MASS BALANCE OF HEAVY METALS IN A WASTEWATER SYSTEM

A case study for enhancement of sludge quality in Eskilstuna, Sweden

DANIEL KUIVAMÄKI

School of Business, Society and Engineering
Course: Degree project in Environmental Engineering
Course code: MTK343
Credits: 30 hp
Program: Master's Programme in Environmental Engineering for Sustainable Development

Supervisor: Aubrey Shenk
Examiner: Lena Johansson Westholm
Date: 2025-06-09
Email:
dki23003@student.mdu.se

ABSTRACT

This study investigates the heavy metal (HM) mass balance within Ekeby Wastewater Treatment Plant (WWTP) in Eskilstuna, Sweden, and its upstream sewage network. The aim was to trace and connect sources of HM accumulated in sludge to assess and identify opportunities for reduction, as a foundation for compliance with the REVAQ certification, which is required for applying sludge as a fertilizer on arable land. The eight analyzed elements are Lead (Pb), Cadmium (Cd), Copper (Cu), Chromium (Cr), Silver (Ag), Zinc (Zn), and Mercury (Hg). As this is an empirical study, empirical pollution data were collected from official environmental reports of 17 industrial actors out of 220, alongside data from literature for the HM sources, households, and excessive water. These sources contribute to 0.3%, 51.7%, and 14.7%, respectively, of the total HM mass flow of the incoming wastewater. Unidentified upstream sources, therefore, add up to 14.7% of incoming HM mass flow. The model was developed in excel and STAN (Substance Flow Analysis) software further revealing sludge HM composition from, households (51%), unidentified upstream sources (15%), excessive water (15%), organic waste (3%), internal unidentified sources (2%), and industry (0.3%). Cd, Cr, Ni, and Hg show over 50% of HM mass coming from unidentified sources. Cd was the only HM substantially exceeding the REVAQ thresholds, by over 100%, while the other analyzed HMs are below or near the threshold value. Cd is therefore the most critical HM to reduce in the sludge. The study further concludes that improved monitoring for both the upstream sewage network and within the WWTP will reduce unidentified mass, resulting in clearer opportunities and actions for minimizing HM in the sludge that supports the compliance of the REVAQ certification.

Keywords: Heavy metals, wastewater treatment, mass balance, sludge quality, REVAQ, upstream pollution, environmental reports, flow analysis, sludge management

PREFACE

This degree project is a part of the Master's Programme in Environmental Engineering for Sustainable Development at Mälardalen University.

As a resident of the Eskilstuna municipality where the WWTP of the work is located, I am personally interested in a better local environmental quality connected to this particular WWTP. The long-standing history of treating wastewater and the ongoing development of the process are intriguing. This motivated the choice of investigating heavy metal flows and understanding, of spreading it to arable land in the region with sewage sludge as fertilizer.

I want to thank Eskilstuna Energi & Miljö for making this degree project possible through access to data and insights. I also wish to express my gratitude to my supervisor, Aubrey Shenk, for continuous guidance throughout the project.

Lastly, a special thanks to my family for their support, as this degree project was completed alongside the arrival of our second child. Seeing the world for the first time, and even though he hasn't spent much time in it, he teaches a master's degree student the true value of time management.

Eskilstuna 2025-05-28

Daniel Kuivamäki

SUMMARY

Sludge as a byproduct from wastewater treatment plants (WWTP) is used throughout the world as a fertilizer on airable land as a substitute for synthetic fertilizers. The reuse of sludge is a circular economy practice and a part of the sustainable development of WWTPs. The applying of sludge as a fertilizer gives the opportunity to recycle nutrients like phosphorus and nitrogen back into the agriculture. However, the sewage sludge also contains hazardous contaminants such as heavy metals (HMs) which are severe to health and the environment.

To ensure a safe and sustainable practice of applying the sludge on arable land, sludge quality must be carefully monitored.

This degree project is a case study at the WWTP Ekeby in Eskilstuna, Sweden with the aim and purpose to identify heavy metal sources accumulating in the sludge by conducting a mass balance. Ekeby WWTP aims to be certified according to REVAQ which is mandatory in Sweden to be able to let the sludge be used as a fertilizer. REVAQ certification is a demanding certification and comes with strict threshold values for heavy metals. The degree project will therefore work as a foundation for the certification.

The project is delimited to the heavy metals, lead (Pb), cadmium (Cd), copper (Cu), chromium (Cr), nickel (Ni), silver (Ag), zinc (Zn), and mercury (Hg). The upstream investigation was conducted with a literature review identifying the largest sources of HM which is households, industries, and excessive water, where excessive water is the sum of stormwater run-off, groundwater infiltration and different undesired leakages. The investigation for sources within the industry sector was conducted by document review of environmental reports for all industrial actors connected to the sewage system. Environmental reports are official documents and was collected from the supervisory authority, Environmental Office in Eskilstuna.
The investigation for households was relying on literature study and the investigation for excessive water was carried out by collecting official groundwater sample data within the municipality and literature-based stormwater run-off data. Leakages have a complex role within the excessive water and is not considered within the project.

The mass flows from the identified sources was balanced towards the monitored incoming flow to the WWTP. From the upstream balance, a mass flow from unidentified sources could be revealed.

The WWTP processes have been analyzed and mapped to understand any additional probable input sources of HM. The resulting mass balance equation within the WWTP consider the inflow and organic input against the effluent and sludge as output. The mass balance reveals an internal unidentified input/output for each one of the analyzed HMs.

The result show the highest unidentified HM mass flows accumulating in the sludge, for Cr, Cu, and Ni where the three elements have approximately 50% of the mass flow from unidentified sources. Household contribution to HM mass in the sludge dominates for Cu, Ni, Zn where Cu and Zn usually are the biggest contributors to HM mass in common sewage sludge. Excessive water dominated the input to the sludge HM mass for Pb, Ag, and Hg. Cd

and Cr have equal distribution between households and excessive water HM mass flow to the sludge. The industry sector is not mentioned dominating any of the mass flows of HM. The method of collecting data from the industry sector resulted in pollution data for 17 out of 220 industrial actors and it is suggested in further work investigate upstream industry pollution with a substitute method such as water sampling. It is also assumed that further upstream investigation can reduce the mass flow from unidentified sources.

As a conclusion, the WWTP stands against a major challenge connected to the REVAQ certification. Cd levels within the sludge are over 100% of the REVAQ threshold values but a successful reduction of the Cd levels is assumed to result in a reduction of Pb, Cu, Cr, Ni, Ag, Zn, and Hg that are already below or near the threshold values. However, to successfully reduce the HM mass flows, the flows must be identified. The findings of major unidentified sources give a solid indication of prioritizing upstream sampling to understand the sources further that gives a foundation for an upstream action plan.

CONTENT

ABBREVIATIONS

Abbreviation	Description
HM	Heavy metals
WWT	Wastewater treatment
WWTP	Wastewater treatment plant
WWTS	Wastewater treatment system
WRRF	Water Resource Recovery Facility
ESEM	Eskilstuna Strängnäs Energi & Miljö
SMP	Svenska miljörapporteringsportalen (Swedish Environmental Reporting Portal)
STAN	Substance Flow Analysis, by Vienna University
PE	Person Equivalents
TS	Total Solids
DM	Dry Matter
IQR-method	Interquartile range-method
EPA	Environmental Protection Agency

1 INTRODUCTION

Land application of sewage sludge is common in EU countries and the United States, and increasing demand for higher sludge quality is critical from a health aspect, but can also prevent circularity. With the opportunity to circulate valuable nutrients back to agriculture, the sludge application on arable land as a fertilizer comes with unwanted contamination of hazardous elements such as heavy metals (HM). Although circular economy practice is a sustainable idea, the sludge quality needs to be carefully monitored to minimize the negative impact of the HM contamination (Yesil et al., 2021, pp. 2-3). Investigating sources of pollution upstream that affect sludge quality is an important aspect within wastewater management; thus, the quality control and sustainability of the sludge (Lin et al., 2025, abstract).

The relatively new concept of Water Resource Recovery Facility (WRRF) is adapted continuously and keeps on being regarded as a recovery facility rather than just Wastewater Treatment Plants (WWTP) (Solon et al., 2019, p. 1). The goal of wastewater treatment is no longer to only protect freshwater resources, but also to achieve the reuse of nutrients, organic matter, and water. Sludge, generated during municipal wastewater treatment, is rich in organic matter with high levels of nutrients that should be circulated back into the loop (Aziz & Mustafa, 2021, p. 12). The goal of this project is to understand the mass flows of HM by conducting a mass balance for streams in a WWTP and the upstream sewage network. Within this case study, the WWTP is managed and owned by *Eskilstuna Strängnäs Energi & Miljö (ESEM),* and it is located in Eskilstuna, Sweden. The hypothesis before the investigation is that the balances will show an imbalance in terms of deviation, and the project will highlight where these deviations occur. The project has developed a steady-state mass balance model based on empirical data, modelling upstream heavy metal mass flow and the WWTP.

1.1 Background

To avoid soil and crops being contaminated with heavy metals, only certified sewage sludge can be used in agricultural lands in Sweden. The certification process is conducted through REVAQ(SPCR 167), with the purpose of continuous improvement of the quality of the sludge and systematically investigating wastewater pollution upstream. REVAQ certification also defines a set of threshold values for certain heavy metals in sewage sludge. (RISE, n.d.)

The development of REVAQ has brought the factor-ratio of mg Cd/kg P (mg Cadmium/kg Phosphorus) as an overall quality indicator. REVAQ includes this quality indicator to have a long-term sustainable goal to limit cadmium to agriculture, and it is an indicator competing with synthetic fertilizers. As agriculture already uses synthetic fertilizers with a Cd/P-ratio of 7, and human activities introduce a ratio around 14, the long-term goal is 7 + 14 = 21 to slowly decrease new cadmium input to the system (Svenskt vatten, 2024, p. 5). However, the use of wastewater sludge in agriculture has decreased with the increased concern about heavy metals in soil. Heavy metal limits have decreased since the introduction of the limits in 1993, and the continuous decrease of the limits has resulted in higher quality and less input of heavy metals to agricultural land (SOU, 2020, p. 85-94).

Additionally, the trend from 2010 to 2016 shows a general decrease in heavy metal content in sewage sludge (SOU, 2020, p. 319). Although, Sylwan and Thorin (2021) states that elevated concentrations of heavy metals can be noted within the environment in general.

Carvalho (2024) states that "our recent findings indicate that the heavy metal mass balances over the treatment process are not fully understood".
As the recovery of the high nutrient content of sewage sludge is constrained by the heavy metal concentrations (previously mentioned), increasing the knowledge of the metals mass balance within the wastewater treatment plants can be crucial to improve the recovery and reuse of valuable nutrients.

According to the 2023 REVAQ report, Svenskt vatten (2024, p. 21) lead (Pb), cadmium (Cd), copper (Cu), Chromium (Cr), Mercury (Hg), Nickel (Ni), and Zinc (Zn) are the most hazardous heavy metals in the sludge, and regulations demand monitoring these in the sludge. These HMs are included in this project. However, REVAQ certification, as the most advanced investigation certification, investigates 60 additional elements that are of concern when sludge is applied to arable land.

The critical sludge quality parameters according to Svenskt vatten (2025, p. 38) are presented in Table 1. Phosphorus is included due to its relevance through the quality indicator Cd/P-ratio. Silver is not considered to be one of the most hazardous heavy metals, but is included in this case study because it is a prioritized trace metal due to its high accumulation rate (Svenskt vatten, 2025, title 3.3.1.4 & appendix 5).

Table 1 Critical quality parameters in sludge (Svenskt vatten, 2025, p. 38). Except for the hazardous metals mentioned earlier, the important nutrient P is included, and Ag is included as well.

Element	mg/kg TS
Lead (Pb)	34.00
Phosphorus (P)	30'000.00
Cadmium (Cd)	0.70
Copper (Cu)	410.00
Chrome (Cr)	55.00
Mercury (Hg)	0.75
Nickel (Ni)	34.00
Silver (Ag)	3.30
Zinc (Zn)	820.00

Besides the critical values, REVAQ certification presents the threshold mass output of heavy metals per hectare of agricultural land the sludge is spread on shown in Table 2.

Table 2 Threshold values for spreading heavy metals to agricultural land. The figures are based on 22 kg P/ha (Svenskt vatten, 2025, appendix 8).

	2024 (g/ha)	2025 (g/ha)	2026 (g/ha)	2027 (g/ha)	Goal (g/ha)
Pb	25	25	25	25	25
Cd	0.51	0.51	0.51	0.51	0.47
Cu	300	300	300	300	300
Cr	40	40	40	40	40
Ni	25	25	25	25	25
Ag	2.4	2.4	2.4	2.4	0.56
Zn	600	600	600	600	600
Hg	0.55	0.55	0.55	0.55	0.23

1.2 Problem area

Direct application of sludge as a fertilizer poses environmental and health risks in the sense that sewage sludge also holds HM and other contaminants. The Swedish Environmental Protection Agency's (Swedish EPA) proposal for concentration limitations of HM is based on circular economy practices, where, in theory, input should be equal to output within the value chain (SOU, 2020, p. 308-309). As per today, the sludge from Ekeby WWTP (case study) ends up in a landfill due to the lack of certification, thus not contributing to circular economy practices for the sludge (EEM.se, 2023, sludge management).

Swedish wastewater plants have limited removal of HM, thus limiting the recovery of nutrients by the use of sludge (Svenskt vatten, 2023, p. 11). To decrease HM in the influent, upstream investigation is required to understand the sources and act at the source. As per today, ESEM does not have an adequate understanding of the distribution of HM mass flow upstream nor the flow in the treatment (ESEM, Personal Communication, 2024-11-08).

The first part of the project is the mass balance upstream from the WWTP. Sweden has an open database for actors' pollution, "Swedish Pollutant Release and Transfer" but only includes larger actors. While Eskilstuna has over 200 actors with notifiable activities and permit requirements connected to Ekeby WWTP, the database only presents 11 of the actors (Swedish EPA, n.d.). This excludes data that requires manual investigation in official documents. Actors with wastewater pollution to the sewage system that are required to report data, report data to SMP (Swedish Environmental report Portal), but the database is restricted for official use. Literature review has shown that the common method is to use water sampling in the data collection of upstream sources. In this project, samples within the WWTP are financed, and official documentation, i.e., environmental reports, will work as an indicator to quantify the industry mass flow of HM upstream from the wastewater plant. The 2023 REVAQ report from Svenskt vatten (2024, p. 14) highlights successful actions based on understanding of the distribution of pollutant contribution upstream, made with mass balance.

The second part of this project is mass balance within the actual treatment process. Where streams are analyzed to conduct a mass balance. The mass balance can give clear insights into how HM travels through the processes of the WWTP and has the potential to highlight where the elements leave the system. As HM in general affects the overall efficiency of the treatment, understanding the mass balance could contribute to efficiency improvement actions (Yoshidaa et al., 2013, p. 881).

1.3 Previous relevant studies

Tuci et al. (2024) evaluates HMs (lead (Pb), cadmium (Cd), nickel (Ni), arsenic (As), and tin (Sn)) in wastewater by using a mass balance method. The overall scope was to analyze the removal efficiency of heavy metals. The chosen HMs were relevant to their focus on wastewater from the textile industry. The study shows a significant and effective removal of the HMs. Even though this project does not specifically consider textile wastewater, the method of mass balance is relevant.

Sylwan and Thorin (2021) review the removal of heavy metals in the primary treatment step of wastewater treatment process. Their review shows that sorption technologies within the primary stage of the treatment have the highest efficiency of HM removal. The HMs of concern are Cd, Chromium (Cr), Copper (Cu), Pb, Zinc (Zn) and Mercury (Hg). Silver (Ag) is also mentioned briefly, regarding its toxicity. Sylwan and Thorin (2021) also means that site-specific investigations of heavy metal removal are needed due to variations site-to-site, this strengthens the importance of this project being an investigation on a single site. The method in the article of reviewing removal of heavy metals does not specifically bring relevance into mass balance methods, but the content and discussions where mass balance, removal and sludge are in focus, are highly relevant.

Yoshidaa et al. (2013) used the mass balance method in a WWTP in Denmark, and the main limitation mentioned was the difficulty of tracking emissions in gaseous form. The author also mentions that internal recycling of reject water from dewatering back to the system can complicate the efficiencies of other removal techniques. Within the process, 12 sensors collected data for concentration and volume flow in specific areas of the process. Water sampling for HMs was made every other week. The treatment process is similar to the process related to this actual thesis, using waste-activated sludge process with a connected anaerobic digestion process. For the data analysis and substance analysis, the software STAN(Substance flow Analysis) model by Vienna University of Technology was used. The authors successfully conducted a mass balance of 24 out of 32 substances, but as mentioned, gas emissions contributed to major uncertainties. Cu, Cr, Pb, Cd, and Zn primarily ended up in the sludge, showing a higher accumulation in the sludge compared to the effluent, while Ni was equally distributed between the sludge output and the effluent, as seen in this project as well.

From the mass balance, Yoshidaa et al. (2013, p. 878) noticed a 6% loss of Hg in the anaerobic digestion, potentially volatilized and leaving with the biogas.

Methods for upstream analysis within the wastewater system are commonly composed of water sampling (Foppe et al., 2021; Iloms et al., 2020; Yoon et al., 2014). As this contributes with direct data collected downstream from the actors, this project analyses data further upstream at the source of pollution. Due to the unavailability of physical water sampling in this project, the closest to the common method is simply to make use for each industry's individual water sampling.

An identified research gap would consider the reliability of using a documentation method rather than actual water sampling for the upstream analysis. This investigation clearly shows how the availability of official documentation can contribute to or be problematic for mass balancing. As Sylwan and Thorin (2021) discusses, site specific investigations are required as every site differ from one another. This type of investigation has not been done at the WWTP and the common procedure for ESEM is to follow concentrations rather than mass flow in the plant, which is dependent on both concentration and volumetric flow.

1.4 Purpose/Aim

The purpose of the thesis is to investigate and conduct a mass balance of HMs and connect it to the relevance of enhancing nutrient recovery with sludge. The investigation includes upstream sources of pollution, but also considers processes within the WWT to conduct the mass balance. The investigation will contribute to improvement opportunities for the actor, both external and internal, as the upstream investigation is a part of the REVAQ certification. Additionally, the mass balance within the plant aims to quantify mass flow streams throughout the treatment.

1.5 Research questions

The research questions for this degree project are the following:

What are the primary upstream sources of the HMs in question within the wastewater system?

What are the quantities of mass balance deviation between measurements and expectations (unidentified sources) within the wastewater system, and how does it affect the output related to sludge?

What current and future challenges can be identified for the actor for using sewage sludge as a fertilizer, enhancing nutrient recovery?

1.6 Delimitation

The study will be delimited to local data within the wastewater system of Eskilstuna Energi & Miljö, Ekeby wastewater treatment plant, official documentation, and literature. The delimited heavy metals are lead (Pb), cadmium (Cd), Copper (Cu), Chromium (Cr), Nickel (Ni), Silver (Ag), Zinc (Zn), and Mercury (Hg), with a focus on investigating challenges and opportunities for enhancing the recovery of sludge to agriculture (REVAQ). The project is delimited to bigger sources of pollution, quantifying big industries upstream from the WWTP, such as permit-required industries and industries with notifiable activities. The deviations between inlet data at the WWTP and defined sources of pollution will result in assumptions about other sources of pollution. The investigation covers the system from the effluent from WWTP to upstream sources of pollution. Actual and potential sources of pollution to effluent and sludge from the WWTP are investigated. As influent is monitored, the project will divide the mass balance between the treatment process in the WWTP and the upstream sewage network.

The material balance formula "accumulation = input – output + generation - consumption" for the treatment process considers only the constructed wetland as accumulation within the system. Inputs are all incoming flows to the system. The output considers the overall effluent but also the dewatered sludge after anaerobic digestion. No consumption or generation is considered in this study due heavy metals being elements. However, the critical data for the study is from upstream sources to sludge output, and the balance reveals HMs ending up in the sludge and quantifies what is not ending up in the sludge. A simple schematic flow chart of the system boundaries is shown in Figure 1.

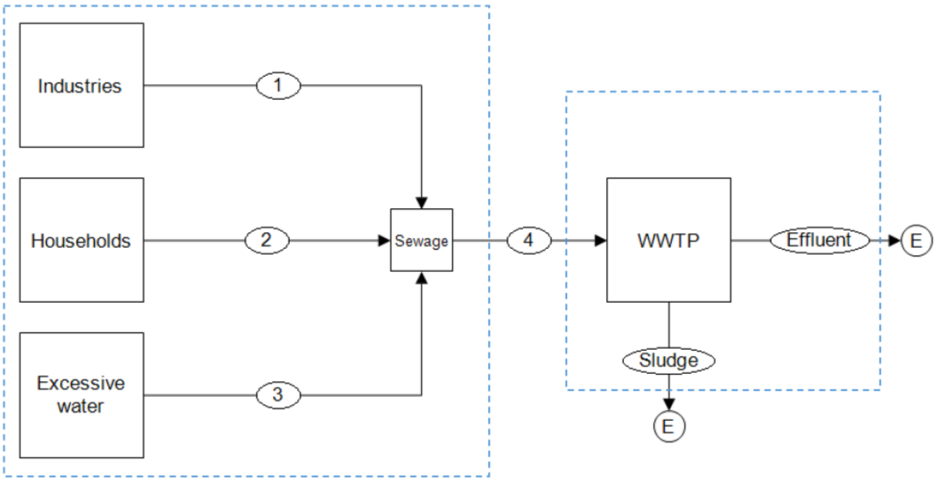

Figure 1 Delimited mass flow analysis schematic of the WWTP. 1: flow from industries, 2: flow from households, 3: flow from excessive water, 4: incoming flow to WWTP, E: export flow from the system

The upstream material balance formula considers input = output. The sum of the input to the sewage system ends up as input to the treatment plant.

The excessive water is defined as leakage, drainage, groundwater infiltration and stormwater. Where proportions can be complex, only groundwater and stormwater pollution concentrations are considered.

Within the project, the sewage network is not revealed to the author and further specific upstream sources and areas are therefore not analyzed.

2 METHODOLOGY AND DATA SOURCES

The degree project focuses on calculations and data collection, and is a case study at ESEM Ekeby WWTP. The calculation is based on empirical data and document analysis. Any identified gaps in measurements are identified, where assumptions and/or literature study fill the gap. Upstream work includes investigating upstream industries and areas. A study visit was done at the supervisory authority, the Environmental Office in Eskilstuna, extracting official documents of measurements for document analysis from their internal document handling system, Castor. The main tool for calculations is Excel, as it's ideal for initial data handling and simple analysis. For overview of mass balance and clarity of flows, STAN (Substance flow Analysis) by Vienna University is used. MATLAB is used when data or correlations get complex. For visualization, Excel and MATLAB presents graphs and tables, STAN presents process schematics.
The result is presented visually, geographically, showing where sources of pollution may be, together with quantitative analysis. Deviations are linked to the literature study to be able to identify probable sources. A steady-state mass balance model based on empirical data is developed upstream from the WWTP, and a second steady-state mass balance model is developed within the WWTP.

Peer-reviewed articles were retrieved mainly from the databases Scopus, Science and Google Scholar using the keywords, wastewater treatment, heavy metals, heavy metal removal, sludge management, upstream pollution, cadmium, mass balance, mass flow, excessive water, household, industry wastewater, carwashes, stormwater run-off, Sweden, sewage system. The keywords were used iteratively in different combinations during the process of the degree project. Recent articles were the main scope of the literature study, and in addition to the database search, backward citation searching was made through relevant articles to find additional sources, but also to review referencing validity.

Additional to peer-reviewed articles, the database Google was used to retrieve governmental reports and documents using the keywords, groundwater quality, stormwater quality, REVAQ, upstream analysis, household wastewater, wastewater sources.

2.1 Upstream sources of heavy metals

To identify primary upstream sources, the literature review works as a foundation for probable sources of pollution. Pollution data from environmental reports for bigger industrial actors within the system, are input for upstream investigation. To cover the larger quantity of actors connected to the sewage system, official environmental reports were collected for actors with notifiable activities and permit requirements. As the latest environmental reports collected present figures from 2023, the data was analyzed towards production (WWTP) data for 2023 for relevant results.

The influent wastewater at the WWTP is frequently monitored due to regulations, and the data collection originates from the WWTP where the total mass is covered within the inlet. The HM data of the inlet is based on monthly measurements and may not cover fluctuations, considering industry pollution might be higher during active hours. This project analyses data in an annual context to avoid the insecurity and fluctuations that daily and monthly figures can bring.

2.1.1 Handling of data

Household annual data is collected throughout literature and is handled as an annual mean in the mass balance. Literature data for stormwater run-off also considers an annual mean. For the groundwater, a mean for the year 2023 is considered within the mass balance, within 4 points throughout the municipality. As the stormwater and groundwater are parts of the incoming excessive water, the excessive water is assumed to be 50% each, due to the unknown or uncertain proportion. Industry data, as mentioned, consider the total pollution of the year 2023 as an annual mean into the mass balance.

2.1.2 Industry data availability constraints

Before collecting data, it's known that actors with notifiable activities and permit requirements are not always required to report an environmental report and when an environmental report is available the actor can present limited to no substantial pollution to the sewage system, giving no further data. Another limitation is that actors do not report the type of pollution related to the thesis. The available yearly pollution analyzed and summarized from environmental reports was quantified towards the inlet data at the WWTP to understand the proportion of pollution available through environmental reports.

2.2 Deviations in mass balance

Before the collection of data, it is expected that identified sources of pollution will not add up to the total incoming mass of HMs in the inlet of the WWTP. These deviations are linked to the previously mentioned data collection of the influent. Data not available for upstream sources relies on assumptions based on literature study and internal (WWTP) assumptions.

Production data and measurements within the actual WWTP are also expected to contribute to deviations. This is quantified towards the actual influent/effluent content.
This project is only financed with a small quantity of water samples by the WWTP owner. It is therefore critical that the available data covers the foundation of the mass balance. Any deviations or missing parameters relies on literature study, however, data from external sources and WWTP comes with limited accuracy for results as the data can vary from one site to another.

2.3 Opportunities

The quantification and results from the mass balance upstream of the WWTP give indications of known and unknown sources of pollution. The project quantifies opportunities to decrease HMs in sludge by actions both upstream and within the plant itself. Quantification of the mass balance within the plant was analyzed in STAN to simplify the overview of opportunities and how HM streams occur in the treatment system.

2.4 Wastewater Treatment Plant

The WWTP flow schematic was carefully mapped to understand the specific plant and treatment methods used. The opportunities for water sampling within the WWTP need to be understood to develop a water sampling plan. The water sampling is the foundation for a robust and detailed mass balance investigation, as HMs are not systematically analyzed throughout the system in the monitoring plan as per today.

Input such as chemicals and external organic slurry input was investigated with general chemical input consumption and slurry analysis to make assumptions. As none of the additional inputs (such as chemicals and organic input) have been analyzed regarding HM by ESEM, the input HM concentrations are based on literature.

The upstream analysis contributes with total input of HM ending up in the sludge. The proportion of HM input was then related to the sludge HM output to give an indication of sources and quantities of the HM in the sludge.

Incoming and outgoing flow data as handled with a weighted average of 5 days, but monthly HM samples were quantified against the weighted average data for mass flow calculation.

