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Determining the Fate of Drinking Water Sludge at the Rya Wastewater Treatment Plant in Gothenburg

Master's thesis in the Master's Programme Infrastructure and Environmental Engineering

HANNES LÖFGREN

DEPARTMENT OF ARCHITECTURE AND CIVIL ENGINEERING
CHALMERS UNIVERSITY OF TECHNOLOGY

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MASTER'S THESIS ACEX30

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Department of Architecture and Civil Engineering
Division of Water Environment Technology
Chalmers University of Technology
SE-412 96 Göteborg
Sweden
Telephone: + 46 (0)31-772 1000

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ABSTRACT

Regulations on effluent nutrient concentrations become increasingly stricter, which puts pressure on the treatment capacities of wastewater treatment plants (WWTPs). Many WWTPs receive and treat drinking water sludge (DW sludge) produced by drinking water treatments plants (DWTPs). The DWTPs use coagulants such iron- or aluminum sulfate to reduce the turbidity of the drinking water, producing sludge as a by-product. This sludge is sometimes discharged into the sewer system and reaches WWTPs with the influent wastewater. The DW sludge can potentially affect the treatment capacity of WWTPs; however, its fate in the wastewater treatment processes is uncertain. This thesis focuses on the Rya WWTP in Gothenburg, Sweden, which receives DW sludge rich in aluminum, from the DWTPs, Lackarebäck and Alelyckan. The main goal of the study was to determine the fate of DW sludge in the primary settlers at the WWTP. The methodology involved analyzing the metal contents in the incoming wastewater, the DW sludge, as well as other sludge samples from various locations in the WWTP. The metals were used as indicator substances to differentiate between the DW sludge and the wastewater sludge (WW sludge). Aluminum and arsenic were used as indicator substances for DW sludge. Based on the results from the specific study period, the DW sludge represented approximately 40% of the aluminum and the arsenic in the incoming wastewater. Metals such as calcium, copper, magnesium and zinc were underrepresented in the DW sludge, 6% or less, and therefore served as indicators of WW sludge. The fate of the two sludge fractions was determined by calculating mass balances of the metals in the WWTP. Based on the metals representative of the WW sludge, approximately 50% was removed in the primary settlers. When using the measured mass flow of incoming wastewater approximately 90% the DW sludge is removed. However, mass balances for many metals in the WWTP could not be closed, indicating uncertainties in the measurements. Therefore, calculations were conducted using a mass flow in the incoming wastewater based on the mass flows of waste activated sludge and primary sludge, which showed that approximately 50% of the DW sludge is removed. The effect of another uncertainty, the DW sludge flow, was evaluated by varying the flow ± 30 %, which showed that the calculated removal of DW sludge decreases if a larger amount of influent DW sludge is assumed and vice versa. The study concluded that the DW sludge is most likely removed in the primary settlers to the same extent as WW sludge, potentially more.

Key words: Drinking water sludge, wastewater sludge, metals, wastewater treatment, sludge disposal, drinking water treatment, mass flow, mass balance

Fördelningen av vattenverksslam i Ryaverkets avloppsreningsverk i Göteborg

Examensarbete inom mastersprogrammet infrastruktur och miljöteknik

HANNES LÖFGREN

Institutionen för arkitektur och samhällsbyggnadsteknik
Avdelningen för Vatten Miljö Teknik
Chalmers tekniska högskola

SAMMANFATTNING

Regler för att begränsa utsläpp av näringsämnen i det utgående vattnet blir allt striktare, vilket ställer högre krav på kapaciteten hos reningsprocesserna i avloppsreningsverken. Många avloppsreningsverk mottar och behandlar vattenverkslammet från vattenverk. Vattenverk använder fällningskemikalier som till exempel järn- och aluminiumsulfat för att minska grumligheten i råvattnet, varpå vattenverkslam bildas som biprodukt. Ibland skickas slammet med det vanliga avloppsnätet och når avloppsreningsverken genom det inkommande avloppsvattnet. Vattenverkslammet påverkar potentiellt avloppsreningsverkets reningsprocesser. Hur vattenverkslammet fördelas när det når avloppsreningsverk är däremot osäkert. Denna rapport fokuserar på avloppsreningsverket Ryaverket i Göteborg, Sverige, som mottar och behandlar aluminiumrikt vattenverkslam från de två vattenverken Lackarebäck och Alelyckan. Det huvudsakliga syftet med rapporten var att undersöka i vilken utsträckning som vattenverkslammet avskiljs när det når försedimenteringen i Ryaverket. Metoden inkluderade analys av flertalet metallers koncentrationer i det inkommande avloppsvattnet, vattenverkslammet och i olika provpunkter på Ryaverket. Metallerna användes som indikatorämnen för att skilja mellan vattenverkslammet och avloppsslammet. Aluminium och arsenik användes som indikatorämnen för vattenverkslammet. Baserat på perioden då prover analyserades utgjorde vattenverkslammet cirka 40 % av aluminium och arsenik, i inkommande avloppsvatten. Bidraget till andra metaller, som kalcium, koppar, magnesium och zink var litet, under 6 %, och användes som indikatorämnen för avloppsslammet. Avskiljningen och fördelningen för de två fraktionerna bestämdes genom beräkning av massbalanser av metallerna i avloppsreningsverket. Baserat på metallerna representativa för avloppsslammet, avskiljs de cirka 50 % i försedimeneringen. När uppmätta värdena för massflödet i inkommande avloppsvatten används avskiljs vattenverkslammet cirka 90%. Massbalanserna för många metaller stämde inte, vilket indikerade att det finns osäkerheter kring mätningarna. Därför utfördes ytterligare beräkningar genom att basera inkommande massflöde i massflödet i överskottsslammet och i primärslammet, vilket visade på en avskiljning på drygt 50 % för vattenverkslammet. Effekten av osäkerheter kring flödet av vattenverkslammet undersöktes genom att variera flödet ±30 %, vilket visade att den beräknade avskiljningen av vattenverkslam minskar när flödet av vattenverkslam ökar, och tvärt om. Slutsatsen är att vattenverkslammet sannolikt avskiljs i samma utsträckning som avloppsslammet, potentiellt i högre utsträckning, i försedimenteringen.

Nyckelord: Vattenverkslam, avloppsslam, metaller, avloppsrening, slamhantering, dricksvattenrening, massflöde, massbalans

Contents

Preface

This thesis was a collaboration between Chalmers University of Technology (CTH), Gryaab AB and Kretslopp och vatten, Göteborg Stad and was conducted during the spring semester of 2021. As a part of determining the fate of drinking water sludge at the Rya wastewater treatment plant, laboratory work was conducted during the months of February, March, April and May. The work was carried out in the Water Environment Technology (WET) laboratory at CTH. I would like to extend my gratitude to those who supported and guided me throughout this project: my examiner Oskar Modin, professor at the WET division at CTH, my supervisor Maria Neth, industrial PhD student from Gryaab AB at the WET division, Ann Mattsson, adjunct professor at the WET division and manager of R & D at Gryaab AB and Kajsa Engblom, specialist at Kretslopp och vatten, Göteborgs Stad. In addition, I would like to thank Sebastien Rauch, professor at the WET division who helped run the samples using the ICP-MS available at the WET laboratory. Finally, I would like thank Amir Saeid Mohammadi, research engineer at the WET division who helped me and answered the many questions I had regarding the laboratory work.

1 Introduction

This chapter includes necessary background information, problem definition, aim, hypothesis as well as the limitations of this thesis.

1.1 Background

The environmental issues of today is a topic of raising concern. Currently, the Intergovernmental Panel on Climate Change which formed in 1988 is working to publish the sixth assessment cycle during 2022 (IPPC, 2020). One of the issues facing mankind today is pollution as well as adverse effects from eutrophication of the world's many water bodies, such as oceans, lakes, estuaries and wetlands. Eutrophication is caused by the unnatural release of nutrients in the form of phosphorus and nitrogen which enables the excessive growth of algae and the subsequent depletion of oxygen, potentially having detrimental effects on aquatic ecosystems (Bindoff et al., 2019; Paerl & Otten, 2013). Over the last 100 years, on a global scale, substantial increase in nutrient flows have been observed and an especially high increase in contributions of phosphorus and nitrogen stemming from wastewater discharges. The further development of urban societies would most likely increase the anthropogenic nutrient load (Preisner et al., 2021). The introduction of discharge limits through regulations have been a way of tackling the issue at hand. The more stringent regulations for nitrogen and phosphorus have pushed the technical development of wastewater treatment plants (WWTPs) further (la Cour Jansen et al., 2019).

One of the sixteen environmental quality goals in Sweden specifically target eutrophication. The main intention of the goal is to eradicate any negative impacts which stem from eutrophication. Phosphorus and nitrogen reaches the environment through a variety of processes, one being the wastewater discharge from WWTPs (Naturvårdsverket, 2020). In Sweden, the problems caused by eutrophication were brought to light in the 1960s. Years of negative impact on the environment led to stricter requirements for wastewater treatment and approximately a decade later, municipal WWTPs would collect the wastewater from almost all households in Sweden (Gårdstam et al., n.d). As mentioned, WWTPs are required to deal with the increasing pressure which follows stricter discharge requirements. In addition, WWTPs receives and treats the sludge which is formed in the treatment of drinking water (Marguti et al., 2018). The latter is the current disposal method for drinking water sludge (DW sludge) in Gothenburg, Sweden. The two drinking water treatment plants (DWTPs) Lackarebäck and Alelyckan produces DW sludge which is sent to the Rya WWTP in Gothenburg (Rambøll, 2016). When producing drinking water it is a common practice to use coagulants as a means of reducing turbidity caused by the suspension of particles (Malik, 2018). There are two different salts which are commonly used as coagulants, either aluminum or iron salts. When added, participates in the form of aluminum or iron hydroxide forms flocs and settle together with unwanted particles and microorganisms, thus removing potentially harmful substances (Turner et al., 2019).

1.2 Problem definition

The Rya WWTP which treats the wastewater for several larger municipalities is currently facing future challenges in the form of increased hydraulic loading, stricter discharge requirements and the lack of space needed for expansion (Nunes et al., 2017). The current solution which

involves treatment of DW sludge, is a topic which has been discussed and research prior to this thesis. The possibility for treating the DW sludge locally and in conjunction with the DWTPs has been evaluated by Kärrman (2017) and Rambøll (2016) comparing the two alternatives with respect to economic, social, environmental and technical aspects. In addition, the potential effects of DW sludge on WWTP processes have been investigated by students at Chalmers university of technology (CTH), Klint et al. (2015) and Graham-Jones (2014). The results indicated that DW sludge negatively affected settling properties of the activated sludge at the Rya WWTP, as well as increased sludge dewatering time. The reports by Kärrman (2017) and Rambøll (2016) was used as decision support when determining the whether the DW sludge should be treated at the Rya WWTP or not. The conclusion was that the current method for disposal should be kept, mainly because the current knowledge on the effects of DW sludge has on wastewater treatment processes comes with a lot of uncertainties (Göteborgs Stad, 2017).

This thesis seeks to investigate the actual fate of the DW sludge when it arrives at the Rya WWTP. The main method is to track the DW sludge through indicator substances, i.e, different metals which are typically present in DW sludge, or found in higher concentrations compared to the sludge at Rya WWTP, which consists WW sludge mixed with DW sludge, making it possible to differentiate between DW sludge and WW sludge.

1.3 Aim and objectives

The aim of this thesis is to provide deeper knowledge for decisions regarding the DW sludge from Lackarebäck and Alelyckan which is received and treated by the Rya WWTP. By doing so, the hope is to contribute to the sustainable development of DW sludge treatment and WWTP processes. This is achieved by determining the fate of the DW sludge when it reaches the primary settlers at the Rya WWTP. In the case of the Rya WWTP an interest in knowing the effects of WTP sludge on wastewater treatment has been shown. If the fate of DW sludge can be determined as it reaches the Rya WWTP, it could potentially assist in further studies on the topic.

1.4 Hypothesis and research question

The hypothesis consists of three possible cases which are presented in Figure 1. The first case assumes that when the DW sludge reaches the primary settlers, it is removed to such an extent that it does not reach the biological treatment at Rya WWTP. In the second case, the DW sludge is not removed in the primary settlers and reaches the biological treatment step. The third case is a combination of the first and second, which means that the DW sludge is removed in the primary settlers to some extent, but a fraction also reaches the biological treatment step. The research question which follows is:

What is the fate of DW sludge when it reaches the primary settlers at the Rya WWTP?

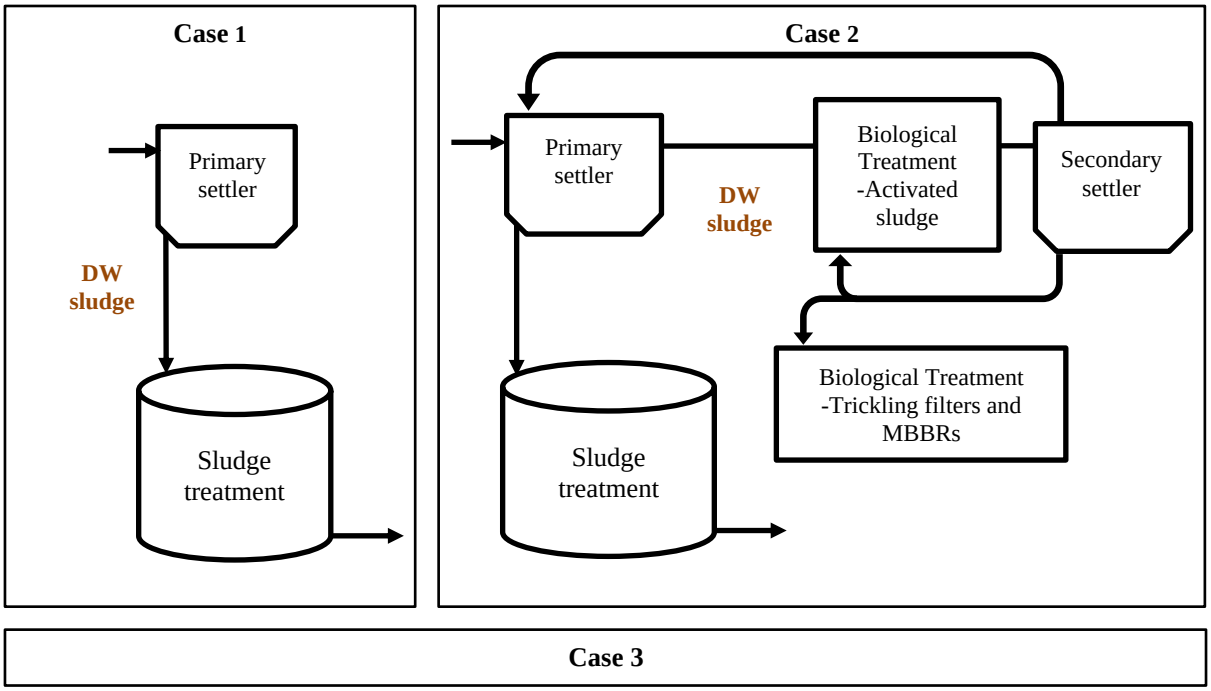

Figure 1. Three cases of the fate of DW sludge when it reaches the primary settlers at Rya WWTP (Davidsson, 2019; Nunes et al., 2017).

