EVALUATING REUSE OF SLUDGE FROM WATER TREATMENT FOR WASTEWATER TREATMENT

AN ASSESSMENT OF EFFECTS OF SPENT ALUM SLUDGES ON WASTEWATER TREATMENT IN GOTHENBURG, SWEDEN

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ABSTRACT

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Symbols

↓	Formation of solid precipitate separated from solution.
→	General purpose reaction arrow (action).
⇌	Equilibrium arrow (reversible process).
(s)	Denotes a solid state.

Abbreviations

DWTP	Drinking water treatment plant
WWTP	Wastewater treatment plant
TOC	Total organic carbon
CEPT	Chemically enhanced primary treatment
COD	Chemical oxygen demand
SS	Suspended solids
P	Phosphorus (mg P/l)
o-P	Orthophosphate (mg P/l)
PO_4^{-3}	Phosphate ion (mg PO_4^{-3}/l)
IC	Ion chromatograph
ICP-MS	Inductively coupled plasma mass spectrometer
NOM	Natural organic matters
EPA	Environmental Protection Agency
Al	Aluminium
WWF	Wet weather flow
SVI	Sludge volume index
AL	Alelyckan (drinking water treatment plant)
LA	Lackarebäck (drinking water treatment plant)
AL sludge	Alum drinking water sludge from the Alelyckan drinking water treatment plant
LA-1 sludge	Alum drinking water sludge from the Lackarebäck drinking water treatment plant, settling tank 1
LA-5 sludge	Alum drinking water sludge from the Lackarebäck drinking water treatment plant, settling tank 5
rpm	Revolutions per minute
SEK (kr)	Swedish Krona. All conversions to/from GBP (£) based on the May 2014 average exchange rate of 1 kr = £0.09.

Referencing

This thesis uses the IEEE citation style, with in-text citations (a citation number in square brackets [ ]) complemented by a reference list at the end of the text. Citations are numbered in the order that they appear in the text.

1. INTRODUCTION

1.1 Overview and problem statement

The concept of sustainability is one which engineers globally need to grasp to ensure the needs of the present are met without compromising the ability of future generations to meet their own needs [1]. This is particularly relevant for water and wastewater engineering where arguably the effects of engineering decisions are observed more rapidly and clearly than in other disciplines.

In Gothenburg, Sweden's second largest city situated on its west coast, the disposal of drinking water treatment plant (DWTP) sludge via the Rya wastewater treatment plant (WWTP) was subject to evaluation in terms of both economic and environmental sustainability. While treating and supplying drinking water for approximately 500,000 inhabitants of Gothenburg [2] [3], several DWTPs generate alum sludge, a by-product of raw water treatment to produce drinking water. The disposal of alum DWTP sludge via the partly combined sewer system through Gothenburg to the Rya WWTP was alleged to be costly and detrimental from a sustainability standpoint [4] [5] [6], such that an evaluation of the detrimental and beneficial effects was desirable.

Previous studies [7] [8] [9] suggested the effects of alum DWTP sludge were limited to physical or primary treatment in the WWTP, with little effect on biological or secondary treatment processes. Consequently, this project focussed particularly, although not exclusively, on evaluating the effects of DWTP sludge on primary treatment, including removal of phosphorus, organics and solids (primary and secondary settling), as well as assessing the handling (thickening and dewatering) of DWTP sludge. Primarily of interest were the chemical, economic and environmental effects of disposing DWTP sludge via the Rya WWTP, and whether any benefits outweighed the drawbacks.

Previous research, although existing globally, was limited in its relevance, with conclusions varying case by case [10]. Upon the conclusion of this 4 month project, a pragmatic solution was sought, such that in-depth chemical analysis was excluded to the benefit of facilitating a project practically relevant to the Rya WWTP.

Founded on a literature review, practical insight in Gothenburg and supported by simple bench-scale jar testing, this project contributed towards a city-wide economic and environmental evaluation of disposing alum DWTP sludge in Gothenburg.

1.2 Aim and objectives

1.2.1 *Overall aim*

As part of a collaboration between Chalmers University of Technology and the companies running the drinking water and wastewater treatment plants in Gothenburg, the chemical, economic and environmental effects of the reuse of two alum DWTP sludges in wastewater treatment at the Rya WWTP were evaluated.

1.2.2 *Individual research objectives*

Evaluating the reuse of alum DWTP sludges at the Rya WWTP was achieved by means of both theoretical and practical studies:

- Current understanding of alum DWTP sludge effects on primary wastewater treatment for phosphorus removal were evaluated through review of existing literature.

- Probable and confirmed effects of handling alum DWTP sludge on major treatment operations at the Rya WWTP were evaluated by means of a brief literature review from case studies nationally and globally.

- Chemical characterisation of two alum DWTP sludges from the Alelyckan and Lackarebäck DWTPs enabled a comparison between the two sludges.

- Wastewater samples from the Tankgatan sampling station in Gothenburg representative of the influent municipal wastewater at the Rya WWTP were also chemically characterised.

- The effects of Alelyckan and Lackarebäck DWTP sludges on primary wastewater treatment were analysed through bench-scale jar testing with municipal wastewater. Effects on total phosphorus, organics content and solids (primary and secondary settling) among other effluent quality parameters were evaluated, both chemically and economically.

- The handling (thickening and dewatering) characteristics of Alelyckan and Lackarebäck DWTP sludges and their influence on the most appropriate sludge processing method was evaluated through experimentation and review of existing literature.

- Upon conclusion of the above research objectives, an appropriate proposal for an economically and environmentally sustainable solution to the management of DWTP sludge in Gothenburg was suggested.

1.3 Value of research

Completion of the aforementioned research objectives benefitted all those directly involved in the project by contributing data and subsequent conclusions towards an economically and environmentally sustainable solution to the management of DWTP sludge in Gothenburg. In combination with a consultant completing a wider review, results of this project were valuable for the companies running the drinking water and wastewater treatment plants in Gothenburg and the municipal government.

1.3.1   Environmental value

The adoption of sustainable environmental policies since the late 1980s transformed Sweden into a role model in water management [11]. Accordingly, DWTP sludge handling in Gothenburg should be sustainable, despite the fact that legislation surrounding disposal of DWTP sludges is deficient globally. As an inescapable by-product of drinking water production, DWTP sludge production is unlikely to decrease in the foreseeable future [12] such that sustainable DWTP sludge management is a proactive aim with high environmental value.

1.3.2   Economic value

Kretslopp och vatten, Göteborg Stad (Department of sustainable waste and water, Gothenburg City) and Gryaab AB (operator of the Rya WWTP) believed the current situation was not sustainable from an economic standpoint, based on previous reports and rough estimations of handling DWTP sludge at the Rya WWTP [6] [7] [8] [13] [14] [15]. Reduced efficiencies in several major treatment operations were inferred, of which biogas production and legislation for WWTP sludge reuse and disposal in Sweden were highlighted as primary concerns for future operating and investment costs.

1.3.3   Limitations

Throughout the conduct of the project, attempts were made to ensure practicality and relevance to the Rya WWTP in Gothenburg. Experimental design used fresh DWTP sludges and wastewater, collected from the Alelyckan and Lackarebäck DWTPs and the Tankgatan wastewater sampling station.

The 4 month time-scale of this project required a balance between sufficient review of literature and ensuring practicality of experimental design. This project focussed experimental design on the chemical and economic effects of DWTP sludge on primary wastewater treatment, while broader aspects of the evaluation, including more

substantial economic analysis and potential sludge re-uses, were analysed in a separate project by a fellow student, in addition to a consultant for the city of Gothenburg.

Experimentation was carried out in Spring 2014, and wastewater and sludge samples were understandably subject to natural time-based and weather-based variations. Appropriate procedures were taken to minimise errors through duplication of tests, maintenance of consistent experimental environments and accurate modelling of actual WWTP conditions.

1.4 Structure of report

1.4.1 Project planning

A theoretical review was considered in section 2.1, focussing on phosphorus species in wastewater and current understanding of the mechanisms of their removal in a WWTP. Additionally, throughout the background study and literature review, attention was given to other parameters which were expected to be affected by DWTP sludge, specifically organics content and solids (primary and secondary settling).

In section 2.2, details of practical insights and specificities of the DWTPs and Rya WWTP in Gothenburg were followed by consideration of handling (thickening and dewatering) alum DWTP sludge. Subsequently, drawing on valuable experience from other case studies and literature, probable and confirmed effects of alum DWTP sludge on major treatment operations at the Rya WWTP were evaluated.

Finally in section 2.3, a literature and methodological review of previous approaches, significant variables, and key conclusions from earlier research with alum DWTP sludge in phosphorus removal was conducted to ensure practically relevant experimental design.

2. BACKGROUND STUDY AND LITERATURE REVIEW

2.1 Phosphorus removal from wastewater

Phosphorus speciation in wastewater is briefly evaluated, followed by consideration of the methods of phosphorus removal in primary wastewater treatment at a WWTP. Subsequently, the behaviours of aluminium and alum DWTP sludge in wastewater, and mechanisms of phosphorus removal by alum DWTP sludge and comparable mineral precipitants (salts) are reviewed.

2.1.1 *Phosphorus and phosphate speciation*

In wastewater, phosphorus occurs as various species of phosphate [16], specifically orthophosphate (o-P), polyphosphates (also referred to as complex or condensed phosphates) such as pyrophosphate, tripolyphosphate and trimetaphosphate [17], and particulate organic phosphates tied up in organic matter [17] [18].

P speciation varies depending on proportions of commercial, industrial or municipal components of wastewater as well as the collection system design and the time of travel before the wastewater reaches the WWTP. Jenkins et al. [19] proposed approximate concentrations of phosphate species in typical raw domestic sewage as shown in Table 2.1 below. A revision 20 years later by the same author [20] saw the constituent proportions relatively unchanged.

Phosphate form	Concentration	
	$(mg\ P\ l^{-1})$ (Jenkins et al. (1971) [19])	$(mg\ P\ l^{-1})$ (Jenkins & Hermanowicz (1991) [20])
Total phosphorus	≲10	≲ 7
Orthophosphates	5	3-4
Tripolyphosphates	3	2-3 (tripoly- and pyro- together)
Pyrophosphates	1	
Organic phosphates	≲ 1	1

Table 2.1 Approximate concentrations of phosphate species in a typical raw domestic sewage

Jenkins et al. [19] and several others [21] [22] [23] [24] concluded that o-P represents the dominant form of P in raw municipal wastewater, typically with an o-P/total P fraction of between 0.6 and 0.9 [25]. While ultimately the measurement and removal of total P is most important for wastewater treatment, the o-P form is the most biologically available and easiest to precipitate [26].

2.1.2 *Wastewater treatment plant*

P removal from wastewater occurs at a wastewater treatment plant (WWTP), where the influent wastewater is treated via a series of unit operations to restore the wastewater to a given standard before discharge to a receiving water body [27].

2.1.2.1 Phosphorus removal

Generally P removal can be part of primary, secondary, or tertiary treatment processes depending on the WWTP configuration [28]. With reference to the simplified schematic of the Rya WWTP in Fig. 2.1 on the following page, primary (or physical) treatment removes the majority of solids via bar screens and subsequently settling tanks, where primary sludge settles and can be removed [29]. Secondary (or biological) treatment makes use of forcefully mixing wastewater with bacteria and oxygen to digest pollutants, and can be tailored specifically, such as for nitrogen (N) removal at the Rya WWTP [29]. Tertiary (or advanced) treatment removes dissolved substances, namely colour, metals and nutrients through a physical, chemical or biological process, such as microscreens in the form of discfilters to remove P at the Rya WWTP [30] [31].

This project focussed on chemical addition to the raw wastewater before primary treatment, termed chemically enhanced primary treatment (CEPT), or pre-precipitation [22], modelling the discharge of alum DWTP sludge from the DWTPs through the partly combined sewer system to the Rya WWTP.

2.1.2.2 Pre-precipitation and co-precipitation

With pre-precipitation, the formed precipitates are removed together with the primary sludge, and the wastewater continues to secondary (biological) treatment, as shown in Fig. 2.1 below [17]. Commonly used chemicals in pre-precipitation include a variety of aluminium compounds, of which hydrated aluminium sulphate (alum) is the most common [22] [32]. However, the full potential of some chemicals for phosphorus removal may not be realised solely in primary treatment, such that phosphorus removal is a combination of chemical and biological treatment [33], termed co-precipitation [34]. This describes the use of iron salts, such as ferrous sulphate in the Rya WWTP, which is used with a non-nitrifying activated sludge system with co-precipitation of phosphorus [35] [36]. The formed precipitates are removed either from primary settling together with the primary sludge or from secondary settling with waste biological sludge, as shown in the schematic of Fig. 2.1 below [17].

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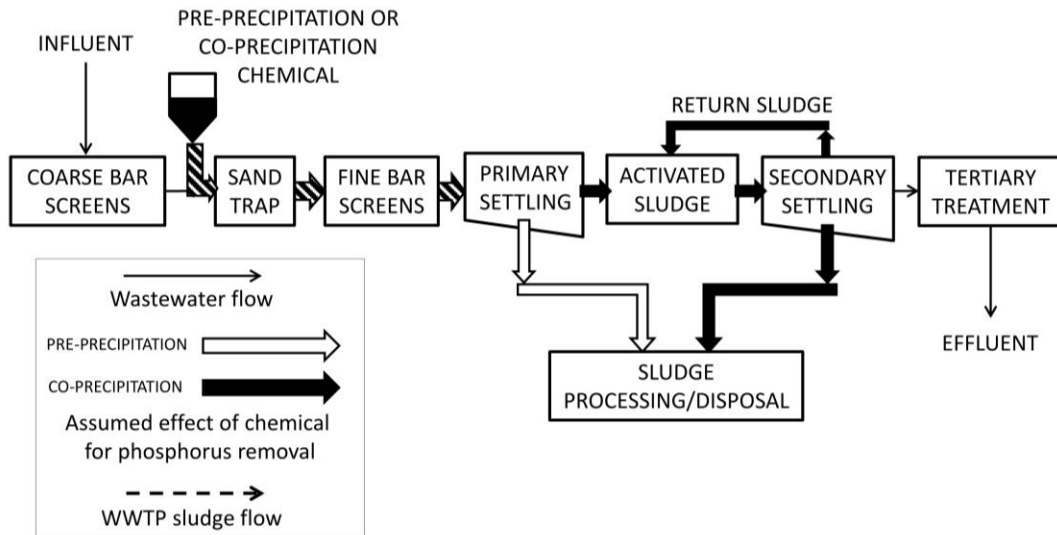
Fig. 2.1 Simplified schematic of pre-precipitation (CEPT) and co-precipitation chemical influence at the Rya WWTP, adapted from Isaias et al. [37], Barr [18] and Gryaab AB [38]

2.1.2.3 Pre-precipitation effects on other parameters

With pre-precipitation, the addition of chemicals often has a multitude of effects apart from solely phosphorus precipitation. Commonly, the metal (aluminium (Al), and iron (Fe)) salts used for chemical P removal can be also used for enhanced particulate, colloidal BOD_5 (5-day biochemical oxygen demand) and SS (suspended solids) removal [22]. As a result, truly soluble, particulate, colloidal and condensed phosphate species can be removed via precipitation, coagulation, flocculation, adsorption and sedimentation during pre-precipitation.

Takács et al. [39] among many others [18] [12] [40] [41] [32] [42] concluded that while chemical phosphorus removal with metal salts is widely used and relatively straightforward to design, complex precipitant and/or adsorption reactions and mechanisms of P binding to metal complexes is not fully understood. Barr [18] highlighted that several factors, both known and unknown, may affect the efficiency of P removal, and the situation is more complex for wastewater, which is heterogeneous by nature, such that reactions are often incomplete and numerous side reactions can occur.

Nonetheless, at present a variety of metal salts can be employed at a number of different locations in the process stream in a WWTP. While ferrous sulphate, ($FeSO_4 \cdot 7H_2O$ in its most common commercial form [43]), is used at the Rya WWTP, a commonly used Al salt in phosphorus removal is aluminium sulphate (alum), ($Al_2(SO_4)_3 \cdot 14H_2O$ in its commercially used form [22]) [27].

2.1.3 Aluminium sulphate and alum DWTP sludge

Alum is also valuable as a flocculating agent in the coagulation and flocculation treatment steps in DWTPs to remove turbidity, colours, humic substances, tastes and odours [44] [45]. Coagulation involves the addition of coagulant chemicals to form larger particles [46], while flocculation, aided by gentle mixing, is the gathering together of particles in the water, forming flocs, which settle and can be removed as sludge in a settling step, such as a sedimentation basin [46].

As shown in the simplified schematic of Fig. 2.2 below, the Alelyckan and Lackarebäck DWTPs operate comparable processes, with four major physical-chemical steps of chemical coagulation and flocculation with aluminium sulphate, sedimentation, and filtration and adsorption, as well as the chemical operations of pH adjustment and disinfection (chlorination) [2] [6] [59] [60].
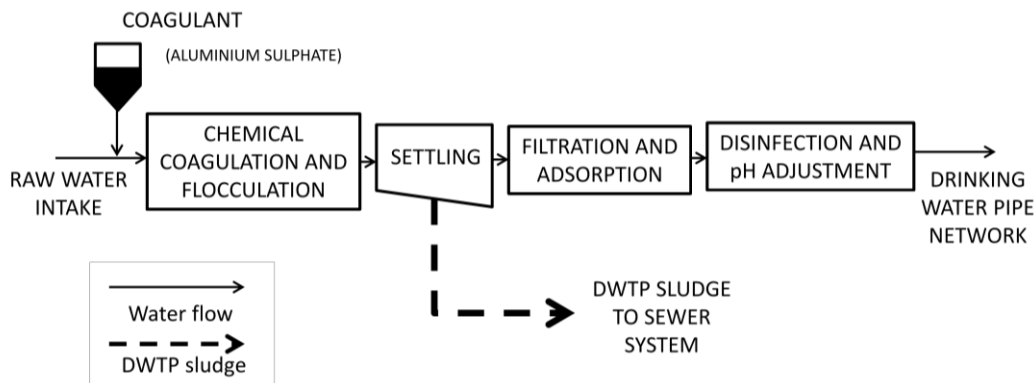
Fig. 2.2 Simplified schematic of Alelyckan and Lackarebäck DWTPs, adapted from van der Schraft [47]

Studies of DWTPs in Canada using alum as a coagulant [48] confirmed that more than 99.98% of the total (dosed) aluminium left the plant in the form of sludge, such that only a small fraction of Al remains in drinking water in a colloidal or dissolved form. Consequently, it can be assumed with negligible error that all the dosed aluminium leaves the DWTP as sludge and enters the sewer system. While disposal via the sewer system is a marked improvement from earlier practices of discharging to the nearest water body [12], it may be environmentally unsustainable, in contrast to the environmental aims of Gothenburg [49]. During wet weather, the partly combined sewer system in Gothenburg relies on overflows into the River Göta to prevent excess water overloading the sewer system [4]. While DWTP sludges are currently classified as non-hazardous in the European List of Wastes [50] (code number 19 09 02) with no specific legislation concerned with DWTP sludge disposal [12], several studies [51] [52] suggested that several forms of aluminium, of which alum DWTP sludge contains

high levels [53], are toxic to aquatic life. However, in a literature review Babatunde & Zhao [12] noted there exists limited research, such that the magnitude of potential toxicity effects due to DWTP sludge and its metals contents and their relevance to the cirumneutral pH typical of water bodies require further investigation.

Kim et al. [54] determined alum DWTP sludge contained significant amounts of aluminium hydroxide, aluminium organic complexes and water-soluble aluminium, and suggested, along with several others [53] [55] [54] [56] [57] [58] [45], alum DWTP sludge can remove phosphorus as various species of phosphate by means of its aluminium components.

2.1.4 *Phosphorus removal by alum DWTP sludge*

2.1.4.1 Aluminium and alum in water

The fate and behaviour of aluminium, and hence also aluminium salts, in aqueous solutions is complex [48]. Hossain & Bache [59] concluded that when aluminium salts were released into water, such as in the flocculation and coagulation processes in a DWTP, most of the aluminium hydrolyses to form aluminium hydroxides, as detailed in studies by Driscoll and Schecher [60], Howells et al. [61] and Sullivan & Singley [62]. Kim et al. [54] reported the amorphous form of aluminium (probably low soluble $Al(OH)_3(s)$ [63]) represented over 75% of the reactive aluminium in spent alum sludge from DWTPs, congruent with Georgantas et al. [45] and several others [43] [64] [65] [66] concluding that spent alum sludge from DWTPs is predominantly amorphous aluminium hydroxide. Consequently, for alum DWTP sludge, mechanisms of P removal by aluminium hydroxides are dominant.

2.1.4.2 Mechanisms of phosphorus removal by aluminium hydroxides

Guan et al. [67] and many others [68] [69] [70] [71] [72] [73] [74] [75] proposed that phosphates (including orthophosphates, polyphosphates and tripolyphosphates) are adsorbed onto metal (hydr)oxides by forming monodentate, bidentate or binuclear complexes through a ligand exchange mechanism. The ligand exchange mechanism, a reaction with hydrous oxides, involves the phosphate ions (in solution) replacing OH groups on the surface of the hydroxylated oxides (on the alum sludge surface), such that the OH groups and the phosphate ions undergo a substitution [69] [76] [77] [78], as suggested by Rajan [79] in a proposed exchange reaction with HPO_4^{-2} in Fig. 2.3 below.