HM samples frequently present concentration values below the detection limit and therefore contribute to an interval in the result.

2.4.1 Handling of data for incoming, outgoing and sludge output

Monthly incoming and outgoing HM to/from the WWTP is input to the mass balance equation and a mean of 2022-2025 was considered. The monthly concentrations of HM was multiplied with dynamic flow, for the mass flow calculation. The sludge HM output was calculated through concentrations and volumetric flow for the years 2023 and 2024 in the mass balance equation.

2.4.2 Sludge and REVAQ

REVAQ thresholds for sludge HM output was converted with consideration of the actor's sludge composition and production for comparison purposes.

2.5 Additional heavy metal samples for the case study

A study visit to the WWTP was conducted to determine where HM analysis is available and not. The purpose of the study visit is also to understand system availability for further HM analysis within this project.
A balance of economical aspect and benefit of HM analysis is needed before making bigger investments in analysis. Therefore, no additional samples are made upstream from the WWTP as the direct benefit is small from a few momentary samples. A total of five measurements at two different datapoints within the WWTP was however conducted.

The samples were made as grab samples at data points F12 and F15 (Figure 5). Two samples were taken at F12 during the days 2025-03-11 and 2025-03-20. Three samples were taken during the days 2025-02-10, 2025-03-03, and 2025-03-12. The analysis method used internally at ESEM is ICP-MS (inductively Coupled Plasma Mass Spectrometry) with Helium KED (Kinetic Energy Discrimination) [SS-EN ISO 17294-2]. Microwave-assisted acid digestion [SS-EN ISO 15587] was used to prepare the samples, which included mixing the sample with nitric acid (HNO_3) and heating with microwave energy.

3 THEORETICAL FRAMEWORK

This section presents the foundation for the mass balance analysis and forms the foundation with theoretical concepts and system models. The section includes system theory, upstream heavy metal sources, and processes within the WWTP.

3.1 System theory

The law of conservation of mass states that material cannot disappear or be destroyed. Continuity occurs, and the expression can therefore also be called the continuity equation (Pedrizzetti, 2022, pp. 55-56). The studied system is considered an open flow system where the process interacts with the surroundings, i.e., input flow into the system boundaries and output flows from the system to the surroundings (Khandan, 2001, p. 20).

As the system will consider multiple different metal mass balances in the system, the classification of algebraic equations is multiple linear equations and will result in one solution set (Khandan, 2001, p. 43).

Conservation of mass formula:

Equation 1

$$\sum \dot{\mathrm{m}}_{\mathrm{in}} = \sum \dot{\mathrm{m}}_{\mathrm{out}}$$

Where,

$\dot{\mathrm{m}}_{\mathrm{in}}: Mass\ flow\ of\ input\ HM\ to\ the\ system\ \left[\frac{kg}{m^3}\right]$

$\dot{\mathrm{m}}_{\mathrm{in}}: Mass\ flow\ of\ output\ HM\ from\ the\ system\ \left[\frac{kg}{m^3}\right]$

Material balance formula:

Equation 2

$$Accumulation = input - output + generation - consumption$$

For simplification of the model, accumulation is only considered within the constructed wetland. As constructed wetlands are mainly used for water purification from pollutants with the help of physical, biological, and chemical processes (Gecheva et al., 2024). When accumulation occurs within the system, the steady-state assumption may not be valid for short term context but can be considered valid for this project given the focus on long-term inputs and outputs. Due to simplification purposes upstream, only input and output are considered for the upstream sewage system, as these are the critical parameters. Additionally, the output effluent is not considered a critical parameter as the project aims towards the output related to the sludge. Furthermore, Figure 2 shows a brief overview of the model within this degree project which results in a numerical model of the HM mass balance.

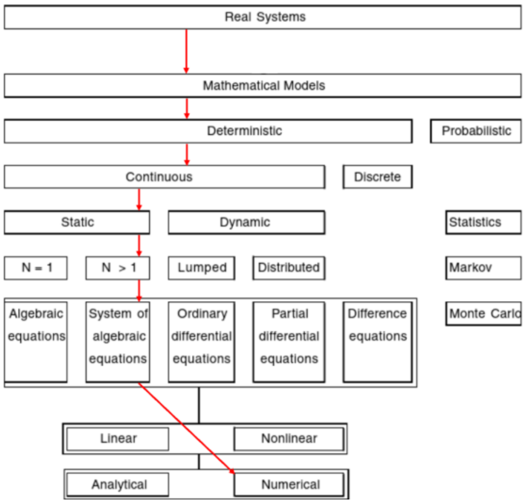

Figure 2 Classification of model type for this study, picture based on (Khandan, 2001, figure 1.1)

3.2 Upstream heavy metal sources

Summarized sources upstream from the WWTP are based on Svenskt vatten (2019, p. 22-26) and presented in Table 3.

Table 3 Probable sources of HM upstream Svenskt vatten (2019, p. 22-26).

	Sources
Pb	Carwash, roads, floor cleaning, households
Cd	Carwash, roads, paint, households (food)
Cu	Carwash, roads, industry, corrosion of sewage pipes (mostly)
Cr	Carwash, roads, industry
Ni	Carwash, roads, industry
Ag	Households (clothes), industry (electrical components)
Zn	Carwash, roads, corrosive protected surfaces, households (food, hygiene products)
Hg	Dentistry, laboratory, industry (electrical components)

3.2.1 Excessive water

Excessive water is unwanted water reaching the WWTP. This includes diffuse water input, such as precipitation and infiltration into the sewage system. The extraneous water also includes direct sources of input to the system, such as leakage or overflows (Molander, 2015, p. 1). Stormwater input is complex to quantify, and measurements are often site-specific and can therefore not be directly valid for another site. The stormwater quality is often based on models where simplifications for land characteristics occur, which affects the stormwater run-off quality (Swedish EPA, 2017, pp. 56-57).

Clementson et al. (2020, p. 28) presents a mean value of excessive water to 20 different WWTP. It ranges from 20-70% of the total treated water and the mean and median value are 43% and 44%, respectively.

Ejhed et al. (2018, appendix 2) published a report on behalf of the Swedish EPA, where the author presents concentration data of stormwater with a focus on representing urban areas, not including industrial areas. The data is based on the Swedish EPAs' screening database, where relevant data for this project is presented in Table 4.

Table 4 Stormwater run-off HM concentration based on (Ejhed et al., 2018, appendix 2)

Metal	Mean (µg/L)	Min (µg/L)	Max (µg/L)
Cd	0.041	0.005	0.088
Ni	3.7	0.69	15
Cu	8.7	1.7	23
Cr	2.5	0.31	9.7
Ag	0.392	0.018	1.9
Hg	0.35	0.003	1.4
Pb	4.5	0.29	26
Zn	47	5.7	80

3.2.2 Carwashes and workshops

In Sweden in 2023, 15 296 184 carwashes were done in approved carwashes (Hållbarbiltvätt.se, 2024, p. 4). Eskilstuna municipality had 107 468 inhabitants in 2023 (Eskilstuna municipality, 2024, table 1) and as Sweden had 10 551 707 inhabitants the same year (SCB, n.d.), Eskilstuna corresponds to approximately 1.02 % of the total population. Assumptions can therefore be made that Eskilstuna municipality should have 1.02% of 15 296 184 carwashes, thus 156 000 carwashes per year.

It is shown in Lagerkvist (2004, pp. 3-5) that floor cleaning from 20 car workshops could contribute to around 0.3% Cd, 1.2% Zn, 1.5% Pb, 0.2% Ni, 0.5% Cr, and 0.6% Cu of the annual incoming HM, considering the incoming flow to Ekeby WWTP.
However, the study is over 20 years old, but these figures can work as a potential pollution. The pollution depends on the handling of the polluted cleaning water. From a search in the local online directory service hitta.se (n.d.), well over 50 such workshops are registered in Eskilstuna. Additionally, a high quantity of small shops can be expected not to be searchable.

3.2.3 Households

A study by Gryaab (n.d.) at Ryaverket in Gothenburg, Sweden, where four 24-hour samples were collected throughout the year showed the following figures of household pollution. Figures are shown in Table 5. Where p*d = person*day for the upcoming tables.

Table 5 Concentration of HM and P-tot for household wastewater to Ryaverket in Gothenburg (Gryaab, n.d., pp. 9-10).

	Pb	Cd	Cu	Cr	Ni	Ag	Zn	Hg	P-tot
2006/2007 [mg/(p*d)]	1	0.03	20	0.7	0.9		30	0.03	1.5
2017/2018 [mg/(p*d)]	0.4	0.02	20	0.5	0.7		30	0.01	1.1

The study was based on 2 urban areas of 865 and 2708 inhabitants with an average flow rate of 210 l/(p*d) and 251 l/(p*d) year 2017/2018.

Older figures from 2010-2013 presented by Eriksson and Lagerkvist (2015, p. 10) in Skarpnäck, Stockholm, show the following pollution from households at 235 l/(p*d). The samples were collected through weekly water samples each year, one in spring and one in the fall. Figures are shown in Table 6.

Table 6 Concentration of HM and P-tot for household wastewater from Skarpnäck, Stockholm during the years 2010-2013 (Eriksson & Lagerkvist, 2015, p. 8)

	Pb	Cd	Cu	Cr	Ni	Ag	Zn	Hg	P-tot
Average [mg/(p*d)]	0.59	0.023	12	0.28	0.71	0.07	24	0.009	1.05
Median [mg/(p*d)]	0.48	0.021	12	0.29	0.68	0.06	25	0.006	1.07

Eriksson and Lagerkvist (2015, p. 10) also means that using a ratio of mg metal/kg P normalizes the values for easier comparison between different wastewaters, and the ratios of the relevant HM are shown in Table 7.

Table 7 Normalized metal values through the metal/P ratio with the unit mg Metal/kg P (Eriksson & Lagerkvist, 2015, p. 10)

	Pb/P	Cd/P	Cu/P	Cr/P	Ni/P	Ag/P	Zn/P	Hg/P
Average [mg/kg]	579	22	11397	273	695	67	23118	9
Median [mg/kg]	488	24	11280	277	627	53	23880	5.3

In the year of 1995, Swedish EPA (1995) published a similar rule of thumb for household pollution to account for within calculations. Which are shown in Table 8.

Table 8 The rule of thumb by the Swedish EPA for household pollution (Swedish EPA, 1995, p. 9)

	Pb	Cd	Cu	Cr	Ni	Ag	Zn	Hg	P-tot	Flow [l/(d*p)]
mg/(p*d)	<3	<0.6	<7.2	<5	<3.1	<0.003	<61	<0.07	2.1	200

All concentrations in Table 8 are higher in the previously mentioned publications (Eriksson & Lagerkvist, 2015) and (Gryaab, n.d.) except for Ag. However, the mean flow of the publications can still be accurate for approximation purposes, and a comparison can be seen in Figure 3.

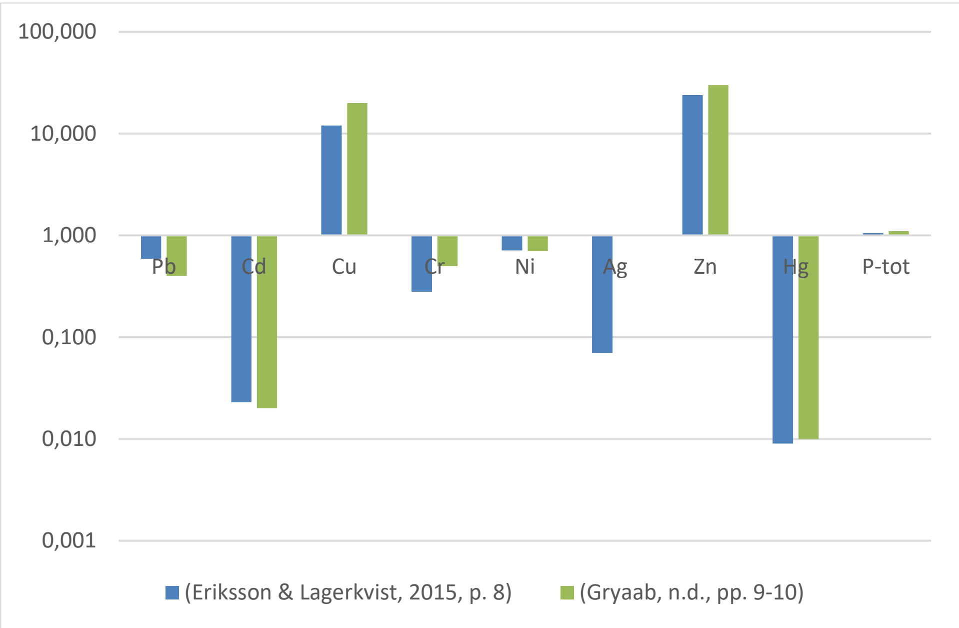

Figure 3 Visual presentation of comparison, household HM concentration, and P-tot (Eriksson & Lagerkvist, 2015; Gryaab, n.d.).

3.3 WWTP mass balance

The following data points within a treatment process, like ESEM's, have been used to compose a mass balance of heavy metals described in Yoshidaa et al. (2013).

- Influent
- Influent to the aeration basin
- Effluent from WWTP
- Primary sludge
- Secondary sludge
- Fats, oils, and grease
- Digested sludge
- Dewatered sludge
- Dried sludge
- Ash from after incineration
- Reject water after dewatering

Furthermore, Yoshidaa et al. (2013, Appendix A) shows significant mass flows of heavy metals in secondary sludge which in this case study is partially circulated back to the incoming sewage water before preliminary treatment and to primary treatment. The following numbers are mass of element in secondary sludge divided by mass of element in influent to the system.

- Ag: 47%
- As: No significant mass
- Cd: 19.4%
- Cr: 41%
- Cu: 40%
- Hg: 30%
- Ni: 26%
- Pb: 31%
- Zn: 37%

HM shows a trend to accumulate in the sludge rather than going to the effluent water. The removal rate of HM is directly proportional to the incoming wastewater concentration, considering Cd, Pb, Cu, and Zn. Potential removal efficiencies from influent to effluent can also be seen in conventional WWTP for the following HMs with increasing efficiency: Cd, Pb, Cu, Zn (Chipasa, 2003).

3.4 Food slurry

Food slurry is defined as kitchen waste, including industrial kitchen waste and restaurants, waste from grocery stores, and producers. The food slurry also includes waste from fat separators (Jones & Jonsson, 2018, p. 6). Different composition of organic waste is presented in Table 9.

Table 9 HM concentration in food slurry input to anaerobic digestion (AD) or digestate after AD. The last row presents average data from a large population of actors in Sweden, a report ordered and published by the Swedish EPA. It should represent the most accurate data for the food slurry input to the actor related to this report.

Source	Pb [mg/ kgDM]	Cd [mg/ kgDM]	Cu [mg/ kgDM]	Cr [mg/ kgDM]	Ni [mg/ kgDM]	Ag [mg/ kgDM]	Zn [mg/ kgDM]	Hg [mg/ kgDM]	DM [%]	Comment
(Persson, 2019, p. VIII)	<2	<0.2	17	4.2	2.1		57	<0.025		
(Golovko et al., 2022, p. 5)	2	0.35	100	8.2	7.2		540	<0.1	3.1	digestate
	2.7	0.34	41	13	11		180	<0.1	4	digestate
	7.4	0.37	67	20	15		220	<0.1	2.9	digestate
(Kuppera et al., 2014, sup.info. table 4)	19	0.13	31	11	9.5		76		50	Compost
	33	0.13	47	16	14		109		54	Compost
	30	0.025	86	23	12		153		54	Compost
	59	0.081	43	13	12		125		46	Compost
	66	0.1	60	21	17		193		58	Compost
	26	0.021	37	17	14		121		52	Compost
	54	0.34	71	25	21		193		55	Compost
	100	0.53	55	15	11		249		55	Compost
(Jones & Jonsson, 2018, p. 12)	**2.6**	**0.07**	**19.4**	**4.6**	**2.7**	**0.42**	**57.5**	**0.03**		**Average incoming food slurry concentration in Sweden**
	n=218	**n=209**	**n=220**	**n=220**	**n=218**	**n=36**	**n=220**	**n=207**		**Number of actors data**

3.5 Input chemicals in the wastewater treatment plant

The following numbers are related to confidential data and sources, and product specifications cannot be presented further due to security considerations.

Table 10 Chemical inputs to the WWTP

Chemical	Density	Annual consumption (2023)	Annual volume (2023)
Ferrous Sulfate	1890 kg/m^3	340 000 kg	180
Ferric Chloride Solution	1400-1440 kg/m^3	756 000-777 600 kg	525-555
Co-polymer	800 kg/m^3	19 000 kg	23.75
Carbon Source	1200 kg/m^3	167 600 kg	140

Literature study of confidential product data sheets shows no heavy metal contamination.

3.6 Dewatered sludge

For the density of dewatered sludge, Andreoli et al. (2007, pp. 5, 9) use 1000 kg/m³ and 1050 kg/m³.

4 CURRENT STUDY

Ekeby WWTP is in Eskilstuna, Sweden, and an overview is shown in Figure 4.

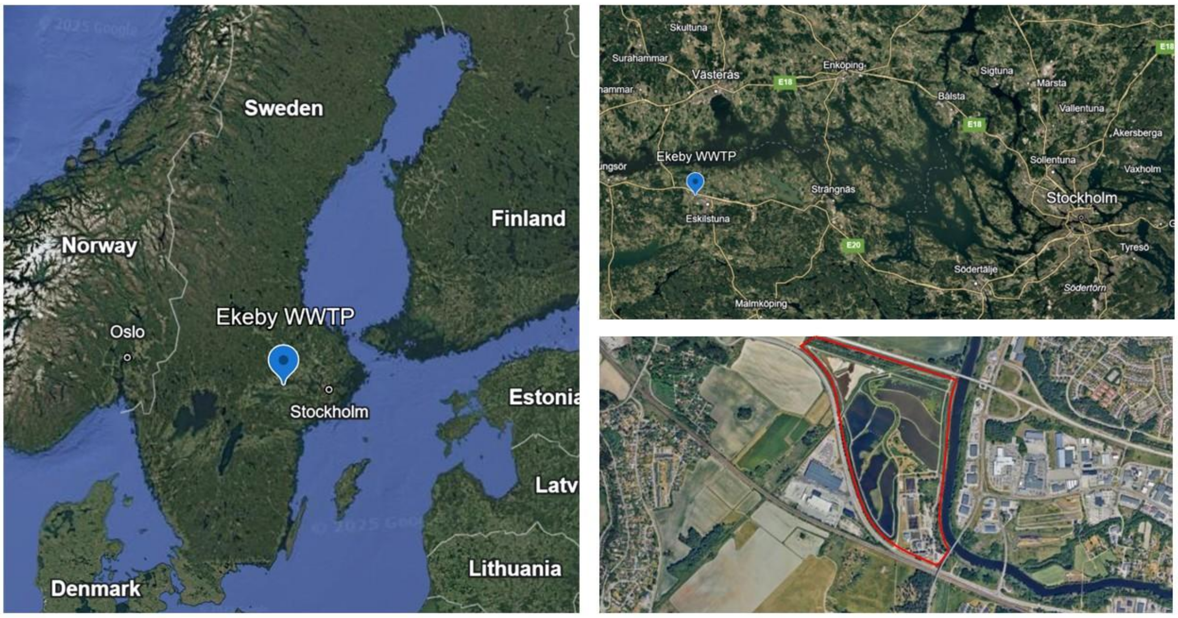

Figure 4 Location of Ekeby WWTP, where 4a is an overview of Sweden, 4b is an overview of Eskilstuna in relationship with nearby cities, 4c a close overview of the WWTP area (Google Earth, 2025).

4.1 Data collection in the WWTP

A study visit was made to the WWTP to discuss available data and to design the flow schematic of the WWTP, resulting in a simplistic overview schematic. Primary and secondary treatment stages have several stages, but are regarded as one process within this report and calculations. The schematic flow chart is shown in Figure 5 and critical flows for HM concentration in sludge are marked red.

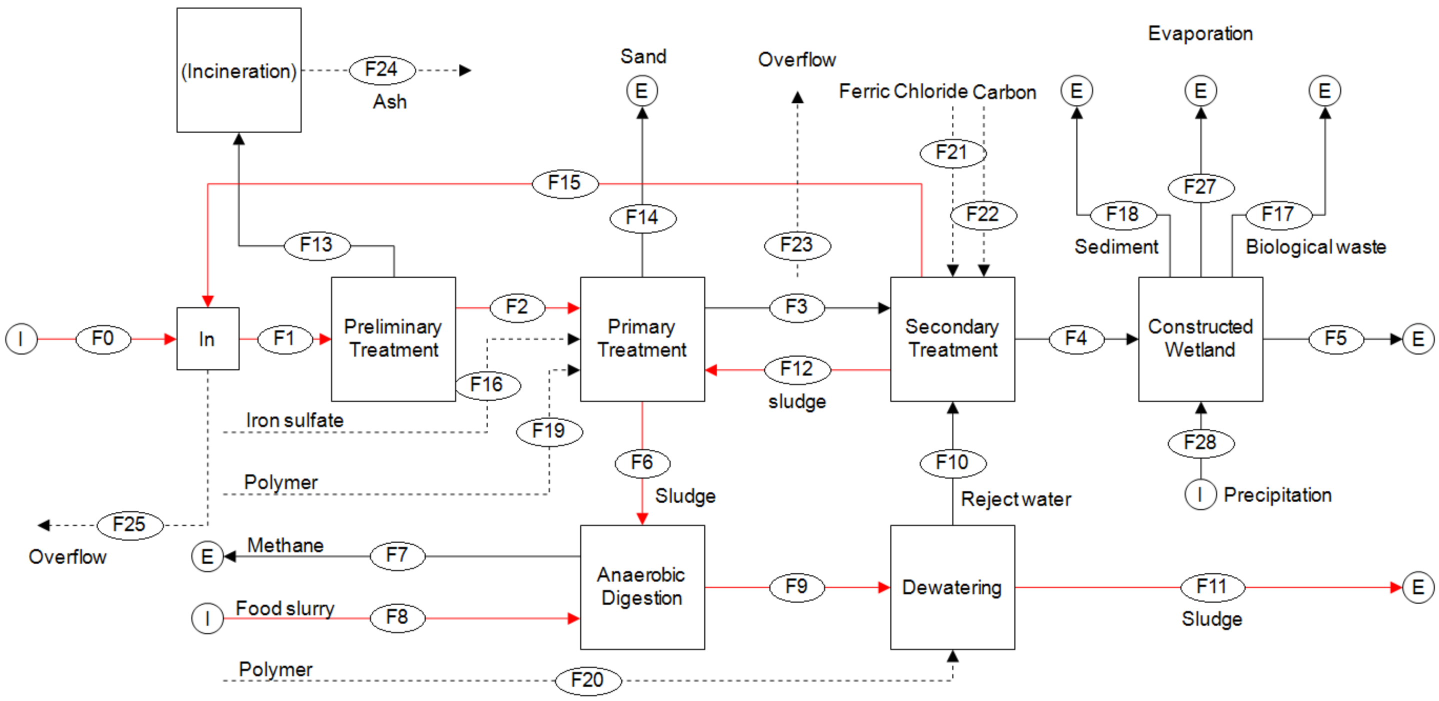

Figure 5 Simplistic schematic flowchart of ESEM's WWTP. F=flow, I=Input (Import), E=Output (Export). Schematic made in STAN software.

The available data for the treatment process is shown in Table 11 where concentrations of HM are analyzed monthly for F1, F4, F5 & F11.

Table 11 Available data in WWTP

Data point	Available data
F1	Volumetric flow, HM concentration
F4	Volumetric flow, Cd & Ag concentration
F5	Volumetric flow, HM concentration
F6	Volumetric flow
F11	Annual mass output, HM concentration, Dry matter
F12	Volumetric flow
F15	Volumetric flow
F16	Annual mass input 2023
F19+F20	Annual mass input 2023
F21	Annual mass input 2023
F22	Annual mass input 2023
F25	Annual volumetric output 2023

During the year 2023, the facility treated 19 320 815 m^3 of wastewater (overview shown in Figure 6) and the average input for 2021-2025 is approximately 17 200 000 m^3 for the raw data at F1 in the schematic flow chart Figure 5.

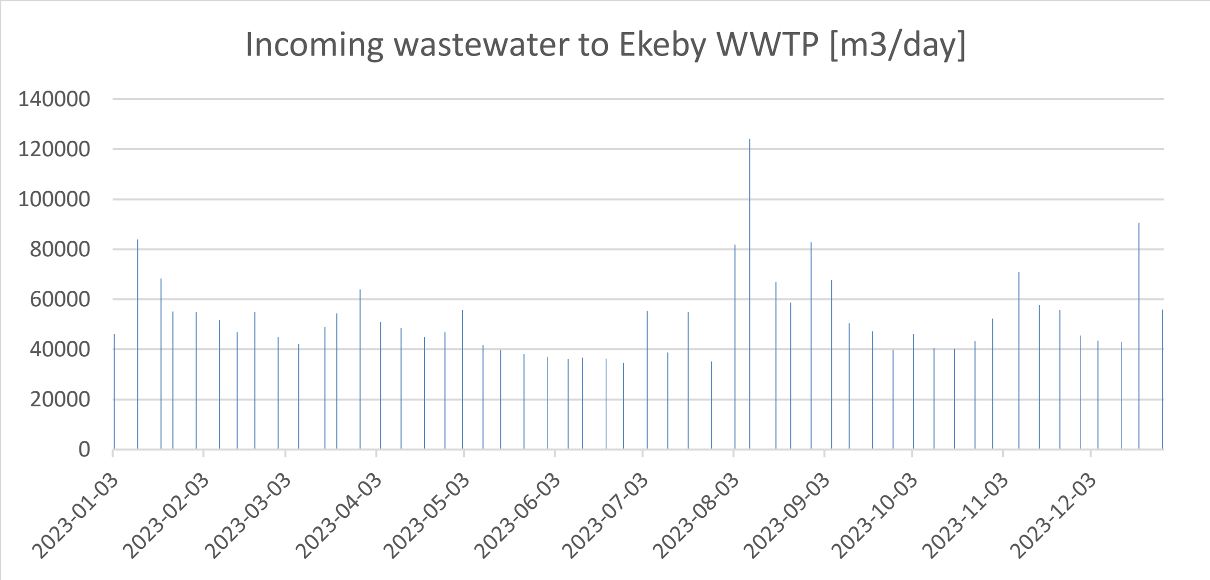

Figure 6 Overview of daily average incoming wastewater.

To understand the relevance of the sludge quality, the actual sludge quality in relation to critical parameters within REVAQ is shown in Table 12.

Table 12 Critical sludge concentration according to REVAQ and actual concentration based on 2023 figures.

	Critical [mg/kg TS] (Svenskt vatten, 2025, p. 38)	Sludge output [mg/kg TS] (ESEM, Environmental report, 2023)
Lead (Pb)	34.00	24.00
Phosphorus (P)	30 000.00	25 630.00
Cadmium (Cd)	0.70	1.90
Copper (Cu)	410.00	428.00
Chrome (Cr)	55.00	46.00
Mercury (Hg)	0.75	0.70
Nickel (Ni)	34.00	34.00
Silver (Ag)	3.30	1.90
Zink (Zn)	820.00	575.00
Cd/P-ratio	23.30 (calculated)	74.10 (calculated)

4.1.1 *Inflow and outflow analysis (F1 & F5)*

The raw data from the WWTP for inflow and outflow are the F1 and F5 flows in the schematic flow chart(Figure 5). Note that F0 is the actual inflow, but the data point available in the WWTP is F1. In Figure 7, the raw inflow data of wastewater is presented.

