

An analysis of phosphorus cycling in waste stabilization ponds (WSPs) in Nunavut

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March 28th, 2014

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2 Acknowledgements

I would like to acknowledge Rob Jamieson for his supervision and guidance. I would also like to acknowledge Jordan Schmidt for his guidance, research assistance, and data collection, and Colin Ragush for his data collection. Funding was provided by the Government of Nunavut and by the Canadian Water Network.

3 Author Contributions

R. Jamieson, J. Schmidt designed the study and developed methodology. J. Schmidt, C. Ragush, and J. Poltarowicz collected data. J. Poltarowicz and J. Schmidt conducted data analysis. J. Poltarowicz produced the report.

4 Abstract

This study examined the forms of and amounts of phosphorus (P) present in water and sediment samples taken from two arctic climate waste stabilization ponds (WSPs) located in Kugaaruk, and Pond Inlet, Nunavut. This information was used to determine the primary mechanisms for P removal from the water column in these types of systems. The central hypothesis was that the dissolved P in the WSPs is removed by precipitation with cations and by algal or bacterial assimilation. The study was exploratory in terms of examining which removal mechanism controls P removal. First, wastewater sample data was analyzed to detect significant differences between P concentrations at the beginning of the treatment season compared to the end of treatment season within the WSPs to determine if P is removed over the

course of treatment. Then, sediment samples collected from the WSPs were analyzed with a P fractionation method to determine what forms of P are present in the sediment. WSP sediment samples were prepared using two P fractionation methods (Golterman, 1996; Lukkari et al., 2007) to extract different species of P. The data obtained with the method that had the highest percent recovery (Lukkari et al., 2007) was chosen for analysis of fractionation results. Organic-bound P was the largest sediment fraction extracted from both locations, indicating deposition of organic P (partly formed by P assimilation with algae) was one of the dominant P removal mechanisms. The water quality data analysis showed an increase in P in the Pond Inlet WSP, and no change in P concentrations in the Kugarauk WSP, which may have been due to mobilization of P fractions in the sediment. Over 50% of sediment P extracted at both locations was bound to mobile P fractions, which indicates the mobilization of P from sediment at both locations may have occurred and resulted in increasing P concentrations (Pond Inlet) or no change in P concentrations (Kugarauk) in the water column at both locations. Other parameters examined at both WSPs included: biological oxygen demand (BOD₅), total suspended solids (TSS), pH, temperature, and solar radiation. These parameters provided additional measurements of treatment performance and characterization of the WSPs to determine if the removal mechanisms proposed could be supported. The findings of this study identify areas for improvement in treatment performance at both WSP locations, as well as provide a focus for the direction of future research on these types of wastewater treatment systems.

5 Key Words

Waste Stabilization Pond, Arctic, Phosphorus Cycling, Phosphorus Fractionation

6 Introduction

6.1 Motivation

WSPs are the main wastewater treatment method used in northern provinces and territories due to their ability to function under arctic climate conditions as well as their minimum maintenance requirements (Krkosek et al., 2012). They are vital in improving the quality of wastewater effluent before it is released into the environment, so that pollution of receiving water bodies is minimized, and so that eutrophication arising from effluent high in nutrient concentrations is also minimized. However, there is minimal research on arctic climate WSPs and the processes that occur in them during the summer treatment season, which control their waste treatment performance (Krkosek et al., 2012). This study examined phosphorus cycling in arctic WSPs through analysis of wastewater sample data, and sediment fractionation data, in order to identify areas for improvement in treatment performance and a direction for future research on these types of wastewater treatment systems.

6.2 Background

6.2.1 Nunavut Wastewater Treatment Program

This study is a component of a larger project, the Nunavut Wastewater Treatment Program, that seeks to better understand how WSPs function in the Northern provinces and territories, specifically in Nunavut (Centre for Water Resources Studies, 2013; Hayward et al., 2012). In 2013 Environment Canada put forth the Wastewater Systems Effluent Regulations (WSER) to be adopted across Canada (Environment Canada, 2013; Krkosek et al., 2012). As a result of the minimal research on arctic climate WSPs, the federal government provided Nunavut with a five-year timeframe during which research can take place to improve understanding on how arctic WSP systems perform in order to create appropriate effluent standards specific for the North (Krkosek et al., 2012).

6.2.2 Challenges in Wastewater Treatment

The territory of Nunavut faces many challenges with regard to wastewater treatment. One challenge is the extreme low temperatures experienced throughout most of the year that result in a permafrost layer in the ground. As a result of the permafrost, most of the communities do not use underground piping because the pipes could freeze and break (Jamieson & Krkosek, 2013). Another challenge is the limited human resource capacity available to provide personnel who could operate and maintain more advanced types of wastewater treatment facilities (Krkosek et al., 2012). Further problems arise with the lack of equipment and materials available for

the construction of wastewater treatment facilities, and the high transportation costs that are associated with transporting such necessities (Krkosek et al., 2012).

As a result of these challenges, conventional treatment systems using underground piping and mechanical equipment would not be suitable for the conditions faced in the North. In contrast, WSPs are more practical for wastewater treatment in the northern arctic climate because they are passive systems that do not require energy inputs or mechanical devices (Jamieson & Krkosek, 2013). This makes them low-cost technologies that require minimal equipment, materials, and maintenance personnel to operate (Jamieson & Krkosek, 2013). For these reasons, WSPs are the most widely used wastewater treatment technology in the north (Schmidt et al., 2013).

