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ENVIRONMENTAL IMPACTS OF FINNISH DRINKING WATER PRODUCTION

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ABSTRACT

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Drinking water treatment is a process that typically requires substantial energy input and can be associated with various environmental impacts, including climate change, resource depletion, and ecotoxicity. However, life cycle assessment (LCA) data for this sector often lack regional specificity, which limits the reliability of impact evaluations. Publicly available LCA databases, such as Ecoinvent, do not include regional data—LCA datasets—that adequately reflects Finnish drinking water treatment practices. To address this gap and support a comprehensive life cycle assessment (LCA) of drinking water production in Finland—reflecting current treatment technologies and electricity consumption—a life cycle inventory (LCI) was developed for three prevalent Finnish drinking water production methods: conventional surface water treatment, groundwater with chemical treatment, and artificially recharged groundwater. The LCI covers approximately 40% of Finland's annual drinking water production and was used to generate process-specific datasets.

Impact assessment using these new datasets revealed that artificially recharged groundwater generally has the lowest environmental impacts, though its performance is affected by the use of polyaluminium chloride (PACl) in pretreatment. Groundwater treatment showed the highest impacts, primarily due to its heavy reliance on electricity, while surface water treatment, despite intensive chemical use, benefited from lower energy demands. Climate change impact values were 0.147 kg CO₂-eq/m³ for groundwater, 0.122 kg CO₂-eq/m³ for artificially recharged groundwater, and 0.119 kg CO₂-eq/m³ for surface water. These values are lower compared the quantifications on climate change impacts done by other studies, due to differences in inventory, methodology and coverage, and especially energy sources.

Comparison with Ecoinvent 3.11 datasets highlighted substantial differences, driven by updated electricity mixes, coagulant types, and energy consumption levels. This led to reductions in climate change impacts quantification by 46% in surface water treatment, 53% in groundwater treatment and 70% in Artificially recharged. A sensitivity analysis incorporating Finland's current electricity mix—dominated by nuclear and wind power—showed a 79% reduction in CO₂-eq/m³ for groundwater treatment, making it the least impactful option under updated conditions. In contrast, surface water and artificially recharged groundwater showed smaller reductions (26% and 42%, respectively), due to their greater dependence on chemical inputs.

Keywords: Life Cycle Assessment (LCA), drinking water production, local inventory data, LCA datasets, environmental impacts.

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PREFACE

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LIST OF SYMBOLS AND ABBREVIATIONS

AE	Acid Equivalent
AP	Acidification Potential
CC	Climate Change
DB	Data Base
EF 3.1	Environmental Footprint 3.1
ET-freshwater	Ecotoxicity, Freshwater
EP-freshwater	Eutrophication Potential, Freshwater
EP-marine	Eutrophication Potential, Marine
EP-terrestrial	Eutrophication Potential, Terrestrial
GHG	Greenhouse gas
GWP	Global warming potential
HT-cancer	Human Toxicity, Cancer
HT-noncancer	Human Toxicity, Non-Cancer
ILCD	International Reference Life Cycle Data System
IR	Ionizing Radiation
ISO	International Organization for Standardization
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LU	Land Use
M	number of non zeros weight
OD	Ozone Depletion
OEF	Organization Environmental Footprint
PACl	Polyaluminium chloride
PEF	Product Environmental Footprint
PM	Particulate Matter
POF	Photochemical Ozone Formation
RU-fossil	Resource Use, Fossils
RU-minerals	Resource Use, Minerals and Metals
SD_w	Weighted standard deviation
SD_{LN}	Standard deviation for the Normal Distribution
UV-lamp	Ultraviolet lamp
w_i	mass flow of water produced
WU	Water Use
x_i	normalized input flow
\bar{x}_w	Weighted average
z_i	Input flow
μ_{LN}	Mean for the normal distribution

1. INTRODUCTION

Drinking water is important not only for human consumption but also for many industrial processes. In modern societies, the increase in the availability of clean water in most of the cities is attached to a series of processes to purify and clean the raw water. The quality and physiochemical characteristics of the raw water are directly related to the amount of treatment required, leading to great differences in water treatment processes across regions. These processes have some impact on the environment such as atmospheric emissions, liquid effluents, and increase in mineral resources. These impacts are mostly related to energy and water treatment chemicals production (Meron et al., 2016).

To evaluate and calculate these impacts, Life Cycle Assessment (LCA) is a widely used method based on the inputs and outputs of processes. LCA quantifies the environmental impacts associated with all stages of a product's life—from raw material extraction through production, use, and disposal—commonly referred to as a "cradle-to-grave" approach (Guinée et al., 2011). However, it is possible to do an LCA for only one or several steps of a process. The methodology is standardized under the ISO 14040 and 14044 series, which outline the four main phases of an LCA: goal and scope definition, inventory analysis, impact assessment, and interpretation (Guinée et al., 2011). The theory of LCA is rooted in systems thinking and environmental accounting, aiming to provide a holistic view of environmental impacts at each step of the processes. It supports decision-making by pinpointing trade-offs between different environmental indicators such as global warming potential, eutrophication, and resource depletion. Moreover, LCA is increasingly integrated into sustainability strategies, eco-design, and policy development, reflecting its role in guiding transitions toward more sustainable production and consumption systems (Guinée et al., 2011).

However, the results of this—as any other—method are just as good as the information that is used to calculate the impacts. Considering the importance of this information in the LCA, data related to processes, such as flows of materials and energy, are collected and organized (datasets) to create different databases (DBs) for LCA, offering the closest results to real process. Some of the most widely used are Ecoinvent, GaBi, and ELCD (European Reference LCA Database). From these, Ecoinvent stands out as the most

comprehensive and widely used (Reinhard et al., 2016). Ecoinvent offers reliable information for several production areas and multiple geographical locations with more than 20,000 datasets (Ecoinvent, 2025).

Nevertheless, in any of the DBs some specific areas (countries) are still represented by global or regional data, which leads to discrepancies between the real environmental impacts and the impacts obtained by the LCA models. This applies to the treatment processes involved in drinking water production in Finland which are currently represented in ECOINVENT version 3.11 by datasets labelled as 'Europe without Switzerland'. These datasets are child versions (modified versions with adjusted volume production and activity links valid for Europe) of the 'Global' datasets for the different drinking water production treatments. The data used for the adjustment represents the higher percentage of drinking water volume production in the region. In this case, Italy, UK, Germany, and France are the biggest producers of drinking water in the region (EurEau, 2021), resulting in datasets that misrepresent the drinking water production in countries as Finland, where the raw water quality and the amount of treatment required to produce drinking water differs from the mentioned countries.

Studies have shown that the environmental impact values for drinking water production can vary widely depending on the dataset used, leading to variations on global warming potential (GWP) values between 0.16 to 3.4 kg CO₂-eq/m³ (Meron et al., 2016). An extended study by Meron et al. (2020) found that considering local conditions (treatment process and energy production) for an LCA of the water supply system in Israel produced more accurate results than using regional values. For the case of Finland, Lehtoranta et al. (2024) found that energy production and consumption, and chemical production and consumption are the largest sources of the total climate impact for drinking water production. These results show that considering the local drinking water production processes and energy production can lead to more accurate results.

The primary objective of this study is to assess the environmental impacts associated with drinking water production in Finland through LCA. To enable this evaluation, representative LCA datasets are developed for Finnish waterworks, tailored to local conditions such as raw water quality, treatment technologies, and energy consumption. The datasets are categorized based on the water source—surface water, groundwater, and artificially recharged groundwater—reflecting the differences in treatment processes. Specifically, the selected treatment types include conventional treatment for surface water, chemical treatment for groundwater, and specialized methods for artificially recharged groundwater. These datasets serve as the foundation for quantifying environmental impacts and allow for comparison with existing studies, official data, and other LCA results.

Additionally, due to the importance of electricity consumption in the drinking water production, a sensitivity analysis of the electricity sources is done to verify the effects of an updated electricity mix on the environmental impacts. This approach ensures the relevance and accuracy of the environmental assessments, which are focused exclusively on drinking water production methods used in Finland.

The system boundaries of this LCA study cover the drinking water production process in Finland, specifically focusing on three types of water sources: underground water, recharge groundwater, and surface water. The study follows a cradle-to-gate approach, meaning it includes water abstraction, pretreatment, and treatment operations (such as filtration, chemical dosing, and disinfection), energy and chemical inputs, and waste management related to treatment by-products. The study excludes downstream activities such as the distribution of treated water, transport to end users, and any use-phase or end-of-life considerations.

2. LITERATURE REVIEW

This chapter presents the basic information to understand the importance of local drinking water datasets in LCA. Considering the impact of the quality of Finnish raw water sources and treatment processes on the environmental impact, the justificative of Finnish datasets are stated. Following, drinking water production treatment and its environmental impacts are presented to recognize the relevance of this information in the field of sustainability. Finally, a review of the current LCA dataset for this process introduces the required information to create a new dataset for the LCA database.

2.1 Raw water quality in central Europe and Finland

Across Europe, surface water and groundwater serve as the primary sources of raw water, with a significant portion of drinking water being either untreated or relying on conventional treatment technologies. The European Federation of National Associations of Water Services (EurEau, 2021) reports that groundwater remains the most important source of drinking water, followed by surface water (Figure 1). While the use of desalination has increased in some Mediterranean countries, its overall contribution remains comparatively low. Across Europe, most of the drinking water production undergoes treatment, with over 98% of the population having access to safe and regulated drinking water (EUROSTAT, 2025a).

However, the quality of these water sources can vary considerably across regions, influenced by differing environmental, geological, and human factors. In particular, Central Europe faces notable challenges from emerging contaminants and disinfection by-products (van der Hoek et al., 2013), alongside substantial pollution from agricultural sources such as nitrates and pesticides (Ockenden et al., 2014, Ortmeyer et al., 2022).

Italy exemplifies these regional contrasts as the largest water producer in Europe generating 9,488 million m³ annually (Statista, 2021), with 85% sourced from groundwater (Statista, 2022). Water quality within Italy itself fluctuates widely from pristine Ca-HCO₃ type mineral waters in mountainous regions (with high concentrations of Ca²⁺, Mg²⁺, and HCO₃⁻, indicating carbonate mineral dissolution) to degraded quality in coastal zones, where agricultural runoff, seawater intrusion (noted by higher values of electric conductivity, Na⁺, and Cl⁻), and urban pollution pose serious risks (Polemio & Limoni, 2006; Beretta, 2014; Sappa et al., 2019). Italian surface waters have long been monitored due

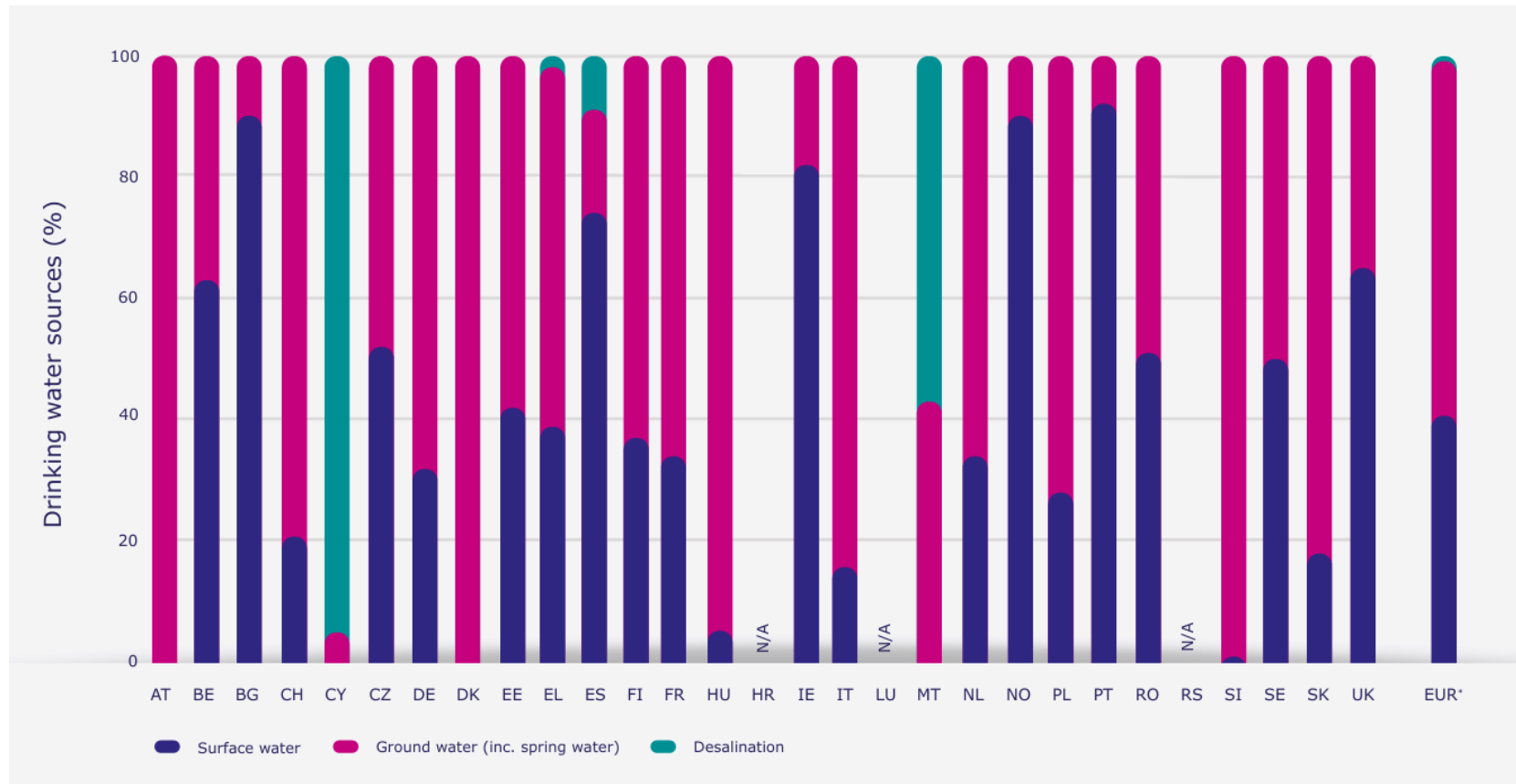


Figure 1. Sources of drinking water in Europe. Source: EurEau, 2021, p.17

to industrial and agricultural contamination. For example, Palazzo et al. (2022) documented significant microbial pollution in the Tiber River and nearby coastal waters around Rome, highlighting the need for ongoing monitoring.

In UK and France, the second and third biggest water producers in Europe (Statista, 2021), significant problems on raw water quality are found, mostly impacted by agricultural practices, leading to high levels of nitrates and pesticides (Charrière & Aumond, 2016; Maréchal & Rouillard, 2020; Ockenden et al., 2014). Besides, in France faecal contamination from both human and animal sources (Jardé et al., 2018; Beaudeau et al., 2009) and chemicals such as perchlorates, bromates, and per- and polyfluoroalkyl substances (Cartier et al., 2012; Teymoorian et al., 2025) have been reported in raw water sources. In the UK, Statista (2025) stated that more than 500 pollution incidents from sewage and water supply assets occurred over the past 10 years. This together with climate change effects lead to more toxic algae blooms and contaminant wash off into rivers (Reid et al., 2024). Groundwater contamination is also a concern, with 33% (France) and 45% (UK) of groundwater bodies in good chemical status (Maréchal & Rouillard, 2020; Statista, 2025).

Other bigger producers are Germany and Spain (Statista, 2021). Germany presents one of the best qualities of raw water in the region, besides of some contamination with nitrate by agricultural runoff in both surface and groundwater sources (Hansen & van Berk, 2004; Birke et al., 2010). Meanwhile in Spain, water quality faces significant challenges due to urban, industrial, and agricultural activities. Water scarcity exacerbates these issues, particularly in regions with intensive irrigation and recurrent droughts (Albiac et al., 2013, p. 328; Alonso Castillo et al., 2014). Despite robust drought management plans, water scarcity continues to impact water quality negatively (Albiac et al., 2013, p. 333-336). Besides this, Spanish waters are contaminated with heavy metals (e.g. nickel, copper, lead), organic pollutants, and nutrients from agricultural runoff (Alonso Castillo et al., 2014; Santos et al., 2009). Some areas, particularly those affected by mining and industrial activities, show high levels of contamination, such as the Guadalquivir and Guadalhorce River basins, studied by Alonso Castillo et al. (2014), showing pollution from both point and non-point sources.

In the Finnish scenario, raw water exhibits considerable variability depending on geographic location and water source type. Groundwater in Finland is typically soft and slightly acidic, conditions that often necessitate treatment to remove dissolved metals such as iron and manganese (Sallanko et al., 2004). Their removal involves oxidation followed by filtration; however, elevated levels of natural organic matter (NOM) can com-

plicate these processes. According to Jokela et al., (2017) artificially recharged groundwater treatment is frequently employed to reduce NOM in surface waters, significantly lowering total organic carbon (TOC) concentrations and improving water quality. In some cases, chemical pretreatment can be applied to reduce NOM before infiltration, ensuring sufficient dissolved oxygen levels in the saturated groundwater zone. However, due to the geological conditions in southern Finland, fluoride concentrations tend to increase after infiltration of surface waters, leading to additional treatment steps (Sehn, 2008). Other key parameters include turbidity and electrical conductivity, which can be elevated in certain groundwater sources, influencing treatment requirements.

Niemi (2007) explains the regional differences on Finnish waters. In southern Finland water exhibit poorer quality due to higher population density, industrial activity, and agricultural practices, resulting in increased pollutant and nutrient loads. Conversely, in northern regions there are lower contaminant levels and better overall water quality. Trace metals such as zinc, nickel, chromium, copper, cadmium, arsenic, lead, and mercury have been detected in various sources, necessitating careful management. Besides this, seasonal variations also affect water chemistry; for example, nitrite concentrations often rise in winter due to reduced ammonium oxidation, and manganese levels can fluctuate significantly even within the same area (Rantanen et al., 2018). Additionally, some groundwater sources display evidence of surface water intrusion, which can introduce contaminants and alter water composition.

All these characteristics increase the treatment challenges, which require advanced oxidation techniques to reduce NOM and iron, combined with filtration to achieve compliance with quality standards. Fluoride concentrations also arise as a problem in certain regions leading to additional treatment steps for drinking water production.

A detailed overview of the main physico-chemical characteristics discussed for each region is provided in Table 1, for easy comparison of the main regions related to the drinking water producing datasets and Finland.

In summary, raw water quality across Europe demonstrates substantial spatial and temporal variability driven by geological conditions, land use, and anthropogenic pressures. While northern regions such as Finland exhibit better water quality, localized challenges necessitate advanced treatment strategies.

On the other hand, southern and central European countries face more severe contamination risks from agricultural runoff, industrial pollutants, and emerging contaminants, compounded by climate change impacts and water scarcity.

Table 1. *Comparative Table of Water Production and Quality Issues in Europe*

Country	Water Production (Mm ³ /year)	Main Water sources	Key Water Quality Issues
Italy	9 488 ¹	85% Groundwater ¹	Pristine mineral waters in mountains; degraded quality in coastal zones due to agricultural runoff, seawater intrusion, and urban pollution; microbial pollution in surface waters ² .
UK	6 050 ¹	Mixed sources	High levels of nitrates and pesticides from agriculture ³ ; over 500 pollution incidents from sewage and water assets ¹ ; toxic algae blooms ⁴ ; 45% of groundwater bodies in good chemical status
France	5 909 ¹	Mixed sources	Nitrates and pesticides from agriculture ³ ; fecal contamination ⁵ ; chemicals like perchlorates, bromates, and PFAS ⁶ ; 33% of groundwater bodies in good chemical status
Germany	5 437 ¹	Surface and groundwater	Generally good quality, some nitrate contamination from agricultural runoff ⁷
Spain	4 078 ¹	Surface and groundwater	Urban, industrial, and agricultural pollution; water scarcity ⁸ ; heavy metals, organic pollutants, and nutrients; high contamination in mining and industrial regions ⁹
Finland	341 ¹⁰	Surface and groundwater	Great quality, especially in northern regions ¹¹ ; high concentration of natural organic matter, iron and manganese ¹² ; Seasonal fluctuation in nitrate concentrations ¹³

These regions often experience higher temperatures and prolonged droughts, which exacerbate pollutant concentrations in surface and groundwater bodies. Additionally, intensive land use and fragmented water governance structures can hinder effective mitigation strategies, making these areas particularly vulnerable to ecological degradation.

¹ Statista (2021); Statista (2025)

² Polemio & Limoni (2006); Beretta (2014); Sappa et al. (2019); Palazzo et al. (2022)

³ Charrière & Aumond (2016); Maréchal & Rouillard (2020)

⁴ Ockenden et al. (2014); Reid et al. (2024)

⁵ Jardé et al. (2018); Beaudeau et al. (2009)

⁶ Cartier et al. (2012); Teymoorian et al. (2025)

⁷ Hansen & van Berk (2004); Birke et al. (2010)

⁸ Albiac et al. (2013); Alonso Castillo et al. (2014)

⁹ Santos et al. (2009)

¹⁰ Vesilaitosyhdistys (2023)

¹¹ Niemi (2007)

¹² Sallanko et al., (2004); Rantanen et al., (2018)

¹³ Sehn, (2008)

2.2 Environmental impacts of drinking water production

Drinking water production affects multiple environmental dimensions, including energy and material use, chemical inputs, and pollution of air, soil, and water (Landu & Brent, 2006; Sharaai et al., 2010). Infrastructure construction and maintenance also contribute to impacts such as terrestrial ecotoxicity and mineral resource depletion (Meron et al., 2020).

Among all contributors, electricity consumption stands out due to its high demand for pumping and filtration. Energy use varies widely depending on the treatment technology, ranging from 0.01 to 1.5 kWh/m³ (Plappally & Lienhard V, 2012), with desalination being the most energy-intensive. Conventional surface water treatment typically consumes between 0.059 and 0.565 kWh/m³ (Sowby & Thompson, 2021) and groundwater with conventional treatment an average of .

Electricity use is a major driver of environmental impacts, especially when sourced from fossil fuels. For example, Klimtová et al. (2025) found that electricity accounted for 64.7% of climate change impacts in a Czech facility. In China, Li et al. (2024) reported that electricity was responsible for 69–90% of greenhouse gas (GHG) emissions across nine plants. In Finland, Lehtoranta et al. (2025) estimated that electricity use contributes 42,557 t CO₂-eq/year—53% of total GHG emissions.

Globally, over 85% of primary energy comes from nonrenewable sources like oil, coal, gas, and uranium (Rempel, 2008). In Europe, 46% of electricity is renewable, followed by nuclear (28.6%) and solid fuels (16.6%) (Eurostat, 2025b). In Finland, the energy mix is dominated by nuclear and renewables (Figure 2), with wind power showing notable growth (Finnish Energy, 2025).

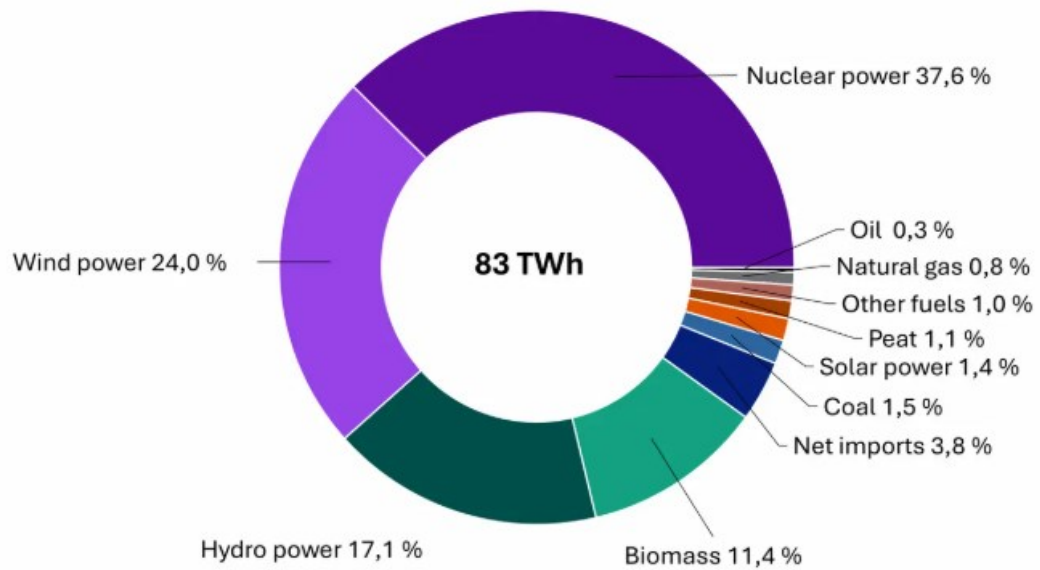


Figure 2. Electricity by energy source and net imports in Finland 2024 (source: Finnish energy, 2025)

However, the Ecoinvent 3.11 dataset still reflects Finland's 2021 energy mix, which includes fossil-based imports from Russia. This outdated dataset overestimates the environmental impact of electricity use, as it reflects a fossil-heavy energy mix. In contrast, Finland's current electricity mix—dominated by nuclear and renewables—results in significantly lower impacts, especially in categories like climate change, resource depletion, ecotoxicity, and human toxicity.