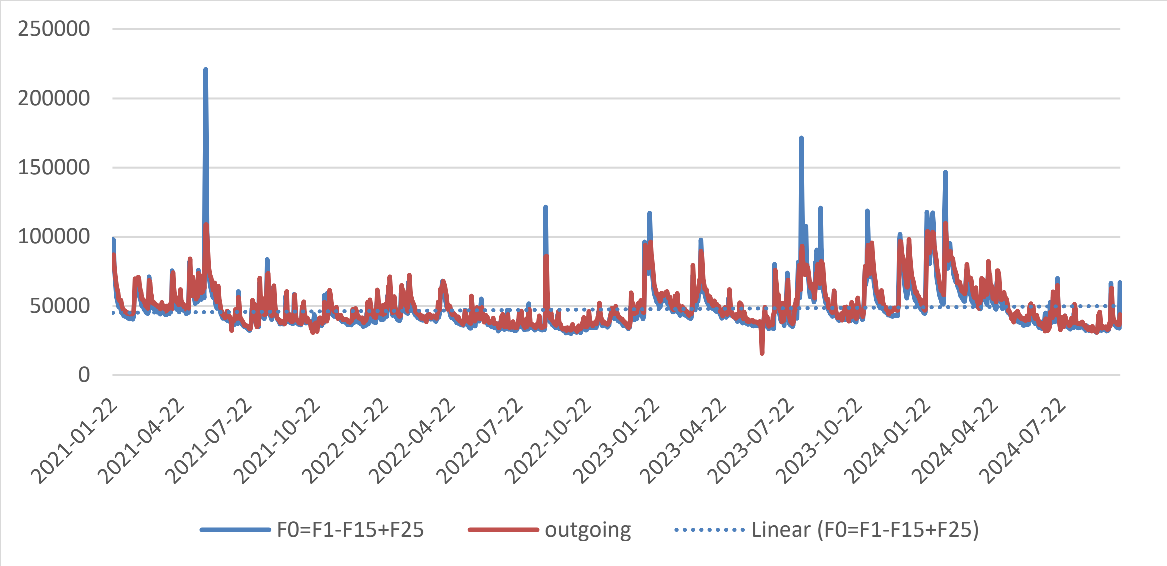

Figure 7 Raw data inflow and outflow 2021-01-22 to 2024-10-09. The trendline is shown in dots.

The available data for outflow has a gap of 2 months after 2024-10-09. Inflow and outflow are therefore only analyzed before the gap.

Analysis of inflow and outflow of a period from 2021 to 2024 shows outflow mean has a significantly higher flow than the input mean. Descriptive statistics of the different analyzed methods of data handling are shown in Table 13.

Table 13 Descriptive statistics and an overview of different data handling methods of raw data. The weights of the weighted mean are 0.05; 0.25; 0.4; 0.25; 0.05.

	Raw data		Weighted mean 5-day		Moving average 30-day		IQR-method	
Deviation [m^3/d]	2160		2124		2101		2591	
R^2	0.83		0.89		0.96		0.86	
Standard deviation inflow/outflow	16323	14385	15173	13714	11126	10999	9861	10705

Considering additional inputs such as precipitation, evaporation, sludge output, chemical inputs and slurry inputs, these inputs to the systems are not significant to the magnitude of deviation and is therefore not the reason for the magnitude of deviation.

The 5-day weighted mean provides a strong relation in combination with lowering standard deviation, keeping the mean deviation of volumetric flow similar to the raw data. This indicates a strong relationship and a close match. For this project, the moving average, and the Interquartile range method (IQR method) might remove important data, as the data naturally fluctuates heavily. The IQR method is assumed to remove true variation as the deviation of input-output did not improve, while the moving average of 30 days oversmooths the variation. The weighted mean is assumed to balance smoothing, real variability preservation, and mass balance integrity and is therefore used for final mass balance analysis of the heavy metals in question.

4.1.2 Input chemicals (F16, F19-22)

In the flow chart Figure 5 chemical input occurs in F16, 19, 20, and 21.

Table 14 Input chemicals to Ekeby WWTP

Chemical	Consumption (2023)	Year	Annual volume (2023)
Iron sulfate	340 000 kg	2023	180 m^3
Ferric Chloride Solution	756 000-777 600 kg	2023	525-555 m^3
Polymer	19 000 kg	2023	23.75 m^3
Carbon Source	167 600 kg	2023	140 m^3
Yearly average			883.75 m^3
Daily average			2.42 m^3

As the mean volumetric inflow is approximately 48000 m^3/d, the accumulated chemical inputs are 0,005% of the annual volumetric flow. Additionally, from the literature study, the chemicals do not contribute to heavy metal input and these inputs can therefore be neglected in this study.

4.1.3 Overflow volume output (F25)

The overflow volume F25 is neglected in the mass balance due to its small impact.

Table 15 Annual overflow volume from F25, critical for calculating F0.

Total flow 2021-2025 [m^3]	Yearly average [m^3]	Daily average [m^3]
45 480	11 534	31.6

4.1.4 Input precipitation and output evaporation

The precipitation in the area is typically 400-600 mm annually (SMHI, n.d., 2nd subtitle). Precipitation is an input to the system boundaries before outflow.

Equation 3

$$Area * Precipitation = Volume$$

Example.

Equation 4

$$10'000m^2(1\ ha) * 0{,}4\ to\ 0{,}6\ m = 4000m^3\ to\ 6000m^3$$

The constructed wetland can be assumed to be the main area of consideration for collecting precipitation, quantity calculated in Table 16.

Table 16 Precipitation flow calculation

Precipitation	400-600 mm
Area of constructed wetland	28 ha (280 000 m^2)
Total additional input annually	112 000-168 000 m^3
Total daily input	307-460 m^3
Average daily input	383.5 m^3

Evaporation, on the other hand, is output from the system and the constructed wetland. Evaporation from water bodies tends to exceed potential evaporation due to the open water areas (Acreman et al., 2003, p. 20). In southern Sweden, the evaporation from such cases is 450 mm/year (Thomeby, 1997, p. 306). This indicates that evaporation and precipitation might cancel each other out within the mass balance of water. Evaporation and precipitation effect on input and output of heavy metals are neglected.

4.1.5 Input organic sludge to anaerobic digestion (F8)

The input in the schematic flow chart Figure 5, F8 consists of food slurry, fat from fat separators, and industry ice cream slurry. No additional characteristics or HM concentration are present within ESEM for these inputs. Ice cream slurry is separated from the other food-related inputs due to a direct input to the anaerobic digestion from a local ice cream manufacturer. The ice cream slurry input is, however, not substantial to the context and is neglected in the result.

4.1.5.1. Fat from fat separators

The input of fat from fat separators to the WWTP is shown in Table 17.

Table 17 yearly average input from fat separators, for 2021 and 2022, the density is fixed and set to 800 kg/m³

Yearly average	Volume [m^3]	Mass [kg]	Density [kg/m^3]
2021	1 586.0	1 268 800	800.0
2022	1 379.4	1 103 520	800.0
2023	1 415.0	1 092 800	772.3
2024	1 595.8	1 343 800	842.1
Mean	1 494.0	1 202 230	803.6
Daily mean	4.1	3 294	

In Table 20, concentration of heavy metals for food slurry is presented. In these values, fat from fat separators is included and HM concentrations for the fat separators are thereby considered the same. No dry matter-% (DM) is provided from internal documentation but for the incoming food waste have DM of 10,2% and within this project, the DM for the mixture is assumed not to change.

The contribution of HM from fat is presented in Table 18.

Table 18 Assumed contribution of HM from fat separators in a mixture of food waste and fat. Concentration source: (Jones & Jonsson, 2018, p. 12)

	Pb	Cd	Cu	Cr	Ni	Ag	Zn	Hg
mg/kgDM	2.60	0.07	19.40	4.60	2.70	0.42	57.50	0.03
input [kg]	0.62	0.05	14.53	3.45	2.02	0.31	43.07	0.02

4.1.5.2. Food slurry

The food waste input to the WWTP is shown in Table 19.

Table 19 Average food slurry input

Year	Volume [m^3]	Daily average volume [m^3]
2022	4 222	11.57
2023	7 853	21.51
2024	9 956	27.28
Mean	7 344	20.12

As the balance will be analyzed through annual mean, the HM input for food slurry is presented as such as well.

Table 20 Food slurry HM input, concentration based on literature study. Concentration source: (Jones & Jonsson, 2018, p. 12)

	Pb	Cd	Cu	Cr	Ni	Ag	Zn	Hg
mg/kgDM	2.60	0.07	19.40	4.60	2.70	0.42	57.50	0.03
HM input [kg]	1.95	0.05	14.53	3.45	2.02	0.31	43.07	0.02

Dry matter for the food slurry going into the anaerobic digestion is 10,2%.

4.1.5.3. Ice cream slurry

The input of ice cream slurry from the local ice cream manufacturer to the WWTP is shown in Table 21.

Table 21 Yearly average ice cream slurry input

Year	Volume [m^3]
2022	198
2023	165
2024	105

The low yearly volume combined with a lack of known characteristics results in neglection of the ice cream slurry as a HM contributor.

4.1.6 Output sludge (F11)

Yearly summary of output sludge F11 in schematic flow chart. The density is assumed to be water density based on the literature study. The analysis for the output dewatered sludge has available data for the years 2023 and 2024. The data set contains 31 samples for the two years and has concentrations for Pb, Cd, Cu, Cr, Ni, Ag, Zn, Hg analyzed together with the actual dry matter content in %. The flow, on the other hand, is presented as follows:

Table 22 Annual dewatered sludge output after anaerobic digestion

Year	2021 [kg]	2022 [kg]	2023 [kg]	2024 [kg]	Average [kg]	Daily average [kg]	Daily volume [m3]
Wet sludge	7 769 000	6 100 000	7 035 000	7 987 960	7 222 990	19 789	19.8
Dry sludge	2 121 000	1 769 000	2 054 000	2 207 000	2 037 750	5 583	5.6
Dry matter (TS) %	27.3	29.0	29.2	28.0	28.4		

Equation 5

$$C_{metal}\left[\frac{kg}{kgDM}\right] * Sludge_{wet}\left[\frac{kg}{year}\right] * DM\ [\%] = \frac{kg\ metal}{year}$$

Where,

C_{metal}:	Metal concentration
$Sludge_{wet}$:	Sludge before the dewatering process
DM:	Dry matter

Equation 5 results in the intermediate results of metal mass in sludge are shown in Figure 8.

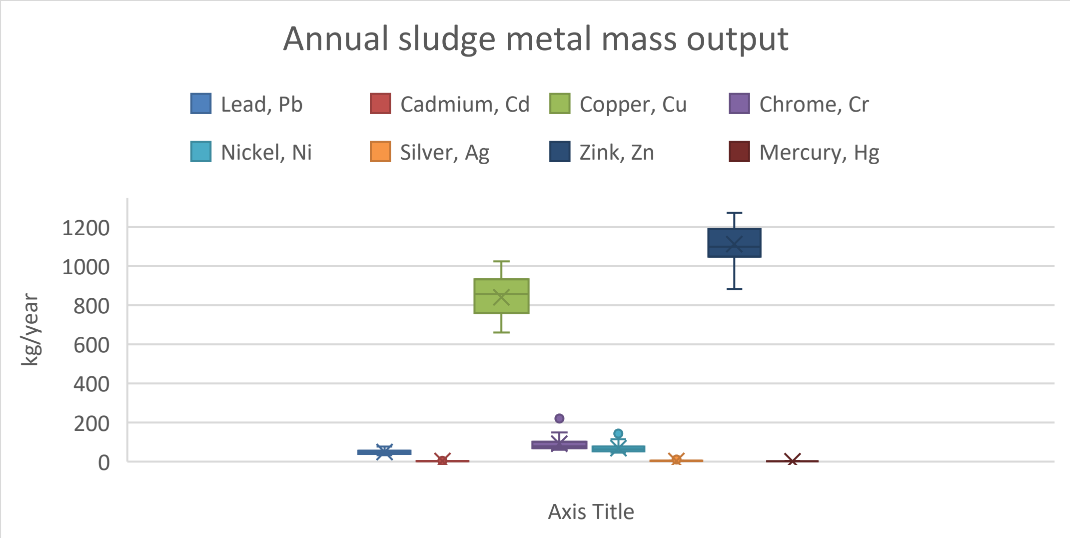

Figure 8 Yearly metal mass output from dewatered sludge [kg/year]

4.1.7 Net volumetric flow (F0 & F5)

To balance the volumetric flows within the WWTP, the inputs and outputs in Table 23 are considered.

Table 23 Summary of input and output flows to the WWT system

Considered inputs	Average flow [m^3/d]	Considered outputs	Average flow [m^3/d]
Precipitation	307-460	Evaporation	450
Food sludge	20.1	Sludge	5.6
Fat from fat separators	4.1		
Chemicals	2.42		
Overflow	31.6		

Net input/output is shown in Table 24.

Table 24 Total input and output flows to the WWT system

	Input	Output
Total	365.2-518.2 m^3	455.6 m^3
Difference interval	-90.4 to 62.6 m^3	

The difference between the additional inputs and outputs is not significant to the data set, and volumetric flow balance considering measurement uncertainty is not known, and the difference between inflow and outflow is well above 2000 m^3/d. To calculate the real inflow F0, F0 = F1 - F15, and F1 is the data point for the raw data. The handled data is presented in Figure 9 as weighted average of five days.

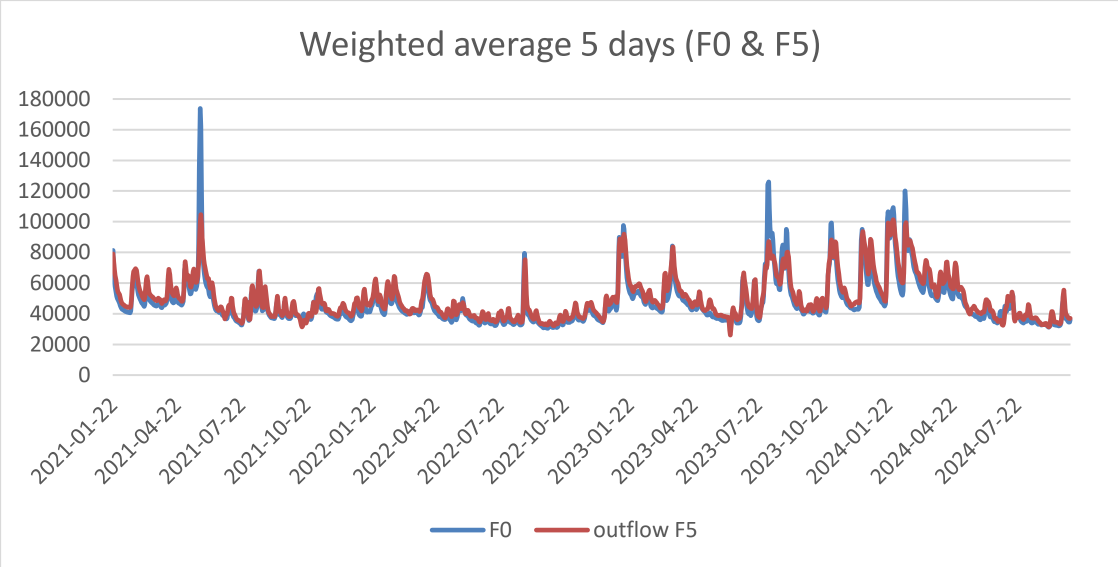

Figure 9 The weighted average of 5 days for the true incoming calculated flow F0 and the total outflow F5. 2021-01-22 to 2024-10-05

The descriptive statistics of the data in Figure 9 is shown in Table 25.

Table 25 Descriptive statistics of weighted average data

	Inflow (F0)	outflow (F5)
n	1353	1353
Mean	47271.3	49819,1
Median	42856.5	46094,7
Min	30488.4	26107,4
Max	173818.2	104623,0
St.dev.	15172.8	13714,3
R^2	0.82	

4.1.8 HM sampling

Available HM sampling points are available at the data points F1, F4, F5, F11(Figure 5) for HM concentration. Data sampling for F4 presents monthly samples of Cd and Ag with a consistency below the detection limit and does not bring direct value to the analysis. The following mass flow calculations are used for calculating mass flow from concentration, where the results are shown in Table 26.

Equation 6

$$C_{metal}\left[\frac{kg}{liter}\right] * 1000 * Inflow\ flow\left[\frac{m^3}{day}\right] * 365 = \frac{kg\ metal\ in\ influent}{year}$$

Equation 7

$$C_{metal}\left[\frac{kg}{liter}\right] * 1000 * Effluent\ flow\left[\frac{m^3}{day}\right] * 365 = \frac{kg\ metal\ in\ effluent}{year}$$

Where,

$C_{metal}: Concentration\ of\ metal$

*Table 26 Yearly mean HM mass flow in WWTP. The data for F1 & F5 is presented in concentration*volumetric flow=mass flow. The data for F11 (sludge) is presented as (kgHM/kgTS)*(average yearly volumetric flow*TS%)=mass flow output. "low": below detection limit = 0, "high": below detection limit = detection limit.*

<table>
<tr><th></th><th>Pb [kg]</th><th>Cd [kg]</th><th>Cu [kg]</th><th>Cr [kg]</th><th>Ni [kg]</th><th>Ag [kg]</th><th>Zn [kg]</th><th>Hg [kg]</th><th>yearly mean WW [m3]</th><th>Samples [n]</th><th>Time frame [yymmdd]</th></tr>
<tr><td>F1 low</td><td rowspan="2">67.0</td><td rowspan="2">2.8</td><td rowspan="2">1280.1</td><td rowspan="2">85.5</td><td rowspan="2">127.4</td><td>3.6</td><td rowspan="2">1682.5</td><td>2.04</td><td rowspan="2">20 167 190</td><td rowspan="2">26</td><td rowspan="2">230123 to 250210</td></tr>
<tr><td>F1 high</td><td>3.1</td><td>0.07</td></tr>
<tr><td>F5 low</td><td>6.4</td><td>0.02</td><td rowspan="2">104.3</td><td>16.9</td><td rowspan="2">67.8</td><td>0.0</td><td>177.7</td><td>0.00</td><td rowspan="2">19 741 680</td><td rowspan="2">26</td><td rowspan="2">230123 to 241202</td></tr>
<tr><td>F5 high</td><td>7.5</td><td>0.60</td><td>19.6</td><td>2.0</td><td>180.7</td><td>1.97</td></tr>
<tr><td>F11</td><td>48.0</td><td>2.9</td><td>841.1</td><td>91.5</td><td>69.1</td><td>3.6</td><td>1112.5</td><td>1.37</td><td>7 488</td><td>21, 22 Ag, 27 Hg</td><td>230331 to 241130</td></tr>
</table>

Further detailed overview of each HM sample in F1 is present in Appendix 2.
As the concentration measurements are monthly samples, the samples do not detect fluctuations and can contribute to false mass flows in calculations. The yearly mean in Table 26 is therefore critical to adjust. Table 27 shows the deviation of the handled data against the sample data.

Table 27 Comparison between F1 and F5 volumetric flow and methods of data handling

	Yearly means for HM samples [m^3]	Actual yearly mean for the period [m^3]	Weighted yearly mean for the period [m^3]
F1	20 167 190	18 502 634	18 494 317
F5	19 741 680	19 602 946	19 575 934

The mass flow of HM may need adjustment to fit the respective weighted yearly mean by calculating an adjustment coefficient from Table 27. The adjustment coefficients for F1 and F5 are presented in Table 28.

Equation 8

$$\frac{1}{\dot{m}_{metal} * \frac{Weighted\ yearly\ mean}{Yearly\ mean\ for\ HM\ samples}} = adjustment\ coefficient$$

Table 28 Adjustment coefficient for adjusting the HM mass flow from raw data to weighted data.

	Adjustment coefficient
F1	1.091
F5	1.009

The result before conducting the adjustment coefficient for F1 is shown in Figure 10. The adjustment coefficient of F5 is near 1, and can be neglected. However, within the mass balance it's chosen not to include the adjustment factors, minimizing complexity and uncertainty.

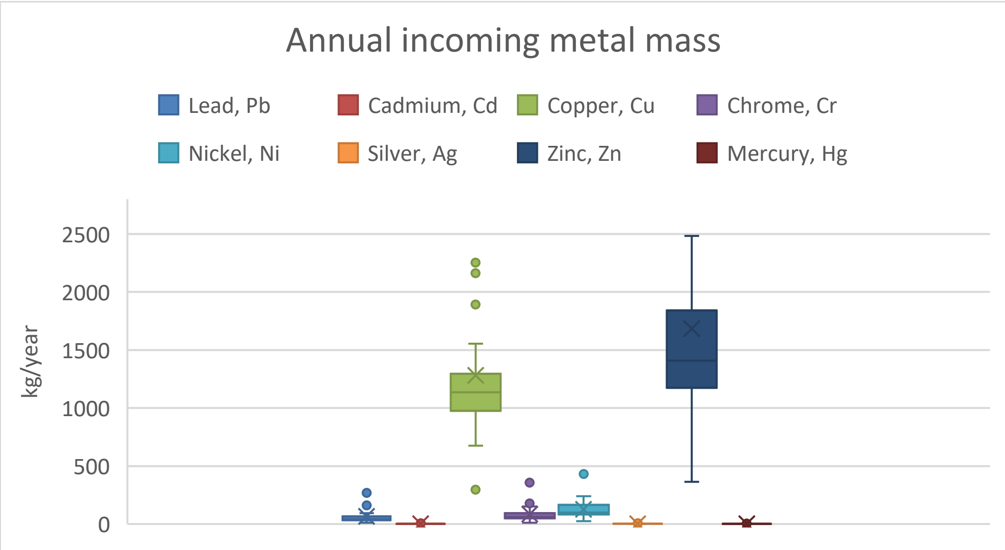

Figure 10 Annual incoming mass of metal to the WWTP based on F1 raw data.

4.1.8.1. *Additional HM samples for the case study*

Additional HM samples were done in the case study at data points F15 to calculate F0(Figure 5). The sampling was made three times during one week and presented in Table 29.

Table 29 Water samples for data point F15

	Date	Cr (ug/L)	Ni (ug/L)	Cu (mg/L)	Zn (ug/L)	Ag (ug/L)	Cd (ug/L)	Pb (ug/L)
Sample 1	250303	20.511	21.050	0.335	712.351	0.513	0.530	49.206
Sample 2	250210	1.077	1918.700	0.037	282.815	0.030	0.142	14.565
Sample 3	250312	34.399	74.275	0.165	217.018	0.431	0.356	8.524

Additional HM samples are done for F12 and presented in Table 30.

Table 30 Water samples for data point F12

	Date	Cr (ug/L)	Ni (ug/L)	Cu (mg/L)	Zn (ug/L)	Ag (ug/L)	Cd (ug/L)	Pb (ug/L)
Sample 1	250311	77.4	74.4	1.5	1304	4.7	3.4	80
Sample 2	250320	62.1	61.1	1.2	1053	3.2	2.5	50

4.2 Data collection upstream

This section presents the data collection upstream in the case study for industries, households, and excessive water.

4.2.1 Industries with data

There are 220 industrial actors with notifiable activities connected to the sewage network. The study visit at the supervisory authority resulted in approximately 10% of 220 actors having available data in environmental reports regarding heavy metals in the sewage system. 72% of the 10% available data from industrial actors comes from bigger carwashes. The quantity of actors with data alongside the total connected actors is shown in Figure 11.

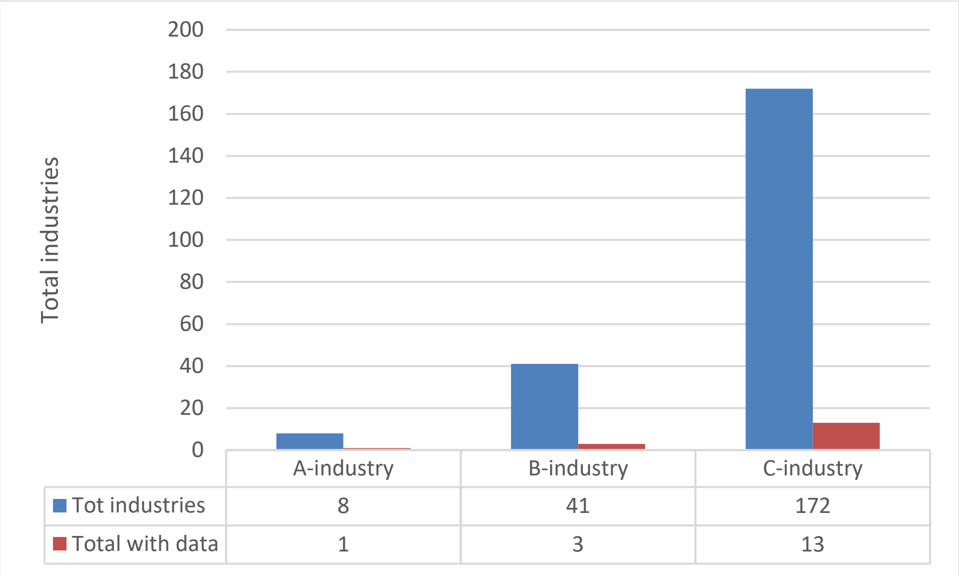

Figure 11 Total industries with available data for the HM to the sewage system.

Additionally, the industrial actors with available data did not present all metals within the delimitation in all cases, as shown in Table 31

Table 31 Number of available data points

Industries	Pb	Cd	Cu	Cr	Ni	Ag	Zn	Hg
A [n]	1	1	1	1	1	0	1	0
B [n]	1	1	2	3	1	1	3	1
C [n]	9	13	8	8	8	0	13	1
tot	11	15	11	12	10	1	17	2

To validate the amount of available data, the availability is cross-checked with 2 persons at the Country administrative board in Södermanland and in Västmanland, who verify that there are no additional official data available (Britt Halling & Ulrika Schröder, Personal Communication, 2025-02-05).

The total HM mass flow connected to the industrial actors with available data is shown in Figure 12, on a logarithmic scale for overview purposes.

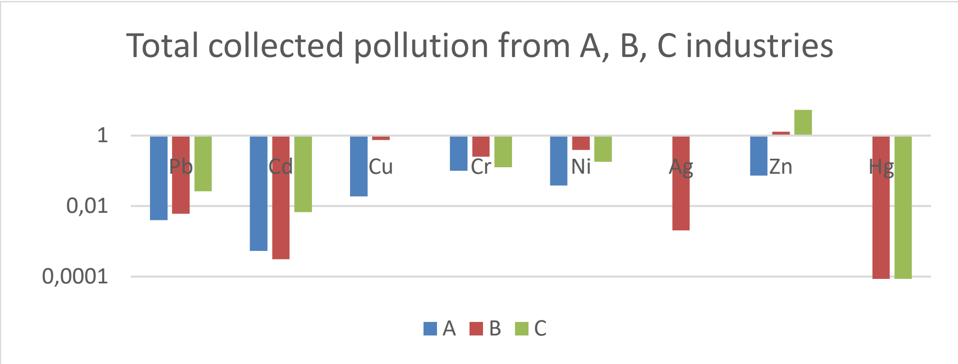

Figure 12 Annual mass flow of heavy metals from industries' environmental reports.