6.2.3 Weather and Climate

Nunavut experiences an arctic climate with extreme low temperatures for most of the year, and very low humidity (Nunavut Tourism, 2014). Winter days have minimal sunlight with as little as zero hours of sunshine on the shortest winter days in communities furthest North (Nunavut Tourism, 2014). In the summer season (from May to August for most communities) daylight extends to 24 hours a day, which can increase algal growth and result in algal blooms within the WSPs (Nunavut Tourism, 2014; Schmidt et al., 2013). Algal blooms can improve waste treatment performance within the WSPs through the production of dissolved oxygen (Schmidt et al., 2013).

6.2.4 Eutrophication

The water bodies that accept the effluent from the WSPs could be at risk of eutrophication if the P content in the effluent became too high. Eutrophication is the overabundance of algae, or algal blooms, that can occur in water bodies with excess nutrients such as P and nitrogen (Powell et al., 2008). An overabundance of algae can create diminished oxygen levels in the water during the night-time because the algae and bacteria use oxygen in respiration for metabolic processes, unlike during the day when algae produce oxygen through photosynthesis (Shilton, 2005). Diminished oxygen levels can have adverse effects on other aquatic organisms that also require oxygen for respiration (Shilton, 2005). P concentrations in un-impacted water systems range from around 4–10 µg/L (CCME, 2004), whereas wastewater system discharges have higher P concentrations that can range from 4-15 mg/L (Shilton, 2005). There is evidence of eutrophication occurring in the receiving environment of a WSP located in the community of Grise Fiord, Nunavut (Fig. 1), which emphasizes the need for more research to prevent such environmental damage in other communities using WSPs (Schmidt et al., 2013)



Figure 1: Image of receiving water environment at Grise Fiord (CWRS, 2012)

6.2.5 Types of Phosphorus

Dissolved P, also called orthophosphate (PO_4^{3-}) is the most bioavailable form of P in WSPs (Gomez et al., 2000; Shilton, 2005). Dissolved P in the water column can be removed by two main mechanisms: either through reaction with cations in the WSPs to form insoluble precipitates which are then removed by sedimentation, or by assimilation within algae or bacteria (Fig. 2; Shilton, 2005). A third, less significant P removal mechanism is P adsorption to the sediment at the bottom of the WSP, or to inorganic crystals formed by metals such as calcium (Ca) and iron (Fe) (Shilton, 2005). Assimilation with algae or bacteria is the process of P uptake by microorganisms in the WSPs (Shilton, 2005). Sedimentation of P can occur through reaction with the cations: Ca or Fe (Shilton, 2005). The P then precipitates to form inorganic P and it settles to the bottom of the WSPs in the sediment layer (Shilton, 2005). When algae and other microorganisms die, their biomass contains organic P, which can also settle in the sediment (Shilton, 2005). Another contributor to the organic P found in the sediment is the deposition, or settling, of organic P originating from raw sewage. The P found at the bottom of the WSPs in the sediment is the least bioavailable form and mainly comprises of Fe, Ca, and some organic-bound P (Shilton, 2005).

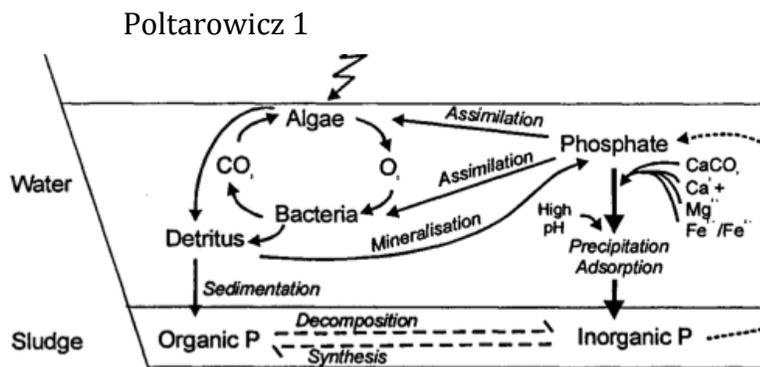


Figure 2: Simple diagram of P removal mechanisms that operate in WSPs (Nguyen & Davies-Colley, 1998)

6.3 Summary of Literature and Knowledge Gaps

Currently, there is little understanding of the processes that occur in WSPs in arctic climates (Krkosek et al., 2012). Studying P removal processes presents certain challenges because the processes are variable due to the many influencing factors that can affect them (Shilton, 2005; Powell et al., 2008). Factors that can affect removal include pH, temperature, and the availability of cations (Shilton, 2005). Several studies have been conducted that examined the removal of P within warm climate WSPs (e.g. Gomez et al., 2000); however, these studies have produced varied results in terms of which P removal mechanisms were most common (Shilton, 2005). The lack of research on arctic WSPs, and the variability among literature findings on warm climate WSPs signifies the need for more studies to examine P cycling under different WSP conditions in different climates. Furthermore, arctic climate WSPs face different climate conditions and physical cycles (e.g. thawing of ice cover) compared to warm climate WSPs. For these reasons, specific studies focused on arctic climate systems should be conducted to determine if warm climate WSP research can be applied to arctic climate WSPs.