1.5 Limitations

This thesis is limited to only analyze the fate and distribution of DW sludge at the Rya WWTP. This means that the effects of DW sludge on different parts of the treatment process at the Rya WWTP will not be investigated. Any reporting of the effects of DW sludge will be based on what prior studies have concluded. Moreover, the study is a case study, thus, mainly representative of the conditions at Lackarebäck, Alelyckan and the Rya WWTP. The literature review will not be the focus of this thesis, which also means that it only includes a few chosen studies on the topic of DW sludge disposal and its effects on wastewater treatment processes.

2 Prior knowledge and background

The following chapter includes a literature review which provides background knowledge regarding the challenges associated with DW sludge disposal, disposal methods and the effects of DW on different wastewater treatment processes. Moreover, the specific case study is presented in greater detail, providing information about the treatment at Rya WWTP and the sludge disposal at Lackarebäck and Alelyckan DWTPs.

2.1 Case study background

In Gothenburg, Sweden's second largest city which is situated on the west coast (Göteborgs Stad, n.d a) , the Rya WWTP operates. The treatment plant is owned by the company Gryaab AB, whose ownership is shared by eight different municipalities, one of them being the Gothenburg municipality (Gryaab, n.d). The treatment plant received just over 810 000 person equivalents (pe) of wastewater. Out of the 810 000 pe, the majority comes from households, and a much smaller fraction, 70 000 pe from industries, in the year of 2015 (Nunes et al., 2017). The drinking water in Gothenburg is produced by two DWTPs, Alelyckan and Lackarebäck

(Göteborgs Stad, n.d b). In the process of treating the raw water, which comes from Göta Älv River, aluminum sulfate is added as a coagulant. In the case of Lackarebäck, the water is first transported from the Göta Älv river to lake Delsjön before used as raw water. As mentioned earlier, the use of aluminum based salt causes participates in the form of aluminum hydroxide which form flocs and settles together with impurities, reducing the turbidity of the raw water, producing DW alum sludge. The current solution, which is applied at both Lackarebäck and Alelyckan is to send the sludge to the Rya WWTP for treatment, using the sewer network. Slightly more than 1400 tons of total solids, TS (dry matter) was sent to Rya WWTP for treatment in 2012 (Rambøll, 2016).

The current practice, which means that the Rya WWTP receives and treats alum sludge has been discussed and researched prior to this thesis. In the case of Rya WWTP, there are future challenges which have to be considered, and therefore, other ways of dealing with the DW sludge have been discussed, mainly by looking at options for treating the WTP sludge locally in conjunction with the DWTPs (Kärrman, 2017; Rambøll, 2016). Rya WWTP is concerned with increased hydraulic loadings. The geographical location of the Rya WWTP makes expansion of the treatment facility difficult. In addition, forecasts which stretches until the year of 2030, suggest that current hydraulic loading will increase due to population growth, changes in industrial actives and because smaller WWTPs will cease their operation and instead connect to the Rya WWTP. Stricter discharge limits are expected as well, and the Rya WWTP must look for ways of reducing the hydraulic loading. Finally, the Rya WWTP also produces sludge which in recent years has become certified under the name of REVAQ. This means that the quality of the sludge must considered (Davidsson, 2020; Nunes et al., 2017).

2.1.1 The Rya WWTP treatment process

An overview of the wastewater treatment process can be seen in Figure 2, which depicts a compact and simplified version of the different processes at Rya WWTP.

The wastewater flow is typically somewhere around 4 m^3/s as a yearly average but varies between 2 to16 m^3/s (M. Neth, personal communication, 2021-05-28) and when it reaches the Rya WWTP it undergoes what is referred as physical treatment in Figure 2. The water is pumped into the treatment plant by specific inlet pumps. Coarse bar screens hinder larger debris from entering the treatment plant. Following the coarse bar screens, the water is led to sand traps where inorganic particles that are heavy enough to sink, such as sand, are removed. The water then passes through finer bar screens which removes finer materials. In the next step, which is referred to primary sedimentation, the water reaches the primary settlers where particles settle and forms what is called primary sludge. The primary sludge, which is mixed with WAS from the secondary settlers is removed by scrapers and sent for further treatment and eventually ends up as dewatered sludge (Davidsson, 2020; Nunes et al., 2017).

Further treatment to remove organic matter and nitrogen occurs in the biological treatment step. To degrade organic matter, the biological treatment process utilizes heterotrophic bacteria which are present in the wastewater. The process of degrading organic matter is aerobic, which means that it requires the addition of oxygen to properly function, which is why specific zones are aerated to enhance/sustain the process of degradation. The nitrification process involves nitrifying bacteria which transforms ammonium, NH_4, to nitrite, NO_2^- and then nitrite to nitrate, NO_3^-, which subsequently is used by denitrifying bacteria in an anoxic process called denitrification. The denitrification process converts nitrate, NO_3^-, to nitric oxide, NO, a then to nitrous oxide, N_2O and finally to nitrogen gas, N_2, which is released back into the atmosphere.

There are zones which are not aerated to promote the growth of denitrifying bacteria, which, in the absence of oxygen uses the nitrate for oxidation (Davidsson, 2020; la Cour Jansen et al., 2019; Nunes et al., 2017). At the Rya WWTP, additional treatment of nitrogen takes place in trickling filters and Moving Bed Bio Reactors (MBBRs). Nitrification occurs in the trickling filters and one MBBR. Denitrification occurs in one MBBR and in the activated sludge (M. Neth, personal communication, 2021-05-28).

In the secondary settlers, the sludge that settles is returned to the activated sludge process and some of the activated sludge, so called Waste Activated Sludge (WAS) is returned to the primary settlers and mixed with the primary sludge. As mentioned, the mixed sludge is removed and sent for further sludge treatment. The final treatment of the wastewater is the removal of suspended particles using disc filters, as seen in Figure 2. The wastewater from both secondary settlers and MBBR denitrification passes the disc filters and finally, the treated water is released into the recipient. In Figure 2, two locations are marked as chemical treatment. In conjunction with the biological treatment, iron sulfate is added to precipitate phosphorus. The precipitated phosphorus becomes a part of the activated sludge. In the case of extreme hydraulic loading, polyaluminum chloride is used (after physical treatment), which causes direct precipitation. The wastewater is then bypassed to make sure that the tanks for activated sludge treatment are not overloaded (Davidsson, 2020; Nunes et al., 2017).

In the sludge treatment, see Figure 2, several steps take place which are not shown in the Figure. The sludge is first thickened by the addition of polymers and then sent to the anaerobic digestion chamber which is used to produce biogas. A substantial amount of the organic contents of the sludge is transformed to methane and carbon dioxide. After the anaerobic digestion, the sludge is dewatered in a screw press and the final product is called dewatered sludge. It should be mentioned that the Rya WWTP receives external loads of organic matter such as grease from industrial kitchens, which is added externally to the system, and becomes a part of the sludge. The dewatered sludge could potentially be used for agricultural purposes, assuming it fulfils the requirements of REVAQ certification system or the requirements for agricultural use (Davidsson, 2020; Nunes et al., 2017).

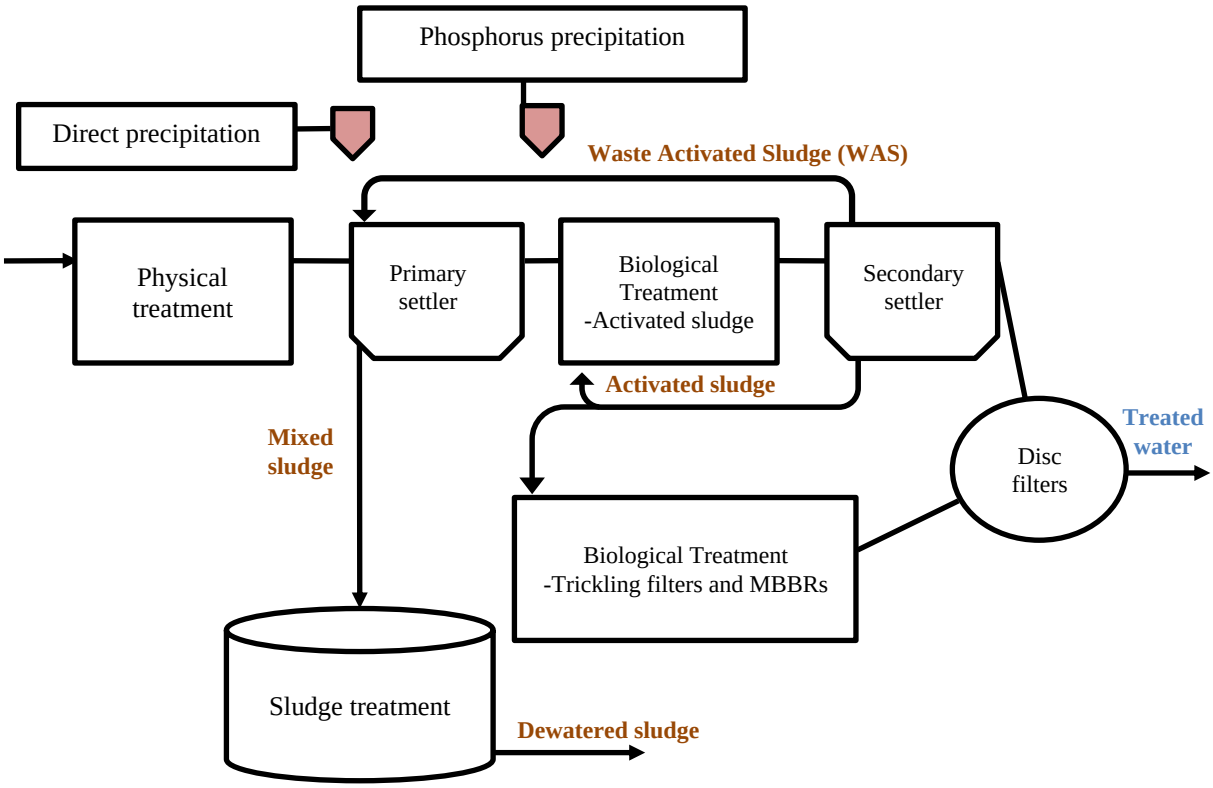

Figure 2. Simplified overview of the treatment process at Rya WWTP (Davidsson, 2019; Nunes et al., 2017).

2.1.2 Lackarebäck and Alelyckan sludge disposal

The description which follows are mainly based on Rambölls report (Rambøll, 2016) and information provided by Kajsa Engblom from Kretslopp och vatten, Göteborgs Stad (K. Engblom, personal communication, 2021-04-30), who has been assisting as an expert on the processes at Lackarebäck and Alelyckan.

At Alelyckan DWTP the system consists of six flocculation and sedimentation systems. The DW sludge that is produced is either removed by scrapers in the sedimentation tanks or released when the flocculation tanks are emptied and flushed. Four flocculation tanks with a volume of 750 m^3 are emptied every twelfth week. The subsequent sedimentation tanks, each with a volume of 1650 m^3 are emptied every fourth week. Two other flocculation tanks with a volume of 730 m^3 each are emptied around every 3,5 week. The subsequent sedimentation tanks, each with a volume of 1700 m^3 are flushed 15 times each year and scraped every fifth hour. The sludge which is emptied, flushed or scraped is transported to a balancing reservoir, if overflowed, releases some of its contents to the nearby storm water network. This means that some amount of the DW sludge, mostly the aqueous phase(K. Engblom, personal communication, 2021-06-21), is released to the Göta River and is not sent to the Rya WWTP for treatment.

The system at Lackarebäck DWTP consists of seven flocculation and sedimentation systems. The flocculation tanks are emptied 1,3 times every week and the sedimentation tanks are scraped 1,3 times every week. There is no balancing reservoir at Lackarebäck DWTP.

2.2 Literature review

2.2.1 Disposal and disposal methods

The disposal of DW sludge poses challenges economically, technically, socially and environmentally. The residues from water treatment could potentially be harmful to the environment, which consists of unwanted substances, e.g pathogens and chemicals used in the process of coagulation, mainly salts in the form of aluminum- or iron sulfate. Economic concerns arise when the sludge must be transported and properly disposed of and treated (Urban & Isaac, 2018). The methods for disposal of DW sludge includes, for instance, landfill disposal, water disposal, cement – and brick industries and treatment at a WWTP. The methods which are mentioned here are being used, or have been used by several European countries, and the methods which are used varies between each country. The most commonly used method among ten European countries which includes Sweden, is landfill disposal, based on data collected in the 1990s (Blomberg, 1999). The reason for using WWTPs for treating DW sludge are for instance, that some DWTPs are located in areas suffering from spatial constraints, which means that necessary space to build proper treatment facilities is lacking (Filho et al., 2013). By using the local sewer network to dispose of the DW sludge and allowing it to be treated in a WWTP, already existing treatment capacities are being used.

2.2.2 Utilization

The potential for using DW sludge to treat phosphorus in wastewater has been the subject of several studies (Mohammed & Rashid, 2012; Yang et al., 2006; Yang et al., 2009; Zhao et al., 2007). These studies have specifically focused on sludge produce by using aluminum salts, creating alum DW sludge. One reason being is that it potentially serves as sustainable option for chemically removing phosphorus in wastewater. The study by Zhao et al. (2007) considered three phosphorus compounds typically found in wastewater: orthophosphate, organic phosphate and polyphosphate, pointed to alum sludge as being a viable adsorbent for treating phosphorus in wastewater. Noticeably, adsorption appeared to vary among the three P species, orthophosphate being the one most prone to adsorption (Zhao et al., 2007).

2.2.3 Effects on WWTP processes

The effects of DW sludge on WWTP processes were studied in early bench-scale testing by Yan (1973) and pilot-scale testing by Salotto et al. (1973) and recent full-scale testing by Marguti et al. (2018). The study by Marguti et al. (2018) looked at the effects of DW sludge produced by the Rio Grande DWTP on different treatment processes at the ABC WWTP, in Brazil. The study conducted was a full-scale study which compared data from where DW sludge was not sent to the WWTP, to when the DW sludge was sent and treated at the WWTP. The ABC WWTP is an activated sludge treatment plant and the Rio Grande DWTP utilizes iron sulfate as a coagulant to reduce water turbidity. The study by Salotto et al. (1973) investigated the effects by setting up a pilot activated sludge WWTP. The local wastewater was accessed and pumped into the pilot WWTP, and the DW sludge from a treatment plant in Ohio, which used aluminum as a coagulant for reducing turbidity. A bench-scale study was conducted by Yan (1973), which used DW sludge that was laboratory made, and was to resemble the DW sludge produced as a result of using aluminum as a coagulant. The wastewater was collected from the various locations from the local sewer network and the Hanover Park WWTP in Chicago.