The resulting sum of the HM mass flow from all the industrial actors investigated is shown in Table 32.

Table 32 Annual numerical mass flow of heavy metals from industries' environmental reports.

	Pb	Cd	Cu	Cr	Ni	Ag	Zn	Hg
Collected pollution data [kg/y]	0.039133	0.007585	1.606105	0.472239	0.534939	0.002053	6.3965	0.000101

Additional analysis at the supervisory authority, the Environmental Office in Eskilstuna municipality, was not made for an overview of industrial actors without notifiable activities. But actors without notifiable activities could still cause significant pollution. For example, smaller car washes can wash up to 5000 cars per year and be classified as non-notifiable activities (Miljöprövningsförordning (2013:251), Ch. 23, 1 §). For this classification, data is generally not demanded by authority and therefore not within the delimitation.

The WWTP assumes that all industrial actors connected to the plant account for 4300 person equivalents (PE), which results in 1,6% of the incoming flow to the WWTP, shown in

Table 33. Incoming data from 2023 needs to be analyzed towards the upstream actors, due to the availability of industry data in environmental reports.

Table 33 Industry wastewater flow contribution to the sewage system based on the actor's assumption of PE.

Raw data flow 2023 [m^3]	19320814.7
Population [p]	96 613
mean load [l/(pd)]	200
Assumed total PE	4300
Industries [m^3/d]	313 900
Output to sewage [%]	1.62

This is cross-checked with the total output from the environmental report analysis, where the total output from the 17 actors is summarized.

Table 34 Calculated PE based on analysis of 17 actors' environmental reports.

Total output from 17 industries [m^3]	173 939
Output to sewage [%]	0.9
Calculated PE	2383

Left-hand circle diagram in Figure 13 shows the internal (ESEM) assumed flow from industries and comparison with the calculated flow. The right-hand circle diagram shows the total flow of the 17 industrial actors connected to the data collection from environmental reports.

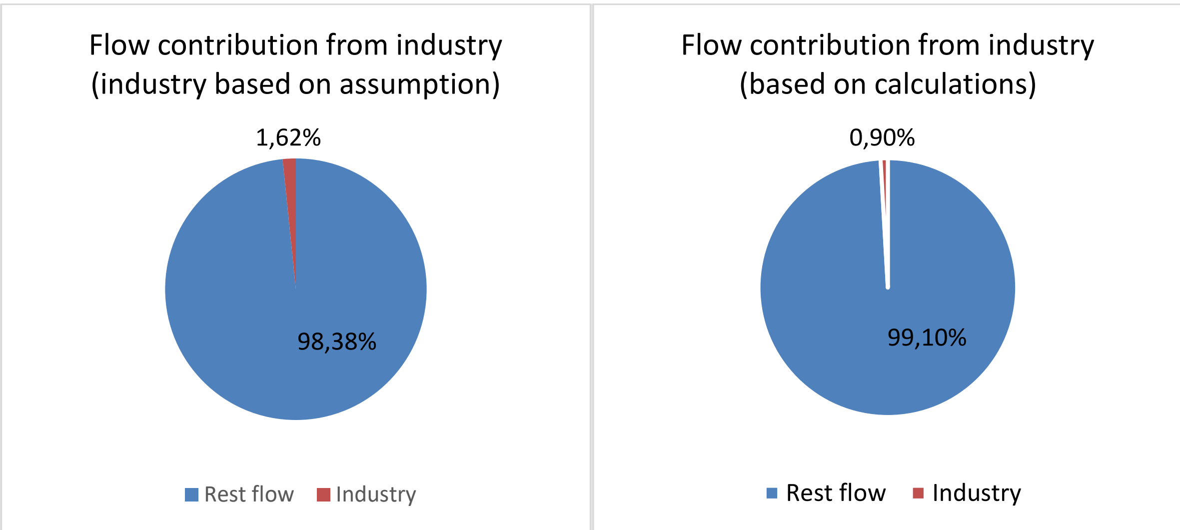

Figure 13 Visual overview of industry wastewater flow contribution to the sewage system based on the actor's assumption of PE (to the left) and based on calculation in this project (to the right). Rest flow is defined as the total flow subtracted with the flow from industries.

4.2.2 Households

The theoretical framework states that for the calculations, we are to use approximately 200 liter/person and day for volumetric flow where the density is assumed to be near water density of 1000 kg/m3 (Swedish EPA, 1995, p. 9). Within the 2023 environmental report from the actor, a population of 96 613 is presented.

Table 35 Household wastewater flow contribution

Raw data flow 2023 [m^3]	19 320 814.7
Population [p]	96 613
mean load [l/(pd)]	200
Households [m3/d]	70 52 749
household [kg/d]	19 322 600
household [kg/y]	7 052 749 000

The household contribution of HM to the sewage system is based on the average presented below of Eriksson and Lagerkvist (2015, p. 8) and Gryaab (n.d., pp. 9-10) presented in Table 6 and Table 7.

Table 36 Average household output to the sewage system for 200 liters/(pd), and a population of 96613 people

	Pb	Cd	Cu	Cr	Ni	Ag	Zn	Hg
Average output [mg/(p*d)]	0.44	0.021	16	0.395	0.69	0.03	27.5	0.008
Total output [kg/year]	15.52	0.723	564.22	13.93	24.33	1.06	969.8	0.282

4.2.3 Excessive water

ESEM reports a 5-year mean for excessive water volume (2020-2024) to be 58% of the total incoming volume of wastewater. The proportion of excessive water is estimated by subtracting the incoming wastewater volume to the WWTP with the sold volume of drinking water, the difference is then divided by the incoming wastewater to the WWTP. The estimation is considered as total proportion of excessive water (ESEM, Personal Communication, 2025-05-20).
Excessive water is the sum of drainage water, stormwater, groundwater, and leakage (Käppalaförbundet, n.d., figure 1).

From Table 3, it is assumed that stormwater run-off contributes with the highest concentration of heavy metals, where the concentration is presented in Table 4.

Table 37 Stormwater run-off calculation assuming stormwater contributes to 100% of the excessive water.

Metal	HM mass flow [kg/y]	influent WWTP [kg/y]	stormwater/ influent	Influent-households-industries [kg/y]	Stormwater/rest HM
Cd	0.41	2.78	14.8%	2.00	20.5%
Ni	37.03	127.36	29.1%	102.42	36.2%
Cu	87.06	1280.10	6.8%	687.64	12.7%
Cr	25.02	85.50	29.3%	68.33	36.6%
Ag	3.92	3.59	109.3%	2.48	158.1%
Hg	3.50	2.04	171.4%	1.76	198.8%
Pb	45.03	66.97	67.2%	46.41	97.0%
Zn	470.34	1682.51	28.0%	646.25	72.8%

As mentioned, the stormwater concentration is assumed to be the maximum concentration input to the excessive water compared to drainage, leakage, and groundwater. Considering that the Hg contribution is almost 200% of the incoming HM, a coefficient of 0,5 for the stormwater can be assumed to be maximum contribution from stormwater, i.e. stormwater is <50% of the excessive water and is decreasing with an increasing concentration for groundwater, drainage and leakage, illustrated in Figure 14.

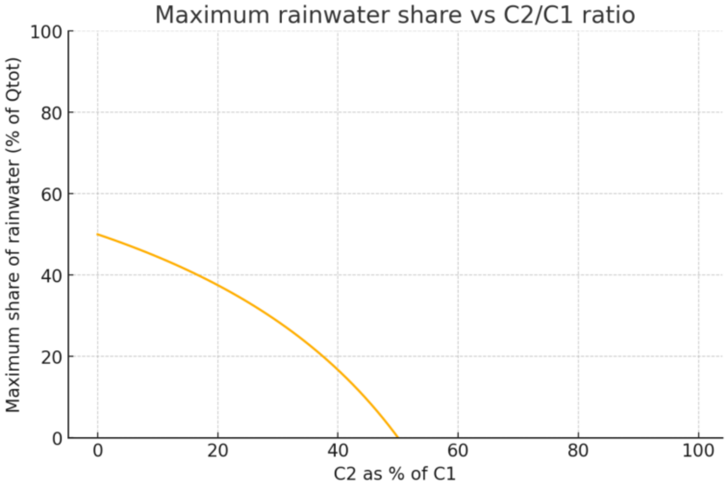

Figure 14 Decrease of stormwater contribution to excessive water with an increasing concentration of groundwater, drainage, and leakage. C1: Stormwater HM concentration, C2: Groundwater, drainage, and leakage HM concentration

Groundwater quality at the WWTP location is not sampled and therefore not possible to analyze. However, four nearby areas can be analyzed, but all of them lack Ag sampling. Locations of the sampling points are shown in Figure 15 and the actual concentrations are shown in Table 38.

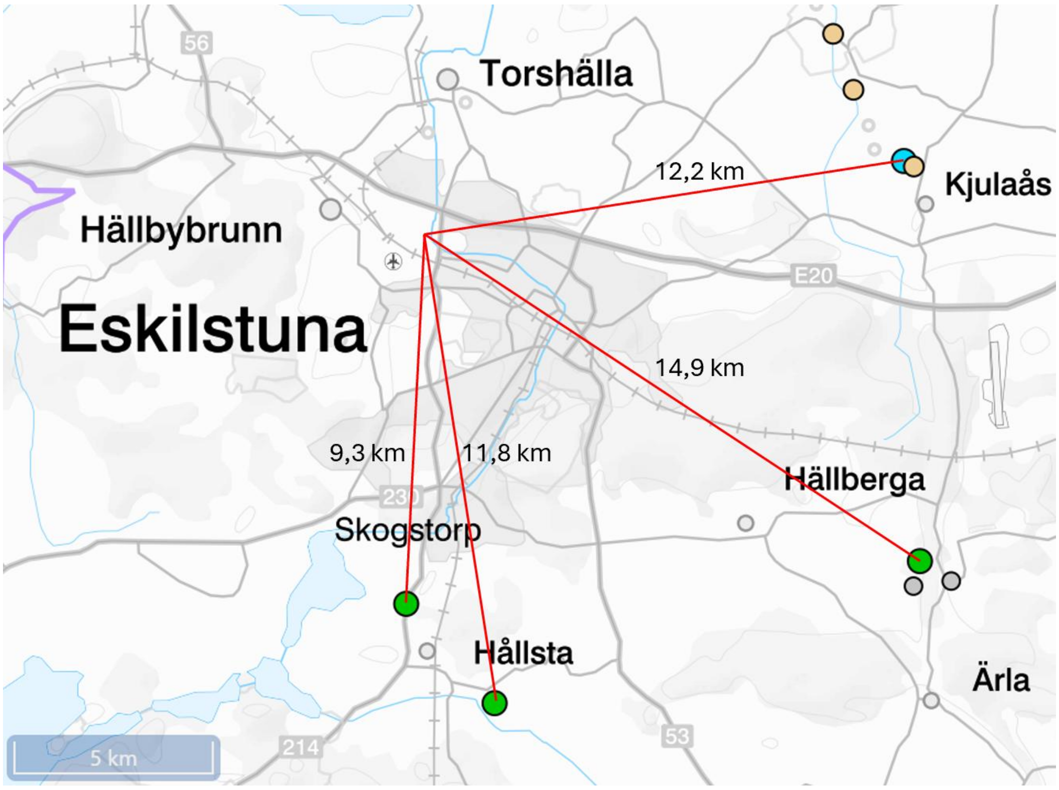

Figure 15 Map of groundwater sampling points analyzed, where the focal point of the red arrows is the location of the WWTP.

Table 38 Groundwater HM concentration from nearby sampling points (SGU.se, n.d.). The mean groundwater concentration neglects Ni 21,8 µg/L and Zn 360 µg/L (marked red) due to being a major outlier.

	Station nystugan (191120)	Station Eskilstuna 2 (061023)	Station Eskilstuna 1 (240925)	Station Storskolans källbrunn (170613)	Stormwater concentration (Table 4)	Mean groundwater concentration
Cd [µg/L]	0.155	0.005	0.043	0.17	0.041	0.093
Ni [µg/L]	21.8	0.14	1.5	0.43	3.7	0.69
Cu [µg/L]	1.82	0.36	3.5	0.83	8.7	1.63
Cr [µg/L]	0.082	0.96	0.06	0.17	2.5	0.32
Ag [µg/L]					0.392	
Hg [µg/L]	0.00014		0.00013		0.35	0.000135
Pb [µg/L]	0.0325	0.02	0.34	0.54	4.5	0.23
Zn [µg/L]	43.6	5.5	11	360	47	20
distance from WWTP (km)	9.3	14.9	12.2	11.8		

From the concentration analysis for the groundwater, the groundwater might dilute the stormwater in all cases except for Cd.

Still considering the stormwater to explain 100% of Hg as a maximum pollution contribution, the adjustment coefficient is:

Equation 9

$$\frac{Rest\ influent\ Hg}{\left(C_{Hg,Stormwater} + C_{Hg,Groundwater}\right) Rest\ flow}$$

Where:

$C_{Hg,Stormwater}$: $Concentration\ of\ Hg\ in\ stormwater\ run-off$

$C_{Hg,Groundwater}$: $Concentration\ of\ Hg\ in\ groundwater$

Giving an adjustment factor of 0.503 for stormwater and 0.497 for groundwater.

However, these can be highly inaccurate proportions due to the insufficient data from the industry sector seen in Table 31 where a total of two industrial actors present values for Hg. Adjustment factors will be more reliable if more data is collected.

The mean concentration of stormwater and groundwater can be considered as other input data is insufficient, as shown in

Table 39. Note that groundwater data is not available for Ag.

Table 39 Mean of stormwater, groundwater, and combined mean.

	Mean stormwater [µg/L] (Table 4)	Mean Groundwater [µg/L] (Table 38)	Mean Stormwater & Groundwater [µg/L]	Mean HM mass flow [kg/y]
Cd	0.041	0.093	0.067	0.72
Ni	3.7	0.69	2.20	24.33
Cu	8.7	1.63	5.16	564.22
Cr	2.5	0.32	1.41	13.93
Ag	0.39	0	0.20	1.06
Hg	0.35	0.00014	0.18	0.28
Pb	4.5	0.23	2.37	15.52
Zn	47	20	33.52	969.75

4.3 REVAQ threshold

The threshold for REVAQ presented in Table 2 is converted to fit the actors' numbers, so the total mass flow is based on the total phosphorus from the actor's sludge.

Equation 10

$$\frac{\frac{kgP}{kgDM} * kgDM}{22\ kgP/ha} * threshold\ \left(\frac{g}{ha}\right) = g\ metal/year$$

5 RESULTS

This chapter introduces the results of the project.

5.1 Upstream analyzed industrial actors

The data collected for the total mass of HM for upstream industrial actors accounts for 0.3% of the total incoming HM mass to the WWTP. It is important to note that this project only includes data from 17 industrial actors.

In Figure 16 a visual presentation of the location of each industry with available data of HM output to the sewage system, as well as the location of the WWTP connected to the project. In the overview, the type of industry (A, B, or C) is identified.

Figure 16 Map of the analyzed industries (A, B, and C industries).

5.2 Upstream flow

The results of the analyzed wastewater flow balance is presented in this section and as the delimitation only includes pollution data from upstream industries from the year 2023, this section is based on the incoming flow to the WWTP the same year. However, excessive water is a five-year mean value.

To visualize the actual flow of each upstream HM source, Figure 17 presents the proportion of the total incoming volumetric wastewater flow (weighted average F0) as a comparison between the calculated and assumed volumetric flow. The left-hand diagram is where the industry proportion is based on internal assumption by ESEM, and the right-hand diagram is calculated within this project. The assumption covers all industrial actors connected to the sewage network. Rest flow is the flow from unidentified sources.

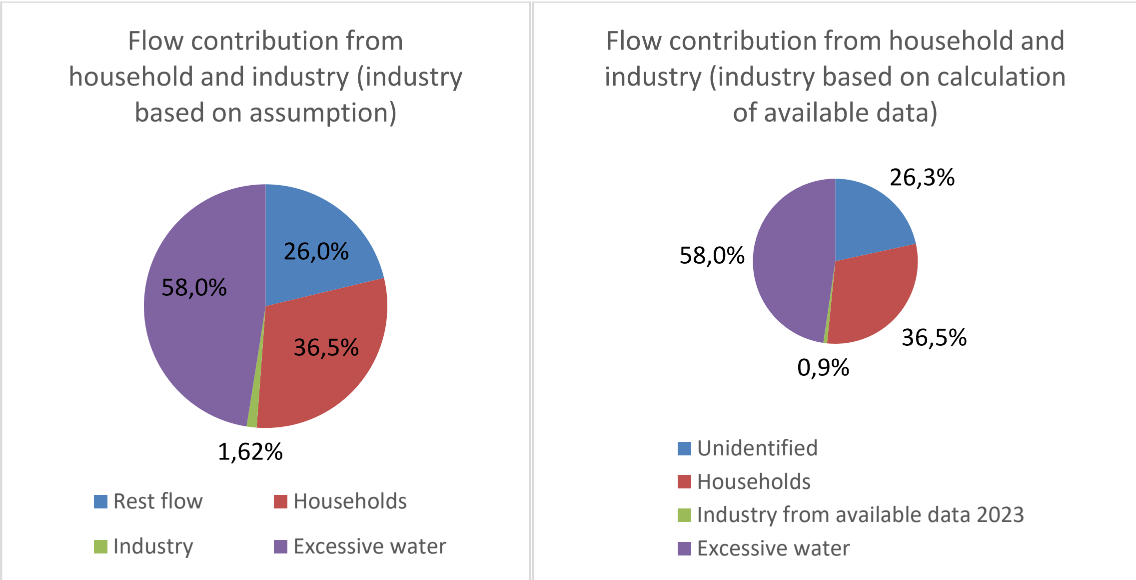

Figure 17 Wastewater contribution from approximate household pollution and the assumption made by ESEM of industry contribution, from all industrial actors connected to the sewage system (to the left). The approximate household pollution and the analyzed industry data from environmental reports from 17 industrial actors (to the right).

5.3 Upstream HM contribution

Upstream HM contribution only includes sources in the sewage network before the inlet of the WWTP. In Figure 18, stormwater and groundwater contribution of HM mass equals excessive water, but due to the unavailability of further characteristics of excessive water, stormwater and groundwater fully represent excessive water. The figure shows the contribution of each source to the incoming HM to the WWTP. The incoming HM in this case is based on F1 weighted average flow from 2023 to 2025-02-10 connected to the HM samples made and therefore represents a yearly average. However, for HM samples below the detection limit, the actual detection limit is presented in this case. Additionally, Figure 18 includes the total sum of the delimited HM and is therefore for overview indication purposes.

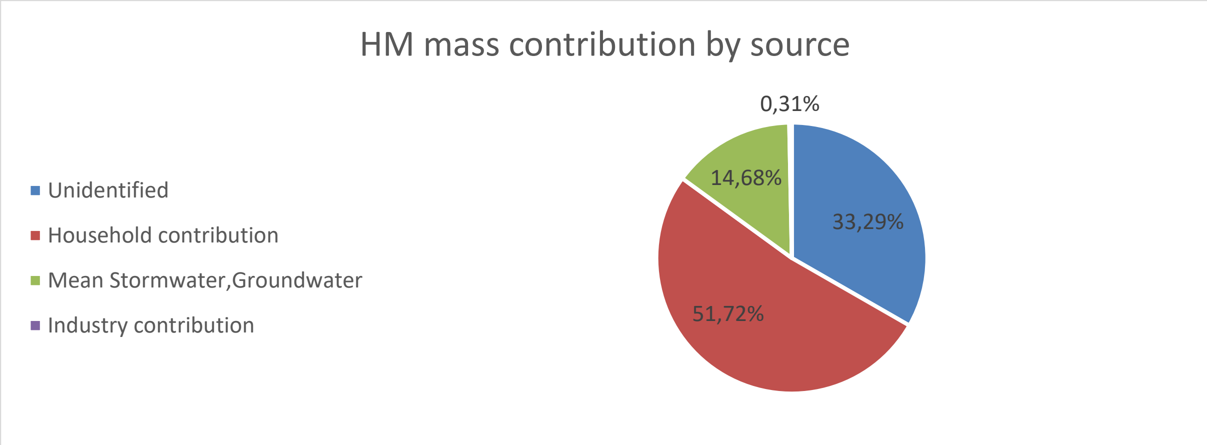

Figure 18 Total HM mass contribution by source.

As Figure 18 is an overview of the sum of all the HM, Table 40 presents detailed contributions from each identified source and per HM within this project. The contribution is divided into F1 and F0, where "high" indicates that HM samples below the detection limit are set to the detection limit, deliberately overestimating the HM concentration. On the other hand, "low" sets values below the detection limit equal to zero. F0 is based on calculations including the circulated flow F15, where Hg samples were not included; Hg contribution is not applicable. Note that "undefined" in Table 40 is the undefined upstream contribution in relation to the inflow to the WWTP.

Table 40 HM mass contribution by source and metal. F1 and F0 are both considering the weighted average of raw data.

	Pb	Cd	Cu	Cr	Ni	Ag	Zn	Hg
Industry contribution								
F1 high	0.06%	0.30%	0.15%	0.61%	0.52%	0.06%	0.43%	0.01%
F1 low						0.06%		0.12%
F0 high	0.06%	0.31%	0.15%	0.64%	3.19%	0.06%	0.44%	N/A
F0 low						0.07%		N/A
Mean Stormwater. Groundwater contribution								
F1 high	39.17%	26.72%	4.26%	17.94%	18.54%	54.26%	21.14%	91.22%
F1 low						61.30%		2061.56%
F0 high	41.62%	27.27%	4.36%	18.59%	114.22%	54.99%	21.96%	N/A
F0 low						62.24%		N/A
Household contribution								
F1 high	25.66%	28.75%	46.56%	17.72%	20.53%	29.26%	61.11%	14.69%
F1 low						33.06%		331.96%
F0 high	27.27%	29.35%	47.60%	18.37%	126.52%	29.66%	63.50%	N/A
F0 low						33.57%		
Unidentified upstream								
F1 high	35.11%	44.22%	49.03%	63.72%	60.41%	16.42%	17.33%	-5.92%
F1 low						5.57%		-2293.64%
F0 high	31.05%	43.08%	47.90%	62.40%	-143.93%	15.30%	14.10%	N/A
F0 low						4.13%		

5.4 Sludge

This section, further focusing on HM in sludge, takes unidentified total inputs and outputs internally within the WWTP.

The overview of HM accumulation in the sludge is shown in Figure 19 where 71% of the total annual mass of HM is accumulated in the sludge based on the F1 weighted average for the sample period 230116-250210. The figure presents the total mass of all HM analyzed and shall therefore be seen as an indicator. The figure does not include downstream sources seen from the inlet, such as internal input within the WWTP.

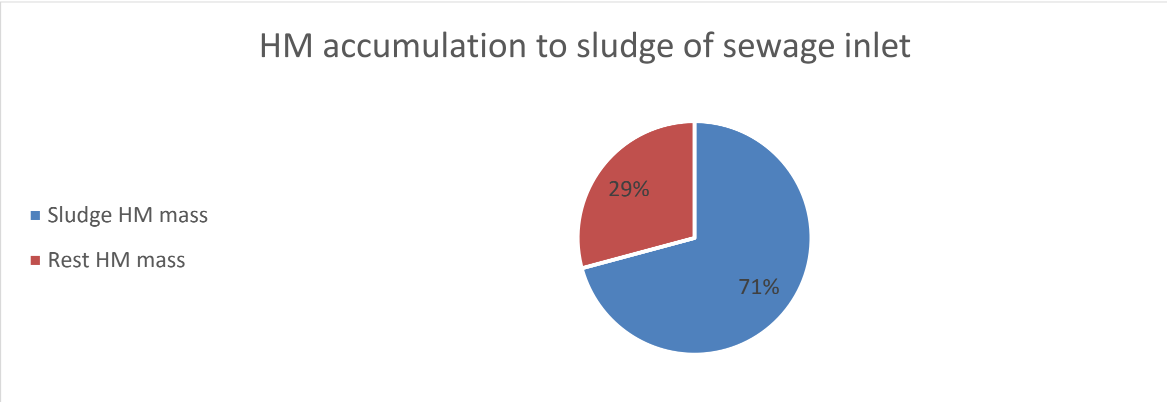

Figure 19 Total yearly HM [kg/year] of the influent to WWTP ending up in the sludge.

Figure 20 shows an overview boxplot making it possible to analyze the variation of the samples in the inlet, sludge, and effluent.

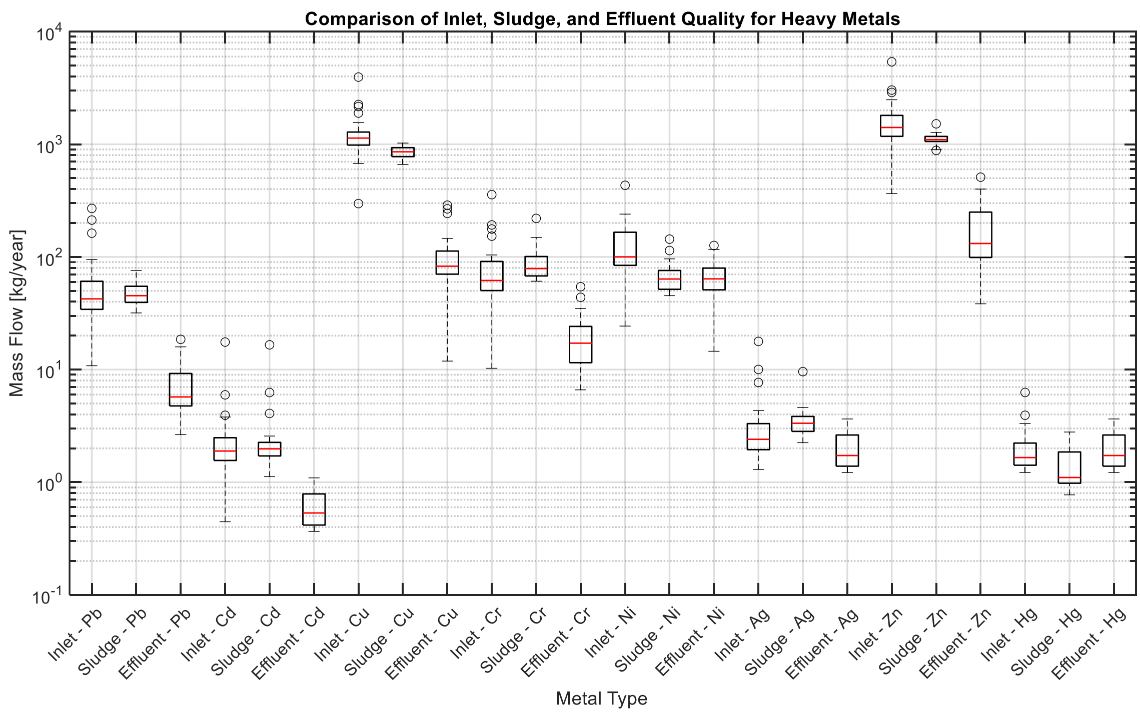

Figure 20 Box plot comparison of F1, F5 and F11(Figure 5) HM mass flows. The data is based on raw data.