Fig. 2.3 Adsorption of HPO_4^{-2} by ligand exchange, adapted from Rajan [79]

Sims & Ellis [80] and others [68] [70] studied further intricacies of the ligand exchange mechanism. Proposed reactions from Rajan [79], and more recently Yang et al. [68] and Kamiyango et al. [70], were substantiated by Georgantas & Grigoropoulou [69] whereupon experiments showed that the uptake of phosphates was associated with an increase of pH in the solution, as would be expected with the ligand exchange mechanism releasing OH^- ions in the solution [68] [76] [77] [80] [81].

However Georgantas & Grigoropoulou [69] and Yang et al. [68] noted that the actual reaction is expected to be yet more complex. Reddy & DeLaune [77] also proposed that organic anions also compete strongly with phosphate for ligand exchange sites.

2.1.5   *Phosphorus removal by metal salts*

When traditional metal salts such as alum and ferrous sulphate are used for P removal, chemical precipitation is expected to be the dominating mechanism [21] [17] [41].

2.1.5.1 Aluminium sulphate

Several authors [21] [19] [82] [83] stressed that the required alum dose in wastewater treatment is larger than the theoretical stoichiometric precipitation reaction of P with alum (molar ratio (Al:o-P) of 1:1) due to reactions with other constituents of wastewater, such as organics, or side reactions in the form of hydroxides [84]. Accordingly, Guyer [83] and others [18] [35] reported actual case studies required a higher molar ratio (Al:o-P) of 2:1, while design manuals [26] recommend molar ratios (Al:o-P) of between 1.72:1 and 2.3:1 for P removal of between 85% and 95% from municipal wastewater.

2.1.5.2 Ferrous sulphate

Many uncertainties surrounding P removal with alum are applicable to other mineral precipitants, including ferrous sulphate [28]. However, knowledge of the dose of iron sulphate at the Rya WWTP, and the cost of purchasing (560 kr/tonne, 2013 [85]) would enable an economic evaluation of the effectiveness of alum DWTP sludge in P removal compared to current precipitation chemicals. Based on operational data from the Rya

WWTP for 2012 and 2013, the current weight ratio of iron sulphate (Quickfloc S, 17.6% Fe^{2+} [85]) to total P was determined as 7.6:1, as shown in Table 2.2 below.

Total P influent* (mg/l) [86]	3.4
Total P before tertiary treatment (discfilters) (mg/l) [30] [87]	0.3
Total P removal by iron sulphate** (mg/l)	3.1
Total wastewater pumped to plant, 2013 (Mm^3) [88]	119.5
Total P removal by iron sulphate, 2013 (tonnes)	370.5
Iron sulphate dosed, 2013 (tonnes) [88]	2822
Weight ratio, iron sulphate (Quickfloc S, 17.6% Fe^{2+}):total P	7.6:1

*Rya WWTP influent modelled by samples from Tankgatan sampling station, October 2012 data [86]
**Total P removal in primary and secondary treatment attributed entirely to iron sulphate addition

Table 2.2 Calculation of weight ratio, iron sulphate (Quickfloc S, 17.6% Fe^{2+}):total P

2.2 Practical insight in Gothenburg

A practical overview of the system of DWTPs and the Rya WWTP in Gothenburg is followed by consideration of handling (thickening and dewatering) alum DWTP sludge.

Secondly, while the effects of alum DWTP sludges on total P, organics content and solids (primary and secondary settling) in primary treatment were analysed experimentally, probable and confirmed effects of handling alum DWTP sludge on other major treatment operations at the Rya WWTP are evaluated via a brief literature review, drawing on past research from the Rya WWTP and other studies case studies nationally and globally.

Finally, previous assessments, relevant future proposals and rough economic evaluations of the effects of alum DWTP sludge on the Rya WWTP are considered.

2.2.1 *Drinking water treatment plants*

As shown in as shown in Fig. 2.4 opposite, the southern branch of the Göta älv (River Göta), flowing southwest through the west coast of Sweden, serves as a major raw water intake for the drinking water supply at Lärjeholm, to the north-west of Gothenburg.
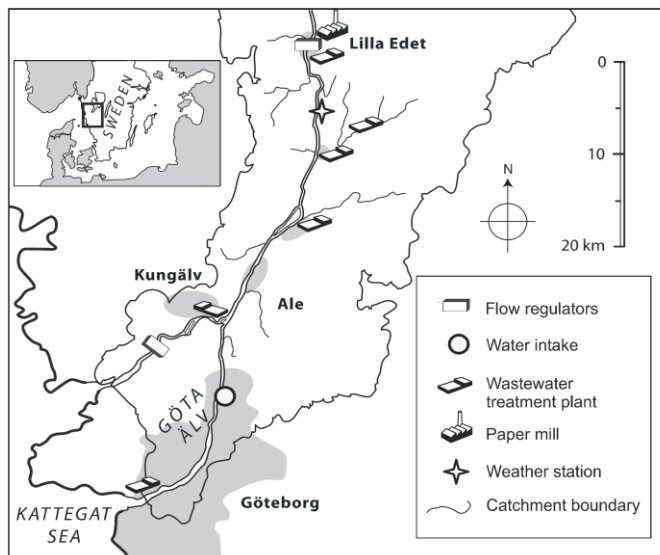
Fig. 2.4 The River Göta catchment, with catchment boundary, locations of WWTPs, PSPs and raw water intake, adapted from Lindhe et al. [3]

DWTP	Total solids from DWTP sludge (tonnes)
Lackarebäck	509
Alelyckan	895
Lerum	36
Mölndal	160
Härryda	24
Total	1624

Table 2.3: Total solids from DWTP sludge received at Rya WWTP, 2012, from Tumlin [6]

Of the seven municipalities which own the Rya WWTP, DWTP sludge is received at the Rya WWTP from Ale (included in Gothenburg), Härryda, Lerum and Mölndal [6]. As shown in Table 2.3, the Alelyckan and Lackarebäck DWTPs accounted for over

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85% of total solids from DWTP sludge received at the Rya WWTP in 2012. Consequently, since the contribution from Härryda, Lerum and Mölndal was relatively small, this project focussed on Alelyckan and Lackarebäck.

2.2.1.1 Alelyckan and Lackarebäck system description

Alelyckan DWTP, to the north-west of Gothenburg, and Lackarebäck DWTP, to the south-west, are each responsible for about half of an (average) 168,000 m^3 of drinking water produced each day for the city [3] [89]. While both DWTPs use a similar treatment process with aluminium sulphate as a coagulant, the raw water intake for the Alelyckan and Lackarebäck DWTPs can differ, resulting in fluctuating qualities and quantities of DWTP sludge [90]. Shown schematically in Fig. 2.5, a unique system of tunnels and reservoirs is used [90].
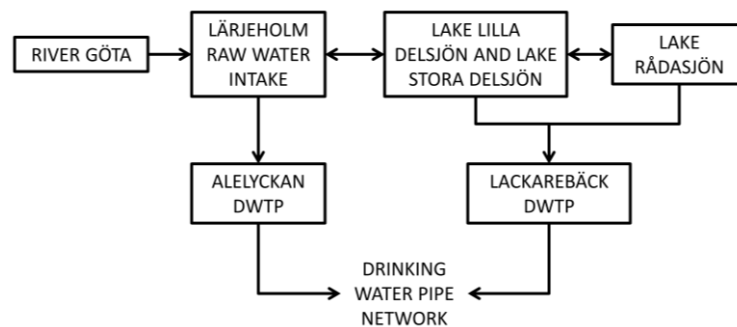
Fig. 2.5 Schematic of water supply in Gothenburg, adapted from Nilsson [91]

From the Lärjeholm raw water intake water can be pumped to the Alelyckan DWTP or to the Delsjöarna Lakes (Lake Lilla Delsjön and Lake Stora Delsjön), which along with Lake Rådasjön, act as reservoirs for both DWTPs with a residence time of approximately four months [90]. The residence time is not necessarily the time taken for water pumped from the raw water intake to reach the Lackarebäck DWTP, which could be a few weeks under unfavourable conditions [91]. With monitoring stations upstream on the River Göta, the Lärjeholm intake can also be closed, due to heavy rainfall [3], construction activities near the river [90], saltwater intrusion [3] or accidental discharges or spills of wastewater or chemicals [3], such that both DWTPs receive water only from the Delsjöarna Lakes, for a maximum of 3-4 weeks [3] [90] [89]. The Lärjeholm intake is closed approximately 100 days per year [3].

Mendel [90] reported high amounts of colour, turbidity and bacteria in the River Göta, while water from the Delsjöarna Lakes carried significantly reduced pollutant loads. Although water quality in the River Göta is generally high, with the majority of

parameters within the old Swedish national guidelines ('gamla kungörelsen') given by SLVFS 1993:35 [90], water quality in the Delsjöarna Lakes is substantially better [90], and this is expected to be reflected in the contents of the DWTP sludges.

The residence time in the Delsjöarna Lakes aids the settling of suspended sediments and microorganisms, resulting in lower total solids as DWTP sludge, as validated in Table 2.4. Not only does the Alelyckan DWTP generate significantly greater total solids than

DWTP	Total solids from DWTP sludge (tonnes)		
	2009	2011	2012
Lackarebäck	429	545	509
Alelyckan	721	798	895
Total	1150	1343	1404

Table 2.4 Total solids from Alelyckan and Lackarebäck DWTP sludge received at Rya WWTP in 2009, 2011 and 2012, from Tumlin [6]

Lackarebäck (an average of over 60% more annually for 2009, 2011 and 2012), but also total solids from all DWTP sludge has increased annually, with an average annual increase for 2011 and 2012 of approximately 85 tonnes, an issue discussed further in later sections with regards to current management at the Rya WWTP.

From Table 2.3, the total solids received at the Rya WWTP could be crudely averaged to approximately 4.45 tonnes per day. However, a continuous discharge of sludge is unlikely due to the storage and flushing mechanisms employed at both Alelyckan and Lackarebäck. At the Alelyckan DWTP 1 of 4 settling tanks is flushed weekly, such that the DWTP sludge may have settled for up to 4 weeks before the bulk of the sludge is flushed into the sewer [92], and while at the Lackarebäck DWTP, the DWTP sludge is flushed more regularly, such that the sludge from Alelyckan is 'older', sludge from Lackarebäck is held in storage tanks such that neither DWTP sludge from Alelyckan or Lackarebäck is 'fresh' upon reaching the Rya WWTP [93]. Such fluctuations could pose a challenge for handling DWTP sludge at the Rya WWTP.

2.2.2   *Rya wastewater treatment plant*

As the sole WWTP in Gothenburg, the Rya WWTP treated wastewater from approximately 918,000 population equivalents (including industry and based on water consumption) in 2013 [88]. Wastewater flows through a partly combined sewer system with transport time at dry weather flow between 16 and 20 hours [38].

2.2.2.1 Wastewater treatment

Wastewater flows up to 10 m^3/s receive full biological/chemical treatment. As explicated in Fig. 2.1 earlier, this involves screening, iron sulphate addition, primary

sedimentation, activated sludge with pre-denitrification, secondary sedimentation, post-nitrification in trickling filters, post-denitrification and finally disc filters, after which treated water is released into the mouth of the River Göta [38] [94]. As explicated by Mattsson et al. [36], for peak wet weather flows (WWF) greater than 10 m^3/s, or when the capacity of secondary treatment is reduced, excess wastewater can be treated without further biological treatment via temporary on-demand direct precipitation in existing primary clarifiers [95], with an average use of 55 days per year between 2006 and 2010 [36]. Such a scenario would not only dilute the DWTP sludge, but also the aforementioned combined sewer overflows may reduce the quantity of DWTP sludge in the influent wastewater.

2.2.2.2 Sludge handling

As well as expected effects on primary treatment, alum DWTP sludges were expected to influence the handling (thickening and dewatering) characteristics of sludge, and consequently influence the most appropriate sludge processing method.

At the Rya WWTP, primary and secondary sludge undergoes belt gravity thickening (with polymer addition) before it enters a digester, along with fats, oils, grease (FOG) and food waste from local restaurants and commercial kitchens [96] [97] [94]. Over 65 GWh of biogas from anaerobic digestion, almost twice the energy consumption of the Rya WWTP [88], was sold and upgraded in 2013 [98] [38]. Finally, the sludge is dewatered via centrifugation (with further polymer addition) for composting as a soil enhancer (or disposal) [38] as shown in the schematic of Fig. 2.6 below.
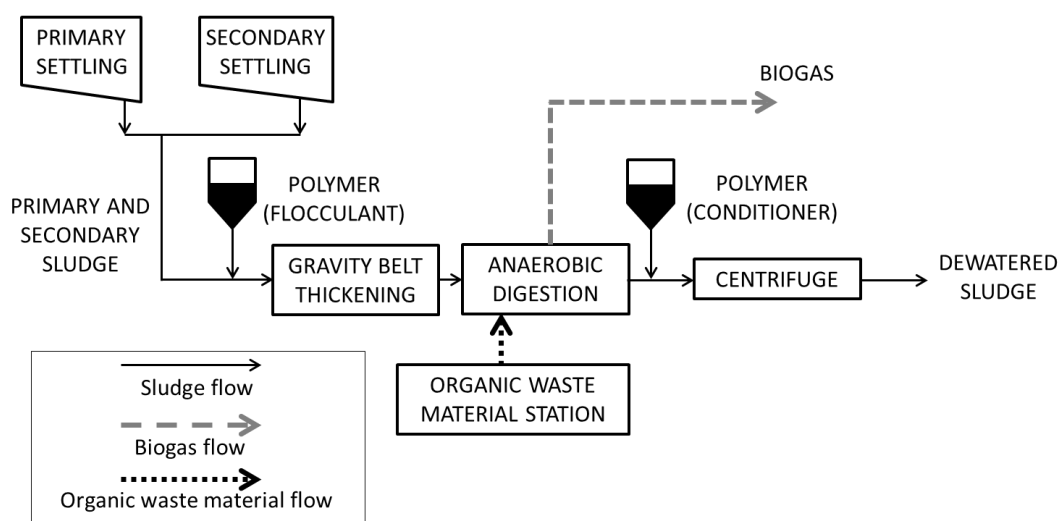
Fig. 2.6 Simplified schematic of sludge processing/disposal at the Rya WWTP, adapted from Gryaab AB [38]

Sludge thickening and dewatering

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Sludge thickening reduces the volume of the sludge for subsequent processing steps [28], although the product retains the properties of a liquid [99]. Common thickening processes include filtration, which can be mechanical, gravity or vacuum based [100]. Sludge dewatering uses mechanical dewatering equipment, such as centrifuges (typically at 1800-3500 rpm [101]), to remove more water and produce material with the properties of a solid [28] [99].

Water distribution and removal in sludge

Sludges can be visualised as consisting of flocs, acting hydrodynamically as single particles [84], where water exists in sludge as identifiable forms, such as in the classification by Vesilind & Martel [102] shown in Fig. 2.7 below.
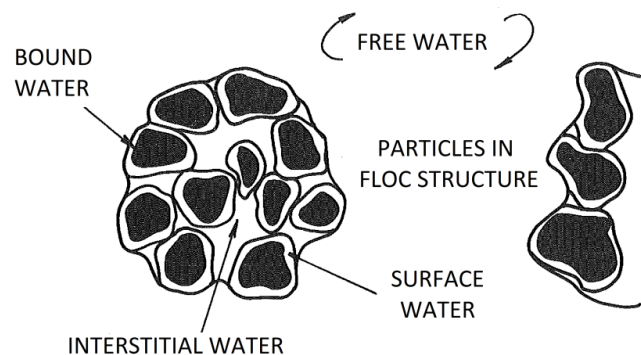
Fig. 2.7 Classification of water distribution in sludge, adapted from Vesilind & Martel [102]

Free water is not bound to the particles and surrounds the sludge flocs, and can be removed by simple gravity or vacuum filtration [102] [103]. Interstitial water is held within the floc structure and can be removed when the floc is broken up by mechanical dewatering devices such as centrifuges [102] [104]. Surface water and bound water can only be released by thermochemical destruction of the particles [102] [105] [106]. Sludge dewatering and thickening processes focus on removal of free and interstitial water, which compose the majority of the water in sludge [106].

Alum DWTP sludge handling

Power et al. [107] noted that alum DWTP sludge can be difficult to thicken and dewater. Wang et al. [64] suggested this behaviour is due to the high affinity of aluminium hydroxide for water, while Pan et al. [108] attributed poor dewaterability to organic materials in the source raw water (at the DWTP) producing smaller flocs with a higher water content.

At WWTPs, Wilson et al. [109] described high concentrations of alum DWTP sludge producing a WWTP sludge that was "difficult to handle", while Öman [7] concluded

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that not only was dewatering deteriorated, but polymer consumption (and hence cost) increased by 11%. Sludge dewatering methods often rely heavily on polymer addition (sludge conditioning) to achieve desirably high percentages of dry solids by weight (in the range 18 to 25% wt. DS. for alum DWTP sludge [110]) [111]. Investigation into appropriate conditioning of alum DWTP sludge was beyond the scope of this project, and has been studied in detail by Wu et al. [111] and Zhao & Bache [110]. However, analysis of the water distribution in the Alelyckan and Lackarebäck sludges enabled a basic evaluation of an appropriate sludge processing method.

2.2.2.3 Further effects of DWTP sludge

Experience and conclusions were attained from comparable treatment processes at the Bromma and Himmerfjärden WWTPs in Stockholm county, Sweden, where pilot-scale testing on handling alum DWTP sludge was carried out [8] [112] [113]. Of note were the effects on influent wastewater, biological treatment, biogas production and heavy metals concentrations in WWTP sludge.

Influent characteristics

Starberg [14] reported a general increase in incoming chemical oxygen demand (COD) while incoming phosphorus content remained unchanged. This corresponds with results from Salotto et al. [9], and estimates from the Rya WWTP which suggested less than 0.2% P in the WWTP sludge originated from the DWTP sludge, as shown in Table 2.7 below. Increases in COD could be attributed to a high organics content of the DWTP sludge, with the Bromma WWTP noting approximately 50% aluminium hydroxide and 50% organics content [7].

An increase of sludge at the primary sludge outlet in was noted at the Bromma WWTP, [7]. Salotto et al. [9] determined the majority of DWTP sludge settled out with the primary sludge in the WWTP, and following an aluminium mass balance at the Bromma WWTP, a similar conclusion was reached [7]. This increase of sludge, estimated as 10% of total solids at the Rya WWTP in 2012 as shown in Table 2.5 on the following page, is expected to have effects on existing sludge handling equipment as noted by Wiechers [114]. Operational experience from the Bromma WWTP noted that bar screens required more maintenance, pump efficiency was reduced in pipelines upstream of primary treatment, along with higher probabilities of pipes clogging when the DWTP sludge had a significant solids content [7].

Parameter		Estimated amount in DWTP sludge, 2012* [kg/year]	Estimated amount in Rya WWTP sludge, 2012 [kg/year]	DWTP sludge share of total amount, 2012 [%]
Solids	Total Solids	1624000	15982000	10
Metals	Zn	113	11783	1.0
	Cd	0.2	15	1.3
	Pb	19	486	3.9
Phosphorus	Total P	730	471000	0.2

* Alelyckan (2009) and Lackarebäck (2012) DWTPs

Table 2.5 Estimated pollutant load in DWTP and WWTP sludge for 2012, from Tumlin [6]

Biological treatment

As noted earlier, the effects of DWTP sludge were expected to be limited to primary treatment [7] [8] [9], coinciding with no effect noted on biological treatment processes at the Bromma WWTP [8], and no significant benefit or detriment noted by Culp & Wilson [115]. Effects on biological treatment for nitrogen (N) removal, although expected to be minimal, were beyond the scope of this study, although extensive work was done by Salotto et al. [9] and Hsu & Pipes [116] on the effects of alum DWTP sludge and aluminium hydroxide on the activated sludge process and secondary settling of activated sludge.

Anaerobic digestion and production of biogas

At the Bromma WWTP, biogas production did not increase corresponding to the increased organic material fed to the anaerobic digesters with DWTP sludge [7]. Starberg [8] contended this was due to inert chemical solids from the DWTP sludge taking up space in the reactor (rather than directly inhibiting the digestion process), a view shared by Boyke & Rupke [117] and several others [7] [9] [118]. A reduction in biogas production could also be due to a reduction in residence time in the digesters due to increased sludge flow, as noted by Öman [7].

Heavy metals and REVAQ certification

The heavy metals of cadmium, zinc and lead were identified by Tumlin [6] as "priority metals" for the Rya WWTP for the proposed limits on metals concentrations in WWTP sludge introduced by the Swedish EPA [7]. Considering Table 2.5, while the DWTP sludge accounted for 10% of total solids in 2012, it accounted for proportionally less cadmium, zinc and lead. Furthermore, Table 2.6 on the following page suggests a dilution effect of the DWTP sludge, to the extent that without the addition of the DWTP sludge the Rya WWTP sludge would exceed proposed limits from the Swedish EPA on zinc concentrations for 2015.