Similar results were obtained in all three studies. The addition of DW sludge both when iron sulfate or aluminum sulfate was used as a coagulant, had no alarmingly adverse effects on the overall treatment process. On the contrary, some positive effects were observed. Removal efficiency of organic matter, phosphorus and suspended solids in the primary settlers increased. Looking specifically at phosphorus removal, concentrations of phosphorus in primary settler effluents have been observed to be even lower with the addition of DW sludge containing ferric hydroxides, suggesting that DW sludge increases phosphorus removal (Marguti et al., 2018). Moreover, it seems that the addition of DW sludge has little impact on activated sludge processes as well, but rather enhances settling properties of the sludge in the secondary settlers. In addition, the main portion of the DW sludge is suspected to be removed in the primary settlers and that particles which are less prone to settling reaches the biological treatment and have potentially positive effects settling properties of activated sludge in the secondary settlers (Marguti et al., 2018; Salotto et al., 1973; Yan, 1973).

The effects of DW sludge on WWTPs processes are discussed by Blomberg and Eksvärd (1999). The discussion is based on prior studies conducted in the late 90s, among them the results from a full-scale project involving the Bromma WWTP, in the Stockholm region and a survey, which was sent to several larger DWTPs which were, at the time, treating their DW sludge at WWTPs. It is stated earlier that increased phosphorus removal could be expected, and that DW sludge potentially could be used in the chemical treatment of phosphorus at WWTPs. Based on experiences collected from the survey, the positive effects with regards to phosphorus reduction was ambiguous. The opinions on whether the DW sludge would reduce the need for precipitation chemicals being added at the WWTP, was inconclusive. Furthermore, the effects on anaerobic digestion could be of interest, since it have been suspected to have negative impacts on the anaerobic digestion and biogas production (Klint et al., 2015). However, it is concluded that based on the survey as well as the full-scale study, that neither positive or negative affects had been observed. Similarly, no negative effects on the dewatering of sludge that could be contributed to the DW sludge, were reported.

Studies which specifically involved the Rya WWTP were conducted by Graham-Jones (2014) and Klint et al. (2015). The study by Graham-Jones (2014) involved bench-scale laboratory work to investigate the potential effects of DW sludge from Lackarebäck and Aleyckan. The results pointed to a potentially increase in phosphorus removal in the primary treatment. Moreover, it was noticed that the settling of solids in the primary settlers could increase to some extent. However, in the secondary settlers, the results pointed to that the secondary settling could be affected negatively. This contradicts previous statements about positive effects on settling properties of activated sludge in the secondary settlers. Further attempts to investigate the effects of DW sludge from Lackarebäck and Alelyckan on the activated sludge were made by Klint et al. (2015). Although, the results were inconclusive. In addition, the potential effect of DW sludge on dewatered was also investigated. The results suggested that the necessary time to dewater the sludge, would increase by the addition of DW sludge.

The literature review suggests the effects of DW sludge on WWTP processes are ambiguous. The study by Graham-Jones (2014) suggested that the DW sludge has negative effects on activated sludge settling properties at the Rya WWTP. However, if the DW sludge is removed in the primary settlers and does not reach the biological treatment, it will most likely not affect the activated sludge. Therefore, the knowledge about to what extent the DW sludge is removed in the primary settlers, could hopefully assist future decisions and research.

3 Methodology

The following chapter provides detailed descriptions of the methodology.

3.1 Method overview

The DW sludge contains a variety of metals, some of which are unique or typical for DW sludge (M. Neth, personal communication, 2021-12-16). For instance, because of the usage of aluminum sulfate as a coagulant at Lackarebäck and Alelyckan, aluminum can be found in very high concentrations compared to the WW sludge. Note that when the wastewater reaches the Rya WWTP the DW sludge and WW sludge are mixed together, but contributes differently to the total metal composition in the incoming wastewater. The idea was to screen for as many metals as possible, and then use the metals which stands out in the DW sludge out as indicator substances. Moreover, some metals are less typical of DW sludge and are found in negligible concentrations, which means that the contribution from those metals are mainly from WW sludge. By measuring the concentrations of the metals at different locations at Rya WWTP and in the DW sludge from Lackarebäck and Alelyckan, it was possible to calculate the mass flow of metals and subsequently set up mass balances. The mass balances were used as a means of confirming the accuracy of the mass flows. The mass flow of metals for which the fraction of DW sludge is significant could then be compared to the mass flow of metals for which the fraction of DW sludge is less significant. One of the main approaches to determine the fate of the DW sludge was to express all mass flows as quotients of the incoming mass flow. Subsequently, any deviations in quotients of metals for which the fraction of DW sludge is significant, were investigated. Finally, by using metals for which the DW fraction is insignificant and significant, and where mass balances were deemed approximately accurate, two simulations was conducted. Detailed descriptions of the methods are described in Sections 3.8 and 3.9. Phosphorus concentrations were also analyzed at external laboratories for each sample, from which mass flows were calculated and mass balances used as validation.

3.2 Samples and sampling locations

In Figure 3, a simplified treatment process schedule is shown along with five sampling locations, from which samples were collected for laboratory analysis: (1) Incoming wastewater, (2) primary sludge including WAS, which will be referred to as mixed sludge, (3) primary sludge excluding WAS, which will be referred to as primary sludge (4) WAS and (5) dewatered sludge. At the Rya WWTP, as seen in Figure 3, WAS is transported from the secondary settlers to the primary settlers, mixing the primary sludge and WAS, creating the mixed sludge. To get a sample of sludge coming from only the incoming wastewater the WAS was turned off for one of the primary settlers. In addition, DW sludge samples from both Alelyckan and Lackarebäck were delivered to the WET laboratory for analysis, and cannot be marked in Figure 3.

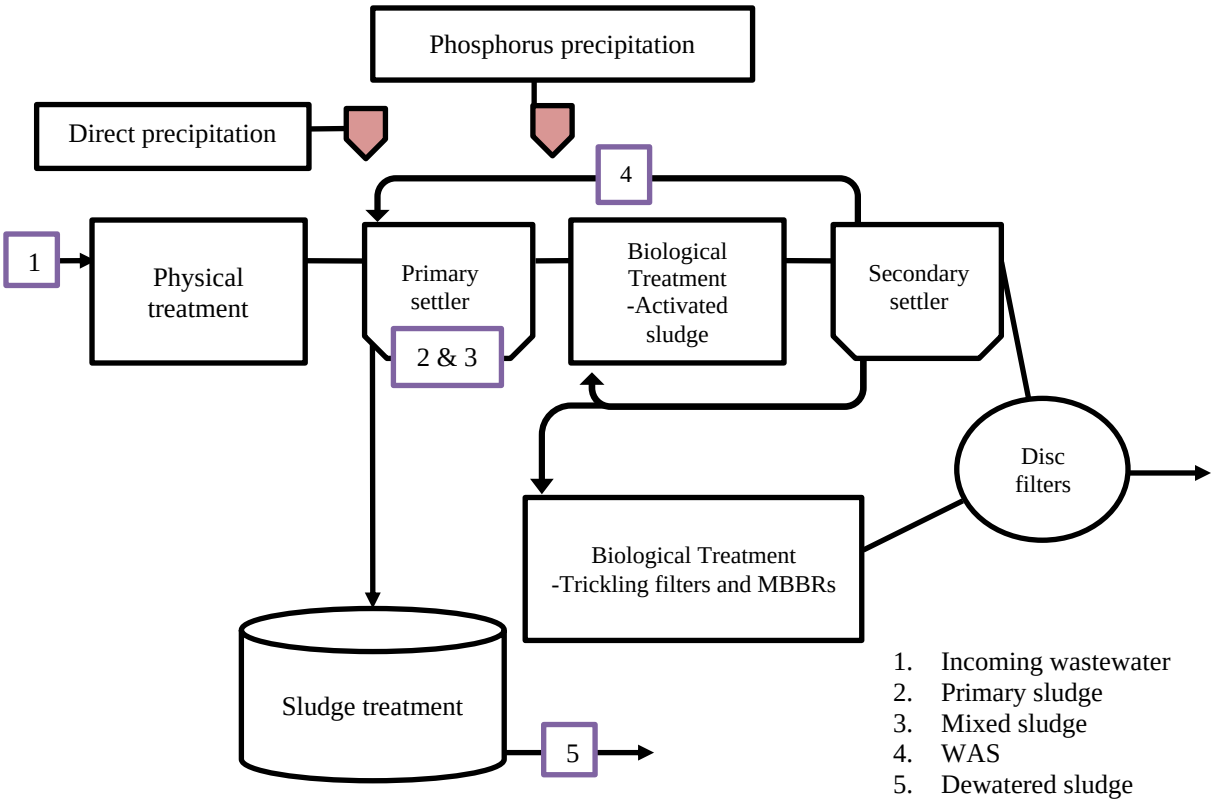

Figure 3. A simplified process schedule including sample locations (Davidsson, 2019; Nunes et al., 2017).

3.3 Indicator substances

The decision on which metals to analyze was based on prior work (M. Neth, personal communication, 2021-12-16), where one analysis for dewatered sludge and DW sludge had been conducted. In this thesis, the fraction of the mass flow of metals which are typical for DW sludge would be significantly higher in the incoming wastewater compared to other metals. Therefore, the fraction of the mass flow in the incoming wastewater was used as basis for determining which metals were significant of the DW sludge.

The metals possible to analyze in the laboratory were discussed with the expert who was going to run the ICP-MS, and a decision was made to analyze for as many metals possible using the ICP-MS at the WET laboratory. The metals which were analyzed can been seen in Table 1. The results produced by the ICP-MS was evaluated by the expert running it. When the ICP-MS is running samples, if the samples contain particles such as salts, it might affect the analysis. Too great deviations might render a sample unreliable (S. Rauch, personal communication). When the results were provided by the expert, information on about which results could be used for further analysis was included. Sodium (Na), Potassium (K) and Silicon (Si) was deemed unreliable and therefore not considered in further calculations or analyses.

*Table 1. Metals which were analyzed in the ICP-MS. Metals marked * were analyzed using ICP-MS but the results were considered unreliable.*

Chemical symbol	**Name of metal**
Al	Aluminum
As	Arsenic
Ca	Calcium

Cd	Cadmium
Ce	Cerium
Co	Cobalt
Cr	Chromium
Cu	Copper
Fe	Iron
K*	Potassium*
Li	Lithium
Mg	Magnesium
Mn	Manganese
Mo	Molybdenum
Na*	Sodium*
Ni	Nickel
Pb	Lead
Sb	Antimony
Si*	Silicon*
Sn	Tin
Ti	Titanium
V	Cerium
Zn	Lead

3.4 Analyses time frame, sample size and storage

Extensive laboratory work was carried out during a period of around 8 weeks, two of which were dedicated to trial and error, practicing the different methods and refine them if needed. The time of three weeks was set to provide an ample number of samples. One sample from each location in Figure 3, (1) incoming wastewater, (2) mixed sludge, (3) WAS (4) primary sludge and (5) dewatered sludge, would arrive Monday to Friday for a period of three weeks, February 22nd to March 12th. Once a week, two DW sludge samples, one from Lackarebäck and one from Alelyckan was delivered by Gryaab staff. The specific delivery dates for the DW sludge were February 23rd, March 2nd and March 9th. The samples from the Rya WWTP were collected by the staff and delivered to the WET laboratory that same day. The total number of samples was 81, where 75 came from the Rya WWTP (locations 1-5) plus 6 DW sludge samples from Lackarebäck and Alelyckan.

The samples were stored in plastic containers, temporarily, in a fridge set at 7.5 ℃ available at Chalmers WET lab. Information provided by staff at Rya WWTP (M. Neth, Personal Communication, 2021-02-24), stated that sludge samples could be stored one month in a fridge at 5 ℃. However, it was assumed that 7.5 ℃ would suffice and that storage for longer periods would not affect the result, meaning that the content of metals would be unaffected. The same assumptions were made for the DW sludge, which was stored under the same conditions.

3.5 Equipment, materials and chemicals

The following sections describe important equipment, materials and chemicals which were used when working in the WET laboratory at Chalmers.

3.5.1 Centrifuge

A centrifuge was used to reduce the water content of all liquid sludge samples and to separate solids from the water phase.

3.5.2 Oven

Samples were dried at 105 ℃ in ovens available in the Chalmers WET laboratory overnight, which usually meant that samples were dried for approximately 20 hours. Communication with staff at Rya WWTP (M. Neth, personal communication, 2021-02-22), revealed that 4 hours could be enough to remove all the water. However, the size of the samples was assumed to be smaller than the ones used in this analysis, hence, by drying over night for approximately 20 hours would guarantee completely dry samples.

3.5.3 Furnace

Samples were burnt at approximately 550 ℃ in a furnace for approximately 20 minutes. It appeared that the samples would rapidly increase the temperature in the furnace. To avoid any unexpected adverse effects, like damaging the heat sensor, samples were burnt in smaller batches. Bigger batches were sometimes placed in the furnace while it was turned off. By turning on the furnace and allowing the temperature to rise slowly, temperature spiking was avoided to some extent.

3.5.4 Acid digestion

To extract the metals, acid digestion was used. In the study by Klint et al. (2015), nitric acid, $HNO_3$was used to extract metals. The same decision was made for this thesis, and concentrated nitric acid (65 %) was used. Samples were then heated, using Milestone Ethos Easy digestion system available at the WET laboratory. The Microwave was set to run the Bottom Ash Leaching program, which meant that the samples were heated for 15 minutes until reaching 120 ℃, and then heated for another 10 minutes at 120 ℃.

3.5.5 ICP-MS

The final metal concentrations were analyzed using Inductively Coupled Plasma Mass Spectrometry (ICP-MS) which was run by an expert at CTH.

3.5.6 External analysis and phosphorus

Samples were collected at Rya WWTP by Gryaab staff and transported to Chalmers WET laboratory. A copy of each sample was also sent to Eurofins, where the sludge was analyzed for total phosphorus and total solids (TS). Therefore, TS was measured at both Chalmers WET laboratory and at Eurofins, thus providing results for comparison. The DW sludge was sent to two external laboratories for analysis of phosphorus and TS, Eurofins and Synlab. The samples from February 23rd were sent to Eurofins for analysis of TS and phosphorus concentrations but also to get one screening of metal concentrations, which means that metal concentrations were analyzed both at Chalmers and Eurofins for the two samples which were collected on February 23rd.

3.6 Sample preparations and analyses

These sections give detailed descriptions of sample preparation and analyses.

3.6.1 Incoming wastewater

The incoming wastewater would arrive in a plastic container from where 1 L would be used for laboratory analysis. The incoming wastewater consists of the untreated WW sludge as well as DW sludge from the two DWTPs. When reaching the primary settlers at Rya WWTP, the wastewater is left to settle, separating particles which settle from the ones which do not, and as a way of simulating the primary sedimentation process at Rya WTP, a container was filled with 1 L of incoming wastewater and left to settle until a clear separation of particles was visible. A photograph showing the separation can be viewed in Appendix A, Figure A1. Following the latter, a substantial amount of the liquid containing non-settled particles was removed, approximately 850 ml. Subsequently, 300 ml out of the 850 ml was collected into six tubes, 50 ml in each tube. The tubes containing the non-settled particles were centrifuged at 4000 Relative Centrifuge Force (RCF), for 7 minutes, separating the particles from the liquid.