Further analyzing F0 and F1, how much of the incoming HM from the sewage system is accumulated in the sludge is shown in Figure 21. Incoming flows F1 and F0 are the weighted average of the HM sample period. This figure is relevant when compared to Figure 22.

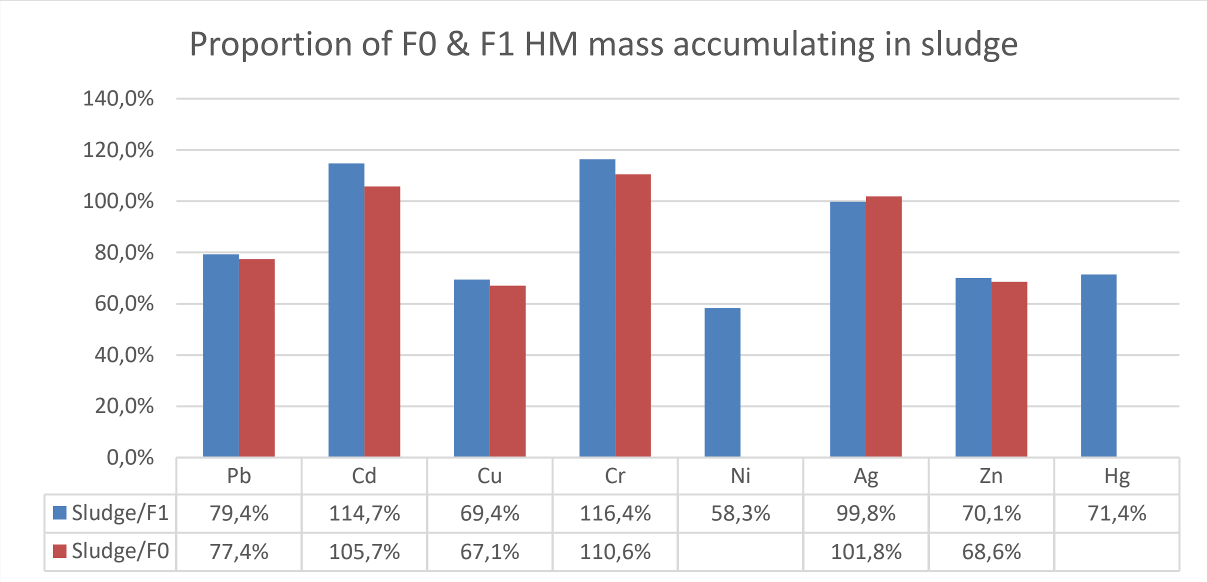

Figure 21 Proportion of mass in the influent that ends up in the sludge. Ni for F0 is neglected due to fluctuations in the F15 sample, and Hg was not analyzed in the F15 sample. F0 and F1 are based on weighted average raw data.

Figure 22 includes the internal input of HM within the WWTP. In this case, the internal input of HM is identified as food waste and fat from fat separators. Unidentified internal input is not considered, which means Figure 22 show results for measured input and not mass balance-adjusted input.

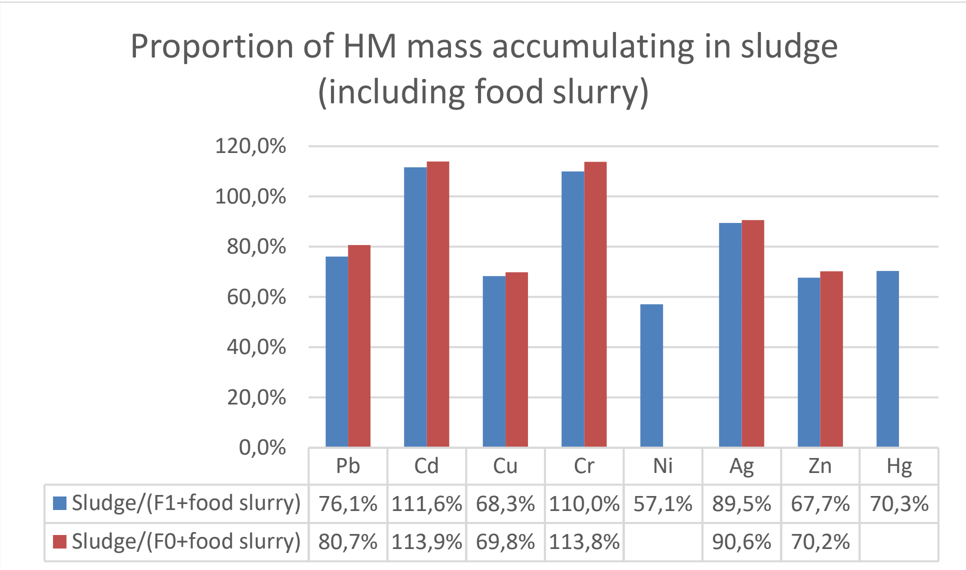

Figure 22 Proportion of HM mass accumulated in sludge, including both upstream and internal sources of HM mass. Ni for F0 is excluded due to the invalid water sampling, while Hg is not included in the sampling.

However, Table 41 shows the balance of the system where unidentified quantities are the errors that balance the equation. The last two rows compare Figure 22 when including unidentified inputs/outputs.

Table 41 Mass balance adjustments quantifying unidentified inputs and outputs in the internal process in the WWTP.

	Pb [kg/y]	Cd [kg/y]	Cu [kg/y]	Cr [kg/y]	Ni [kg/y]	Ag [kg/y]	Zn [kg/y]	Hg [kg/y]
Total input	59.47	2.53	1204.60	80.38	21.90	3.77	1584.10	1.03
Total output	54.95	3.19	945.40	109.75	136.95	4.59	1291.73	2.36
Unidentified upstream input	17.67	1.06	567.76	47.32	-27.68	0.34	215.30	-1.03
Unidentified internal input	-4.53	0.66	-259.21	29.37	115.05	0.82	-292.37	1.33
Unidentified total	13.14	1.72	308.55	76.69	87.37	1.16	-77.07	0.29
sludge/input (Figure 22)	81%	114%	70%	114%	316%	96%	70%	133%
sludge/(input+unidentified internal input)	87%	90%	89%	83%	50%	79%	86%	58%

Given the proportion of the total inputs accumulated in sludge and "Unidentified internal input"=0 if <0, as a negative input equals an actual output.

Equation 11

$$\left[\dot{m}_{source} * (1 - \frac{-Undefined\ internal\ input}{Total\ unidentified\ input})\right] * \frac{Sludge\ output_{metal}}{All\ inputs} = Sludge\ content_{metal}$$

Where:

$\dot{m}_{source}$: $Mass\ flow\ of\ metal\ from\ source\ [\frac{kg}{year}]$

Equation 11 generates the content in Figure 23 that shows the sludge composition by HM. However, as the complete flow within the system for each metal is unknown, the internal input of HM accumulating within the sludge is uncertain. Hg is the only HM where the sludge content exceeds the WWTP input. The data in Figure 23 concerning Hg is therefore adjusted, subtracting the upstream output proportionally distributed over the sources.

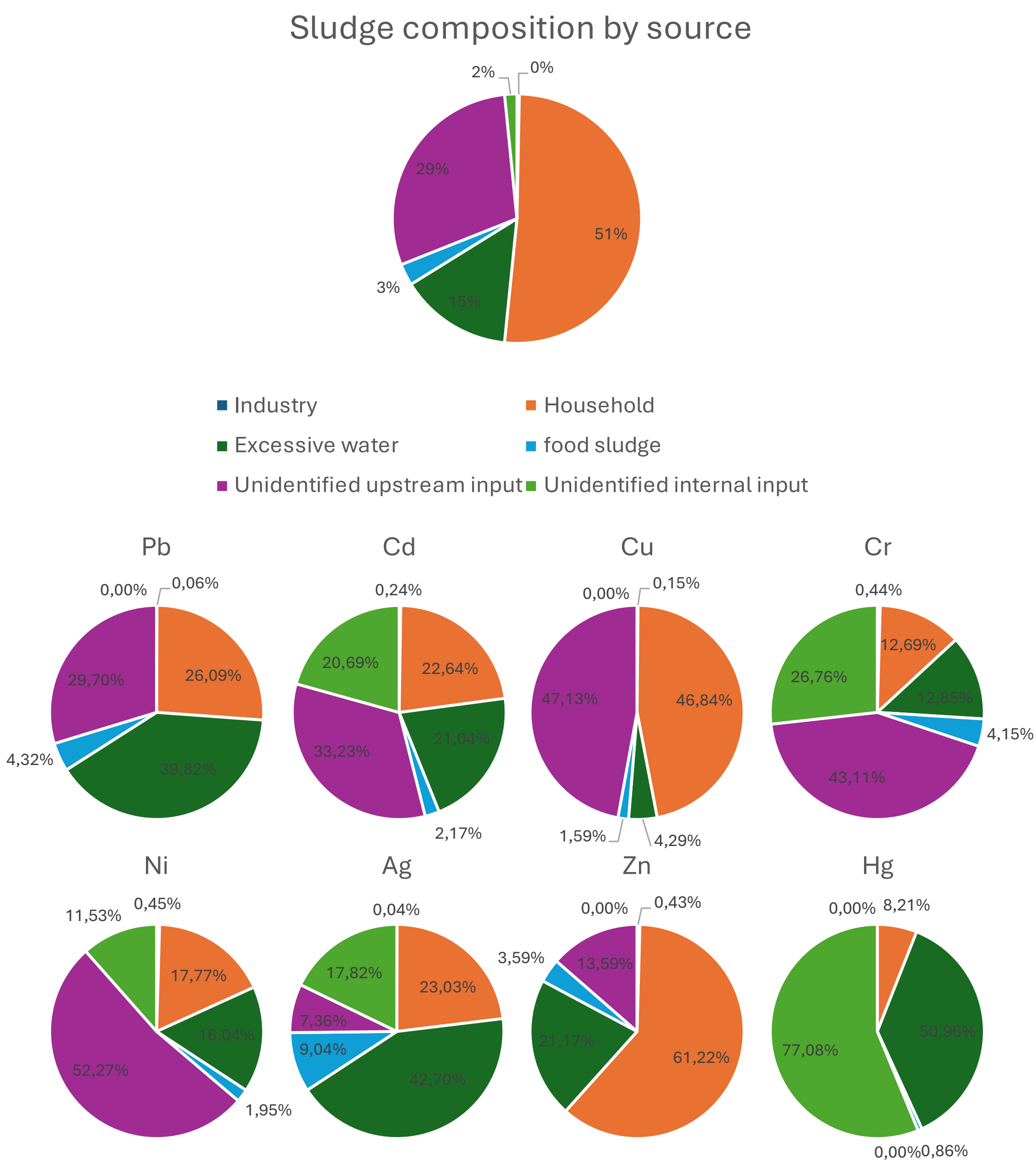

Figure 23 Sludge composition by source, Pb, Cd, Cu, Cr, Ni, Ag, Zn, and Hg

Complementary presentation of Figure 23 is shown in

Table 42 where the total mass of each HM from each identified source is shown. The accumulation is, however, excluding internal unidentified inputs or outputs in this content due to uncertainty, and over 100% indicates that more than the sum of incoming HM to the WWTP and food sludge is accumulated in the sludge. Therefore, an additional unidentified internal source is present. An assumption is made for the accumulation, it is proportionally distributed between the sources of HM.

Table 42 Annual sludge composition by source and HM. The accumulation is based on Figure 21.

Sludge	Pb [kg]	Cd [kg]	Cu [kg]	Cr [kg]	Ni [kg]	Ag [kg]	Zn [kg]	Hg [kg]
Accumulation [%]	76,1%	111,6%	68,3%	110,0%	57,1%	89,5%	67,7%	70,3%
Total mass, metal	47,98	2,88	841,14	91,48	69,13	3,61	1112,51	1,37
Industries	0,03	0,01	1,20	0,53	0,35	0,00	4,57	0,00
Households	11,81	0,81	385,50	15,33	13,88	0,95	656,30	0,20
Excessive water	18,03	0,75	35,31	15,51	12,53	1,76	227,00	1,23
Food waste	1,48	0,06	9,93	3,79	1,15	0,28	29,15	0,02
Fat separators	0,48	0,02	3,18	1,22	0,37	0,09	9,34	0,01
Unidentified upstream source	16,16	1,24	406,02	55,10	40,84	0,53	186,14	-0,08

Table 43 shows the proportion of each HM by source. Note that the proportions do not add up to 100% due to unidentified internal input/output. The unidentified internal input/output is shown in Table 41.

Table 43 Composition of HM mass that is accumulated in the sludge, divided by type of HM and source. When excluding internal unidentified inputs/outputs.

Sludge	Pb	Cd	Cu	Cr	Ni	Ag	Zn	Hg
Total mass, metal [kg/year]	47.98	2.88	841.14	91.48	69.13	3.61	1112.51	1.37
Industries	0.06%	0.26%	0.14%	0.53%	0.51%	0.05%	0.41%	0.01%
Households	24.61%	25.07%	45.83%	15.23%	20.08%	26.25%	58.99%	14.47%
Excessive water	37.57%	23.29%	4.20%	15.41%	18.13%	48.66%	20.40%	89.84%
Food waste	3.09%	1.82%	1.18%	3.77%	1.67%	7.81%	2.62%	1.15%
Fat separators	0.99%	0.58%	0.38%	1.21%	0.54%	2.50%	0.84%	0.37%
Unidentified	33.68%	48.98%	48.27%	63.86%	59.08%	14.73%	16.73%	-5.83%

In the Background Table 2, certification thresholds for REVAQ were presented. In Table 44, these thresholds are converted with the case study findings. The table also presents the actual sludge HM mass output along with the proportion this output represents relative to the 2024 REVAQ threshold. Years 2025-2027 are presented to show the planned trend of the threshold change.

Table 44 Converted threshold for mass flow, based on the actor's total phosphorus output. The calculations are based on ESEM numbers from 2023, with the spread threshold presented in Table 2.

	2024 [kg/y]	2025 [kg/y]	2026 [kg/y]	2027 [kg/y]	Goal [kg/y]	Actual output [kg/y]	Actual/(2024 kg/year)
Pb	59.82	59.82	59.82	59.82	59.82	47.98	80.2%
Cd	1.22	1.22	1.22	1.22	1.12	2.88	236.3%
Cu	717.87	717.87	717.87	717.87	717.87	841.14	117.2%
Cr	95.72	95.72	95.72	95.72	95.72	91.48	95.6%
Ni	59.82	59.82	59.82	59.82	59.82	69.13	115.6%
Ag	5.74	5.74	5.74	5.74	1.34	3.61	62.8%
Zn	1435.75	1435.75	1435.75	1435.75	1435.75	1112.51	77.5%
Hg	1.32	1.32	1.32	1.32	0.55	1.37	104.2%
Cd/P-ratio	23.18	23.18	23.18	23.18	21.36	54.78	

The conventional way is to convert the concentration of heavy metal to grams/hectare. The method in Table 44 to convert the thresholds to kg/year gives indication of the real and actual load, considering mass flows.

Table 45 shows the proportion of HM in sludge by source connected to the REVAQ threshold in Table 44.

Table 45 Proportion of HM mass in sludge by source, connected to the REVAQ thresholds 2024.

	Pb	Cd	Cu	Cr	Ni	Ag	Zn	Hg
REVAQ threshold 2024 [kg/year]	59,82	1,22	717,87	95,72	59,82	5,74	1435,75	1,32
Industries	0,0%	0,7%	0,2%	0,6%	0,6%	0,0%	0,3%	0,0%
Households	19,7%	66,1%	53,7%	16,0%	23,2%	16,5%	45,7%	15,1%
Excessive water	30,1%	61,5%	4,9%	16,2%	21,0%	30,6%	15,8%	93,6%
Food waste	2,5%	4,8%	1,4%	4,0%	1,9%	4,9%	2,0%	1,2%
Fat separators	0,8%	1,5%	0,4%	1,3%	0,6%	1,6%	0,7%	0,4%
Unidentified	27,0%	101,7%	56,6%	57,6%	68,3%	9,2%	13,0%	-6,1%

5.5 Magnifying industrial heavy metals

By magnifying (multiplying) industry contribution, it gives an indication of how a larger data set for industries can affect the balance and unidentified sources of HM pollution. By magnifying the collected industry contribution by 41.7, all HM except Hg are still positive values. Hg before magnifying was already negative. Zn was optimized to zero by magnifying the industry contribution, giving Figure 24.

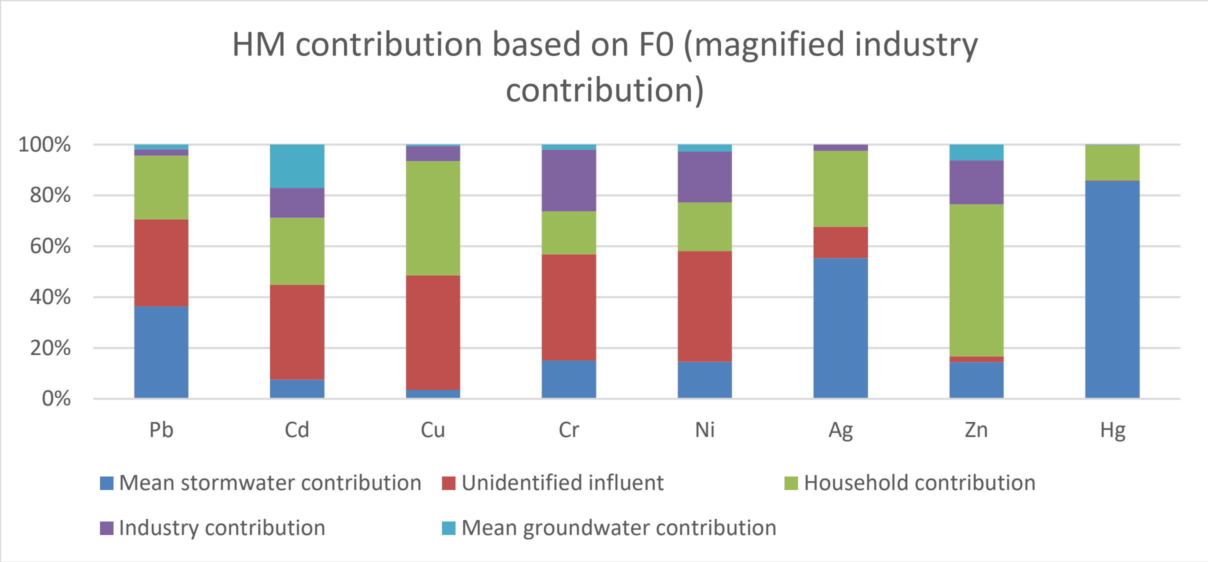

Figure 24 Magnifying industry contribution.

5.6 Mass balance of HM

This section summarize the general mass balance equation for the degree project together with finalized visual overview HM mass flow analysis. Imbalance is shown as a “balance error”.

Steady state mass balance equation from source to the effluent of the WWTP:

Equation 12 & Equation 13

$$\dot{m}_{out} - \dot{m}_{in} = 0 \qquad \text{but in practice} \qquad \dot{m}_{out} - \dot{m}_{in} = \varepsilon$$

Equation 14

$$\left(\dot{m}_{effluent} + \dot{m}_{sludge}\right) - \dot{m}_{in} = \varepsilon$$

Where,

$\dot{m}$: $Mass\ flow\ of\ HM\ [\frac{kg}{year}]$

In concentration*flow terms:

Equation 15

$$\left[\left(C_{effluent} * Q_{effluent}\right) + \left(C_{sludge,dry} * Q_{sludge,wet} * DM\right)\right] - \dot{m}_{in} = \varepsilon_{total}$$

Where,

C: $Concentration\ [\frac{kg}{m^3}]$

Q: $Volumetric\ flow\ [\frac{m^3}{year}]$

DM: $Dry\ matter\ [\%]$

ε_{total}: $Total\ error\ \left[\frac{kg}{year}\right] (= \varepsilon_{upstream} + \varepsilon_{internal})$

Mass flow input is defined as:

Equation 16

$$\dot{m}_{in} = \dot{m}_{industry} + \dot{m}_{exc.water} + \dot{m}_{f.slurry} + \dot{m}_{households} + \varepsilon_{total}$$

Where,

$\dot{m}_{exc.water}$: $Mass\ flow\ of\ HM\ for\ excessive\ water$

$\dot{m}_{f.slurry}$: $Mass\ flow\ of\ HM\ for\ food\ slurry\ (fat + food)$

In concentration*flow terms:

Equation 17

$$\dot{m}_{in} = C_{industry} * Q_{industry} + C_{exc.water} * Q_{exc.water} + C_{f.slurry} * Q_{f.slurry} + C_{households} * Q_{households}$$

Full equation:

Equation 18

$$\left[\left(C_{effluent} * Q_{effluent}\right) + \left(C_{sludge,dry} * Q_{sludge,wet} * DM\right)\right] - \left[\left(C_{industry} * Q_{industry}\right) + \left(C_{exc.water} * Q_{exc.water}\right) + \left(C_{f.slurry} * Q_{f.slurry}\right) + \left(C_{households} * Q_{households}\right)\right] = \varepsilon_{total}$$

Full equation from upstream sources to the inlet of the WWTP:

Equation 19

$$F_{0,weighted} - \left[\left(C_{industry} * Q_{industry}\right) + \left(C_{exc.water} * Q_{exc.water}\right) + \left(C_{households} * Q_{households}\right)\right] = \varepsilon_{upstream}$$

Where,

$F_{0,weighted} = F_{1,weighted} - F_{15,mean}$ (Figure 5)

$F_{0,weighted}$: $5\ day\ weighted\ average\ mass\ flow\ of\ incoming\ HM\ to\ WWTP\ [\frac{kg}{year}]$

The full equation from the inlet to the outlet of the WWTP, where definitions of Fx can be seen in Figure 5:

Equation 20

$$\left[\left(C_{effluent} * Q_{effluent}\right) + \left(C_{sludge,dry} * Q_{sludge,wet} * DM\right)\right] - \left[F_{0,weighted} + \left(C_{f.slurry} * Q_{f.slurry}\right)\right] = \varepsilon_{internal}$$

$$(F_5 + F_{11}) - (F_{0,weighted} + F_8) = \varepsilon_{internal}$$

Numerical input in the balance for the sum of Pb, Cd, Cu, Cr, Ni, Ag, Zn, and Hg is shown in Figure 25. Further balance for each HM is visually shown in Appendix 1.

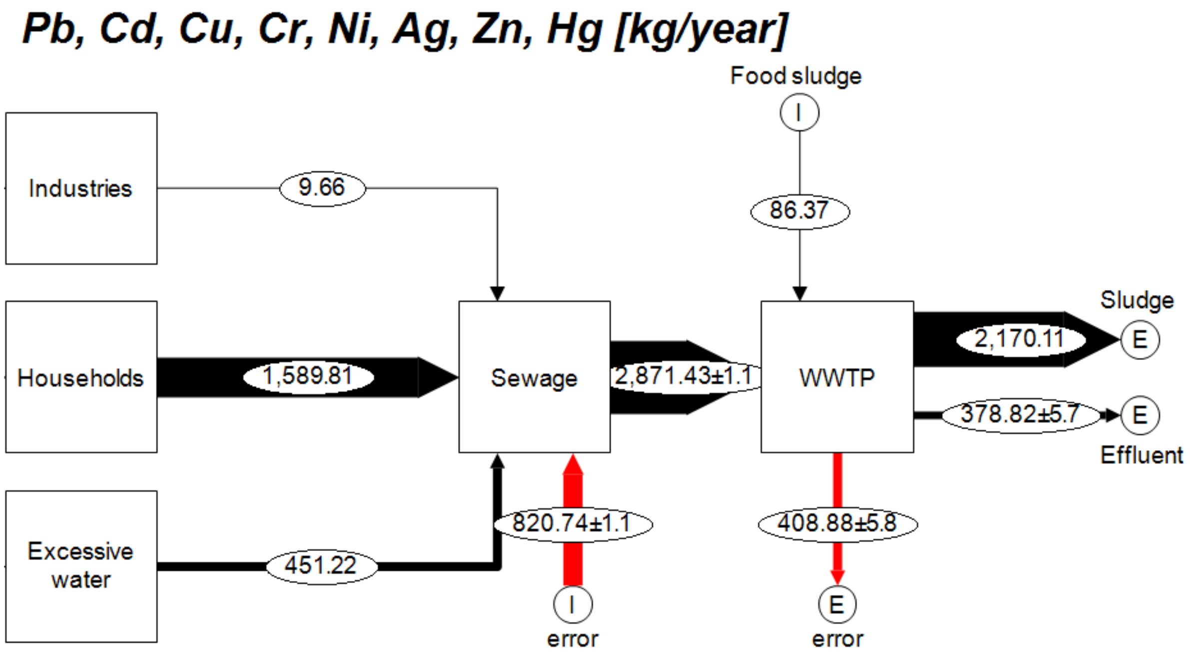

Figure 25 Numerical input in the mass balance. Red shows the error/undefined mass input/output. I: import, E: export

6 DISCUSSION

This section discusses methodology and the results from the case study.

6.1 Upstream industries

The investigation of environmental reports describing the discharge of HM from upstream industries only resulted in data collection from 17 industrial actors. These actors are the only actors with a legal requirement to report HM pollution to the sewage. It is assumed that other industrial actors still have a significant pollution to the sewage system regarding HM. This is a political balance between how many resources are demanded for companies with lower official pollution than the 17 that this project covers. Additionally, unofficial pollution could also mean significant pollution to the sewage, such as cases where highly concentrated wastewater is handled incorrectly due to expensive waste handling costs or similar.

The method of data collection through environmental reports is insufficient in this case and leaves the result with major undefined sources of HM pollution. It is necessary to introduce sampling upstream to give a stronger foundation to a mass balance study like this one.

Magnifying industrial HM mass flow (Figure 24) give a brief quantity indication for industry contribution if more industrial actors had been included in the data set. This magnification of industry pollution can potentially further explain the unidentified sources of HM mass flow, but the ratio between HM is, however, expected to be different. Different ratio is not captured by magnifying the collected pollution. The majority of the collected industrial HM mass flow is from car washes, and the ratio between HM can therefore cause inaccuracy of assumptions when magnifying. For example, Cu, Ag, and Hg are relatively low for the collected industry data, while they can be high for other types of industries.

Furthermore, this project questions the validity of the internal assumption of total flow from industries to the sewage system due to the data collected from 17 industrial actors. These actors contribute to over 50% of the assumed total flow from all industrial actors connected to the sewage system. Despite the total quantity is unknown regarding industries connected to the sewage system, the 17 industrial actors are expected to contribute to a lower proportion.