Parameter		Average in Rya WWTP sludge including DWTP sludge, 2012 [mg/kg TS]	Average in Rya WWTP sludge excluding DWTP sludge, 2012 [mg/kg TS]	Proposed maximum for 2015 [mg/kg TS]	Proposed maximum for 2023 [mg/kg TS]
Metals	Zn	770	813	800	750
	Cd	0.95	1.0	1.0	0.9
	Pb	32	33	35	30
	Ni	19	19	40	35

Table 2.6 Effect of DWTP sludge on pollutant load in WWTP sludge for 2012, from Tumlin [6]

Similar conclusions were reached at the Bromma WWTP, where the addition of DWTP sludge resulted in approximately 20% reduction in metals concentrations in WWTP sludge (lead, cadmium, cobalt, chromium, copper, mercury, manganese, and zinc) [

2.2.3   *Economic analysis of alum DWTP sludge effects*

Primary concerns in an economic evaluation of the effects of alum DWTP sludge on the Rya WWTP were future quantities of DWTP sludge (affecting operating costs) and the installation of sludge hygienisation at the Rya WWTP (affecting investment costs).

2.2.3.1 Quantity of DWTP sludge

The future quantity of DWTP sludge is highly dependent on the operations of the DWTPs and the dose of aluminium sulphate as a flocculant. Tumlin [6] contended that future decreases in raw water quality from the River Göta could result in higher doses of flocculant at the Alelyckan DWTP and increased DWTP sludge generation. Conversely, at the time of this study, an ultrafiltration plant was under construction at the Lackarebäck DWTP [119]. When in operation, this membrane filtration system was expected to reduce flocculant dose requirements at the Lackarebäck DWTP, such that DWTP sludge generation was decreased [6]. Despite the annual increases in total solids from DWTP sludge detailed in Table 2.4, Kretslopp och vatten, Göteborg Stad believe future quantities of DWTP sludge will be unchanged [6].

2.2.3.2 Hygienisation of sludge at the Rya WWTP

Hygienisation processes, such as thermophilic digestion or thermal hydrolysis [120] [121], are designed to kill harmful microorganisms before reusing sludge in for agriculture or for making soil by REVAQ certification (Ren Växtnäring från Avlopp – pure nutrients from sewage) [122]. In 2012 less than 6% of total sludge from the Rya WWTP went to agriculture [38], and options for improving the hygienisation of WWTP sludge are under consideration for increasing REVAQ sludge quantities [122]. While development of a hygenisation process at the Rya WWTP was still in the early planning

stages at the time of writing this report, it was believed such an investment would be increased by handling the DWTP sludge [6] [122].

2.2.3.3 Operating and investment Costs

Operating and investment costs of handling alum DWTP sludge at the Rya WWTP were rough economic estimations obtained from previous assessments and future proposals. Operating costs are summarised in Table 2.7 below. The foremost investment cost surrounded the development of the hygienisation processes, expected to cost in the region of SEK 100-200 million [6]. Rough estimates from Tumlin [6] suggested handling DWTP sludge increased investment costs by SEK 10-20 million depending on the specific hygienisation process and its location in the treatment process [122].

DWTP sludge effect	Justification of cost	Operating cost (per year)
Operating costs of sludge handling*	DWTP sludge estimated as 10% of total sludge (based on total solids). Cost is 10% of electricity use, polymer and water consumption for treating sludge, transport and disposal cost. Includes 10% income from biogas sales.	SEK 2.76 million
Lost income from biogas production	Lost income from equivalent quantity of sewage sludge, assuming no biogas production by DWTP sludge.	SEK 1 million
Nitrogen removal from DWTP sludge supernatant	Highly dependent on future cost of nitrogen removal [6].	SEK 0.2 – 1 million
Total costs of handling DWTP sludge at Rya WWTP		SEK 3.96 – 4.76 million (≈ £356,400 - £428,400)

*Excluding staff costs and potential increased wear in equipment, due to lack of conclusive data

N.B. All costs based on 2011 financial data and analysis detailed by Tumlin [6]

Table 2.7 Operating costs of handling alum DWTP sludge at the Rya WWTP

It was expected, should the alum DWTP sludge be useful for P removal, that the DWTP sludge offered savings in the use of ferrous sulphate as a precipitation chemical at the Rya WWTP. Attempts to quantify this saving based on experimental data, and comparison to the above estimated operating costs, formed the basis of the economic evaluation of the effects of alum DWTP sludge at the Rya WWTP.

2.3 Literature and methodological Review

An overview of chemical characterisation of alum DWTP sludges from recent literature is followed by a review of experimental handling of alum DWTP sludge samples and applicability to ensuring a practically relevant project.

Conclusions from literature evaluating alum DWTP sludge effects on total P removal, organics content and solids (primary and secondary settling) among other effluent quality parameters are summarised.

Finally, consideration of the factors affecting P removal with alum DWTP sludge is presented while detailing limitations and assumptions for a pragmatic experimental design. Attention is also given to the challenge of accurately measuring total P.

2.3.1 Chemical composition of alum DWTP sludge

With alum typically dosed at a rate of 10 to 150 mg/l (or approximately 1.58 to 23.66 mg/l as Al) as a coagulant in DWTPs [123], it was expected that the Al component of alum DWTP sludge dominated its chemical composition. Babatunde et al. [72] noted that the Al component could be 1-5 orders of magnitude greater than all other elements.

DWTP sludge could also contain substantial proportions of inorganic suspended solids and organic matter. Inorganic suspended solids includes mineral solids, of which iron and calcium typically dominate in alum DWTP sludge, while organic matter includes humic substances, plankton, algae, and bacteria [14]. Mineral solids such as iron and calcium were expected to have a beneficial effect on P removal, due to common use as metal salts for P removal [84], while Ghassemi & Recht [124] suggested organics could reduce phosphate precipitation efficiency through formation of soluble organic-metal complexes (as proposed in Fig. 2.8 below) rather than metal-phosphate precipitates.
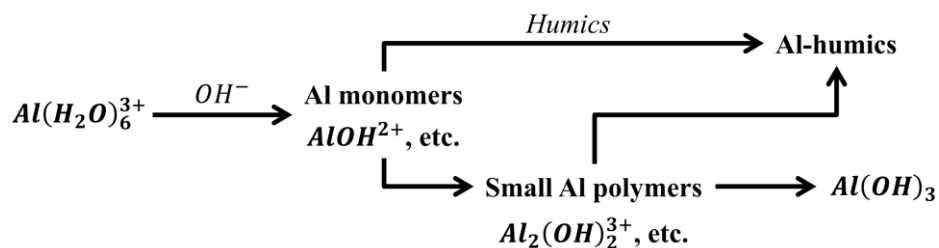
Fig. 2.8 Alum coagulation of humic substances, adapted from Rebhun and Lurie [125]

The summary of chemical compositions of alum DWTP sludges from literature in Table 2.8 on page __ confirmed the dominance of the Al and organics (often analysed as total

organic carbon (TOC)) components. The aforementioned "priority metals" of cadmium, zinc and lead are also included in Table 2.8.

The summary in Table 2.8 also highlighted the variability of both proportional and absolute concentrations of components, attributed to different raw water and treatment processes of DWTPs [68], but also different treatment (handling) of the alum sludge during experimentation. Throughout this project, attempts were made to ensure the handling of the alum sludge during analysis resulted in practically relevant experimentation, as detailed in the review of previous experimental approaches (section 2.3.2) and the limitations and focus on a pragmatic experimental design (section 2.3.3).

2.3.2   *Review of previous experimental approaches*
Relevant studies with alum DWTP sludge and its effects on primary wastewater treatment have been carried out globally, with notable previous studies from Ireland [53] [72] [126] [127] [55] [128], Greece [45] [69] [129], Canada [130] [18] [127] [131] [132], China [56] [133], Korea [54], Australia [134] and Iraq [58]. Evaluation of previous research and the various experimental approaches adopted was required to ensure practically relevant experimentation.

2.3.2.1 Experimental handling of alum DWTP sludge
The gelatinous metal hydroxide content and the aforementioned affinity for water was reported to make experimental handling of alum DWTP sludge challenging [18] [131] [130]. While the moisture content of a collected DWTP sludge sample was dependent on the dewatering processes (if any) employed at the DWTP, of more interest were the different approaches to treating sludge during experimentation.

Sludge collected as dewatered (moisture content 72-75% [55] [53] [128]) was commonly ground, sieved and analysed. Without dewatering, Georgantas & Grigoropoulou [69] and Georgantas et al. [45] used the sludge 'as collected' from the bottom of a sedimentation tank at the DWTP. By far the most common approaches to handling the sludge were air drying [53] [134] [54] [72] [133] (moisture content approximately 10% [53]) or oven drying [58] [57] [56] (no moisture) and grinding to a powder which could be handled in a dry or re-suspended form [57].

Parameter		Unit*	Sample number (see below)											
			1	2	3	4	5	6	7	8	9	10	11	12
Solids	% solids	%	-	25.6	56.2	23.0	53.8	-	-	-	-	-	69.9	57.8
Metals	Al as Al_2O_3	mg/g	110	151	177	170	137	461	43	297	38-125	15-300	-	-
	Fe as Fe_2O_3	mg/g	17	8.6	5.7	6.7	16.6	12.1	3.3	102	16.3-26.1	5-66	-	-
	Ca as CaO	mg/g	7.2	-	-	4.0	-	11.7	0.82	29	4.5-54.6	3-50	-	56
	Zn	mg/kg	-	20.8	17.2	65.0	14.2	-	30.0	33.9	1.7-50	-	150	79
	Cd	mg/kg	0.3	< 1.10	< 0.49	0.51	< 0.50	-	-	0.50	-	-	1.10	<0.30
	Pb	mg/kg	<1	3.6	3.0	19.0	7.5	-	5.0	44.0	5-32	-	43.0	6.0
Phosphorus	Total P	g/kg	0.99	-	-	0.58	-		0.12	3.50	0.5-4.4	0.2-4.4	0.80	0.58
NOM	TOC	g/kg	78	-	-	173	-	97	98	-	-	8.5-225	-	-
pH	pH	-	6.8-7.1	7.2	5.9		6.7	-	-	7.0	-	5.0-8.2	-	-

* /kg or /g is per kg or g of DWTP sludge; air dried, dewatered or untreated as detailed below   - not analysed

Sample	Location	Date	Reference	Treatment
1.	Loveland , Colorado, USA	2011	[71]	Air dried
2.	Charlotte, Florida, USA	2001	[135]	None
3.	Desoto, Florida, USA	2001	[135]	None
4.	Kildare, Ireland	2014	[126]	Dewatered
5.	Sarasota, Florida, USA	2001	[135]	None
6.	Dublin, Ireland	2006	[53]	Dewatered

Sample	Location	Date	Reference	Treatment
7.	Kildare, Ireland	2009	[72]	Dewatered
8.	Literature review from Babatunde & Zhao	-	[12]	-
9.	Literature review from DeWolfe	-	[136]	-
10	Literature review from Makris & O'Connor	-	[137]	-
11.	Alelyckan DWTP, Gothenburg	1993	[13]	None
12.	Alelyckan DWTP, Gothenburg	2009	[13]	None

Table 2.8 Major chemical composition of alum DWTP sludge from literature

Parameter	Unit	Concentration		
		Tankgatan, 2006/2007*	Tankgatan, October 2012	Tankgatan, November 2012**
Suspended solids	mg/l	294	200	170
NOM (as TOC)	mg/l	40	-	-
Total N	mg/l	14	24	16
Total P	mg/l	1.7	3.4	1.8

*substantial dilution noted due to unusually high precipitation [86]   - not analysed

**dilution noted due to high precipitation throughout November 2012 [86]

Parameter	Unit	Concentration		
		'Weak'	'Medium'	'Strong'
Total solids	mg/l	300	700	1250
Suspended solids	mg/l	70	200	450
NOM (as TOC)	mg/l	80	150	280
Total N	mg/l	20	50	90
Total P	mg/l	5	10	18
Alkalinity (as $CaCO_3$)	mg/l	50	100	160

Table 2.9 Major chemical composition of municipal wastewater from Tankgatan sampling station, adapted from Davidsson & Mattsson [86]

Table 2.10 Classification of municipal wastewater by major chemical composition from Sincero & Sincero [138]

2.3.2.2 Sludge processing

Without dewatering, alum DWTP sludge was expected to have a solids concentration of around 1% if automatically removed from the sedimentation tank, or 2% if manually removed [139]. While considerable literature exists on treatment and disposal of alum DWTP sludge, Droste [140] and several design manuals [141] [142] stress that every sludge should be considered separately due to significant site-specific influences. Nonetheless, mechanical dewatering, including vacuum filters, filter presses and centrifuges, has been reported to achieve up to 20% solids [143], while alternative techniques reported achieving higher solids concentrations, including sludge freezing (25-30%) and drying beds (30-50%) [144]. Numerous plant-based studies [145] [146] [147] have concluded centrifugation to be practically (and economically) effective for alum DWTP sludge processing.

2.3.2.3 P removal rates and alum DWTP sludge doses

Pilot-scale testing at the Bromma WWTP, showed an increase in P reduction in primary treatment from 21% to 32% with an average of 433 kg Al/day as DWTP sludge [7]. However, few laboratory studies focussed on a practically relevant setup, with the majority modelling wastewater [53] [55] [54] [56] [57] [58] [45], commonly as KH_2PO_4 [69] [45] [55] [128] [57], focussing analysis on particular phosphate species, specifically o-P [58] [57] [134] [53], condensed phosphates [133] [55] and organic phosphates [54], or modelling the alum sludge as aluminium hydroxide [118] [116].

However, Georgantas & Grigoropoulou [69] completed a practically applicable study based on jar testing, with alum DWTP sludge collected from a primary sedimentation tank and dosed, untreated, into municipal wastewaters without pH control, summarised in Table 2.11 below.

Study	Molar ratio (Al:PO_4^{-3})	% Total P removal (%)
Georgantas & Grigoropoulou (1) [69]	0.68:1	11%
	1.35:1	18%
	2.04:1	31%
	3.40:1	46%
Georgantas & Grigoropoulou (2) [69]	0.96:1	18%
	1.90:1	37%
	2.87:1	50%
	4.78:1	64%

Table 2.11 Total P removal from wastewater in jar testing with spent alum DWTP sludge from literature

Total P measurement

Thermal acidic persulphate digestion was traditionally used for in the analysis of total P [148], converting the P into o-P, which could be measured by ion chromatography [129] [149], or more commonly via a colorimetric or spectrophotometric method using appropriate reagents [53] [129] [55] [133] [45].

2.3.2.4 Effects of alum DWTP sludge addition on other effluent quality parameters

Effects of alum DWTP sludge on organics content and solids (primary and secondary settling) among other effluent quality parameters including total N and pH were also evaluated.

Organics, total N and pH

Organics

Dosing untreated alum DWTP sludge into municipal wastewater and measuring organics as COD, Guan et al. [150] reported a maximum of over 15% enhanced COD removal with 75 mg Al/l sludge addition, compared to controls without sludge addition (28 to 38% COD removal). However, dosing 75 mg Al/l required a huge and impractical volume of sludge [150]. After maximum COD removal, decreases in removal could be attributed to significant organic matter being released by the sludge. Georgantas & Grigoropoulou [69] also reported enhanced COD removal (approximately 40% removal at a molar ratio $(Al:PO_4^{-3})$ 4.78:1), while in a plant-based study, Nelson et al. [151] reported no changes in efficiency of COD removal. It was concluded that organics removal depended on the individual characteristics of the sludge, determining whether organics removed by the sludge exceeded the organics released [150].

Total N

Barr [18] evaluated total Kjeldahl nitrogen (organic nitrogen, ammonia (NH_3), and ammonium (NH_4^+)) and ammonia when dosing alum and alum DWTP sludge to municipal wastewater, and concluded insignificant effects on either. Due to low levels of oxidation in primary treatment, nitrate and nitrite concentrations in the influent were negligible, such that no effect on the nitrate and nitrite forms was detectable either. An earlier study by Hsu & Pipes [116], modelling alum DWTP sludge as aluminium hydroxide, reached similar conclusions, with doses of up to 300 mg Al/l having no effect on ammonia, organic nitrogen, nitrite or nitrate.

pH

The aforementioned ligand exchange mechanism suggested pH increases with uptake of phosphates [69]. However, pH variation depends on the alkalinity of the wastewater, or 'buffering capacity' to neutralise acids. The carbonate system and ammonia contribute to the buffer characteristics [152], such that wastewater with alkalinity (as $CaCO_3$) above 80 mg/l could prevent significant quick changes in pH [153].

With the majority of studies modelling wastewater [53] [55] [54] [56] [57] [58] [45], and thus lacking the 'buffering capacity', pH control was required and had a significant effect on P removal [53] [55], influencing the solubility of Al with an optimum P removal around pH 5 to 6 [54] [45] [129]. When dosing alum DWTP sludge to actual municipal wastewater, Huang & Chiswell [134] and Georgantas et al. [45] noted very small increases in pH, citing this natural buffering capacity of wastewater.

Primary settling
Typical measurements of primary settling efficiency were suspended solids (SS) (filterable through 0.45 μm filter paper) in the settled wastewater. Past studies on settling were rare and somewhat inconclusive. Hsu & Pipes [118] modelled alum DWTP sludge by dosing aluminium hydroxide to municipal wastewater and concluded less than 30 mg Al/l as sludge would increase SS. However, with further Al dose SS decreased and it was noted that large doses (above 150 mg Al/l) of aluminium hydroxide in municipal wastewater altered settling mechanisms from 'flocculant settling' to 'zone settling', as described by Fitch [154]. Conversely, Guan et al. [150] did not report any increases in SS when alum sludge was added, reporting only increased removal efficiencies, with a maximum of 90% SS removal with 30 mg Al/l compared to controls without sludge addition (52-66%).

Secondary settling
While several studies [7] [9] confirmed the majority of DWTP sludge settled out with the primary sludge in the WWTP, consideration of alum DWTP sludge effects on secondary settling with activated sludge was included to attempt to clarify the limited conclusions on primary settling. Unfortunately however, past literature was similarly inconclusive. Hsu & Pipes [116] modelled adding aluminium hydroxide to various biological treatment processes, and concluded aluminium hydroxide addition increased the settling velocity of activated sludge from approximately 3.75 cm/min (control, no DWTP sludge) to a maximum of 4.75 cm/min (20 mg Al/l), after which settling velocity

decreased with increased aluminium hydroxide addition. Conversely, a plant-based study with alum DWTP sludge by Camp, Dresser & McKee, Inc. [155] reported only decreased efficiency of secondary settling, consequently requiring either increased secondary settling capacity or addition of polymers to aid settling.

2.3.3   Limitations and focus on a pragmatic experimental design

In addition to the aforementioned pH control, several other experimental design factors could influence P removal with alum DWTP sludge. Limitations of experimental design were defined to ensure practicality and relevance to the Rya WWTP. Jar testing would model primary wastewater treatment at the Rya WWTP with alum DWTP sludge dosed as a precipitation chemical for P removal.

Mixing and settling time and energy

While Lijklema [156] and Gillberg et al. [157] concluded orthophosphate adsorption onto aluminium was significantly influenced by mixing speed, several recent jar-testing studies with alum DWTP sludge [18] [69] [45] [150] modelled the mixing and settling with three distinct mixing periods of rapid mixing, slow mixing and quiescent settling. In this study, selection of the mixing and settling time and energy was based on the approximate 1 hr 40 min retention time for wastewater in primary treatment at the Rya WWTP [38] and recent jar-testing studies with alum DWTP sludge from literature.

pH

The influence of pH on P removal was dependent on the buffering capacity of the wastewater. pH was not controlled in the jar tests as it detracted from practically modelling the Rya WWTP, where pH adjustment would be economically unviable.

Temperature

The temperature of wastewater during primary treatment at the Rya WWTP was approximately 10 ℃ [158], while jar testing was carried out at room temperature (approximately 20 ℃). Hossain [132] reported inconsistent responses of alum DWTP sludge capacity for P adsorption from wastewater when temperature was varied from 5 to 19 ℃. It was therefore assumed that potential effects of temperature variation were insignificant for this study. More of concern in previous literature were the effects of storage conditions on the capacity of alum DWTP sludge to remove P.

Storage and aging of alum DWTP sludge

After 2 months aging at 25 ºC, Georgantas et al. [45] reported a 20% decrease in efficiency of alum DWTP sludge in P removal from synthetic wastewater. Conversely, Yang et al. [128] reported marginal effects of aging on P removal from synthetic wastewater, even after 18 months of storage at room temperature (20 ºC). Potential effects of aging were believed to be attributable to mineralisation of aluminium and structural transformation of aluminium hydroxide [128] [80] [159], and were beyond the scope of this study. Sludge samples collected from DWTPs and stored at approximately 10 to 15ºC were used for approximately 2 months after collection in this study, assuming negligible changes of the alum DWTP sludge characteristics.