Given the electricity-intensive nature of drinking water production, shifts toward cleaner energy sources and more energy efficient process are crucial, in the search of carbon neutrality goals (Lehtoranta et al., 2025).

Chemical consumption presents relevant contributions in categories such as ecotoxicity-freshwater, human toxicity, eutrophication-freshwater, resource use-mineral & metals. Most of the impacts are associated to upstream in chemical production and they can account up to 37% of the GHG emissions (Lehtoranta et al., 2025).

Coagulation is a key chemical-intensive step in surface water treatment, primarily used to reduce turbidity and NOM. Aluminium-based coagulants, such as aluminium sulphate or Polyaluminium chloride (PACl), are commonly used but are associated with significant environmental impacts, particularly in terms of ecosystem toxicity (Klimtová et al., 2025). To mitigate these effects, alternative coagulants—such as iron-based salts, lanthanides, and organic polymers—have been explored. Studies indicate that these alternatives can

reduce environmental impacts by 50% to 90% across several categories (Klimtová et al., 2025; Niquette et al., 2004).

The use of some raw water sources for drinking water production also contributes to water depletion. The quality of water and its availability to other users are also critical considerations (Boulay et al., 2011). For example, groundwater depletion is a critical issue globally, especially in regions where it is used extensively for irrigation, industry and drinking water (tap and bottled water). Excessive extraction of groundwater leads to significant depletion, which is not easily replenished, causing long-term sustainability issues (Aeschbach-Hertig & Gleeson, 2012; Kinzelbach et al., 2022; Dalin, 2020). On other case, in Singapore, recycled water production (NEWater) proves to have a much lower contribution to water depletion compared to conventional drinking water production 0.00344 m^3 vs 0.882 m^3 per m^3 produced (Hsien et al., 2019). In the case of desalination processes, it reduces freshwater use by utilizing seawater, which is crucial for regions with limited freshwater supply (Meron et al., 2020). However, desalination plants represent a major contribution to all impact categories considered, including water consumption (Del Borghi et al., 2013).

The construction and maintenance of infrastructure also contribute to environmental impacts. The extraction of materials for metal components production (such as iron, copper, carbon, aluminium, etc.), and for cement production (such as calcium silicates, magnesium oxides, aluminium and iron) required for the construction and maintenance of the water potabilization plants are major contributors to terrestrial ecotoxicity and mineral resource scarcity environmental impacts, as mentioned by Meron, et al (2020). In France, the contribution of infrastructure to the overall impact.

2.3 LCA – ISO 14040 and ISO 14044

ISO 14040 and ISO 14044 are international standards developed by the International Organization for Standardization (ISO) that provide a structured framework for conducting LCA. These standards are part of the ISO 14000 series, which focuses on environmental management.

ISO 14040 outlines the general principles and framework for conducting an LCA. It defines the purpose, scope, and essential phases of an LCA study, which include goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation (ISO, 2006a). The goal and scope definition phase establishes the intent of the study, the system boundaries, and the functional unit that serves as the basis for comparison. The LCI involves collecting data on energy, material inputs, and emissions

associated with each stage of the product's life cycle. Following this, the LCIA evaluates the potential environmental impacts based on inventory data, translating raw data into meaningful environmental indicators. Finally, the interpretation phase draws conclusions from the results, identifies significant issues, and provides recommendations to support decision-making. Together, these components ensure that LCA studies are systematic, transparent, and scientifically grounded.

ISO 14040 emphasizes the importance of transparency, consistency, and reproducibility in LCA studies, ensuring that the results are credible and comparable across different contexts and applications (ISO, 2006b). This standard also provides more detailed requirements and methodological guidelines for each phase of the LCA process. It outlines specific rules for conducting both LCI and LCIA, ensuring that data collection and impact evaluation are carried out systematically. Additionally, it sets standards for data quality, allocation procedures, and the handling of multifunctional processes, which are critical for maintaining the integrity of the assessment. The standard also includes guidelines for conducting critical reviews, particularly for studies intended for public disclosure or those involving comparative assertions. Furthermore, ISO 14044 addresses the limitations and assumptions inherent in LCA studies, helping practitioners understand and communicate the uncertainties and constraints that may influence the interpretation of results.

2.4 LCA Databases

Given the importance of information about materials and processes in LCA, numerous databases (DBs) have been developed to provide results that closely reflect real world conditions. Ecoinvent DB is developed as a standalone that is available for several LCA software (including open-source versions), allowing wider access than others. With more than 20,000 datasets (Ecoinvent, 2025) is considered the most reliable database for several production areas and multiple geographical locations, and the is one of the most famous LCA databases in the world, used by more than 5000 organizations worldwide (GreenDelta, 2024; Reinhard et al., 2016). GaBi was created by Sphera to work with its proprietary Enterprise Sustainability Management (ESM) software, however it is possible to be imported in some open-source LCA software. It includes around 20,000 data sets focused on a wide range of industries and processes (Sphera, 2024). The International Reference Life Cycle Data System (ILCD) is developed by the European Commission, providing structured LCA datasets throughout nodes that each creator manages, though the exact count of datasets is not publicly specified.

The quality of LCA datasets significantly affects the results of the assessment. An LCA dataset content general information about the process that represents, such as input

flows—raw materials, electricity, water consumption—and output flows—emissions, waste, products and by products— all in relation to the functional unit. This data allows to quantify the environmental impacts and ensure consistency across different studies. Generic datasets, which represent average market conditions, may not accurately reflect specific processes used by individual manufacturers. This can hinder the ability to track supply chain impacts and compare environmental performance across different suppliers. Efforts to improve data specificity include blockchain-based frameworks for real time data acquisition and enhanced data accuracy (Lin et al., 2021).

However, in several cases, the LCI phase, which involves extensive data collection, often from multiple sources such as publications, databases, and site-specific measurements, can offer a closer dataset to the real process. This phase is labor intensive and requires careful planning and organization to ensure data reliability and consistency (Ayoub, A. (2017).

2.5 Dataset categories for drinking water production in Ecoinvent 3.11

To understand the classification of the water treatment process in the different DBs, a small review of each dataset category is presented Table 2. Inside each dataset, information about the process inputs—the normalized amount of resources such as materials, energy or data—and outputs—the normalized amount of products, emissions and waste generated. Drinking water treatment is classified in several production processes, including sources such as surface water, groundwater, artificially recharge groundwater and seawater. The latter will not be considered in this study, because it is not a relevant source of water in Finland due to the small volume of production in comparison to the total produced in Finland.

Table 2. *Drinking water production methods available in Ecoinvent 3.11*

Source	Treatment	Steps	Inputs ²	Outputs ³
Surface water	Conventional Treatment ¹	Sieving/screening, coagulation, oxidation, flocculation, sedimentation, filtration, pH stabilization, and disinfection	Surface water, chemicals (coagulants, disinfectants), energy	Treated potable water, sludge, minor emissions
	Direct Filtration	Filtration without sedimentation, and disinfection	Raw water, filtration media, disinfectants	Clean water, filter waste
	Microstrainer Treatment	Fine filtration using microstrainers, and disinfection	Raw water, filtration membranes, disinfectants	Treated water, membrane waste
	Ultrafiltration	High-precision membrane filtration, removing bacteria & viruses	Raw water, filtration membranes, energy	High-purity water, membrane waste

Groundwater	Chemical Treatment¹	Filtration, chemical treatment (iron/manganese removal and pH stabilization)	Groundwater, chemical additives	Treated water, minor chemical residues
	Disinfection Treatment	Chlorination, ozonation, UV treatment	Groundwater, disinfectants	Safe potable water, negligible residues
	Untreated	Direct use without treatment	Naturally pure groundwater	Direct potable water (requires monitoring)
Artificially Recharged Groundwater¹		Surface water infiltration into groundwater for storage followed by disinfection	Surface water, aquifer system	Stored groundwater, natural filtration

¹ Treatments relevant for Finland.

² Resources such as materials, energy or data used to carry out the process.

³ Products, emissions and waste generated by the process.

Surface water treatment is essential for ensuring safe drinking water, as it often contains suspended solids, organic matter, and microbial contaminants. The conventional treatment method is widely used and involves multiple steps: sieving, coagulation, flocculation, sedimentation, filtration, and disinfection. Coagulation and flocculation help aggregate fine particles, which are then removed through clarification. Filtration further purifies the water by passing it through sand or activated carbon filters, and disinfection—typically using chlorine or ozone—eliminates pathogens.

Direct filtration is a simplified version of conventional treatment, omitting the sedimentation step (Kajosaari & Suomen rakennusinsinöörien liitto, 1981, p.404). It is suitable for water sources with lower turbidity, where filtration and disinfection alone are sufficient to produce potable water (Kajosaari & Suomen rakennusinsinöörien liitto, 1981, p. 122). This method reduces infrastructure requirements and operational costs while maintaining effective contaminant removal.

Microstrainer treatment employs fine mesh screens to remove larger suspended particles before further filtration and disinfection (Kajosaari & Suomen rakennusinsinöörien liitto, 1981, p.404). This method is particularly useful for removing algae and other biological contaminants from surface water (Kajosaari & Suomen rakennusinsinöörien liitto, 1981, p.122). One facility in Québec accounts for nearly 100% of the drinking water produced with this technology, which consist in intake pumping, microfiltration through stainless steel strainers and disinfection (Ecoinvent, 2025).

Ultrafiltration is an advanced membrane-based treatment that removes bacteria, viruses, and fine particulates (Kajosaari & Suomen rakennusinsinöörien liitto, 1981, p.404). It operates at a higher precision than conventional filtration methods, ensuring superior water quality. Ultrafiltration is increasingly used in regions with stringent water quality requirements or where surface water sources are highly contaminated.

Groundwater generally requires less treatment than surface water due to its natural filtration through soil and rock layers (Vesi.fi, 2025). However, depending on the source, different treatment approaches are necessary.

Chemical treatment is applied when groundwater contains high levels of minerals or contaminants such as iron, manganese, or arsenic (Kajosaari & Suomen rakennusinsinöörien liitto, 1981, p.133). This process involves adding specific chemicals to neutralize or precipitate unwanted substances, followed by filtration to remove them.

Disinfection-based treatment is used when groundwater is microbiologically unsafe (Kajosaari & Suomen rakennusinsinöörien liitto, 1981, p.152). Chlorination, ozonation, or ultraviolet (UV) treatment ensures the elimination of bacteria and viruses, making the water safe for consumption.

In some cases, untreated groundwater can be directly supplied if it meets drinking water standards. This is common in regions where groundwater is naturally pure and free from harmful contaminants. However, periodic monitoring is necessary to ensure continued safety (Suomen ympäristökeskus, 2019).

Artificially recharged groundwater is designed to enhance groundwater levels by introducing surface water into underground aquifers. The process involves directing surface water into specially constructed wells, where it settles and undergoes natural filtration through soil layers before reaching the aquifer (Kajosaari & Suomen rakennusinsinöörien liitto, 1981, p. 219-220). Once stored, the water is pumped, disinfected, and distributed for use. Artificially recharged groundwater helps maintain groundwater sustainability and improve water availability in regions facing water scarcity.

In Finland, water treatment primarily relies on conventional treatment and groundwater with chemical treatment, as the country has abundant high-quality freshwater resources. Conventional drinking water production methods are widely used for surface water purification, ensuring compliance with stringent drinking water standards (Suomen ympäristökeskus, 2019). Additionally, groundwater sources are commonly utilized, often requiring minimal treatment beyond disinfection. Artificially recharged groundwater is less prevalent but are mostly used in southwest coastal areas where groundwater levels need replenishment (Suomen ympäristökeskus, 2019).

To account for local characteristics and potential variations in drinking water treatment, a survey is designed to collect detailed operational data from Finnish waterworks. The survey focuses on key parameters including the type of drinking water production method used, chemical consumption at each treatment stage, electricity usage, volumes of water produced, and information on side streams such as effluents and solid material flows.

However, data related to facility infrastructure or sensitive operational details are deliberately excluded for security and confidentiality reasons.

3. RESEARCH METHODOLOGY

Based on the guidelines of ISO 14040, goals and scope for the datasets are defined, an inventory is created for each of the different water sources, using a survey in cooperation with water producers and an impact assessment is done to evaluate dataset performance. This LCA is done using datasets based on the survey answers and all the quantification and impact assessments are done with SimaPro.

3.1 Goals

The main goal of this study is to evaluate the environmental impacts of the drinking water production in Finland. To achieve this, a series of datasets are created for each of the most common drinking water treatment in Finland. These datasets will be compared to the publicly available datasets in LCA database. An electricity sources sensitivity analysis is done to understand the implications in changes on the electricity mix used for the impact assessment.

3.2 Scope

This study examines three drinking water production methods: surface water with conventional treatment, groundwater with chemical treatment, and artificially recharged groundwater. System boundaries (Figure 4) extend from raw water intake to drinking water production at the facility gate.

Energy inputs include intake pumping, treatment processes, building lighting and heating, and initial pressurization for distribution. All chemicals and materials used during treatment are included. Emissions from treatment are considered negligible compared to those from energy production and upstream emissions of input flows. Wastewater from cleaning and filter rinsing is assumed to be treated within wastewater facilities. Solid residues are managed through recycling, composting, or energy recovery. Environmental impacts from inputs and outputs are allocated physically.

Based on the datasets available for other regions in Ecoinvent DB (2025), the functional unit for this study is defined as 1 kg of water produced. The geographical scope of the study is Finland. During the LCI the most representative water treatment plants were included.

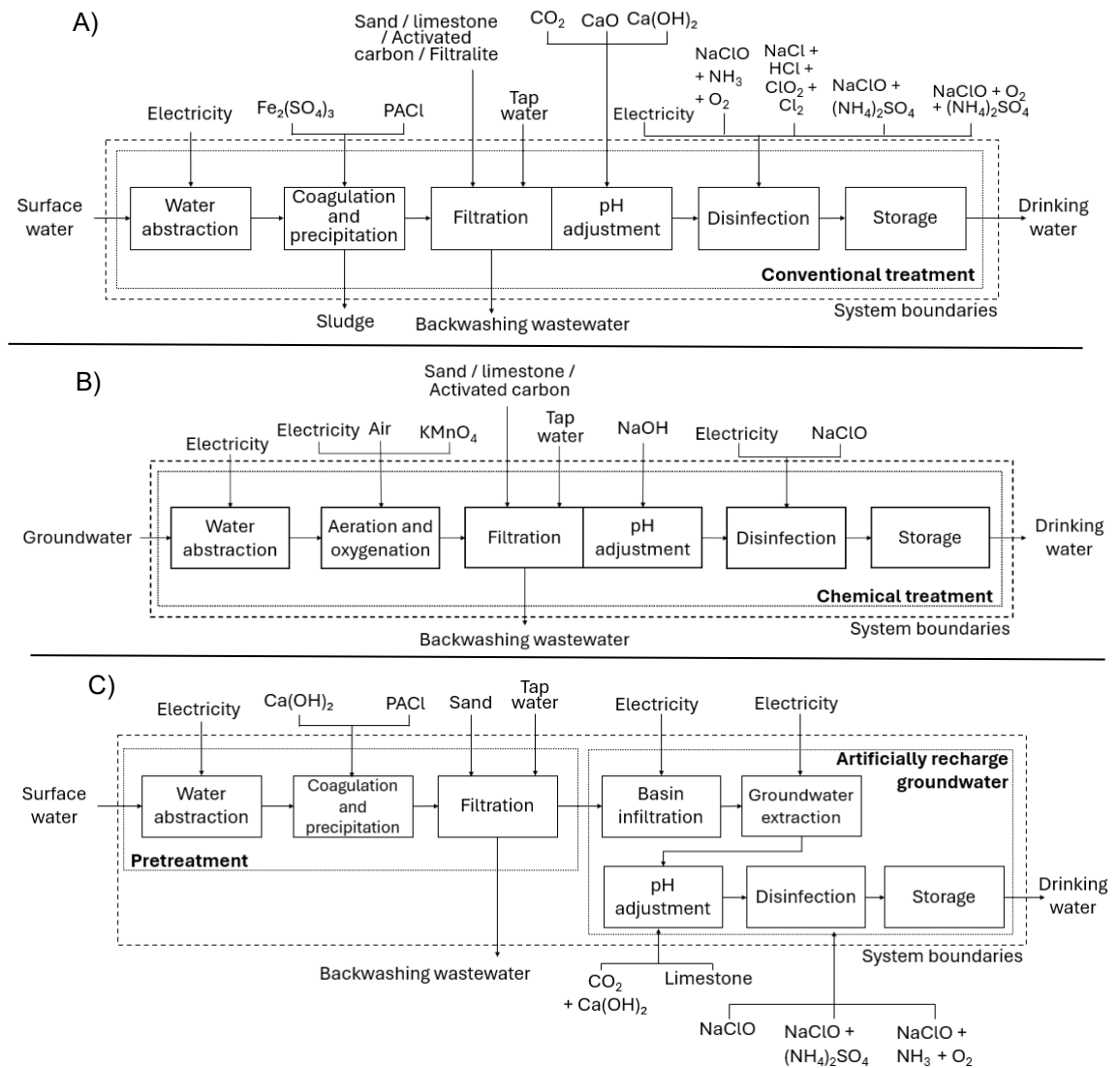


Figure 3. system boundaries for A) Surface water with conventional treatment B) Groundwater with chemical treatment and C) Artificially recharged groundwater

The total amount of water produced for the all the water facilities participating in this study account approximately for 40% of the total of the water produced in Finland. They are distributed on western and southern Finland, due that these are the zones more densely populated.

3.3 Research strategy

The research strategy for this study (Figure 3) begins with a review of publicly available databases, such as *vesi.fi* (ELY-keskus, 2020) and *Vesihuollon tietojärjestelmä–VEETI* (SYKE, 2025), were consulted to understand the drinking water production processes currently used in Finland. Based on this initial analysis, a targeted survey was designed

to gather detailed operational data from water treatment facilities (See Appendix A). Several facilities were contacted and invited to participate in the study.

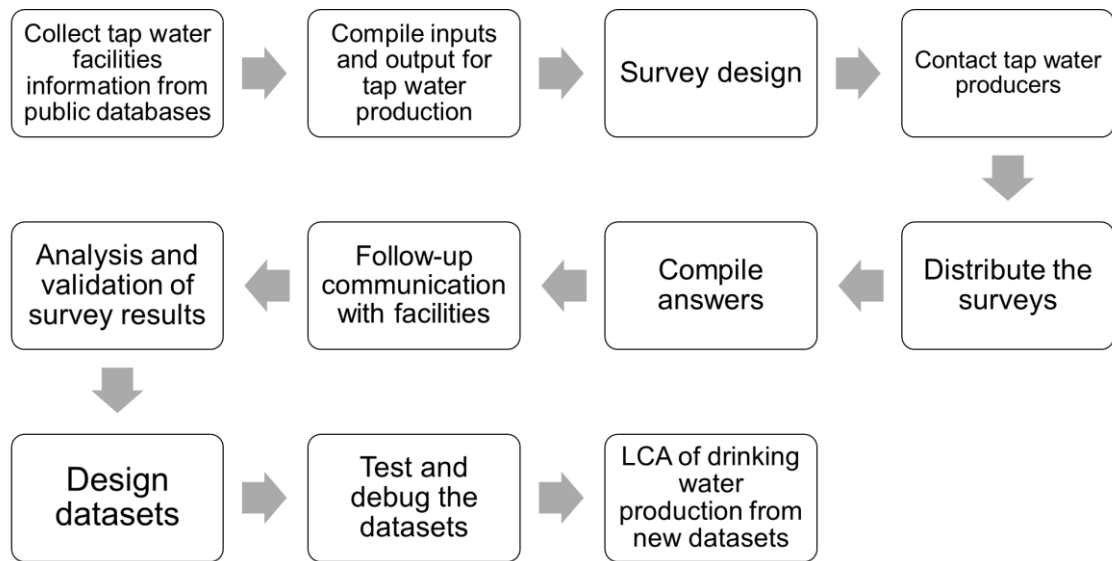


Figure 4. Research Strategy for LCA of Drinking Water Production in Finland

The survey was then shared with the participating facilities, focusing on aspects such as treatment methods, chemical usage per treatment step, electricity consumption, water production volumes, and side streams including effluents and solid material flows. Information related to infrastructure or sensitive operational details was excluded for security reasons. Some following up communication was done to collect more information and review some of the answers with the facilities. After collecting the responses, the data were compiled, statistically analysed, and validated to ensure consistency and reliability. These validated datasets were then used to perform the LCA and the LCIA. The results were compared with the results from existing datasets to assess the accuracy and relevance of the findings. Additionally, a sensitivity analysis was conducted using updated electricity mix data to evaluate the influence of energy sources on the overall environmental impact of drinking water production in Finland.

3.4 Assumptions

In this study, the coagulant PIX-322, which is commonly employed in Finnish water treatment facilities, is represented as iron sulphate in the input data. This simplification is based on the predominant active component, while other constituents of the formulation are excluded due to insufficient compositional information. The concentration of iron sulphate is estimated at approximately 44.75%, according to information reported by Zhang et al. (2021).

Filtralite, a composite material used for filtration in one of the facilities, has been excluded from the analysis. This decision is based on the lack of publicly available data regarding its chemical composition, which prevents accurate modelling within the scope of this study.

Slaked lime is considered as equivalent to hydrated lime, despite variations in production methods. This assumption aligns with the classification used in the database, where slaked lime is compiled under hydrated lime, thereby ensuring consistency in data interpretation.

For regenerated activated carbon, the values utilized in this study are derived from existing datasets. This approach was adopted because not all facilities provided specific data, and among those that did, the reported values showed significant variability. Thus, a standardized dataset value was deemed the most reliable representation.

The tap water used considered in the analysis encompasses both the water used for dissolving chemicals and the water employed in cleaning operations, including facility surfaces and filtration units. This comprehensive inclusion reflects typical operational water usage patterns.

The packing material used in the aeration towers is assumed as 1¼" Tri-Packs made of polypropylene, manufactured by Tri-Mer Corporation. This assumption is based on the widespread use of this specific packing type, which is the industry standard in high-performance random packing towers for scrubber and stripper applications (Rasching USA Inc., 2020), making it a reasonable proxy for typical conditions.

In the sensitivity analysis, the electricity sources reported as fossil-free are assumed to be nuclear power sources, while the electricity sources reported as renewable are considered to be wind powered energy. This assumption is based on the current share of energy sources used in the Finnish market, according to the information exposed in figure 2.

3.5 Life Cycle Inventory (LCI)

The inventory was done using a survey considering the water sources, treatment types, treatment steps and the inputs that apply to Finland scenario as follows:

- **Water sources:** The main water sources in Finland are surface water (lakes and rivers), and groundwater.
- **Treatment types:** Surface water with conventional treatment, groundwater with chemical treatment, and artificially recharged groundwater.

- **Treatment steps:** The treatment steps were defined grouping similar processes—such as pre-disinfection and final disinfection— together. All the treatment steps are presented in Table 3 for each of the water treatment process.
- **Material Inputs** Chemical compounds, consumables, or replaceable components, which depend on the water source and the type of treatment. A classification of all the material inputs used and considered in this study is presented in Table 3, together with the steps and water sources.
- **Other inputs:** Energy used by the processes, as electricity or heat, water used as raw material and drinking water for cleaning or chemical mixing.
- **Outputs:** Treated water, wastewater (from cleaning), waste paperboard, waste-paper, and municipal solid waste. the wastewater and solid waste residues are treated according to the Finnish regulation (incineration for energy production and recycling).

Table 3. *Chemical products used as input for drinking water production*

Treatment Process	Treatment step	Material inputs
Conventional treatment for surface water	Coagulation and sedimentation	Polyaluminium chloride (PACl), Slaked lime, Ferric sulphate (as PIX-322)
	Filtration	Activated carbon, Calcium carbonate, and Sand
	Disinfection	Ammonia, Ammonium sulfate, Chlorine, Chlorine dioxide, Hydrochloric acid, Oxygen, Sodium chloride solution, Sodium hypochlorite, ultraviolet lamps (UV-lamps), and Vacuum salt.
	pH stabilization	Carbon dioxide, Hydrated lime, and Calcium oxide.
Groundwater chemical treatment	Aeration and oxygenation	Potassium permanganate.
	Filtration	Limestone, activated carbon, Sand, and Lime
	Disinfection	Ammonia water, Sodium hypochlorite, and UV-lamps.
	pH stabilization	Sodium hydroxide and Calcium hydroxide.
Artificially recharged groundwater	Aeration	Polypropylene
	Filtration	Limestone, activated carbon, and sand
	Disinfection	Ammonia, Ammonium sulfate, Sodium hypochlorite, and UV-lamp

Based on the defined inputs and outputs for each treatment process, a survey was designed with an open-ended format using a straightforward approach. This survey was presented to some representatives of one of the drinking water producers and an expert in the water field production. Feedback for the survey's questions and contents were

received and adapted to create a final version. Several drinking water producer companies, public and private, were contacted by email, most of them answer positively. Meetings were scheduled with each of the companies, to explain the study, its goals and to introduce the survey, solve doubts and check what kind of information was accessible for them and for the study. These meetings also gave key information about how to approach some of the assumptions for the datasets.