6.4 Introduction to study

The goal of this study was to examine P removal mechanisms in arctic climate WSPs through the analysis of sediment fractionation data, water quality data, and physical parameters such as temperature, pH and solar radiation. The findings contribute to the overall knowledge on arctic climate WSPs, and they identify areas for improvement in wastewater treatment performance. The information gathered can also aid in the creation of new wastewater effluent regulations in Nunavut.

One of the key contaminants in municipal wastewater is phosphorus (P), as high concentrations of this nutrient can cause eutrophication of water bodies where effluent is discharged (Shilton, 2005). The WSPs to be examined in this study all discharge into water bodies where eutrophication could pose a problem. Therefore, a better understanding of P removal in the WSPs is key to preventing eutrophication. In addition, P is a limiting nutrient to algae, which provide an essential environment for bacteria that decompose the waste in the WSPs (Schmidt, 2012). Improving the understanding of P cycling could also foster enhanced treatment performance in the WSPs as this nutrient can improve algal and bacterial growth, which are vital in the treatment of the sewage (Schmidt, 2012; Shilton, 2005).

6.4.1 Research questions

In order to examine P cycling in arctic climate WSPs, the following research questions were investigated:

1. Does P decrease in the water column over the treatment season?

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2. Do the WSP physical parameters support the mechanisms hypothesized?
3. Is P predominantly removed through deposition of organic materials or through precipitation with cations?
4. Which P fractionation method is most time efficient and has the highest percent recovery: Golterman (1996) or Lukkari et al., (2007)?

6.4.2 Spatial and temporal scope

Water and sediment samples were collected from WSPs located in two small communities in Nunavut (Fig. 3): Kugaaruk (68° N, 89° W), and Pond Inlet (77° N, 77° W), to obtain a representation of arctic climate WSPs. Sampling of water quality samples, sediment samples, and recording of physical parameters (pH, temperature and solar radiation) was conducted over the summer season to obtain a representation of the treatment season and conditions within the WSPs during this timeframe.



Figure 3: Map of Nunavut showing communities of Kugaaruk and Pond Inlet (Schmidt et al., 2013, PP)

7 Literature Review

7.1 Introduction

In order to provide a background on the literature that covers the topics of this study, the following literature review has been prepared and summarizes the main published research relevant to this study. The scope of research covered includes general research conducted on the biochemical processes that occur in WSPs, studies conducted on cold climate WSPs and warm climate WSPs, as well as the differences between these two systems. Methods for fractionating sediment P samples are also discussed.

7.2 General Research on WSPs

General studies exist on nutrient cycling in WSPs that are not specific to cold or warm climate systems. The literature includes reviews that have outlined the main removal mechanisms for P in WSPs (precipitation with cations and assimilation with algae) and have also identified the differences in removal mechanisms among different pond designs (Nguyen & Davies-Colley, 1998). Such reviews have found that nutrient cycling and removal mechanisms can vary between lagoons, depending on factors such as hydrodynamics and depth of the WSP (Nguyen & Davies-Colley, 1998).

7.3 Research covering cold climate WSPs

Existing research that focuses on WSPs in cold climates is limited and covers a broad scope of the topic of cold climate WSPs. Previous studies have covered topics

such as examining lagoon design, rather than exploring a narrower scope, such as the biogeochemical processes that occur in WSPs. To my knowledge, there have been no studies on the biogeochemical processes that occur in cold climate WSPs.

Research conducted by Heaven et al. (2003) and Prince et al. (1995) covers general aspects of cold climate WSPs such as lagoon design, maintenance and operation (Heaven et al., 2003), economic suitability (Prince et al., 1995), and public consultation (Prince et al., 1995). Research of this broad scope provides a foundation for the use and general understanding of extreme climate WSPs, but it does not cover specifics on the biochemical processes that govern how these lagoons operate, such as P cycling.

7.4 Research covering warm climate WSPs

Research on WSPs in warmer climates ranges from broad topics such as treatment, performance and design of WSPs (Parissopoulos et al., 2003; Harvey et al., 1984), to specific research on P cycling (e.g., Ouzzani et al., 1997). General research pertaining to pond design and phosphorus removal efficiency has been conducted on experimental WSPs under warm climate temperatures of 20 °C (Harvey et al., 1984). Various pond designs, such as facultative, aerobic and anaerobic, have been examined and compared for P removal efficiency as well as for how efficiently the algae remove the P from the water column (Harvey et al., 1984). Pond designs have also been compared under non-experimental conditions in WSPs treating public wastewater located in northern Greece. Findings have indicated better wastewater

treatment with facultative and aerobic ponds, rather than anaerobic ponds (Parissopoulos et al., 2003).

Specific research regarding P removal mechanisms in warm climate lagoons has produced conflicting results with respect to which removal mechanisms control P removal (Shilton, 2005). For example, Somiya and Fujii (1984) found algal assimilation to be more important than precipitation, while Gomez et al. (2000) found that precipitation was a main removal mechanism and found that assimilation accounted for only 6-8% for P removal. The reasons that have been suggested to explain these conflicting findings in the literature are that conditions can vary between lagoons depending on factors such as light exposure, pH, and cation concentrations, and these conditions can influence the removal mechanisms in the lagoons (Shilton, 2005). The existence of conflicting findings between various research shows that removal mechanisms may vary between WSPs and this emphasizes the need for not only more research on the subject of P cycling but also the need for identifying reasons why removal mechanisms may vary between ponds.