Wastewater and alum DWTP sludge samples

The use of synthetic wastewater or modelling alum DWTP sludge with aluminium hydroxide in previous studies did not produce a practically relevant model. This study used actual samples of municipal wastewater and alum DWTP sludge, which although may have introduced uncertainty due to heterogeneities, were sought to model the practical situation at the Rya WWTP accurately.

Alum DWTP sludges collected from DWTPs were handled 'as collected' from the DWTPs as much as possible throughout experimentation. Common approaches from past literature of air drying or oven drying prior to experimental handling were deemed detrimental to ensuring this study was practically relevant, as no sludge treatment (thickening or dewatering) took place at the Alelyckan or Lackarebäck DWTPs.

Finally, to obtain a wastewater sample not 'contaminated' by the regular release of DWTP sludge into the sewer system, influent from the Tankgatan sampling station was considered and assumed to be a representative sample of the influent at the Rya WWTP, with past characterisation detailed in **Table 2.9** on pg __ alongside a classification of municipal wastewater by Sincero & Sincero [138] in **Table 2.10**.

Metal ion dose

The molar ratio (metal: PO_4^{-3}) was commonly used for dose of precipitation chemicals [84] [40]. Previous studies with alum DWTP sludge dosed in municipal wastewater reported a range of ratios ($Al:PO_4^{-3}$) dosed into wastewater, from 0.68 to 4.78 [69]. An approximation of the molar ratio for the current scenario at the Rya WWTP, based on 2012 data is shown in Table 2.12 below.

Total P received at Rya WWTP, 2012 (tonnes) [88]	451
Assumed o-P/total P fraction*	0.75
Total Al dosed at DWTPs, 2012** (tonnes) [15]	215
Molar ratio Al:PO_4^{-3}	0.73

*Based on typical o-P/total P fraction for municipal wastewater of 0.6 to 0.9 [25]
**Based on data from Alelyckan and Lackarebäck DWTPs, assuming all dosed Al is received at Rya WWTP

Table 2.12 Estimation of molar ratio (Al:PO_4^{-3}) for current situation at Rya WWTP

With the molar ratio (Al:PO_4^{-3}) of the current scenario approximated as low relative to past studies, dose of DWTP sludge would be based on modelling the current scenario and higher molar ratios (Al:PO_4^{-3}) of 2:1 and 3:1. In addition to facilitating comparison with literature for DWTP sludge, Barr [18] and O'Blenis & Warriner [131] used a similar molar ratio to compare the capacity of DWTP sludge for P removal with alum, concluding alum DWTP sludge was between 5 and 10 times less effective than alum (as Al). A comparison with alum was deemed more relevant than with the current precipitant of ferrous sulphate in the Rya WWTP due to the latter removing P more effectively in secondary unit operations than primary treatment [17] [22] [33] [84] [124].

Total P measurement

With the aforementioned ligand exchange mechanism, several species of P were removed by alum DWTP sludge, such that measurement of total P was most relevant experimentally (and also practically for wastewater treatment).

Ion chromatography is one of the most commonly used methods of analysis of anions and cations in water and wastewater [160], offering quick, safe and highly sensitive analysis [161] [162]. However, Ruiz-Calero & Galceran [163] and several others [164] [165] expressed concern at the interference of high concentrations of some ions causing false readings of other ions, particularly the high concentrations of sulphate produced with thermal acidic persulphate digestion and its interference with measuring phosphate. Consequently, following thermal acidic persulphate digestion to convert P into o-P, in this study total P was measured using both ion chromatography and a colorimetric method with reagents to determine whether the use of expensive and toxic reagents in the colorimetric method could be replaced with the quicker and cleaner alternative of ion chromatography.

3. METHODS AND MATERIALS

Details of the collection and storage of DWTP sludge and wastewater samples (section 3.1) is followed by a summary of the analysis methodologies for characterisation of the DWTP sludge and wastewater samples (section 3.2 to 3.4). Since the majority of analyses were carried out to standard methods, only the aforementioned total P methodologies (ion chromatography and colorimetric method) and metals analysis are described comprehensively.

Finally the bench-scale jar testing (section 3.5), further solids (settling) with activated sludge (section 3.6) and DWTP sludge handling (section 3.7) setups are outlined.

3.1 Sample collection and storage

All sample collection locations referred to throughout this chapter are shown on the map in Fig. B.2 in Appendix B. All analyses were carried out at the Environmental Chemistry Laboratory at Chalmers University of Technology.

3.1.1 DWTP sludges

Alum DWTP sludge samples were collected from the Alelyckan and Lackarebäck DWTPs on the morning of 20th March 2014. Sludge was manually scraped/collected from the bottom of one of four sedimentation tanks at Alelyckan DWTP (denoted AL), as shown in a) and b) of Fig. B.1 in Appendix B prior to the flushing of the tank. At the Lackarebäck DWTP, sludge was automatically removed from the eight sedimentation tanks into storage tanks. Sludge samples were collected from two storage tanks (denoted LA-1 and LA-5) via a tap as shown in c) of Fig. B.1 in Appendix B. AL and LA DWTP sludges were stored 'as collected' in 1 and 5 litre HDPE plastic containers respectively. The containers were kept in basement storage with temperatures approximately 10 to 15 ºC and were used for approximately 2 months after collection.

3.1.2 Wastewater samples

Wastewater samples were collected on the mornings of 18th March 2014 and 16th May 2014 from the Tankgatan sampling station by Fredrik Davidsson, Environmental Engineer at Gryaab AB. The Tankgatan sampling station in the north of Gothenburg, as shown on the map in Fig. B.2 in Appendix B, was not part of a combined sewer system [166]. Overnight weather preceding the collection of the first sample was dry, whereas the second sample was collected after a period of heavy rainfall.

Wastewater samples were stored in 10 litre HDPE plastic containers in basement storage (with the DWTP sludge samples) with temperatures approximately 10 to 15 ºC. Testing and characterisation with the first wastewater sample (25 litres) was completed within 20 days of collection, while experimentation with the second sample (10 litres) was completed within 10 days of collection.

3.1.3 Activated sludge sample

A sample of activated sludge was collected for analysis of DWTP sludge effects on secondary settling. The activated sludge sample was collected ahead of secondary settling tanks at the Rya WWTP, as shown in d) and e) of Fig. B.1 in Appendix B, and stored in 10 litre HDPE plastic containers. Samples were collected on the morning of 8th May 2014 after a period of heavy rainfall, and testing and analysis was completed in the laboratory within 6 hours of collection.

3.2 Analysis methodologies

A summary of analysis methodologies for all analysed parameters is shown in Table 3.1 on pages __. Due to the page limit for this thesis, a detailed description of all methodology is not feasible. Accordingly reference has been made to the standard methods followed.

Appropriate procedures were taken to minimise errors through duplication of tests (as detailed in Table 3.1), maintenance of consistent experimental environments in the laboratory (room temperature 20 ºC) and thorough inverting/shaking of samples after removing from storage. All containers of the same 'batch' of collected sludge or wastewater were assumed to have the same characteristics. Samples, particularly after jar testing, were analysed as soon as possible after completion of the test. Otherwise samples were preserved overnight by refrigeration at 4 ºC.

3.2.1 Digestion for total P measurement

Digestion for total P measurement in wastewater used peroxodisulphate/alkali (Oxisolv oxidizing decomposition reagent, Merck). 15 ml of unfiltered wastewater sample and 350 mg Oxisolv were added to a digestion vial. A duplicate wastewater sample was also used as a control. Lids were secured and the digestion vials heated in a CEM MARS 5 Microwave oven at 100 psi ($\approx$ 689 kPa) for 30 minutes to raise the temperature over 120 ºC according to the microwave manual. When heated over 120 ºC, nitrogen containing compounds were oxidized to nitrate by peroxodisulphate and the release of acid

lowering the solution to pH < 2 enabled the oxidation of P-containing compounds to o-P.

3.2.2   Ion chromatography

Ion chromatography measures concentrations of ions by separating them based on their interaction with a resin (stationary phase) and eluent (mobile phase) [167]. These phases differ between an anion column, which attracts anions (including phosphate, sulphate, nitrate and nitrite), and a cation column, which attracts cations (including ammonium and calcium) [168]. Ionic species move through the columns at different rates, and the retention time of different species, measured at outlet by conductivity, determines the concentrations of ionic species in the sample [167] [169]. Conductivity is plotted against time to produce a chromatogram with the concentration of each ion correlated to the height and the breadth of the [168].

Digested wastewater samples were filtered through a 0.45 µm syringe filter and diluted $10 \times$ to ensure the high sulphate concentration (from peroxodisulphate/alkali digestion) was within detection limits. Samples were transferred into 6 ml polymeric vials and analysed in duplicate, measuring the phosphate concentrations in order to calculate total P.

3.2.3   Inductively coupled plasma mass spectrometer

Metals analysis (Al and Fe in DWTP sludge and wastewater) was performed by inductively coupled plasma mass spectrometry (ICP-MS) following acid digestion of the samples. The principles of ICP-MS analysis have been described in detail by Thomas [170] and Batsala et al. [171]. 2 ml of sample was mixed with 8 ml of 1 mol l^{-1} HNO_3 and added to a digestion vial. A duplicate sample was also used as a control. Lids were secured and the digestion vials heated in a CEM MARS 5 Microwave oven for 30 minutes at 120 ºC (200 kPa).

Sludge samples were diluted $100 \times$, $500 \times$ and $1000 \times$, while wastewater samples were diluted $100 \times$. Standards of 5 mg/l, 1mg/l, 0.1 mg/l, 0.01 mg/l and 0.001 mg/l were prepared with multi-element ICP-MS standard (23 elements) before the analysis was completed by Jesper Knutsson, Doctoral student at Chalmers University of Technology.

Parameter	Preparation/ Analysis	Method, Comments	Instrument(s)	Measurement range	Detection limit	Replication	Sample volume (ml)
Metals	Preparation	Adapted from 3030 E – Standard Methods Nitric acid (HNO_3) digestion	CEM MARS 5 Microwave oven	-	-	-	-
	Analysis	SS-EN ISO 17294-1:2006, SS-EN ISO 17294-2:2005 Digested sludge diluted 1000x, 500x, 100x prior to analysis	Inductively coupled plasma mass spectrometer (ICP-MS)*	0 to 0.1 μg/l Al 0 to 0.1 μg/l Fe	0.001 μg/l Al 0.002 μg/l Fe	Triplicate	10
Alkalinity (as $CaCO_3$)	Analysis	2320 B - Standard Methods Determination of carbonate alkalinity by titration method	Titration vessel	0 to 200 mg/l $CaCO_3$	0.5 mg/l $CaCO_3$	Single	50
pH	Analysis	Determination of pH using a pH-meter ISO 10523:1994	WTW Multi 350i pH/ISE/DO/conductivity measuring instrument	- 2.00 to 20.00	0.01	Single	50
Organics (NOM as TOC and DOC)	Preparation	Dilution and/or filtration prior to analysis	-	-	-	-	-
	Analysis	Determination of total organic carbon SS-EN 1484	Shimadzu TOC-VCPH Total Organic Carbon Analyser	0 to 25000 mg/l TC 0 to 30000 mg/l IC	4 μg/l	Duplicate	30
Total P	Preparation	Digestion with peroxodisulphate/alkali (Oxisolv oxidizing decomposition reagent) and filtration through 0.45 μm filter paper Adapted from 4500-P B.5 – Standard Methods**	CEM MARS 5 Microwave oven	-	-	-	-
	Analysis (Ion chromatography)	Determination of dissolved anions by liquid ion chromatography of ions SS-EN ISO 10304-2	Dionex ICS-900	0 to 500 μS	0.0001 μS	Duplicate	6
	Analysis (Colorimetric method)	Determination of reactive phosphorus with PhosVer 3 phosphate reagent (ascorbic acid method) 4500-P E – Standard Methods	Hach DR/890 Portable Colorimeter	420, 520, 560, 610 nm	1 nm	Duplicate	10
Total N	Preparation	Dilution and/or filtration prior to analysis	-	-		-	-
	Analysis	Pyrolysis and chemiluminescence detection for total nitrogen in water ASTM D5176 - 08	Shimadzu TN (Total Nitrogen) TNM-1 unit	0 to 4000 mg/l	5 μg/l	Duplicate	30

Suspended solids	Preparation	Vacuum filtration through 0.45 μm filter paper	Filtration apparatus (filter flask, aspirator and filter funnel)	-	-	-	-
	Analysis	Total suspended solids dried at 103–105 °C 2540 D – Standard Methods	Thermo Scientific drying oven, Sartorius analytical balance	0 to 220g	0.1 mg	Duplicate	50
Total solids	Analysis	Total solids dried at 103-105 °C 2540 B – Standard Methods	Thermo Scientific drying oven, Sartorius analytical balance	0 to 220g	0.1 mg	Duplicate	50
Dewaterability	Analysis (water content)	Determination of dry matter and water content on a mass basis*** ISO 11465:1993	Thermo Scientific drying oven, Sartorius analytical balance	0 to 220g	0.1 mg	Duplicate	50
	Analysis (CST)	Tests on sludges – capillary suction time 2710 G – Standard Methods,	Triton Type 304M Laboratory CST	> 0.1 sec	0.1 sec	Duplicate	10
	Analysis (filtration)	Adaptation of time-to-filter test with vacuum filtration through 1.2 μm filter paper Adapted from 2710 H – Standard Methods	Filtration apparatus (filter flask, aspirator and filter funnel)	0 to 220g	0.1 mg	Duplicate	30
	Analysis (centrifugation)	Extraction of sludge pore water Adapted from 8080 C.1 – Standard Methods,	Sigma 4 -16 centrifuge, Sartorius analytical balance	0 to 220g	0.1 mg	Triplicate	50
Zone settling velocity	Analysis	Zone settling rate test with activated sludge Adapted from 2710 E – Standard Methods	1l measuring cylinders	0 to 1000 ml	2.5 ml	Duplicate	1000
Sludge volume index (SVI)	Analysis	Index of sludge ability to settle and compact Adapted from 2710 C, 2710 D and 2540 D – Standard Methods	1l measuring cylinders	Expected between 50 to 150 ml/g	-	Duplicate	5

*Sample preparation by the author, ICP-MS analysis carried out by Jesper Knuttson, Chalmers University of Technology.

**Method 'Determination of Total Phosphorus in Wastewater at Rya WWTP Laboratory' by Peter Robinsson, Gryaab AB.

***% solids calculated as dry matter expressed as a percentage of mass as per ISO 11465:1993 and equation 3.1 below.

$$\% \, solids = \frac{mass \, of \, total \, solids}{mass \, of \, sludge \, sample} \times 100 \qquad \text{(Eqn 3.1)}$$

N.B.   'Standard Methods' are Standard Methods for the Examination of Water and Wastewater, 20th ed., 1999 [172].

Several dewaterability tests were carried out to determine classification of water distribution in sludge.

Table 3.1 Summary of analysis methodology for all analysed paramete

3.3 DWTP sludge characterisation

Characterisation of the alum DWTP sludges involved measurement of solid content (% solids), metals (Al and Fe), total N, organics (NOM (natural organic matter) as TOC (total organic carbon)) and pH by the methodology in Table 3.1.

Sludges were analysed 'as collected' for all analyses bar organics and total N analyses. To avoid the gelatinous metal hydroxide content and the aforementioned affinity for water of the sludge causing damage to/clogging the TOC analyser or total N unit, the sludges were oven dried, ground to a fine powder with a mortar and pestle and 50 mg dried sludge was re-suspended in 200 ml ultrapure (milli-Q) water.

Heavy metals (Zn, Cd, Pb), calcium (as CaO) and total P in Alelyckan DWTP sludge had been analysed by Nordén [13] in 2009 where samples were collected similarly from the bottom of one of four sedimentation tanks at Alelyckan DWTP. Data from Nordén [13] was included in the characterisation and these parameters were not re-analysed.

3.4 Wastewater characterisation

The wastewater posed no experimental handling challenges and all analyses were carried out to standard methods detailed in Table 3.1.

The first wastewater sample (collected 18th March 2014) was characterised in detail, with total solids, suspended solids, organics (NOM (natural organic matter) as TOC (total organic carbon) and DOC (dissolved organic carbon)), total N, total P, o-P, metals (Al and Fe), alkalinity (as $CaCO_3$) and pH measured to enable a classification of the wastewater by major chemical composition from Sincero & Sincero [138]. The first wastewater sample was used in the initial jar test (section 3.5).

The second wastewater sample (collected 16th May 2014) was characterised solely for comparison in the second jar test, with a more simple classification of organics (NOM (natural organic matter) as TOC (total organic carbon) and DOC (dissolved organic carbon)), total N, total P and o-P.

In both characterisations, the 'dissolved' organic carbon refers to compounds filterable through a 0.45 μm filter, before measurement with a Shimadzu TOC-VCPH TOC Analyser. Likewise, o-P was defined as the dissolved filterable 'reactive phosphorus' by Standard Methods 4500-P [172], measured via a colorimetric method with a Hach

DR/890 Portable Colorimeter following reaction with the PhosVer 3 phosphate reagent (ascorbic acid method) as detailed in Table 3.1.

3.5 Jar testing

Two jar test experiments were carried out during this study. The first jar test, as detailed in Table 3.2 below, was run on the morning of 2nd April 2014 to determine effects of DWTP sludge on total P (measured by ion chromatography), pH and solids (settling) through analysis of total and suspended solids.

Following inconclusive results surrounding P removal (measured by ion chromatography) from the first jar test , a second jar test as detailed in Table 3.3 below, was run on the morning of 20th May 2014, analysing effects of DWTP sludge on total P (measured by a colorimetric method), total N and organics (TOC and DOC).

Jar test setup	Jar 1	Jar 2	Jar 3	Jar 4	Jar 5
DWTP sludge	None (control)	AL (current scenario)*	AL	LA-1	LA-5
Molar ratio (Al:PO_4^{-3})	-	0.79:1*	3:1	3:1	3:1
Wastewater (l)	0.9	0.9	0.9	0.9	0.9
DWTP sludge added (ml)	0	2.06	7.81	10.25	23.32
Al added (mg Al/l wastewater)	0	1.78	6.74	6.74	6.74

*Actual molar ratio (Al:PO_4^{-3}) of current scenario defined following characterisation of first wastewater sample and definition of o-P/total P fraction

Table 3.2 Jar test 1 setup and DWTP sludge addition

Jar test setup	Jar 1	Jar 2	Jar 3	Jar 4	Jar 5	Jar 6
DWTP sludge	None (control)	AL (current scenario)	AL	AL	AL (diluted)*	LA-5
Molar ratio (Al:PO_4^{-3})	-	0.79:1	2:1	3:1	3:1	3:1
Wastewater (l)	0.9	0.9	0.9	0.9	0.9	0.9
DWTP sludge added (ml)	0	1.82	4.60	6.90	20.61	20.61
Al added (mg Al/l wastewater)	0	1.57	3.97	5.96	5.96	5.96

*Dilution of AL sludge to model LA-5 sludge by dilution based on aluminium concentration. AL sludge diluted with ultrapure (milli-Q) water and refrigerated at 4 ℃ for 1 week prior to jar test.

Table 3.3 Jar test 2 setup and DWTP sludge addition

Jar tests were carried out with a Kemira Kemwater Flocculator with capacity for 6 parallel agitators in 1 l glass beakers controlled by predefined 'fast' (rapid mixing), 'slow' (slow mixing) and 'sediment' (quiescent settling) periods, shown during the first jar test in Fig. 3.1.

With all jars at room temperature with no pH control, experimentation was based on the following procedure with 900 ml wastewater samples each subject to the same agitation:

1) Addition of the desired volume and type of alum DWTP sludge by pipette
2) Rapid mixing (200 rpm) for 1 minute, slow mixing (40 rpm) for 30 minutes followed by a quiescent settling period for 60 minutes
3) Careful pipetting of the required volume of sample for each analysis (in duplicate) (as per Table 3.1) from the surface of the settled wastewater (supernatant)

Fig. 3.1 Jar test 1 setup during slow mixing phase

3.6 Further solids (settling) testing

Investigation of alum DWTP sludge effects on secondary settling with activated sludge was carried out on 8th May 2014 in an attempt to clarify the limited conclusions on primary settling from literature and from the initial jar test.

3.6.1 *Zone settling velocity and sludge volume index (SVI)*

The high concentrations of suspended solids in activated sludge enable a clear zone-settling regime of settling under quiescent conditions with a distinct interface between the supernatant liquor and the sludge zone [172]. The height of the sludge interface was measured over a 30 minute period as 1 l of activated sludge settled under quiescent conditions at room temperature (20 ºC). Tests were completed in duplicate in two 1 l glass measuring cylinders with 70 mm diameters. Plotting the curve of interface level against time enabled the zone settling velocity (m/hr) to be defined as the gradient of the linear part of the settling curve. The 30 min settlablility (ml) was also recorded with

increasing DWTP sludge addition, with the setup (and results) detailed in Table A.7 in Appendix A.