Answers from all the companies that agreed to participate in the study were compiled and follow-up communication was done with some facilities, to verify some information, or ask for more relevant information that was omitted in the answers. The answers were classified into each of the water sources included in the scope of the study. Adjustments to the flows—some facilities use different concentrations in the chemical dissolution; to standardize the input flows in the datasets, the concentration of the solute is adjusted to the concentrations available in the databases—were made to fit to the dataset input materials available in Ecoinvent.

3.6 Validation and statistics

After data compilation for each of the treatment processes, the calculation and statistical treatment is carried on. First, the intensity of each input is calculated equation (1) and a weighted average for each input is obtained using equation (2). This average will reflect the importance contribution of each facility in relation to the volume produced, giving a more realistic approach to the global drinking water production scenario in Finland.

$$x_i = \frac{z_i}{w_i}, \quad (1)$$

where x_i denotes normalized input flow (kg of material/kg of water or kWh/kg of water), z_i means input flow (kg/m³ or kWh/m³), and w_i means the mass flow of water produced (kg/year).

$$\bar{x}_w = \frac{\sum_{i=1}^n w_i x_i}{\sum_{i=1}^n w_i}, \quad (2)$$

where \bar{x}_w denotes the weighted average (m³/year). The weighted average is used to calculate the weighted standard deviation, which allow SimaPro to simulate a Monte Carlo distribution for the impacts of the inputs. The weighted standard deviation is calculated with equation (3).

$$SD_w = \sqrt{\frac{\sum_{i=1}^n w_i (x_i - \bar{x}_w)^2}{\frac{(M-1)}{M} \sum_{i=1}^n w_i}}, \quad (3)$$

where SD_w means the weighted standard deviation (kg of material/kg of water or kWh/kg of water) and M means the number of non-zeros weight.

Besides these descriptive statistics, a Monte Carlo simulation is used to validate the data. Monte Carlo simulation models systems or processes that involve uncertainty and randomness, as described by Thomopoulos (2012, pp. 1-7). It works by representing uncertain input variables with probability distributions and then performing repeated random sampling to generate a large number of possible scenarios. By aggregating these results, Monte Carlo provides an empirical approximation of the probability distribution of the output, allowing analysts to estimate metrics such as mean, variance, confidence intervals, and risk probabilities. Because it relies on repeated sampling, the accuracy of Monte Carlo estimates improves with the number of iterations, though at the cost of computational time.

These data points present a lognormal distribution, because they are physical measurements, positive skewed with a peak near to zero. For this reason, a lognormal Monte Carlo distribution is simulated. The normalized inputs are transformed into a logarithmic distribution (using natural log), from these values an average and standard distribution are calculated using equations (4) and (5).

$$\mu_{LN} = \frac{\sum_{i=1}^n \ln x_i}{M}, \quad (4)$$

where μ_{LN} denotes the mean for the logarithmic distribution (kg of material/kg of water or kWh/kg of water),

$$SD_{LN} = \sqrt{\frac{\sum_{i=1}^n (\ln x_i - \mu_{LN})^2}{(M-1)}}, \quad (5)$$

where SD_{LN} denotes the standard deviation for the logarithmic distribution.

Using excel and the normal distribution mean and standard deviation, a Monte Carlo simulation for a lognormal distribution can be done using the following excel command:

$$=LOGNORM.INV(RAND(); \mu_{LN}; SD_{LN})$$

where the Excel function $RAND()$ represents the probability density of the data simulated. The return of this function is a value (normalized input) for the variable simulated according to a lognormal distribution that represents the data simulated.

The Monte Carlo simulation was done to 100 iterations and a new average, geometric average, and percentiles (5% and 95%) were calculated to validate the data (Appendix B).

As some process inputs have only one data point, it is not possible to do a simulation for these inputs, instead only the weighted normalized value is calculated and included into the datasets. A standard deviation is then estimated using the Pedigree Uncertainty Calculation in SimaPro.

3.7 Datasets creation

Child datasets are created in SimaPro, using the following datasets;

- 'Tap water {Europe without Switzerland}| tap water production, conventional treatment | Cut-off, U',
- 'Tap water {Europe without Switzerland}| tap water production, groundwater with chemical treatment | Cut-off, U', and
- 'Tap water {RoW}| tap water production, artificially recharged wells | Cut-off, U'.

These child datasets were created as unit processes. All inputs and outputs amounts were replaced with the weighted average of the data collected and validated, along with the corresponding standard deviation. As some of the process inputs were different from the {Europe without Switzerland} and {RoW} locations, new inputs were included.

3.8 Impact assessments

The impact assessment for the drinking water production methods was done using SimaPro, after the creation of the datasets for each of the water treatment processes. The functional unit was defined in the datasets as 1 kg of drinking water), and the system boundaries (from raw material extraction to gate).

The selected impact assessment method was Environmental Footprint (EF) 3.1. This method is a standardized LCIA framework developed by the European Commission to support consistent and policy-relevant environmental evaluations of products and organizations. It is the official method used in the Product Environmental Footprint (PEF) and Organisation Environmental Footprint (OEF) initiatives, and it is designed to enhance comparability across sectors and regions (EPLCA, 2013).

EF 3.1 applies a midpoint modelling approach to evaluate 16 impact categories (Table 4), translating life cycle material flows into environmental impacts using scientifically derived characterization factors. It is an EU-centric method, with normalization based on EU-27 environmental impacts and it is aligned with the EU regulations. Also, it integrates models such as USEtox (for toxicity), ILCD (for climate and resource use), and other EU-endorsed frameworks.

Several network calculation setups were designed aiming to evaluate the impact assessment of each drinking water production method separately. Also, other calculation setups were designed to compare the new datasets with the current ones, and as sensitivity analysis for electric sources.

Table 4. *Impact categories evaluated on EF 3.1 (Earthster, 2023)*

Impact Category	Abbreviations	Unit	Indicator
Acidification	AP	mol H ⁺ -eq	AE
Climate Change	CC	kg CO ₂ -eq	GWP100
Ecotoxicity (Freshwater)	ET-freshwater	CTUe	USEtox
Eutrophication (Freshwater)	EP-freshwater	kg P-eq	EUTREND
Eutrophication (Marine)	EP-marine	kg N-eq	EUTREND
Eutrophication (Terrestrial)	EP-terrestrial	mol N-eq	AE
Particle Matter	PM	disease incidence	Impact on human health
Human Toxicity (Cancer)	HT-cancer	CTUh	USEtox
Human Toxicity (Non-Cancer)	HT-noncancer	CTUh	USEtox
Ionizing Radiation	IR	kBq U235-eq	Human exposure
Land Use	LU	Dimensionless(pt)	Soil quality index
Ozone Depletion	ODP	kg CFC-11-eq	ODP
Photochemical Ozone Formation	POF	kg NMVOC-eq	POFP
Resource Use (Fossils)	RU-fossil	MJ	Energy content
Resource Use (Minerals & Metals)	RU-minerals	kg Sb-eq	Abiotic depletion
Water Use	WU	m ³ world-eq	AWARE

The impact assessment is done with the network calculation function for all the newly created datasets for Finnish drinking water production methods, and the current available datasets. A comparison calculation function is done for the newly created datasets and the current datasets. This will allow to compare the impacts generated with the local data and the current data presented in the Ecoinvent DB.

3.9 Electric source sensitivity analysis

A sensitivity analysis was conducted to evaluate the influence of electricity source assumptions on the environmental impacts of drinking water production in Finland. Initially, the LCA datasets for drinking water production were created including as electricity source the Finnish electricity mix market dataset available in Ecoinvent DB. However, upon review, this dataset was found to be outdated, including imports from markets no longer active and failing to reflect recent advances in renewable energy integration within Finland's power system. To address this limitation, a sensitivity analysis was implemented to quantify the effect of using updated electricity source information.

Data on electricity sources were collected through the survey and subsequent interviews with participating water utilities. Each facility's electricity consumption was allocated according to the reported energy source, and weighted averages were calculated to represent the overall distribution of electricity types. Most responses referred to certified energy categories, specifically renewable or fossil-free electricity. For fossil-free electricity, nuclear power was selected as the representative source, while wind power was used for renewable electricity, as these technologies currently hold the largest shares in Finland's energy mix. In cases where respondents provided more specific sources, such as solar or biogas, these were allocated accordingly. Facilities reporting the use of standard market electricity retained the original Finnish electricity mix dataset.

A new set of LCA datasets was generated incorporating these updated allocations. Additionally, the environmental impacts associated with electricity transmission were considered, including inputs and outputs of sulphur hexafluoride (SF_6) and the transmission network. Finally, a comparative characterization of environmental impacts was performed for each water production method under both the original and updated electricity scenarios, enabling assessment of the sensitivity of results to changes in energy sourcing.

4. RESULTS AND DISCUSSION

4.1 Finnish drinking water datasets

The surveys collected data from 13 water treatment companies, some of them associate several facilities, especially groundwater treatment. These facilities produced 138 287 875 m³ during 2024, from this 83% correspond to surface water, 4% to groundwater and 13% to artificially recharged. This amount of water represents approximately 40.5% of the total drinking water produced in Finland, considering an estimated volume of 340 million m³ of water produced in 2022 (Vesilaitosyhdistys, 2023). This value gives us a good representability of the total amount of water produced, especially for surface water. Nevertheless, groundwater and artificially recharged groundwater cases will require more studies to have better representability.

Three derivative datasets were developed, including supplementary inputs according to predefined assumptions to address gaps in the primary data (Table 5). The inventory of each drinking water production method shows that most of them rely entirely or partly on chemical usage. Surface water treatment facilities tend to consume more chemicals—17 substances—than those treating groundwater or artificial groundwater —9 substances each. These remarks go in line with the observations made by Lehtoranta et al., (2023) in a study that covered 70% of the drinking water production from a 2011 inventory. This is due to the extensive treatment processes required by surface water, especially when dealing with high turbidity levels and NOM concentration (Verlicchi et al., 2024).

Electricity consumption in relation to the water source, varies according to economy of scale, water quality, aquifer locations, etc. as explained by different authors (EPA, 2015; Horváthová, 2022; Verlicchi et al., 2024). In this case, the electricity consumption from surface water— 2.17×10^{-4} kWh per kg of water produced—and artificially recharged groundwater— 3.81×10^{-4} kWh per kg of water produced—facilities benefit from economies of scale and the water quality, leading to lower electricity use, while smaller, decentralized groundwater plants consume more energy— 6.24×10^{-4} kWh per kg of water produced.

Table 5. *Weighted average for input flows in Finnish water treatment datasets*

Materials/fuels	Units	Artificially recharge groundwater	Groundwater	Surface water
Occupation, industrial area*	m ²	1.18E-10		
Transformation, from unspecified*	m ²	2.36E-12		
Transformation, to industrial area*	m ²	2.36E-12		
Water, lake	m ³	1.03E-03	1.03E-03	
Water, well	m ³			1.03E-03
Activated carbon	kg		8.85E-07	2.04E-06
Ammonia, anhydrous, liquid	kg	2.66E-08	6.15E-08	4.10E-07
Ammonium sulfate	kg	5.61E-08		1.75E-08
Building, hall, steel construction*	m ²	2.36E-12		
Carbon dioxide	kg	1.46E-06		1.20E-05
Chlorine dioxide	kg			3.06E-08
Chlorine, liquid	kg			6.90E-08
Excavation, hydraulic digger*	m ³	1.12E-10		
Hydrated lime	kg	1.04E-05	1.64E-07	1.27E-05
Hydrochloric acid 30% sln. without water	kg			1.26E-07
Iron(III) sulfate 12.5% iron sln. without water	kg			2.00E-05
Limestone	kg	1.92E-05	2.46E-06	1.40E-05
Oxygen, liquid	kg			8.59E-06
Polyaluminium chloride (PACl)	kg	1.46E-05		1.31E-06
Polypropylene (as tower packing)	kg	1.50E-08	1.60E-06	
Potassium permanganate	kg		1.98E-08	
Pump station*	p	2.06E-11	2.06E-11	
Quicklime	kg		8.20E-07	7.53E-06
Silica sand	kg	1.68E-05	7.02E-06	1.94E-06
Sodium chloride, brine solution	kg			6.10E-08
Sodium chloride	kg			1.56E-07
Sodium hydroxide, w/o water, in 50% sln.	kg		4.04E-06***	
Sodium hypochlorite, w/o water, in 15% sln.	kg	1.75E-06	3.64E-07	5.13E-07
Spent activated carbon	kg		-8.59E-07	-1.98E-06
Tap water	kg	5.19E-03	2.78E-02	4.30E-02
Ultraviolet lamp	p**	1.23E-09	2.10E-09	1.22E-09
Water works*	p**			1.52E-12
Electricity, medium voltage	kWh	3.81E-04	6.26E-04	2.17E-04

Among the outputs generated by the studied processes, drinking water production was identified as the primary product. Additionally, secondary streams such as effluents and solid materials were considered according to the scope of this study (Table 6). These side streams are managed in accordance with current Finnish wastewater treatment protocols, including recycling of solids and incineration for energy recovery.

Surface water treatment has the biggest wastewater output than the other drinking water production methods. This is directly proportional to the amount of clean water used for cleaning the filters and dissolution of some of the chemical substances. In the case of artificially recharged groundwater, it also includes the use of clean water for the settling tank, reported by one of the facilities.

Table 6. *Output flows for Finnish water treatment datasets*

Products/waste outputs	Units	Artificially recharge groundwater	Groundwater	Surface water
Tap water (treated drinking water)	kg	1.0	1.0	1.0
Wastewater	m ³	6,11E-06	2.78E-05	4.11E-05
Municipal solid waste to incineration*	kg	2.30E-07		4.30E-05
Core board to recycling	kg			6.93E-05
Paper recycling	kg			2.62E-06
Mixed plastics to recycling	kg		1.55E-06	

Due to the lack of direct measurements—none of the facilities has records of the amount of residual material, such as plastic packages, paper or mixed waste to incineration—the solid waste data is not fully reliable, and only some estimations were reported by 2 facilities. The same applies for the materials for recycling, even though this does not have an environmental impact according to the environmental footprint 3.1 method used for the LCA.

4.2 Life cycle assessment of Finnish drinking water production methods

The comparative evaluation of the impact assessment of the three drinking water production methods (Figure 5) exhibits similar environmental impacts across most categories. This convergence is attributed to the use of a common electricity mix in all processes, which is a major contributor to the overall environmental impact. Notable exceptions include ecotoxicity-freshwater, Human Toxicity–noncancer, ionizing radiation, Resource use-fossils, and Resource use-minerals and metals, where more pronounced differences are present. These variations are attributable to the chemical consumption of each drinking water production method.

The groundwater with chemical treatment shows the highest impacts in 9 out of 16 categories, primarily due to its elevated electricity demand, linked to pumping operations. Surface water with conventional treatment follows with 4 categories, with significant impacts driven by the extensive use of chemicals given the inherent vulnerability of surface water to contamination as reported by Klimtová et al. (2025) and Karnaningroem & Anggraeni (2021). These findings confirm that the environmental performance of each drinking water production method is closely tied to both the nature of the water source and the operational inputs required for treatment.

Among the drinking water production methods assessed, artificially recharged groundwater present higher environmental impacts in less categories, 3 out of 16. However, it exhibits a markedly higher impact in the ecotoxicity-freshwater category— 1.21×10^{-3}

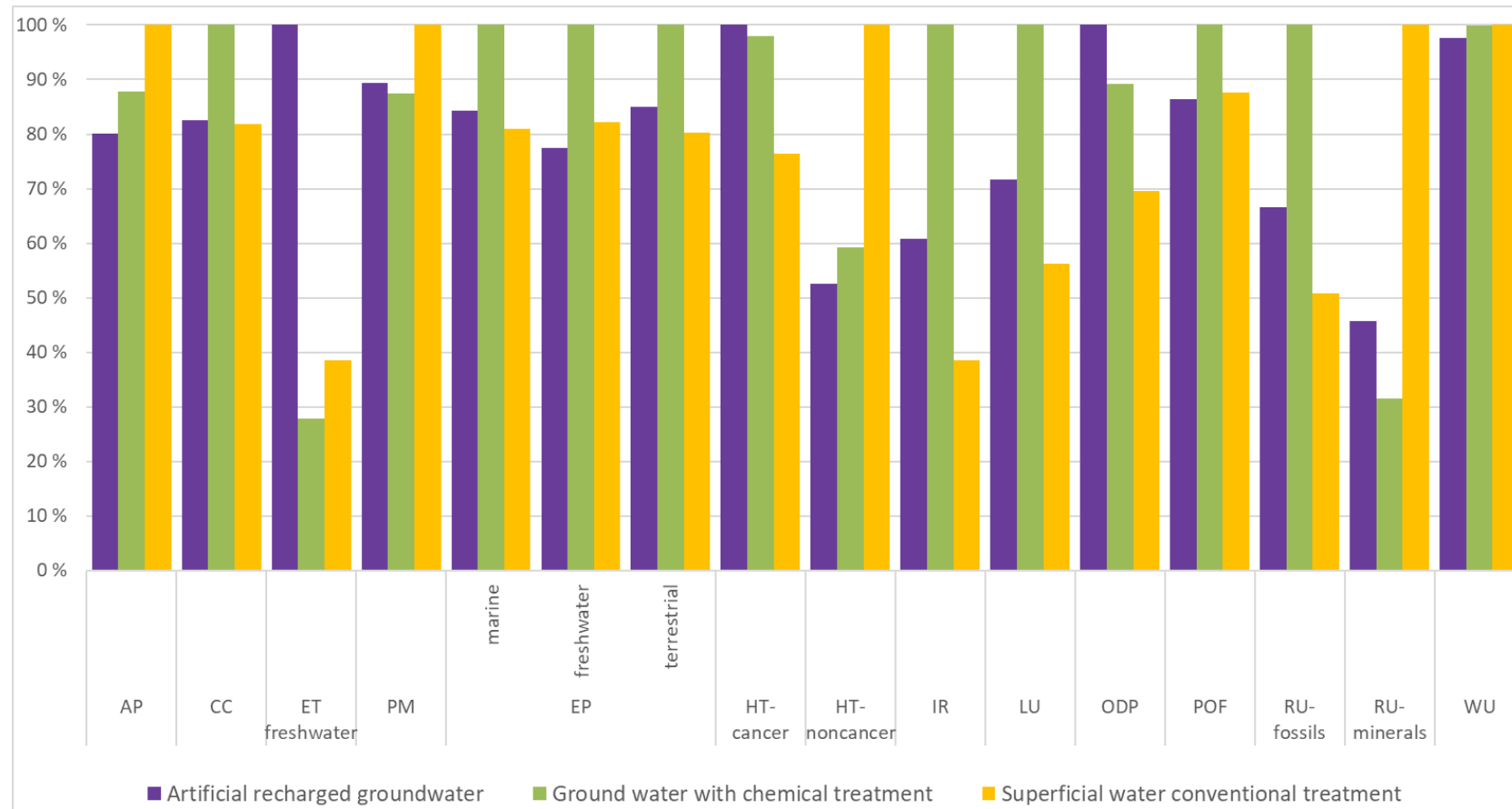


Figure 5. Comparison of environmental impact characterization of drinking water production methods in Finland. In each category the method with the highest impact has a value of 100%, and the other ones as the correspondent percentage of that total. AP = Acidification, CC = Climate Change, ET = Ecotoxicity, PM = Particulate Matter, EP = Eutrophication, HT = Human Toxicity, IR = Ionizing Radiation, LU = Land Use, ODP = Ozone Depletion, POF = Photochemical Ozone Formation, RU = Resource Use, WU = Water Use

CTUe/kg water—, exceedingly up 72% the other drinking water production methods— surface water: 4.68×10^{-4} CTUe/kg water, groundwater: 3.37×10^{-4} CTUe/kg water.

Climate change category presents an average of 3.37×10^{-4} kg CO₂-eq/kg water, which translates into 0.04 Gt CO₂ per year, considering the annual production of drinking water in Finland. This represents 0.117% from the 37.8 Gt CO₂-eq emissions energy-related emissions in 2024 (IEA, 2025).

An additional analysis conducted in this study involved the normalization of impact values, which scales the environmental impact results by comparing them (dividing by) to a reference value (normalization factor, see Appendix C) that represents the total annual environmental impact of an average person in Europe. This allows different impact categories to be expressed on a common scale, making it easier to compare their relative significance. As illustrated in Figure 6, the environmental impacts associated with the Finnish drinking water production methods fall below the European average values— normalized values are below 1.87×10^{-7} —indicating low impacts per kilogram of water produced, in all the categories.

However, certain impact categories are highlighted in the normalization results. The most evident is water use— 1.79×10^{-7} —, which shows the greatest deviation from the other categories. These results are expected, given that water is the primary resource in drinking water production and the abstraction water rates are inherently high. Other categories with relevant impacts include climate change— avg. 1.72×10^{-8} —, Eutrophication—freshwater—avg. 2.98×10^{-8} —, Resource use—fossils—avg. 5.22×10^{-8} —, and ionizing radiation—avg. 3.63×10^{-8} . These impacts are associated with conventional electricity generation and the significant electricity demand of water treatment processes (Klimtová et al., 2025; Bonton et al., 2012; Barjoveanu et al., 2019).

Nonetheless, as discussed in Chapter 2, Finland's energy matrix has undergone rapid transformation in recent years, shifting toward cleaner and more sustainable energy sources. While it is expected that this transition will reduce environmental impacts in these categories, the current results do not reflect these improvements due to the use of outdated electricity market data in the assessment. These deviations suggest that while the overall environmental performance of Finnish drinking water production is favourable in a European context, specific inputs may contribute disproportionately to certain impact areas. This stresses the importance of improvements in key impact categories, together with regular updates to background datasets, to ensure that LCA accurately reflect evolving energy profiles and effectively reduce the overall environmental footprint.

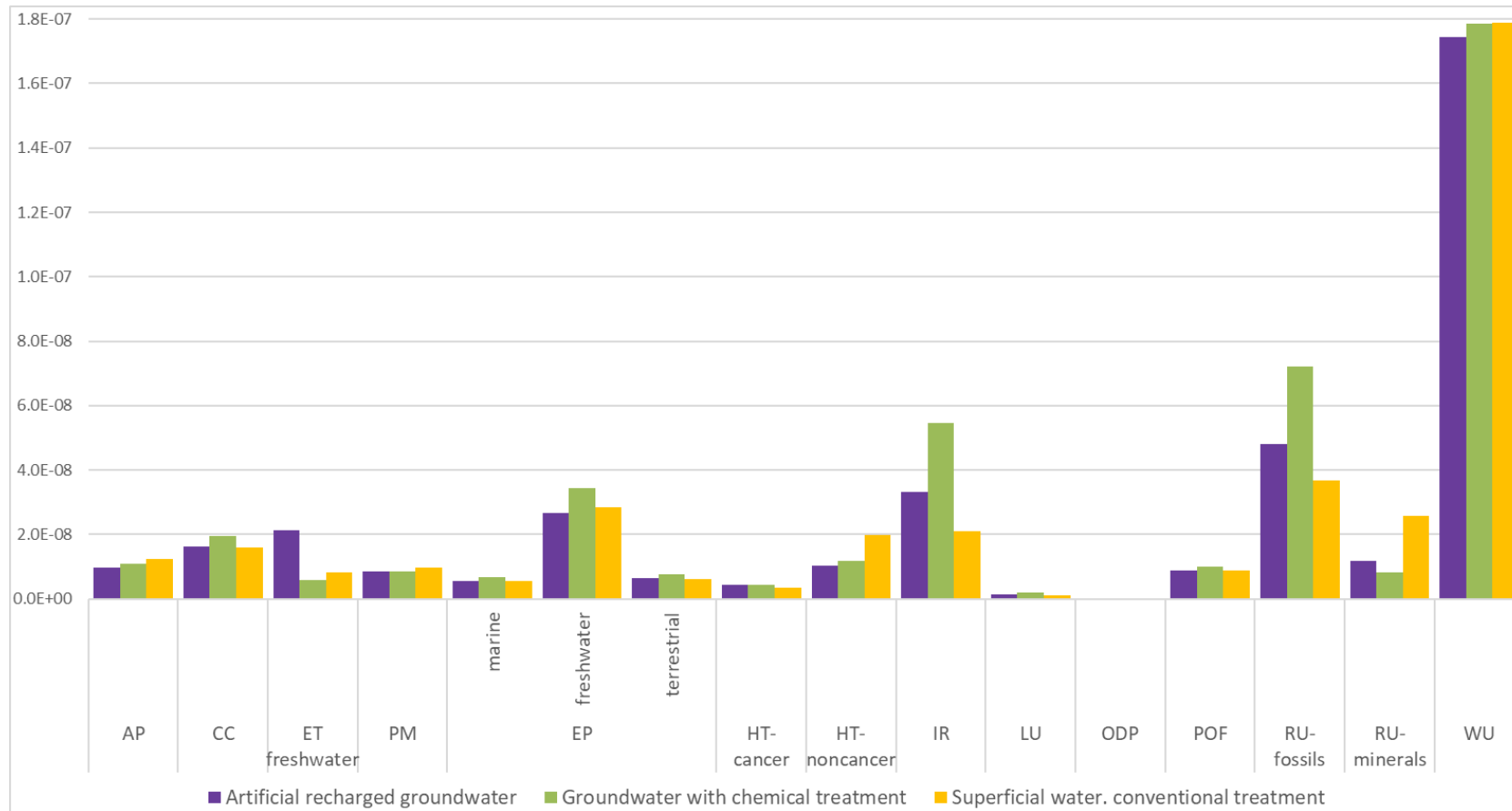


Figure 6. Comparison of normalized values for environmental impacts, according to the Environmental Footprint 3.1 normalization values, from drinking water production in Finland.

