs per 100,000 people in 2023		
	Lower	Central	Upper
Diphtheria	0.331129	0.331132	0.331134
Hib	1.61850	1.61906	1.61960
Tetanus	0.03496	0.03505	0.03517
Sum	1.984	1.985	1.986

The combined DALYs for the three diseases range from 1.984 to 1.986 per year. These values were first adjusted for the general population served by the Leiduin plant (approximately 1,000,000 consumers) and then further adjusted for PFAS exposure from drinking water (using the WHO recommended limit of 20%), resulting in a final range of 3.969 to 3.972 per year.

Table 3.3: Estimation of DALYs per 1,000,000 people using different assumptions per year

DALYs per 1,000,000 people in 2023	Lower	Central	Upper
For the population that drinks from Leiduin	19.845	19.852	19.859
Based on the WHO limit of 20% for drinking water	3.969	3.970	3.972
Correcting for the cases caused by exposure to PFAS in drinking water	0.4	1.99	4

Diphtheria and Tetanus have a vaccination rate of 93%, while the vaccination rate for Hib stands at 89% [24]. However, despite these high vaccination rates, studies suggest that exposure to PFAS may negatively impact vaccine efficacy. According to the study by Abraham et al. [10], there is a negative link between exposure to PFAS and antibodies in vaccinated children. This implies that exposure to PFAS could undermine the protective effects of vaccines, potentially increasing susceptibility to diseases despite high vaccination coverage.

There are no studies to support the fact that these diseases are only caused by PFAS exposure from drinking water. Assumptions are made to link the number of cases of these three diseases caused by exposure to PFAS from drinking water. The lower estimate assumes that 10% of cases can be attributed to reduced immune response due to PFAS. The central estimate assumes that this percentage could be as high as 50%, while the higher estimate assumes that up to 100% of cases could be linked to compromised immune responses due to PFAS exposure. These assumptions were applied to the values that were adjusted to WHO's limit of 20% for drinking water.

Considering these assumptions, the estimated DALY range was between 0.4 and 4 with 1.99 being the central value as seen in Table 3.3.

The results of the Health Impacts of Reduced PFAS Concentration for both the estimated methods (in DALY/10^6 people/year) are shown in the graph below.

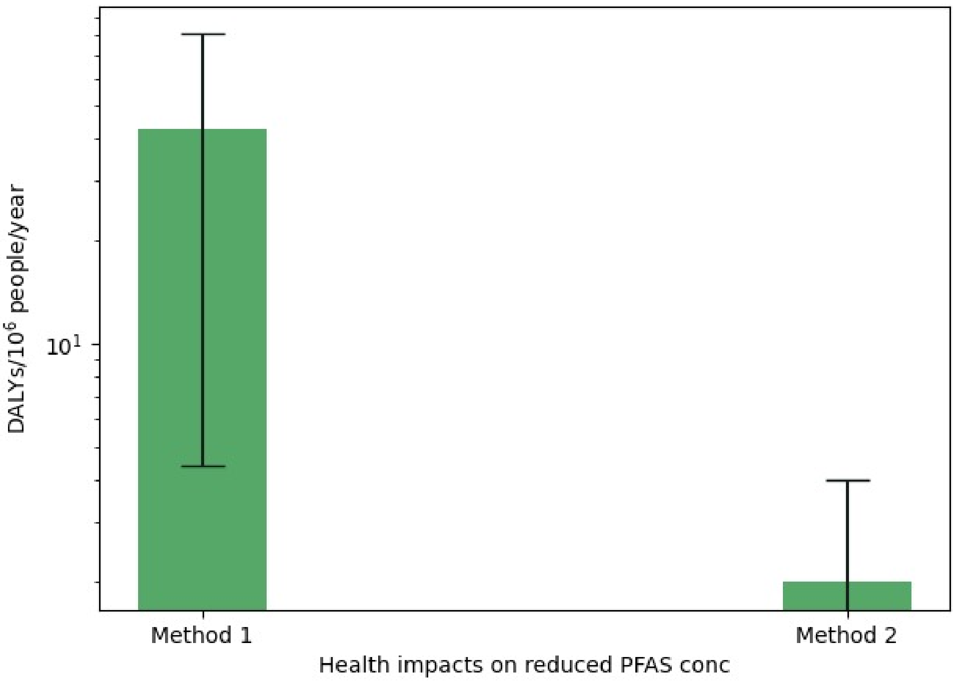

Figure 3.1: The results of Health Impacts of Reduced PFAS Concentration in DALY/10^6 people/year in logscale.

3.2. Life Cycle Assessment

Estimation Method 1 - Calculated based on increased CO_2 emissions

The DALYs mentioned in Table 3.4 are only related to carbon emissions. A range of DALYs per kg CO_2 emissions were taken which is why we have upper and lower values.

Table 3.4: The DALYs based on CO_2 emission per year

	DALYs lost per kg CO_2 emitted per year	DALYs lost due to upgrading treatment plant per year
Lower	1.13 x 10^{-8} [46]	0.057
Upper	1.76 x 10^{-5} [46]	88

Estimation Method 2 - Life Cycle Assessment of Leiduin water treatment plant

The DALYs from Simapro are specific to the functional unit of 1 m^3 of water treated. Considering this, the DALYs lost due to the treatment system at the Leiduin site were calculated for two scenarios: the current setup with reactivation every 1.5 years and the implementation of the future guideline of 4.4 ng PEQ/L with reactivation every 0.5 years. These calculations were performed for wood- and coal-based carbon, resulting in a broader DALY range.

Table 3.5: DALYs from LCA of Leiduin using wood-based and coal-based activated carbon for two scenarios per year

Type of Carbon	DALYs for scenario 2023 per m^3 per year	DALYs for scenario of 4.4 ng PEQ/L per m^3 per year
Wood based activated carbon	9.38 x 10^{-7}	9.60 x 10^{-7}
Coal based activated carbon	9.47 x 10^{-7}	9.93 x 10^{-7}

The DALYs difference from Table 3.5 were multiplied with the yearly water treated (in m^3) resulting in the DALYs attributable to the implementation of the guideline, as shown in Table 3.6 below.

Table 3.6: DALYs lost for GAC in the Leiduin water treatment process due to the new 4.4 ng PEQ/L guideline per year

Type of Carbon	DALYs lost for the GAC part in Leiduin due to the new guideline per year
Wood based activated carbon	1.55
Coal based activated carbon	3.25

The results of the Life Cycle Assessment for both the estimated methods (in DALY/10^6 people/year) are shown in the graph below.

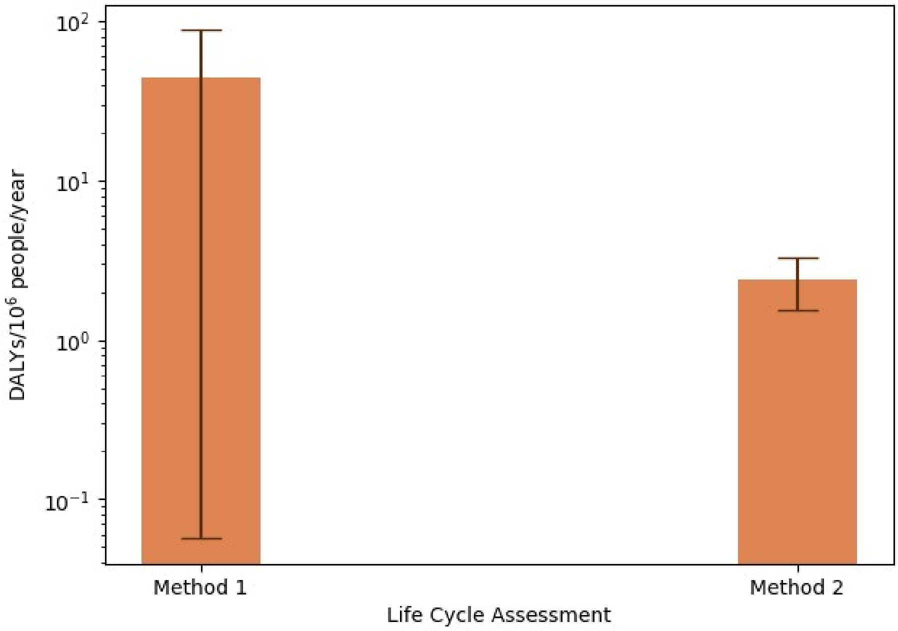

Figure 3.2: The results of Life Cycle Assessment in DALY/10^6 people/year in logscale

4
Discussion

4.1. Is it worth removing PFAS from drinking water to 4.4 ng PEQ/L?

4.1.1. DALYs from Plass et al. vs DALYs calculated for the three diseases

Using the data from Plass et al. [9], the DALYs lost due to PFAS exposure for a population of 1 million people was estimated to be in the range of 3.4 to 81 per year. The DALYs attributed to Diphtheria, Hib, and Tetanus due to PFAS exposure for the same population were calculated to be between 0.4 and 4 per year.