The sludge volume index (SVI), defined as the volume in milliliters occupied by 1 g of a suspension after 30 min settling [172], was also defined as per equation 3.2 below by Standard Methods 2710 D to characterise the activated sludge sample.

$$SVI = \frac{settled\ sludge\ volume\ (ml/l) \times 1000}{suspended\ solids\ (mg/l)} \hspace{2cm} \text{(Eqn 3.2)}$$

3.7 DWTP sludge handling

Experimentation evaluated the dewaterability of the DWTP sludge, including capillary suction time (CST) and classification of water distribution in the sludge.

3.7.1 Capillary suction time (CST)

The capillary suction time (CST) test evaluates the rate of water release from sludge via measurement of the time (in seconds) of liquid extraction from a sludge sample between two contact points on chromatography paper, in Standard Methods 2710 G [172]. Although typically used for sewage sludge, a short CST would indicate a filterable sludge while a longer CST would suggest slow and problematic filtration of DWTP sludge. The CST test was run using a Triton Type 304M Laboratory CST apparatus with a control of ultrapure (milli-Q) water and three DWTP sludges 'as collected' (AL, LA-1 and LA-5).

3.7.2 Water and solids content

As detailed in Table 3.1, a basic classification of water distribution in sludge from Veselind & Martel [102] was applied to alum DWTP sludge via a series of simple experiments. Free water was identified as the mass of water filterable through 0.45 μm filter paper after 5 minutes using filtration apparatus. The mass of free and interstitial water was determined as the supernatant or centrate following centrifugation of the sludge at 4000 rpm for 5 minutes. The surface water and bound water could then be determined by subtracting the free and interstitial water from the total water content; the complement of the '% solids' from characterisation, and detailed in equation 3.1 earlier.

4. RESULTS

Results are presented in chronological order according to Methods and Materials, with characterisation of DWTP sludges (section 4.1) and wastewater (section 4.2) followed by results from jar testing and further solids (settling) with activated sludge (section 4.3) and DWTP sludge handling (section 4.4). Raw data is included Appendix A.

4.1 DWTP sludge characterisation

4.1.1 Initial experience of alum DWTP sludges

Experimentation with alum DWTP sludges was a new experience, with a uniform light brown colour and a feathery, bulky, gelatinous nature. The DWTP sludge settled well in storage, but as described in section 4.4, did not dewater easily. Despite apparently high water content, the sludges behaved as a gel, with Alelyckan sludge (AL) a 'thicker' gel than Lackarebäck sludges (LA-1, LA-5).

4.2.2 Characterisation and comparison

Table 4.1 on page __ details the characterisation of DWTP sludges from this study along with averages from literature, taken from samples 2, 3, 5, 8, 9 and 10 in Table 2.8, where DWTP sludge samples had no treatment (dewatering or drying) during experimentation, although treatment prior to collection was likely. Comparison revealed a substantial dilution effect as a result of analysing the sludge without treatment, with all parameters very low compared to literature. More comparable data from a 2009 analysis of Alelyckan sludge [13], where treatment was likely, revealed a very high Zn concentration, a high Ca concentration, and low heavy metals concentrations.

Analysis of DWTP sludge 'as collected' without treatment (no dewatering or drying) was rare in literature, although a limited characterisation of alum DWTP sludge 'as collected' from Georgantas & Grigoropoulou [69] is detailed in Table 4.2 on page __. Comparison suggested AL, LA-1 and LA-5 sludges were slightly weaker with lower metals concentrations for comparable solids %.

While proportionally the elemental constituents were somewhat comparable with some literature, with Al concentration dominating other constituents in the AL and LA-1 sludges and NOM (as TOC) proportionally high in the LA-5 sludge, it was clear that, as explicated in section 5.3, the composition and relative abundance of constituents were specific for each DWTP sludge.

Parameter		Unit*	Date of analysis	DWTP sludge			Comparison with previous studies	
				AL	LA-1	LA-5	Average from literature	Comments, relative to previous studies
Solids	% solids	%	28-Mar	2.63	1.63	0.76	45.20	AL, LA-1, LA-5 very low. AL highest % solids.
Metals	Al as Al_2O_3	mg/g	28-Mar	0.78	0.57	0.26	166.83	AL, LA-1, LA-5 very low. AL highest g/kg wet sludge. LA-5 lowest and .
	Fe as Fe_2O_3	mg/g	28-Mar	0.06	0.02	0.01	31.60	AL, LA-1, LA-5 very low.
	Ca as CaO	mg/g	-	56	-	-	28.35	AL high.
	Zn	mg/kg	-	79	-	-	22.39	AL very high.
	Cd	mg/kg	-	<0.30	-	-	0.50	AL low.
	Pb	mg/kg	-	6	-	-	15.32	AL low.
P	Total P	g/kg	-	0.58	-	-	3.52	AL very low.
N	Total N	g/kg	25-Mar	0.02	0.01	0.01	-	Rarely analysed.
NOM	TOC	g/kg	25-Mar	0.47	0.24	0.26	233.50	AL, LA-1, LA-5 very low. AL notably highest g/kg wet sludge, LA-5 notably highest relative to Al concentration.
pH		pH	26-Mar	7.71	7.72	7.69	6.68	AL, LA-1, LA-5 slightly alkaline.

- not analysed

*/kg or /g is per kg or g of wet DWTP sludge

Shaded data are from 2009 analysis of Alelyckan DWTP sludge by Nordén [173], where samples were collected similarly from the bottom of one of four sedimentation tanks at Alelyckan DWTP, although treatment (dewatering or drying) during experimentation was likely.

Table 4.1 Major chemical composition of Alelyckan and Lackarebäck DWTP sludge and comparison with literature

Parameter		Unit	Average from Georgantas & Grigoropoulou [69]
Solids	% solids	%	2.35
Metals	Al as Al_2O_3	mg/g	3.60
	Fe as Fe_2O_3	mg/g	0.49

Table 4.2 Chemical composition of alum DWTP sludge from Georgantas & Grigoropoulou [69]

4.2 Wastewater characterisation

Characterisations of the first and second wastewater samples from the Tankgatan sampling station and their classification according to Sincero & Sincero [138] from Table 2.10 are detailed in Table 4.3 and Table 4.4 respectively.

Parameter	Unit	Date of analysis	Concentration	Classification by Sincero & Sincero [138]
Total solids	mg/l	24-Mar	626.67	Weak-Medium
Suspended solids	mg/l	20-Mar	169.00	Weak-Medium
NOM (as TOC)	mg/l	19-Mar	116.60	Weak-Medium
NOM (as DOC)	mg/l	19-Mar	91.36	-
Total N	mg/l	19-Mar	18.77	Weak
Total P	mg P/l	26-Mar	3.73	Weak
o-P*	mg P/l	19-Mar	2.58	-
o-P/total P fraction	-	-	0.69	-
Al as Al_2O_3	mg/l	28-Mar	-1.34**	-
Fe as Fe_2O_3	mg/l	28-Mar	-0.86**	-
Alkalinity (as $CaCO_3$)	mg/l	26-Mar	114.00	Medium-Strong
pH	pH	26-Mar	6.43	-

- not analysed

Table 4.3 Chemical composition of wastewater (18-Mar-2014) from Tankgatan sampling station

Parameter	Unit	Date of analysis	Concentration	Classification by Sincero & Sincero [138]
NOM (as TOC)	mg/l	26-May	54.17	Weak
NOM (as DOC)	mg/l	26-May	20.89	-
Total N	mg/l	26-May	19.38	Weak
Total P	mg P/l	21-May	3.28	Weak
o-P*	mg P/l	20-May	2.28	-
o-P/total P fraction	-	-	0.70	-

- not analysed

Table 4.4 Chemical composition of wastewater (16-May-2014) from Tankgatan sampling station

The first wastewater sample was classified as a typical weak-medium wastewater with a distinctly high alkalinity (and hence a large 'buffering capacity' to neutralise acids and prevent significant quick changes in pH). The second wastewater sample was classified as a weak wastewater, likely more diluted than the first sample, although the o-P/total P fraction remained similar. Both samples were comparable in total P, total N and suspended solids to the earlier characterisations of municipal wastewater from Tankgatan sampling station in Table 2.9, although NOM (as TOC) was distinctly higher in the first sample.

The metals concentrations in Table 4.3 were detected as negative during ICP-MS analysis, although when compared to the magnitude of metals concentrations detected in the DWTP sludge (as shown in Table A.2 in Appendix A), and noting the potential for contamination of standard solutions, a comparably negligible concentration of metals in the wastewater would be detected as negative, as discussed later (section 5.3).

While data for total P and o-P in Table 4.3 and Table 4.4 were measured via a colorimetric method, Fig. A.1 and Table A.1 in Appendix A from ion chromatography highlighted the high concentrations of sulphate produced with thermal acidic persulphate digestion and its potential to interfere with measuring phosphate concentrations, as discussed in section 5.4. Sulphate represented 98.52% of the relative area in the chromatogram while the phosphate peak was barely visible in Fig. A.1.

4.3 DWTP sludge effects on primary wastewater treatment

4.3.1 Chemical analysis

Alum DWTP sludge effects on P removal, organics, total N, pH, primary settling (total and suspended solids) from jar testing, and secondary settling with activated sludge are described. In both jar tests, AL sludge (the dominant sludge by total solids received at the Rya WWTP) was dosed in increasing concentrations while LA-1 and LA-5 sludges were dosed only at the artificially high molar ratio ($Al:PO_4^{-3}$) of 3:1. Raw data from jar testing is detailed in Table A.3 and Table A.4 in Appendix A.

4.3.1.1 P removal

Fig. 4.1 shows increasing addition of AL DWTP sludge resulted in increased removal of total P, with removal enhanced by almost 30% at the molar ratio ($Al:PO_4^{-3}$) of 3:1. However, the model of the current scenario at the molar ratio ($Al:PO_4^{-3}$) of 0.79:1 enhanced removal by only 4% from settling alone. Enhancement of total P removal was comparable with the practically relevant study from Georgantas & Grigoropoulou [69] as shown in Fig. 4.2 below, although total P removal was less efficient at lower doses of DWTP sludge.

Total P data was from jar test 2, with total P measured by colorimetric method following digestion and filtration. As discussed in section 5.7, total P data from jar test 1 was measured by ion chromatography and distorted by high sulphate concentrations. Consequently, no data from ion chromatography is included in this study.
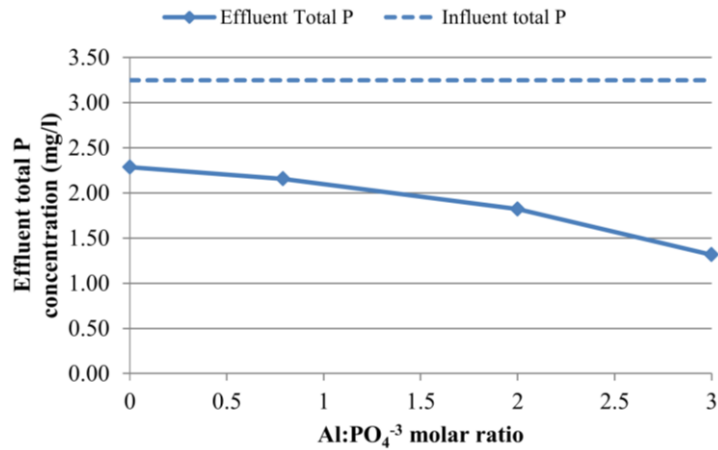
Fig. 4.1 Effluent total P concentration with AL DWTP sludge addition
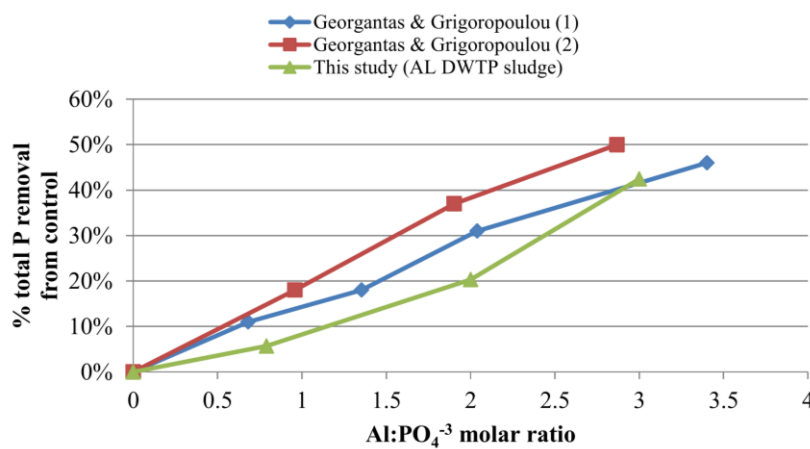
Fig. 4.2 Comparison of total P removal (AL DWTP sludge addition) with literature [69]

N.B.   '0 molar ratio' represents control jar, with no alum DWTP sludge addition.

Comparison of P removal by alum DWTP sludge and alum

Using the molar ratio for alum (Al:total P), based on case histories from Guyer [83] and others [18] [35] with a molar ratio (Al:o-P) of 2:1, and adjusted for the o-P/total P fraction for wastewater from Tankgatan sampling station, the alum DWTP sludge in this study was estimated at between 3.5 and 10 times less effective than alum for total P removal (as Al) depending on dose and type of sludge. LA-5 sludge was more efficient (as Al) than AL sludge at the same high dose (molar ratio (Al:PO_4^{-3}) 3:1).

DWTP sludge type and molar ratio (Al:PO_4^{-3})	AL sludge (0.79:1)	AL sludge (3:1)	LA-5 sludge (3:1)
Total P removed (from control) (mg/l)	0.13	0.97	1.41
Al added (as DWTP sludge) (mg Al/l)	1.57	5.96	5.96
Molar ratio for DWTP sludges (Al:total P removed)	13.83:1	7.05:1	4.85:1
Molar ratio for alum* (Al:total P)	1.40:1		
Dose of alum DWTP sludge required compared to alum	9.9 times greater	5 times greater	3.5 times greater

Table 4.5 Comparison of alum DWTP sludge performance with alum

4.3.1.2 Organics, total N and pH

As shown in Fig. 4.3, total N showed negligible change (maximum 5%) relative to the control jar with increasing addition of AL sludge. DOC removal was enhanced slightly, up to 9% enhanced removal at the molar ratio ($Al:PO_4^{-3}$) of 3:1. However, TOC in the supernatant was increased by almost 30% relative to the control at the molar ratio ($Al:PO_4^{-3}$) of 0.79:1. Higher doses of AL sludge reduced TOC concentrations, although it remained 6% higher than without sludge addition at the molar ratio ($Al:PO_4^{-3}$) 3:1.
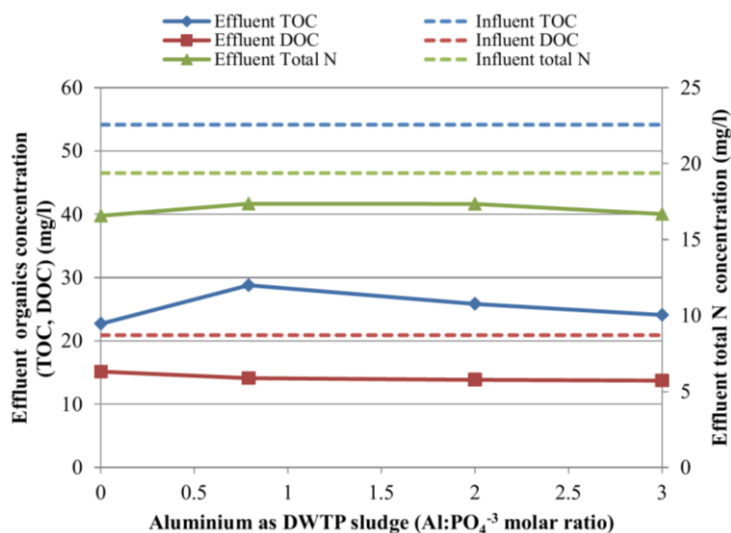
Fig. 4.3 Effluent organics and total N concentration with DWTP sludge addition

N.B.   Organics (TOC, DOC) and total N data from jar test 2, where '0 molar ratio' represents control jar.

Changes in pH, measured in jar test 1, were too small to be seen graphically and are detailed in Table 4.6 below. A maximum pH change from 6.54 to 6.59 was noted even at the high molar ratio ($Al:PO_4^{-3}$) of 3:1.

DWTP sludge type and molar ratio ($Al:PO_4^{-3}$)	Control, no sludge	AL sludge (0.79:1)	AL sludge (3:1)	LA-1 sludge (3:1)	LA-5 sludge (3:1)
pH	6.54	6.55	6.58	6.58	6.59

Table 4.6 pH variation and % change from control jar with DWTP sludge addition

4.3.1.3 Primary settling

Solids (settling) data from jar test 1 is summarised in Fig. 4.4 below. Without sludge addition, total and suspended solids removal due to settling was 32% and 88% respectively. At a low dose of AL sludge (molar ratio ($Al:PO_4^{-3}$) 0.79:1), this was enhanced slightly by 7% and 4% respectively while at the higher dose of AL sludge (molar ratio ($Al:PO_4^{-3}$) 3:1) the total and suspended solids removal was negligible, with a 3% increase in suspended solids and 4% decrease in total solids relative to the control jar. Conversely, at the higher doses of LA-1 and LA-5 sludges (molar ratio ($Al:PO_4^{-3}$) 3:1) total and suspended solids removal was enhanced by up to 6%.
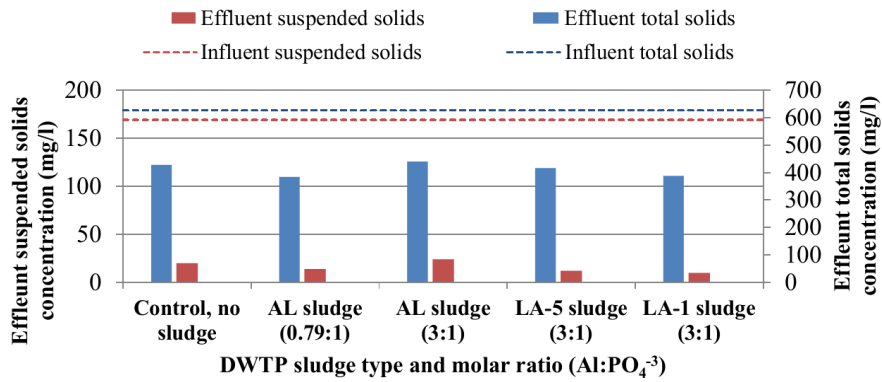
Fig. 4.4 Effluent suspended and total solids concentration with DWTP sludge addition

4.3.1.4 Secondary settling

As shown in Fig. 4.5 below, increased addition of AL sludge decreased the zone settling velocity and increased the 30 minute settlability of the activated sludge relative to the control. Additionally, as detailed in Table A.7 in Appendix A, when 10 ml of DWTP sludge was added, AL sludge decreased the zone settling velocity and increased the 30 minute settlability more than the LA-1 sludge.

Much like when high volumes of sludge were dosed in the jar test, as shown in jars 3, 4 and 5 of Fig. 3.1, the supernatant liquor was left turbid and light brown in colour after the sludge zone had settled when increasing volumes of AL sludge were added. The SVI of the activated sludge control, detailed in Table A.6 in Appendix A, was relatively low at 95.56 ml/g compared to the typical SVI in an activated sludge plant of 50 to 150 ml/g [174].
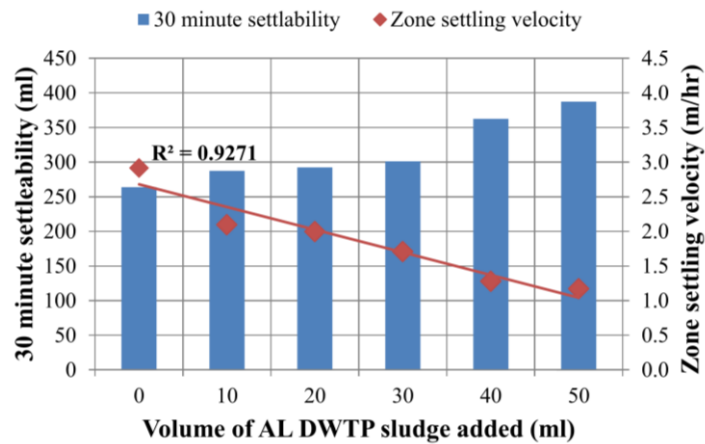
Fig. 4.5 Effect of AL DWTP sludge addition on settling of activated sludge

N.B.   '0 molar ratio' represents control with no sludge addition.