The remaining impact categories do not exhibit significant deviations from the European average consumption values—between 3.13×10^{-11} and 1.52×10^{-8} . While this does not imply that their environmental impacts are negligible, it suggests that they are less prominent in comparison to the categories with more pronounced differences. The survey data collected for this study reveal consistent impact profiles across the participating facilities resembling those reported by Klimtová et al., (2025), and Bonton et al., (2012), and the profiles that can be obtained with the available datasets in Ecoinvent.

This indicates a high degree of reliability and contextual relevance in the data gathered. The alignment between the newly developed datasets and those currently in use supports the representativeness of the study and validates the methodological assumptions applied during dataset construction.

4.3 Surface water conventional treatment impact assessment

The environmental impact assessment of drinking water production via surface water with conventional treatment reveals significant contributions from electricity consumption—12% to 88% depending on impact category—, ferric sulphate—1% to 67% depending on impact category—, and drinking water use—0.3% to 12% depending on impact category —, as shown in Figure 7. Barjoveanu et al., (2019) also identified electricity consumption and ferric sulphate as the main contributors for drinking water production from surface water. Unlike the other drinking water production methods assessed, this involves a broader and more varied chemical input profile, resulting in diverse distribution of contributors across impact categories. This characteristic makes harder to reduce the environmental impacts generated. Reducing the impact of surface water treatment requires a combined approach: cleaner energy, optimized chemical use, and substitution of chemicals (Lehtoranta et al., 2025) .

This method also exhibits the highest water consumption rate,—approximately 0.043 kg/kg of water produced—which is clearly reflected in the water use impact category. The elevated demand for both, treatment chemicals, and tap water, amplifies the environmental impact in categories where electricity production has lower impacts, such as ecotoxicity-freshwater, both human toxicity and resource use-minerals & metals. Most of these contributions are particularly sensitive to impacts from upstream processes, one clear case is the iron sulphate contribution in resource use-minerals & metals.

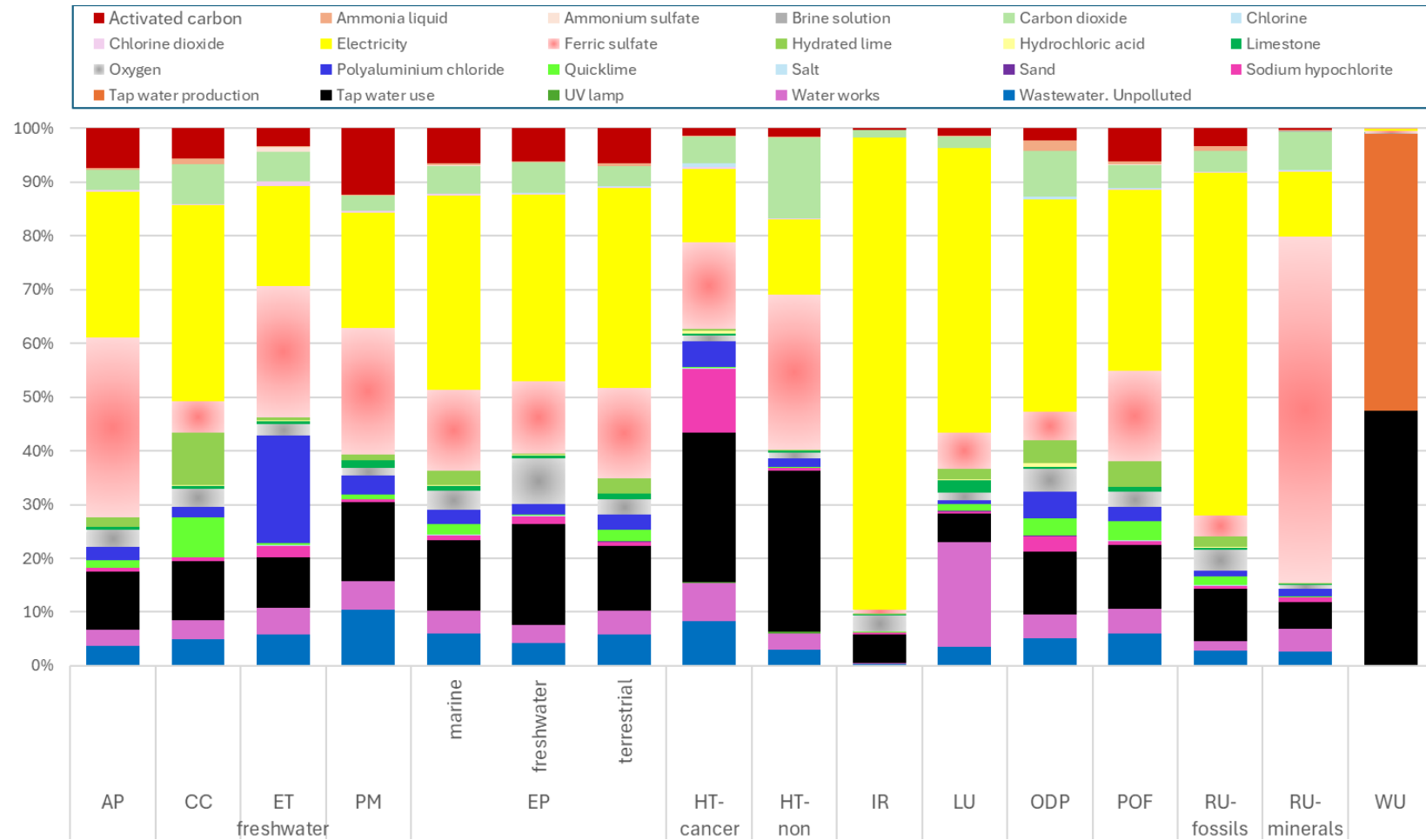


Figure 7. Impact assessment characterization of water production via conventional treatment of surface water. Each impact category is normalized to 100%, with the individual contributions segmented by colour

The climate change network (Figure 8a) confirms electricity consumption—35.9%— as the primary contributor, consistent with findings across other publications (Klimtová et al., 2025; Bonton et al., 2012). Drinking water use is the second contributor—10.7%— due to the upstream electricity consumption and its high input flow to this process.

Chemical consumption—such as hydrated lime(9.6%), quicklime(7.4%), ferric sulphate (7.3%), carbon dioxide(7.3%) and activated carbon(5.5%)—also contribute meaningfully to the climate change impact. These contributions are also related to the upstream emissions from the production process of these chemical compounds.

The majority of climate change impacts—approximately 99%—are associated with GWP from fossil-based sources (Appendix D). These results verify that electricity consumption has a more significant influence on climate-related impacts than chemical usage in water potabilization.

The climate change impact is 0.119 kg CO₂-eq/m³, which is consistent with values reported in previous studies, despite differences in methodologies and system boundaries. Lehtoranta et al. (2025) reported GHG emissions of 0.2 kg CO₂-eq/m³, based on production and distribution using a 2011 inventory. Li et al. (2024) reported GHG emissions between 0.167–0.272 kg CO₂-eq/m³, including fossil fuel combustion, reservoir emissions, electricity and heat supply, chemicals use, waste disposal, transportation, and maintenance. Meron et al. (2016) reported values between 0.16–3.4 kg CO₂-eq/m³, including treatment and transportation for surface water, groundwater and seawater. The lower value in this study can be attributed to the exclusion of distribution and waste disposal and the use of updated, region-specific inventory data.

The Human Toxicity–cancer process network (Figure 8b) shows a more distributed contribution profile, with tap water use accounting for 26.9%, ferric sulfate for 19.2%, and electricity consumption for 13.1%. The Human Toxicity–cancer impact is quantified as 5.78×10^{-14} CTUh— is considered negligible when evaluated against the characterization factors established by the USEtox model (Rosenbaum et al., 2008). This value represents an expected number of cancer cases is 0.02 per year if all the drinking water in Finland is produced by surface water with conventional treatment method.

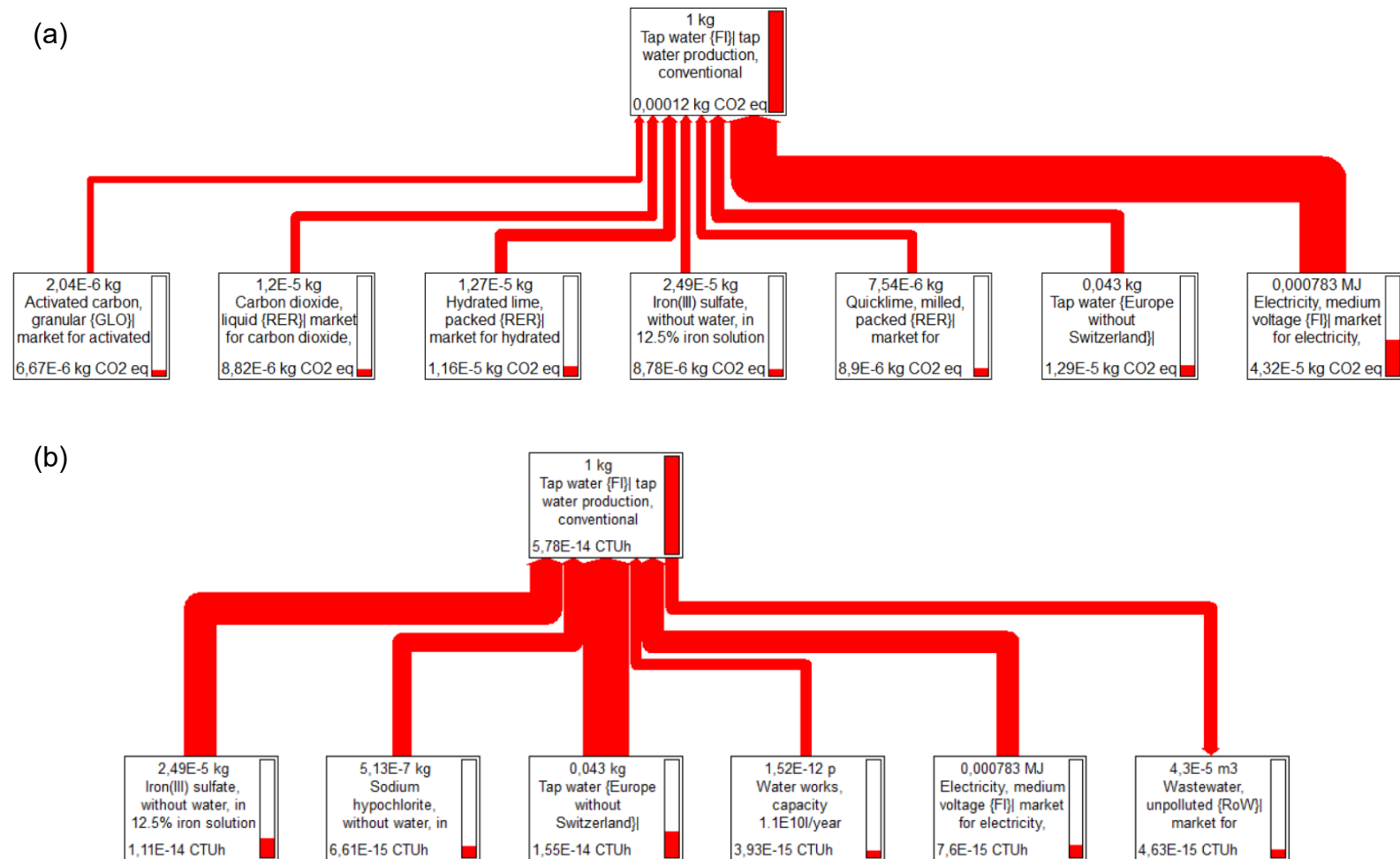


Figure 8. Process network for (a) climate change (kg CO₂-eq) and (b) Human Toxicity-cancer (CTUh) in Drinking Water Production via conventional treatment of surface water, with 5% threshold.

In summary, surface water conventional treatment shows a complex environmental impact profile, primarily driven by electricity consumption (up to 88%) and ferric sulphate use (up to 67%), with additional contributions from tap water use and various chemicals. Its broad chemical input makes impact reduction more challenging, requiring cleaner energy, optimized dosing, and chemical substitution. The method also has the highest water consumption rate, amplifying impacts in categories like ecotoxicity and mineral resource use. Climate change impact is estimated at 0.119 kg CO₂-eq/m³, mostly from fossil-based sources, with electricity as the main contributor. While human toxicity–cancer impacts are negligible, the overall results highlight the importance of upstream processes and region-specific data in assessing and mitigating environmental burdens.

4.4 Groundwater with chemical treatment impact assessment

The environmental impact assessment of groundwater treatment with chemical processes (Figure 9) reveals electricity consumption as the dominant contributor—26% to 98% depending on impact category—across all categories, except for water use. Sodium hydroxide has high contributions in ecotoxicity-freshwater—12%—and human toxicity-cancer—39%—related to its direct use in the drinking water production. Tap water use has a relevant contribution—31%—to human toxicity-noncancer impact, while pump station infrastructure does it in resource use-minerals & metals—27%. These impacts, like those related to electricity consumption, are linked to the upstream emissions of these inputs. Detailed characterization analysis is shown in Appendix E.

A key distinction from the surface water with conventional treatment method is the higher electricity consumption, which impacts all the categories significantly. This is an advantage in terms of impact reduction, focusing on transition to cleaner sources of energy can reduce most of the impacts associated to drinking water production methods from groundwater sources.

The climate change category network (Figure 10a) shows that electricity consumption accounts for 83% of the total impact, with other contributors falling below 6%. The quantified impact is 0.147 kg CO₂-eq/m³ water, the highest among the methods assessed. As in the surface water conventional treatment results, this value is lower than the ones reported by Lehtoranta et al. (2025) and Meron et al.,(2016). However, this difference is acceptable considering the differences in the studies exposed previously, added to the lower representability for groundwater with chemical treatment in the inventory data.

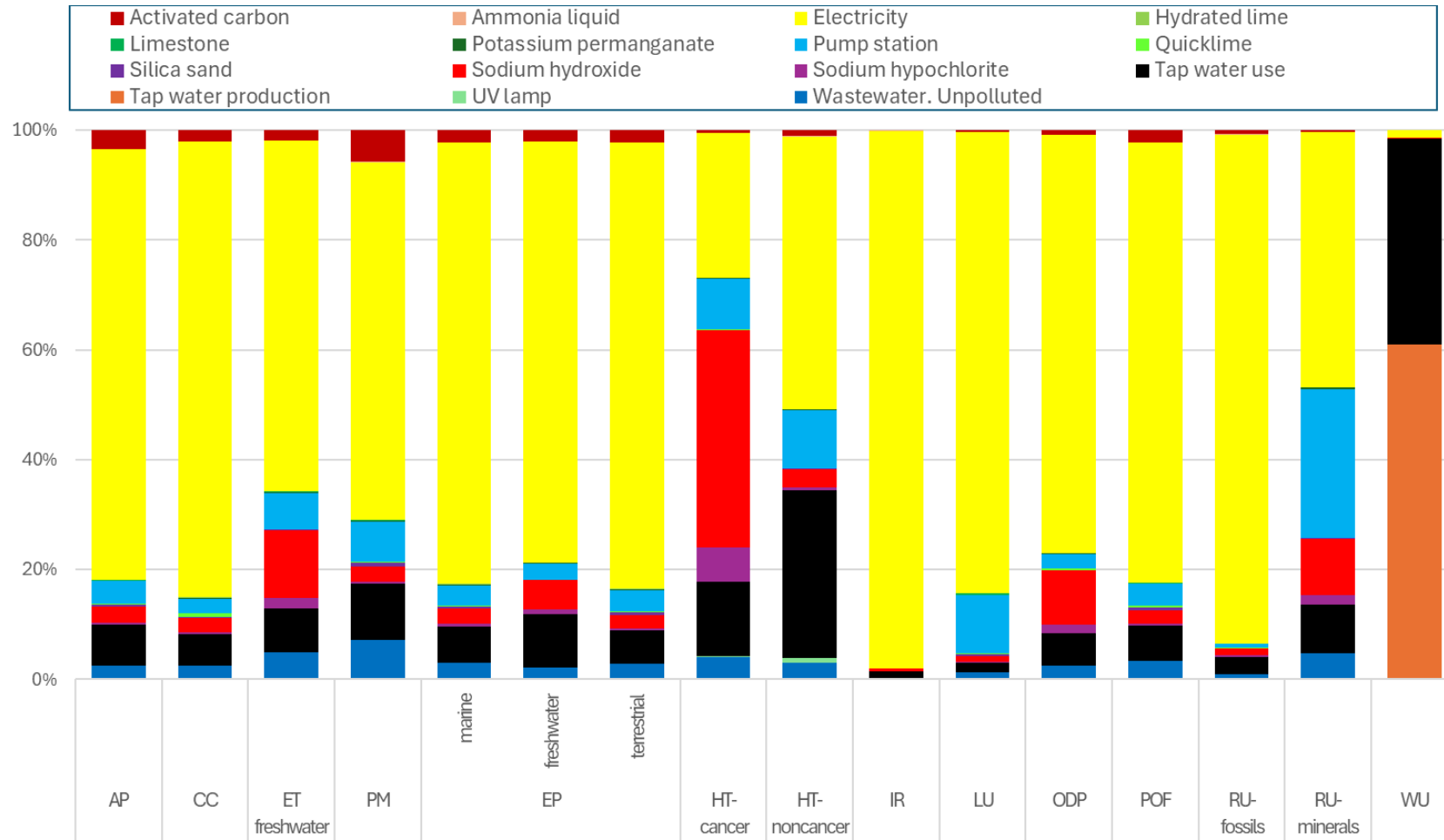


Figure 9. Impact assessment characterisation for water production via groundwater with chemical treatment. Each impact category is normalized to 100%, with the individual contributions segmented by colour.

Human Toxicity–cancer (Figure 10b) presents a more diverse set of contributors. Sodium hydroxide (50% solution) is the leading source, accounting for nearly 40% of the impact, followed by electricity—26%—percent and tap water use—14%. These contributions are primarily linked to upstream emissions associated with the infrastructure used in chemical production and the electricity sources mentioned in chapter 2.2. Despite this, the total impact—estimated at 7.41×10^{-14} CTUh—is considered negligible, representing 1 cancer case every 40 years.

In review, groundwater treatment with chemical processes exhibits the highest environmental impacts across many categories due to its substantial energy consumption, especially from carbon-intensive sources. These findings highlight the critical need for cleaner energy integration to improve the sustainability of this drinking water production method.

4.5 Artificially recharged groundwater impact assessment

The impact assessment characterization shows similar contribution as in the case of groundwater with chemical treatment (Figure 11). Electricity consumption is the dominant contributor—between 12% and 98%—across most environmental impact categories. This is partly due to the substantial electricity demand— 3.81×10^{-4} kWh/kg water vs. 2.17×10^{-4} kWh/kg for surface water—associated with drinking water production, but more significantly, it reflects the characteristics of the electricity dataset used in the assessment, as previously discussed.

The second most significant contributor is the polyaluminium chloride (PACl)—up to 81%—, which plays a notable role in several categories, especially ecotoxicity-freshwater, particle matter, ozone depletion, and human toxicity–cancer. The contribution to ecotoxicity-freshwater is result of direct used on water treatment, PACl can dissolve in water, releasing trivalent aluminium ions (Al^{3+}), which are toxic to aquatic organisms. Additionally, residual aluminium may accumulate in sediments, posing long-term risks to benthic species, as noted by Niinikoski-Fußwinkel et al. (2020).

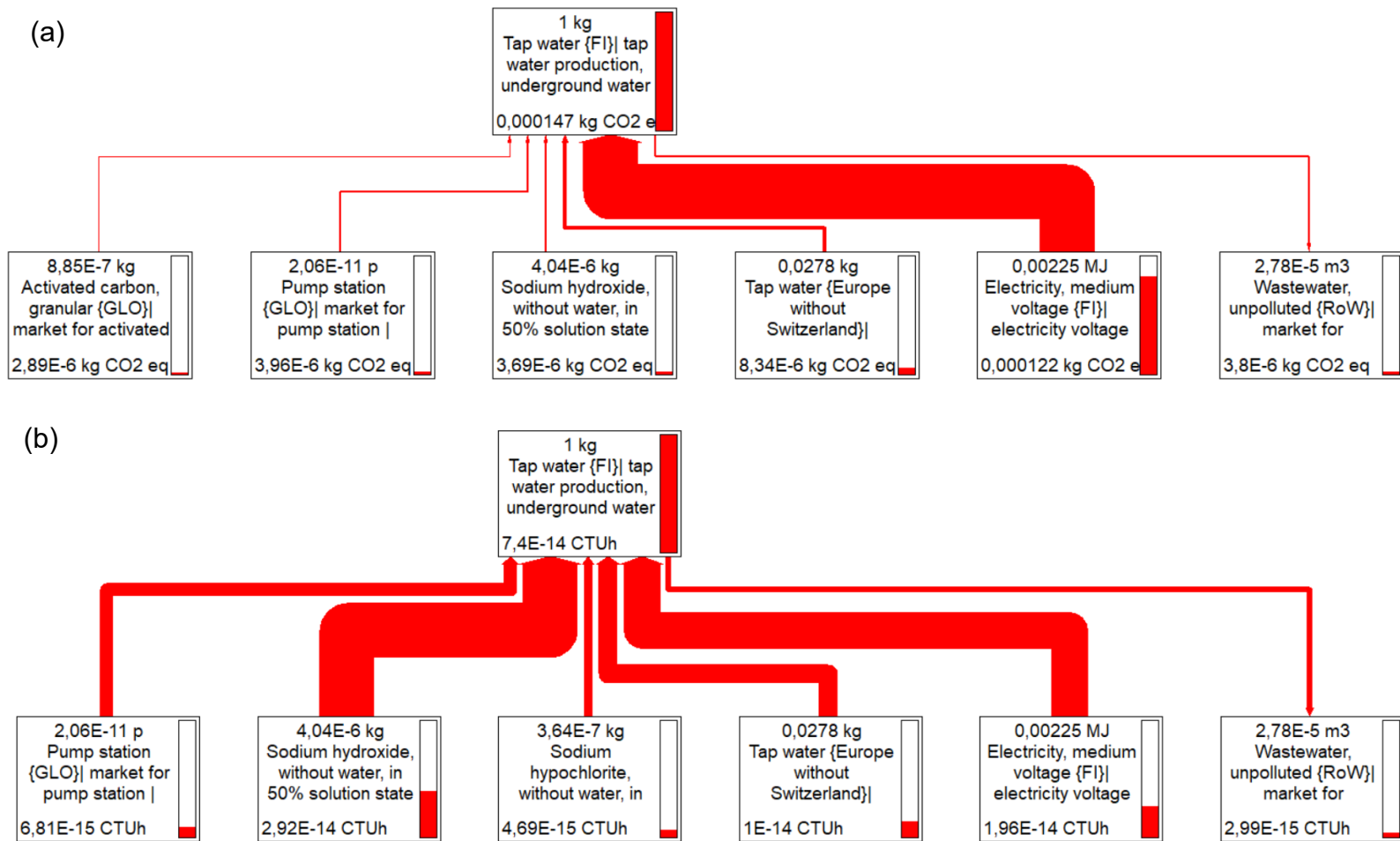


Figure 10. Process network for (a) climate change (kg CO₂ eq) (b) Human Toxicity-cancer (CTUh) in Drinking Water Production via groundwater with chemical treatment, with 1% threshold.