When these estimates are compared with the WHO guideline of 10^{-6} DALYs per person per year for drinking water, they exceed the recommended limit. For a population of 1 million, the WHO guideline translates to a maximum of 1 DALY per year for the entire population. Both the broader PFAS-related health effects from Plass et al. [9] and the decreased immune response mentioned in Abraham et al. [10] significantly surpass this threshold. This comparison raises serious concerns: the potential health risks from PFAS exposure in drinking water far surpass the levels deemed acceptable by international guidelines. Several uncertainties, however, should be considered when interpreting these results.

Firstly, the data from Plass et al. [9] pertains to Belgium and estimates DALYs for diseases linked to PFAS exposure without solid scientific backing specific to these diseases. Conversely, the calculations for Diphtheria, Hib, and Tetanus are based on research by Abraham et al. [10], which relates decreased antibody response to vaccinations for these diseases to PFAS. However, this data is also not specific to the Netherlands, and thus may not fully represent the local population's risk.

Plass et al. [9] aggregate the DALYs from multiple PFAS effects, many of which are primarily associated with high PFAS exposures than what is typically found in current drinking water concentrations. Meanwhile, the immune effects noted by Abraham et al. [10] occur at lower exposures, which are relevant to the drinking water concentrations being considered.

The 20% recommended WHO limit that was applied to both scenarios can vary depending on the person. A key factor to consider is the high vaccination coverage in the municipalities served by the Leiduin plant with rates exceeding 90-100%. Even though there is a high vaccination rate, the only connection between these diseases and PFAS is the vaccination response. So a high vaccination rate might mean a stronger link with PFAS, not a weaker one. The connection between PFAS and diseases like Diphtheria, Hib, and Tetanus lies solely in the vaccination response, and higher vaccination rates may not necessarily mitigate the risks posed by PFAS.

While both sets of estimates; Plass et al. [9] for broader health effects and Abraham et al. [10] for Diphtheria, Hib and Tetanus exceed the WHO DALY limit of 10^{-6} per person per year, the Abraham et al. [10] method is likely more applicable to the current drinking water conditions.

4.1.2. DALYs from calculated CO_2 emissions vs DALYs from LCA

The DALYs associated with carbon emissions from water treatment were calculated to range between 0.057 and 88. These values are based on typical CO_2 emission ranges for water treatment plants. This approach aimed to quantify the health impacts, measured in DALYs, resulting from the system upgrade necessary to meet the new PFAS standards.

The LCA provided DALYs specifically for the GAC used in PFAS removal from drinking water, covering both the current 2023 scenario (with reactivations every 1.5 years) and the future scenario (with reactivation every 0.5 years) under the new guideline. The DALY estimates from the LCA were 1.55 for wood-based GAC and 3.25 for coal-based GAC. .

The DALYs associated with the GAC component fall within the range estimated for CO_2 emissions. However, there are uncertainties to consider. The analysis incorporated DALYs for both wood-based and coal-based activated carbon; different treatment facilities may use various types of carbon, which could result in varying emission levels and impact the DALYs related to water treatment.

While coal-based activated carbon tends to be more energy-intensive, leading to higher human health impacts due to resource depletion and combustion emissions, wood-based activated carbon exhibits higher impacts on ecosystems due to land use and emissions related to biomass production.

Waternet's use of wood-based activated carbon reflects a more sustainable choice, leading to reduced emissions compared to the coal-based counterpart. Nonetheless, both wood- and coal-based activated carbons showed similar contributions to global warming potential in the analysis, largely because of the intensive energy use during activation processes [51].

At the Leiduin plant, PFAS levels in drinking water are currently at 10 ng PEQ/L due to the surface water source. Although other treatment sites may handle lower PFAS levels, this difference is not significant enough to substantially alter the emissions related to using hard coal or wood-based carbon in GAC.

Overall, the DALYs from the LCA are considered more reliable because they account for multiple environmental factors, including GHG emissions, ecosystem effects, and human health implications, which are often omitted in more simplified based CO_2 assessments.

4.1.3. Implications on water treatment guidelines and technologies

The central question addressed in this research is whether implementing the new PFAS guideline of 4.4 ng PEQ/L results in a net health gain when compared to the health losses associated with enhanced water treatment processes. By comparing the DALYs associated with PFAS exposure under the current and new guidelines from Section 3.1 and Section 3.2, it is indicated that there are no significant health benefits from adopting the new guideline.

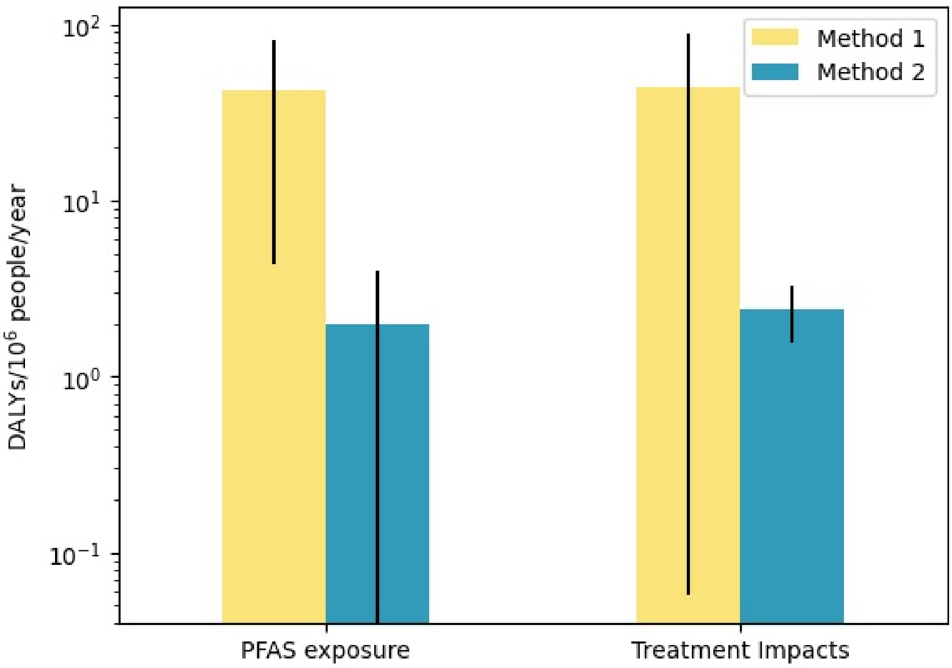

Figure 4.1: The results between the two methods for health gain due to reduced PFAS conc. in drinking water and the health loss due to treatment technologies used to achieve the new guideline respectively in DALY/10^6 people/year in logscale.

The research, which focused on the Leiduin plant of Waternet, shows that the DALYs for PFAS exposure and the DALYs resulting from increased emissions due to advanced water treatment fall within a similar range. This indicates that the potential health benefits of reducing PFAS concentrations may be offset by the negative health impacts of increased emissions from the treatment process.