The volume of the remainder of the incoming wastewater would be approximately 150 ml including the settled particles. However, this would vary because difficulties in pouring the liquid between different vessels. Because of the small fraction of suspended particles left in the 150 ml, the fraction of settled particles was assumed to be dominant and therefore assumed to be representative of the settled particles. The contents of the container were gently stirred to ensure proper mixing of the settled particles and then poured into three tubes and then centrifuged at 4000 RCF. The non-settled and the settled particles were collected from the tubes after being centrifuged. The small fractions which had been collected at the bottom of the tubes were mixed either with deionized water to make it suitable for pouring or, in most cases, some amount of the water was not removed, and used for the same purpose. The contents of the tubes were then poured into two separate glass bowls, one for each sample. The samples were then dried at 105℃ for approximately 20 hours and subsequently burnt at 550 ℃ for approximately 20 minutes.

The amount of ashes which is suitable for ICP-MS was determined to be 0.5 g (S. Rauch, Personal communication). However, because of the extremely low content of settled particles and non-settled particles available, much less was used in this experiment.

3.6.2 Primary sludge, mixed sludge and WAS

The primary sludge, mixed sludge and the WAS were prepared in the same manner. The volume of sludge required would vary as the thickness of the sludge, i.e, the water contents would vary. The container of the sample was turned upside down for several times to make sure that its contents were properly mixed. The sample was then poured into tubes, approximately 50 ml in each tube. As mentioned earlier, the aim was to produce around 0.5 g of ashes. After the first few results it was possible to determine the required volume of sludge to produce 0.5 g of ashes. Even though it varied among the samples, it typically ranged from 150 ml to 300 ml. The samples were then centrifuged at 4000 RCF for seven minutes. The liquid phase was removed and samples scraped into glass bowls which would then be dried at 105 ℃ for 20 hours and subsequently burn at 550 ℃ for approximately 20 minutes.

3.6.3 DW Sludge

As mentioned, once a week the DW sludge from Alelyckan and Lackarebäck would arrive. The sludge would be prepared in the same way as the sludge from the Rya WWTP in Section 3.6.2.

3.6.4 Dewatered sludge

The characteristics of the dewatered sludge differed greatly from the wet sludge as it had been treated and dewatered, hence, it was quite dry in comparison as it arrived at the laboratory. Therefore, the preparation required little effort and the sludge could be transferred to a glass bowl by using a plastic spoon. To reach around 0.5 g of ashes, roughly 4-5 g of dewatered sludge was needed. As for the other samples, the dewatered sludge was dried at 105 ℃ for 20 hours and then burnt at 550 ℃ for approximately 20 minutes.

3.6.5 Microwave digestion

The ashes from each sample were either poured or scooped using a plastic spoon into microwave digestion tubes. The amount of ashes added was carefully noted by weighing an empty small plastic cup, with and without the ashes. Afterwards, 5 ml of the concentrated nitric acid was added to each sample. The tubes were thoroughly sealed by tightening the caps properly, to avoid any toxic gas from leaking while running the microwave. The microwave was set to run the bottom ash leaching program which would run the samples for a total of 25 minutes, 15 minutes to reach a maximum temperature of 120 ℃, and then at 120 ℃ for 10 minutes. After the digestion was complete, the samples were left to cool down, preferably a couple of hours, and sometimes overnight, after which the samples were poured into smaller tubes.

3.6.6 Dilution and ICP MS

To run samples in the ICP-MS, each sample had to be diluted using an appropriate dilution factor. The ICP-MS provides results in the unit of parts per billion (PPB), or $\mu g/l$. The ICP-MS was calibrated to run samples to a maximum concentration of 1000-2000 $\mu g/l$. A trial run early in the laboratory work process using a dilution factor of 100, suggested that some concentrations of certain metals, for instance, aluminum were in the order of magnitude 10^5 $\mu g/l$. This meant that the samples would most likely require a higher level of dilution to account for samples with higher concentrations of certain metals. To ensure that both lower and higher concentrations were accounted for, the samples were diluted twice using different dilution factors. Firstly, to run a sample in the ICP-MS it had to be around 1 % acid, in this case nitric acid, which was used for the digestion. The first level of dilution was set to 100. An amount of tubes corresponding to the number of samples were filled with 9.9 ml of milli-Q water and then 0.1 ml of the sample. The second batch was decided to be diluted 20 000 times but ended up being diluted 20 100 for practical reasons. A fresh batch of tubes were filled with 10 ml of milli-Q water mixed with acid to ensure the concentration of acid was around 1 %. Subsequently, 0.05 ml from each sample in the first batch, containing samples diluted 100 times, was added. The results obtained from the ICP-MS analyses would consist of two concentrations of each sample, one stemming from the batch with the lower dilution factor of 100 and one from the one using a factor of 20 100.

3.7 Calculations

The following subsection provides details about calculations conducted.

3.7.1 TS – total solids

For each sample the total solids, TS, was calculated. The amount of total solids, TS, in the sludge refers to the percentage of or total solids in the wet sludge, which were obtained after drying the sample at 105 ℃, also referred to as dry matter (SUEZ, n.d). The TS for the primary sludge, mixed sludge, WAS and DW sludge was calculated the as weight of the dry sample divided by the volume of the wet sludge sample. The final unit is then $\frac{g}{ml}$, however, TS is usually expressed as [%]. For the dewatered sludge, the TS was calculated using dry weight divided by the weight of the sample before drying, obtaining the unit [g/g], but expressed as [%] (O. Modin, personal communication). For all samples expect incoming wastewater, TS was measured at the external laboratories which the samples were sent to, not requiring any calculations. In addition, TS is measured regularly at Gryaab as well. Therefore, TS was measured for mixed sludge, WAS and dewatered sludge at three different laboratories, WET, Eurofins and Gryyab. In the case of DW sludge, it was measured at the WET laboratory, Eurofins and Synlab.

The TS for WAS which was measured by Eurofins was considered unreliable. Some values were very different from the ones measured at the WET laboratory and by Gryaab. Morover, some values were deviating from the mean value almost two times the standard deviation. See Appendix D, Table D2, which summarizes all values for TS, and Section 4.1, which presents all the mean values and standard deviations. The TS for WAS measured by Gryaab was considered the most accurate based on Gryyab staff experience (M. Neth, personal communication, 2021-03-25). Therefore, the choice to use TS measured by Gryyab as much as possible was made. It should be noted that the Rya WWTP measures TSS in the WAS and the TSS was used as TS. Since Gryaab does not measure TS for primary sludge and DW sludge, the results from the WET laboratory was used instead.

3.7.2 Concentration of metals and phosphorus

The concentration of phosphorus was not calculated, but all samples were analyzed at external laboratories and provided in the unit of $\frac{mg\ P}{kg\ TS}$. In the case of incoming wastewater and effluent water, concentrations of phosphorus in kg/m^3 were used for calculations, and obtained from Gryaab (see Appendix C, Table C1).

The results obtained from the ICP-MS analysis was in the unit of μg/l. But calculations to obtain the unit $\frac{mg\ metal}{kg\ TS}$, were conducted. The same method was applied to all samples.

The first step was to calculate how many grams of metal were in the sample before dilution. The following equation was used:

$$\frac{concentration\ of\ metal\ in\ sample\ \times\ diution\ factor\ \times\ acid\ added}{10^6} \quad (1)$$

where,

- the $concentration\ of\ metal\ in\ sample$ refers to the sample which was analyzed in the ICP-MS in μg/l
- the $diution\ factor$ represents how much the sample was diluted before analyzed in the ICP-MS
- and $acid\ added$ is the volume of nitric acid which was added before microwave digestion in ml.

The second step was then to use the fact that the amount of ashes which had been transferred to the sample before microwave digestion was known, as well as the total amount ashes obtained from burning a specific amount of dry matter, to obtain how many grams of metal were in the total amount of ashes produced. The amount of ashes transferred was sometimes less than the total amount produced. Both were necessary for performing the calculations. The second equation used was as follows:

$$\frac{(1)}{ashes\ added} \times total\ ashes \tag{2}$$

where,

- $ashes\ added$ represent the amount of ashes added to the sample before microwave digestion in g
- and $total\ ashes$ represent the amount of ashes which was produced from burning a specific amount of TS, dry matter, in g.

The third and final step aimed at converting the results from eq. (2), using the fact that the amount of TS, dry matter used, to produce the total amount of ashes was known, thus obtaining the unit $\frac{mg\ metal}{kg\ TS}$, for each sample.

$$\frac{(2) \times 1000}{weight_{TS}} \tag{3}$$

where,

- $weight_{TS}$ is the amount of TS, dry matter, burnt to produce the total amount of ashes, in g.

3.8 Mass flow

As a part of determining the fate of the DW sludge, the flow of mass for all metals and phosphorus was calculated in the incoming wastewater, DW sludge, primary sludge, mixed sludge and dewatered sludge. The mass flow was calculated for each date, a total of 15 days, separately, from which the mean mass flow was used for final analysis and discussion. Measurements of flow was not conducted as a part of this thesis, but made available by supervisor Maria Neth, since Gryaab measures flows and other quality parameters on a regular

basis (see Appendix B, Table B1). During 11th and 12th of March, the incoming flow approximately twice as high compared to the other days, 7.4 m^3 and 7.5 m^3 respectively, and was therefore not included in calculations of mean values. The flow of DW sludge from Alelyckan and Lackarebäck had to be estimated and the methodology is elaborated on in Section 3.8.5. To make the mass flows easier to analyze and to easily comparable, all flows were also calculated as quotients of the mass flows of incoming wastewater. The incoming mass flows were then equal to 1.0, and other flows could be compared relative to the incoming mass flows.

Figure 4 shows a schematic and simplified overview of the mass flows considered. It should be noted that mass flows in the effluent were only calculated for phosphorus since metal concentrations were not analyzed for the effluent water, contrary total phosphorus, which is regularly measured by Gryaab (see Appendix C, Table C1).

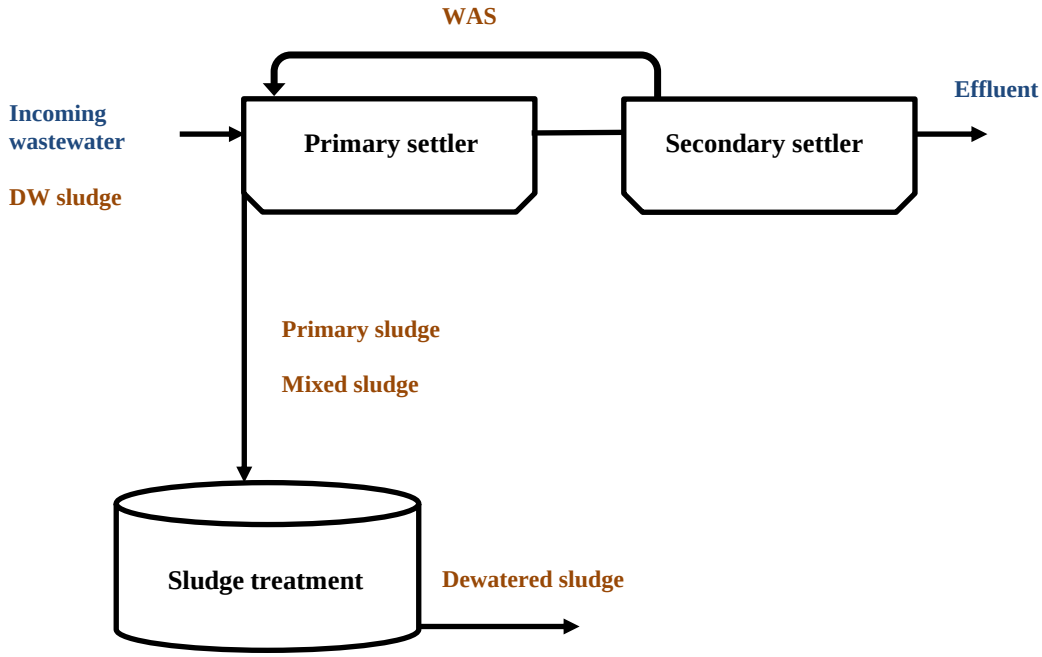

Figure 4. A simplified overview of chosen mass flows (Davidsson, 2019; Nunes et al., 2017).

3.8.1 Calculations of mass flow of primary sludge, mixed sludge, WAS and DW sludge

The mass flows in kg/day of phosphorus and all metals in the DW sludge, primary sludge mixed sludge and WAS were calculated using the following equation:

$$Flow_{sludge} \times TS_{sludge} \times \frac{Concentration_{metal\ or\ phosphorus}}{10^6} \quad (4)$$

Where,

- $Flow_{sludge}$ represents the flow of sludge in l/day,

- TS_{sludge} represents the TS of sludge in $\frac{\%}{100}$
- and $Concentration_{metal\ or\ phosphorus}$ represents the concentration of metal calculated in Section 3.7.2, the final of results of (3), or the phosphorus concentration measured at external laboratories, in $\frac{mg\ metal\ or\ phosphorus}{kg\ TS}$.

The flow of primary sludge is not measured by Gryaab since the WAS is usually not turned off for any of the primary settlers. The flow of primary sludge was assumed to be the same as for the mixed sludge.

3.8.2 Mass flow in dewatered sludge

The mass flows in the dewatered sludge were based on the metal and phosphorus concentrations in mg/kg TS, the TS and the flow of dewatered sludge. However, the dewatered sludge is measured in accumulation of sludge in kg or ton. The daily accumulation of dewatered sludge from February 22nd to March 12th, was provided since it is monitored by Gryaab, see Appendix B, Table B1. The following equation was used to calculate the flow of mass in the dewatered sludge:

$$\frac{accumulated\ dewatered\ sludge\ \times\ TS_{sludge}\ \times\ Concentration_{metal\ or\ phosphorus}}{10^6} \quad (5)$$

where,

- $accumulated\ dewatered\ sludge$ refers to the dewatered sludge accumulated every day in kg/day,
- TS_{sludge} refers to the TS, dry matter, of the dewatered sludge in $\frac{\%}{100}$ and
- $Concentration_{metal\ or\ phosphorus}$ refers to the concentration of metal or phosphorus in the dewatered sludge in $\frac{mg}{kg\ TS}$.

3.8.3 Mass flow of metals and in incoming wastewater

The methodology for calculating mass flows in the incoming wastewater was quite different from the one in Section 3.8.1. As mentioned earlier, the flow of incoming wastewater was made available, see Appendix B, Table B1, and used to determine the mass flow in the incoming wastewater. The laboratory analysis conducted measured concentration of metals in settled particles and non-settled particles, as well as TS. However, it would be inaccurate to use the relationship of flow multiplied by TS multiplied by the concentration in mg/kg TS, as done for samples in Section 3.8.1. Since the concentration of metals for both settled particles and non-settled were based on 1 L of the incoming wastewater, it was possible express the concentration of metals as kg/l, or kg/m3.