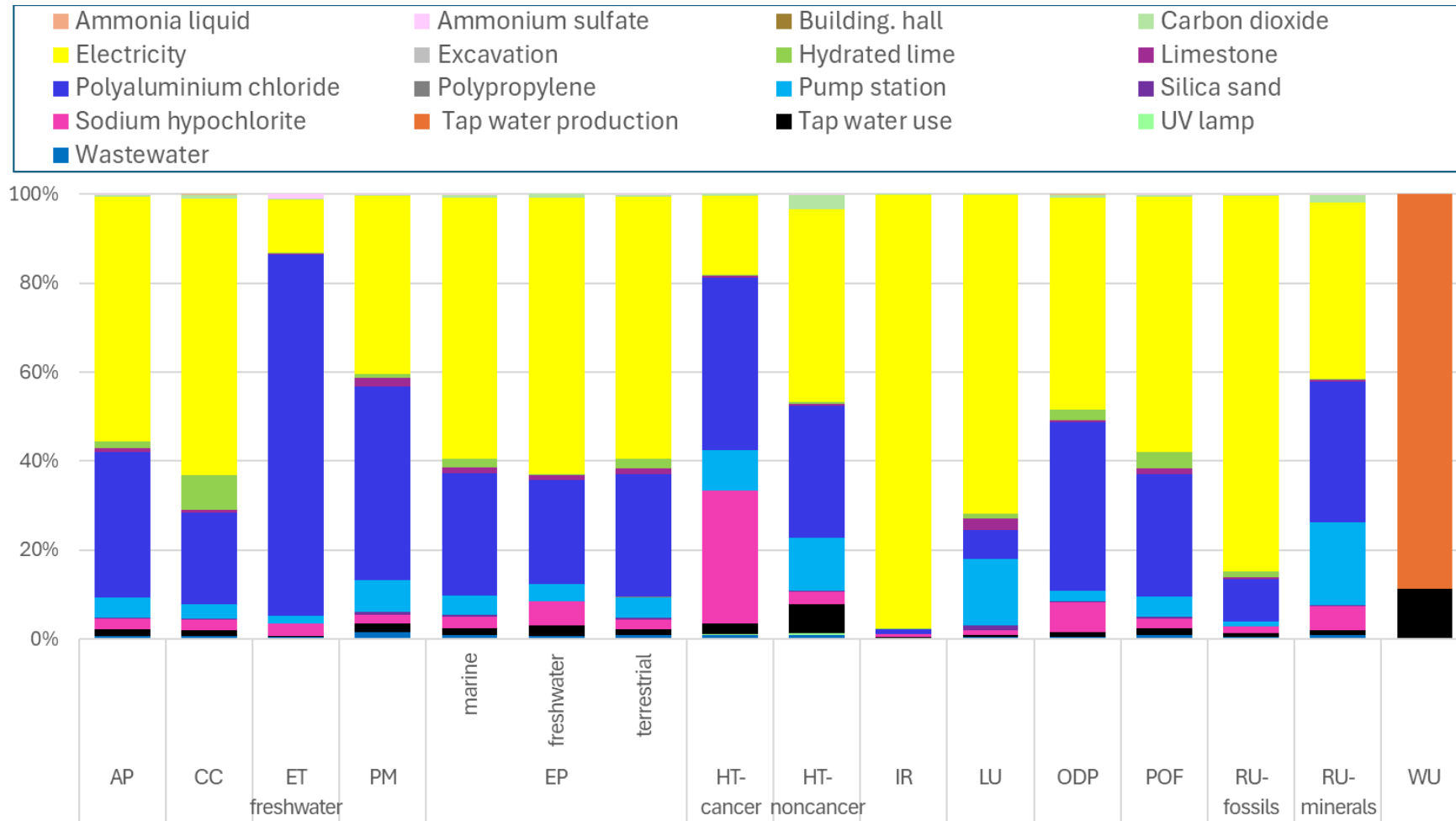


Figure 11. Impact assessment characterisation for water production via groundwater with chemical treatment. Each impact category is normalized to 100%, with the individual contributions segmented by colour

Sodium hypochlorite has a relevant contribution—31%—to human toxicity-cancer and has minor but consistent impacts across all categories. Further details on the characterization analysis are provided in Appendix F.

The impact assessments for artificially recharged groundwater and surface water with conventional treatment (Figures 7 and 11) enable a comparison of the contributions from ferric sulphate and PACl. Although both coagulants have relatively similar input flows—ferric sulfate 2.00×10^{-5} kg/kg water; PACl at 1.46×10^{-5} kg/kg water—their environmental impacts differ notably. PACl shows higher contributions than ferric sulfate in several categories, particularly climate change, ecotoxicity-freshwater, land use, and resource use-fossil. This disparity significantly influences the overall performance of the artificially recharged groundwater method, as reflected in Figures 5 and 6.

The climate change network process (Figure 12) shows electricity consumption as the main contributor, accounting for nearly 60% of the total. This is followed by PACl, which contributes approximately 20%. The network also illustrates upstream contributions associated with PACl production, revealing that the upstream emission related to manufacturing of aluminium hydroxide and hydrochloric acid are responsible for nearly 70% of the climate change impacts linked to PACl.

The climate change impact associated with drinking water production is primarily driven by the global warming potential (GWP), which is almost entirely—approximately 99%—attributable to fossil-based greenhouse gas emissions. The quantified impact is relatively low, 0.000122 kg CO₂-eq/kg water produced. This value is consistent with the values from the other drinking water production methods, and the values reported by Lehtoranta et al. (2025), Li et al. (2024), and Meron et al.,(2016), considering the differences between the studies, and the low representability of this method in the inventory data.

The freshwater ecotoxicity process network (Figure 13a) indicates that 81% of the contributions are linked to the direct use of PACl as coagulant during pretreatment, due to the chemical behavior of PACl in water, as explained before. Despite this, the total impact value— 0.00123 (CTUe)—remains at the lower end of the spectrum for chemical-related impacts in water treatment, which typically range from 0.001 to 0.1 CTUe according to the Joint Research Centre (2017), exhibiting higher eco-toxicity values than the other drinking water production methods, but it does not pose a significant ecological risk to aquatic species.

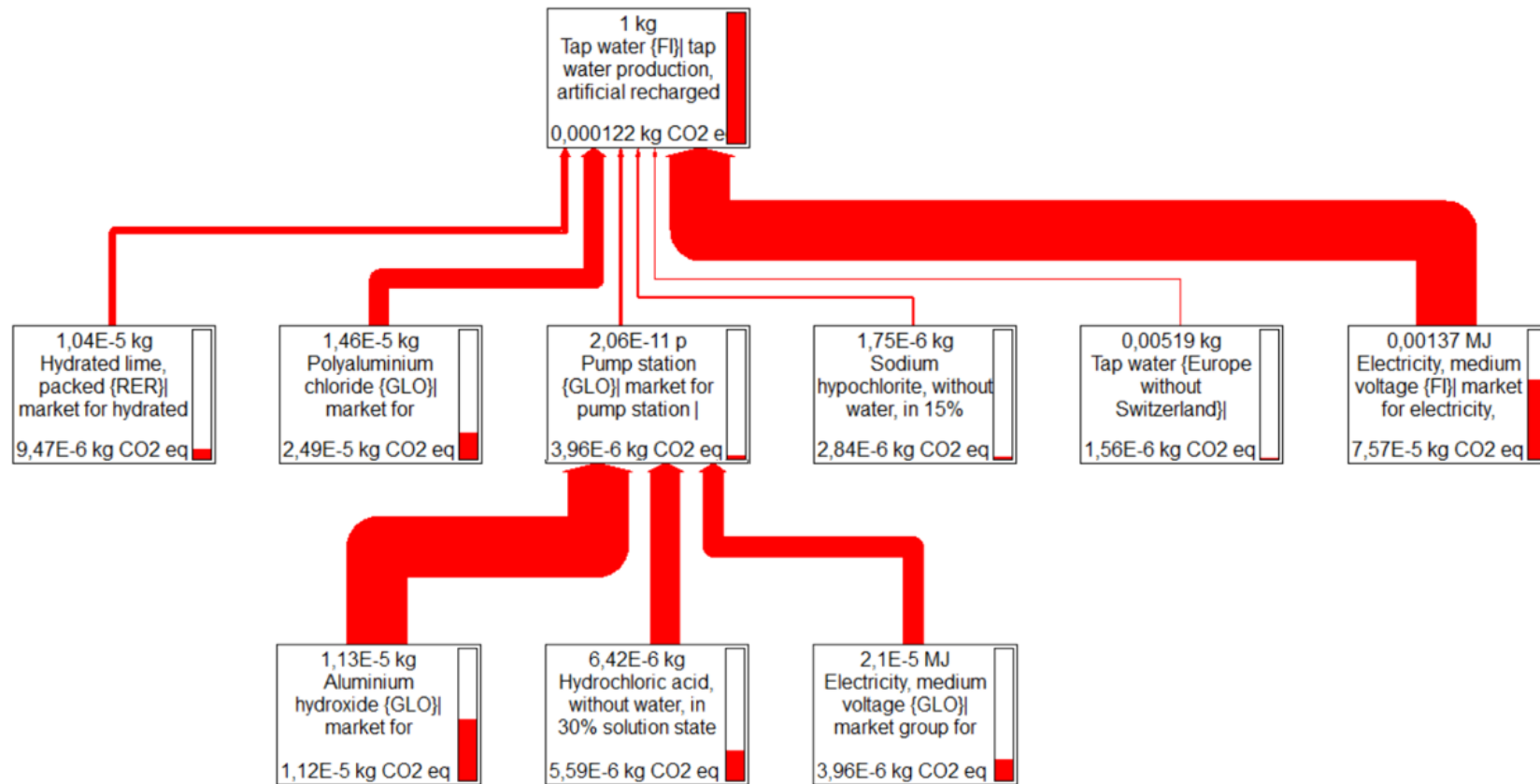


Figure 12. Process network for climate change (kg CO₂ eq) in drinking water production via artificially recharged groundwater, with 1% threshold.

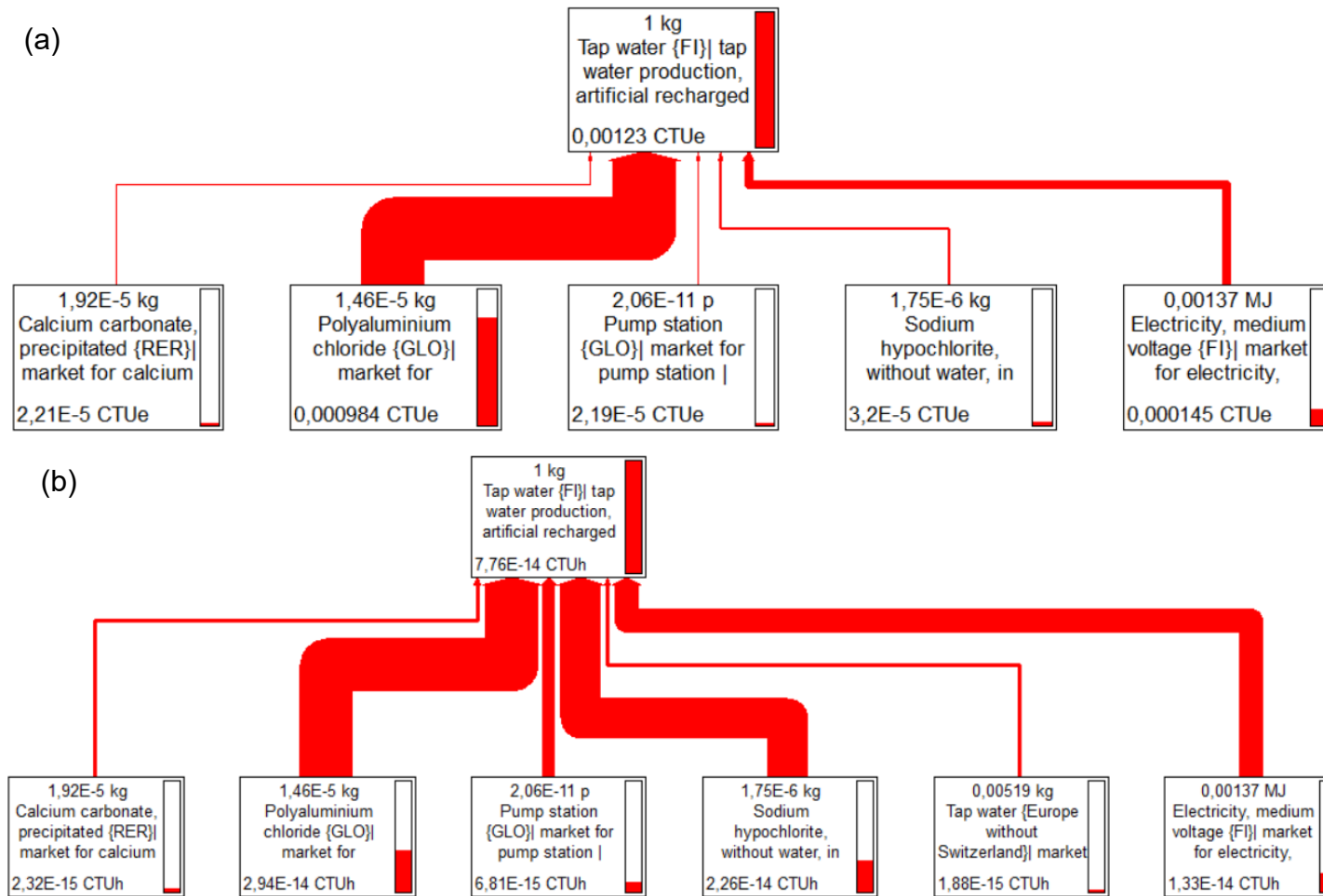


Figure 13. Process Network for (a) ecotoxicity-freshwater (CTUe) and (b) Human Toxicity-cancer (CTUh) in drinking water production via artificially recharged groundwater, with 1% threshold.

While the artificially recharged groundwater method exhibits the highest impact value in the human toxicity–cancer category (Figure 13b), this value —quantified as 7.78×10^{-14} comparative toxic units for humans (CTUh)— is considered negligible when evaluated against the characterization factors established by the USEtox model (Rosenbaum et al., 2008). Nonetheless, due to the relevance of this impact category, a closer examination of its contributors is reasonable. The analysis reveals that PACl is the primary contributor, accounting for approximately 38% of the impact, followed by sodium hypochlorite at 29%, electricity at 17%, and the pump station at nearly 9%. All of these contributions are linked to multiple up-stream emissions of toxic substances, reinforcing the importance of optimizing chemical use in water treatment systems.

In summary, the contribution scenario for artificially recharged groundwater is similar to the groundwater, where electricity consumption emerges as the principal contributor to most environmental impact categories. The main difference is the role of PACl in most of the impact categories. Other chemicals used in the final stages of treatment —primarily for disinfection— also show relevance in certain categories, alongside the impacts associated with the use and construction of pump stations. Despite these contributing factors, drinking water production via artificially recharged groundwater generally results in lower environmental impacts compared to the other two production methods assessed. This highlights its potential as a more sustainable alternative, particularly when opportunities for reducing chemical pretreatment are further explored.

4.6 Comparison against current datasets available in Ecoinvent 3.11

In addition to assessing the environmental impacts of each process individually, this study includes a comparative analysis against the existing dataset currently applied for drinking water production in Finland.

4.6.1 Surface water conventional treatment

For surface water conventional treatment, the newly developed Finnish dataset indicates slightly higher environmental impacts in three categories compared to the existing Ecoinvent dataset ('Tap water {Europe without Switzerland}, tap water production, conventional treatment'; see Figure 14). These differences, ranging from 2% to 11%, are primarily due to variations in chemical inputs, particularly coagulants. Finnish facilities use ferric sulphate and PACl, whereas the European dataset reflects the use of ferric sulphate and aluminium sulphate. Such differences are linked to regional physicochemical characteristics of surface water and seasonal conditions, as discussed in Chapter 2.

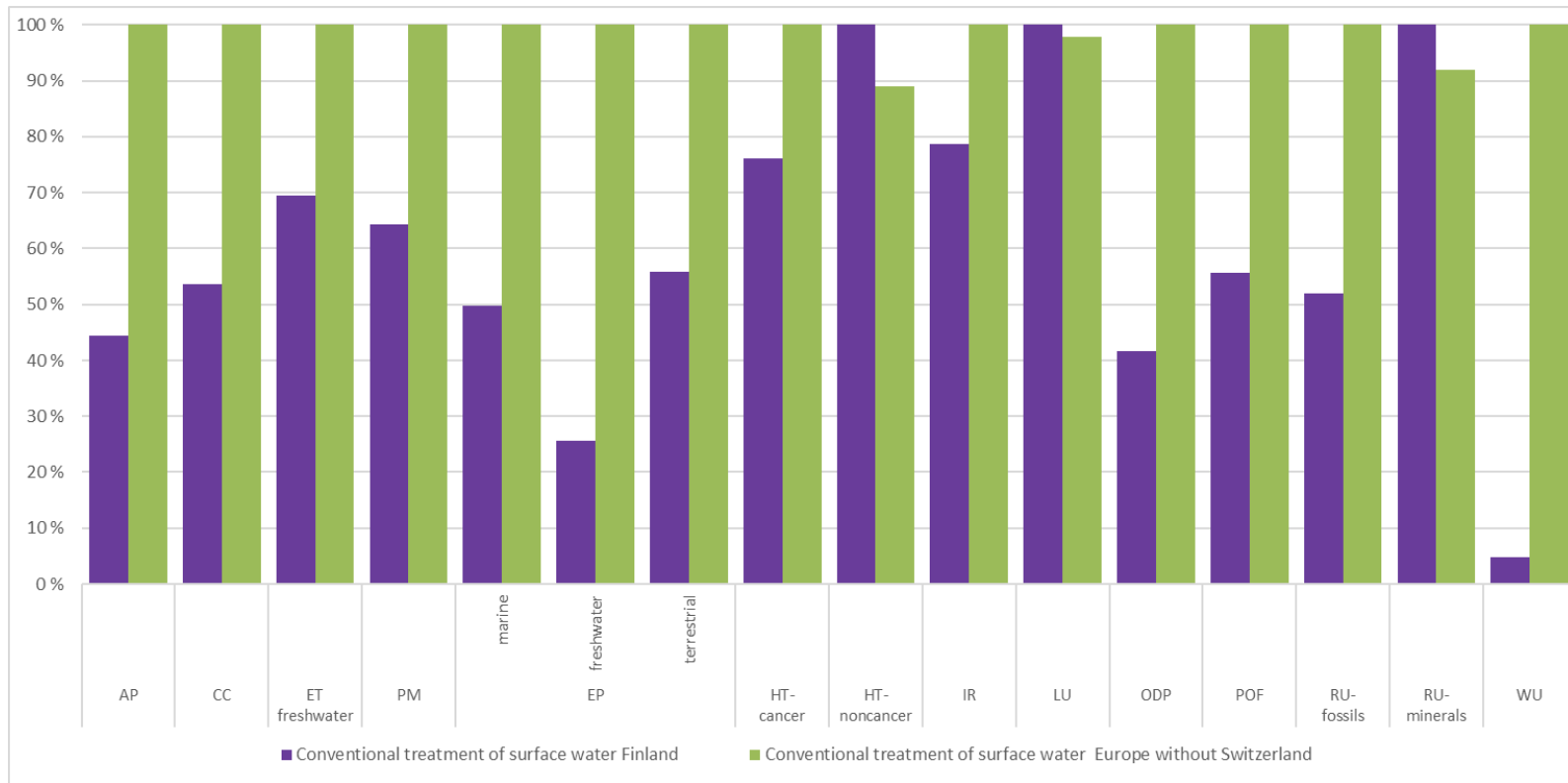


Figure 14. *Relative environmental impact comparison between Finnish and European datasets for surface water conventional treatment (highest impact normalized to 100%).*

However, the Finnish dataset present lower impacts in most of the categories—13 out of 16. In climate change impact presents a reduction 46%—from 0.22 to 0.12 kg CO₂-eq/m³ water—related in grand part to the difference in the electricity consumption—Finnish: 0.217 kWh/m³ water, European: 0.427 kWh/m³ water. Despite the big difference, both values correlate with data reported by Sowby & Thompson, (2021) —0.059-0.565 kWh/m³ water — for nine surface water drinking production plants.

In addition to the higher demand, the European electricity mix includes sources with greater environmental impacts, such as lignite, hard coal, and natural gas—particularly in countries like Germany and Poland—as well as nuclear energy in France. This energy-intensive production method contributes significantly to the overall environmental footprint in both datasets, with a more pronounced effect in the European case.

Other factor that affects the climate change impact is the sources of heat energy. While Finnish facilities reported use of heat pumps or district heating—main fuel biomass (Laihanen et al., 2023)—, the European dataset includes district heating and diesel-based heating.

Additionally, the use of aluminium sulphate in the European dataset contributes significantly to impact categories such as acidification potential, ecotoxicity–freshwater, Particle matter, Human Toxicity—both cancer and non-cancer— and resource use–minerals and metals. These elevated impacts are associated with the upstream production of aluminium sulphate and the relatively high quantities required for coagulation in European water treatment facilities.

4.6.2 Ground water with chemical treatment

In the comparison of tap water production via groundwater with chemical treatment (Figure 15), the Finnish dataset shows higher environmental impacts in only two categories: Ionizing radiation and land use. The elevated ionizing radiation impact is attributed to the higher share of nuclear energy within Finland's electricity mix, which significantly influences the kBq U235-eq indicator. The higher land use impact is associated with the use of wood chips in cogeneration systems for electricity production, a common feature of the Finnish energy profile.

Comparing the impact in climate change category a difference of 52%%—from 0.31 to 0.15 kg CO₂-eq/m³ water—shows a big reduction in the quantification in favour of the newly created Finnish dataset. This reduction, as in the case of surface water, is mainly related to the energy consumption values—Finnish: 0.624 kWh/m³ water, European: 0.841 kWh/m³ water.

In both cases, surface water and groundwater, the profile of the newly datasets are similar, showing almost same patterns compared to its European counterparts. This aligns with Lehtoranta et al. (2025), who emphasize that process optimization and the adoption of advanced technologies can significantly reduce overall emissions.

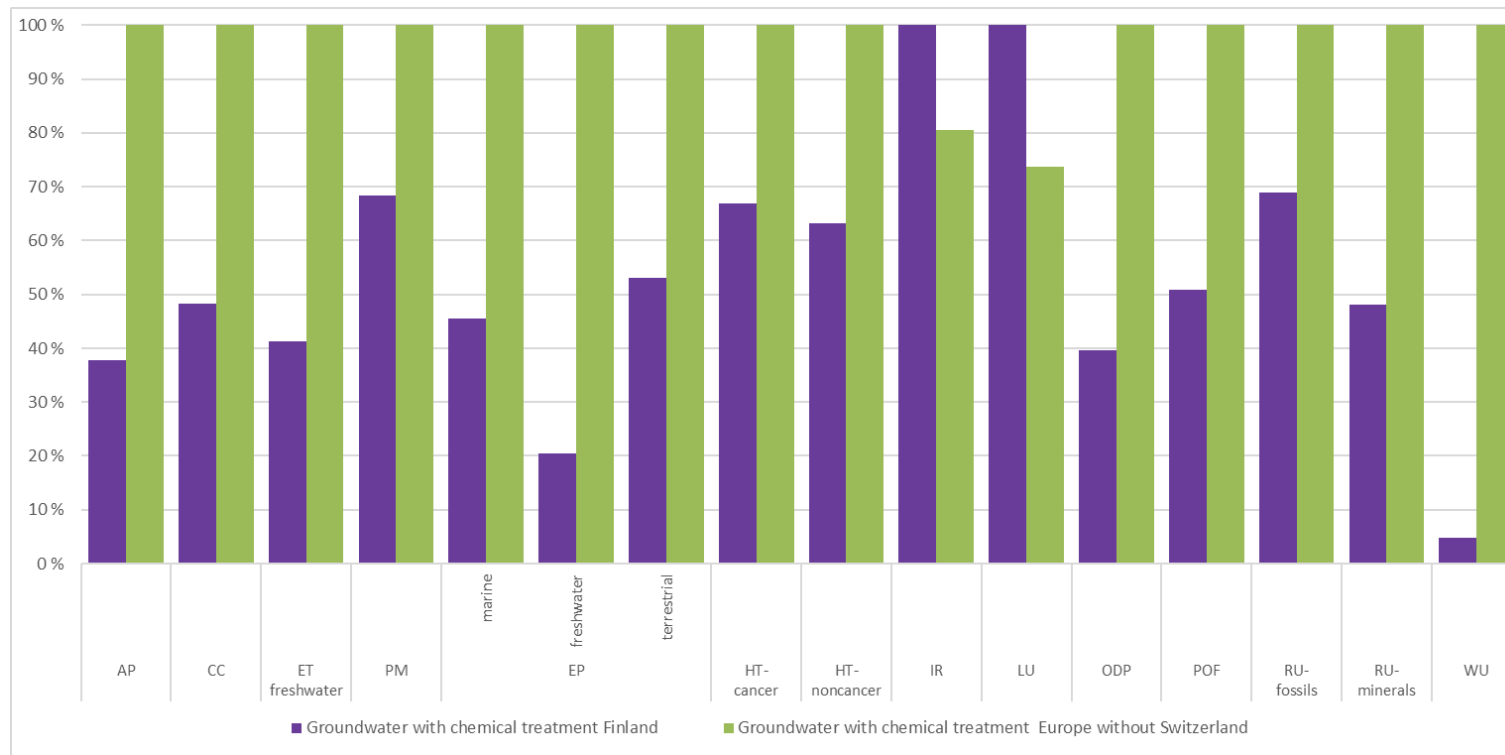


Figure 15. *Relative environmental impact comparison between Finnish and European datasets for groundwater with chemical treatment (highest impact normalized to 100%).*

4.6.3 Artificially recharged groundwater

Ecoinvent 3.11 does not include a European-specific dataset for artificially recharged groundwater. Consequently, a comparative analysis was performed between the newly developed dataset for Finland and the existing dataset for the Rest of the world (RoW) 'Tap water {RoW}, tap water production, artificially recharged wells' (Figure 16). It is important to note that the RoW dataset only includes input flows related to the disinfection process—chlorine and UV lamps—, electricity consumption, and shared infrastructure inputs, while the newly Finnish dataset includes chemical inputs for the pretreatment, as outlined in Table 4.