It is necessary to note that the values reported are specific to the Leiduin plant and are based on certain assumptions, including the use of activated carbon and the existing PFAS levels in the water supply. These assumptions could lead to different outcomes in other contexts. For instance, water treatment sites using alternative carbon sources or those with varying PFAS levels might experience different balances between health gains and losses.

Furthermore, while the current analysis provides valuable insights, it is limited by the assumptions and data specific to the Leiduin plant. To fully assess the health implications of the new guideline, it would be beneficial to conduct similar evaluations at other treatment sites and consider a broader range of factors, including different types of carbon filters and local PFAS concentrations.

While the intention behind the new guideline is to improve public health by reducing PFAS levels, the evidence from this study suggests that the health gains may not justify the increased health impacts from water treatment emissions. Future studies should focus on gathering more comprehensive data and exploring alternative treatment methods that minimize both PFAS exposure and total emissions from treatment technologies to ensure that health benefits are maximized.

4.2. Ethical Considerations

The central research question driving this research is how the decrease in DALYs attributable to lower PFAS exposure compares against the associated negative health impacts of the required drinking water treatment technologies. This complex issue is not just a scientific or technical challenge but also an ethical one, demanding careful consideration of various moral and social dimensions.

When viewed through an ethical lens, the reduction of PFAS-23 concentrations in drinking water to 4.4 ng PEQ/L in the Netherlands involves weighing the rights of consumers to safe, uncontaminated water against the economic and operational burdens placed on water providers. Furthermore, it raises questions about justice, particularly how the benefits and costs of such measures are distributed across different segments of the population. By exploring these ethical perspectives, we can better understand the broader implications of our actions and ensure that our responses to PFAS contamination are not only effective but also equitable and just.

The Rights Perspective [52] focuses on issues of responsibility and morals, emphasizing the moral obligations owed to various stakeholders. In this context, there is an inherent conflict between the rights of consumers and the operational challenges faced by water companies. Consumers have an unmistakable right to uncontaminated drinking water that does not pose any health risks. This right is fundamental and aligns with the moral obligation of water providers to ensure public safety.

However, achieving the stringent PFAS level of 4.4 ng PEQ/L presents significant challenges. While water companies adhere to existing Dutch drinking water standards, implementing such a low threshold for PFAS can increase production costs. These additional costs may subsequently raise the price of drinking water, potentially making it less affordable for consumers. Thus, fulfilling the moral obligation to provide safe drinking water may inadvertently lead to financial burdens on consumers, creating a moral dilemma where satisfying one obligation compromises another.

This situation raises the question of fairness: should drinking water companies or consumers bear the responsibility for contamination that they did not cause? This leads us to consider the issue through the lens of the Justice Perspective

The Justice Perspective [52] argues for the equitable treatment of all individuals, ensuring that no group is unfairly burdened or disadvantaged. From this viewpoint, the goal is to balance the need for safe drinking water with the principles of fairness and equality.

Implementing the 4.4 ng PEQ/L standard may disproportionately impact low-income communities, who might struggle to afford increased water prices. This raises concerns about distributive justice, where the benefits of reduced PFAS exposure must be weighed against the potential economic disparities created by higher costs. Ensuring that all individuals have access to safe and affordable drinking water is a matter of justice, requiring policies that do not worsen the existing inequalities.

Ethical considerations also extend to the allocation of resources and the economic impact of implementing advanced water treatment technologies. Policymakers must balance the costs of achieving the 4.4 ng PEQ/L standard against other public health needs, ensuring that resources are used efficiently to maximize societal well-being. This involves a utilitarian approach, aiming to achieve the greatest good for the greatest number while minimizing harm.

The Utilitarian Perspective [52] seeks to achieve the greatest good for the greatest number. From this viewpoint, the primary consideration is to maximize overall societal well-being. Reducing PFAS levels in drinking water is expected to result in significant public health benefits, as evidenced by the potential decrease in DALYs. However, this must be balanced against the costs and potential negative impacts associated with advanced water treatment technologies.

From this perspective [52], the key is to ensure that the long-term health benefits of reducing PFAS exposure outweigh the immediate economic costs and potential negative side effects of treatment technologies. This involves a careful analysis of the trade-offs to achieve an outcome that enhances overall societal health and well-being.

Reducing PFAS concentrations in drinking water to 4.4 ng PEQ/L involves navigating complex ethical considerations. It requires balancing the rights of consumers to safe water with the operational challenges and cost implications for drinking water companies. The public should be kept in the loop regarding the negative health impact of processes that are involved and how the government plans to mitigate them. Ethical reflections regarding who should be held responsible for PFAS contamination and if all PFAS should be eventually banned should be considered as well.

5
Conclusions

The research aimed to evaluate the potential health benefits of implementing the new PFAS guideline of 4.4 ng PEQ/L. By comparing the current PFAS concentration of 10 ng PEQ/L at the Leiduin drinking water treatment plant to this proposed stricter guideline, the study found that while the guideline intends to enhance public health, the actual health benefits might not justify the resources and effort required for its implementation.

The analysis revealed that the health gains from adopting the new guideline ranged from 0.4 to 4 DALYs per year. On the other hand, the increased PFAS removal efforts at the Leiduin plant result in DALY losses between 1.55 and 3.25 per year, depending on the type of activated carbon used. These results indicate that the effort to reduce the concentration of PFAS in drinking water to 4.4 ng PEQ/L may not translate into a significant health benefit, especially when factoring in the increased emissions and energy demands.

The DALYs estimated in this research exceed the 10^{-6} DALYs per person per year set by the WHO guideline for drinking water. While stricter PFAS guidelines are necessary to protect public health, the real-world benefits could be marginal compared to the economic and environmental costs. Water treatment companies, such as Waternet, may face increased operational costs, potentially leading to higher water prices for consumers, with minimal observable health improvements.

However, these findings are subject to certain limitations. The analysis relies on risk-based assessments and various assumptions. A major limitation is the lack of direct evidence connecting PFAS concentrations in drinking water to health impacts, highlighting a need for empirical data.

Future studies should focus on direct health assessments linked to PFAS exposure, moving beyond theoretical or risk-based approaches. Research should also explore the practical effectiveness of these guidelines in real-world scenarios to better inform decision-making. Current regulations, such as those proposed by RIVM, are based on animal studies, which may not fully capture human health risks.

In conclusion, while the proposed PFAS guideline represents a well-meaning step toward improving public health, this research suggests that further improvement is needed. The guideline's effectiveness may be limited without stronger, human-centred data to justify the increased costs and operational challenges. More robust and human-specific research is crucial to ensuring that future regulations truly safeguard public health.

References

[1] Aida Garcia-Toledo. *C4 vs C6 vs C8: What are these PFAS chemicals and how are these different? — 3 Little Plums*. en-US. Aug. 2022. URL: https://3littleplums.com/blog/c4-vs-c6-vs-c8-what-are-these-pfas-chemicals-and-how-are-these-different.

[2] ECHA. *Per- and polyfluoroalkyl substances (PFAS) - ECHA*. en-GB. URL: https://echa.europa.eu/hot-topics/perfluoroalkyl-chemicals-pfas.

[3] DAC Network. *Promoting Pro-Poor Growth: Employment*. en. 2009. URL: https://www.oecd.org/greengrowth/green-development/43514554.pdf.

[4] Wisconsin Department of Health Services. en. Apr. 2024. URL: https://www.dhs.wisconsin.gov/chemical/pfas.htm.

[5] Hope O' Dell. *Can you get rid of PFAS? More countries are finding out*. en. May 2024. URL: https://globalaffairs.org/bluemarble/pfas-forever-chemicals-countries-regulations#:~:text=The%20European%20Union%20began%20regulating,health%20treaty%20between%20186%20countries..

[6] Marlies Warming et al. *Short-chain polyfluoroalkyl substances (PFAS)*. en. Ed. by Jesper Kjølholt et al. 978-87-93352-15–5. 2015. URL: https://cswab.org/wp-content/uploads/2018/05/Short-chain-PFAS-literature-review-Danish-EPA-2015.pdf.