The assumption made by the author for upstream industries is that the year 2023 pollution figures are representative in the mass balance. As the input considers samples from 2023 and 2024, upstream industries' pollution is put against a larger time frame. Appendix 2 shows concentration trends and flow trends for the incoming wastewater for the water samples in F1, considering that the flow has a decreasing trend. The mass flows in Appendix 2 consider the concentrations and the average yearly flow at the date of the sample. Most concentrations in Appendix 2 show a decreasing trend or stable trend over the time frame, but Ag concentration shows an increasing trend. The mass flow of Pb, Cd, Cu, Cr, Ni, Zn, and Hg all have a decreasing trend, while Ag has an increasing trend. Even though trends are not stable, the model can still be valid to be used. The result of this degree project is a momentary overview and can work as a foundation for near future assumptions, as the proportions should slowly change over time. However, new additional inputs for specific HM from new sources, such as new industries, can have a substantial impact on the proportions of HM mass flow. Furthermore, the decreasing trend of total incoming wastewater does not reveal the whole picture, more samples need to be included for this trend analysis, as for the HM trends.

Assumption connected to upstream industries by ESEM is the total flow from all industrial actors connected to the sewage system, which is 1.62% of the total incoming flow (Figure 13). Compared to the 0.9% (Figure 13) that accounts for a total of 17 industrial actors in Eskilstuna, the additional 0.72% should be considered as unrealistically low. ESEM does not have further background for the 1.62% (ESEM, Personal Communication, May 2025).

6.2 Excessive water

Excessive water in this project is delimited to include stormwater run-off and groundwater infiltration to the sewage network. ESEM approximates an excessive water quantity of 58% of the total annual incoming wastewater, which is high considering the mean throughout Sweden is 43% and the median is 44% (Clementson et al., 2020, p. 28). The method of using the mean of groundwater and stormwater concentration is not precise, but can give an indication. Foundation for any more precise approximation of the total excessive water concentration is lacking. By approximating the area of stormwater uptake, the stormwater proportion of the excessive water could be more precise and valid. As the sewage water network area is not revealed from ESEM, this is not possible. The method of collecting groundwater quality data includes nearby data points, but is not directly connected to the area of the sewage network. This lowers the validity, and it is suggested to include more local data for further validity.

Leakage from the drinking water network is a part of excessive water as well and can mean a lower concentration of HM than is assumed in this project. However, the indication of excessive water contribution to HM mass flow can work as an indicator of the importance of more adequate data as a foundation for these approximations and assumptions. The result shows excessive water to be the biggest HM mass contributor for Pb, Cr, Ag, and Hg. Importantly to note is that the concentration of groundwater concerning Ag is deliberately set to zero, which in practice means that 50% of the excessive water has no Ag concentration. This could mean underestimating the Ag mass from excessive water.

Overviews of total HM mass are presented in the results, but can give a false picture of priority, as the severity and thresholds are different for each HM, where Cu and Zn incoming mass dominate, which is normal. Cd is just 1.78 % points below the household contribution, and these sources contribute with almost 50%, together with 50% from unidentified sources. Svenskt vatten (2024, p.19) shows that REVAQ-certified WWTP eliminates Cd to a high extent from the excessive water source, meaning excessive water as a Cd source can be a “low-hanging fruit” and easy to argue for increased priority for upstream investigation and investment. Importantly, Cd/P-ratio shown in Table 12 exceeds the REVAQ-threshold by over 3 times.

Assumption by ESEM related to excessive water is mainly the proportion of excessive water of 58% as a 5-year mean that is applied in this project as well. This calculation of excessive water proportion is dependent on the difference between sold drinking water and incoming wastewater (ESEM, Personal Communication, May 2025). This assumes that all drinking water ends up as wastewater, which does not account for, for example, irrigation that might end up in a nearby lake or river. The figure might therefore actually be higher, underestimating the excessive water load.

6.3 Cd/P-ratio

Cd/P-ratio shown in Table 12 exceeds the REVAQ threshold by over 3 times. But the mean Cd/P-ratio shown in Table 44, show around 2 times the threshold together with over 230%. As the REVAQ-certification focuses on this key performance indicator, full priority should be given to Cd sources. Elimination of Cd sources is assumed to give lower HM mass input to the system in general, including the other HM considered in this project.

6.4 Households

The method of handling households' pollution of HM to the system includes empirical data from two different areas in Sweden, in Gothenburg and Stockholm. As the areas are different and not closely located (400 km), they validate each other, and the mean output is assumed to be reasonable. However, the actual flow of 200 liters/person used in this project is just an approximation and a rule of thumb that can cause major differences when assumed for a bigger population. This must be considered when analyzing the result.

The household contribution, from an overview perspective looking at the total mass by source, shows a contribution of over 50% of the total HM mass. However, as discussed previously, households have a high contribution to the HM, which are commonly high in sewage wastewater (Eriksson & Lagerkvist, 2015, p. 8) (Gryaab, n.d., pp. 9-10). Results in Table 43 show that household contribution to HM mass in the sludge dominates for Cd, Cu, Ni, Zn where Cu and Zn usually are the biggest contributors to HM mass in common sewage sludge.

Ling et al. (2011, p. 2) and Sörme and Lagerkvist (2002, pp. 141-143) mean that the root cause for Pb, Cd, Cu and Zn in household wastewater is mainly plumbing related where fixtures and piping are the main cause of these HM in the wastewater. Furthermore Sörme and Lagerkvist (2002, pp. 141-143) mean that Cr in household wastewater is not fully understood but also discusses the high possibility of stainless steel surface HM emission can be a root cause, as well as the root cause for Ni in the household wastewater, WHO (2021, pp. 6-8) validates this and mean that chromium-plated surfaces cause pollution for Cr and Ni.

One big root cause for Ag in household wastewater is simply from the treatment of sportswear, functioning as an odor-reducing element. When washed, 72% of the Ag is lost from the sportswear to the wastewater system (Svenskt vatten, 2018, p. 4).

6.5 Food sludge

Food sludge in this project is divided into food waste and fat from fat separators. The collected concentration data for food sludge includes both food waste and fat from fat separators but does not consider the proportions. As the concentration is based on dry matter, incorrect values can occur when using the concentration separately for food waste and fat, as the combined mixture can change the dry matter. The fractions are separate inputs to the WWTP in this project, where dry matter is defined for food waste but not for the fat, but the dry matter is set as the same for both fractions cause of no available characteristics.

Additionally, the waste from ice cream industry is blindly neglected without any known characteristics, as it is not available. However, the quantity of mass is low and therefore it is valid to assume the effect to the balance is neglectable.

6.6 Flow 0, 1, 5 and 15

Flow 1 (F1) is the flow monitored by the WWTP but is located after a circulated flow F15 that is not monitored with regards to HM. F15 is only monitored with regards to volumetric flow which leaves insecurity of the validity of F1. However, this project included HM sampling of F15 that can only represent momentarily characteristics regarding HM.
As the calculated actual inflow F0 is based on F15, it leaves uncertainty of F0's validity as well. However, the results do not show significant differences between the analyses comparing F0 and F1, except for Ni due to extreme fluctuations and outliers in the HM sampling of F15.

Additionally, concerning the validity of F1, the volumetric flow balance show errors. The inflow F1 and outflow after the constructed wetland F5 show F5 to have over 2000 m^3/day additional flow compared to F1. This was not possible to explain during the project but could be due to measurement error. F5, on the other hand, is not a critical parameter for this project as it is located downstream from the sludge output. The adjustment coefficient calculated in 4.1.8 was chosen not to apply for the resulting mass balance due to minimizing complexity and altering the data set further. Not applying the adjustment coefficient but presenting the option shows transparency. Furthermore, monthly samples already contribute to approximations of the concentrations in the wastewater.

The method of analyzing HM with the weighted average of F1 brought more realistic volumetric flows, considering the HM samples, which is critical to not over- or underestimating the concentrations. Short-term major fluctuations of flows can be assumed to be natural for this process, since 58% of the incoming yearly flow comes from excessive water, it can be assumed to be highly driven by precipitation. That means it's important how outliers and extreme peaks are handled. However, the method for handling HM samples in F1 only considered the actual five-day weighted average of that specific day, which can cause incorrect yearly mean values due to fluctuations between each sample. Sample frequency could be higher than one per 30 days as it is today, but it needs to be balanced with the benefit.

The purpose of returning an activated sludge, such as F15, is to return microorganisms to increase the efficiency of flocculation and coagulation in the aeration basin. This process can increase the overall efficiency in the WWTP (W&WW, n.d., purpose of RAS).

6.7 Unknown sources upstream

This section discusses the unknown sources identified in this project and refers mainly to Table 40 and Table 43.

6.7.1 Lead (Pb)

Around 30-35% of the mass of lead is from unidentified sources and those sources could possibly be from incorrect handling of petrol, paint, electrical products and probably a substantial part from sedimentation in piping and floor cleaning water from industries. (Svenskt vatten, 2019, p. 23). As mentioned in 3.2.2 , a total of 20 car workshops could contribute to 1.5% of incoming Pb if floor cleaning water is not handled correctly (Lagerkvist, 2004, pp. 3-5). As there are over car workshops in Eskilstuna, the potential for pollution is over 3%.

6.7.2 Cadmium (Cd)

Almost 45% of the total incoming Cd and almost 50% in the sludge are from unidentified sources in this degree project. Svenskt vatten (2019, p. 23) mean that sources are mainly from households, stormwater run-off, art organizations, sedimentation in piping, and car washes. Based on this, a substantial part of the unidentified sources could come from art organizations and sedimentation in piping, which are not defined in this project.

As there are no exact data on art activities in Eskilstuna, the conclusion can be made that Eskilstuna has an active art community with galleries, institutions, workshops, and organizations (Eskilstuna kommun, 2020; Eskilstuna Makerspace, n.d.; Visiteskilstuna.se, n.d.). Floor cleaning in car workshops can additionally contribute to a potential pollution of over 0.6% (3.2.2)(Lagerkvist, 2004, pp. 3-5).

6.7.3 Copper (Cu)

Almost 50% of the Cu is from unidentified sources. Within this project, based on the sources presented in Svenskt vatten (2019, p. 23), Cu from piping is likely a substantial part. The sewage network to Ekeby WWTP is over 600 km, and the drinking water piping system is almost 700 km (ESEM, 2025, table 1). Additionally, Svenskt vatten (2019, p. 23) mention circuit board manufacturers as a specific source of Cu pollution to sewage, and there is at least one such manufacturer in Eskilstuna. Additionally, car workshops have the potential to contribute over 1.2% (3.2.2) of the annual incoming Cu (Lagerkvist, 2004, pp. 3-5).

6.7.4 Chromium (Cr)

Cr within this project contributes to the highest proportion of unidentified sources, at over 60%. The major source of chromium is generally from manufacturing industries (Svenskt vatten, 2019). Manufacturing industries are a probable high contributor of the unidentified sources in this project. This could argue for the still low proportion industry contributes with even though analyzing a magnitude of over 40 for the collected industrial actors where most are from car washes, seen in Figure 24 in Ch. 5.5. In the list of actors analyzed in this project, industrial actors connected to the sewage system with notifiable activities (A, B and C - industries), 20% of 220 are such manufacturing industries. Three of these actors contribute to the HM pollution data included in this project. Additionally, floor cleaning water in car workshops has the potential to contribute to over 1% (3.2.2) of the total incoming Cr to the WWTP.

6.7.5 Nickel (Ni)

Ni often occurs with Cr (Svenskt vatten, 2019, p. 25). This section, therefore, refers to 6.7.4. But in addition to this, the potential pollution from floor cleaning water from car workshops is over 0.4% (3.2.2) annually.

6.7.6 Silver (Ag)

In this degree project, Ag sources are over 85% explained by households and excessive water, which only gives room for 15% unidentified sources. A major source that is not defined within the project is dentistry (Svenskt vatten, 2019, p. 25). Amneklev et al. (2014, table 4-1) Show that 5.6% and 0.7% of the silver mass coming into a WWTP in Stockholm, Sweden, comes from hospitals and dentistry, respectively. The article also shows a proportion of 42.5% coming from households, which is around 10% higher than the results of this project shown in Table 40. This could explain undefined sources even further, as hospitals and dentists are not investigated.

Vården.se (n.d.) show there are at least 18 dental practices in the city, potentially contributing to Ag pollution.

6.7.7 Zinc (Zn)

Zn has a small proportion of undefined sources in this project, at around 14-17%. Most is explained by household pollution, and according to Svenskt vatten (2019, p. 26), a majority comes from the transportation industry. Excessive water that includes stormwater run-off from roads do explain around 20% of the total incoming Zn, but the excessive water concentration is uncertain in this project and could underestimate the Zn contribution. Floor cleaning water has an additional pollution potential of over 2.4% (3.2.2) annually.

6.7.8 Mercury (Hg)

Hg have a negative undefined proportion of HM incoming mass. Furthermore, Hg are at low concentrations in the water samples and often below detection limit, resulting in high uncertainty. However, excessive water explain at a minimum of 91% when all concentration below detection limit is set to the limit value. As the uncertainty of excessive water is high, it can overestimate the Hg contribution.

Even though the result shows a negative, undefined figure for Hg, potential sources for HM pollution are dentist practices and hospitals (Svenskt vatten, 2019, p. 24). (Region Sörmland, n.d.; Vården.se, n.d.) show there are at least 18 dental practices and one hospital in the city, potentially contributing to Hg pollution.

6.8 Steady state and mass balance

The method of assuming steady state comes with complexity if including constructed wetland that accumulates substantial volumes. However, the main results consider annual mass flows which is therefore assuming steady state. The steady state model should be considered a first step into developing a dynamic model and the steady state model also fits longer period of times, such as in this project where annual means are considered. When a dynamic model is developed, the timeframe can be shorter, giving further understanding of the system behavior. However, at this stage considering the data unavailability, data is insufficient to develop a dynamic model.

The mass balance in the steady state model is straightforward, but when including the unidentified input/output internally, uncertainty is present. As the overall flow within the WWTP is not known for HM, the proportion of accumulation of this unidentified input/output to the sludge is not known. Assumptions have been made that all inputs have a proportional distribution of accumulation to the sludge. However, results excluding internal inputs/outputs are also present for further understanding. Lastly, both methods of presenting the results can be misleading until further analysis of flows is possible.

6.9 Future challenges and possibilities

This section discusses challenges and possibilities, divided into upstream and WWTP.

6.9.1 Upstream possibilities

Since this degree project is limited due to the lack of data for upstream sources, the tracing of upstream pollution sources is limited. Upstream analysis of water quality is a major possibility for improvement for source indicators. One simple possibility is simple water samples, but fluctuations in concentrations are always a concern when water samples are made. Another solution could be implementing aquatic mosses and freshwater mussels to give indications of HM concentration in different upstream areas within the sewage network. Aquatic mosses and freshwater mussels accumulate HM and can be an effective investigation method for analyzing Cr, Ni, Pb, and Zn, but also Fe, Ca, K, and Mg (Mersch & Johansson, 1993, p. 1) (Figueira & Ribeiro, 2005, p. 1).

To get more input of HM pollution from industries, the number of identified car washes without notifiable activities (below 5000 car washes per year) can be retrieved from the environmental office in the municipality. An approximation of 2500 washes per year and car wash could then contribute to lower unidentified HM sources, but as this project is limited to industrial actors with notifiable activities, this approximation is not possible with the collected data.
Assumptions and approximations can also be made for dentists, surface treatment, and art organizations (Cd) to further lower the unidentified HM sources (Olsson, 2018, pp. 14-18). Further, Olsson (2018, p. 14) uses an effective calculation tool including assumptions for several upstream sources with the possibility to include own measurement data.
The unknown proportion in the excessive water could, as mentioned mean substantial differences for the approximate concentration and mass flow. Further physical analysis for quantifying and asses excessive water will contribute to more correct calculations. Quantification of mass flow is dependent on this data (Almeida et al., 2025).

6.9.2 Upstream challenges

Cadmium in the sludge is by far the one HM in this study that is critically exceeding the REVAQ thresholds (Table 44) and a decrease of over 100% is needed to comply with the certification. In this project, Cd is shown to accumulate in the sludge at a 100% rate, which means that incoming Cd must decrease or that the accumulation must decrease by internal actions within the WWTP. However, households contribute the highest proportion of Cd mass to the sludge and Schaefer et al. (2020, figure 3) show mitigation strategies on a policy level rather than a level at which ESEM can contribute, except for being REVAQ-certified to contribute to fertilizer management. Except for the households, excessive water contribute to over 20% of the incoming Cd but if ESEM accomplish a decrease from 58% of excessive water to 43% which is the mean inflow of excessive water, this mean a reduction of 4% of the cadmium mass flow and will therefore not contribute to a high benefit/cost when considering

Cd (Clementson et al., 2020, p. 28). Cadmium is high from unknown sources in this project, which is a critical factor to ease the compliance with REVAQ and the threshold values. However, with a successful decrease of Cd, other HM can be expected to follow.

The increasing trend for Ag input mass flow needs to be carefully considered and as above 48% is explained by excessive water, it gives a good indication how the work of lowering Ag input should be prioritized.

6.9.3 Wastewater treatment plant possibilities

The Cd/P ratio is around 100% higher than the threshold and the ratio can decrease by increasing the Phosphorus in the sludge. This is, however, related to the efficiency of the WWTP which is not within the scope of this project.
Biochar made from sewage sludge has been shown to remove Cd, but also U (Uranium that is of concern within the WWTP but not within the project scope) (Kapnisti et al., 2025, p. 1). Considering Kapnisti et al. (2025, equation 1 & 2), the mass of BC3 biochar would add up to a total of over 90’000 tons/year to remove 50% of the Cd. This is approximately over 450’000 tons of sludge mass, assuming a 20% pyrolysis yield based on Kapnisti et al. (2025, table 3). Additionally, this amount would also remove a substantial mass of uranium. Although the WWPT only produces around 4,5% of this mass, which questions the feasibility of this method.
The chemical precipitation is assumed to work well for Cd accumulation in the sludge, but as this is the issue within this project. A pre sludge separation or similar process is a possibility to reduce the Cd within the sludge.

Sludge treatment methods such as adsorption through nanofiltration membranes or graphene oxide/carbon nanotubes could be alternatives to remove the desired HM from the process. These methods are suitable for the selective removal of HM and particularly Cd (Hamid et al., 2024, pp. 319-323). These methods, as engineered absorbents, are reliable, but other potential sustainable and low-cost methods, such as biosorption, where biological material is used for binding HM, producing low amounts of additional sludge. However, this solution could be complex due to variability in performance, but with operational simplicity (Hamid et al., 2024, pp. 323-328).

7 CONCLUSIONS

The WWTP stands against a major challenge as Cd levels within the sludge are over 100% of the threshold values for the REVAQ certification. Reduction of Cd mass flow into the WWTP assumes a reduction of Pb, Cu, Cr, Ni, Ag, Zn, and Hg that are already below or near the threshold values. However, the findings show a high quantity of unidentified sources, which pose a challenge in deciding potential actions upstream to prevent and reduce the incoming mass flow of HM. To meet and comply with REVAQ, priority is suggested for developing data collection methods and internal monitoring. Additionally, collecting data from environmental reports is not sufficient to find HM mass flow from the industry sector.

The sources with the majority of HM mass flow to the sewage network are households and excessive water, having a mean contribution of 28.8% and 32.2% of the HM mass to dewatered sludge. Household HM input dominates Cd, Ni, and Zn contribution to the sludge of the identified sources. Excessive water HM input dominates Pb, Ag, and Hg in the sludge of the identified sources. Furthermore, unidentified upstream sources of Cd, Cu, Cr, and Ni mass contribute to a proportion of 49, 48, 64, and 59% to the sludge, respectively (Table 43). Where a substantial part is assumed to come from industrial actors for Cu, Cr, and Ni, and where Cd sources could be art organizations and/or piping sedimentation. The assumption of total flow from the industry sector made by ESEM is unrealistically low compared to the 0.9% collected from 17 industrial actors within this project, the assumption is just above 180% of the collected actors. 17 industrial actors in Eskilstuna present HM data in official documentation, which should be considered as insufficient for upstream analysis, given that 0.31% of incoming HM mass to the WWTP is explained by the industry sector. The data collection of industrial contribution of HM mass flow is limited, and the true HM mass flow from the industry sector likely contributes significantly higher mass flow, considering 17 of 220 industrial actors with notifiable activities are analyzed.

Mass balance within this degree project is conducted successfully upstream regarding overall sources and highlights the quantity of unidentified sources. However, the literature of HM contribution from upstream sources needs validation, requiring internal measurements and investigations by ESEM. HM contribution from excessive water is highly uncertain considering the proportions of stormwater, groundwater, and leakage are not known, and this project only considers a mean of the literature-based stormwater pollution concentration and local groundwater samples. The closest data point for groundwater samples is over 9 km from the WWTP.

The mass balance within the WWTP is straightforward for balancing the HM mass flow from inlet to sludge accumulation, but more data points are needed measuring HM concentration throughout the WWTP to understand further possibilities and challenges of the internal HM flows. The mass balance show critical deviations for Cr and Hg, and uncertainty for Cd and Ag. The uncertainty is the result of concentrations below detection limit.

Lastly, analyzing official environmental reports captures an insufficient quantity of data to make conclusions upon. Analysis equipment is therefore critical to implement throughout the sewage network to localize specific sources of pollution.

8 SUGGESTIONS FOR FURTHER WORK

This degree project presents a solid foundation for how to focus upstream investigations regarding heavy metals accumulating in sewage sludge. It shows indications of possible sources and connected quantities of mass flow. However, the project also gives clear insights of limitations where suggestion for further work can be summarized upon.

The upstream monitoring is suggested to be developed, but this project lacks detail on where in the sewage network monitoring would be efficient. Therefore, it is suggested to further work on developing the plan of upstream monitoring, where and how it should be conducted. Suggestions are discussed regarding monitoring and samples with aquatic mosses and mussels that accumulate heavy metals over time in a cost-efficient way, but further investigation is needed to determine the most suitable method.

As the current WWTP monitoring program lacks data points for heavy metal analysis in several critical flows to understand how heavy metals flow within the WWTP, this is suggested to investigate. An investigation must be conducted to determine the value of additional samples, where further understanding might or might not have an efficient cost-to-value ratio. Considering REVAQ, the value for further understanding within the WWTP may not be of highest priority, but as shown in this degree project, there are unidentified sources of inputs/outputs of heavy metals internally within the WWTP that can be an actual source of the heavy metals accumulated in the sludge.

As the excessive water is according to ESEM, 58% of the total incoming wastewater, development of the knowledge for the proportion of the sources, stormwater run-off, groundwater, and leakage, is critical. This project relies on literature concentrations of stormwater run-off that should be validated with local figures. Within this project, no insight into how the sewage network is spread has been included, and the possibilities of understanding groundwater infiltration are therefore limited. The data points of groundwater analysis are far from the WWTP, more local groundwater analysis is therefore suggested. Further a correlation analysis between precipitation and incoming wastewater can reveal the actual effect and proportion stormwater run-off is within the excessive water.

Lastly, as the owner of the sewage network, a monitoring program demanding sewage load data for a high quantity of industrial actors with notifiable activities is suggested. This could support substantial accuracy for upstream investigation within the REVAQ compliance, considering the REVAQ demands are getting stricter. The monitoring program could also include heavy metal analysis demands for the sewage load, further increasing the accuracy and traceability of heavy metals upstream from the WWTP. Additionally, several REVAQ-certified WWTPs have active cooperation with the local environmental supervisory authority concerning upstream investigation (Svenskt vatten, 2024, p. 25). Which is suggested in this case as well.

9 ETHICAL CONSIDERATIONS

This project will not contribute to any changes to the wastewater system and therefore will not contribute to added pollution and environmental effects. The aim of the investigation is to contribute to the certification of using sewage sludge in agricultural land. The purpose is therefore to decrease the input of heavy metals and other severe elements to the local system by decreasing demand from external sources and increasing circularity of local sources. The resulting sludge can have worse quality than other conventional fertilizer sources, but REVAQ certification aims to lower pollution with time by circulation, which contributes to sustainability. Therefore, the aim is to minimize the risk to public health and heavy metal uptake with sustainable sludge handling. However, even though official documentation will serve as the documentation analysis, it will point out specific polluters and industrial actors of concern. With the risk of damaging the trademark of industries. However, specific industrial actors are not named, but the location presented can indicate which industrial actor is analyzed. Importantly, this risk comes with transparency standards of ethical writing, which is one important goal. Transparency is also achieved through clearly presenting the method used for various parts of the report and project, which data sources are used, and what assumptions have been made, and why. All external sources have been properly referenced according to APA7 standard to ensure traceability and give any reader the possibility to revise the results. Additionally, to APA7, page numbers or similar are included for each reference to further increase and ease the traceability. Peer-reviewed articles and government documents are included for critical information.

No data within the data collection has been manipulated or falsified to fit the purpose of the project, ensuring academic integrity.

Lastly, the project follows general research ethics.