To calculate the concentration of metals in the volume of liquid which contained mostly settled particles, the following equation was used:

$$Concentration_{metal}\ \times\ weight_{TS} \quad (6)$$

where,

- $Concentration_{metal}$ represents the concentration of metal calculated in Section 3.7.2, the final of results of (3), in $\frac{mg\ metal}{kg\ TS}$,
- $weight_{TS}$ is the actual amount of dry matter, before burning, to produce the total amount of ashes, in kg. More specifically, kg TS/volume of settled particles before drying, which varied a somewhat. But the calculation was made for each separate sample.

For non-settled particles, the following equation was used to calculate the concentration of metals in the total volume which did not contain any settled particles (total volume of sample minus volume of settled particles).

$$Concentration_{metal} \times weight_{TS} \times \frac{tot.vol\ non\ settled}{vol.non\ settled\ analysis} \quad (7)$$

- where $Concentration_{metal}$ represents the concentration of metal calculated in 3.7.2, the final of results of (3), in $\frac{mg\ metal}{kg\ TS}$.
- $weight_{TS}$, the actual amount of TS which was burnt to produce the total amount of ashes in kg,
- $tot.vol\ non\ settled$ represents the total volume of the non-settled particles, in ml.
- and $tot.vol\ non\ settled\ analysis$ refers to the volume of non-settled particles used for the laboratory analysis, in ml.

The mass flow was finally calculated as follows:

$$\frac{Flow_{IN} \times Concentration_{In}}{1000} \quad (8)$$

Where,

- $Flow_{IN}$ is the flow of the incoming wastewater in m^3/day
- $Concentration_{In}$ is the concentration of metals in mg/l, the sum of (6) and (7).

3.8.4 Mass flow of phosphorus in incoming wastewater and effluent water

The mass flow of phosphorus was calculated using the incoming flow of wastewater and the concentrations of total phosphorus in the incoming and effluent wastewater. Concentrations of phosphorus can be found in Appendix C, Table C1, and flow of incoming wastewater, Appendix B, Table B1. The effluent flow was assumed to be the same as for the incoming wastewater.

The mass flow of phosphorus in the incoming wastewater was calculated as follows:

$$Concentration_{In} \times Flow_{IN} \quad (9)$$

where,

- $Concentration_{In}$, is the concentration of phosphorus in the incoming wastewater in kg/m^3 and

- $Flow_{IN}$ is the flow of the incoming wastewater in m^3/day.

The mass flow of phosphorus in the effluent wastewater was calculated as follows:

$$Concentration_{effluent} \times Flow_{effluent} \quad (10)$$

where,

- $Concentration_{effluent}$, is the concentration of phosphorus in the effluent water in kg/day and
- $Flow_{effluent}$ is the flow of the incoming wastewater in m^3/day, and $Flow_{effluent} = Flow_{IN}$.

3.8.5 Determining the flow of DW sludge into to Rya WWTP

The estimation of flow of DW sludge from the two DWTPs Lackarebäck and Alelyckan, would require some assumptions and calculations.

As mentioned in 2.4.2, the disposal of DW sludge occurs through different processes. The DW sludge which is disposed of by scraping the sedimentation tanks, was assumed to be representative of the samples which were analyzed in the laboratory. The DW sludge which is released by flushing or by emptying the flocculation tanks is diluted and contains more water than the actual samples analyzed in the laboratory. Therefore, an estimation that when the sludge is either flushed or a tank is emptied, 30 % of the volume is representative of the DW sludge which was analyzed in the laboratory and the remaining 70 % is water (K. Engblom, personal communication, 2021-04-30). The way DW sludge is released from the two DWTPs differs to some extent and therefore, calculations were made separately for both DWTPs. Calculations were kept separate until the very end, when the flow of mass from both DWTPs was added to represent the total flow of mass into Rya WTP. Any differences in characteristics between the two were not accounted for.

In the case of Lackarebäck, the total volume of sludge which was disposed of during February this year, amounted to 19193 m^3, and in March 23128 m^3 (K. Engblom, personal communication, 2021-04-30). A mean value of 21160.5 m^3/month was used as a representative value of the volume. As described in chapter 2.4.2, the method for disposal at Lackarebäck involves both scraping the sludge in the sedimentation tanks as well as emptying flocculation tanks. The total volume provided is the sum of both scraped sludge and emptied sludge, hence, it does not consider the fact that the sludge from the flocculation tanks is diluted with water. Based on prior calculations by Rambøll, made available (K. Engblom, personal communication, 2021-04-30) roughly 23 % of the sludge was emptied from flocculation tanks and 77 % removed using scrapers in the sedimentation tanks. The same distribution was assumed for the

mean volume value of 21160.5 m^3/month and the fraction of 23 % was assumed to be diluted. Therefore, for that specific fraction to be representative of the sample analyzed in the laboratory, 30 % of the volume was used for calculations.

At Alelyckan, information on the actual emptying and flushing of systems was made available (K. Engblom, personal communication, 2021-05-18) which included a detailed schedule on weekly disposals. Based on the schedule, during the three weeks of sampling, sedimentation tanks with a volume of 1650 m^3 was flushed and emptied three times, and at one occasion a flocculation tank with a volume of 750 m^3 was emptied. In addition, continuous removal of sludge in the sedimentation tanks using scrapers, every fifth hour, was included in the calculations. As for Lackarebäck, 30 % of the volume from emptying and flushing was assumed representative of the DW sludge analyzed in the laboratory. The balancing reservoir was not accounted for because of difficulties estimating the fraction of DW sludge in the surcharged water.

The final flows from both DWTPs can be viewed in Appendix B, Table B1.

3.8.6 Mass balances

Mass balances were used as a way of validating the mass flows. It was assumed that by considering the mean values for all mass flows, a representative mass balance could be set up. The mass balance considered only measured values, and included the mass flows which are shown in Figure 4 above.

The following assumption was made for the mass flow of phosphorus:

$$Mass_{IN\ P} = Mass_{effluent\ P} + Mass_{mixed\ sludge\ P} \tag{11}$$

where,

- $Mass_{IN\ P}$ is the mass flow of phosphorus in the incoming wastewater in kg/day,
- $Mass_{effluent\ P}$, is the mass flow of phosphorus in the effluent water in kg/day and
- $Mass_{mixed\ sludge\ P}$, is the mass flow of phosphorus in the mixed sludge.

The following assumption were made for the mass flow of metals:

$$Mass_{IN\ metal} = Mass_{mixed\ sludge\ metal} \tag{12}$$

- $Mass_{IN\ metal}$ is the mass flow of metals in the incoming wastewater in kg/day,
- $Mass_{mixed\ sludge\ metal}$ is the mass flow of metals in the dewatered sludge in kg/day.

No analyses of metal concentrations in the effluent was conducted, and therefore not included in the mass balance. However, it was assumed that the fraction of metals in the effluent would be small, 10 % of the fraction in the incoming wastewater (A. Mattson, personal communication, 2021-05-20). Therefore, (12) was deemed fairly accurate.

Also, it was assumed the following for both metals and phosphorus that:

$$Mass_{mixed\ sludge=}\ Mass_{primary\ sludge} + Mass_{WAS} \tag{13}$$

where,

- $Mass_{mixed\ sludge}$ is the mass flow of either phosphours or metals in the mixed sludge in kg/day,
- $Mass_{\ primary\ sludge}$ is the flow of either phosphorus or metals in the primary sludge in kg/day
- and $Mass_{WAS}$ is the flow of either phosphorus or metals in the WAS in kg/day.

3.9 Simulations

The final step towards an actual estimation of the percentage of DW sludge which is removed in the primary settlers, was made by performing two different simulations.

3.9.1 Simulation 1

The first simulation conducted included different scenarios. Each Scenario would represent a specific removal percentage of DW sludge in the primary settlers. The first step was to choose metals for which the mass balance was roughly accurate. In other words, metals where:

$$Mass_{IN\ metal} \approx Mass_{mixed\ sludge\ metal} \tag{14}$$

The second step involved choosing the metals which were typically found in high concentrations in DW sludge, where the fraction in the incoming wastewater was significant, approximately 40 % in this case, as well metals where the fraction of the DW sludge was insignificant, 6 % or lower in this case. It was assumed that by looking at mass flow of metals where the fraction of DW sludge is insignificant, the removal of those metals in the primary sludge, was representative of the WW sludge. Therefore, by assuming the same level of removal of WW sludge for metals where the fraction of DW sludge is significant, it was possible to determine the fraction of DW sludge removed in the primary sludge. Different removal percentages for DW sludge were tested and then compared to the measured values of mass flow in the primary sludge for significant metals, which made it possible to approximately determine a percentage removal of DW sludge. It should be clarified that:

$$WW\ sludge\ mass\ flow = total\ mass\ flow\ incoming\ wastewater - DW\ mass\ flow$$

The following equation was used:

$$Mass_{WW\ sludge} \times fraction_{insignificant} + Mass_{DW} \times fraction_{significant} = Mass_{Primary\ sludge\ metal} \tag{15}$$

where,

- $Mass_{ww\ sludge}$ is the mass flow of metals in the WW sludge in kg/day,
- $Mass_{DW}$ is the mass flow of DW in the incoming wastewater in kg/day,
- $fraction_{insignificant}$ is the mean value of the fraction of the mass flow in the mixed sludge, for insignificant metals in $\frac{\%}{100}$,
- $fraction_{significant}$ is the fraction which is assumed as removal percentage for the DW sludge and

- $Mass_{primary\ sludge\ metal}$ is the mass flow of metals in the primary sludge in kg/day.

Looking at equation (15), if $Mass_{DW}$ is small, which is the case for the metals where the fraction of DW sludge is insignificant, then an increase in $fraction_{significant}$ would not cause a significant overall increase. However, if the case was to be the opposite, and the fraction of $Mass_{DW}$ is significant, an increase in $fraction_{significant}$ would lead to a noticeable increase. By starting at 0 % of $fraction_{significant}$, and gradually increasing it, metals for which the fraction of DW sludge is significant should approach the measured value.

Each scenario was also tested using a different mass flow of DW sludge in the incoming wastewater. As mentioned in Section 3.8.5, the estimation of DW sludge flow into the Rya WWTP required some assumptions regarding sludge volume. A reduction and an increase of 30 % of the flow of the DW sludge was tested along with the scenarios. It should be noted, that by changing the DW sludge flow, the fraction of the DW sludge in the incoming wastewater changes.

3.9.2 Simulation 2

In the second simulation, the same approach was used as in the first simulation. However, instead of using the calculated values of the mass flow in the incoming wastewater, the mass flow of the incoming wastewater was calculated as $Mass_{IN\ metal} = Mass_{primary\ sludge} + Mass_{WAS}$, based on equations (12) and (13).

4 Results and Discussion

This chapter presents and discusses the results which were obtained from laboratory work and calculations.

4.1 TS – Total solids

In Table 2, mean values and standard deviations of TS which were calculated in the CTH WET laboratory, external laboratories EUROFINS and SYNLAB, and Gryaab, are shown. Note that Synlab only analyzed samples from Alelyckan and Lackarebäck. The cells which are marked yellow are the laboratories' TS values which were used for calculations of mass flows. The number of samples used for mean values and standard deviations of primary sludge, mixed sludge, WAS and dewatered sludge were, in all cases, 13, leaving out the 11th and 12th of March. For Lackarebäck and Alelyckan, the results from the WET laboratory includes three samples, one samples from Eurofins and two samples from Synlab.

Table 2. Mean values of TS for all analyses. Cells marked [-], means that no value of TS was measured or available, or that calculations could not be carried out. Cells marked yellow are the values of TS which were used in further calculations of mass balances.

Sample	**Laboratory**							
	WET [%]		Eurofins [%]		Synlab [%]		Gryaab [%]	
	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
Primary sludge	1.7	0.44	2.1	0.84	-	-	-	-
Mixed sludge	2.5	0.55	2.4	0.72	-	-	2.5	0.36

WAS	0.84	0.12	0.91	0.77	-	-	1.2	0.07
Dewatered sludge	30	1.2	29	0.54	-	-	30	0.45
Lackarebäck	0.45	0.10	0.3	-	0.82	0.59	-	-
Alelyckan	1.8	0.052	2.1	-	2.1	0.21	-	-

Looking at Table 2, the results show that, generally, the TS obtained from all the different laboratories WET, Eurofins, Synlab and Rya WWTP, were fairly similar. However, a few exceptions were noticed. In the case of WAS, as mentioned in Section 3.7.1, the TS for WAS from Eurofins, varied greatly and some samples were measured to be around 0.4 % TS and others 2.4 % TS, see Appendix D, Table D2. The standard deviation in the case of WAS is 0.77 % and when considering the mean value of 0.91 %, values higher than 2 % deviates almost twice from the mean value. The lowest standard deviations can be observed for the Rya WWTP when comparing all samples which are measured by the Rya WWTP.

4.2 Concentrations of metals and phosphorus

Table 3 summarizes all the final concentrations of metals and phosphorus in all samples as mean values based on 13 samples, excluding 11th and 12th of March. In the case of non-settled particles, February 23rd is excluded as well due to measurement errors which made it impossible to calculate the concentrations for that specific date. Table 4 displays the mean values as well as standard deviations for all metals in the case of non-settled particles. The phosphorus concentrations in settled and non-settled concentrations were not measured. In Figure 5, 6, 7, 8 and 9, specific metals are shown to enable comparison of metals which are found in high concentrations, low concentrations and concentrations comparable to other, in the DW sludge.

Table 3. Mean concentrations of metals and phosphorus for all samples as mean values. Cells marked [-] means that the sample was not analyzed for phosphorus or metals.

[mg/kg TS]	Non-settled particles	Settled particles	Mixed sludge	Primary sludge	WAS	Dewatered sludge	Lackarebäck DW sludge	Alelyckan DW sludge
Al	25789	19153	19338	16892	21453	39364	91770	91718
As	2.67	1.37	1.43	1.32	1.57	4.25	5.40	6.75
Ca	30624	15625	14396	11525	15347	30488	2278	3251
Cd	2.76	0.888	0.807	0.714	1.08	1.64	0.334	0.232
Ce	28.8	22.4	19.5	18.0	23.9	46.4	30.1	42.2
Co	4.20	3.16	6.24	5.64	9.29	14.15	5.10	8.80
Cr	15.7	14.7	16.8	15.6	21.1	34.0	15.6	26.3
Cu	529.4	312.5	262.5	220.7	368.2	509.5	71.2	49.1
Fe	8683	6792	21468	12712	44232	48128	8872	15119
Li	136	2.99	4.81	4.97	5.19	10.6	2.72	12.8
Mg	6361	2957	2571	2216	32292	5443	1161	3565
Mn	224	147	270	224.5	378	504	558	358
Mo	7.65	4.28	3.84	3.37	4.47	7.40	1.94	0.562
Ni	17.0	9.32	13.3	11.8	17.4	31.5	16.5	19.9
Pb	17.5	13.3	12.4	12.2	13.0	25.5	11.5	11.7
Sb	0.372	0.0341	0.679	0.437	0.901	1.14	0.00468	0
Sn	11.3	6.5	11.1	10.3	15.0	24.0	1.13	0.476

Ti	324	187	251	147	298	475	147	317
V	13.4	12.3	15.3	14.3	18.0	29.0	25.4	34.8
Zn	738.4	550.6	419.9	375.8	721.2	833.9	144.0	135
Phosphorus	-	-	19231	10731	35615	33000	297	577

Table 4 displays the mean values of non-settled particles separately together with the standard deviations for each metal.