Despite incorporating more detailed pretreatment steps and input flows, the Finnish dataset shows lower environmental impacts in 11 out of 16 categories. Although similar electricity consumption values—Finnish: 0.381 kWh/m³ water, RoW: 0.358 kWh/m³ water—the Finnish dataset climate change impact presents an equivalent to 70% of the RoW value—Finnish: 0.122 kg CO₂-eq/m³ water, RoW : 0.407 kg CO₂-eq/m³. These reductions are directly related to differences in heat energy sources and electricity sources. For heat sources Finnish facilities rely on heat pumps or district heating, whereas the RoW dataset assumes diesel-based heating—which account for 40% of the impact—. Finnish electricity sources present a higher share of cleaner energy than the global mix presented in the RoW dataset.

These differences between the electricity sources also explain the higher impact values of the Finnish dataset in the impact categories land use, ionising radiation, and resource use-minerals & metals. The first one is related to the cogeneration based on woodchip, while the others are linked to nuclear power operation and construction of power plants.

The difference in ecotoxicity-freshwater—Finnish: 1.21 CTUe/m³ water, RoW: 0.69 CTUe/m³ water—, is related to the contribution of the PACl in the pretreatment coagulation, for the Finnish drinking water production. As mentioned before, the RoW do not include any pretreatment for the water used to recharge the basin.

In brief, the newly created datasets for Finnish drinking water production, presents several differences in the impact assessment compared to the current datasets available in Ecoinvent. For drinking water production sourced from surface water and groundwater, the differences are related to the differences in electricity consumption. For artificially recharged groundwater the differences are related to the electricity sources, which are notable different due to the geographical region of the current available dataset. This highlights the importance of using local datasets when evaluating process impacts, a conclusion also emphasized by Meron et al. (2016).

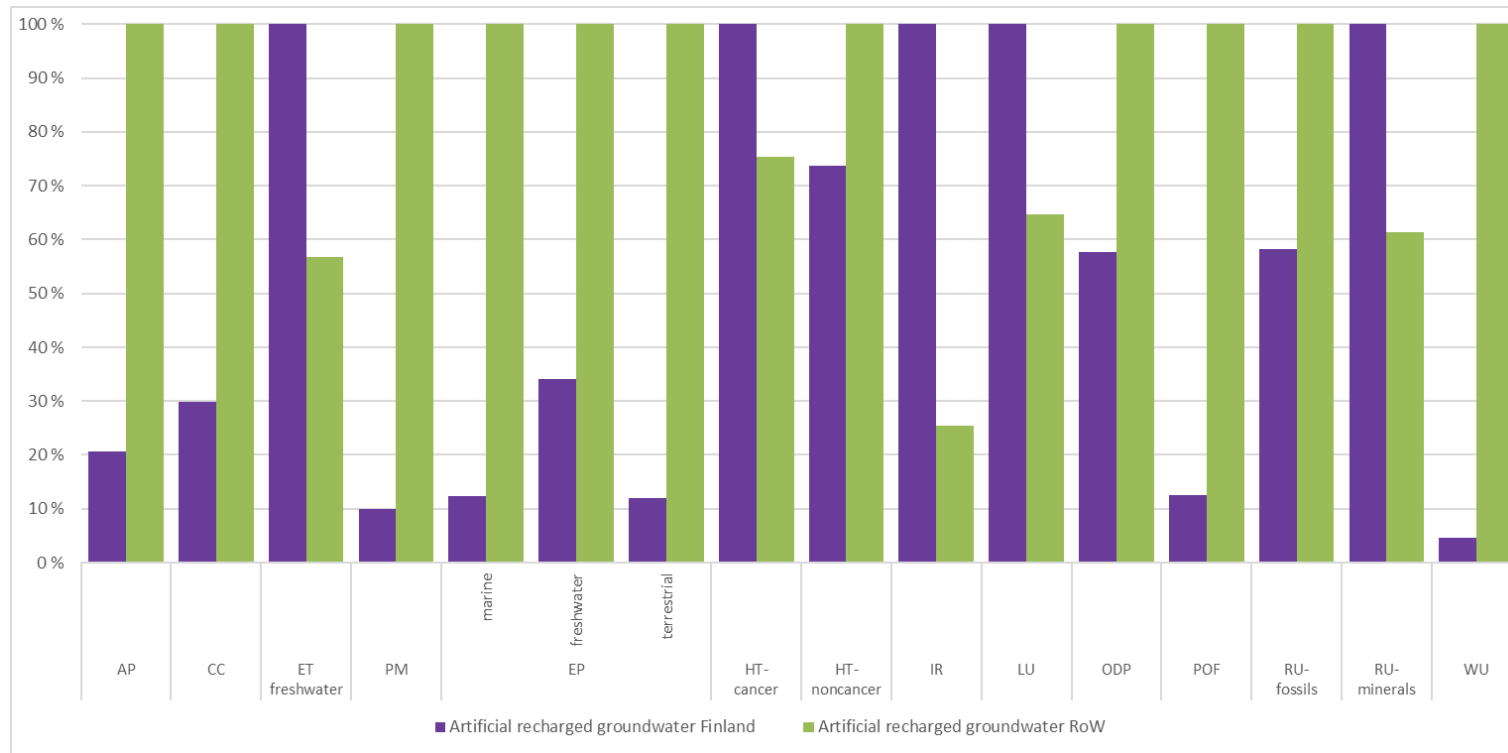


Figure 16. Relative environmental impact comparison between Finnish and European datasets for artificially recharged groundwater (highest impact normalized to 100%)

4.7 Electricity source sensitivity analysis

Due to the outdated information in the currently available electricity mix datasets, a sensitivity analysis was conducted to evaluate the influence of electricity sources on the environmental impact assessment of the three tap water production methods considered in this study. Instead of using the generic dataset 'Electricity, medium voltage {FI} | market for electricity', alternative electricity datasets categorized by fuel type were selected based on the actual energy sources reported by the participating facilities. The distribution of these sources is presented in Table 7.

Table 7. Datasets used for electricity source sensitivity analysis

Dataset	Units	Artificially Recharge groundwater	Groundwater	Surface water
Electricity, low voltage {RoW} biomethane, low pressure burned in polymer electrolyte membrane fuel cell 2kWe	kWh			2.91E-05
Electricity, high voltage {FI} electricity production, hydro, run-of-river	kWh			1.49E-05
Electricity, medium voltage {FI} market for electricity, medium voltage	kWh	9.94E-05		1.32E-05
nuclear	kWh	1.97E-04	6.22E-04	9.89E-05
Electricity, low voltage {FI} electricity production, photovoltaic, 3kWp slanted-roof installation, single-Si, panel, mounted	kWh		2.46E-06	1.83E-06
Electricity, high voltage {FI} electricity production, wind, >3MW turbine, onshore	kWh	8.42E-05	2.29E-06	5.95E-05
Sulfur hexafluoride, liquid {RER} market for sulfur hexafluoride	kg	3.18E-11	7.08E-11	2.31E-11
Transmission network, electricity, medium voltage {GLO} market for transmission network, electricity, medium voltage	km	5.25E-12	1.17E-11	3.81E-12
Emission to air - sulfur hexafluoride	kg	3.18E-11	7.08E-11	2.31E-11

In addition to updating the electricity source datasets, inputs related to sulphur hexafluoride emissions and transmission infrastructure were calculated to account for the environmental impacts of electricity distribution from the newly selected sources. Sulphur hexafluoride emissions to air were included based on values expressed per kWh in the existing dataset 'Electricity, medium voltage {FI} | market for electricity'.

For conventional surface water treatment (Figure 17), 94% of the electricity sources were reallocated based on facility-reported data: nuclear (45%), wind (37%), biogas (13%), hydroelectric (7%), and solar (1%). This updated energy mix led to reductions in most environmental impact categories, such as climate change, with 26% less emissions—from 0.12 to 0.09 CO₂/m³ water—due to the reduction on gas and carbon-intensive fuels. However, the magnitude of these reductions are small, due to the lower overall electricity demand in this process and the relatively high share of biogas, which carries moderate environmental impacts.

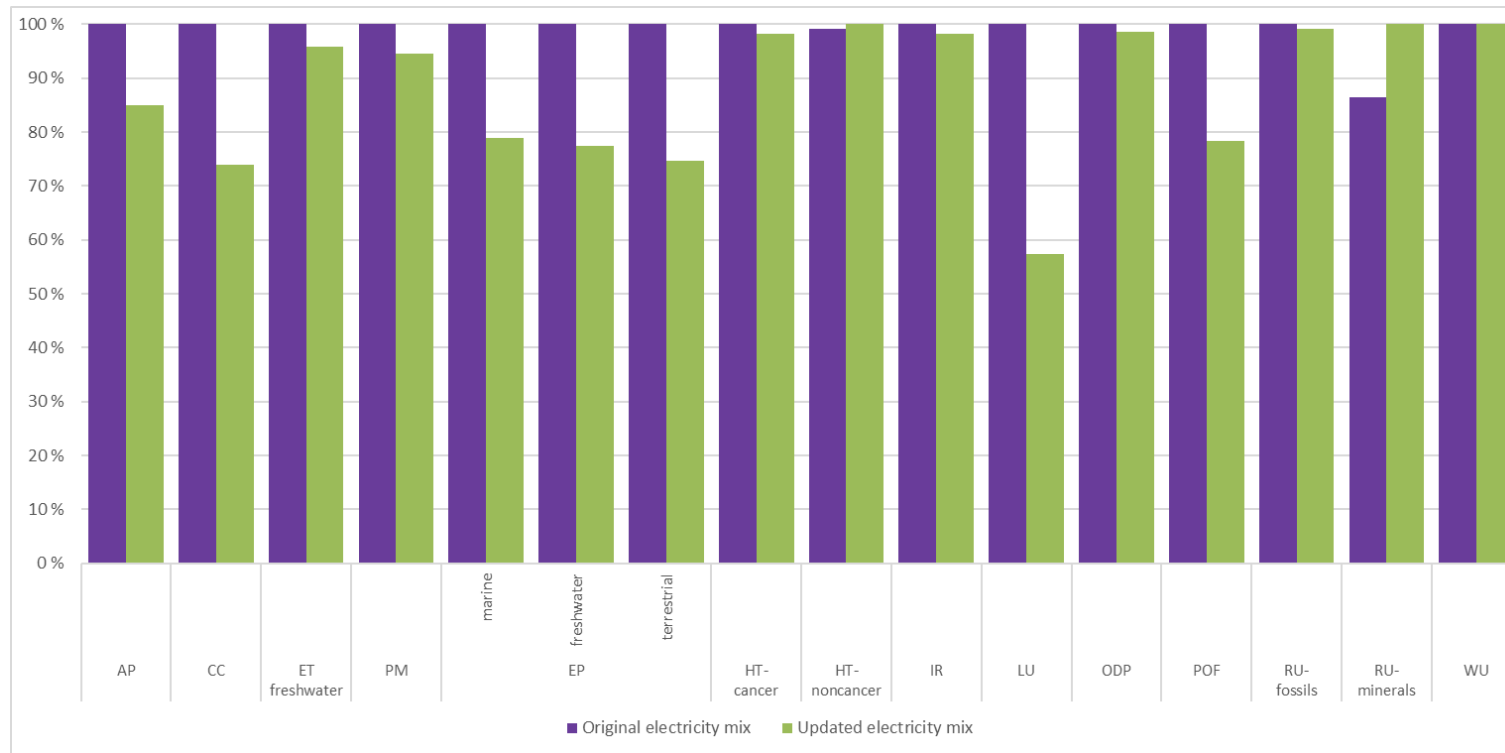


Figure 17. Relative environmental impacts for electricity source sensitivity analysis in surface water with conventional treatment (highest impact normalized to 100%)

For groundwater facilities using chemical treatment, all electricity sources were allocated as 99.2% sourced from nuclear power, with the remaining 0.8% derived from wind and solar energy. As shown in Figure 18, this reallocation leads to reductions in most environmental impact categories. The reductions are particularly notable in acidification potential, climate change, Eutrophication-freshwater, Eutrophication-terrestrial, land use, and ozone depletion. The climate change impacts were reduced by 79%—from 0.15 to 0.03 CO₂/m³ water—. This is a remarkable reduction

considering that the electricity consumption is the same, and only adopting cleaner fuels make a great advance towards drinking water production carbon zero.

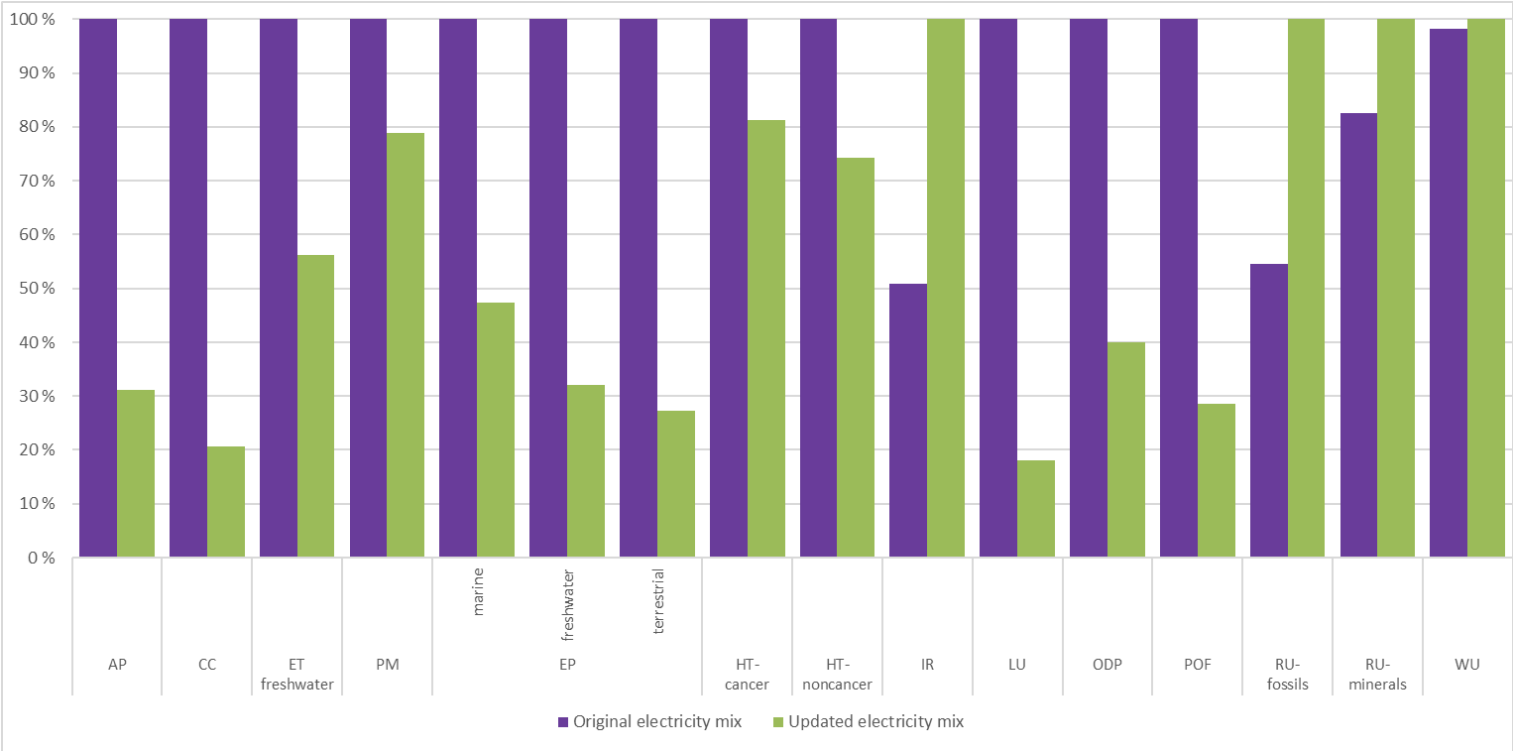


Figure 18. Relative environmental impacts for electricity source sensitivity analysis in groundwater with chemical treatment (highest impact normalized to 100%).

However, increases are observed in ionizing radiation and resource use—minerals and metals, consistent with the higher share of nuclear energy. These increases are linked to the upstream impacts of nuclear infrastructure, and the material demands associated with renewable energy technologies, such as copper for wind turbines and concrete for nuclear facilities.

For artificially recharged groundwater facilities, 76% of the electricity consumption was reallocated to specific energy sources—nuclear (57%) and wind (22%)—based on survey responses and follow-up communications. The remaining 24% retained the original dataset due to lack of detailed energy source information. The updated electricity mix resulted in reduced environmental impacts across most categories, as shown in Figure 19.

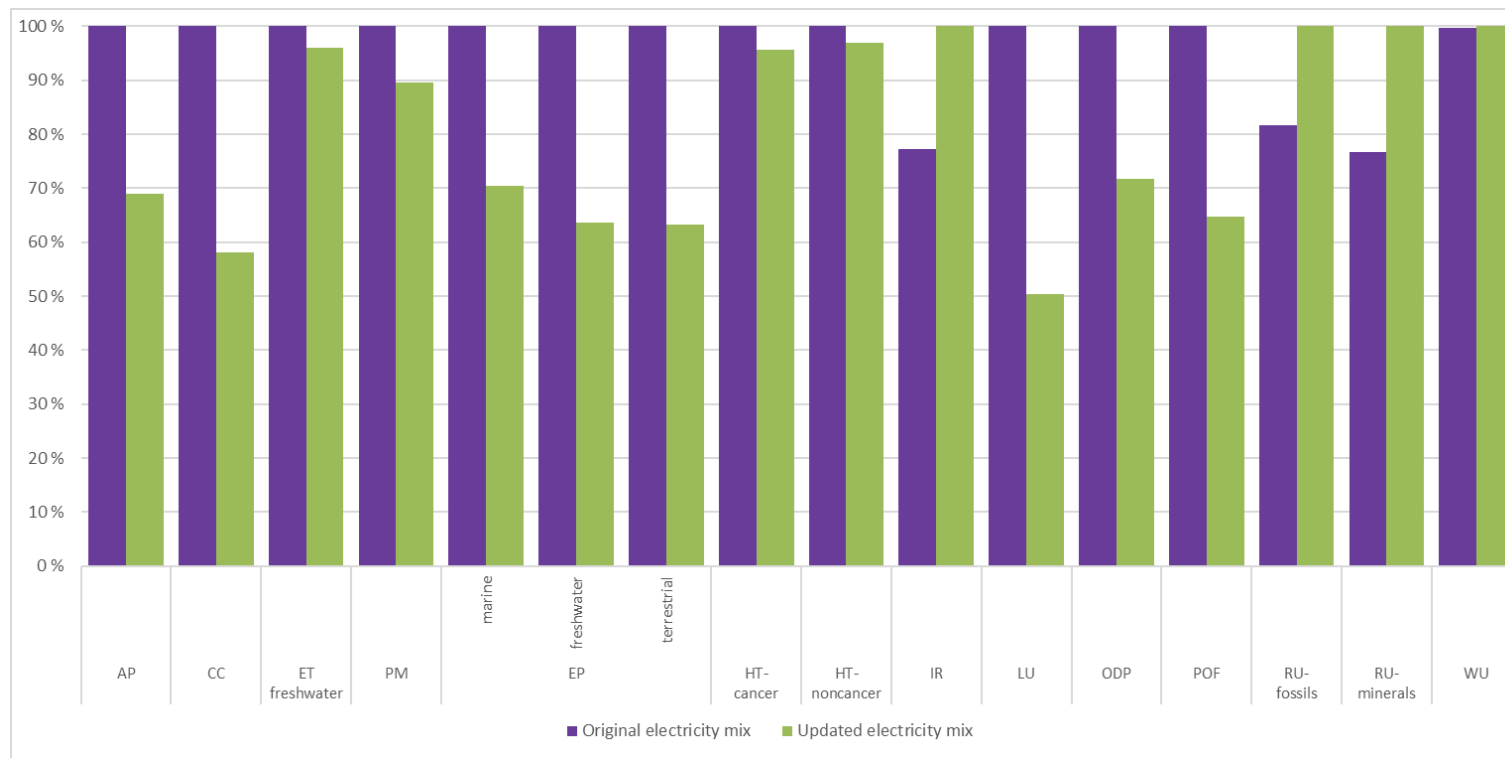


Figure 19. Relative environmental impacts for electricity source sensitivity analysis in artificially recharged groundwater (highest impact normalized to 100%).

These reductions are primarily due to lower greenhouse gas emissions from imported electricity and decreased land use impacts associated with replacing wood chip-based cogeneration. However, increases were observed in ionizing radiation and resource use—minerals and metals, driven by the higher share of nuclear energy and the material demands of wind and nuclear infrastructure, including copper, concrete, and fossil fuels used in construction. The change in the electricity sources for artificially recharged groundwater reduce the impact in climate change by 42%—from 0.122 to 0.07 kg CO₂/m³ water —, this is a direct result of a bigger share of fossil-free and renewable energy.

The sensitivity analysis, based on Finland's updated electricity mix, revealed substantial reductions in climate change impacts across all drinking water treatment methods. Groundwater treatment, previously the most impactful due to its high electricity demand, showed the greatest improvement—a 79% reduction in CO₂-eq/m³—making it the most environmentally favourable option under current energy conditions. In contrast, surface water and artificially recharged groundwater treatments exhibited smaller reductions (26% and 42%, respectively), reflecting their continued reliance on chemical inputs. These findings highlight the critical role of energy sourcing in shaping the environmental performance of water treatment systems and the importance of using regionally accurate datasets in life cycle assessments.

CONCLUSIONS

The primary objective of this study is to assess the environmental impacts associated with drinking water production in Finland through LCA. Previous studies have associated drinking water production with various environmental impacts, including climate change, resource depletion, ecotoxicity and eutrophication, due to the high consumption of electricity and use of coagulants. The environmental assessment of Finnish drinking water production revealed that groundwater treatment using chemical processes has the highest environmental impacts across most categories, primarily due to its substantial electricity consumption. This is followed by surface water treatment which relies more heavily on chemical inputs. Artificially recharged groundwater demonstrated lower overall environmental impacts, largely due to reduced chemical consumption. While electricity and PACl remain dominant contributors—linked to upstream fossil-based energy and ecotoxic aluminum ion release—their impacts are mitigated by Finland’s cleaner electricity mix. Other inputs, such as disinfection chemicals and infrastructure, play minor roles. This analysis shows that the optimization of pretreatment practices and material sourcing are essential to reinforcing artificially recharged groundwater as a more sustainable alternative.

Climate change impact values mirror this trend, with groundwater chemical treatment showing the highest emissions (0.147 kg CO₂-eq/m³), followed by artificially recharged groundwater (0.122 kg CO₂-eq/m³) and surface water treatment (0.119 kg CO₂-eq/m³). The slightly elevated impact of artificially recharged groundwater, compared to the surface water treatment, is notably influenced by the use of PACl, which has high contributions to both climate change and freshwater ecotoxicity.