REFERENCES

Acreman, M. C., Harding, R. J., Lloyd, C. R., & McNeil, D. D. (2003). Evaporation characteristics of wetlands: experience from a wet grassland and a reedbed using eddy correlation measurements. *Hydrology and Earth System Sciences, 7(1), 11–21*. https://hess.copernicus.org/articles/7/11/2003/hess-7-11-2003.pdf

Almeida, M. d. C., Brito, R. S., & Jorge, C. (2025). Inflows into Wastewater and Stormwater Systems: Sources,

Causes, and Assessment. *Water 2025, 17, 1082*. https://doi.org/10.3390/w17071082

Amneklev, J., Bergbäck, B., Sörme, L., Lagerkvist, R., Kotsch, M., & Augustsson, A. (2014). Strategier att reducera silver och vismut i urbant avloppsvatten. *[Strategies to reduce silver and bismuth in urban wastewater] [In Swedish]. Svenskt Vatten Utveckling*. https://vattenbokhandeln.svensktvatten.se/produkt/strategier-att-reducera-silver-och-vismut-i-urbant-avloppsvatten/

Andreoli, C. V., Sperling, M. v., & Fernandes, F. (2007). SLUDGE TREATMENT AND DISPOSAL. *Water Intelligence Online 6, 9781780402130–9*. https://doi.org/10.2166/9781780402130

Aziz, S. Q., & Mustafa, J. S. (2021). Wastewater sludge characteristics, treatment techniques and energy production. *Recycling and Sustainable Development 15, 9–26*. https://doi.org/10.5937/ror2201009A

Carvalho, L. (2024). Understanding the mass balance of heavy metals in wastewater

treatment plants (30 hp). *[Project description]*. https://www.va-malardalen.se/download/18.105af44918afe71ffbe1bf6f/1697095925240/Exjobbsannons%20Mass%20balance%20of%20heavy%20metals.pdf

Chipasa, K. B. (2003). Accumulation and fate of selected heavy metals in a biological wastewater treatment system. *Waste Management, Volume 23, Issue 2, 2003, Pages 135-143*. https://doi.org/10.1016/S0956-053X(02)00065-X

Clementson, I., Alenius, E., & Gustafsson, L.-G. (2020). Tillskottsvatten i avloppssystem – nya tankar om nyckeltal. *[Inflow and infiltration in wastewater systems – new thoughts on KPIs] [In Swedish]. Svenskt Vatten Utveckling*. https://vattenbokhandeln.svensktvatten.se/wp-content/uploads/2020/11/svu-rapport-2020-13.pdf

EEM.se. (2023). *Vattenrening i flera steg*. [How we treat your water – Ekeby wastewater treatment plant] [Webpage] [In Swedish]. https://www.eem.se/privat/vatten-avlopp/ditt-avlopp/vara-reningsverk/ekeby-reningsverk/sahar-renar-vi-ditt-vatten

Ejhed, H., Hansson, K., Olshammar, M., Lind, E., Nguyen, M., Hållén, J., Allard, A.-S., Stadmark, J., Jutterström, S., Löfgren, S., & Hellgren, S. (2018). Belastning och påverkan från dagvatten. *SMED Rapport Nr 12, 2018 [in Swedish]*. https://www.naturvardsverket.se/contentassets/34e231a6ea91468ba0168816d8e3abd1/belastning-och-paverkan-fran-dagvatten-smed-underlagsrapport.pdf#:~:text=aluminium%207429,30%2013%20100

Eriksson, M., & Lagerkvist, R. (2015). Hushållsspillvatten från Skarpnäck. *[Household wastewater from Skarpnäck – a compilation 1995–2013] [In Swedish]. Stockholm Vatten och Avfall*. https://www.stockholmvattenochavfall.se/globalassets/pdfer/rapporter/avlopp/

paverkan-av-industri-och-samhalle/15sv468_hushallsspillvatten-fran-skarpnack-en-sammanstallning-fran-1995-2013.pdf#:~:text=Trenden%20f%C3%B6r%20fosfor%20och%20de,efter%20f%C3%B6rbudet%20mot%20fosfater%20i
ESEM. (2025). *Reinvestment Plan for the Wastewater Network 2024–2030 [unpublished document].*
Eskilstuna kommun. (2020). Offentlig konst. *[Public art] [in Swedish].* https://offentligkonst.eskilstuna.se/download/18.9b7f0da172e504825f243e/1593077586047/Broschyren%20Offentlig%20konst%20i%20Eskilstuna%20kommun%202020_%20webb_uppslag.pdf?utm_source=chatgpt.com
Eskilstuna Makerspace. (n.d.). Eskilstuna Makerspace. *[organisation] [in Swedish].*
Eskilstuna municipality. (2024). Statistik - Befolkning. *[Population] [Webpage] [In Swedish].* https://www.eskilstuna.se/kommun-och-politik/fakta-statistik-och-kartor/befolkning
Figueira, R., & Ribeiro, T. (2005). Transplants of aquatic mosses as biomonitors of metals released by a mine effluent. *Environmental Pollution, Volume 136, Issue 2, July 2005, Pages 293-301*. https://doi.org/10.1016/j.envpol.2005.01.003
Foppe, K. S., Kujawinski, E. B., Duvallet, C., Endo, N., Erickson, T. B., Chai, P. R., & Matus, M. (2021). Analysis of 39 drugs and metabolites, including 8 glucuronide conjugates, in an upstream wastewater network via HPLC-MS/MS. *Journal of Chromatography B*

Volume 1176, 30 June 2021, 122747. https://doi.org/10.1016/j.jchromb.2021.122747
Gecheva, G., Varadinova, E., & Milkova, T. (2024). Constructed wetlands for controlled bioremediation of wastewater: case studies on bioremediation of wastewaters for the elimination of heavy metals, pesticides, microplastics. *Biotechnologies for Wastewater treatment and Resource Recovery*

Current Trends and Future Scope

2025, Pages 317-327. https://doi.org/10.1016/B978-0-443-27376-6.00004-9
Golovko, O., Asp, H., Ahrens, L., Hultberg, M., Schelin, J., Wiberg, K., Sörengård, M., & Bergstrand, K.-J. (2022). Organic micropollutants, heavy metals and pathogens in anaerobic digestate based on food waste. *Journal of Environmental Management*

Volume 313, 1 July 2022, 114997. https://doi.org/10.1016/j.jenvman.2022.114997
Google Earth. (2025). Map of Sweden and Eskilstuna, Sweden. *[Google Maps screenshot] Retrieved april 5, 2025, from*. https://earth.google.com/web/
Gryaab. (n.d.). Vad innehåller hushållsspillvatten? *[Household wastewater – substance content and variations] [Presentation] [In Swedish]. Vattenråd i Väst*. https://www.vattenradivast.se/download/18.56bb6db916ff44d996933b53/1580456471222/Presentation_2020-01-24_Hush%C3%A5llsspillvatten_Gryaab.pdf
Hamid, N. H. A., Rushdan, A. I., Nordin, A. H., Husna, S. M. N., Faiz Norrrahim, M. N., Knight, V. F., Tahir, M. I. H. M., Li, G. X., Quan, T. L., Abdullah, A. M., Azwa, N. F. T., & Asyraf, M. R. M. (2024). A state-of-art review on the sustainable technologies for cadmium removal from wastewater. *Water Reuse*, *14*(3), 312-341. https://doi.org/10.2166/wrd.2024.143
hitta.se. (n.d.). [local directory/yellow pages search engine]. https://www.hitta.se/s%C3%B6k?vad=bilverkstad%20eskilstuna

Hållbarbiltvätt.se. (2024). Stora Biltvättsrapporten. *[The Big Car Wash Report 2024] [In Swedish]*. https://hallbarbiltvatt.se/wp-content/uploads/2024/04/stora-biltvattsrapporten-2024-web.pdf
Iloms, E., Ololade, O. O., Ogola, H. J. O., & Selvarajan, R. (2020). Investigating Industrial Effluent Impact on Municipal Wastewater Treatment Plant in Vaal, South Africa. *International Journal of Environmental Research and Public Health*, *17*(3), 1096. https://doi.org/10.3390/ijerph17031096
Jones, C., & Jonsson, K. (2018). Insamling av kunskap om organiska miljöföroreningar och metaller i matavfall. *[Collection of knowledge on organic environmental pollutants and metals in food waste] [In Swedish]. Kemakta Konsult AB*. https://www.naturvardsverket.se/4ac3c7/contentassets/7e7d3f211e4a4c91a56105dcc232571d/kemakta-rapport-matavfall.pdf#:~:text=De%20sammanst%C3%A4llda%20resultaten%20visar%20att,omr%C3%A5den%20omfattar%20ett%20st%C3%B6rre%20antal
Kapnisti, M., Samaras, P., Lanaras, K., Liaska, A., & Noli, F. (2025). Removal of cadmium and (radio)toxic metal ions using activated sludge-based sorbents. *Sustainable Chemistry for the Environment , 2025, Vol.10, p.100230*. https://doi.org/10.1016/j.scenv.2025.100230
Khandan, N. (2001). Modeling Tools for Environmental Engineers and Scientists. *Waste Management*

Volume 34, Issue 5, May 2014, Pages 867-874.
Kuppera, T., Bürgeb, D., Bachmannb, H. J., Güsewella, S., & Mayer, J. (2014). Heavy metals in source-separated compost and digestates. https://doi.org/10.1016/j.wasman.2014.02.007
Käppalaförbundet. (n.d.). Tillskottsvatten. *[Infiltration and inflow] [Webpage] [In Swedish]*. https://www.kappala.se/vad-vi-gor/avloppsrening/tillskottsvatten/
Lagerkvist, R. (2004). Golvskurvatten från industrier och verkstäder. *[Floor cleaning water from industries and workshops] [in Swedish]*. https://www.stockholmvattenochavfall.se/globalassets/pdfer/rapporter/avlopp/paverkan-av-industri-och-samhalle/golvskurvatten.pdf
Lin, H. C., Hsieh, P. Y., Wang, G. S., Wang, D. W., Wang, T. H., Hsu, Y. C., & Wu, C. F. (2025). Establishment of Methods to Identify Pollution Sources in a River Reach through Receptor Models [Article]. *Journal of Water Resources Planning and Management*, *151*(3), Article 04024072. https://doi.org/10.1061/JWRMD5.WRENG-6320
Ling, E. J., Benham, B., & Forrester, S. (2011). Virginia Household Water Quality Program: Heavy Metals in Household Water. *Virginia Cooperative Extension, pub. 442-657*. https://extension.umd.edu/sites/extension.umd.edu/files/2022-05/Heavy%20Metals.PDF
Mersch, J., & Johansson, L. (1993). Transplanted aquatic mosses and freshwater mussels to investigate the trace metal contamination in the rivers Meurthe and Plaine, France. *Environmental Technology*

Volume 14, 1993 - Issue 11. https://doi.org/10.1080/09593339309385379
Miljöprövningsförordning (2013:251). (2013). Miljöprövningsförordning (2013:251). *[Environmental Assessment Ordinance (2013:251)] [In Swedish]*.

https://www.riksdagen.se/sv/dokument-och-lagar/dokument/svensk-forfattningssamling/miljoprovningsforordning-2013251_sfs-2013-251/

Molander, C. (2015). Influence of excessive water on wastewater treatment performance. *[Master thesis, Chalmers University]*. https://publications.lib.chalmers.se/records/fulltext/223718/223718.pdf#:~:text=The%20extraneous%20water%20includes%20storm%20water%20derived%20from,of%20water%20influences%20the%20performance%20of%20the%20WWTP.

Olsson, M. (2018). Analys av föroreningar i avloppsvatten i Falun. *[Master thesis, Uppsala University]*. https://fev.se/download/18.13665a917b37353d82f3a33/1631599527152/Bilaga%205%20Analys%20av%20f%C3%B6roreningar%20i%20avloppsvatten%20i%20Falun-Malin%20Olsson-Exjobb.pdf#:~:text=%C2%B5g%2Fl%20Zink%20Kadmium%20Koppar%20Krom,V%C3%A4rden%20som%20rapporterades%20som%20mindre

Pedrizzetti, G. (2022). *Conservation of Mass. In: Fluid Mechanics for Cardiovascular Engineering. Springer, Cham, p.55-60*. https://doi.org/10.1007/978-3-030-85943-5_4

Persson, F. (2019). Analys av miljöfarliga metaller i olika biogassubstrat från matavfall. *[Bachelor thesis, Linné University]*. https://www.diva-portal.org/smash/get/diva2:1507941/FULLTEXT01.pdf#:~:text=Examensarbete%20i%20milj%C3%B6vetenskap%20Analys%20av,Examinator%3A%20Mats%20%C3%85str%C3%B6m%20Termin%3A%20VT19

Region Sörmland. (n.d.). Mälarsjukhuset Eskilstuna. *[Mälar Hospital Eskilstuna] [in Swedish]*. https://regionsormland.se/halsa-vard/sjukhus-i-sormland/

RISE. (n.d.). Certifiering av avloppsreningsverk, Revaq (SPCR 167). *[Certification of wastewater treatment plants, Revaq (SPCR 167)] [Webpage] [In Swedish]*. https://www.ri.se/sv/vad-vi-gor/tjanster/certifiering-av-avloppsreningsverk-revaq

SCB. (n.d.). Folkmängd efter region och år. *[Population by region, marital status, age, and sex] [Dataset] [In Swedish]*. https://www.statistikdatabasen.scb.se/pxweb/sv/ssd/START__BE__BE0101__BE0101A/BefolkningNy/table/tableViewLayout1/

Schaefer, H. R., Dennis, S., & Fitzpatrick, S. (2020). Cadmium: Mitigation strategies to reduce dietary exposure. *Journal of Food Science*, *85*(2), 260-267. https://doi.org/10.1111/1750-3841.14997

SGU.se. (n.d.). Kartvisare och diagram för miljöövervakning av grundvattenkemi. *[Map viewer and diagrams for groundwater chemistry monitoring] [Webpage] [In Swedish]*. https://www.sgu.se/grundvatten/miljoovervakning-av-grundvatten/kartvisare-och-diagram-for-miljoovervakning-av-grundvattenkemi/

SMHI. (n.d.). Sveriges klimat. *[Sweden's climate] [Webpage] [In Swedish]*. https://www.smhi.se/kunskapsbanken/klimat/sveriges-klimat/#:~:text=%C3%85rsnederb%C3%B6rd%20f%C3%B6r%20Sverige%2C%20medelv%C3%A4rde%20f%C3%B6r%20normalperioden%201991-2020.%20Nederb%C3%B6rd,hamnar%20den%20mesta%20nederb%C3%B6rden%20i%20landets%20v%C3%A4stra%20delar.

Solon, K., Volcke, E. I. P., Spérandio, M., & Van Loosdrecht, M. C. M. (2019). Resource recovery and wastewater treatment modelling. *Environmental Science: Water Research & Technology*, *5*(4), 631-642. https://doi.org/10.1039/c8ew00765a

SOU. (2020). Hållbar slamhantering. *[Sustainable sludge management] [SOU 2020:3] [In Swedish]. Regeringskansliet*. https://www.regeringen.se/contentassets/3d68880d2e6942f3a1dccb158e46beb7/hallbar-slamhantering-sou-20203/

Svenskt vatten. (2018). Silver Leaching, a report on silver in sportswear. *Message M146*. https://vattenbokhandeln.svensktvatten.se/produkt/silver-leaching-a-report-on-silver-in-sportswear/

Svenskt vatten. (2019). Råd vid mottagande av avloppsvatten från industri och annan verksamhet. *[Advice on receiving wastewater from industry and other operations] [In Swedish]*. https://www.svensktvatten.se/globalassets/dokument/avlopp-och-miljo/p95-2019-rad-vid-mottagande-av-avloppsvatten-fran-industri-och-annan-verksamhet.pdf

Svenskt vatten. (2023). REVAQ - Årsrapport 2021. *[Revaq Annual Report 2021] [In Swedish]*. https://issuu.com/svensktvatten/docs/revaq-arsrapport-2021#:~:text=44%20procent%20av%20de%20certifierade%20reningsverken%20har%20redan,kadmiuminneh%C3%A5llet%20i%20sitt%20slam%20med%20minst%2010%20procent.

Svenskt vatten. (2024). REVAQ - Årsrapport 2023. *[Revaq Annual Report 2023] [In Swedish]*. https://www.svensktvatten.se/globalassets/dokument/avlopp-och-miljo/revaq/revaq-arsrapport-2023.pdf

Svenskt vatten. (2025). Regler för certifieringssystemet. *[Revaq Rules 2025: Rules for the Certification System] [In Swedish]*. https://www.svensktvatten.se/globalassets/dokument/avlopp-och-miljo/revaq/revaq-regler-2025-utgava-10.0-vit.pdf

Swedish EPA. (1995). Vad innehåller avlopp från hushåll? *[What does household wastewater contain?] [In Swedish]. Naturvårdsverket*. https://www.naturvardsverket.se/4ac2b2/globalassets/media/publikationer-pdf/4400/978-91-620-4425-7.pdf

Swedish EPA. (2017). Analys av kunskapsläget för dagvattenproblematiken. *[Analysis of the state of knowledge on stormwater issues] [In Swedish]. Naturvårdsverket*. https://www.naturvardsverket.se/4ac3c3/globalassets/forskning/analys-kunskapslaget-dagvattenproblematiken.pdf

Swedish EPA. (n.d.). Swedish Pollutant Release and Transfer Register - Utsläpp i siffror – Eskilstuna kommun. *[Emissions in figures – Eskilstuna municipality] [Webpage] [In Swedish]*. https://utslappisiffror.naturvardsverket.se/en/Search/Plant-list/?kommun=0484

Sylwan, I., & Thorin, E. (2021). Removal of Heavy Metals during Primary Treatment of Municipal Wastewater and Possibilities of Enhanced Removal: A Review. *Water*, *13*(8), 1121. https://doi.org/10.3390/w13081121

Sörme, L., & Lagerkvist, R. (2002). Sources of heavy metals in urban wastewater in Stockholm. *Science of The Total Environment, Volume 298, Issues 1–3, 21 October 2002, Pages 131-145*. https://doi.org/10.1016/S0048-9697(02)00197-3

Thomeby, L. (1997). Constructed Wetlands as a Treatment Method for Landfill Leachate. *Water 2021, 13(8), 1121*. https://doi.org/10.15626/Eco-Tech.1997.036

Tuci, F., Antal, A., Doumett, S., Fibbi, D., Camisa, R., Bettazzi, E., Coppini, E., Daddi, D., & Gori, R. (2024). Monitoring and Studying the Behavior of Metals in an Industrial Wastewater Treatment Plant in Italy. *Water*, *16*(22), 3164. https://doi.org/10.3390/w16223164

Visiteskilstuna.se. (n.d.). Färg & Formverkstaden. *[webpage] [in Swedish]*. https://visiteskilstuna.se/besokswebbar/rademachersmedjorna/hantverkare/farg--formverkstaden

Vården.se. (n.d.). Tandläkare i Eskilstuna. *[Dentists in Eskilstuna] [web search] [in Swedish]*. https://www.varden.se/hitta/tandlakare-c/eskilstuna-p

W&WW. (n.d.). Return Sludge: Understanding Its Role in Wastewater Treatment. *[Webpage]*. https://www.waterandwastewater.com/return-sludge-understanding-its-role-in-wastewater-treatment/#:~:text=Return%20sludge%20is%20a%20crucial%20component%20in%20the,level%20of%20microorganisms%20that%20break%20down%20organic%20matter.

WHO. (2021). Nickel in drinking water: background document for development of WHO Guidelines for drinking-water quality. https://iris.who.int/handle/10665/350934

Yesil, H., Molaey, R., Calli, B., & Tugtas, A. E. (2021). Removal and recovery of heavy metals from sewage sludge via three stage integrated process. *Chemosphere*

Volume 280, October 2021, 130650. https://doi.org/10.1016/j.chemosphere.2021.130650

Yoon, T., Rhodes, C., & Shah, F. A. (2014). Upstream water resource management to address downstream pollution concerns: A policy framework with application to the Nakdong River basin in South Korea. *Water Resources Research 51, 787–805*. https://doi.org/10.1002/2013WR014201

Yoshidaa, H., Christensena, T. H., Guildalb, T., & Scheutz, C. (2013). A comprehensive substance flow analysis of a municipal wastewater

and sludge treatment plant. *Chemosphere*

Volume 138, November 2015, Pages 874-882. https://doi.org/10.1016/j.chemosphere.2013.09.045