Many studies have focused on solely one removal mechanism and the influencing factors on that mechanism. Ouazzani et al. (1997) and Powell et al. (2007), who conducted both field and experimental studies respectively, examined P uptake by algae and factors affecting this mechanism such as the season (Ouazzani et al., 1997), and light intensity (Powell et al., 2008). Similarly, but focusing on P precipitation with cations, Peng et al. (2007) examined other factors influencing this removal mechanism such as pH.

As summarized above, various detailed research exists on WSP removal mechanisms in warm climate field studies, and in laboratory studies conducted under warm climate temperatures. Despite the vast array of studies that have examined P removal mechanisms, there is still inconsistency in the findings of which removal mechanisms dominate P removal in WSPs. The conflicting findings make the research difficult to apply for hypothesizing what removal mechanisms may dominate in other WSPs. As Shilton (2005) suggested, there are physical factors in the ponds that may have effects on the removal mechanisms that occur within them, but these factors need to be further examined in future literature. Furthermore, this type of detailed research on removal mechanisms has not been applied to cold climate WSPs. Due to this lack of specific research applied directly to northern climate WSPs and due to the inconsistency in findings within studies focused on warm climate WSPs, there is a need for more research on nutrient cycling in WSPs overall, and especially in extreme cold climates.

7.5 Differences Between Cold and Warm Climate Conditions

The lack of research on northern WSPs signifies the need for more studies to focus on cold climate systems as well as the need for the warm climate research to be applied to cold climate WSPs. This section addresses the differences between cold climate WSPs and warm climate WSPs that may impede the applicability of warm climate research to the WSPs located in northern climates.

Firstly, there is a need to examine the applicability of the research conducted on warm climate systems to cold climate systems because of the drastically different

amounts of sunlight that cold climate lagoons experience in different seasons. Over the summer season, communities in Nunavut experience 24-hour sunlight conditions, unlike locations under warmer climates that are located at lower latitudes (Nunavut Tourism, 2014). Such long periods of sunlight have a great impact on algal growth within the WSPs, and under ideal conditions the lagoons can experience significant algal blooms, which can improve waste treatment performance (Schmidt et al., 2013).

Secondly, in comparison to warm climate lagoons, there are different physical processes that occur in cold climate WSPs over the winter season. Literature in the field of limnology recognizes many physical differences between seasonally ice-covered lakes, similar to the lagoons studied in this project, and non-freezing lakes. For example, the physical processes such as winter ice-cover, freeze-thaw cycles, and various mixing patterns below the ice layer drive thermodynamic changes as well as hydrodynamic changes in the water column in cold climate lakes, but not in warm climate lakes (Kirillin et al., 2012). In their review, Nguyen and Davies-Colley (1998) determined that these different physical conditions within the WSPs can influence nutrient cycling, contributing to possible differences in main removal mechanisms between warm climate and cold climate WSPs. For example, the freeze-thaw processes that occur can have a de-watering effect that may affect P removal from the water column by influencing P adsorption to sediment (Kvarnstrom et al., 2000). In addition, over the wintertime, cold climate lakes experience their lowest annual light intensity and temperatures under the ice cover that cause decreases in

biological activity; an annual change that does not occur in warm climate lakes (Shuter et al., 2012).

In summary, there are physical and biological processes that can affect P removal in WSPs, and these processes are very different between cold and warm climate WSPs. For these reasons, there is a need to examine the applicability of warm climate WSP research to northern WSPs as well as a need for the difference to be distinguished between warm and cold climate WSPs in the literature. This study addresses the above mentioned knowledge gaps in terms of examining P cycling in arctic WSPs and identifying dominant P removal mechanisms.

7.6 Phosphorus Fractionation Methods

The purpose of using a P fractionation method to analyze sediment P is to separate various P fractions, or species, in sequence from one sediment sample. The fractions are separated in order from the least stable (easiest to extract; requiring weaker extracting solutions) to the most stable (less easily extracted; requiring stronger extracting solutions) so that all the fractions originate from one sample. By extracting all fractions from one original sample, the concentration error due to variation amongst different samples is minimized.

Many P fractionation procedures have been described in the literature but one single method has not been agreed upon (Lukkari et al., 2007). This signifies the need for research that should compare the various methods to determine which one is the most appropriate and applicable for fractionating P in sediments. Various studies have examined the methods published in the literature, but many of these studies

were published over a decade ago and do not examine newer methods that have been developed more recently (Barbanti et al., 1994; Golterman 1996). Two methods were chosen for comparison in this study: the Golterman (1996) method, and the Lukkari et al. (2007) method. Out of the two, the most time efficient method with the highest percent recovery was chosen, and further data analysis was conducted on the results collected from that method. An overview of the applicability of these two methods is given, and other widely cited methods in the literature are reviewed.