Compared to previous studies, the quantified climate change impacts are slightly lower, largely due to updated inventory data and the incorporation of Finland’s electricity mix, which includes a higher proportion of fossil-free energy sources. Normalization analysis further supports these findings, showing consistent impact patterns across all treatment methods. Dominant categories include resource use—fossils, freshwater eutrophication, climate change, and ionizing radiation. The first three are closely tied to fossil-based electricity production, while ionizing radiation reflects the role of nuclear power in Finland’s energy landscape. This high reliance in electricity consumption opens the opportunity to reduce the environmental impacts focusing on higher use of renewable energies and new technologies that optimize the electricity consumption in the drinking water production sector.

In the search for representative LCA datasets for Finnish waterworks, new datasets were created, based on the inputs provided by the water facilities. The comparison between the newly developed Finnish datasets and the existing Ecoinvent datasets revealed important differences in impact assessment across all drinking water production methods. One of those is the reduction in the climate change impact quantification, where surface water conventional treatment presented a 46% difference, groundwater with chemical treatment 52%, and artificially recharged groundwater up to 70%. These findings bring out the critical importance of region-specific datasets, as variations in electricity consumption, energy sources, and chemical inputs can significantly influence environmental outcomes. The Finnish datasets demonstrate that updated inventories reflecting local energy profiles and operational practices provide a more accurate representation of real-world conditions.

Assessing the relevance of electricity consumption in drinking water production, the sensitivity analysis of electricity sources revealed that the existing dataset for Finland overestimates environmental impacts due to its high share of fossil-based imports. In contrast, the scenario using updated electricity data—characterized by a greater proportion of fossil-free sources, primarily nuclear and wind—significantly reduces the impacts across all treatment methods. This effect is most pronounced in energy-intensive processes, particularly groundwater treatment with chemical processes, which showed a 79% reduction in climate change impact quantification (from 0.147 to 0.07 CO₂-eq/m³) making it the most environmentally favourable option under current energy conditions. Surface water and artificially recharged groundwater treatments exhibited smaller reductions (26% and 42%, respectively), reflecting their continued reliance on chemical inputs. These results align with the findings by other studies, which conclude that electricity efficiency and renewable energy are some of the best strategies to get closer to a carbon-neutral production in this sector.

All these findings highlight the importance of using region-specific and up-to-date energy profiles in life cycle assessments to ensure accurate environmental evaluations. The significant differences observed between the newly developed Finnish datasets and those available in generic databases like Ecoinvent emphasize the need for localized data that reflect actual practices, technologies, and resource mixes. It is therefore both necessary and worthwhile to invest in the creation of local inventories for key sectors such as water production, electricity generation, and food systems—areas with substantial environmental footprints and societal relevance. However, building robust and representative datasets requires efforts across multiple sectors, including utilities, industry, government

agencies, and research institutions. Such collaboration is essential to capture the diversity of local conditions and operational realities, ultimately enabling more informed decision-making and effective sustainability strategies.

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APPENDIX A: SURVEY FORM FOR LCI OF DRINKING WATER FACILITIES IN FINLAND

The survey was conducted using Microsoft forms. It started with contact information and followed operational information. It contains 4 sections, the first one collects general information about the raw water sources, and the other three are related to each of the drinking water production methods.

General information (These questions help to select the following categories, according to the drinking water treatment method)

- Raw water source(s):
 - a. Surface water
 - b. Groundwater
 - c. Artificial groundwater
- What is the percentage of water sources used in the facility?
 - a. lake water:
 - b. river:
 - c. groundwater:

Surface water conventional treatment

- Facility/Facilities that are being included in this report:
- Total amount of water produced per year:
- Chemicals used for flocculation and precipitation: [include the annual amounts consumed and concentrations of the chemicals used]
- Materials used in filtration: [Write down all the materials used in filtration (sand, activated carbon, etc.) and the amount per year or service life (include the units, e.g. how much sand will be replaced per year)]
- Chemicals used for disinfection: [Write down all chemicals and materials used in all the disinfection steps, and quantities per year (including units, enter UV lamp life and amount of lamps or total water output per lamp)]
- Alkalizing chemicals and pH control chemicals: [Write down all chemicals and quantities used per year (include units)]

- Energy consumption (KWh/year): [Mention all the energy sources used in the production and the consumption of each source (Do not include distribution pumps. If they are included, please explain)]
- Internal consumption of clean household water (m³/year): [E.g. filter flushing water, dilution of chemicals, washing and rinsing of equipment]
- Wastewater generated by a water utility (m³/year): [Total wastewater per year (Filter flushing water, dilution of chemicals, washing and rinsing of equipment), also state how much of the generated wastewater is sewerred]
- Waste generated per year: [All types of waste generated that are collected through waste management, e.g. chemical packaging, etc. (include units)]

Groundwater with chemical treatment

- Facility/Facilities that are being included in this report:
- Total amount of water produced per year:
- Enter the type and amounts of oxidizing chemicals used per year (include units). If the aeration tower has filler pieces, write down the materials, volume, and quantities per year or period of use
- Chemicals used for flocculation and precipitation: [include the annual amounts consumed and concentrations of the chemicals used]
- Materials used in filtration: [Write down all the materials used in filtration (sand, activated carbon, etc.) and the amount per year or service life (include the units, e.g. how much sand will be replaced per year]
- Chemicals used for disinfection: [Write down all chemicals and materials used in all the disinfection steps, and quantities per year (including units, enter UV lamp life and amount of lamps or total water output per lamp)]
- Alkalizing chemicals and pH control chemicals: [Write down all chemicals and quantities used per year (include units)]
- Energy consumption (KWh/year): [Mention all the energy sources used in the production and the consumption of each source (Do not include distribution pumps. If they are included, please explain)]
- Internal consumption of clean household water (m³/year): [E.g. filter flushing water, dilution of chemicals, washing and rinsing of equipment]

- Wastewater generated by a water utility (m³/year): [Total wastewater per year (Filter flushing water, dilution of chemicals, washing and rinsing of equipment), also state how much of the generated wastewater is sewerred]
- Waste generated per year: [All types of waste generated that are collected through waste management, e.g. chemical packaging, etc. (include units)]

Artificially recharged groundwater (Including pretreatment steps)

- Facility/Facilities that are being included in this report:
- Total amount of water produced per year:
- Enter the type and amounts of oxidizing chemicals used per year (include units). If the aeration tower has filler pieces, write down the materials, volume, and quantities per year or period of use
- Chemicals used for flocculation and precipitation: [include the annual amounts consumed and concentrations of the chemicals used]
- Materials used in filtration: [Write down all the materials used in filtration (sand, activated carbon, etc.) and the amount per year or service life (include the units, e.g. how much sand will be replaced per year]
- Chemicals used for disinfection: [Write down all chemicals and materials used in all the disinfection steps, and quantities per year (including units, enter UV lamp life and amount of lamps or total water output per lamp)]
- Alkalizing chemicals and pH control chemicals: [Write down all chemicals and quantities used per year (include units)]
- Energy consumption (KWh/year): [Mention all the energy sources used in the production and the consumption of each source (Do not include distribution pumps. If they are included, please explain)]
- Internal consumption of clean household water (m³/year): [E.g. filter flushing water, dilution of chemicals, washing and rinsing of equipment]
- Wastewater generated by a water utility (m³/year): [Total wastewater per year (Filter flushing water, dilution of chemicals, washing and rinsing of equipment), also state how much of the generated wastewater is sewerred]
- Waste generated per year: [All types of waste generated that are collected through waste management, e.g. chemical packaging, etc. (include units)]

APPENDIX B: MONTE CARLO SIMULATION RESULTS

Table B1. *Statistical values calculated using Monte Carlo simulation for surface water conventional treatment, based on 100 iterations. Inputs included in the simulation were selected based on inventory data containing multiple initial values.*

Input	Unit	Geometric		Standard	Percentile 5%	Percentile 95%
		mean	Median	Deviation		
PACl	kg/y	5.96E-02	4.93E-02	6.17E-01	1.85E-02	1.22E-01
Fe ₂ (SO ₄) ₃	kg/y	2.66E-01	2.37E-01	4.55E-01	1.25E-01	5.15E-01
Sand	kg/y	5.15E-02	4.88E-03	1.98E+00	2.10E-04	1.25E-01
Activated carbon	kg/y	1.05E-02	4.79E-03	1.30E+00	5.99E-04	3.81E-02
CaCO ₃	kg/y	4.11E-02	1.68E-02	1.41E+00	1.72E-03	1.43E-01
NaOCl	kg/y	5.33E-03	1.23E-03	1.95E+00	6.53E-05	2.65E-02
NH ₃	kg/y	5.65E-04	5.48E-04	2.47E-01	3.72E-04	7.88E-04
(NH ₄) ₂ SO ₄	kg/y	1.03E-03	8.41E-04	6.61E-01	2.69E-04	2.11E-03
O ₂	kg/y	4.05E-02	1.95E-02	1.21E+00	2.67E-03	1.31E-01
UV lamp	lamp/y	1.14E-05	5.47E-06	1.24E+00	7.89E-07	3.60E-05
CO ₂	kg/y	1.13E-02	1.05E-02	4.27E-01	4.77E-03	1.84E-02
Ca(OH) ₂	kg/y	3.08E-02	1.67E-02	1.10E+00	2.23E-03	1.23E-01
Electricity total	MWh/y	5.35E-01	3.76E-01	8.55E-01	9.73E-02	1.38E+00
Electricity market mix	MWh/y	6.33E-01	3.19E-01	1.17E+00	5.36E-02	1.76E+00
Electricity Renewable	MWh/y	3.54E-01	1.32E-01	1.35E+00	1.66E-02	9.83E-01
Electricity Solar	MWh/y	4.62E-03	1.61E-03	1.44E+00	1.63E-04	1.90E-02
Heating total	MWh/y	5.35E+01	8.28E-03	4.40E+00	7.05E-06	2.14E+01
Heating district	MWh/y	5.65E-05	5.54E-05	1.98E-01	4.04E-05	7.73E-05
Tap water use	m ³ /y	7.77E-02	3.48E-02	1.27E+00	4.42E-03	2.74E-01
Wastewater	m ³ /y	7.11E-02	4.02E-02	1.06E+00	6.39E-03	2.09E-01

Table B2. *Statistical values calculated using Monte Carlo simulation for groundwater with chemical treatment, based on 100 iterations. Inputs included in the simulation were selected based on inventory data containing multiple initial values.*

Input	Unit	Geometric		Standard		
		mean	Median	Deviation	Percentile 5%	Percentile 95%
Polypropylene	kg/y	1.22E-03	1.07E-03	7.20E-04	4.76E-04	2.70E-03
Sand	kg/y	8.83E-03	8.58E-03	2.11E-03	5.70E-03	1.28E-02
NaOCl	kg/y	4.77E-04	4.72E-04	7.12E-05	3.51E-04	5.90E-04
UV lamp	lamp/y	9.33E-06	7.01E-06	7.70E-06	2.24E-06	2.38E-05
Na(OH) 50% sln.	kg/y	4.14E-03	4.12E-03	3.63E-04	3.54E-03	4.70E-03
Electricity total	MWh/y	6.73E-04	2.38E-04	1.22E-03	2.56E-05	2.73E-03
Electricity nuclear	MWh/y	7.63E-01	7.50E-01	1.37E-01	5.73E-01	9.83E-01
Electricity renewable	MWh/y	8.13E-04	1.88E-04	1.80E-03	5.05E-06	2.81E-03
Tap water use	m3/y	2.03E-02	1.70E-02	1.34E-02	6.73E-03	4.06E-02
Wastewater	m3/y	2.24E-02	1.89E-02	1.37E-02	7.58E-03	4.84E-02

Table B3. *Statistical values calculated using Monte Carlo simulation for artificially recharged groundwater, based on 100 iterations. Inputs included in the simulation were selected based on inventory data containing multiple initial values.*

Input	Unit	Geometric		Standard		
		mean	Median	Deviation	Percentile 5%	Percentile 95%
CaCO ₃	kg/y	0.02865	0.021089	0.02357	0.005451	0.082377
NaOCl	kg/y	0.00334	0.003245	0.000802	0.002068	0.004573
UV lamp	lamp/y	2.48E-06	2.46E-06	3.21E-07	2.01E-06	2.97E-06
Electricity total	MWh/y	0.46215	0.262202	0.798216	0.058681	1.507531
Electricity renewable	MWh/y	0.618464	0.252158	1.143162	0.02196	2.077669
Electricity nuclear	MWh/y	0.636444	0.91377	1.290862	0.032919	2.477633
Tap water use	m3/y	10.66945	8.927377	7.083013	3.88572	22.58322
Wastewater	m3/y	0.010874	0.007429	0.012953	0.002426	0.031653

APPENDIX C: NORMALIZATION FACTORS FROM EF 3.1

Table C1. Normalization factors from Environmental Footprint 3.1 method (Bassi et al., 2023)

Impact category	Abbreviations	Unit	EF3.1 Normalization		Principal contributors
			Factor	Indicator	
Acidification	AP	[mol H+ eq./person]	5.56E+01	USEtox	SO ₂ , NO _x , NH ₃ emissions
Climate change	CC	[kg CO ₂ eq./person]	7.55E+03	AE	GHG emissions (CO ₂ , CH ₄ , N ₂ O)
Ecotoxicity, freshwater	ET-freshwater	[CTUe/person]	5.67E+04	ODP	Toxic chemicals in water
Eutrophication, freshwater	EP-freshwater	[kg P eq./person]	1.61E+00	Human exposure	Phosphorus emissions
Eutrophication, marine	EP-marine	[kg N eq./person]	1.95E+01	Soil quality index	Nitrogen emissions
Eutrophication, terrestrial	EP-terrestrial	[mol N eq./person]	1.77E+02	USEtox	NH ₃ , NO _x emissions
Human toxicity, cancer	HT-cancer	[CTUh/person]	1.73E-05	USEtox	Heavy metals, carcinogens
Human toxicity, non-cancer Ionising radiation, human health	HT-noncancer IR	[CTUh/person] [kBq U235 eq./person]	1.29E-04 4.22E+03	EUTREND AE	Solvents, metals Nuclear energy, isotopes
Land use	LU	[pt/person]	8.19E+05	POFP	Agriculture, deforestation
Ozone depletion	ODP	[kg CFC-11 eq./person]	5.23E-02	GWP100	Emissions of CFCs, halons
Particulate matter	PM	[disease incidences/person]	5.95E-04	EUTREND	
Photochemical ozone formation, human health	POF	[kg NMVOC eq./person]	4.09E+01	Impact on human health	VOCs, NO _x emissions
Resource use, fossils	RU-fossil	[MJ/person]	6.50E+04	AWARE	Fossil fuel extraction
Resource use, minerals and metals	RU-minerals	[kg Sb eq./person] [m ³ water eq. of deprived water/person]	6.36E-02	Abiotic depletion	Mining of scarce metals
Water use	WU		1.15E+04	Energy content	Water consumption in stressed areas

APPENDIX D: IMPACT ASSESSMENT RESULTS FOR SURFACE WATER CONVENTIONAL TREATMENT

Table D1. *Impact assessment for surface water conventional treatment*

Impact category	Unit	Total	Electricity	TWU	Fe ₂ (SO ₄) ₃	CO ₂	Wwork	PACI	DWP.	AC
Acidification	mol H+ eq	6.31E-07	1.71E-07	6.88E-08	2.12E-07	2.33E-08	1.82E-08	1.60E-08	0.00	4.67E-08
Climate change	kg CO2 eq	1.19E-04	4.32E-05	1.29E-05	7.07E-06	8.82E-06	4.21E-06	2.24E-06	0.00	6.67E-06
CC - Biogenic	kg CO2 eq	6.48E-07	1.13E-07	2.48E-08	1.58E-08	5.56E-09	2.42E-08	2.07E-09	0.00	2.36E-09
CC - Fossil	kg CO2 eq	1.17E-04	4.25E-05	1.29E-05	7.04E-06	8.81E-06	4.18E-06	2.24E-06	0.00	6.66E-06
CC – LU and LU change	kg CO2 eq	6.65E-07	5.87E-07	2.55E-08	1.34E-08	6.49E-09	5.92E-09	2.39E-09	0.00	3.56E-09
Ecotoxicity. freshwater	CTUe	4.42E-04	8.25E-05	4.20E-05	1.08E-04	2.42E-05	2.18E-05	8.85E-05	0.00	1.44E-05
ET.freshw - inorganics	CTUe	4.29E-04	8.15E-05	4.08E-05	1.07E-04	1.90E-05	2.11E-05	8.70E-05	0.00	1.42E-05
ET.freshw - organics	CTUe	1.26E-05	9.70E-07	1.22E-06	9.33E-07	5.16E-06	6.79E-07	1.43E-06	0.00	1.66E-07
Particulate matter	disease inc.	5.44E-12	1.17E-12	7.98E-13	1.28E-12	1.50E-13	2.91E-13	2.02E-13	0.00	6.72E-13
Eutrophication. marine	kg N eq	1.02E-07	3.69E-08	1.34E-08	1.54E-08	5.25E-09	4.37E-09	2.73E-09	0.00	6.69E-09
Eutrophication. freshwater	kg P eq	4.41E-08	1.52E-08	8.27E-09	5.95E-09	2.56E-09	1.46E-09	9.09E-10	0.00	2.68E-09
Eutrophication. terrestrial	mol N eq	1.05E-06	3.90E-07	1.28E-07	1.76E-07	3.96E-08	4.57E-08	2.87E-08	0.00	6.88E-08
Human toxicity. cancer	CTUh	5.57E-14	7.60E-15	1.55E-14	8.95E-15	2.71E-15	3.93E-15	2.64E-15	0.00	7.41E-16
HT. cancer - inorganics	CTUh	2.60E-14	3.61E-15	9.46E-15	7.42E-15	9.24E-16	1.24E-15	5.89E-16	0.00	3.97E-16
HT. cancer - organics	CTUh	2.97E-14	3.99E-15	6.09E-15	1.53E-15	1.78E-15	2.69E-15	2.05E-15	0.00	3.43E-16
HT. non-cancer	CTUh	2.38E-12	3.31E-13	7.16E-13	6.87E-13	3.58E-13	7.15E-14	3.57E-14	0.00	3.74E-14
HT. non-cancer - inorganics	CTUh	2.02E-12	3.17E-13	7.11E-13	6.47E-13	7.31E-14	6.80E-14	3.44E-14	0.00	3.61E-14
HT. non-cancer - organics	CTUh	3.57E-13	1.40E-14	4.06E-15	4.01E-14	2.85E-13	3.55E-15	1.30E-15	0.00	1.29E-15
Ionising radiation	kBq U-235 eq	8.87E-05	7.80E-05	4.79E-06	5.83E-07	1.20E-06	1.48E-07	1.32E-07	0.00	2.66E-07
Land use	Pt	9.53E-04	5.05E-04	4.99E-05	6.43E-05	2.03E-05	1.87E-04	7.29E-06	0.00	1.31E-05
Ozone depletion	kg CFC11 eq	1.62E-12	6.40E-13	1.91E-13	8.54E-14	1.37E-13	7.02E-14	8.04E-14	0.00	3.66E-14
POF	kg NMVOC eq	3.47E-07	1.17E-07	4.17E-08	5.86E-08	1.53E-08	1.55E-08	8.82E-09	0.00	2.10E-08
RU. fossils	MJ	2.36E-03	1.50E-03	2.32E-04	9.26E-05	9.19E-05	3.92E-05	2.69E-05	0.00	7.94E-05
RU. minerals and metals	kg Sb eq	1.41E-09	1.70E-10	7.06E-11	9.10E-10	1.02E-10	5.81E-11	2.12E-11	0.00	3.35E-12
Water use	m3 depriv.	2.05E-03	1.52E-05	1.85E-03	1.12E-05	1.64E-06	1.39E-06	5.59E-07	2.00E-3	4.31E-07

* TWU= tap water use; Wwork= water works; DWP= drinking water production; AC= activated carbon.

Table D1. continuation. *Impact assessment for surface water conventional treatment*

Impact category	Unit	Total	WW	O ₂	NaOCl	Ca(OH) ₂	CaCO ₃	CaO	(NH ₄) ₂ SO ₄
Acidification	mol H+ eq	6.31E-07	2.35E-08	2.01E-08	3.88E-09	1.12E-08	3.42E-09	8.47E-09	2.34E-10
Climate change	kg CO2 eq	1.19E-04	5.87E-06	4.06E-06	8.33E-07	1.16E-05	6.55E-07	8.90E-06	1.63E-08
CC - Biogenic	kg CO2 eq	6.48E-07	2.69E-07	8.36E-09	2.06E-09	1.99E-09	1.73E-07	1.25E-09	1.01E-11
CC - Fossil	kg CO2 eq	1.17E-04	5.59E-06	4.04E-06	8.30E-07	1.16E-05	4.80E-07	8.90E-06	1.63E-08
CC – LU and LU change	kg CO2 eq	6.65E-07	5.38E-09	1.19E-08	1.38E-09	4.25E-10	8.40E-10	2.85E-10	7.61E-12
Ecotoxicity. freshwater	CTUe	4.42E-04	2.55E-05	9.02E-06	9.37E-06	2.56E-06	2.52E-06	1.88E-06	3.57E-06
ET.freshw - inorganics	CTUe	4.29E-04	2.50E-05	8.93E-06	9.31E-06	2.38E-06	2.45E-06	1.75E-06	2.67E-06
ET.freshw - organics	CTUe	1.26E-05	4.84E-07	8.92E-08	5.40E-08	1.82E-07	7.10E-08	1.33E-07	9.02E-07
Particulate matter	disease inc.	5.44E-12	5.65E-13	7.26E-14	3.01E-14	5.63E-14	7.53E-14	4.04E-14	1.55E-15
Eutrophication. marine	kg N eq	1.02E-07	6.14E-09	3.60E-09	8.35E-10	2.72E-09	1.02E-09	2.03E-09	6.48E-11
Eutrophication. freshwater	kg P eq	4.41E-08	1.87E-09	3.69E-09	6.75E-10	1.12E-10	2.79E-10	7.59E-11	3.18E-12
Eutrophication. terrestrial	mol N eq	1.05E-06	6.10E-08	3.10E-08	7.36E-09	3.02E-08	1.02E-08	2.27E-08	3.40E-10
Human toxicity. cancer	CTUh	5.57E-14	4.63E-15	6.00E-16	6.61E-15	2.30E-16	2.21E-16	1.58E-16	3.69E-18
HT. cancer - inorganics	CTUh	2.60E-14	1.35E-15	3.55E-16	1.31E-16	7.60E-17	5.29E-17	5.51E-17	1.83E-18
HT. cancer - organics	CTUh	2.97E-14	3.27E-15	2.45E-16	6.48E-15	1.54E-16	1.68E-16	1.03E-16	1.86E-18
HT. non-cancer	CTUh	2.38E-12	6.99E-14	2.83E-14	1.10E-14	7.11E-15	4.65E-15	5.11E-15	1.94E-16
HT. non-cancer - inorganics	CTUh	2.02E-12	6.70E-14	2.73E-14	1.04E-14	6.01E-15	4.08E-15	4.31E-15	1.55E-16
HT. non-cancer - organics	CTUh	3.57E-13	2.94E-15	9.57E-16	5.96E-16	1.10E-15	5.70E-16	8.01E-16	3.96E-17
Ionising radiation	kBq U-235 eq	8.87E-05	2.83E-07	2.65E-06	2.32E-07	1.42E-07	1.08E-07	1.15E-07	1.14E-09
Land use	Pt	9.53E-04	3.30E-05	1.38E-05	3.58E-06	1.90E-05	2.20E-05	1.19E-05	3.96E-08
Ozone depletion	kg CFC11 eq	1.62E-12	8.30E-14	6.77E-14	4.66E-14	6.84E-14	6.88E-15	5.22E-14	4.17E-16
POF	kg NMVOC eq	3.47E-07	2.10E-08	9.96E-09	2.28E-09	1.66E-08	3.00E-09	1.26E-08	5.90E-11
RU. fossils	MJ	2.36E-03	6.73E-05	9.41E-05	1.37E-05	4.87E-05	7.67E-06	3.73E-05	2.60E-07
RU. minerals and metals	kg Sb eq	1.41E-09	3.82E-11	9.39E-12	1.20E-11	2.04E-12	1.51E-12	1.47E-12	2.03E-13
Water use	m3 depriv.	2.05E-03	-1.85E-03	8.59E-06	2.81E-07	1.31E-07	6.52E-07	8.92E-08	1.70E-08

* WW=wastewater.