[7] Laura Anderko et al. "Exposures to per-and polyfluoroalkyl substances (PFAS): Potential risks to reproductive and children's health". In: *Current Problems in Pediatric and Adolescent Health Care* 50.2 (Feb. 2020), p. 100760. DOI: 10.1016/j.cppeds.2020.100760. URL: https://doi.org/10.1016/j.cppeds.2020.100760.

[8] EurEau. *PFAS and drinking water*. en. Oct. 2020. URL: https://www.eureau.org/resources/briefing-notes/5236-briefing-note-on-pfas-and-drinking-water/file.

[9] Dietrich Plass et al. *ETC HE Report 2023/13: Estimating the burden of disease due to lead, PFAS, phthalates, cadmium, pyrethroids and bisphenol A using HBM4EU data – test of feasibility and first results for selected countries*. en-gb. Jan. 2024. URL: https://www.eionet.europa.eu/etcs/etc-he/products/etc-he-products/etc-he-reports/etc-he-report-2023-13-estimating-the-burden-of-disease-due-to-lead-pfas-phthalates-cadmium-pyrethroids-and-bisphenol-a-using-hbm4eu-data-2013-test-of-feasibility-and-first-results-for-selected-countries.

[10] Klaus Abraham et al. "Internal exposure to perfluoroalkyl substances (PFASs) and biological markers in 101 healthy 1-year-old children: associations between levels of perfluorooctanoic acid (PFOA) and vaccine response". In: *Archives of Toxicology* 94.6 (Mar. 2020), pp. 2131–2147. DOI: 10.1007/s00204-020-02715-4. URL: https://doi.org/10.1007/s00204-020-02715-4.

[11] European Food Safety Authority. "PFAS in food: EFSA assesses risks and sets tolerable intake". en. In: *European Food Safety Authority* (Sept. 2020). URL: https://www.efsa.europa.eu/en/news/pfas-food-efsa-assesses-risks-and-sets-tolerable-intake.

[12] Van Der Aa et al. *PFAS in Nederlands drinkwater vergeleken met de nieuwe Europese drinkwaterrichtlijn en relatie met gezondheidskundige grenswaarde van EFSA*. en. 2022. DOI: 10.21945/RIVM-2022-0149.

[13] ZeroWater Europe. en-US. June 2024. URL: https://www.zerowater.eu/zerowater-knowledge-center/pfas-in-tap-water/.

[14] Veolia. *PFAS Technology, Remediation and Treatment*. en. URL: https://www.watertechnologies.com/applications/pfas-remediation#:~:text=How%20do%20you%20treat%20PFAS,called%20Reverse%20Osmosis%20or%20Nanofiltration..

[15] N.G.F.M. Van Der Aa et al. *PFAS in Nederlands drinkwater vergeleken met de nieuwe Europese Drinkwaterrichtlijn en relatie met gezondheidskundige grenswaarde van EFSA*. en. 13. 2022, pp. 2–52. DOI: 10.21945/RIVM-2022-0149. URL: https://www.rivm.nl/bibliotheek/rapporten/2022-0149.pdf.

[16] Dieter Schrenk et al. “Risk to human health related to the presence of perfluoroalkyl substances in food”. In: *EFSA Journal* 18.9 (Sept. 2020). DOI: 10.2903/j.efsa.2020.6223. URL: https://doi.org/10.2903/j.efsa.2020.6223.

[17] Van Leeuwenhoeklaan. *Notitie implementatie van de EFSA Som-TWI PFAS*. en. Apr. 2021.

[18] Wieneke Bil et al. “Risk assessment of per□ and polyfluoroalkyl substance mixtures: A Relative Potency factor approach”. In: *Environmental Toxicology and Chemistry* 40.3 (Sept. 2020), pp. 859–870. DOI: 10.1002/etc.4835. URL: https://doi.org/10.1002/etc.4835.

[19] Wikipedia-bijdragers. *Rijksinstituut voor Volksgezondheid en Milieu*. nl. May 2024. URL: https://nl.wikipedia.org/wiki/Rijksinstituut_voor_Volksgezondheid_en_Milieu.

[20] Monique Van Der Aa et al. *Analyse Bijdrage drinkwater en voedsel aan blootstelling EFSA-4 PFAS in Nederland en advies drinkwaterrichtwaarde*. en. M/270071. Mar. 2021. URL: https://www.rivm.nl/documenten/analyse-bijdrage-drinkwater-en-voedsel-aan-blootstelling-efsa-4-pfas-in-nederland.

[21] Niklas Andersson. *How to bring your registration dossier in compliance with REACH: Tips and Hints - Part 5: Read-across*. Feb. 2014.

[22] WHO. en. Dec. 2020. URL: https://www.who.int/data/gho/indicator-metadata-registry/imr-details/158#:~:text=Definition%3A-,One%20DALY%20represents%20the%20loss%20of%20the%20equivalent%20of%20one,health%20condition%20in%20a%20population..

[23] Prüss-Üstün A et al. “Introduction and methods: Assessing the environmental burden of disease at national and local levels.” en. In: *World Health Organization Protection of the Human Environment Geneva* (Jan. 2003), p. 35. URL: https://www.popline.org/node/251104.

[24] Ajm Pluijmakers et al. “The National Immunisation Programme in the Netherlands. Surveillance and developments in 2022-2023”. en. In: *hdl.handle.net* (Nov. 2023). DOI: 10.21945/RIVM-2023-0330. URL: https://doi.org/10.21945/RIVM-2023-0330.

[25] Waternet. nl. URL: https://www.waternet.nl/.

[26] Leon Kors et al. *Drinkwater van bron tot tap*. nl. URL: https://www.waternet.nl/innovatie/schoon-water/drinkwater-van-bron-tot-tap/.

[27] Bert. *Klanten Waternet gebruiken gemiddeld 141 liter drinkwater per dag*. nl-nl. June 2023. URL: https://www.h2owaternetwerk.nl/h2o-actueel/klanten-waternet-gebruiken-gemiddeld-141-liter-drinkwater-per-dag.

[28] P. K. Mohapatra et al. “Improving eco-efficiency of Amsterdam water supply: A LCA approach”. In: *Aqua* 51.4 (June 2002), pp. 217–227. DOI: 10.2166/aqua.2002.0019. URL: https://doi.org/10.2166/aqua.2002.0019.

[29] Drinkwater Productie Waternet. *Drinkwater Productie Waternet*. en. July 2023.

[30] Oscar Quiñones et al. “Occurrence of Perfluoroalkyl Carboxylates and Sulfonates in Drinking Water Utilities and Related Waters from the United States”. In: *Environmental Science & Technology* 43.24 (Nov. 2009), pp. 9089–9095. DOI: 10.1021/es9024707. URL: https://doi.org/10.1021/es9024707.

[31] Timothy D. Appleman et al. “Treatment of poly- and perfluoroalkyl substances in U.S. full-scale water treatment systems”. In: *Water Research* 51 (Mar. 2014), pp. 246–255. DOI: 10.1016/j.watres.2013.10.067. URL: https://doi.org/10.1016/j.watres.2013.10.067.

[32] Cristina Tuser. “What is Granular Activated Carbon (GAC)?” en. In: *Wastewater Digest* (Jan. 2022). URL: https://www.wwdmag.com/what-is-articles/article/10939799/what-is-granular-activated-carbon-gac.

[33] Total Water. *Understanding activated carbon filtration systems - total water*. en-US. Mar. 2018. URL: https://www.total-water.com/blog/understanding-activated-carbon-filtration-systems/.

[34] A.M. Motelica. *Milieu-impact van verdergaand PFAS verwijdering op drinkwaterzuivering*. July 2023, pp. 2–5.

[35] Adriana Laca et al. “Life cycle assessment in biotechnology”. In: *Elsevier eBooks*. Jan. 2019, pp. 994–1006. DOI: 10.1016/b978-0-444-64046-8.00109-9. URL: https://www.sciencedirect.com/topics/earth-and-planetary-sciences/life-cycle-assessment.