Both methods chosen extract inorganic and organic P fractions, which are of interest in this study because they represent removal by precipitation and assimilation, respectively. By determining which fractions are the largest, the main removal mechanism can be hypothesized for the WSPs studied in this project. Both methods are also sequential, which means that one sample of sediment is used for the entire procedure. The Lukkari et al. (2007) method was chosen because it was written to be easily reproduced, it is very comprehensive, and it is an updated modification of an older, widely cited method by Psenner et al. (1984), that was modified by Jensen and Thamdrup (1993). In addition, the Lukkari et al. (2007) method was tested with sediment reference material and had a P recovery between 96% and 112%, making it an accurate method with respect to fractionating P from sediment (Lukkari et al., 2007). The method by Golterman (1996) was chosen because it has been tried and tested for a much longer time frame, and is widely cited in the literature. Furthermore, it was compared against other commonly cited methods and obtained better recovery rates for various P fractions (Golterman, 1996). This comparison is further discussed below.

Two other commonly cited methods for P fractionation in the literature are the SEDEX method, developed by Ruttenberg (1992), and the Standards Measurements and Testing (SMT) procedure, which was developed by the European Commission's Standards Measurements and Testing Program (Garcia-Albacete et al., 2012). The SMT method is non-sequential, which means it uses different samples for extracting each type of P fraction (Garcia-Albacete et al., 2012). The use of a non-sequential method introduces variability between the fractions since the samples used are not identical and this creates additional confounding factors to the procedure. In addition, the method uses strong extractants to separate the various fractions, such as 3.5 M HCl, which can react with Ca-bound P (Golterman, 1996), and give inaccurate representation of the fractions. In contrast, the SEDEX method is a sequential procedure, which uses one sample throughout the entire procedure to sequentially extract the P fractions one-by-one. However, in a comparison of the SEDEX method to the method by Golterman (1996) the SEDEX method was less efficient as it extracted less Ca-bound P than the Golterman (1996) method.

Finding a standard method for future studies examining P fractionation is important to reduce variability among future research. With the number of different fractionation methods that have been published in various studies, there is a need for more uniformity and consistency in the methodology using P fractionation. This study addresses the issue of inconsistent methodology with regard to P fractionation in the literature by identifying a method with the highest time efficiency and percent recovery out of the two methods chosen: the Lukkari et al. (2007) method, and the Golterman (1996) method.

8 Methods

8.1 Introduction

This section of the proposal briefly outlines the experimental design, how the sediment and water samples were obtained, and a thorough review is given of the methods for analysis of water quality data, as well as the preparation and analysis of the sediment samples.

8.2 Experimental Design

The study was conducted on two WSPs located in Kugaaruk and Pond Inlet because these two communities experience an arctic climate and are an appropriate representation of other arctic communities in Nunavut. Water samples, sediment samples, and physical parameter measurements were collected over the course of the summer season (from June to August in Kugaaruk, and from June to September in Pond Inlet) to obtain a representation of the treatment season and conditions within the WSPs during this timeframe.

Total P concentrations (dissolved P concentrations were also examined for the Kugaaruk WSP) were measured each month in the WSPs, raw wastewater and in the last month in decant water (Pond Inlet) and in wetland water (Kugaaruk). WSP P concentrations of each month were compared to one another using t-tests to determine if there was a significant decrease in the P concentrations in the water column over the treatment season. P concentrations in raw wastewater, and the wetland (Kugaaruk), or decant samples (Pond Inlet), were also compared to one

another and to the WSP P concentrations to test for significant differences, which would indicate if P is adequately removed from the raw wastewater over the course of treatment.

Other water quality parameters that were also examined include: total suspended solids (TSS), biological oxygen demand (BOD), water pH and temperature. Water pH and temperature were measured daily with a water quality sensors (YSI 6600 Sondes) suspended in the WSP water column. Solar radiation at the WSP sites was also measured with an Onset HOB0 weather station. TSS and BOD₅ were measured to provide additional water quality characterization. TSS indicates the amount of suspended matter that is present in the water column. Higher levels of TSS indicate less solids removal from the water column and lower levels of TSS indicate more solids removal from the water column. BOD₅ data illustrates organic carbon levels in the water column.

Solar radiation and temperature were measured to determine if these parameters are in the appropriate ranges to support algal growth, and therefore, if they can support P removal through algal assimilation.

The water pH was measured to determine if it was in the appropriate range to allow P removal through precipitation with cations. Precipitation with Ca is most significant in higher pH ranges of pH > 8 (Peng et al., 2007; Shilton, 2005). Precipitation with Fe is dominant in lower pH ranges of about pH 7-8 (Peng et al., 2007).

Sediment samples were obtained at the end of the treatment season to obtain a representation of the deposition of organic and inorganic P over the treatment

season. Two methods were used to fractionate, or extract, the P from the sediment samples: Lukkari et al. (2007) and Golterman (1996). Sediment fractionation data collected with the method that had the highest percent recovery was chosen for analysis. The largest P fractions extracted from the sediment indicated which P removal dominates in the WSPs.