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4.3.1.5 DWTP sludge comparison in treatment efficiency

Evaluation of the efficiency of sludges at high doses (molar ratio (Al:PO$_4^{-3}$) 3:1) revealed AL sludge was most efficient in removal of all parameters per g of sludge added. Dilution of AL sludge to model LA-5 sludge based on aluminium concentration revealed the LA-5 sludge was generally more efficient as aluminium despite the AL sludge being more efficient as sludge.
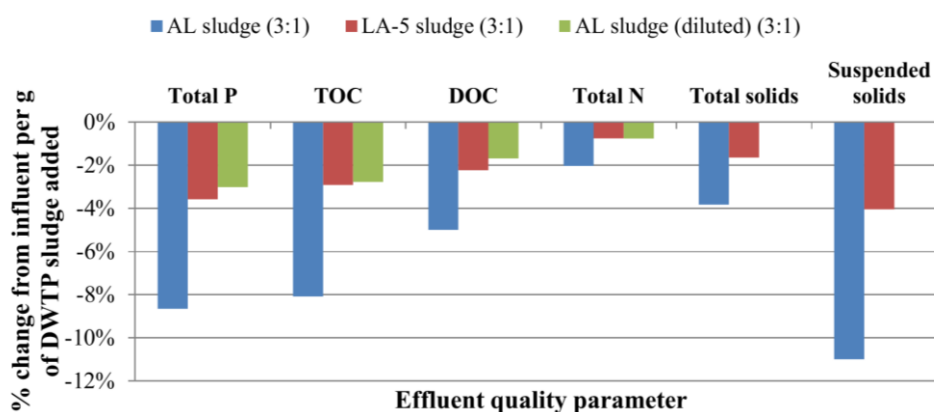
Fig. 4.6 Comparison of efficiency (% change from influent per g of DWTP sludge added) of AL and LA-5 sludges at molar ratio (Al:PO$_4^{-3}$) **3:1**

N.B.   Total and suspended solids data from jar test 1, all other parameters from jar test 2

4.3.2   Economic analysis

An economic analysis of the effects of alum DWTP sludge summarised in Table 4.7 below was based on total P only, and based on data from the model of the current scenario, molar ratio (Al:PO$_4^{-3}$) 0.79:1 with AL DWTP sludge, assuming DWTP sludge from Alelyckan and Lackarebäck share this similar P removal rate. The change from the control jar calculation excludes P removal due to settling, and reduces the potential savings of alum DWTP sludge in the current scenario by a factor of 10.

Parameter	Change from influent wastewater	Change from control jar
Total P removal per g of DWTP sludge (mg)	0.56	0.065
DWTP sludge from Alelyckan* (tonnes/year)	33987	33987
DWTP sludge from Lackarebäck* (tonnes/year)	66590	66590
Total DWTP sludge received at Rya WWTP (tonnes/year)	100577	100577
Total P removal by DWTP sludge (tonnes/year)	56.01	6.51
Equivalent iron sulphate saved** (tonnes/year)	426.68	49.61
Equivalent cost of iron sulphate saved (SEK/year)***	238940.32 (≈ £21504.63)	27783.76 (≈ £2500.54)

*Quantities of sludge based on total solids from Alelyckan and Lackarebäck DWTP sludge received at Rya WWTP in 2012 (from Tumlin [6]) and characterisation of AL and LA-5 sludges in Table 4.1.
**Based on calculated weight ratio for iron sulphate (Quickfloc S, 17.6% Fe^{2+}) in Table 2.2.
***2013 pricing of Quickfloc S for Gryaab AB of SEK 560 per tonne [85].

Table 4.7 Economic analysis of alum DWTP sludge for P removal at Rya WWTP

4.4 DWTP sludge handling

4.4.1 Capillary suction time (CST)

Parameter	Unit	Date of analysis	Ultrapure water	DWTP sludge		
				AL	LA-1	LA-5
Dewaterability (as capillary suction time)	sec	20-Mar	3.7	-*	-*	-*

*no noticeable development of wetted area on blotting paper

Table 4.8 Dewaterability (as capillary suction time) analysis of DWTP sludges

The CST test was unsuccessful with all DWTP sludges demonstrated no noticeable liquid extraction onto the chromatography paper, even after several minutes of testing.

4.4.2 Water and solids content

The solids content and classification of water distribution in the DWTP sludges are detailed in Table A.5 and summarised in Fig. 4.7 below. While AL sludge has the lowest free water content, it was noted during experimentation that while filtration (to determine the free water content) was successful for the LA-1 and LA-5 sludges, the AL sludge rapidly clogged the filtration apparatus. Although experimentation was conducted in duplicate, an artificially low free water content may have been recorded.

Finally, although all sludges had a low solids content, the sludges had a negligible metals content in the supernatant when compared to the compared to the magnitude of metals concentrations detected in the sludge as detailed in Table A.2 in Appendix A, such that the majority of metals are found in the sludge solids.
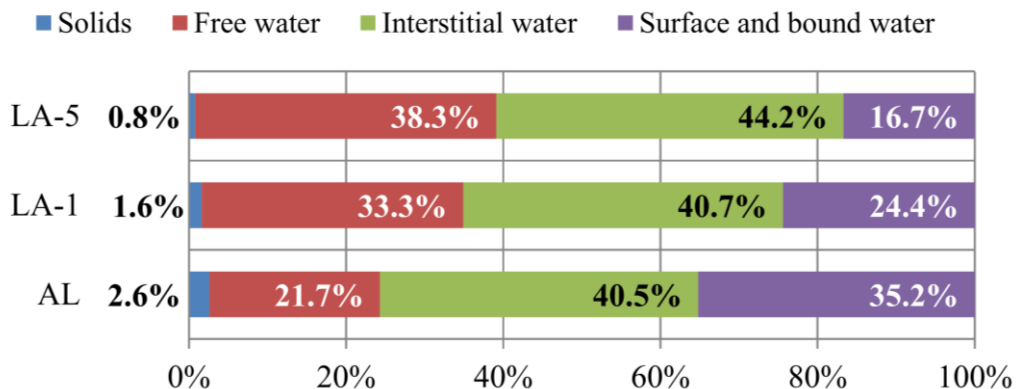
Fig. 4.7 Solids content and water distribution of AL, LA-1 and LA-5 DWTP sludges

5. DISCUSSION

5.1 Current understanding of alum DWTP sludge effects on P removal

5.2 Sample storage and collection

5.3 Characterisation and comparison of DWTP Sludge

5.3.1 *Initial experience of DWTP sludge*

5.3.2 *Characterisation and comparison*

5.4 Characterisation of wastewater

5.5 Effects of alum DWTP sludge on wastewater treatment at the Rya WWTP

5.5.1 *Chemical effects*

5.5.1.1 Influent characteristics

5.5.1.2 Anaerobic digestion and production of biogas

5.5.1.3 Heavy metals and REVAQ certification

5.5.1.4 P removal

5.5.1.5 Solids (settling)

Primary settling

Secondary settling

5.5.1.6 Organics, total N and pH

5.5.2   Comparison of sludges in treatment efficiency

5.5.3   Economic effects

5.5.4   Environmental effects

5.6 DWTP sludge handling

5.6.1   Capillary suction time (CST)

5.6.2   Water and solids content

5.6.3   DWTP sludge processing method

5.7 Experimental methodology

5.7.1   Analysis of total P

6. CONCLUSIONS

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7. RECOMMENDATIONS AND SUGGESTIONS FOR FUTURE WORK

8. References

[1] UNWCED: United Nations World Commission on Environment and , "Our Common Future (Brundtland Report)," Oxford University Press, Oxford, 1987.

[2] Asea Brown Boveri, "A Secure Supply of Clean Water for the City of Gothenburg," Asea Brown Bover, Västerås, Sweden, 1996.

[3] A Lindhe et al., "Risk assessment case study – Göteborg, Sweden," TECHNEAU, Gothenburg, Sweden, 2008.

[4] J Lindh, Sustainable Stormwater Management to Address Pollution and Climate Change, 2013, Master's Thesis, Univeristy of Gothenburg, Sweden.

[5] Göteborgs Stad. (2014, January) Förvaltningen kretslopp och vatten. [Online]. http://goteborg.se/wps/poc?urile=wcm%3Apath%3Agoteborg.se_enhetssidor%2FOrganisation%2FFackforvaltningar%2FKretslopp+och+vatten%2FOm+Kretslopp+och+vatten%2Fart_vatten_avlopps_och_avfallshistorik&page=GBG.Enh.Fackforvaltning.kov

[6] S Tumlin, "Vattenverksslam i Gryaabs upptagningsområde - hur och var skall det hanteras? [In Swedish]," Gryaab AB, Gothenburg, Sweden, [Unpublished - draft from 2014].

[7] J Öman, "Överledning av vattenverksslam från Lovö vattenverk till Bromma reningsverk," Stockholm Vatten, Stockholm, Sweden, 2001.

[8] K Starberg, "Överledning av vattenverksslam till Käppalaverket ," Sweco VIAK AB, Stockholm, Sweden, 2004.

[9] B V Salotto, J B Farrell, and R B Dean, "The effect of water-utility sludge on the activated-sludge process," *Journal (American Water Works Association)*, vol. 65, no. 6, pp. 428-431, June 1973.

[10] N M Johnson, R J Scholze, S Liehr, P M Temkar, and E D Smith, "Water Sludge Management for Military Installations," Construction Engineering Research Laboratory, US Army Corps of Engineers, Champaign, IL, USA, USACERL Technical Report N-90/04, 1989.

[11] K Bäckstrand, *Environmental Politics and Deliberative Democracy: Examining the Promise of New Modes of Governance*, J Khan, A Kronsell, and E Lövbrand, Eds.: Edward Elgar Publishing Ltd, 2010.

[12] A O Babatunde and Y Q Zhao, "Constructive approaches towards water treatment works sludge management: An international review of beneficial reuses," *Critical Reviews in Environmental Science and Technology*, vol. 37, no. 2, pp. 129-164, March 2007.

[13] L Nordén, "Vattenverksslam bidrag till föroreningshalterna i ryaverkets slam [In Swedish]," Gryaab AB, Gothenburg, Sweden, 2010.

[14] K Starberg, "Slamhantering vid Görvälnverket [In Swedish]," Vap VA-Projekt AB, Stockholm, Sweden, 2002.

[15] A Mattsson, Ifylld Mall Vattenverksslam [In Swedish], 2013, Personal communication - Ann Mattson, Head of development, quality and environment, Gryaab AB, ann.mattsson@gryaab.se.

[16] P Balmér and B Hultman, "Control of Phosphorus Discharges: Present Situation and Trends," in *Phosphorus in Freshwater Ecosystems*, G Persson and M Jansson, Eds.: Springer Netherlands, 1988, pp. 305-319.

[17] R I Sedlak, *Phosphorus and Nitrogen Removal from Municipal Wastewater: Principles and Practice*, 2nd ed.: CRC Press, 1991.

[18] A J Barr, The use of coagulants and coagulant sludges in wastewater phosphorus reduction, 1992, Master's Thesis, University of Alberta, Canada.

[19] D Jenkins, J F Ferguson, and A B Menar, "Chemical processes for phosphate removal," *Water Research*, vol. 5, no. 7, pp. 369-389, July 1971.

[20] D Jenkins and S W Hermanowicz, "Principles of Chemical Phosphorus Removal," in *Phosphorus and Nitrogen Removal from Municipal Wastewater: Principles and Practice*, 2nd ed., R I Sedlak, Ed.: Lewis Publishers, 1991.

[21] S Rybicki, "Phosphorus removal from wastewater - A literature review," Royal Institute of

Technology , Stockholm, Sweden, 1997.

[22] Water Environment Federation, *Operation of Nutrient Removal Facilities, WEF MOP 37*, 1st ed.: Water Environment Federation, 2013.

[23] M H Gerardi, *Wastewater Bacteria*, 1st ed.: John Wiley & Sons, 2006.

[24] J C Converse, "Design and Construction Manual for Wisconsin Ponds," University of Wisconsin, Madison, Wisconsin, USA, 1978.

[25] A Persaud, P Banerjee, P Palomino, and T H Boyer, "Organic-Rich Surface Water Treatment: Sustainable Pre-Treatment for Drinking Water Utilities," University of Florida, Gainesville, Florida, USA, 2010.

[26] Black and Veatch Consulting Engineers, "Process Design Manual for Phosphorus Removal," U.S. Environmental Protection Agency, Washington, D.C., USA, 1971.

[27] J E Drinan, *Water and Wastewater Treatment: A Guide for the Nonengineering Professional*, 1st ed., N E Whitning, Ed.: CRC Press, 2001.

[28] Water Environment Federation, *Wastewater Treatment Plant Design*, 1st ed., P A Vesilind, Ed.: IWA Publishing, 2003.

[29] Safe Drinking Water Foundation. (2007, August) Wastewater Treatment - Safe Drinking Water Foundation. [Online].
http://www.safewater.org/PDFS/resourcesknowthefacts/WastewaterTreatment.pdf

[30] B-M Wilén, A Johansen, and A Mattsson, "Assessment of sludge particle removal from wastewater by disc filtration," *Water Practice & Technology*, vol. 7, no. 2, June 2012.

[31] Y Abudouweili, Assessing the Performance of the Discfilters at the Rya Wastewater Treatment Plant in Gothenburg, 2012, Master's Thesis, Chalmers Univeristy of Technology, Sweden.

[32] C Lancaster, G Moller, A B Pincince, S Smith, and H Zhang, "Tertiary Phosphorus Removal ," Water Environment Research Foundation, Alexandria, Virginia, USA, 2008.

[33] Y Filali-Meknassi, M Auriol, R D Tyagi, Y Comeau, and R Y Surampalli, "Phosphorus Co-Precipitation in the Biological Treatment of Slaughterhouse Wastewater in a Sequencing Batch Reactor," *Practice Periodical of Hazardous, Toxic, and Radioactive Waste Management*, vol. 9, no. 3, pp. 179-192, July 2005.

[34] N McTigue and J M Symons, *The Water Dictionary: A Comprehensive Reference of Water Terminology*, 2nd ed.: American Water Works Association, 2010.

[35] D W de Haas, M C Wentzel, and G A Ekama, "The use of simultaneous chemical precipitation in modified activated sludge systems exhibiting biological excess phosphate removal Part 1: Literature review," *Water SA*, vol. 26, no. 4, pp. 439-452, October 2000.

[36] A Mattsson, G Nivert, and M Heinonen, "Direct precipitation on demand at large Scandinavian WWTPs reduces the effluent phosphorus load," *Water Science & Technology*, vol. 65, no. 12, pp. 2106-2111, 2012.

[37] P Isaias, S Nilsson, A Stathaki, and R E King, "Mediterranean Conference on Control and Automation Organizing Networks," in *Proceedings of the 13th Mediterranean Conference on Control and Automation*, Limassol, Cyprus, 2005, pp. 932-937.

[38] Gryaab AB, "Gryaab AB: General Statistics 2012," Gryaab AB, Gothenburg, Sweden, 2012.

[39] I Takács, B R Johnson, S Smith, A Szabó, and S Murthy, "Chemical P removal – from lab tests through model understanding to full-scale demonstration," in *Proceedings of the 11th IWA Specialised Conference on Design, Operation and Economics of Large Wastewater Treatment Plants*, Budapest, Hungary, 2011, pp. 101-108.

[40] Water Environment Federation, *Nutrient Removal, WEF MOP 34*, 1st ed.: Water Environment Federation, 2010.

[41] Lenntech. (2014, February) Phosphorous removal from wastewater. [Online].
http://www.lenntech.com/phosphorous-removal.htm

[42] S Smith et al., "The Significance of Chemical Phosphorus Removal Theory For Engineering Practice," in *Proceedings of the Water Environment Federation, Nutrient Removal 2007*,

Baltimore, Maryland, USA, 2007, pp. 1436-1459.

[43] N P Cheremisinoff, *Handbook of Water and Wastewater Treatment Technologies*, 1st ed.: Butterworth-Heinemann, 2002.

[44] M Davis, *Water and Wastewater Engineering: Design Principles and Practice*, 4th ed.: McGraw-Hill, 2006.

[45] D A Georgantas, V M Matsis, and H P Grigoropoulou, "Soluble phosphorus removal through adsorption on spent alum sludge," *Environmental Technology*, vol. 27, no. 10, pp. 1081-1088, October 2006.

[46] Wisconsin Department of Natural Resources, "Introduction to Phosphorus Removal Study Guide," Wisconsin Department of Natural Resources, Madison, Wisconsin, USA, 2009.

[47] E F van der Schraft, Sustainability Assessment of Göteborg Urban Water System using Stakeholder - Indicator Combined Approach, 2006, Master's Thesis, Chalmers Univeristy of Technology, Sweden.

[48] Environment Canada, "Priority Substances List Assessment Report," Environment Canada, Gatineau, Quebec, Canada, 2008.

[49] Helena Mehner. (2013, January) Göteborgs miljömål [In Swedish]. [Online]. http://goteborg.se/wps/portal/invanare/miljo/goteborgs-miljomal

[50] European Commission. (2002, January) List of Wastes - Commission Decision No. 2000/532/EC. [Online]. http://ec.europa.eu/eurostat/ramon/other_documents/ewc/index.cfm?TargetUrl=DSP_EWC

[51] D S Lamb and G C Bailey, "Acute and chronic effects of alum to midge larva (Diptera: Chironomidae)," *Bulletin of Environmental Contamination and Toxicology* , vol. 27, no. 1, pp. 59-67, July 1981.

[52] C T Driscoll, J P Baker, J J Bisogni, and C L Schofield, "Effect of aluminium speciation on fish in dilute acidified waters," *Nature*, vol. 284, no. 5752, pp. 161-164, March 1980.

[53] Y Yang, D Tomlinson, S Kennedy, and Y Q Zhao, "Dewatered alum sludge: A potential adsorbent for phosphorus removal," *Water Science & Technology*, vol. 54, no. 5, pp. 207-213, June 2006.

[54] J G Kim, J H Kim, H-S Moon, C-M Chon, and J S Ahn, "Removal capacity of water plant alum sludge for phosphorus in aqueous solutions," *Chemical Speciation and Bioavailability*, vol. 14, no. 1-4, pp. 67-73, November 2002.

[55] M Razali, Y Q Zhao, and M Bruen, "Effectiveness of a drinking-water treatment sludge in removing different phosphorus species from aqueous solution," *Separation and Purification Technology*, vol. 55, no. 3, pp. 300-306, July 2007.

[56] J Tie et al., "Phosphorus adsorption characteristics of alum and iron sludge from drinking-water treatment works," in *2010 4th International Conference on Bioinformatics and Biomedical Engineering (iCBBE)*, Chengdu, Sichuan, China, 2010, pp. 1-3.

[57] K Piaskowski, "Orthophosphate removal from aqueous solutions using drinking-water treatment sludge," *Water Science & Technology*, vol. 68, no. 8, pp. 1757-1762, 2013.

[58] W T Mohammed and S A Rashid, "Phosphorus removal from wastewater using oven-dried alum sludge," *International Journal of Chemical Engineering*, vol. 2012, no. Article ID 125296, pp. 0-11, 2012.

[59] M D Hossain and D H Bache, "Composition of alum flocs derived from a coloured, low-turbidity water," *Journal of Water Supply Research and Technology - Aqua*, vol. 40, no. 5, pp. 298-303, 1991.

[60] C T Driscoll and W D Schecher, "The Chemistry of Aluminum in the Environment," *Environmental Geochemistry and Health*, vol. 12, no. 1-2, pp. 28-49, March 1990.

[61] G Howells, T R K Dalziel, J P Reader, and J F Solbe, "Eifac Water Quality Criteria for European Freshwater Fish: Report On Aluminium," *Chemistry and Ecology*, vol. 4, no. 3, pp. 117-173, 1990.

[62] J H Sullivan and J E Singley, "Reactions of Metal Ions in Dilute Aqueous Solution: Hydrolysis of Aluminum," *Journal (American Water Works Association)*, vol. 60, no. 11, pp. 1280-1287, November 1968.

[63] E Galarneau and R Gehr, "Phosphorus removal from wastewaters: Experimental and theoretical support for alternative mechanisms," *Water Research*, vol. 31, no. 2, pp. 328-338, February 1997.

[64] M C Wang, J Q Hull, M Jao, B A Dempsey, and D A Cornwell, "Engineering Behavior of Water Treatment Sludge," *Journal of Environmental Engineering*, vol. 118, no. 6, pp. 848-864, November/December 1992.

[65] A M Evuti and M Lawal, "Recovery of coagulants from water works sludge: A review ," *Advances in Applied Science Research*, vol. 2, no. 6, pp. 410-417, November 2011.

[66] P Prakash and A K Sengupta, "Selective coagulant recovery from water treatment plant residuals using Donnan membrane process," *Environmental Science & Technology*, vol. 37, no. 19, pp. 4468-4474, September 2003.

[67] X-H Guan, Q Liu, G-H Chen, and C Shang, "Surface complexation of condensed phosphate to aluminum hydroxide: An ATR-FTIR spectroscopic investigation," *Journal of Colloid and Interface Science*, vol. 289, no. 2, pp. 319-327, September 2005.

[68] Y Yang et al., "Characteristics and mechanisms of phosphate adsorption on dewatered alum sludge," *Separation and Purification Technology*, vol. 51, no. 2, pp. 193-200, September 2006.

[69] D A Georgantas and H P Grigoropoulou, "Phosphorus removal from synthetic and municipal wastewater using spent alum sludge," *Water Science & Technology*, vol. 52, no. 10-11, pp. 525-532, May 2005.