[36] Mohammad Feisal Rahman et al. “Behaviour and fate of perfluoroalkyl and polyfluoroalkyl substances (PFASs) in drinking water treatment: A review”. In: *Water Research* 50 (Mar. 2014), pp. 318–340. DOI: 10.1016/j.watres.2013.10.045. URL: https://pubmed.ncbi.nlm.nih.gov/24216232/.

[37] WHO. en. URL: https://immunizationdata.who.int/global/wiise-detail-page/diphtheria-reported-cases-and-incidence?CODE=NLD&YEAR=.

[38] Jeffrey C. Kwong et al. “The impact of infection on population health: Results of the Ontario Burden of Infectious Diseases Study”. In: *PloS One* 7.9 (Sept. 2012), e44103. DOI: 10.1371/journal.pone.0044103. URL: https://doi.org/10.1371/journal.pone.0044103.

[39] PAHO/WHO. en. Apr. 2023. URL: https://www.paho.org/en/topics/diphtheria#:~:text=Diphtheria%20is%20fatal%20in%205,antibiotics%20to%20kill%20the%20bacteria..

[40] Shaun A Truelove et al. “Clinical and Epidemiological Aspects of Diphtheria: A Systematic review and pooled analysis”. In: *Clinical Infectious Diseases* 71.1 (Aug. 2019), pp. 89–97. DOI: 10.1093/cid/ciz808. URL: https://doi.org/10.1093/cid/ciz808.

[41] Allan R. Tunkel et al. “Practice guidelines for the management of Bacterial meningitis”. In: *Clinical Infectious Diseases/Clinical Infectious Diseases (Online. University of Chicago. Press)* 39.9 (Nov. 2004), pp. 1267–1284. DOI: 10.1086/425368. URL: https://doi.org/10.1086/425368.

[42] Immunize.org. en. Oct. 2023. URL: https://www.immunize.org/wp-content/uploads/catg.d/p4206.pdf.

[43] WHO. en. URL: https://immunizationdata.who.int/global/wiise-detail-page/tetanus-reported-cases-and-incidence?CODE=NLD&DISEASE=&YEAR=.

[44] William Atkinson et al. *Epidemiology and prevention of vaccine-preventable diseases*. en. 9th ed. Centers for Disease Control and Prevention, 2006. URL: https://stacks.cdc.gov/view/cdc/78725.

[45] Immunization Profile–Pch-Icp et al. *Tetanus (Lockjaw)*. en. URL: https://doh.wa.gov/you-and-your-family/illness-and-disease-z/tetanus-lockjaw#:~:text=Tetanus%20leads%20to%20death%20in,vaccine%20will%20always%20be%20needed..

[46] Matthew J. Eckelman et al. “Estimated global disease burden from US health care sector greenhouse gas emissions”. In: *American Journal of Public Health* 108.S2 (Apr. 2018), S120–S122. DOI: 10.2105/ajph.2017.303846. URL: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5922190/.

[47] Laura Golsteijn. en-US. May 2024. URL: https://pre-sustainability.com/articles/life-cycle-assessment-lca-basics/.

[48] Zijp Mc et al. “Life cycle assessment of two drinking water production schemes”. en. In: *RIVM Letter Report 2015-0209* (Feb. 2016). URL: https://rivm.openrepository.com/rivm/bitstream/10029/596126/3/2015-0209.pdf.

[49] M.A.J. Huijbregts et al. *ReCiPe 2016: A harmonized life cycle impact assessment method at midpoint and endpoint level*. 2016, pp. 2–191. URL: https://www.rivm.nl/bibliotheek/rapporten/2016-0104.pdf.

[50] Hongmei Gu et al. *Life cycle assessment of activated carbon from woody biomass*. 2018, pp. 1–15. DOI: 10.22382/wfs-2018-024. URL: https://www.researchgate.net/publication/326800658.

[51] Anna Vilén et al. "Comparative life cycle assessment of activated carbon production from various raw materials". In: *Journal Of Environmental Management* 324 (Dec. 2022), p. 116356. DOI: 10.1016/j.jenvman.2022.116356. URL: https://www.sciencedirect.com/science/article/pii/S0301479722019296#appsec1.

[52] Shannon Vallor et al. "Technology and Engineering Practice: Ethical Lenses to look through". en. In: *Ethics in Technological Practice* (2022). URL: https://www.scu.edu/ethics/..

[53] Chun Fung Wong et al. "Applications of charcoal, activated charcoal, and biochar in aquaculture – A review". In: *The Science of the Total Environment* 929 (June 2024), p. 172574. DOI: 10.1016/j.scitotenv.2024.172574. URL: https://www.sciencedirect.com/science/article/pii/S0048969724027207.

[54] Y. Abdallas Chikri et al. *Decarbonisation options for the Dutch activated carbon industry*. 2021, p. 4. URL: https://www.pbl.nl/uploads/default/downloads/pbl-2021-decarbonisation-options-for-the-dutch-activated-carbon-industry-3885.pdf.

[55] Et Al. Bayer et al. *PORTABLE SOLUTION FOR THE ELECTROCHEMICAL REGENERATION OF ACTIVATED CARBON*. Jan. 2018. URL: https://www.aspire2050.eu/sites/default/files/users/user735/Deliverables/WP6/D6%201_Virgin%20activated%20carbon%20%20Thermal%20regeneration_v4_FINAL.pdf.

[56] PRé et al. *SimaPro Database Manual*. June 2020. URL: https://simapro.com/wp-content/uploads/2020/06/DatabaseManualMethods.pdf.

[57] European Commission. en. URL: https://climate.ec.europa.eu/eu-action/european-climate-law_en#:~:text=Climate%20neutrality%20by%202050%20means,and%20protecting%20the%20natural%20environment..

A

Health Impacts of Reduced PFAS Concentration

While using the data from The National Immunization Report [24] for the three diseases mentioned in Abraham et al. [10], it was noted that among the three diseases, Hib has the most number of reported cases in the Netherlands. The RIVM is not sure why but links it to the circulation of the pathogen. The pathogen of Diphtheria and Tetanus has been contained with vaccine rates above 90% in the population which is why there is a significantly lesser number of cases for these diseases as compared with Hib.

A.1. Diphtheria

There were seven confirmed cases of Diphtheria in 2022 but unfortunately, their vaccination history is unknown.

The table below gives the details about the mortality caused by Diphtheria in the Netherlands from the year 2013 to 2022

Table A.1: Mortality rates of Diphtheria from 2013 to 2022 [24]

Year	Age					
	0	1-4	5-9	10-19	20-49	50+
2013	0	0	0	0	0	0
2014	0	0	0	0	0	0
2015	0	0	0	0	0	0
2016	0	0	0	0	0	0
2017	0	0	0	0	0	0
2018	0	0	0	0	0	0
2019	0	0	0	0	0	0
2020	0	0	0	0	0	0
2021	0	0	0	0	0	0
2022	0	0	0	0	0	0

The table below gives the details of the number of cases hospitalized due to Diphtheria from 2013-2022.

Table A.2: Hospitalized cases of Diphtheria from 2013 to 2022 [24]

Year	Age						
	0	1-4	5-9	10-19	20-49	50+	Total
2013	0	0	0	0	0	0	0
2014	0	0	0	0	0	2	2
2015	0	0	0	0	0	0	0
2016	0	0	0	0	0	0	0
2017	0	0	0	0	0	0	0
2018	0	0	0	0	0	0	5
2019	0	0	0	0	0	0	0
2020	0	0	0	0	0	0	0
2021	0	0	0	0	0	0	0
2022	0	0	0	0	0	0	0

A.2. Hib

There was no explicit data about the number of hospitalizations of Hib cases in The National Immunization Report 2022[24].