Table 4. Mean values and standard deviations for non-settled particles. Cells marked [-] means that the sample was not analyzed for phosphorus or metals.

Non-settled particles [mg/kg TS]	**Mean**	**Standard deviation**
Al	25789	26500
As	2.67	3.07
Ca	30624	15323
Cd	2.76	2.47
Ce	28.8	32.8
Co	4.20	5.69
Cr	15.7	24.1
Cu	529.4	551
Fe	8683	10889
Li	136	287
Mg	6361	3311
Mn	224	192
Mo	7.65	14.4
Ni	17.0	10.9
Pb	17.5	17.5
Sb	0.372	1.01
Sn	11.3	14.0
Ti	324	331
V	13.4	20.6
Zn	738.4	890
Phosphorus	-	-

Figure 5 shows the concentrations of aluminum for all samples.

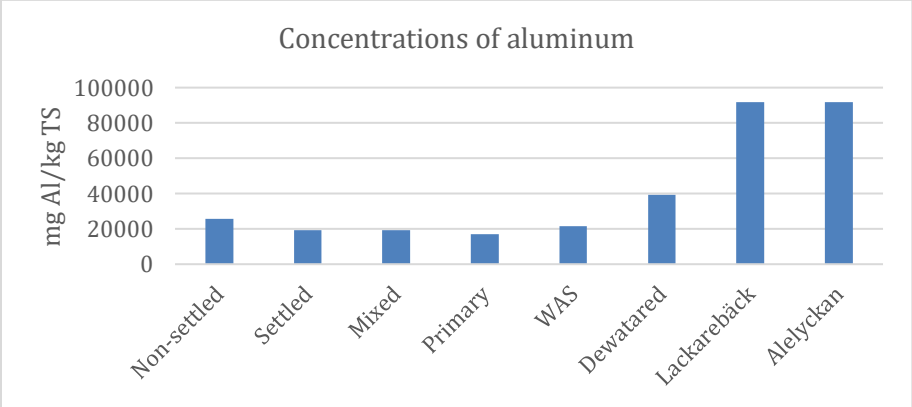

Figure 5. Concentration of aluminum in all samples as mean values.

Figure 6 displays the concentrations of manganese in all samples.

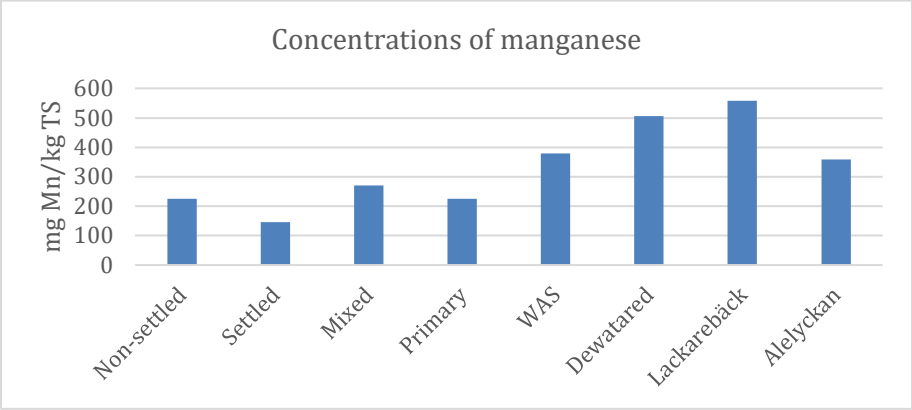

Figure 6. Concentration of manganese in all samples as mean values.

Figure 7 shows the concentrations of arsenic in all samples.

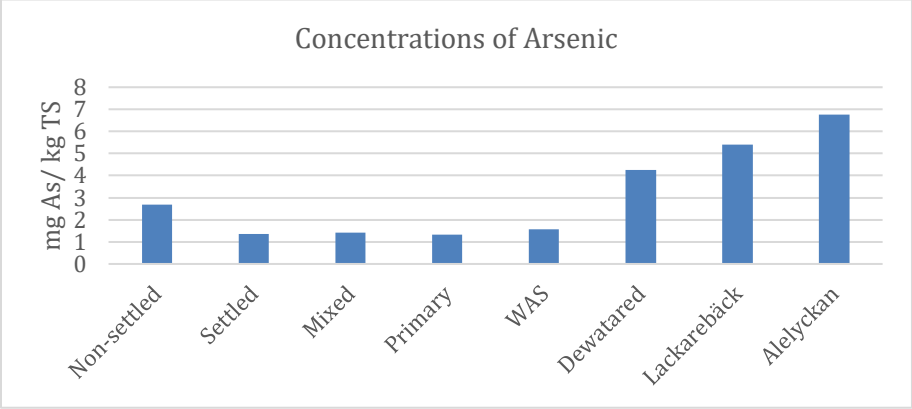

Figure 7. Concentration of Arsenic in all samples as mean values.

Figure 8 shows the concentrations of copper in all samples.

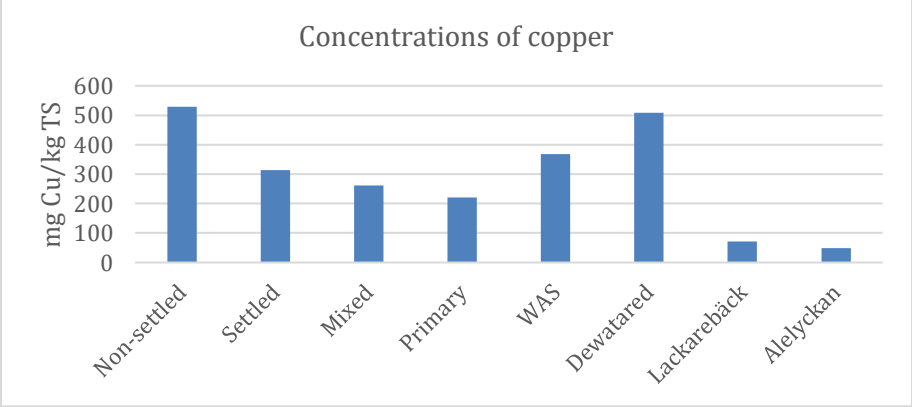

Figure 8. Concentration of Copper in all samples as mean values.

Figure 9 shows the concentrations of lead in all samples.

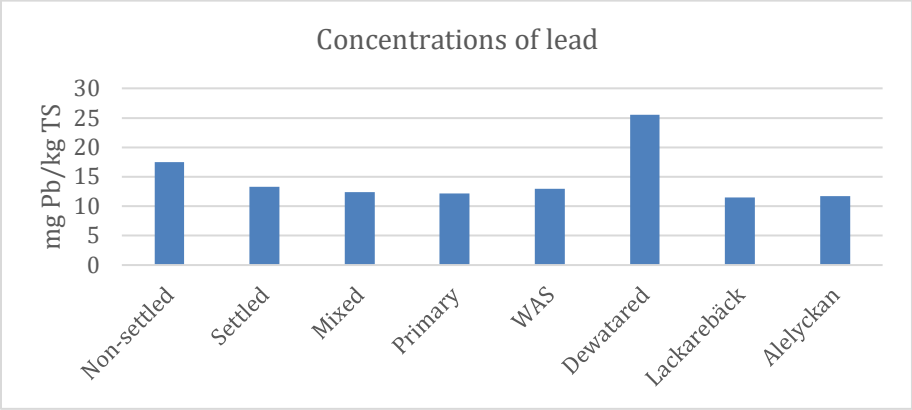

Figure 9. Concentration of lead in all samples as mean values.

Since the results presented in Table 3 are mean values, there is a possibility for each individual value to vary. It was especially noticeable in the case of non-settled particles, which can be viewed in Table 4. For instance, the mean value of lithium is 136 mg/kg TS, but has a standard deviation of 287 mg/kg TS. In the case of aluminum, the mean value is 25 789 mg/kg TS and a standard deviation of 26 500 mg/kg TS, indicating that the concentrations when comparing the individual samples, vary greatly.

Furthermore, looking at the results in Table 3, it is evident that there are differences between the DW sludge and the other samples. For instance, as shown in Figure 5, 6 and 7, aluminum, manganese and arsenic are found in high concentrations in the samples from Lackarebäck and Alelyckan. In Figure 8, for concentrations of copper, the opposite is true, and concentrations in DW sludge is significantly lower when comparing to all other samples. The same is true for several metals such as calcium, zinc, antimony, tin and molybdenum. Looking at Figure 9, concentrations of lead in DW sludge does not stand out compared to other samples. Similar results can be observed for titanium, iron and cerium. It is evident that some metal concentrations are higher for drinking water sludge and vice versa. The particularly high concentrations observed for aluminum is most likely that aluminum sulfate is used as a coagulant when reducing the turbidity of the raw water at the two DWTPs.

The concentration of metals in non-settled particles is higher for all metals when comparing to settled particles (see Table 3). However, the difference varies for each metal. While it is almost 50 times higher for lithium, it is only approximately 1.3 times higher for iron. The fraction of non-settled particles in the incoming wastewater is much smaller than the fraction of settled particles, which means that the contribution of metals from the settled particles would be much higher in terms of mass flow. The usefulness of the TS and the concentration as mg /kg TS of the non-settled and settled particles is uncertain as one cannot simply multiply the incoming flow by the TS and concentration to obtain the flow of mass, as done for other samples. In addition, the volume which were used to determine the TS for settled and non-settled particles would vary because of practical difficulties in the laboratory. The methodology for determining the mass flow of non-settled and settled particles can be reviewed in Section 3.8.3.

4.3 Mass flows of metals and phosphorus

In Table 5, the mean mass flows of all metals and phosphorus for all samples are shown, and in Table 6 all mass flows are shown as quotients of the mass flows in the incoming wastewater. The metals which are marked yellow are three metals for which the fraction of DW sludge is the most significant in the incoming wastewater.

Table 5. Mass flows of metals and phosphorus. Cells marked [-], means that the sample was not analyzed for metals. Cells marked yellow represents metals where the fraction of DW sludge in the incoming wastewater is significant.

kg/day	Incoming wastewater	DW sludge	Mixed sludge	Primary sludge	WAS	Dewatered sludge	Effluent water
Al	1117	454	1341	738	659	1502	-
As	0.090	0.034	0.101	0.059	0.048	0.161	-
Ca	992	13.6	1023	513	477	1162	-
Cd	0.070	0.001	0.057	0.031	0.032	0.062	-
Ce	1.28	0.179	1.39	0.812	0.759	1.77	-
Co	0.182	0.034	0.443	0.250	0.286	0.537	-
Cr	0.799	0.103	1.16	0.685	0.633	1.29	-
Cu	1.9	0.298	18.3	9.74	11.2	19.3	-
Fe	388	59	1592	556	1395	1841	-
Li	1.29	0.031	0.340	0.224	0.163	0.402	-
Mg	197	1.2	186	99.0	103	208	-
Mn	8.7	2.3	19.0	10.0	11.3	1.2	-
Mo	0.150	0.006	0.266	0.150	0.138	0.281	-
Ni	0.577	0.091	0.941	0.528	0.544	1.20	-
Pb	0.777	0.058	0.881	0.550	0.423	0.974	-
Sb	0.006	0.000	0.049	0.019	0.029	0.043	-
Sn	11.1	10.3	15.0	24.0	1.13	0.476	
Ti	11.8	1.14	18.0	6.57	9.70	18.0	-
V	0.684	0.149	1.07	0.635	0.555	1.10	-
Zn	31.4	0.700	29.1	16.6	15.7	31.6	-
Phosphorus	1333	2.15	1367	484	1091	1251	53.1

Table 6. Mass flows of metals and phosphorus as quotients of incoming mass flow. Cells marked [-], means that the sample was not analyzed for metals. Cells marked yellow represents metals where the fraction of DW sludge in the incoming wastewater is significant.

Quotients [-]	Incoming wastewater	DW sludge	Mixed sludge	Primary sludge	WAS	Dewatered sludge	Effluent water
Al	1.0	0.41	1.20	0.66	0.59	1.34	-
As	1.0	0.38	1.12	0.66	0.53	1.80	-
Ca	1.0	0.01	1.03	0.52	0.48	1.17	-
Cd	1.0	0.02	0.81	0.45	0.46	0.89	-
Ce	1.0	0.14	1.09	0.63	0.59	1.38	-
Co	1.0	0.19	2.43	1.37	1.57	2.94	-
Cr	1.0	0.13	1.45	0.86	0.79	1.62	-
Cu	1.0	0.02	0.97	0.52	0.59	1.02	-
Fe	1.0	0.15	4.10	1.43	3.60	4.74	-

Li	1.0	0.02	0.26	0.17	0.13	0.31	-
Mg	1.0	0.06	0.94	0.50	0.52	1.06	-
Mn	1.0	0.27	2.19	1.15	1.30	2.20	-
Mo	1.0	0.04	1.78	1.00	0.93	1.88	-
Ni	1.0	0.16	1.63	0.91	0.94	2.08	-
Pb	1.0	0.07	1.13	0.71	0.54	1.25	-
Sb	1.0	0.00	8.59	3.42	5.13	7.64	-
Sn	1.0	0.01	2.20	1.13	1.16	2.27	-
Ti	1.0	0.10	1.53	0.56	0.82	1.53	-
V	1.0	0.22	1.56	0.93	0.81	1.61	-
Zn	1.0	0.02	0.93	0.53	0.50	1.01	-
Phosphorus	1.0	0.002	1.03	0.36	0.82	0.94	0.04

In Figure 10, the quotient between primary sludge and mixed sludge as $\frac{mass\ flow\ primary\ sludge}{mass\ flow\ mixed\ sludge}$, and how it changes as the fraction of DW sludge in the incoming wastewater as $\frac{mass\ flow\ DW\ sludge}{mass\ flow\ incoming\ wastewtater}$, increases, is shown. Each point represents a metal, but the purpose of the graph is to see if there is a pattern between the increasing fraction of DW sludge and the how much that is removed in the primary sludge compared to the mixed sludge.