[70] M W Kamiyango, S M I Sajidu, and W R L Masamba, "Removal of phosphate ions from aqueous solutions using bauxite obtained from Mulanje, Malawi," *African Journal of Biotechnology*, vol. 10, no. 56, pp. 11972-11982, September 2011.

[71] Q Liang, Simultaneous Phosphorus and Nitrogen Removal Using Aluminum Based Water Treatment Residual, 2011, Master's Thesis, Colorado State University, Colorado, USA.

[72] A O Babatunde, Y Q Zhao, A M Burke, M A Morris, and J P Hanrahan, "Characterization of aluminium-based water treatment residual for potential phosphorus removal in engineered wetlands," *Environmental Pollution*, vol. 157, no. 10, pp. 2830-2836, October 2009.

[73] Y S R Chen, J N Butler, and W Stumm, "Kinetic study of phosphate reaction with aluminum oxide and kaolinite," *Environmental Science and Technology*, vol. 7, no. 4, pp. 327-332, 1973.

[74] L Lijklema, "Interaction of orthophosphate with Iron (III) and aluminum hydroxides," *Environmental Science and Technology*, vol. 14, no. 5, pp. 537-541, 1980.

[75] P Persson, N Nilsson, and S Sjöberg, "Structure and bonding of orthophosphate ions at the iron oxide-aqueous interface," *Journal of Colloid and Interface Science*, vol. 177, no. 1, pp. 263-275, January 1996.

[76] G Sposito, *The Environmental Chemistry of Aluminum*, 2nd ed.: Taylor & Francis, 1995.

[77] K R Reddy and R D DeLaune, *Biogeochemistry of Wetlands: Science and Applications*.: CRC Press, 2004.

[78] R E White, *Principles and Practice of Soil Science: The Soil as a Natural Resource*.: John Wiley & Sons, 2013.

[79] S S S Rajan, "Adsorption of divalent phosphate on hydrous aluminium oxide," *Nature*, vol. 253, pp. 434-436, February 1975.

[80] J T Sims and B G Ellis, "Changes in Phosphorus Adsorption Associated with Aging of Aluminum Hydroxide Suspensions," *Soil Science Society of America Journal*, vol. 47, no. 5, pp. 912-916, September 1983.

[81] K R Reddy, G A O'Connor, and C L Schelske, *Phosphorus Biogeochemistry of Sub-Tropical Ecosystems*.: CRC Press, 1999.

[82] R M Harrison and S J de Mora, *Introductory Chemistry for the Environmental Sciences*, 2nd ed.:

Cambridge University Press, 1996.

[83] J P Guyer, *Advanced Wastewater Treatment (An Engineering SoundBite).*: Guyer Partners, 2012.

[84] M Henze, P Harremoes, J Jansen, and E Arvin, *Wastewater Treatment: Biological and Chemical Processes*, 3rd ed.: Springer, 2002.

[85] D I'Ons, Iron Sulphate Costs, 2014, Personal communication - David Ions, Development Engineer, Gryaab AB, david.ions@gryaab.se.

[86] F Davidsson and A Mattsson, "Referensprovtagning i Gryaabs tunnlar 2012 - delrapport metaller [In Swedish]," Gryaab AB, Gothenburg, Sweden, 2013.

[87] J Nunes, O Fredriksson, P Lindqvist, and A Mattsson, "Experience of full scale operation of disc filters as a final treatment step at Gryaab," Gryaab AB, Gothenburg, Sweden, 2013.

[88] Gryaab AB, "Gryaabs verksamhet 2013 [In Swedish]," Gryaab AB, Gothenburg, Sweden, 2013.

[89] C Zhang, A Three-Dimensional Model of Göta Älv for Water Quality Simulation, 2009, Master's Thesis, Chalmers University of Technology, Sweden.

[90] V M Mendel, Raw Water Storage Case study: Göteborg's Water Supply, 2005, Master's Thesis, Chalmers Univeristy of Technology, Sweden.

[91] P Nilsson, The use of water treatment SCADA data to quantify hazardous microbiological events and risks arising – A case study from Sweden, 2006, Master's Thesis, Lund University, Sweden.

[92] J Brcic, DWTP sludge at Alelyckan, 2014, Personal communication - Jasna Brcic, Alelyckan DWTP, jasna.brcic@kretsloppochvatten.goteborg.se.

[93] I Kjellberg, DWTP Sludge at Lackarebäck, 2014, Personal communication - Inger Kjellberg, Operations Engineer, Lackarebäck DWTP, inger.kjellberg@kretsloppochvatten.goteborg.se.

[94] Gryaab AB, "Clean facts about Gryaab and your wastewater," Gryaab AB, Gothenburg, Sweden, 2010.

[95] N Hanner et al., "Reducing the total discharge from a large WWTP by separate treatment of primary effluent overflow," *Water Science and Technology*, vol. 50, no. 7, pp. 157-162, 2004.

[96] D Forgie, "Investigation of Examples of Integrated Resource Management in Sweden," Capital Regional District, British Columbia, Canada, 2008.

[97] J Held, A Mathiasson, and A Nylander, "Biogas in Sweden," Swedish Gas Centre, Swedish Gas Association, Swedish Biogas Association, Stockholm, Sweden, 2008.

[98] H Borgestedt and I Svanäng, Towards Sustainable Phosphorus Management: Material Flow Analysis of phosphorus in Gothenburg and ways to establish nutrient recycling by improving urban wastewater systems, 2011, Master's Thesis, Chalmers Univeristy of Technology, Sweden.

[99] L K, Tay, J-H Wang, S T L Tay, and Y-T Hung, *Environmental Bioengineering: Volume 11.*: Springer, 2010.

[100] National Biosolids Partnership, *National Manual of Good Practice for Biosolids.*: Water Environment Federation, 2005.

[101] A C Twort, D D Ratnayaka, and M J Brandt, Eds., *Water Supply*, 5th ed.: Butterworth Heinemann, 2000.

[102] P A Vesilind and C J Martel, "Freezing of Water and Wastewater Sludges," *Journal of Environmental Engineering*, vol. 116, no. 5, pp. 854-862, September 1990.

[103] J Kopp and N Dichtl, "The Influence of Free Water Content on Sewage Sludge Dewatering," in *Proceedings of the 9th Gothenburg Symposium 2000*, Istanbul, Turkey, 2000, pp. 347-356.

[104] F D Sanin, W W Clarkson, and P A Vesilind, *Sludge Engineering: The Treatment and Disposal of Wastewater Sludges.*: DEStech Publications, 2011.

[105] G Agoda-Tandjawa, E Dieudé-Fauvel, and J C Baudez, "Water/solid matter interactions in sewage sludge: Linking rheology and water activity," Institut national de recherche en sciences et technologies pour l'environnement et l'agriculture (IRSTEA), Montoldre, France, 2013.

[106] O Gokyay. (2012, March) ENVE 425 Sludge Treatment, Disposal and Reuse - Marmara Üniversitesi. [Online]. http://mimoza.marmara.edu.tr/~orhan.gokyay/enve425/ch2.pdf

[107] S P B Power, G A Ekama, M C Wentzel, and G v R Marais, Chemical phosphorus removal from municipal wastewater by the addition of waste alum sludge to the activated sludge system, 1992, Research Report No. W66, University of Cape Town, South Africa.

[108] J R Pan, C Huang, Y-C Chuang, and C-C Wu, "Dewatering characteristics of algae-containing alum sludge," *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, vol. 150, no. 1-3, pp. 185-190, May 1999.

[109] T E Wilson, R E Bizzari, T Burke, P E Langdon, and C M Courson, "Upgrading primary treatment with chemicals and water treatment sludge," *Journal (Water Pollution Control Federation)*, vol. 47, no. 12, pp. 2820-2833, December 1975.

[110] Y Q Zhao and D H Bache, "Integrated effects of applied pressure, time, and polymer doses on alum sludge dewatering behaviour," *Waste Management*, vol. 22, no. 7, pp. 813-819, November 2002.

[111] C C Wu, C Huang, and D J Lee, "Effects of polymer dosage on alum sludge dewatering characteristics and physical properties," *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, vol. 122, no. 1-3, pp. 89-96, April 1997.

[112] B Björlenius, "Removal of Antibiotic Substances in Existing and Extended STPs - full scale and pilot tests in Stockholm, Sweden," in *Proceedings of the International Workshop on the Environmental Dimension of Antibiotic Resistance*, Xiamen, Fujian, China , 2013.

[113] Sydvästra stockholmsregionens va-verksaktiebolag - SYVAB. (2009, November) Anläggningsdata - Himmerfjärdsverket [In Swedish]. [Online]. http://www.syvab.se/himmerfjardsverket/anlaggningsdata

[114] H N S Wiechers, "Chemical phosphate removal from municipal waste waters: current practice and recent innovations," *Water SA*, vol. 12, no. 4, pp. 197-202, October 1986.

[115] R Culp and W Wilson, "Is Alum Sludge Advantageous in Wastewater Treatment?," *Water & Wastes Engineering*, vol. 16, no. 7, pp. 16-19, July 1979.

[116] D Y Hsu and W Pipes, "Aluminum hydroxide effects on wastewater treatment processes," *Water Pollution Control Federation*, vol. 45, no. 4, pp. 681-697, April 1973.

[117] B I Boyko and J W G Rupke, "Phosphorus removal within existing wastewater treatment facilities," Ontario Ministry of the Environment, Toronto, Ontario, Canada, 1976.

[118] D Y Hsu and W O Pipes, "The effects of aluminium hydroxide on primary wastewater treatment processes," in *Proceedings of the 27th Industrial Waste Conference*, West Lafayette, Indiana, USA, 1972, pp. 579-586.

[119] L Hjertberg. (2012, March) Vattenverken i Alelyckan och Lackarebäck byggs ut [In Swedish]. [Online]. http://www.vartgoteborg.se/prod/sk/vargotnu.nsf/1/miljo_o_kretslopp,vattenverken_i_alelyckan _och_lackareback_byggs_ut

[120] I S Turovskiy and P K Mathai, *Wastewater Sludge Processing*.: John Wiley & Sons, 2006.

[121] R Riffat, *Fundamentals of Wastewater Treatment and Engineering*.: CRC Press, 2012.

[122] A Mattsson, Hygienisation at Gryaab AB, 2014, Personal communication - Ann Mattsson, Head of Development, Quality and Environment, Gryaab AB, ann.mattsson@gryaab.se.

[123] K J Howe, D W Hand, J C Crittenden, R Rhodes Trussell, and G Tchobanoglous, *Principles of Water Treatment*.: Wiley, 2012.

[124] M Ghassemi and H L Recht, "Phosphate Precipitation with Ferrous Iron," U.S. Environmental Protection Agency, Washington, D.C., USA, 1971.

[125] M Rebhun and M Lurie, "Control of Organic Matter by Coagulation and Floc Separation," *Water Science & Technology*, vol. 27, no. 11, pp. 1-20, 1993.

[126] Y Zhao, "Environmental Technology: Development of an Alum Sludge-Based Constructed Wetland System for Improving Organic Matter and Nutrients Removal in High-Strength Wastewater," Environmental Protection Agency, Johnstown Castle, Co.Wexford, Ireland, 2014.

[127] W W Baldwin and H D Monteith, "Phosphate removal using waste alum sludge from water

purification," Royal Military College of Canada, Kingston, Ontario, Canada, Royal Military College of Canada Kingston Ont. Department of Civil Engineering Research Report 1974.

[128] Y Yang, Y Q Zhao, and P Kearney, "Influence of ageing on the structure and phosphate adsorption capacity of dewatered alum sludge," *Chemical Engineering Journal*, vol. 145, no. 2, pp. 276-284, April 2008.

[129] D A Georgantas and H P Grigoropoulou, "Phosphorus removal from synthetic wastewater using alum and aluminium hydroxide," in *Proceedings of Protection and Restoration of the Environment VII*, Chania, Crete, 2006, pp. 233-234.

[130] A Oda, "Disposal of Sludge and Wastewaters from Water Treatment Plant," The Ontario Water Resources Comission, Ontario, Canada, 1968.

[131] J D O'Blenis and T R Warriner, "The effects of aluminum sludge from water purification on municipal primary sewage treatment," *Water Quality Research Journal of Canada*, vol. 8, pp. 122-417, 1973.

[132] T Hossain, Phosphorus Removal from Raw Sewage Using Waste Alum Sludge, 2006, Master's Thesis, University of Alberta, Canada.

[133] S Gao and C, Pei, Y Wang, "Comparison of different phosphate species adsorption by ferric and alum water treatment residuals," *Journal of Environmental Sciences*, vol. 25, no. 5, pp. 986-992, May 2013.

[134] S-H Huang and B Chiswell, "Phosphate removal from wastewater using spent alum sludge," *Water Science & Technology*, vol. 42, no. 3-4, pp. 295-300, June 2000.

[135] T G Townsend, Y-C Jang, P Jain, and T Tolaymat, "Characterization of Drinking Water Sludges for Beneficial Reuse and Disposal," State University System of Florida, Gainesville, Florida, USA, 2001.

[136] J DeWolfe, "Water Residuals to Reduce Soil Phosphorus," American Water Works Association Research Foundation, Denver, Colorado, USA, 2006.

[137] K C Makris and G A O'Connor, "Beneficial utilization of drinking-water treatment residuals as contaminant-mitigating agents," in *Developments in Environmental Science, Volume 5*.: Elsevier, 2007, pp. 609-635.

[138] A P Sincero and G A Sincero, *Physical-Chemical Treatment of Water and Wastewater*.: CRC Press, 2002.

[139] R-L Cooke. (2004, September) Sedimentation and Flotation - ENV 295 - Mountain Empire Community College. [Online]. http://water.me.vccs.edu/courses/ENV295WWII/Lesson3_print.htm

[140] R L Droste, *Theory and Practice of Water and Wastewater Treatment*.: Wiley, 1996.

[141] O E Albertson et al., "Design Manual: Dewatering Municipal Wastewater Sludges," U.S. Environmental Protection Agency, Cincinnati, OH, USA, 1987.

[142] New Zealand Water and Wastes Association, "Management of Water Treatment Plant Residuals in New Zealand," New Zealand Water and Wastes Association, Auckland, New Zealand, 1998.

[143] American Water Works Association, *Water Treatment: Principles and Practices of Water Supply Operations*, 3rd ed.: American Water Works Association, 2003.

[144] S Kawamura, *Integrated Design and Operation of Water Treatment Facilities*, 2nd ed.: John Wiley & Sons, 2000.

[145] K Flammer and T Nguyen, "Rinconada Water Treatment Plant Residuals Management Project - Planning Study Report," Santa Clara Valley Water District, San Jose, CA, USA, 2010.

[146] H L Nielson, K E Carns, and J N DeBoice, "Alum Sludge Thickening and Disposal," *Journal (American Water Works Association)*, vol. 65, no. 6, pp. 385-394, June 1973.

[147] City of Grants Pass, "City of Grants Pass WTP Facility Plan," City of Grants Pass, Grants Pass, OR, USA, 2004.

[148] K Grasshoff, M Ehrhardt, and K Kremling, Eds., *Methods of Seawater Analysis*, 2nd ed.: Verlag Chemie, 1983.

[149] E Nilsson and A Stigsson, Pollutant Removal Efficiencies and Flow Detention of Infiltration Trenches , 2012, Master's Thesis, Chalmers University of Technology, Sweden.

[150] X-H Guan, G-H Chen, and C Shang, "Re-use of water treatment works sludge to enhance particulate pollutant removal from sewage," *Water Research*, vol. 39, no. 15, pp. 3433-3440, September 2005.

[151] J O Nelson, C A Joseph, and R L Culp, "Beneficial disposal of water purification plant sludges in wastewater treatment," U.S. Environmental Protection Agency, Cincinnati, OH, USA, 1978.

[152] T Hvitved-Jacobsen, J Vollertsen, and A H Nielsen, *Sewer Processes: Microbial and Chemical Process Engineering of Sewer Networks*, 2nd ed.: CRC Press, 2013.

[153] F R Spellman, *Spellman's Standard Handbook for Wastewater Operators: Volume III, Advanced Level*, 2nd ed.: CRC Press, 2010.

[154] E B Fitch, "Anaerobic digestion and solids-liquid separation," in *Biological Treatment of Sewage and Industrial Wastes*, J McCabe and W W Eckenfelder, Eds.: Reinhold Publishing Corporation, 1958, pp. 159-170.

[155] Camp, Dresser & McKee, Inc., "City of Norfolk, 37th Street Water Treatment Plant, sludge disposal study," Camp, Dresser & McKee, Inc., Raleigh, NC, USA, 1989.

[156] L Lijklema, "Interaction of Orthophosphate with Iron (III) and Aluminum Hydroxides," *Environmental Science & Technology*, vol. 14, no. 5, pp. 537-541, May 1980.

[157] L Gillberg, D Nilsson, and M Åkesson, "The Influence of pH When Precipitating Orthophosphate with Aluminum and Iron Salts," in *Chemical Water and Wastewater Treatment IV*, H H Hahn, E Hoffman, and H Ødegaard, Eds.: Springer Berlin Heidelberg, 1996, pp. 95-105.

[158] B-M Wilén, Primary Treatment at the Rya WWTP, 2014, Personal communication - Britt-Marie Wilén, Professor/Head of Division, Water Environment Technology, Chalmers University of Technology.

[159] J Berkowitz, M A Anderson, and C Amrhein, "Influence of aging on phosphorus sorption to alum floc in lake water," *Water Research*, vol. 40, no. 5, pp. 911-916, March 2006.

[160] R Michalski and I Kurzyca, "Determination of Nitrogen Species (Nitrate, Nitrite and Ammonia Ions) in Environmental Samples by Ion Chromatography," *Polish Journal of Environmental Studies*, vol. 15, no. 1, pp. 5-18, 2006.

[161] R Michalski, "Environmental Applications of Ion Chromatography in Eastern and Central Europe," *Journal of Chromatographic Science*, vol. 48, no. 7, pp. 559-565, August 2010.

[162] R Michalski, "Ion Chromatography as a Reference Method for Determination of Inorganic Ions in Water and Wastewater," *Critical Reviews in Analytical Chemistry*, vol. 36, no. 2, pp. 107-127, 2006.

[163] V Ruiz-Calero and M T Galceran, "Ion chromatographic separations of phosphorus species: a review," *Talanta*, vol. 66, no. 2, pp. 376-410, April 2005.

[164] Dionex Corporation, "Determination of Total Phosphorus Using Two-Dimensional Ion Chromatography," in *Environmental Water Applications Notebook*.: Thermo Fisher Scientific, 2012, pp. 26-29, Application Note 244.

[165] L Van Kuren. (2012, October) Phosphorus - Northeast Section of the Ohio Water Environment Association (NESOWEA). [Online]. http://www.nesowea.org/pdf/OWEA_Phosphorus.pdf

[166] F Davidsson, Wastewater sample, 2014, Personal communication - Fredrik Davidsson, Environmental Engineer, Gryaab AB, fredrik.davidsson@gryaab.se.

[167] M Dalefield, L Nguyen, Z Zheng, and C Naiman. (2011, November) Ion Chromatography - Theory - Ohio State University. [Online]. https://research.chemistry.ohio-state.edu/reel/research-modules/environmental-chemistry/instrumentation/instrument-calibration/ion-chromatography-theory/

[168] M Z Bruckner. (2013, December) Ion Chromatography - Montana State University. [Online]. http://serc.carleton.edu/microbelife/research_methods/biogeochemical/ic.html

[169] F Rouessac and A Rouessac, *Chemical Analysis: Modern Instrumentation Methods and*

Techniques, 2nd ed.: John Wiley & Sons, 2007.

[170] R Thomas, *Practical Guide to ICP-MS: A Tutorial for Beginners*, 3rd ed.: CRC Press, 2013.

[171] M Batsala, B Chandu, B Sakala, S Nama, and S Domatoti, "Inductively Coupled Plasma Mass Spectrometry (ICP-MS)," *International Journal of Research in Pharmacy and Chemistry*, vol. 2, no. 3, pp. 671-680, July-September 2012.

[172] American Public Health Association, American Water Works Association, Water Environment Federation, *Standard Methods for the Examination of Water and Wastewater*, 20th ed., L S Clesceri, A E Greenberg, and A D Eaton, Eds.: American Public Health Association, 1999.

[173] L Nordén, "Vattenverksslam bidrag till föroreningshalterna i ryaverkets slam," Gryaab AB, Gothenburg, Sweden, 2010.

[174] G Bitton, *Wastewater Microbiology*, 4th ed.: John Wiley & Sons, 2011.

[175] American Water Works Association, *Treatment Process Selection for Particle Removal*, J B McEwen, Ed.: American Water Works Association, 1998.

[176] G Howells, T R K Dalziel, J P Reader, and J F Solbe, "Aluminium and Freshwater Fish Water Quality Criteria," in *Water Quality for Freshwater Fish*, G Howells, Ed.: CRC Press, 1994, ch. 3, pp. 55-116.