The table below gives the details about the mortality caused by Hib in the Netherlands from the year 2013 to 2022

Table A.3: Mortality rates of Hib from 2013 to 2022 [24]

Year	Age					
	0	1-4	5-9	10-19	20-49	50+
2013	0	0	0	0	0	0
2014	0	0	0	0	0	0
2015	0	0	0	0	0	0
2016	0	0	0	0	0	0
2017	0	0	0	0	0	0
2018	0	0	0	0	0	0
2019	0	0	0	0	0	0
2020	0	0	0	0	0	0
2021	0	0	0	0	0	0
2022	0	0	0	0	0	0

A.3. Tetanus

Two females lost their lives in 2022 due to Tetanus as noticed in the table given below. They had not received the vaccine in their childhood for tetanus which made them susceptible to the disease.

Table A.4: Mortality rates of Tetanus from 2013 to 2022 [24]

Year	Age					
	0	1-4	5-9	10-19	20-49	50+
2013	0	0	0	0	0	0
2014	0	0	0	0	0	0
2015	0	0	0	0	0	0
2016	0	0	0	0	0	0
2017	0	0	0	0	0	0
2018	0	0	0	0	0	0
2019	0	0	0	0	0	0
2020	0	0	0	0	0	0
2021	0	0	0	0	0	0
2022	0	0	0	0	0	1

The hospitalized cases for tetanus were one male each in 2015,2016 and 2018, one female in 2017, one male and female each in 2020 and two females in 2022 as stated in the table below.

Table A.5: Hospitalized cases of Tetanus from 2013 to 2022 [24]

Year	Age						
	0	1-4	5-9	10-19	20-49	50+	Total
2013	0	0	0	0	0	0	0
2014	0	0	0	0	0	0	0
2015	0	0	0	1	0	0	1
2016	0	0	0	0	0	1	1
2017	0	0	0	0	0	1	1
2018	0	0	0	0	0	1	1
2019	0	0	0	0	0	0	0
2020	0	0	0	1	0	1	2
2021	0	0	0	0	0	0	0
2022	0	0	0	0	0	2	2

A.4. DALYs

The table below gives the results of the DALYs of the three mentioned diseases from 2018 to 2022 as mentioned by RIVM [24].

Table A.6: DALYS of the three diseases from 2018 to 2022 [24]

	2018	2019	2020	2021	2022	DALYS/100 infections
Diphtheria	3	0	3	0	11	150
Haemophilus Influenzae	1000	970	1000	890	1500	410
Tetanus	1	0	11	0	2	75

Haemophilus Influenza are of different strains but only Haemophilus influenzae type b (Hib) has been associated with PFAS concentrations. In the year 2022, 28% of the total cases were associated with the vaccine-preventable Hib which is higher than 50% in 2021 and 47% in 2020 [24]. The table below is the adjusted DALYs according to these assumptions.

Table A.7: Adjusted DALYs of the three diseases from 2018 to 2022 [24]

	2018	2019	2020	2021	2022	DALYS/100 infections
Diphtheria	3	0	3	0	11	150
Haemophilus Influenzae type b	290	270	480	450	420	146
Tetanus	1	0	11	0	2	75

It must be noted that the total disease burden for Haemophilus influenzae disease is higher than presented here, as the analyses were limited to (laboratory-confirmed) invasive disease. Furthermore, the burden of these diseases, as well as HPV (Human papillomavirus) infection, is not fully preventable through vaccination because not all types are covered by the vaccine [24]. The cases for diphtheria and tetanus are not an over-approximation.

B
Life Cycle Assessment

B.1. Wood-based activated carbon

The table below has the input parameters used to create wood-based activated carbon for Table 2.3 and Table 2.4.

Table B.1: Input parameters for LCI of wood GAC production per 1 kg GAC [50]

Input	Amount	Unit	Source
Electricity, medium voltage NL market for | APOS, S	1.7	kWh	Literature [50]
Charcoal GLO| production | APOS, S	2.11	kg	Vilen et al.[51] and Gu et al [50] suggested using Biochar. This was not available on Simapro so charcoal was used instead [53].
Heat, district or industrial, natural gas NL| heat and power co-generation, natural gas, conventional power plant, 100MW electrical | APOS, S	13.30	MJ	Literature [50]
Tap water Europe without Switzerland| market for | APOS, S	2.11	kg	Literature [50]

Table B.2: Input parameters for emissions of LCI of wood GAC production per 1 kg GAC [51]

Emissions to	Substance	Amount
Water	WasteWater	2.11 kg
Air	Carbon dioxide, biogenic	1.81 kg
	Water	0.09 kg
	Nitrogen, atmospheric	1.83 kg
	Oxygen	1.59 kg
	Hydrogen	5.0×10^{-3} kg
	Carbon monoxide	9.0×10^{-3} kg
	Methane	1.0×10^{-3} kg
	Sulfur dioxide	1.0×10^{-3} kg
	Hydrogen chloride	1.25×10^{-6} kg
	Nitrogen oxides, NL	9.06×10^{-5} kg
	Particulates	4.6×10^{-2} kg
	Acetaldehyde	1.14×10^{-5} kg
	Benzene	8.56×10^{-5} kg
	Formaldehyde	2.73×10^{-8} kg
	Methanol	4.10×10^{-6} kg
	Naphthalene	7.23×10^{-6} kg
	Phenol	2.04×10^{-6} kg
	Propanal	7.14×10^{-8} kg

The table below is for wood-based reactivated carbon used in Table 2.3 and Table 2.4.

Table B.3: Input parameters for LCI of wood GAC reactivation per 1 kg GAC [51]

Input	Amount	Unit	Source
Water, completely softened RER| market for water, completely softened | APOS, S	4.02	kg	Literature [51]
Activated wood	0,10	kg	Literature [51]
Spent activated carbon, granular GLO| market for spent activated carbon, granular | Cut-off, S	1	kg	Literature [51]
Transport, freight, lorry 16-32 metric ton, euro3 RER| market for transport, freight, lorry 16-32 metric ton, EURO3 | APOS, S	0.15	tkm	This is based on the calculation that the activated carbon source is Cabot Norit Nederland [54]
Electricity, medium voltage NL| market for | APOS, S	0.55	kWh	Literature [51]
Heat, district or industrial, natural gas NL| heat and power co-generation, natural gas, conventional power plant, 100MW electrical | APOS, S	1.23	kWh	Literature [51]

Assumptions:
- Vilén et al. [51] calculated only the LCI of wood GAC production and not of wood GAC reactivation. The values used for wood reactivation in Table B.3 are based on the values of coal reactivation which was mentioned in [51]. However, the corresponding value for activated carbon produced from hard coal mentioned in Table B.7 applicable for wood-based carbon was replaced by Table B.1. Simapro had no suitable wood production values that could be used in this scenario.
- The values other than transport, electricity and heat are not specific to the Netherlands.
- The activated carbon supplier for Waternet was not known. From an online search, Cabot Norit Nederland [54] was assumed to be a potential supplier and hence the distance from the company to Leiduin was used above.

B.2. Coal-based activated carbon

The table below shows the input for creating the coal-based activated carbon process to be used in Table 2.3 and Table 2.4

Table B.4: Input parameters for LCI of coal GAC production per 1 kg GAC [55]

Input	Amount	Unit	Source
Electricity, medium voltage NL market for | APOS, S	1.84	kWh	Literature [55]
Hard coal RoW| market for | APOS, S	3	kg	Literature [55]
Water, decarbonised RoW| market for water, decarbonised | APOS, S	12.43	kg	Literature [55]
Industrial furnace, coal, 1-10MW GLO| market for | APOS, S	3.21×10^{-8}	p	Literature [55]
Heat, district or industrial, natural gas NL| heat and power co-generation, natural gas, conventional power plant, 100MW electrical | APOS, S	13.30	MJ	Literature [55]

The emissions considered per 1 kg of coal-based GAC are given in the table below.