8.3 Study Area

Both of the studied WSPs (in Kugaaruk and Pond Inlet) consist of a holding cell, or lagoon, where raw sewage is stored throughout the winter months of the year and then decanted (their effluent released) annually or twice per year into tundra wetlands or the ocean (Krkosek et al., 2012). The Pond Inlet (Fig. 4) lagoon serves a community of about 1,300 residents and utilizes a lagoon that can hold about 90,000 m³ with a depth ranging from 1.4 m to 1.6 m (Krkosek et al., 2012). Kugaaruk (Fig. 5) has about 770 residents and utilizes a deeper lagoon with a depth of 5 m that can hold about 46,600 m³ (Schmidt et al., 2013). The treatment system in Kugaaruk also consists of a decant cell (a secondary, smaller lagoon) that accepts the wastewater from the main lagoon and helps to disperse it into the receiving wetland (Schmidt et al., 2013).



Figure 4: Aerial view of Pond Inlet WSP.



Figure 5: Aerial view of Kugaaruk WSP.

Table 1: Number of wastewater samples collected from the Kugaaruk WSP over the months of June and August

Month	Raw wastewater samples	WSP Samples	Wetland water samples
June	2	4	
August		4	5

8.4 Sampling Procedure for Water Quality Samples

Water quality samples were obtained in June and August of 2013 in Kugaaruk, and in June, July and September of 2013 for Pond Inlet (Tables 1 & 2). Sampling locations in the WSPs were chosen to account for spatial variability in the water column (Figs. 6 & 7).

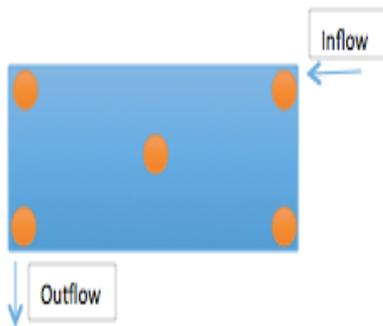


Figure 6: Sampling locations within the WSP located at Pond Inlet marked with orange dots. Decant samples were obtained at the Outflow.

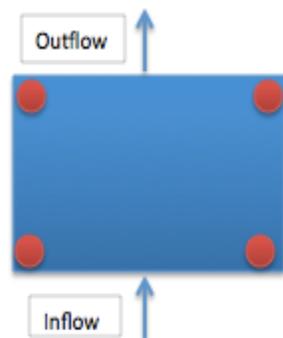


Figure 7: Sampling locations within the WSP located at Kugaaruk marked with orange dots. Decant samples were obtained at the Outflow.

Table 2: Number of wastewater samples collected from the Pond Inlet WSP over the months of June, July and September

Month	Raw wastewater samples	WSP Samples	Decant water samples
June	3	7	
July	3	9	
September	2	7	6

Taiga Laboratories in Yellowknife, Northwest Territories, conducted water quality analysis on samples obtained in Kugaaruk and the Northern Water Quality Laboratory in Iqaluit, Nunavut conducted water quality analysis on samples obtained in Pond Inlet. Samples were transported in cooled containers with icepacks, and all water quality analyses were conducted using Standard Methods for the Examination of Water and Wastewater (Baird et al. 2012).

8.5 Water quality Analysis Kugaaruk

An independent sample t-test at a 95% confidence interval was conducted to compare the means of dissolved and total phosphorus concentrations in raw wastewater samples, lagoon samples taken in June and August, and samples taken from the receiving wetland. The comparisons were done between every combination of mean pairs (Table 4). BOD₅ and TSS were also measured on the samples.

8.6 Water quality Analysis Pond Inlet

An independent samples t-test at a 95% confidence interval was conducted to compare the means of total P concentrations in samples taken of raw wastewater, samples taken from within the Pond Inlet lagoon in June, July, September, and decant

samples. The comparisons were done between every combination of mean pairs (Table 5). BOD₅ and TSS were also measured on the samples.

8.7 Analysis of physical parameters

Temperature and solar radiation data for both locations were plotted against time over the course of the treatment season. Two species of algae have been previously isolated from both locations: *Chlorella vulgaris* and *Chlamydomonas reinhardtii*. The examination of temperature and solar radiation indicates if these parameters are in the appropriate ranges to support the growth of the algal species isolated, and therefore, if the physical parameters can support the P removal mechanism of algal assimilation.

8.8 Sampling Procedure for Sediment Samples

Samples were collected in WSPs located in Pond Inlet and in Kugaaruk, Nunavut. Time-integrated samples were collected in each pond using buckets that had been sunk from 1 to 3 feet into the ponds with anchors to keep them in place. The buckets were designed to collect the sediment settling through the water column over the entire treatment season. A buoy was attached to the buckets so that they could later be located. The buckets were constructed with holes in the bottom portion so that water could drain out. Sediments were trapped in the bucket with a non-woven geotextile that was placed over the holes. The buckets were placed in both locations in June, and the Kugaaruk buckets were collected in August, whereas the Pond Inlet buckets were collected in September. Three buckets were placed in

the Kugaaruk and Pond Inlet WSPs. They were positioned so that they could best survey how the sediment was deposited throughout the WSPs: from where the waste was loaded at the inlet, to the farthest point from the inlet. One bucket was placed closest to the inlet, one was in the middle of the pond and one was furthest from the inlet. Only the buckets nearest the inlet collected enough sediment for analysis for both locations, which indicates spatial variability in sediment accumulation.