[177] P T Srinivasan, T Viraraghavan, and K S Subramanian, "Aluminium in drinking water: An overview," *Water SA*, vol. 25, no. 1, pp. 47-56, January 1999.

[178] J Knutsson, ICP-MS Analysis, 2014, Personal communication - Jesper Knutsson, Doctoral student, Chalmers University of Technology.

[179] Institution of Chemical Engineers, *Energy: Money, Materials and Engineering: Institution of Chemical Engineers Symposium Series No. 78.*: Pergamon Press, 1982.

[180] A Flaga and J Schnotale, "Sewage sludge thermal drying and hygienization in a closed loop energy recovering system," Cracow University of Technology, Kraków, Poland, 2009.

[181] F Zhu, Z Zhang, H Jiang, and L Zhao, "The study of sewage sludge thermo-drying efficiency," in *Proceedings of the Seventh International Conference on Waste Management and Technology (ICWMT 7)*, Beijing, China, 2012, pp. 363-367.

[182] L K Wang, Y Li, N K Shammas, and G P Sakellaropoulos, "Drying Beds," in *Handbook of Environmental Engineering, Volume 6: Biosolids Treatment Processes*, L K Wang, Shammas, N K , and Y-T Hung, Eds.: Springer, 2007, ch. 13, pp. 403-430.

[183] A C van Haandel and J van der Lubbe, *Handbook of Biological Wastewater Treatment: Design and Optimisation of Activated Sludge Systems*, 2nd ed.: IWA Publishing, 2012.

[184] K Stendahl, C Färm, I Fritzdorf, and H Ulmert, "The REAL process – a process for recycling sludge from water works," *Water Science & Technology*, vol. 54, no. 5, pp. 235-242, 2006.

[185] D Orhon and N Artan, *Modeling of Activated Sludge Systems.*: CRC Press, 1994.

APPENDICES

Appendix A – Raw data

A.1 Wastewater characterisation

Characterisation of digested and filtered wastewater sample by ion chromatography
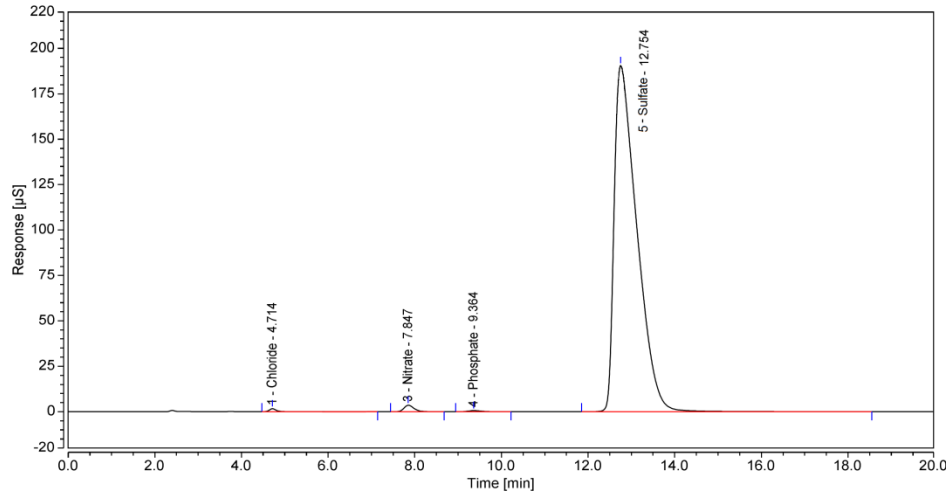
Fig. A.1 IC chromatogram (anions) of digested and filtered wastewater sample

Peak name	Retention time (min)	Area (µS×min)	Relative area (%)	Amount (mM)
Chloride	4.714	0.557	0.48%	0.1654
Nitrate	7.847	0.962	0.82%	0.2833
Phosphate	9.364	0.214	0.18%	0.0945
Sulphate	12.754	115.387	98.52%	69.7272

Table A.1 IC integration results (anions) of digested and filtered wastewater sample

A.2 DWTP sludge characterisation

Parameter		Unit	Date of analysis	Concentration					
				DWTP sludge			DWTP sludge supernatant		
				AL	LA-1	LA-5	AL	LA-1	LA-5
Metals	Al as Al_2O_3	mg/l*	28-Mar	777.13	591.73	260.15	-7.74	-1.83	-1.57
	Fe as Fe_2O_3	mg/l*	28-Mar	62.86	25.77	5.00	-6.42	-1.11	-0.99

* /l is per l of wet DWTP sludge without treatment (no dewatering or drying).

Table A.2 Metals analysis of DWTP sludge and DWTP sludge supernatant from centrifugation

A.3 Jar testing results

Parameter	Unit	Date of analysis	Concentration				
			Jar 1	Jar 2	Jar 3	Jar 4	Jar 5
DWTP sludge type and molar ratio (Al:PO$_4^{-3}$)	-	-	Control, no sludge	AL sludge (0.79:1)	AL sludge (3:1)	LA-1 sludge (3:1)	LA-5 sludge (3:1)
Total solids	mg/l	03-Apr	428.00	384.00	440.00	416.00	388.00
Suspended solids	mg/l	02-Apr	20.00	14.00	24.00	12.00	10.00

Table A.3 Analysis of total and suspended solids from jar test 1

Parameter	Unit	Date of analysis	Concentration					
			Jar 1	Jar 2	Jar 3	Jar 4	Jar 5	Jar 6
DWTP sludge type and molar ratio (Al:PO$_4^{-3}$)	-	-	Control, no sludge	AL sludge (0.79:1)	AL sludge (2:1)	AL sludge (3:1)	AL sludge (diluted) (3:1)	LA-5 sludge (3:1)
Total P*	mg/l	21-May	2.29	2.16	1.82	1.32	1.24	0.88
TOC	mg/l	27-May	22.72	28.79	25.84	24.09	23.42	21.93
DOC	mg/l	27-May	15.15	14.11	13.84	13.73	13.69	11.41
Total N	mg/l	27-May	16.57	17.36	17.35	16.69	16.40	16.42

* Total P measured by colorimetric method following digestion and filtration

Table A.4 Analysis of otal P, TOC, DOC and total N from jar test 2

A.3 DWTP sludge handling

Parameter	Unit	Date of analysis	DWTP sludge		
			AL	LA-1	LA-5
Wet sludge sample	g/l	28-Mar	996.67	1074.00	995.33
Solids (oven drying)	g/l	28-Mar	26.24	16.92	7.59
Total water	g/l	28-Mar	970.43	1057.08	987.75
Solids content	%	28-Mar	2.63%	1.58%	0.76%
Total water content	%	28-Mar	97.37%	98.42%	99.24%
Free water (filtration)	%	28-Apr	21.70%	33.30%	38.30%
Interstitial and free water (centrifugation)	%	20-Mar	62.20%	74.00%	82.50%
Interstitial water*	%	-	40.50%	40.70%	44.20%
Surface and bound water*	%	-	35.20%	24.40%	16.70%

*Calculated as per Vesilind & Martel [102]

Table A.5 Solids and water content of AL, LA-1 and LA-5 sludges

A.4 Secondary settling

Suspended solids (mg/l)	2760.00
Sludge volume index (SVI) (ml/g)	95.56

Table A.6 Sludge volume index for activated sludge sample

Volume (and type) of DWTP sludge added (ml)	Al added as sludge (mg Al/l)	Date of analysis	Gradient* (cm/min)	Zone settling velocity(m/hr)	30-min settlablility (ml)
0 (control, no sludge)	0.00	09-May	4.86	2.92	263.75
10 (LA-1)	5.92	09-May	3.81	2.28	271.25
10 (AL)	7.77	09-May	3.49	2.10	287.50
20 (AL)	15.54	09-May	3.33	2.00	292.50
30 (AL)	23.31	09-May	2.84	1.71	301.25
40 (AL)	31.09	09-May	2.13	1.28	362.50
50 (AL)	38.86	09-May	1.95	1.17	387.50

*Gradient of linear part of settling curves defines the zone settling velocity

Table A.7 Addition of alum DWTP sludge to activated sludge in zone settling rate tests

Appendix B – Sludge and wastewater sample collection

B.1 Sample collection
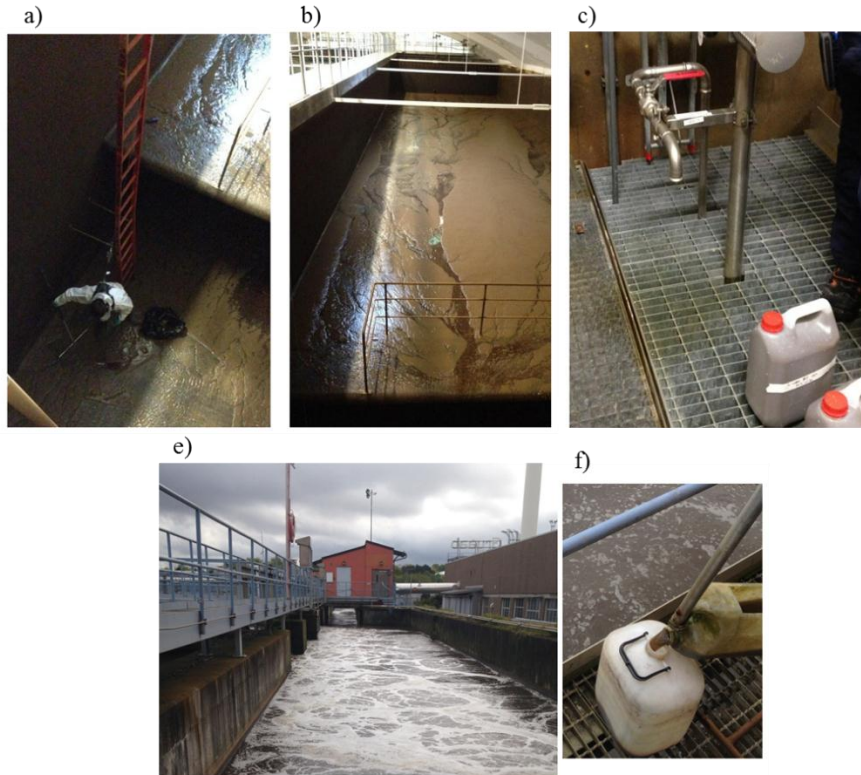
Fig. B.1 Collection of sludge and wastewater samples. a) and b) Manual collection (by the author) of DWTP sludge sample from drained settling tank at Alelyckan DWTP, used with permission from Professor Britt-Marie Wilén, Chalmers University of Technology. c) Tap enabling collection of DWTP sludge sample from storage at Lackarebäck DWTP, taken by the author at the site. e) and f) Collection of activated sludge from secondary settling tanks at Rya WWTP, taken by the author at the site.

B.2 Map of Gothenburg and sample collection and analysis locations

1 Lackarebäck DWTP
2 Alelyckan DWTP
3 Rya WWTP
4 Tankgatan sampling station
5 Environmental Chemistry Laboratory, Chalmers University

Fig. B.2 Sampling/analysis locations. Map data © 2013 Nokia © 2014 Microsoft Corporation

Appendix C – Project Management

Project Management - Gantt Charts - First and Second Half-Sessions 2013-2014

Project Name: Evaluating Reuse of Sludge from Water Treatment for Wastewater Treatment

Key — Preparation, Scheduled action, Unscheduled action, Break, Early, Delayed, Milestone ✔

First Half-Session

Time (week beginning Monday)

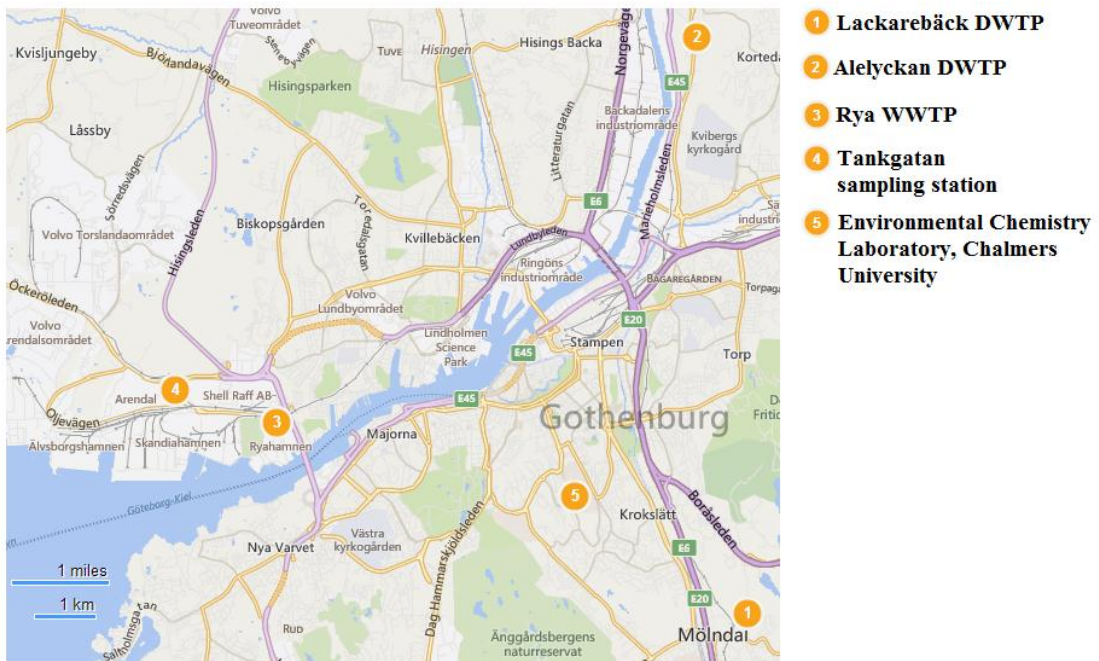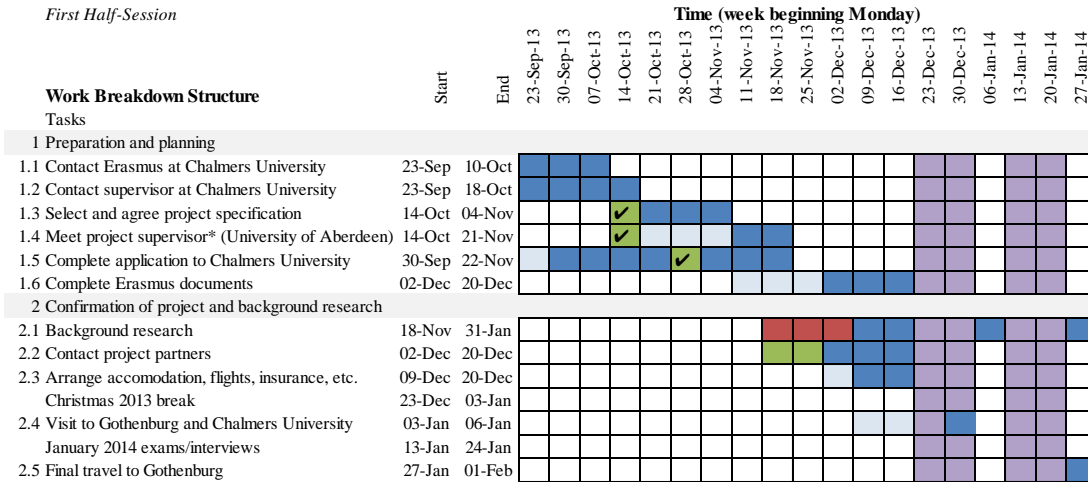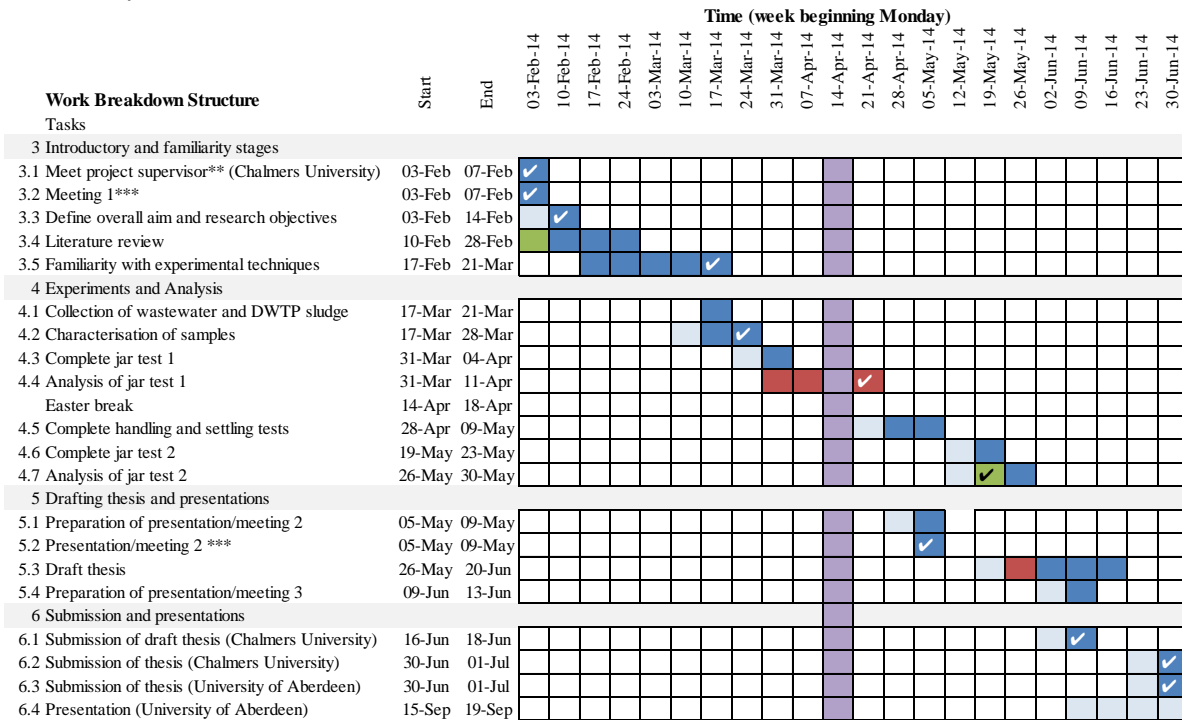| Work Breakdown Structure / Tasks	Start	End
1 Preparation and planning		
1.1 Contact Erasmus at Chalmers University	23-Sep	10-Oct
1.2 Contact supervisor at Chalmers University	23-Sep	18-Oct
1.3 Select and agree project specification	14-Oct	04-Nov
1.4 Meet project supervisor* (University of Aberdeen)	14-Oct	21-Nov
1.5 Complete application to Chalmers University	30-Sep	22-Nov
1.6 Complete Erasmus documents	02-Dec	20-Dec
2 Confirmation of project and background research		
2.1 Background research	18-Nov	31-Jan
2.2 Contact project partners	02-Dec	20-Dec
2.3 Arrange accomodation, flights, insurance, etc.	09-Dec	20-Dec
Christmas 2013 break	23-Dec	03-Jan
2.4 Visit to Gothenburg and Chalmers University	03-Jan	06-Jan
January 2014 exams/interviews	13-Jan	24-Jan
2.5 Final travel to Gothenburg	27-Jan	01-Feb

Second Half-Session

Time (week beginning Monday)

Work Breakdown Structure / Tasks	Start	End
3 Introductory and familiarity stages		
3.1 Meet project supervisor** (Chalmers University)	03-Feb	07-Feb
3.2 Meeting 1***	03-Feb	07-Feb
3.3 Define overall aim and research objectives	03-Feb	14-Feb
3.4 Literature review	10-Feb	28-Feb
3.5 Familiarity with experimental techniques	17-Feb	21-Mar
4 Experiments and Analysis		
4.1 Collection of wastewater and DWTP sludge	17-Mar	21-Mar
4.2 Characterisation of samples	17-Mar	28-Mar
4.3 Complete jar test 1	31-Mar	04-Apr
4.4 Analysis of jar test 1	31-Mar	11-Apr
Easter break	14-Apr	18-Apr
4.5 Complete handling and settling tests	28-Apr	09-May
4.6 Complete jar test 2	19-May	23-May
4.7 Analysis of jar test 2	26-May	30-May
5 Drafting thesis and presentations		
5.1 Preparation of presentation/meeting 2	05-May	09-May
5.2 Presentation/meeting 2 ***	05-May	09-May
5.3 Draft thesis	26-May	20-Jun
5.4 Preparation of presentation/meeting 3	09-Jun	13-Jun
6 Submission and presentations		
6.1 Submission of draft thesis (Chalmers University)	16-Jun	18-Jun
6.2 Submission of thesis (Chalmers University)	30-Jun	01-Jul
6.3 Submission of thesis (University of Aberdeen)	30-Jun	01-Jul
6.4 Presentation (University of Aberdeen)	15-Sep	19-Sep

*Supervisor meetings continued on a weekly basis (after lectures) at University of Aberdeen
**Supervisor meetings continued at least on a weekly basis at Chalmers University
***Meetings with Kretslopp och vatten, Göteborg Stad, Gryaab AB and Professor Britt-Marie Wilén, Chalmers University

Fig. C.1 Gantt charts with work breakdown structure for first and second half sessions (2013/2014) of project