Table B.5: Emissions for LCI of coal GAC production per 1 kg GAC [55]

Emissions to	Substance	Amount (kg)
Water	Water	0.01 m^3
Air	Aluminum	6.18×10^{-4}
	Antimony	9.13×10^{-8}
	Arsenic	1.46×10^{-6}
	Barium	7.28×10^{-5}
	Benzene	2.89×10^{-5}
	Benzo(a)pyrene	5.78×10^{-10}
	Beryllium	7.28×10^{-8}
	Boron	2.74×10^{-5}
	Bromine	5.48×10^{-7}
	Cadmium	9.13×10^{-8}
	Calcium	7.28×10^{-5}
	Carbon dioxide, fossil	7.00
	Carbon monoxide, fossil	5.78×10^{-3}
	Chromium	1.30×10^{-6}
	Chromium VI	1.61×10^{-7}
	Cobalt	1.83×10^{-7}
	Copper	9.60×10^{-7}
	Dinitrogen monoxide	5.78×10^{-5}
	Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	1.16×10^{-12}
	Ethane	8.67×10^{-5}
	Ethene	1.73×10^{-4}
	Ethyne	2.89×10^{-5}
	Formaldehyde	4.62×10^{-6}
	Hydrocarbons, aliphatic, alkanes, unspecified	2.89×10^{-6}
	Hydrocarbons, aliphatic, unsaturated	2.89×10^{-5}
	Hydrogen chloride	2.34×10^{-3}
	Hydrogen fluoride	7.28×10^{-5}
	Iodine	6.59×10^{-7}
	Iron	2.55×10^{-4}
	Lead	4.38×10^{-6}
	Lead-210	2.69×10^{3} kBq
	Magnesium	2.19×10^{-4}
	Manganese	1.28×10^{-6}
	Mercury	1.64×10^{-7}
	Methane, fossil	5.78×10^{-4}
	Molybdenum	2.74×10^{-7}
	Nickel	1.10×10^{-6}
	Nitrogen oxides	1.21×10^{-3}
	NMVOC, non-methane volatile organic compounds	9.94×10^{-5}
	Particulates $<$ 2.5 um	1.16×10^{-3}
	Particulates $>$ 10 um	5.78×10^{-4}
	Particulates $>$ 2.5 um, and $<$ 10 um	1.16×10^{-3}
	Phosphorus	3.65×10^{-6}
	Polonium-210	4.91×10^{-3} kBq
	Potassium	7.28×10^{-3}
	Potassium-40	7.80×10^{-4} kBq

Table B.6: Emissions for LCI of coal GAC production per 1 kg GAC continued [55]

Emissions to	Substance	Amount (kg)
Air	Propane	5.78×10^{-5}
	Propene	2.89×10^{-5}
	Radium-226	6.94×10^{-4} kBq
	Radium-228	3.76×10^{-3} kBq
	Radon-220	5.78×10^{-5} kBq
	Radon-222	5.78×10^{-5} kBq
	Scandium	7.28×10^{-8}
	Selenium	5.48×10^{-7}
	Silicon	9.13×10^{-4}
	Sodium	3.65×10^{-5}
	Strontium	1.10×10^{-5}
	Sulfur dioxide	2.89×10^{-2}
	Thallium	9.13×10^{-8}
	Thorium	1.10×10^{-7}
	Thorium-228	3.18×10^{-4} kBq
	Thorium-232	2.02×10^{-4} kBq
	Tin	3.65×10^{-5}
	Titanium	2.19×10^{-5}
	Toluene	5.78×10^{-6}
	Uranium	1.46×10^{-7}
	Uranium-238	5.78×10^{-4} kBq
	Vanadium	2.19×10^{-6}
	Water/m^3	1.86×10^{-3} m^3
	Xylene	5.78×10^{-6}
	Zinc	1.83×10^{-7}

Table B.7 shows the input parameters used for coal reactivation in Table 2.3 and Table 2.4.

Table B.7: Input parameters for LCI of coal GAC reactivation per 1 kg GAC [55]

Input	Amount	Unit	Source
Water, completely softened RER| market for water, completely softened | APOS, S	4.96	kg	Literature [55]
Spent activated carbon, granular GLO| market for spent activated carbon, granular | Cut-off, S	1.1	kg	Literature [55]
Industrial furnace, coal, 1-10MW GLO| market for | APOS, S	1.98×10^{-9}	p	Literature [55]
Electricity, medium voltage NL| market for | APOS, S	0.67	kWh	Literature [55]
Heat, district or industrial, natural gas NL| heat and power co-generation, natural gas, conventional power plant, 100MW electrical | APOS, S	5.47	MJ	Literature [55]

Table B.8: Emissions parameters for LCI of coal GAC reactivation per 1 kg GAC [55]

Emissions to	Substance	Amount
Water	Water	4.22×10^{-3} m^3
Air	Aluminum	3.82×10^{-5} kg
	Antimony	5.63×10^{-9} kg
	Arsenic	9.02×10^{-8} kg
	Barium	4.5×10^{-7} kg
	Benzene	1.78×10^{-6} kg
	Benzo(a)pyrene	3.56×10^{-11} kg
	Beryllium	4.5×10^{-9} kg
	Boron	1.68×10^{-6} kg
	Bromine	3.377×10^{-8} kg
	Cadmium	5.63×10^{-9} kg
	Calcium	4.5×10^{-6} kg
	Carbon dioxide, fossil	2.22 kg
	Carbon monoxide, fossil	3.56×10^{-4} kg
	Chromium	8.03×10^{-8} kg
	Chromium VI	9.92×10^{-9} kg
	Cobalt	1.12×10^{-8} kg
	Copper	5.92×10^{-8} kg
	Dinitrogen monoxide	3.56×10^{-6} kg
	Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	7.133×10^{-14} kg
	Ethane	5.35×10^{-6} kg
	Ethene	1.07×10^{-5} kg
	Ethyne	1.78×10^{-6} kg
	Formaldehyde	2.85×10^{-7} kg
	Hydrocarbons, aliphatic, alkanes, unspecified	1.78×10^{-6} kg
	Hydrocarbons, aliphatic, unsaturated	1.78×10^{-6} kg
	Hydrogen chloride	1.40×10^{-4} kg
	Hydrogen fluoride	1.68×10^{-6} kg
	Iodine	3.84×10^{-8} kg
	Iron	2.5×10^{-4} kg
	Lead	6.5×10^{-6} kg
	Lead-210	2.69×10^{3} kBq
	Magnesium	2.5×10^{-4} kg
	Manganese	2.38×10^{-7} kg
	Mercury	1.55×10^{-8} kg
	Methane, fossil	1.9×10^{-3} kg
	Nickel	7.9×10^{-8} kg
	Nitrogen oxides	1.22×10^{-3} kg
	NMVOC	5.63×10^{-5} kg
	Sulfur dioxide	2.45×10^{-2} kg
	Zinc	4.8×10^{-7} kg

Table B.9: Emissions parameters for LCI of coal GAC reactivation per 1 kg GAC continued [55]

Emissions to	Substance	Amount
Air	Selenium	3.37×10^{-8} kg
	Silicon	5.63×10^{-5} kg
	Sodium	2.25×10^{-6} kg
	Strontium	6.778×10^{-7} kg
	Sulfur dioxide	1.78×10^{-3} kg
	Thallium	5.63×10^{-9} kg
	Thorium	6.77×10^{-9} kg
	Thorium-228	1.96×10^{3} kBq
	Thorium-232	1.24×10^{4} kBq
	Tin	2.25×10^{-9} kg
	Titanium	1.35×10^{-6} kg
	Toluene	3.56×10^{-7} kg
	Uranium	9.02×10^{-9} kg
	Uranium-238	3.56×10^{5} kBq
	Vanadium	1.35×10^{-7} kg
	Water/m^3	3.58×10^{-3} m^3
	Xylene	3.56×10^{-7} kg
	Zinc	1.12×10^{-8} kg

Assumptions:
- The values other than electricity and heat are not specific to the Netherlands.

B.3. Damage Assessment graphs for Wood and Coal-based activated carbon

The damage assessment graphs of Fig. B.1 and Fig. B.2, depict the differences in impacts on human health, ecosystems, and resources between the two scenarios for both wood and coal-based activated carbon.