8.9 Phosphorus Fractionation Methods

Two P fractionation methods were chosen to prepare the sediment samples for P analysis. The comparison and determination of which method is most appropriate was another component of this study. The methods published by Lukkari et al. (2007) and by Golterman (1996) were used to fractionate the sediment samples in order to obtain both inorganic and organic P concentrations. A hypothesis was formed on what the main removal mechanism might be in the pond by examining which fractions are most prevalent in the sediment. If the organic fraction was the largest, then it would have been hypothesized that deposition of organic-bound P is the main removal mechanism. If the inorganic P fractions were the largest then the hypothesis would have stated that precipitation with cations is the main removal mechanism. Both fractionation methods were tested on samples from the Halifax Wastewater Treatment Facility in order to familiarize the researchers with the methods and to ensure minimal human error when the Nunavut samples were analyzed.

8.10 Sample Preparation

Both P fractionation methods separate inorganic P fractions and an organic P fraction from the sediment. The inorganic fractions that are the same in both methods are Fe, and Ca-bound P. However, the Lukkari et al. (2007) method separates 5 fractions while the Golterman (1996) method separates only the 3 fractions as described above. The Lukkari et al. (2007) method separates an

	Golterman Method	Lukkari Method
Fractions Separated	Fe-P	Loosely sorbed P
		Redox sensitive Fe-P
		Non-reducible Fe-P
	Ca-P	Ca-P
	Organic P	Organic P

additional fraction of loosely bound P found in pore water (Lukkari et al., 2007), and it divides the Fe-bound P into two separate fractions; the redox sensitive Fe-bound, and the non-reducible Fe-bound P (Table 3).

Table 3: Fractions separated by the Golterman (1996) method and by the Lukkari et al., (2007) method.

Furthermore, the two methods use different extractants, and the Lukkari et al. (2007) method includes rinsing steps, which the Golterman (1996) method omits. Lastly, the two methods have different procedures for the separation of the organic fraction. The Golterman (1996) method requires this extraction to be carried out at 90 °C, while the Lukkari et al. (2007) method requires a drying step at 105 °C and an

ashing step at 550 °C to separate the organic P. Flow charts of the fractionation scheme, concentrations of extractants, and duration of extractions, for both methods, are shown in Appendices B and C and may be referred to in conjunction with the procedure described below.

8.11 General Procedure for P Extractions

Three subsamples, weighing about 1 gram, were collected from each sediment sample to serve as replicates to ensure consistency throughout the fractionation procedure. These subsamples were placed into 50 mL plastic vials in which the extractions were carried out. For each extraction, 50 mL of the required extractant, solution, made to extract P from the sediment samples, was added to the sediment samples in the vials, which was then be placed on a shaker table for the required time (Lukkari et al., 2007). After the extraction on the shaker table was completed the samples were centrifuged at 4000 rpm for 15 minutes (Lukkari et al., 2007). A portion of the supernatant, the liquid portion of the sample suspended above the sediment pellet at the bottom of the sample tube, was then poured into a new 50 ml sample vial for analysis of total P. The remainder of the supernatant was filtered using a vacuum filtration system and Whatman Nuclepore Track-Etched filter papers with 4µm pore size to obtain the dissolved P, which was then poured into a 10 ml vial for later measurement. The remaining sediment in the 50 ml plastic vial was put through the procedure again with the following extractant as outlined per each method until all fractions were separated.

As required by the procedure for the HACH Total Phosphate Reagent kit (which was used to prepare the samples for the measurement of P concentrations), the pH of all samples extracted with an acid or base was adjusted to pH 6-8 before they were prepared with the phosphate reagent. The samples that required this neutralization were from steps 3 a., and 3 b., for the Golterman (1996) method, and from steps 3., 4., and 5., for the Lukkari et al. (2007) method. A 2 M NaOH solution was used to neutralize the samples extracted with an acid and 1 M HCl was used to neutralize the samples extracted with a base. The neutralization step was carried out in Erlenmeyer flasks, before the samples were partitioned to obtain an aliquot for total P.

The directions for preparing the 0.11 M NaBD solution for the Lukkari et al. (2007) method, and for the Ca-EDTA and Na₂-EDTA solutions from the Golterman (1996) method are described in Appendix A.

8.12 Additional Steps for Lukkari et al. (2007) Method

Rinsing steps were carried out the same way as described above; however, the supernatant from each rinse was poured into an Erlenmeyer flask containing a combination of the initial supernatant. In this manner, all the rinsing steps were combined with the supernatant from the original extraction for each particular extraction step. Once all of the rinses were collected with the original supernatant, the procedure was followed as previously described; an aliquot was poured into a 50 mL vial for the measurement of total P, and the rest of the supernatant was filtered to

collect the dissolved P in a 10 mL vial. Extractions from step 2 required aeration for 15 minutes to remove the dithionite (Lukkari et al., 2007).

In the last extraction, step 5, the remaining portion of the sediment samples was dried and ashed in ceramic dishes. They were then extracted with 1 M HCl for the required time, using the general procedure described above (Lukkari et al., 2007).

8.13 Additional Steps for the Golterman (1996) Method

The second extraction step was repeated until the P extracted was less than 10 % of the P extracted previously for that step (Golterman, 1996). In the 5th extraction step a hot water bath was used to maintain the extraction at 90 °C. The extraction vial was shaken manually every 10 minutes for the duration of the extraction. After the extraction, the sample was placed in the centrifuge and the rest of the procedure was followed as described in the general procedure above.