APPENDIX 1: MASS BALANCE OF HM

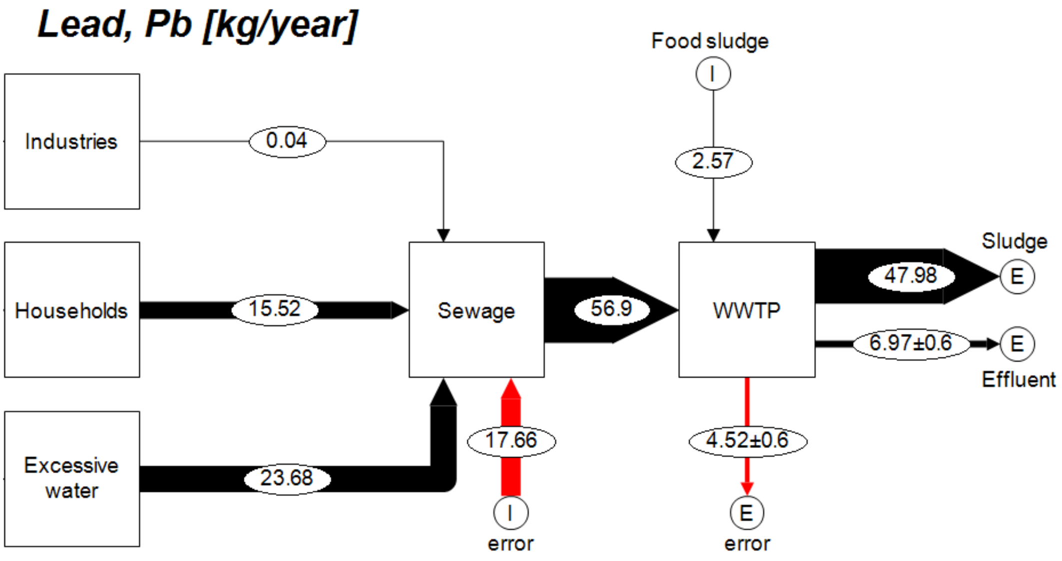

Figure 26 Mass balance for Pb

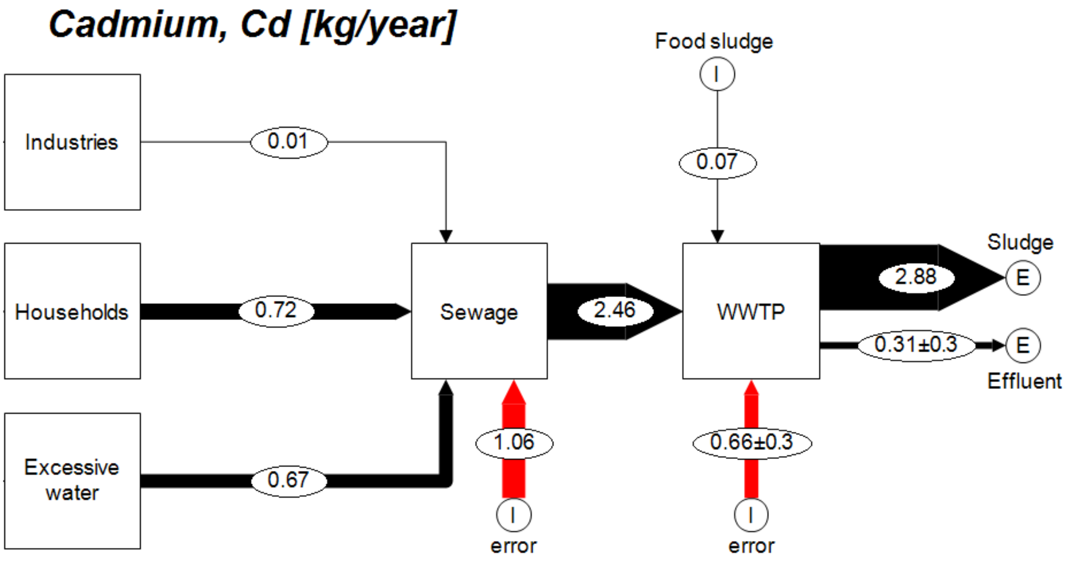

Figure 27 Mass balance for Cd

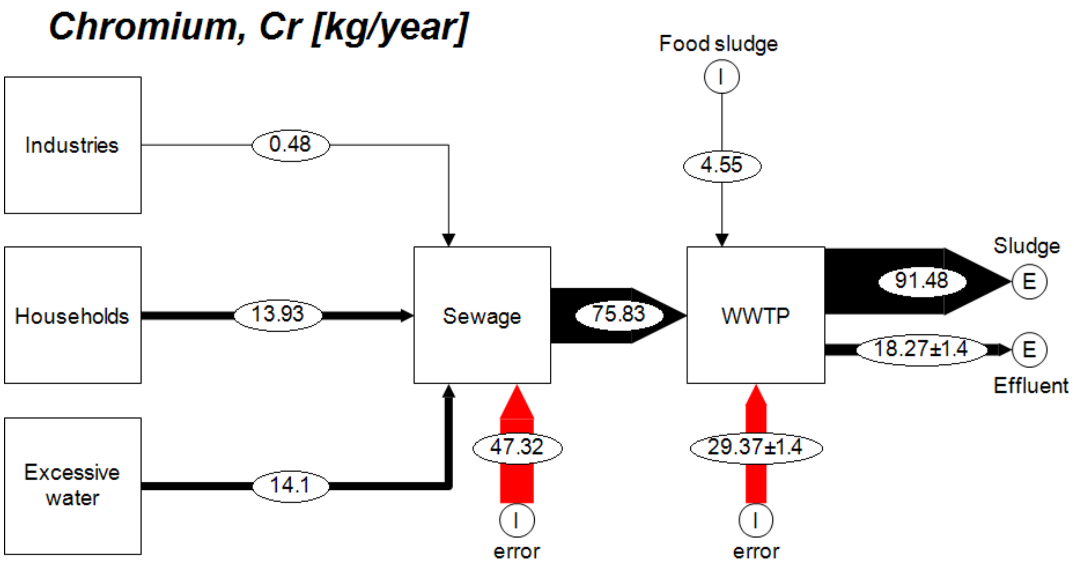

Figure 28 Mass balance for Cr

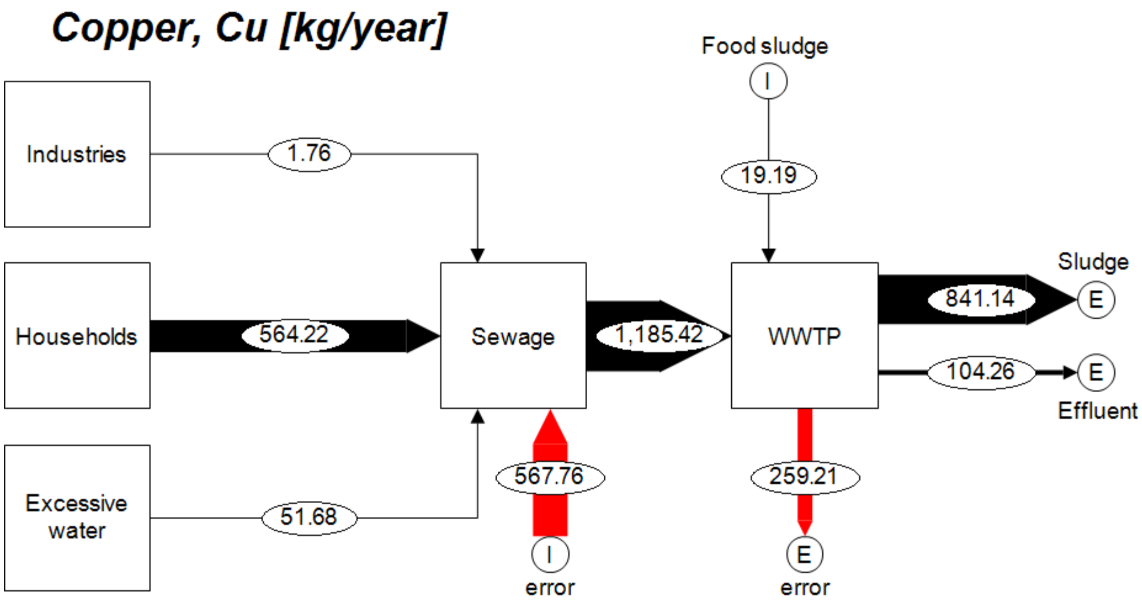

Figure 29 Mass balance for Cu

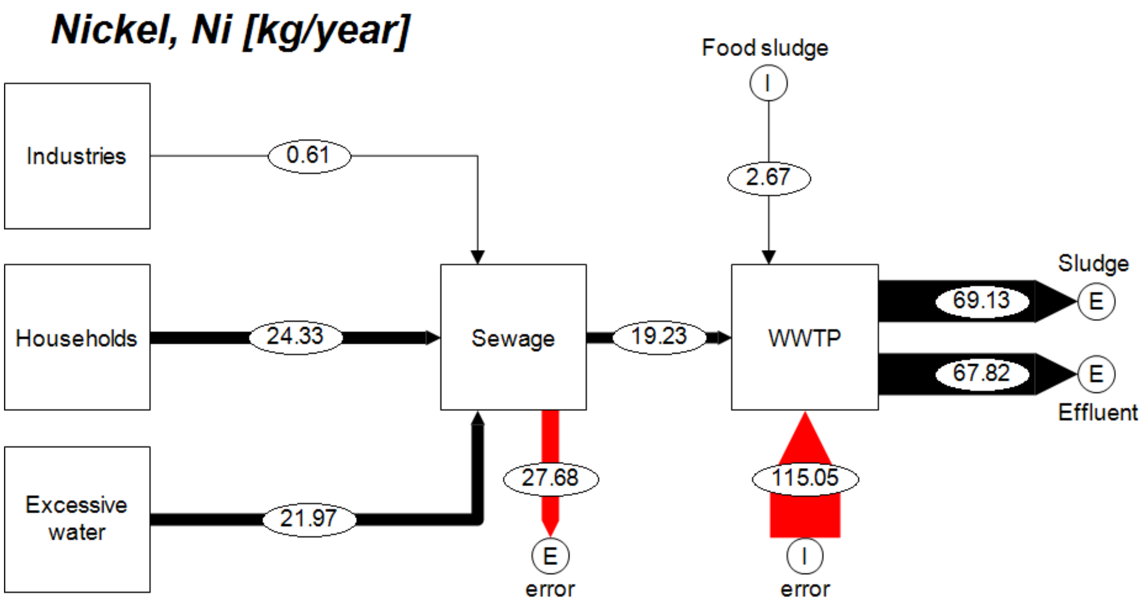

Figure 30 Mass balance for Ni

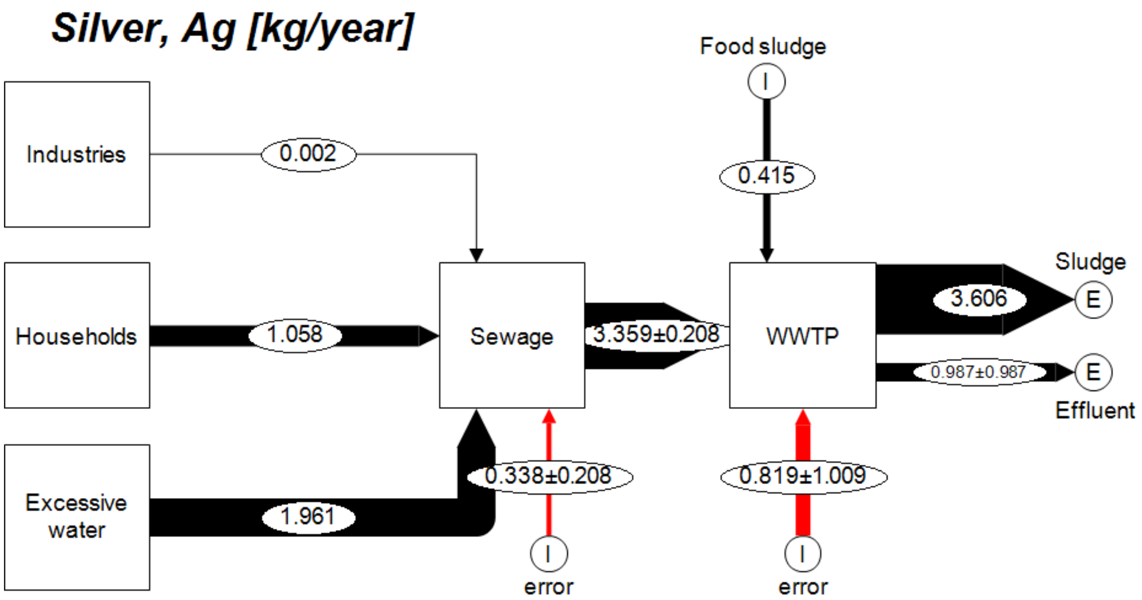

Figure 31 Mass balance for Ag

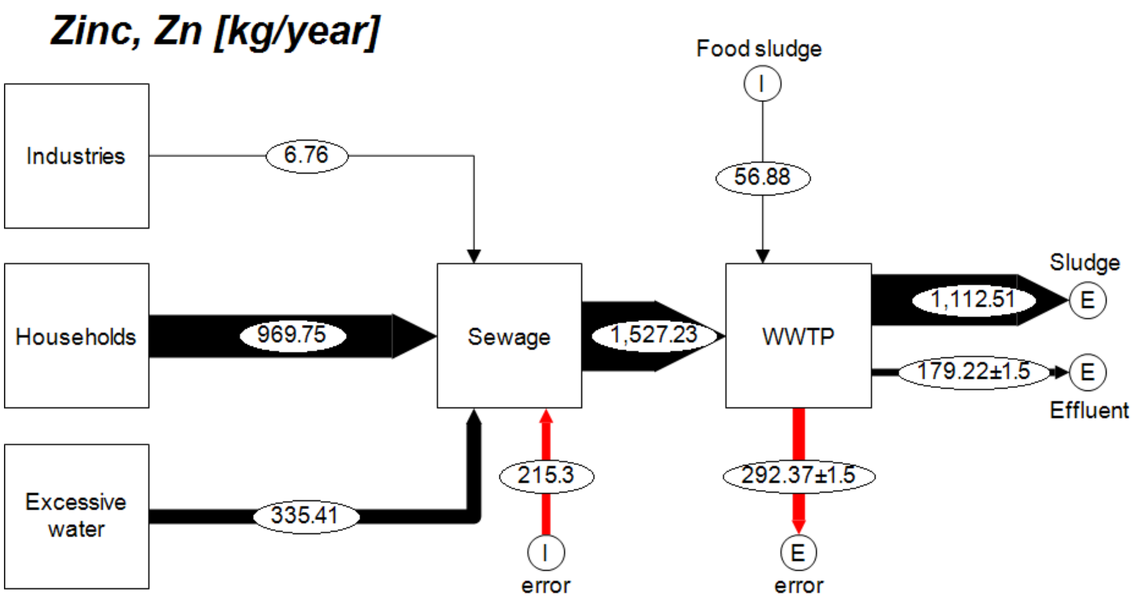

Figure 32 Mass balance for Zn

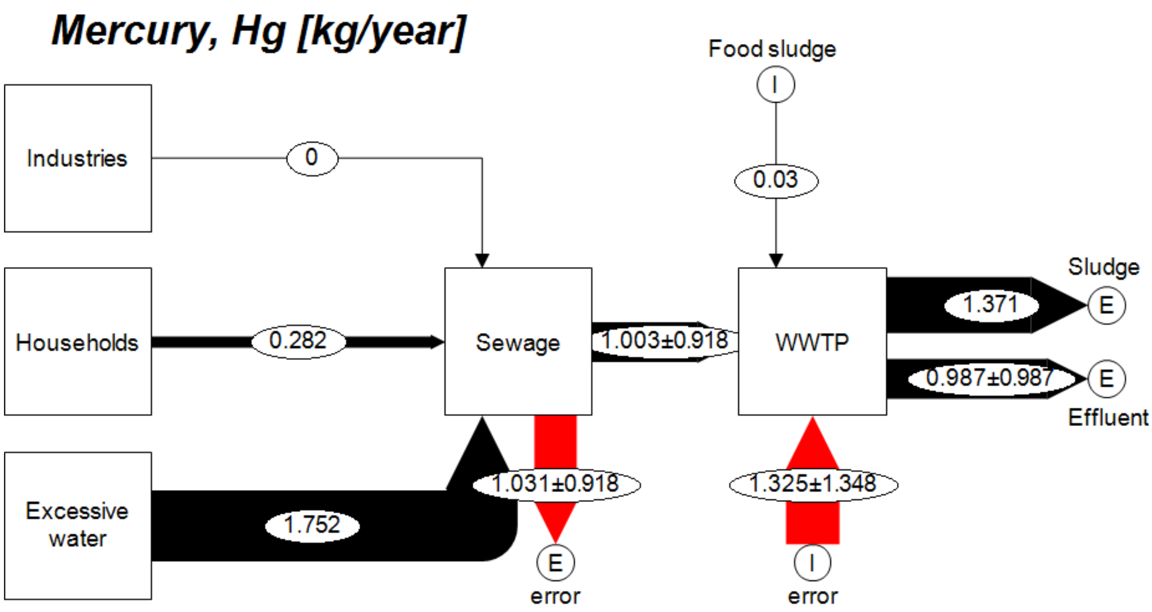

Figure 33 Mass balance for Hg

APPENDIX 2: CONCENTRATION TREND IN INCOMING FLOW TO WWTP FOR SAMPLING

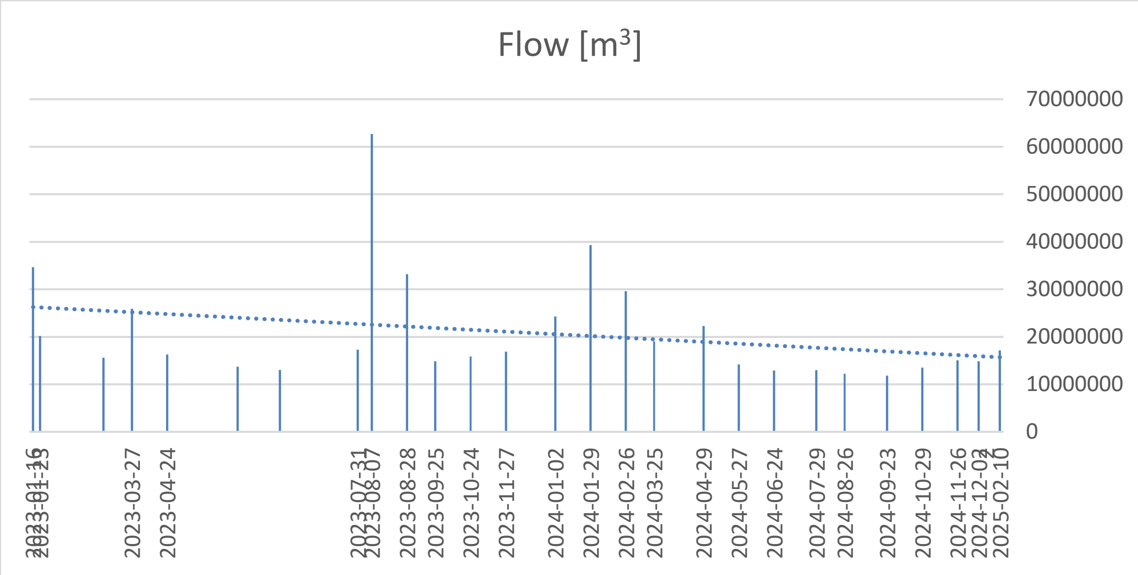

Figure 34 Total yearly flows for each sample in F1

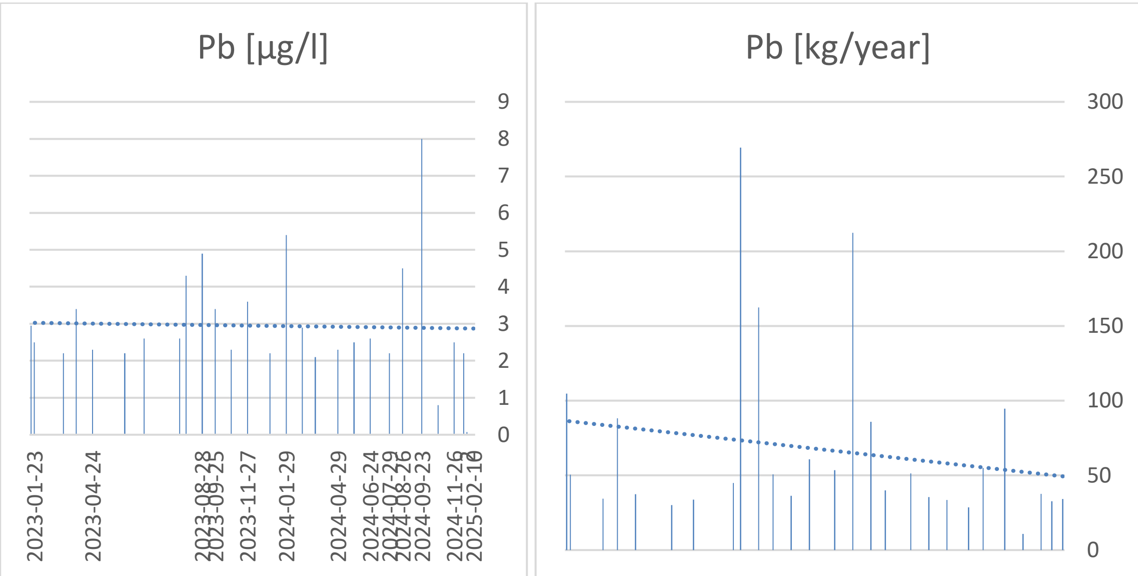

Figure 35 Samples for concentration (left), mass flow for each sample (right)

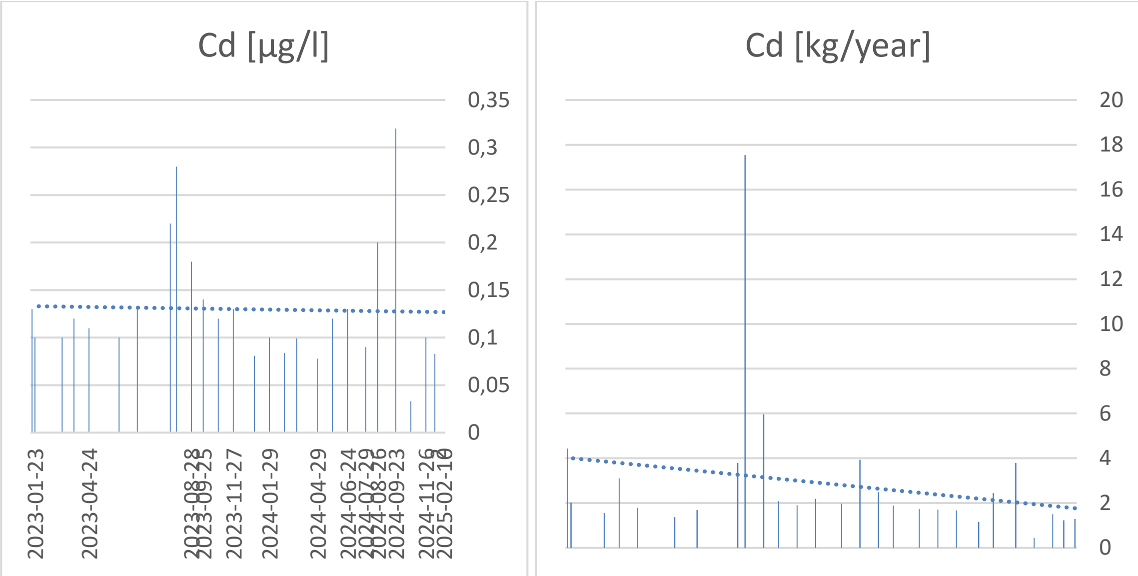

Figure 36 Samples for concentration (left), mass flow for each sample (right)

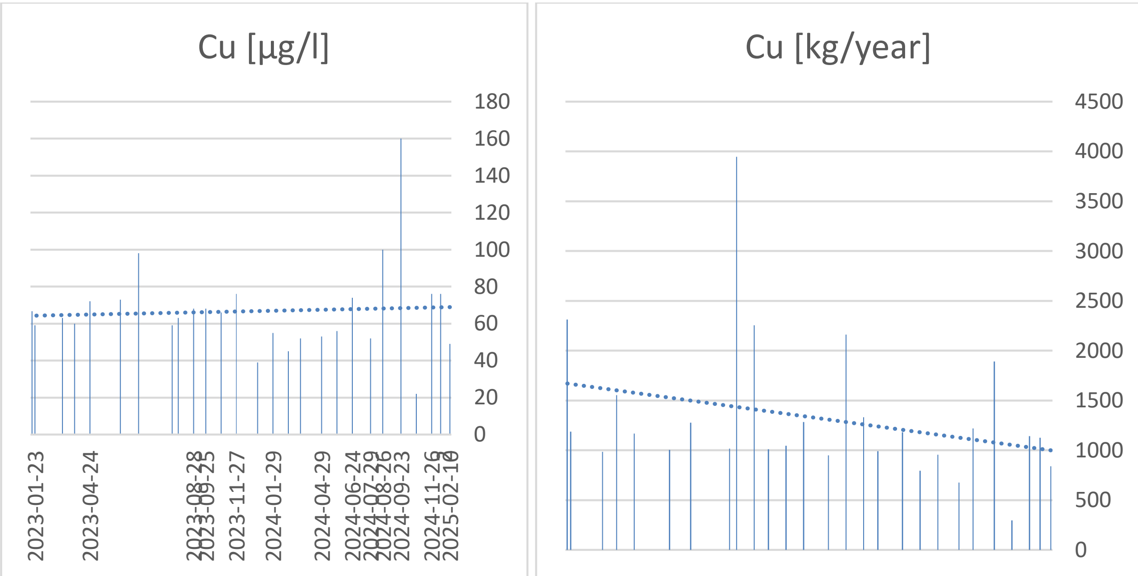

Figure 37 Samples for concentration (left), mass flow for each sample (right)

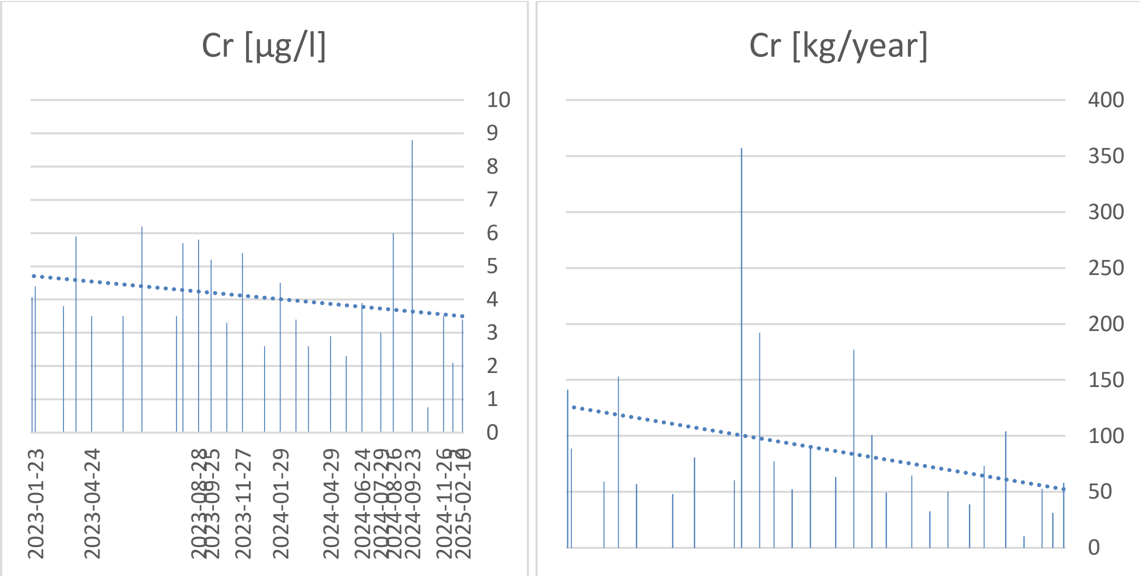

Figure 38 Samples for concentration (left), mass flow for each sample (right)

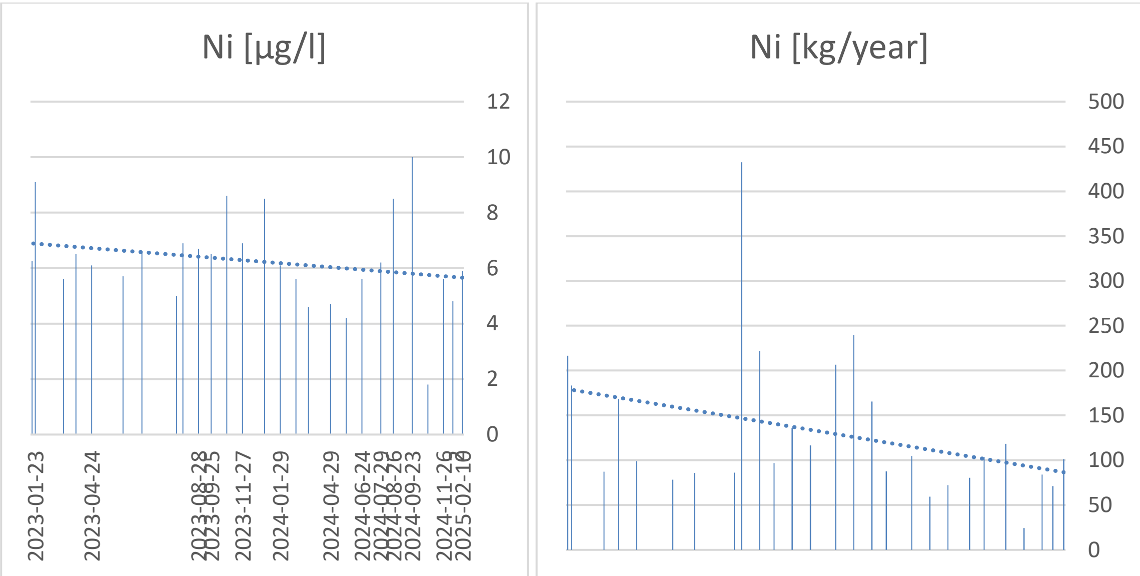

Figure 39 Samples for concentration (left), mass flow for each sample (right)

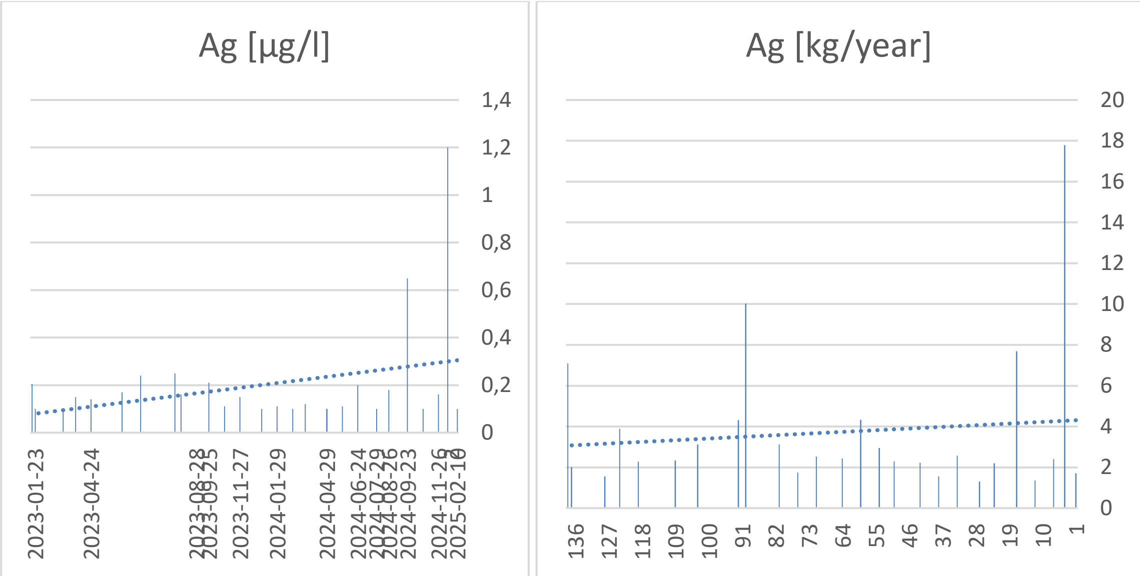

Figure 40 Samples for concentration (left), mass flow for each sample (right)

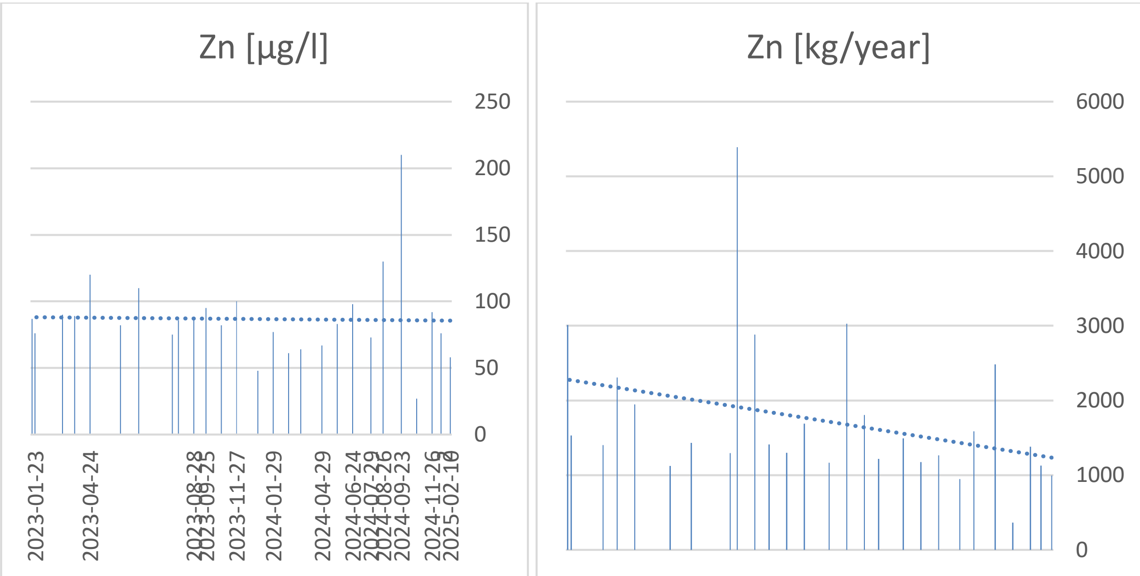

Figure 41 Samples for concentration (left), mass flow for each sample (right)

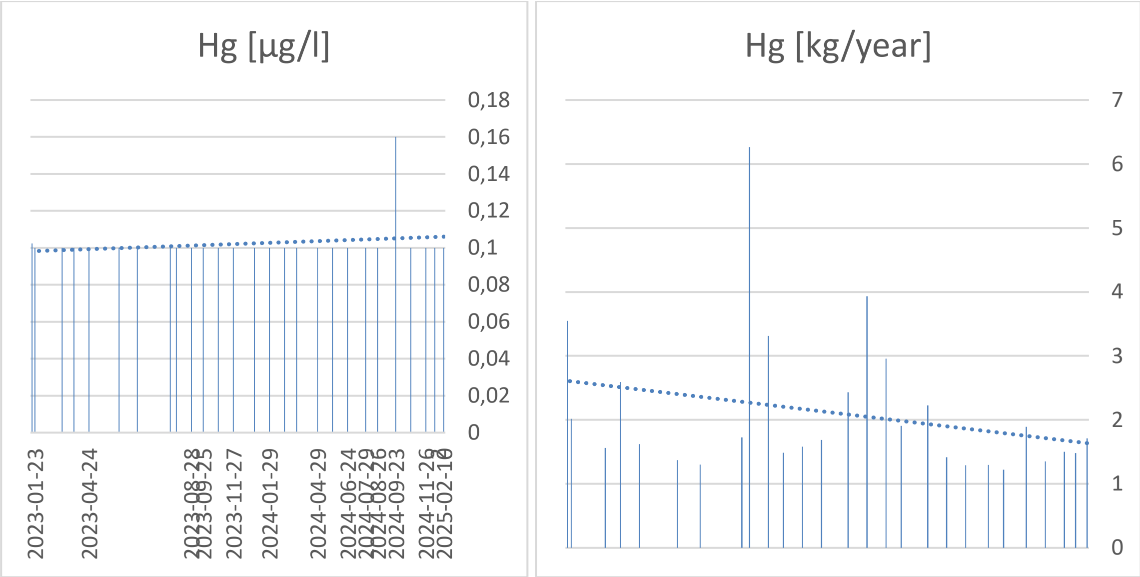

Figure 42 Samples for concentration (left), mass flow for each sample (right)