For wood-based activated carbon, the human health impact in the 2023 scenario is slightly lower at 9.38×10^{-7} compared to 9.6×10^{-7} in the 4.4 scenario. The ecosystem impact shows a reduction in the 2023 scenario, with a value of 4.78×10^{-9} versus 4.93×10^{-9} in the 4.4 scenario. The most notable difference is in resource depletion, where the 2023 scenario has a value of 0.00658, significantly lower than the 0.00723 observed in the 4.4 scenario.

For coal-based activated carbon, the 2023 scenario shows a slightly lower impact on human health, with a value of 9.47×10^{-7} compared to 9.93×10^{-7} in the 4.4 scenario. The ecosystem impact is reduced in the 2023 scenario, with a value of 4.78×10^{-9} compared to 4.92×10^{-9} in the 4.4 scenario. In terms of resource depletion, the 2023 scenario demonstrates a significant reduction, with a value of 0.00665, whereas the 4.4 scenario shows a higher impact of 0.00753.

For both materials, the 2023 scenario consistently demonstrates lower impacts on human health, ecosystems, and resources compared to the 4.4 scenario.

Ecosystems are expressed as the loss of species over a certain area over a certain period and are represented by the unit species.yr. Resource scarcity is expressed with the unit USD2013 which is surplus costs of future resource production over an infinitive timeframe [56].

The global warming,human health in DALY for wood-based activated carbon is 1.13×10^{-7} for the 2023 scenario and 1.29×10^{-7} for the 4.4 ng PEQ/L scenario. Similarly, for coal-based activated carbon, it is 1.2×10^{-7} DALYs for the 2023 scenario and 1.54×10^{-7} DALYs for the 4.4 ng PEQ/L scenario. It is difficult to compare it with global warming potential values mentioned in Section 2.2.

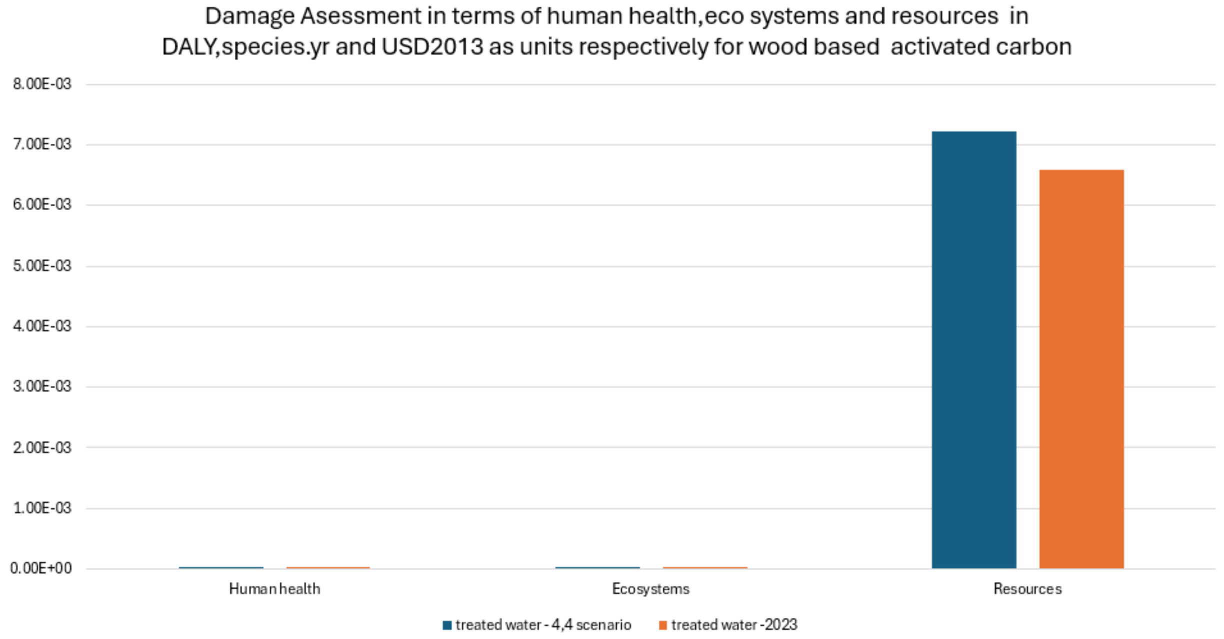

Figure B.1: Damage assessment graph in terms of human health, ecosystem and resources along with their units for wood-based activated carbon

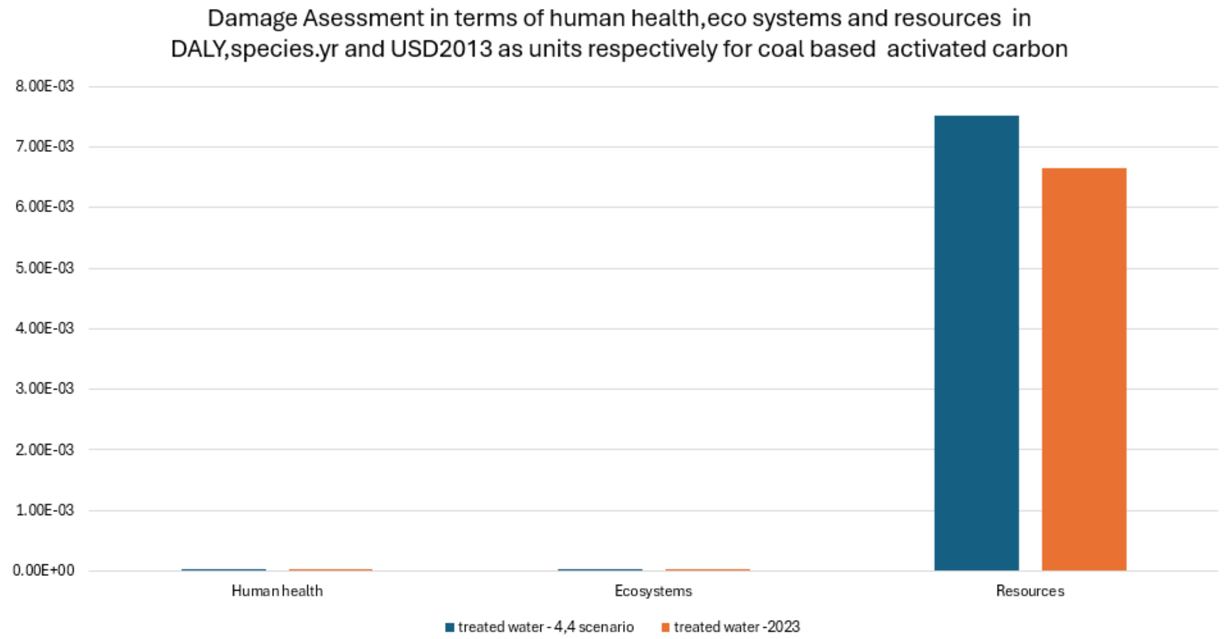

Figure B.2: Damage assessment graph in terms of human health, ecosystem and resources along with their units for coal-based activated carbon

B.4. LCA of Leiduin drinking water treatment plant if the Carbon Neutrality policy is considered

The European Climate Law has set to achieve carbon neutrality by 2050 which means achieving net zero greenhouse gas emissions for the EU countries, including the Netherlands. The law aims to reduce greenhouse gas emissions by 55% by 2030 from the 1990 levels [57].

The input for electricity was replaced by electricity by wind power to see the effect this would have on the DALYs. The DALYs for wood-based activated carbon decreased to 1.20 DALYs/year, while the DALYs for coal-based activated carbon dropped to 2.80 DALYs/year.

Replacing the industrial furnace in Table B.4 and Table B.7, with one powered by renewable energy, such as wind, would further reduce the environmental burden. However, the current version of Ecoinvent 3 in Simapro does not include a suitable process for this. Incorporating renewable energy into the entire activated carbon production process, in alignment with carbon neutrality goals, would likely result in even greater reductions in DALYs.