Table D1. continuation. *Impact assessment for surface water conventional treatment*

Impact category	Unit	Total	ClO₂	Cl₂	NH₃	HCl	UV lamp	Salt	Sand	Brine
Acidification	mol H+ eq	6.31E-07	1.81E-09	3.96E-10	1.48E-09	4.19E-10	6.91E-12	2.96E-10	1.71E-10	6.31E-11
Climate change	kg CO2 eq	1.19E-04	2.58E-07	7.35E-08	1.16E-06	7.28E-08	1.25E-09	4.16E-08	2.54E-08	7.39E-09
CC - Biogenic	kg CO2 eq	6.48E-07	4.43E-09	1.22E-10	2.21E-10	1.17E-10	5.51E-12	9.61E-11	1.49E-11	1.62E-11
CC - Fossil	kg CO2 eq	1.17E-04	2.53E-07	7.32E-08	1.16E-06	7.26E-08	1.25E-09	4.15E-08	2.54E-08	7.36E-09
CC – LU and LU change	kg CO2 eq	6.65E-07	4.68E-10	1.29E-10	1.77E-10	9.00E-11	2.68E-12	7.16E-11	1.61E-11	1.18E-11
Ecotoxicity. freshwater	CTUe	4.42E-04	3.58E-06	5.31E-07	9.65E-07	7.91E-07	5.13E-09	3.85E-07	5.89E-08	6.14E-08
ET.freshw - inorganics	CTUe	4.29E-04	3.57E-06	5.26E-07	9.24E-07	7.45E-07	4.94E-09	3.80E-07	5.71E-08	6.06E-08
ET.freshw - organics	CTUe	1.26E-05	1.59E-08	5.17E-09	4.16E-08	4.55E-08	1.91E-10	4.42E-09	1.79E-09	7.41E-10
Particulate matter	disease inc.	5.44E-12	1.71E-14	3.96E-15	8.35E-15	2.96E-15	4.11E-16	3.06E-15	3.09E-15	5.59E-16
Eutrophication. marine	kg N eq	1.02E-07	2.88E-10	8.03E-11	3.76E-10	6.95E-11	1.22E-12	6.39E-11	5.88E-11	8.39E-12
Eutrophication. freshwater	kg P eq	4.41E-08	1.25E-10	3.30E-11	6.20E-11	4.04E-11	3.37E-13	2.35E-11	4.02E-12	5.49E-12
Eutrophication. terrestrial	mol N eq	1.05E-06	2.91E-09	8.00E-10	4.02E-09	6.01E-10	1.28E-11	6.09E-10	6.48E-10	9.23E-11
Human toxicity. cancer	CTUh	5.57E-14	2.29E-16	3.72E-16	1.28E-16	2.63E-16	6.72E-17	1.92E-17	9.28E-18	5.36E-18
HT. cancer - inorganics	CTUh	2.60E-14	1.88E-16	9.79E-18	4.40E-17	1.13E-17	6.67E-17	1.16E-17	2.25E-18	3.73E-18
HT. cancer - organics	CTUh	2.97E-14	4.04E-17	3.62E-16	8.41E-17	2.52E-16	4.79E-19	7.63E-18	7.03E-18	1.63E-18
HT. non-cancer	CTUh	2.38E-12	4.16E-15	8.70E-16	3.46E-15	9.68E-16	7.89E-15	9.84E-16	1.92E-16	3.17E-16
HT. non-cancer - inorganics	CTUh	2.02E-12	3.94E-15	8.34E-16	3.13E-15	9.02E-16	7.89E-15	9.29E-16	1.72E-16	2.99E-16
HT. non-cancer - organics	CTUh	3.57E-13	2.12E-16	3.61E-17	3.30E-16	6.57E-17	3.62E-19	5.56E-17	2.03E-17	1.75E-17
Ionising radiation	kBq U-235 eq	8.87E-05	2.39E-08	6.87E-09	1.86E-08	1.50E-08	3.54E-11	3.93E-09	7.00E-10	9.55E-10
Land use	Pt	9.53E-04	7.16E-07	2.14E-07	8.10E-07	2.72E-07	3.21E-09	2.74E-07	1.62E-06	6.50E-08
Ozone depletion	kg CFC11 eq	1.62E-12	1.89E-15	7.12E-15	3.14E-14	1.22E-14	1.47E-17	3.99E-16	3.24E-16	8.69E-17
POF	kg NMVOC eq	3.47E-07	8.79E-10	2.41E-10	2.35E-09	2.08E-10	4.53E-12	1.81E-10	2.06E-10	2.79E-11
RU. fossils	MJ	2.36E-03	3.17E-06	9.30E-07	1.74E-05	1.26E-06	1.68E-08	5.10E-07	3.39E-07	9.58E-08
RU. minerals and metals	kg Sb eq	1.41E-09	4.04E-12	6.31E-13	3.98E-12	1.14E-12	4.95E-14	1.30E-12	1.02E-13	4.82E-13
Water use	m3 depriv.	2.05E-03	2.68E-07	3.48E-08	6.68E-07	3.50E-08	1.90E-10	1.98E-08	8.90E-08	-1.78E-09

APPENDIX E: IMPACT ASSESSMENT RESULTS FOR GROUNDWATER WITH CHEMICAL TREATMENT

Table E1. *Impact assessment for groundwater with chemical treatment*

Impact category	Unit	Total	Electricity	TWU	Na(OH)	PS	DWP	WW	AC	NaOCl
Acidification	mol H+ eq	6.01E-07	4.72E-07	4.44E-08	1.72E-08	2.47E-08	0.00	1.52E-08	2.03E-08	2.75E-09
Climate change	kg CO2 eq	1.47E-04	1.22E-04	8.34E-06	3.69E-06	3.96E-06	0.00	3.80E-06	2.89E-06	5.91E-07
CC - Biogenic	kg CO2 eq	5.61E-07	3.25E-07	1.60E-08	9.09E-09	3.48E-09	0.00	1.74E-07	1.03E-09	1.46E-09
CC - Fossil	kg CO2 eq	1.45E-04	1.20E-04	8.31E-06	3.68E-06	3.95E-06	0.00	3.62E-06	2.89E-06	5.88E-07
CC – LU and LU change	kg CO2 eq	1.73E-06	1.70E-06	1.64E-08	6.12E-09	2.81E-09	0.00	3.48E-09	1.55E-09	9.81E-10
Ecotoxicity. freshwater	CTUe	3.38E-04	2.16E-04	2.71E-05	4.14E-05	2.19E-05	0.00	1.65E-05	6.24E-06	6.64E-06
ET.freshw - inorganics	CTUe	3.33E-04	2.13E-04	2.63E-05	4.12E-05	2.16E-05	0.00	1.62E-05	6.17E-06	6.60E-06
ET.freshw - organics	CTUe	4.54E-06	2.67E-06	7.85E-07	2.39E-07	3.35E-07	0.00	3.13E-07	7.21E-08	3.83E-08
Particulate matter	disease inc.	5.06E-12	3.30E-12	5.15E-13	1.35E-13	3.71E-13	0.00	3.65E-13	2.92E-13	2.14E-14
Eutrophication. marine	kg N eq	1.31E-07	1.05E-07	8.65E-09	3.71E-09	4.76E-09	0.00	3.98E-09	2.90E-09	5.92E-10
Eutrophication. freshwater	kg P eq	5.54E-08	4.24E-08	5.34E-09	2.98E-09	1.63E-09	0.00	1.21E-09	1.16E-09	4.79E-10
Eutrophication. terrestrial	mol N eq	1.36E-06	1.11E-06	8.27E-08	3.28E-08	5.36E-08	0.00	3.95E-08	2.99E-08	5.22E-09
Human toxicity. cancer	CTUh	7.41E-14	1.96E-14	1.00E-14	2.92E-14	6.81E-15	0.00	2.99E-15	3.21E-16	4.69E-15
HT. cancer - inorganics	CTUh	1.82E-14	8.30E-15	6.11E-15	5.79E-16	1.91E-15	0.00	8.75E-16	1.72E-16	9.27E-17
HT. cancer - organics	CTUh	5.59E-14	1.13E-14	3.93E-15	2.86E-14	4.90E-15	0.00	2.12E-15	1.49E-16	4.60E-15
HT. non-cancer	CTUh	1.51E-12	7.50E-13	4.62E-13	4.88E-14	1.60E-13	0.00	4.53E-14	1.62E-14	7.80E-15
HT. non-cancer - inorganics	CTUh	1.46E-12	7.22E-13	4.59E-13	4.61E-14	1.53E-13	0.00	4.34E-14	1.57E-14	7.38E-15
HT. non-cancer - organics	CTUh	4.42E-14	2.79E-14	2.62E-15	2.65E-15	7.74E-15	0.00	1.90E-15	5.58E-16	4.22E-16
Ionising radiation	kBq U-235 eq	2.30E-04	2.26E-04	3.09E-06	1.03E-06	8.35E-08	0.00	1.83E-07	1.15E-07	1.64E-07
Land use	Pt	1.73E-03	1.45E-03	3.22E-05	1.60E-05	1.85E-04	0.00	2.14E-05	5.69E-06	2.54E-06
Ozone depletion	kg CFC11 eq	2.10E-12	1.60E-12	1.23E-13	2.06E-13	5.68E-14	0.00	5.37E-14	1.59E-14	3.30E-14
POF	kg NMVOC eq	4.14E-07	3.31E-07	2.69E-08	1.02E-08	1.65E-08	0.00	1.36E-08	9.12E-09	1.62E-09
RU. fossils	MJ	4.69E-03	4.34E-03	1.50E-04	6.06E-05	3.38E-05	0.00	4.36E-05	3.44E-05	9.69E-06
RU. minerals and metals	kg Sb eq	5.16E-10	2.40E-10	4.56E-11	5.31E-11	1.40E-10	0.00	2.48E-11	1.45E-12	8.51E-12
Water use	m3 depriv.	1.99E-03	4.38E-05	1.19E-03	1.24E-06	1.02E-06	1.94E-03	-1.19E-03	1.87E-07	2.00E-07

* TWU= tap water use; PS= pump station; DWP= drinking water production; WW= Wastewater AC= activated carbon.

Table E1. continuation *Impact assessment for groundwater with chemical treatment*

Impact category	Unit	Total	CaCO₃	Sand	CaO	UV lamp	KMnO₄	NH₃	Ca(OH)₂
Acidification	mol H+ eq	6.01E-07	5.99E-10	2.25E-09	9.21E-10	1.19E-11	4.57E-10	1.41E-10	1.45E-10
Climate change	kg CO2 eq	1.47E-04	1.15E-07	3.00E-07	9.68E-07	2.16E-09	7.71E-08	1.11E-07	1.49E-07
CC - Biogenic	kg CO2 eq	5.61E-07	3.03E-08	1.22E-10	1.36E-10	9.48E-12	1.10E-10	2.12E-11	2.58E-11
CC - Fossil	kg CO2 eq	1.45E-04	8.42E-08	2.99E-07	9.68E-07	2.14E-09	7.68E-08	1.11E-07	1.49E-07
CC – LU and LU change	kg CO2 eq	1.73E-06	1.47E-10	2.71E-10	3.09E-11	4.61E-12	1.22E-10	1.70E-11	5.50E-12
Ecotoxicity. freshwater	CTUe	3.38E-04	4.41E-07	6.91E-07	2.04E-07	8.83E-09	9.60E-07	9.25E-08	3.31E-08
ET.freshw - inorganics	CTUe	3.33E-04	4.29E-07	6.41E-07	1.90E-07	8.50E-09	9.55E-07	8.85E-08	3.08E-08
ET.freshw - organics	CTUe	4.54E-06	1.24E-08	4.94E-08	1.44E-08	3.28E-10	5.49E-09	3.99E-09	2.36E-09
Particulate matter	disease inc.	5.06E-12	1.32E-14	4.09E-14	4.40E-15	7.06E-16	4.30E-15	8.00E-16	7.29E-16
Eutrophication. marine	kg N eq	1.31E-07	1.79E-10	5.01E-10	2.21E-10	2.09E-12	8.39E-11	3.61E-11	3.52E-11
Eutrophication. freshwater	kg P eq	5.54E-08	4.89E-11	6.08E-11	8.25E-12	5.79E-13	3.24E-11	5.94E-12	1.45E-12
Eutrophication. terrestrial	mol N eq	1.36E-06	1.79E-09	5.44E-09	2.46E-09	2.20E-11	8.71E-10	3.85E-10	3.91E-10
Human toxicity. cancer	CTUh	7.41E-14	3.87E-17	9.31E-17	1.72E-17	1.16E-16	1.49E-16	1.23E-17	2.98E-18
HT. cancer - inorganics	CTUh	1.82E-14	9.27E-18	2.44E-17	6.00E-18	1.15E-16	1.13E-17	4.22E-18	9.83E-19
HT. cancer - organics	CTUh	5.59E-14	2.94E-17	6.87E-17	1.12E-17	8.24E-19	1.37E-16	8.06E-18	2.00E-18
HT. non-cancer	CTUh	1.51E-12	8.14E-16	2.24E-15	5.56E-16	1.36E-14	1.17E-15	3.31E-16	9.20E-17
HT. non-cancer - inorganics	CTUh	1.46E-12	7.15E-16	2.07E-15	4.69E-16	1.36E-14	1.11E-15	3.00E-16	7.78E-17
HT. non-cancer - organics	CTUh	4.42E-14	9.99E-17	1.67E-16	8.71E-17	6.23E-19	5.93E-17	3.16E-17	1.42E-17
Ionising radiation	kBq U-235 eq	2.30E-04	1.90E-08	4.48E-09	1.26E-08	6.10E-11	7.96E-09	1.78E-09	1.84E-09
Land use	Pt	1.73E-03	3.85E-06	7.70E-06	1.29E-06	5.52E-09	3.23E-07	7.76E-08	2.46E-07
Ozone depletion	kg CFC11 eq	2.10E-12	1.21E-15	2.43E-15	5.68E-15	2.52E-17	8.17E-16	3.01E-15	8.85E-16
POF	kg NMVOC eq	4.14E-07	5.25E-10	1.71E-09	1.37E-09	7.79E-12	2.69E-10	2.25E-10	2.15E-10
RU. fossils	MJ	4.69E-03	1.34E-06	3.31E-06	4.05E-06	2.89E-08	9.62E-07	1.67E-06	6.30E-07
RU. minerals and metals	kg Sb eq	5.16E-10	2.64E-13	6.68E-13	1.60E-13	8.52E-14	1.03E-12	3.82E-13	2.64E-14
Water use	m3 depriv.	1.99E-03	1.14E-07	3.40E-07	9.70E-09	3.27E-10	3.54E-08	6.41E-08	1.69E-09

APPENDIX F: IMPACT ASSESSMENT RESULTS FOR ARTIFICIALLY RECHARGED GROUNDWATER

Table F1. *Impact assessment for groundwater with chemical treatment*

Impact category	Unit	Total	Electricity	PACI	PS	NaOCl	DWP	CaCO ₃	CO ₂	TWU
Acidification	mol H+ eq	6.01E-07	3.30E-07	1.96E-07	2.72E-08	1.46E-08	0.00	5.16E-09	3.13E-09	9.14E-09
Climate change	kg CO2 eq	1.47E-04	9.17E-05	3.02E-05	4.79E-06	3.44E-06	0.00	1.09E-06	1.30E-06	1.89E-06
CC - Biogenic	kg CO2 eq	5.61E-07	2.17E-07	2.52E-08	3.81E-09	7.68E-09	0.00	2.60E-07	7.42E-10	3.27E-09
CC - Fossil	kg CO2 eq	1.45E-04	8.99E-05	3.01E-05	4.77E-06	3.42E-06	0.00	7.96E-07	1.30E-06	1.88E-06
CC – LU and LU change	kg CO2 eq	1.73E-06	1.66E-06	4.30E-08	4.54E-09	7.64E-09	0.00	1.86E-09	1.28E-09	4.97E-09
Ecotoxicity. freshwater	CTUe	3.38E-04	4.03E-05	2.74E-04	6.11E-06	8.92E-06	0.00	9.63E-07	8.22E-07	1.41E-06
ET.freshw - inorganics	CTUe	3.33E-04	4.00E-05	2.71E-04	6.04E-06	8.91E-06	0.00	9.40E-07	6.49E-07	1.38E-06
ET.freshw - organics	CTUe	4.54E-06	3.50E-07	3.26E-06	6.88E-08	3.79E-08	0.00	2.00E-08	1.29E-07	3.02E-08
Particulate matter	disease inc.	5.06E-12	2.02E-12	2.20E-12	3.65E-13	1.01E-13	0.00	1.01E-13	1.79E-14	9.47E-14
Eutrophication. marine	kg N eq	1.31E-07	7.69E-08	3.61E-08	5.66E-09	3.38E-09	0.00	1.66E-09	7.60E-10	1.92E-09
Eutrophication. freshwater	kg P eq	5.54E-08	3.45E-08	1.31E-08	2.11E-09	2.98E-09	0.00	4.94E-10	4.03E-10	1.29E-09
Eutrophication. terrestrial	mol N eq	1.36E-06	8.06E-07	3.77E-07	6.32E-08	2.96E-08	0.00	1.65E-08	5.70E-09	1.82E-08
Human toxicity. cancer	CTUh	7.41E-14	1.30E-14	2.88E-14	6.67E-15	2.21E-14	0.00	2.96E-16	3.23E-16	1.84E-15
HT. cancer - inorganics	CTUh	1.82E-14	6.81E-15	7.05E-15	2.05E-15	4.80E-16	0.00	7.81E-17	1.21E-16	1.23E-15
HT. cancer - organics	CTUh	5.59E-14	6.65E-15	2.17E-14	4.66E-15	2.10E-14	0.00	2.19E-16	2.07E-16	6.99E-16
HT. non-cancer	CTUh	1.51E-12	6.53E-13	4.48E-13	1.81E-13	4.23E-14	0.00	7.19E-15	4.92E-14	9.74E-14
HT. non-cancer - inorganics	CTUh	1.46E-12	6.49E-13	4.48E-13	1.79E-13	4.16E-14	0.00	6.54E-15	1.04E-14	1.00E-13
HT. non-cancer - organics	CTUh	4.42E-14	1.26E-14	7.38E-15	3.96E-15	1.04E-15	0.00	4.00E-16	1.78E-14	2.51E-16
Ionising radiation	kBq U-235 eq	2.30E-04	2.25E-04	2.42E-06	1.37E-07	1.30E-06	0.00	2.44E-07	2.41E-07	9.51E-07
Land use	Pt	1.73E-03	1.24E-03	1.13E-04	2.58E-04	1.71E-05	3.27E-08	4.21E-05	3.45E-06	8.40E-06
Ozone depletion	kg CFC11 eq	2.10E-12	1.00E-12	7.98E-13	5.07E-14	1.42E-13	0.00	8.43E-15	1.49E-14	2.06E-14
POF	kg NMVOC eq	4.14E-07	2.37E-07	1.14E-07	1.92E-08	9.04E-09	0.00	4.77E-09	2.16E-09	5.85E-09
RU. fossils	MJ	4.69E-03	3.96E-03	4.49E-04	5.09E-05	7.01E-05	0.00	1.58E-05	1.68E-05	4.20E-05
RU. minerals and metals	kg Sb eq	5.16E-10	2.06E-10	1.63E-10	9.68E-11	2.83E-11	0.00	1.43E-12	8.55E-12	5.89E-12
Water use	m3 depriv.	1.99E-03	2.65E-05	6.17E-06	1.01E-06	9.53E-07	1.99E-03	8.87E-07	1.98E-07	2.21E-04

* PS= pump station; DWP= drinking water production; TWU= tap water use.

Table F1. *Impact assessment for groundwater with chemical treatment*

Impact category	Unit	Total	Ca(OH) ₂	(NH ₄) ₂ SO ₄	WW	Sand	UV lamp	NH ₃	PP	BH	Excav.
Acidification	mol H+ eq	6.01E-07	1.01E-08	8.26E-10	3.68E-09	1.63E-09	7.63E-12	1.05E-10	4.20E-11	9.72E-12	6.32E-13
Climate change	kg CO2 eq	1.47E-04	1.15E-05	6.33E-08	1.01E-06	2.66E-07	1.53E-09	9.14E-08	2.53E-08	1.17E-09	7.94E-11
CC - Biogenic	kg CO2 eq	5.61E-07	1.79E-09	3.55E-11	4.18E-08	1.41E-10	6.05E-12	1.57E-11	1.27E-11	2.79E-12	8.85E-15
CC - Fossil	kg CO2 eq	1.45E-04	1.14E-05	6.31E-08	9.60E-07	2.65E-07	1.51E-09	9.11E-08	2.52E-08	1.16E-09	7.92E-11
CC – LU and LU change	kg CO2 eq	1.73E-06	5.63E-10	3.95E-11	1.24E-09	2.25E-10	4.34E-12	1.86E-11	1.80E-11	1.59E-12	1.36E-14
Ecotoxicity. freshwater	CTUe	3.38E-04	5.86E-07	3.20E-06	1.01E-06	1.42E-07	1.44E-09	1.75E-08	1.72E-08	2.09E-09	1.50E-11
ET.freshw - inorganics	CTUe	3.33E-04	5.46E-07	2.40E-06	9.96E-07	1.39E-07	1.39E-09	1.68E-08	1.69E-08	2.07E-09	1.40E-11
ET.freshw - organics	CTUe	4.54E-06	3.07E-08	5.95E-07	1.41E-08	3.18E-09	3.93E-11	5.56E-10	2.77E-10	2.08E-11	8.10E-13
Particulate matter	disease inc.	5.06E-12	4.54E-14	4.90E-15	7.89E-14	2.63E-14	4.05E-16	5.33E-16	3.27E-16	1.29E-16	1.60E-17
Eutrophication. marine	kg N eq	1.31E-07	2.65E-09	2.47E-10	1.04E-09	6.05E-10	1.45E-12	2.90E-11	1.86E-11	1.60E-12	3.15E-13
Eutrophication. freshwater	kg P eq	5.54E-08	1.19E-10	1.32E-11	3.43E-10	4.49E-11	4.36E-13	5.20E-12	4.64E-12	3.03E-13	4.05E-15
Eutrophication. terrestrial	mol N eq	1.36E-06	2.92E-08	1.29E-09	1.02E-08	6.61E-09	1.52E-11	3.08E-10	1.13E-10	3.76E-11	3.42E-12
Human toxicity. cancer	CTUh	7.41E-14	1.85E-16	1.16E-17	6.44E-16	7.86E-17	6.61E-17	8.15E-18	7.80E-18	6.24E-19	8.62E-21
HT. cancer - inorganics	CTUh	1.82E-14	6.71E-17	6.32E-18	2.07E-16	2.10E-17	7.21E-17	3.08E-18	4.63E-18	2.71E-19	2.95E-21
HT. cancer - organics	CTUh	5.59E-14	1.20E-16	5.68E-18	4.43E-16	5.78E-17	4.57E-19	5.20E-18	3.48E-18	3.67E-19	5.77E-21
HT. non-cancer	CTUh	1.51E-12	6.56E-15	7.03E-16	1.12E-14	1.87E-15	8.93E-15	2.53E-16	1.11E-15	1.14E-17	1.42E-19
HT. non-cancer - inorganics	CTUh	1.46E-12	5.76E-15	5.81E-16	1.11E-14	1.74E-15	9.26E-15	2.37E-16	1.14E-15	1.13E-17	1.26E-19
HT. non-cancer - organics	CTUh	4.42E-14	4.60E-16	6.50E-17	2.14E-16	8.98E-17	1.86E-19	1.10E-17	3.65E-18	2.27E-19	9.07E-21
Ionising radiation	kBq U-235 eq	2.30E-04	1.92E-07	6.03E-09	6.62E-08	9.95E-09	5.85E-11	1.98E-09	3.54E-09	4.65E-11	8.50E-13
Land use	Pt	1.73E-03	2.18E-05	1.77E-07	6.55E-06	1.96E-05	4.50E-09	7.34E-08	7.24E-08	6.58E-09	8.39E-11
Ozone depletion	kg CFC11 eq	2.10E-12	5.00E-14	1.20E-15	1.05E-14	2.50E-15	1.31E-17	1.82E-15	1.17E-16	7.80E-18	9.35E-19
POF	kg NMVOC eq	4.14E-07	1.58E-08	2.20E-10	3.46E-09	2.07E-09	5.28E-12	1.77E-10	3.60E-11	5.10E-12	1.01E-12
RU. fossils	MJ	4.69E-03	6.00E-05	1.25E-06	1.44E-05	4.40E-06	2.53E-08	1.70E-06	1.76E-07	1.51E-08	1.28E-09
RU. minerals and metals	kg Sb eq	5.16E-10	1.16E-12	4.50E-13	3.76E-12	6.09E-13	3.44E-14	1.79E-13	4.59E-14	1.35E-14	2.12E-17
Water use	m3 depriv.	1.99E-03	1.06E-07	5.40E-08	-2.60E-04	7.64E-07	1.89E-10	4.31E-08	1.45E-09	2.38E-10	2.37E-12

* WW= wastewater; PP=polypropylene; BH= Building hall; Excav. = excavation.