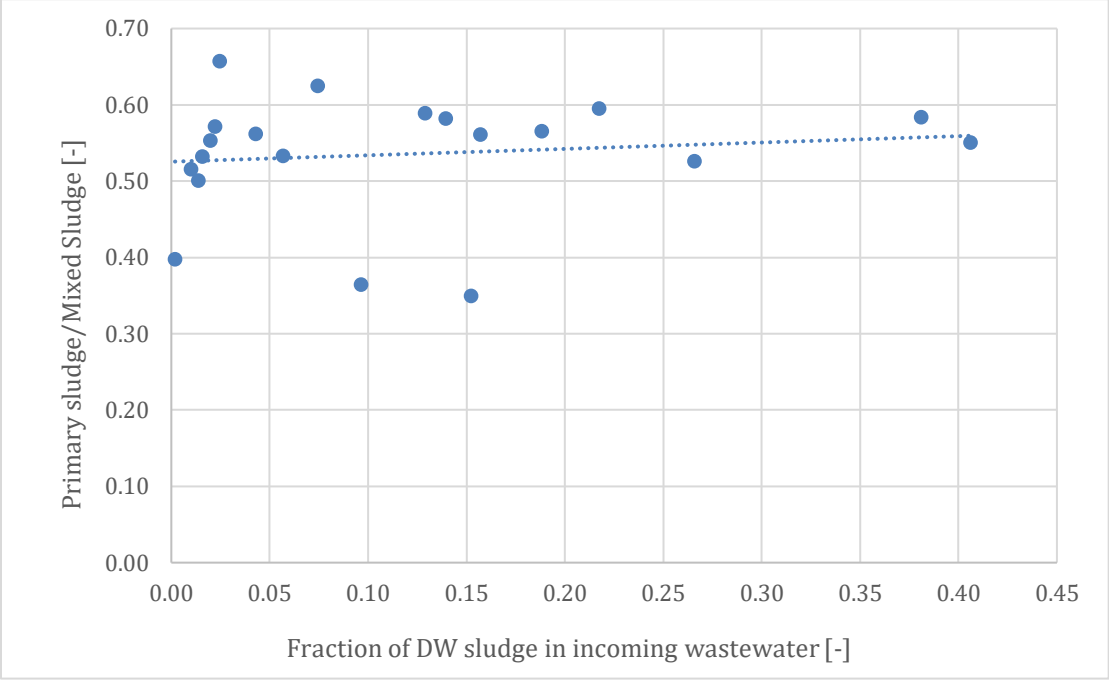

Figure 10. The quotient of primary sludge and mixed sludge for increasing fractions of DW sludge.

Based on equation (11), it is assumed that the amount of phosphorus which enters the system should also leave the system. This means that the flow of phosphorus in the incoming wastewater should be approximately equal to the sum of the flow of phosphorus in the mixed sludge and effluent water. It appears to be the case (see Table 6), considering that 1.0 enters the system and 0.04 in the effluent plus 1.03 in the mixed sludge, leaves the system. Moreover, looking at mixed sludge, it should be roughly equal to the sum of primary sludge plus WAS, which also appears to be the case. The contribution of phosphorus from the DW sludge is shown as a separate mass flow, to illustrate the fraction of mass which comes from the DW sludge. It is noticeably small in comparison to the mass flow, and as seen in Table 6, makes up for 0.2 %

of the total incoming mass flow of phosphorus. Considering equation (12), it was assumed that mass flow of metals in the incoming wastewater would be approximately equal to mass flow in the mixed sludge. Also, the sum of primary sludge plus WAS was assumed to be approximately equal to mixed sludge, as assumed in equation (13). Looking at the quotients in Table 6, it appears to be the case that primary sludge plus WAS is roughly equal to mixed sludge in all cases, with some differences. It can also be observed that the mass flow in the mixed sludge is approximately equal the mass flow in the dewatered sludge. However, the assumption, equation (14) that the mass flow in the incoming wastewater would be roughly equal to the mass flow in the mixed sludge, only holds for some metals. A difference lower than $\pm$10 % is observed for magnesium, calcium, copper, zinc and cerium. A difference of $\pm$10-20 % can be observed for aluminum, arsenic, cadmium and lead. In some cases, the mass flow in the mixed sludge is approximately two to three times higher than the mass flow in the incoming wastewater.

In the latest version of Gryaabs environmental report by (Videbris, 2021), the mass flows in kg/day of some metals in the incoming wastewater are presented. For instance, the mass flow of cadmium is 0.04 kg/day which is lower than the one measured in table 5. The mass flow of chromium is 0.9 kg/day, and comparing to 0.8 kg/day in Table 5, there is a slight underestimation. In the case of copper, it is 19 kg/day comparing to 1.9 kg/day in Table 5, which is a substantial underestimation. For nickel, it is 1.2 kg/day and in Table 5, 0.577 kg/day, which is a substantial underestimation as well. In the case of lead, it is 1.0 kg/day compared to 0.777 kg/day in Table 5. For zinc, it is 31 kg/day compared to 31.4 kg/day in Table 5. This comparison points to that the mass flow certain metals in the incoming wastewater could be underestimated, and to some extent strengthens the results obtained from the mass balances, which suggest that the mass flows of metals in the incoming wastewater are low.

In Table 6, metals for which fraction of DW sludge mass flow in the incoming waste water is significant, are marked yellow. The metals are aluminum, manganese and arsenic. Looking at aluminum as an example, the fraction of DW sludge in the incoming wastewater is 41%. The mass flow of aluminum in the primary sludge is 66 % of the total incoming aluminum. If the mass balance is approximately accurate this means that 66 % of the aluminum is removed in the primary settlers. However, it is difficult to determine the actual fraction of the 66 % that stems from the DW sludge. If the mass flow of DW sludge into the WWTP would have been much higher, close to a 100% of the total aluminum mass flow, then it would have been possible to establish a 66 % removal of aluminum, since all aluminum would have stemmed from DW sludge, and therefore a 66 % removal of DW sludge in the primary settlers. Looking at Figure 10, it is observed that the quotient of primary sludge and mixed sludge does not change significantly as the fraction of the DW sludge increases, perhaps only a slight increase when looking at the trend line. If it is assumed that DW sludge is removed to a greater extent in the primary settlers than WW sludge, then the mass flows of primary sludge and mixed sludge should be similar. In addition, their quotient in Figure 10 would move towards 1.0 as the fraction of DW sludge increases, since the mass flow of metals in the WAS would be lower, and therefore, in the mixed sludge as well. The opposite would apply if the DW sludge is not removed in the primary settlers to the same extent as WW sludge, then the quotient in Figure 10 would decrease as the fraction of DW sludge increases.

The results from Figure 10, suggest that the DW sludge does not seem behave significantly differently than WW sludge.

4.4 Uncertainties affecting mass flows

4.4.1 External sources

The results suggest that an external is source of certain metals is possibly added in WWTP since the mass flow of many metals in the mixed sludge is much greater than in the incoming mass flow. Potentially, some of these deviations is the result of iron sulfate being used for chemical precipitation of phosphorus. The iron sulfate is added prior to the biological treatment step and any addition of metals would be present in the mixed sludge. The iron sulfate which is used at Rya WWTP is the by-product from production of titanium dioxide. The iron sulfate is not pure, which means that it contains certain amount of other metals which would also be added to the system when the iron sulfate is being used (Mattsson et al., 2012).

Looking at Table 6, the mass flow of iron in the mixed sludge is four times greater than the mass flow in the incoming wastewater. The iron sulfate was carefully analyzed by Gryaab in 2011, where it was sent to three different laboratories for analysis. Some of the metals which could be found in significant amounts were zinc, chromium, cobalt, nickel and manganese. The results suggested that the contribution relative to the dewatered sludge from zinc was approximately 2 % and approximately 2 % relative to the incoming wastewater. As seen in Table 6, in Section 4.3, the mass flow of zinc in the mixed sludge is 7 % lower than in the incoming wastewater, which does not indicate any addition of zinc. For chromium, the contribution relative to the dewatered sludge was approximately 4 % and approximately 3-4 % relative to the incoming wastewater. However, the mass flow in the mixed sludge is 45 % higher. In the case of cobalt, the contribution relative to the dewatered sludge was approximately 100 % and the mass flow in the mixed sludge more than twice the mass flow in the incoming wastewater. The mass flow of nickel in the mixed sludge is 63 % higher than in the incoming wastewater and the addition from iron sulfate measured to be around 50 % of the dewatered sludge and approximately 20 % relative to the incoming wastewater. The final, significant, contribution was observed for manganese, a 20 % contribution, approximately, relative to the dewatered sludge. The mass flow in the mixed sludge is more than twice as high (Mattsson et al., 2012). Based on this, the iron sulfate could be a potential source of error regarding some of the metals. However, the exact extent is difficult to determine.

The Rya WWTP also receives external organic material which is added to the anaerobic digestion. The material consists of, for instance, fat and food waste which comes from different industries such as restaurants and schools. The waste is pumped at a specific station from where it is grinded and sent to the anaerobic digestion chamber (Ridelius, 2018). The sludge liquor from the dewatered sludge is sometimes added to the trickling filters, and therefore, metals present in the external organic material could potentially affect the metal contents in, for instance, the WAS and the mixed sludge. However, the common practice typically does not involve sending the sludge liquor to the trickling filters (M. Neth, personal communication, 2021-06-22). If a fraction of the sludge liquor would reach any of the other processes, the contribution would most likely be minor. In the report by Ridelius (2018) the contributions from nickel, lead, cadmium, chromium, copper and zinc, in the year of 2018, were small. Chromium contributed the most by making up for 1 % of the concentration in the dewatered sludge.

4.4.2 Laboratory analysis

The methodology for analyzing metals in the incoming wastewater could be improved. It is perhaps a reason to why the mass flow in the incoming wastewater is, in many cases, low compared to mixed sludge, which subsequently causes the mass balances for many metals to be inaccurate. Adding to this is the fact that the mass balance for phosphorus is quite accurate, including the mass flow in the incoming wastewater. The concentration of phosphorus was obtained from measurements continuously made by Gryaab, and it is reasonable to expect that the analysis is more reliable than the one conducted for metals in the incoming wastewater at the WET laboratory. The laboratory analysis mainly focused on analyzing sludge, the settled particles and the non-settled particles, which was separated from the liquid using a centrifuge, were treated as any other sludge analyzed. However due to the incoming wastewater mainly consisting of water, the fractions of particles were very small and therefore, it was impossible to extract roughly 0.5 grams of ashes for the ICP-MS analysis, which was considered the necessary amount.

The ICP-MS did manage to produce results for most of the samples. However, it would have been preferable to have had access to greater quantities of particles when analyzing the incoming wastewater. Although, by using a centrifuge to separate the particles, unrealistically large sample volumes of incoming wastewater would have been required, hence, perhaps another method for analyzing metals would be preferable. Moreover, any metals still present in the liquid phase after centrifuging would have been removed when the liquid was removed from the sample. Although, as mentioned in Section 3.6.1, a small amount of liquid was kept to enable transferring of the small volume of centrifuged particles to the bowls used for drying the samples. Also, deionized water was added in cases where it was deemed necessary. This means that there was an inconsistency regarding the way settled and non-settled particles were prepared. The volume of incoming wastewater kept for pouring would vary and therefore and perhaps the metal contents as well. As mentioned in Section 4.2, based in standard deviations, it was noticeable that concentrations used to calculate the mean value of the concentration varied in the case of non-settled particles.

The reason as to why the mass flow of certain metals in the incoming wastewater is much smaller than in the primary sludge could be the contribution of iron sulfate, as mentioned, but considering the uncertainties surrounding the samples of settled and non-settled particles, it could possibly be the case that the concentration of metals in the incoming wastewater were underestimated and subsequently the mass flow of metals into Rya WWTP. Although, the mixed sludge, primary sludge, WAS and DW sludge were all centrifuged, meaning that liquid was removed from the samples before drying.

4.4.3 DW sludge and dewatered sludge mass flow

The flow of DW sludge from Lackarebäck and Alelyckan was difficult to determine. The method for calculating the flow of DW sludge into the Rya WWTP which is described in Section 3.8.5 involves assumptions, one being that roughly 30 % of the tanks which are emptied or flushed is actual DW sludge, remaining 70 %, water. In addition, the balancing reservoir at Alelyckan is not included in the calculations. Any DW sludge which is lost to the storm water network is therefore not included, making the estimation conservative.

All samples were collected on specific dates. However, the dewatered sludge undergoes several treatment processes before it takes its final form as dewatered sludge and has a retention time of approximately three weeks in the anaerobic digestion chamber (M. Neth, personal communication, 2021-05-28). This means that metal concentrations in the dewatered sludge stems from wastewater which arrived at the Rya WWTP prior the date of the analysis.

4.5 Simulations

The following two sections includes the results and an analysis and discussion of the results obtained from simulation 1 and simulation 2.

4.5.1 Simulation 1

In Table 7, 8 and 9, the results from the first simulation are shown. The metals for which the fraction of DW sludge in the incoming wastewater is insignificant and mass balances fairly accurate based on equation (14), are magnesium, calcium, copper and zinc, each with a difference lower than a difference lower than $\pm$10 %. The average mass flow in the primary sludge of the four metals is 52 %, and used as a representative removal percentage of the WW sludge in the primary settlers. The metals for which the fraction of the DW sludge in the incoming wastewater is significant and the mass balance fairly accurate, are aluminum and arsenic, with a difference of plus 20 % and 13 % respectively. The cells which are marked yellow show the metals where the fraction of DW sludge is significant, and which removal percentage corresponds to the measured value of the mass flow of primary sludge.

Table. 7 Calculated flow of the DW sludge. Cells marked yellow represents metals where the fraction of DW sludge in the incoming wastewater is significant.

kg/day of metal in primary sludge	0 % removal	25 % removal	50 % removal	87 % removal	100 % removal	Measured value
Al	343	456	569	737	796	738
As	0.0286	0.0371	0.0457	0.0583	0.0627	0.0570
Ca	505	508	512	517	519	513
Cu	9.61	9.68	9.76	9.87	9.91	9.74
Mg	95.8	98.6	101	105	107	99
Zn	15.9	16.0	16.2	16.5	16.6	16.6

Table 8. A 30 % increase of the flow of the DW sludge. Cells marked yellow represents metals where the fraction of DW sludge in the incoming wastewater is significant.

kg/day of metal in primary sludge	0 % removal	25 % removal	50 % removal	79 % removal	100 % removal	Measured value
Al	272	420	567	738	862	738
As	0.0233	0.0344	0.0455	0.0584	0.0677	0.0570
Ca	503	507	512	517	521	513
Cu	9.56	9.66	9.75	9.87	9.95	9.74
Mg	94	98	101	106	109	99
Zn	15.7	16.0	16.2	16.5	16.7	16.6

Table 9. A 30 % reduction of the flow of the DW sludge. Cells marked yellow represents metals where the fraction of DW sludge in the incoming wastewater is significant.

kg/day of metal in primary sludge	0 % removal	25 % removal	50 % removal	100 % removal	100 % removal	Measured value
Al	413	492	572	730	730	738
As	0.0339	0.0399	0.0458	0.0578	0.0578	0.0570
Ca	507	509	512	517	517	513
Cu	9.65	9.71	9.76	9.86	9.86	9.74
Mg	97.5	99.5	101	105	105	99
Zn	16.0	16.1	16.2	16.5	16.5	16.6

Looking at Table 7 which is based on the calculated value the flow of DW sludge, it appears that the mass flow of primary sludge corresponds to a removal of 87 % of DW sludge. In Table 8, where the flow of DW sludge is increased by 30 %, it is noticed that the measured value corresponds to a removal of 79 % of DW sludge. And finally, in Table 9, where a reduction by 30 % of the flow of DW sludge was assumed, the removal of DW sludge corresponds to 100 % The removal percentage is directly linked to the chosen mass flows, which in return, are dependent of flows and concentrations. By increasing the flow of DW sludge, the calculated removal of DW sludge in the primary settler decreases. By decreasing the flow of DW sludge, the calculated removal of DW sludge in the primary settler increases. An increase of the mass flows of the incoming wastewater would also increase the calculated removal of the DW sludge since the fraction of DW sludge in the incoming wastewater would be smaller. This points to the importance of finding appropriate estimations of flows, concentrations and mass flows. However, by simulating the different scenarios using different mass flows for DW sludge, underestimations and overestimations for the DW sludge by 30 % are covered.

The simulation was based on metals for which the mass balances were approximately accurate. As mentioned on several occasions, the mass balances when comparing the mass flow in the incoming wastewater and the mass flow in the mixed sludge, were, in most cases, not accurate. In addition, one of the metals used in the simulation was zinc. As mentioned, the addition of iron sulfate could substantially increase the mass flow of zinc in the system, approximately 20 % of the concentration in the dewatered sludge. In addition, the mass balance for aluminum was less accurate than other mass balances, 1.0 in the incoming wastewater compared to 1.2 in the mixed sludge. It could therefore be reasonable to question the reliability of the mass balances that are accurate and used in the simulation. Changes to the mass flows in the incoming wastewater are made in Section 4.5.2.

4.5.2 Simulation 2

In Table 10, 11 and 12, the results from the second simulation are shown. As described in Section 3.9.2, the mass flow in the incoming wastewater was assumed to be the sum of the mass flow in the primary sludge and WAS, based on equations (12) and (13). The removal percentage of WW sludge is still assumed to be 52 %, based on the average mass flow of metals in the primary sludge for calcium, copper, magnesium and zinc.

Table 10. Calculated mass flow of DW sludge. Cells marked yellow represents metals where the fraction of DW sludge in the incoming wastewater is significant.

kg/day of metal in primary sludge	0 % removal	25 % removal	50 % removal	55 % removal	100 % removal	Measured value
Al	487	601	714	737	941	738
As	0.0373	0.0458	0.0543	0.0561	0.07	0.0570
Ca	504	507	511	511	517	513
Cu	10.6	10.7	10.8	10.8	10.9	9.74
Mg	98.4	101	104	105	110	99
Zn	16.3	16.5	16.7	16.7	17.0	16.6

Table 11. A 30 % increase of the flow of the DW sludge. Cells marked yellow represents metals where the fraction of DW sludge in the incoming wastewater is significant.

kg/day of metal in primary sludge	0 % removal	25 % removal	50 % removal	54 % removal	100 % removal	Measured value
Al	417	565	712	736	1007	738
As	0.0320	0.0431	0.0542	0.0560	0.0763	0.0570
Ca	502	506	511	511	519	513
Cu	10.6	10.7	10.8	10.8	11.0	9.74
Mg	96.7	100	104	105	111	99
Zn	16.2	16.5	16.7	16.7	17.1	16.6

Table 12. A 30 % reduction of the flow of the DW sludge. Cells marked yellow represents metals where the fraction of DW sludge in the incoming wastewater is significant.

kg/day of metal in primary sludge	0 % removal	25 % removal	50 % removal	57 % removal	100 % removal	Measured value
Al	558	637	716	739	875	738
As	0.0426	0.0485	0.0545	0.0562	0.0664	0.0570
Ca	506	508	511	511	515	513
Cu	10.7	10.7	10.8	10.8	10.9	9.74
Mg	100	102	104	105	108	99
Zn	16.5	16.6	16.7	16.7	16.7	16.9

Looking at Table 10, the removal percentage which corresponds to the measured value is approximately 55 %. When increasing the DW sludge flow by 30 %, in Table 11, it corresponds to 54 % and as seen in Table 12, when decreasing the flow by 30 %, it corresponds a removal percentage of 57 %. Clearly, by assuming a mass flow in the coming wastewater as the sum of primary sludge and WAS, the removal percentage in the primary settler becomes significantly lower compared to using the measured values of the mass flow in the incoming wastewater, as

done in simulation 1. Based on the trend in Figure 10, which indicates that the DW sludge and WW sludge behaves similarly, is supported by the results from simulation 2, considering the assumed removal of 52 % for WW sludge compared to 55 % removal of DW sludge in Table 9.

As mentioned on several occasions, the mass balances indicate that there are uncertainties regarding the mass flows in the incoming wastewater. Therefore, the results from simulation 1, should most likely be interpreted by also considering the results from simulation 2. An advantage of using the results form of simulation 2 is that when considering equation (13), which does not consider the mass flow in the incoming wastewater, the mass balances are fairly accurate in most cases when looking at Table 6.

It should be noted, that in both simulation 1 and 2, the removal of WW sludge is assumed to be 52 %, which is an assumption based on the four metals, calcium, copper, manganese and zinc. By changing the removal percentage of WW sludge, the removal percentage of DW sludge would change as well.

4.6 The fate of DW sludge

To summarize, in Section 4.3, it was concluded that the DW sludge did not stand out in terms of removal in the primary settlers. A slightly higher removal of DW sludge compared to WW sludge is noticed based on the trend in Figure 10. However, the difference is very minor, and most likely suggest that the DW sludge would behave similarly to WW sludge. Based on the three cases presented in Section 1.4, this points to case 3 being true. The case states that the DW sludge is removed to some extent in the primary settlers but reaches the biological treatment step. The results simulation 1 in Section 4.5.1 indicates that the removal percentage of DW sludge is 87 % in the primary settlers, or at least 79 % when accounting for higher mass a flow of DW sludge into the Rya WWTP or 100 % when decreasing the mass flow of DW sludge. However, when not using the measured values of mass flows in the incoming wastewater, which are associated with uncertainties, but using the mass flow in the incoming wastewater as the sum of primary sludge and WAS, as done in simulation 2, the removal percentage corresponds to 54 %. By including an increase in DW sludge flow, the removal percentage decreases to 54 % and by decreasing the DW sludge flow by 30 % it increases to 57 %.

By including these findings, the results would at least indicate that case 2 is unrealistic, which stated that the DW sludge is not removed in the primary settlers but reaches the biological treatment step. The more reasonable approach would be to argue that the DW sludge is removed to the same extent as WW sludge, potentially more.

4.7 Improvements and suggestions

To strengthen and confirm the results in this thesis, it is recommended that the mass flow of the incoming wastewater and the flow of DW sludge is investigated further. When looking the mass balances of primary sludge, mixed sludge and WAS, they are approximately accurate, meaning that even though the mass flow in the mixed sludge is high compared to the mass flow in the incoming wastewater, the assumptions that WAS plus primary sludge equals mixed sludge, still holds. Therefore, it is suspected that the fault lies in the estimation of mass flows in the incoming wastewater and DW sludge. Another possibility is that the concentrations of metals

in the sludge are inaccurate for the WAS, primary sludge, mixed sludge and dewatered sludge. However, during the analyses in the WET lab, sufficient amounts of ashes were analyzed in the ICP-MS, and the analyses of the sludge samples are deemed quite robust in comparison to the analysis of incoming wastewater. The latter favors the assumption that the mass flow in the incoming wastewater or DW sludge could be investigated further.

The literature review covers some prior studies which focus on the effects of DW sludge on WWTP treatment processes. However, it is recommended that further research is made. Particularity studies which focus on this specific case study, that seeks to determine the potential effects of DW sludge on the WWTP treatment processes. The results from this thesis indicates that some of the DW sludge does reach the biological treatment step, and therefore the effects on other treatment processes become of interest.

5 Conclusions

This thesis sought to determine the fate of DW sludge as it arrives to the Rya WWTP. The initial hypothesis included three cases,

- Case 1: The DW sludge is removed to such an extent that it does not reach the biological treatment step,
- Case 2: The DW sludge is not removed in the primary settlers but reaches the biological treatment and
- Case 3: The DW sludge is removed to some extent in the primary settlers and a fraction reaches the biological treatment step.

The results indicate that Case 1 and Case 2 are unlikely. If approximately 50 % of the metals deemed representative of the WW sludge is removed in the primary settlers, the results suggest that the DW sludge is at least removed to the same extent, or potentially an even greater extent than the WW sludge. The results from simulation 1 indicates that the removal is 87 % and 79 % or 100 % when accounting for 30 % higher and lower DW sludge flow. However, it is recognized that the mass flow in the incoming wastewater is uncertain and potentially underestimated in many cases, as revealed by the mass balances. The results from simulation 2, which attempts to eliminate the underestimation, indicates that the removal of DW sludge is 55 % and 54 % or 57% when accounting for 30 % higher and lower DW sludge flow. Ultimately, this suggests that some the DW sludge is removed in the primary settlers and that the remainder reaches the biological treatment step, which points to Case 3 being the more likely out of the three. Moreover, the potential for underestimating or overestimating the mass flow of DW sludge into the Rya WWTP is recognized. The mass balance approach is sensitive to the assumed amount of DW sludge. If more DW sludge than assumed enters the system this would result in lower calculated removal rate in the primary settlers, and more DW sludge would reach the biological treatment step. Changes in the mass flows into the Rya WWTP would have a direct impact in the fraction of DW sludge which enters the treatment plant, thus affecting the results. Mass balances of metals revealed potential uncertainties with respect to the mass flow in the incoming wastewater, which adds further uncertainties to the results. In addition, the removal of approximately 50 % of WW sludge is an assumption based on metals deemed typical of the WW sludge, and any changes would directly affect the removal of DW sludge in the simulations conducted. It is therefore recognized that the results in this thesis

could be improved and investigated further, specifically focusing on metal concentration in the incoming wastewater and flow of DW sludge into the Rya WWTP.

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7 Appendix

7.1 Appendix A: Photograph of the incoming wastewater

Figure A1. One litre of the incoming wastewater, contents left to settle. Photo by the author of this thesis.

7.2 Appendix B: All flows used in calculations of mass balances

Table B1. All the flows used to calculate mass flows.

Date	Incoming wastewater m^3/s	Incoming wastewater m^3/day	Mixed sludge l/day	Primary sludge l/day	WAS l/day	Dewatered sludge kg/day	Effluent water m^3/day	Dw sludge Lackarebäck l/day	DW sludge Alelyckan l/day
Feb 22nd	3.93	339 805	3 310 811	3 310 811	4 254 551	123 251	339 805	571 979	135 189
Feb 23rd	3.90	336 742	2 898 344	2 898 344	3 894 837	129 093	336 742	571 979	135 189
Feb 24th	3.95	341 492	2 484 139	2 484 139	3 478 645	140 076	341 492	571 979	135 189
Feb 25th	3.81	329 547	4 072 642	4 072 642	3 322 190	140 326	329 547	571 979	135 189
Feb 26th	3.89	336 432	2 944 162	2 944 162	3 077 088	158 336	336 432	571 979	135 189
Mar 1st	3.35	289 791	2 711 807	2 711 807	2 151 587	118 002	289 791	571 979	135 189
Mar 2nd	3.35	289 496	2 752 690	2 752 690	1 950 247	143 481	289 496	571 979	135 189
Mar 3rd	3.31	285 935	2 728 848	2 728 848	1 881 537	135 829	285 935	571 979	135 189
Mar 4th	3.30	284 809	2 474 797	2 474 797	1 913 865	118 634	284 809	571 979	135 189
Mar 5th	3.22	278 023	2 333 904	2 333 904	1 868 715	136 344	278 023	571 979	135 189
Mar 8th	3.02	260 698	2 383 642	2 383 642	1 715 744	72 501	260 698	571 979	135 189
Mar 9th	2.91	251 285	2 282 960	2 282 960	1 777 767	111 155	251 285	571 979	135 189
Mar 10th	3.07	265 337	2 277 470	2 277 470	1 711 113	118 157	265 337	571 979	135 189
Mar 11th	7.41	640 218	2 785 319	2 785 319	1 648 479	134 364	640 218	571 979	135 189
Mar 12th	7.49	647 327	2 639 589	2 639 589	1 868 251	141 177	647 327	571 979	135 189

7.3 Appendix C: Concentrations of phosphorus

Table C1. Concentrations of phosphorus in the incoming wastewater and effluent water.

Total P	**Incoming wastewater** **kg/m^3**	**Effluent water** **kg/m^3**
February 22nd	0.0033	0.00023
February 23rd	0.0043	0.00019
February 24th	0.0042	0.00017
February 25th	0.0041	0.00016
February 26th	0.004	0.00015
March 1st	0.0041	0.00015
March 2nd	0.005	0.0002
March 3rd	0.0045	0.00019
March 4th	0.0047	0.00017
March 5th	0.0047	0.00018
March 8th	0.0048	0.00022
March 9th	0.0058	0.00018
March 10th	0.0051	0.00016
March 11th	0.0054	0.00029
March 12th	0.0037	0.00017

7.4 Appendix D: TS for all samples

Table D1. The TS for primary sludge and mixed sludge.

[%]	Primary sludge			Mixed Sludge		
	WET	Eurofins	Rya WWTP	WET	Eurofins	Gryaab
Feb 22nd	1.6	1.4	-	3.3	2.6	2.7
Feb 23rd	1.9	3.2	-	2.1	1.6	3.1
Feb 24th	1.8	2.1	-	2.4	3.7	2.7
Feb 25th	0.9	1.6	-	3.6	3.0	2.7
Feb 26th	2.0	1.0	-	2.8	2.5	2.9
March 1st	1.5	3.0	-	2.2	3.2	2.8
March 2nd	1.2	1.6	-	2.3	1.8	2.4
March 3rd	1.5	1.5	-	2.3	2.7	2.1
March 4th	1.2	1.4	-	1.9	1.4	2.1
March 5th	2.0	1.8	-	2.2	1.7	2.2
March 8th	2.0	3.7	-	2.6	2.2	2.7
March 9th	2.6	2.9	-	3.0	2.1	2.1
March 10th	1.5	1.9	-	1.7	3.3	2.0
March 11th	2.0	2.6	-	2.3	2.0	3.5
March 12th	6.2	7.3	-	1.98	7.4	3.3

Table D2. The TS for WAS and dewatered sludge.

[%]	WAS			Dewatered sludge		
	WET	Eurofins	Rya WWTP	WET	Eurofins	Gryaab
Feb 22nd	0.90	0.40	1.3	29	30	30
Feb 23rd	0.52	0.40	1.3	31	29	30
Feb 24th	0.95	0.70	1.3	28	29	30
Feb 25th	0.97	0.60	1.2	32	29	30
Feb 26th	0.69	0.70	1.2	29	29	30
March 1st	0.83	1.4	1.1	31	29	30
March 2nd	0.89	0.60	1.1	30	29	30
March 3rd	0.84	2.4	1.2	29	30	30
March 4th	0.89	1.2	1.1	30	29	30
March 5th	0.91	2.5	1.2	30	29	30
March 8th	0.85	0.40	1.2	31	30	31
March 9th	0.86	0.40	1.1	31	30	31
March 10th	0.77	0.10	1.1	32	29	30
March 11th	1.02	0.30	1.2	30	28	30
March 12th	1.1	0.60	1.3	30	29	30

Table D3. The TS for DW sludge from Lackarebäck and Alelyckan.

[%]	Lackarebäck			Alelyckan		
	WET	Eurofins	Synlab	WET	Eurofins	Synlab
Feb 23rd	0.46	0.30		1.8	2.1	
March 2nd	0.54		1.2	1.8		2.2
March 8th	0.35		0.40	1.8		1.9

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