8.14 Measurement of Phosphorus Concentrations in Sediment

Once all the P fractions were collected, the P concentrations were measured using the Ascorbic Acid method from Standard Methods for the Examination of Water and Wastewater (Baird et al. 2012), with potassium persulfate. A HACH Total Phosphate testing kit was used in conjunction with a HACH DR 5000 Spectrophotometer for the P analysis.

As required by the procedure for the HACH Total Phosphate Reagent kit, the pH of all samples extracted with an acid or base was adjusted to pH 6-8 before they were

prepared with the phosphate reagent. The samples that required this neutralization were from steps 3 a., and 3 b., for the Golterman (1996) method, and from steps 3., 4., and 5., for the Lukkari et al. (2007) method. 2 M NaOH was used to neutralize the samples extracted with an acid and 1 M HCl was used to neutralize the samples extracted with a base.

8.15 Determination of Phosphorus Concentrations

The spectrophotometer measured the P concentrations in mg PO₄/L and this was converted to mg PO₄/g sediment using the weights of the original sediment weighed at the beginning of the procedure.

For both methods the concentrations obtained for each of the three replicates were averaged for each particular fraction. For the Golterman (1996) method the concentrations obtained for total P for steps 1 a. and 1 b. were added to determine the total Fe-bound P. The same was done for all repetitions of step 2 to obtain the total Ca-bound P, and for steps 3 a., and 3 b., to obtain the entire organic P concentration.

The Lukkari et al. (2007) method indicates that the dissolved P concentrations should be used for the determination of the concentrations of each fraction. Therefore, for this method the dissolved P concentrations were averaged for each fraction. The organic P for this method was determined by finding the differences between average total and average dissolved P concentrations for each fraction, and by adding these differences together along with the average found for the last

fraction, which is specified as the organic fraction in the flowchart in Appendix B (Lukkari et al., 2007).

8.16 Comparison of Methods

The Lukkari et al. (2007) and Golterman (1996) methods were to be compared for time efficiency and reliability of results. The method with the highest time efficiency and percent recovery was to be chosen as the most appropriate method, and the results from that method were to be used to identify the largest P fraction in the sediment. It was hypothesized that the mechanism which formed the fraction with the largest concentration was the main removal mechanism. For example, if the largest fraction was organic-bound P, then it would be hypothesized that deposition of organic-P (partially formed through algal assimilation) was the main removal mechanism.

Results were obtained using both methods: Lukkari et al. (2007) and Golterman (1996). However, the percent recovery for P with the Golterman (1996) method was below 5% and the samples turned a brown/yellow color rather than blue during preparation for P measurement in the Spectrophotometer. In addition, a white precipitate formed (Fig. 8). Due to the low recovery with the Golterman (1996) method only the data obtained



Figure 8: P samples extracted with the Golterman (1996) method as seen after preparation for measurement of P with spectrophotometer. Samples turned a brown/yellow color and a white precipitate formed.

from the Lukkari et al. (2007) method was used for analysis.

9 Results

9.1 Water Quality Analysis Results Kugaaruk

The mean total P concentrations for raw wastewater samples, and WSP samples taken in June, and in August, were not found to be significantly different from one another (Table 4). Only the average total P in the final samples taken from the wetland was found to be significantly different from all the other total P averages. Dissolved P averages were all significantly different from one another except for the averages in samples obtained from the WSP in June and the samples obtained from the wetland (these two averages were not found to be significantly different).

The average total and dissolved P concentrations in the pond at the end of the treatment season in August (total: 9.75 mg/L P, dissolved: 8.05 mg/L P) decreased from the average total and dissolved P concentrations in the raw wastewater (total P: 15.05 mg/L P, dissolved P: 9.42). The total and dissolved P concentrations slightly increased over the treatment months from June to August, increasing from 6.98 mg/L

Table 4: Comparison of mean concentrations of total and dissolved P concentrations for water samples from the Kugaaruk WSP. BOD₅, and TSS are provided for wastewater characterization.

Sample	Average Total P concentration in mg/L P	Average Dissolved P concentration in mg/L P	Average BOD in mg/L dissolved oxygen	Average TSS in mg/L solids
Raw wastewater	15.05 ^a	9.42 ^a	398	294
WSP June	6.98 ^a	5.56 ^b	121	29
WSP August	9.75 ^a	8.05 ^c	162	28
Wetland	6.09 ^b	4.88 ^b	25	13

Note: Means with differing superscript letters were significantly different ($p < 0.05$), and the means with the same superscript letters were not significantly different.

total P and 5.56 mg/L dissolved P in June, to 9.75 mg/L total P and 8.05 mg/L dissolved P in August.

Average BOD₅ decreased between raw samples (398 mg/L dissolved oxygen) and the lagoon samples (121 mg/L and 162 mg/L dissolved oxygen). Within the lagoon average BOD₅ decreased throughout treatment months going from 121 mg/L dissolved oxygen in June to 162 mg/L dissolved oxygen in August. Final wetland samples had the lowest average BOD₅ measurement of 25 mg/L dissolved oxygen.

Average TSS also decreased between raw samples (294 mg/L) and the lagoon samples (29 mg/L and 28 mg/L). Within the lagoon average TSS decreased over the treatment months, going from 29 mg/L in June, to 28 mg/L in August. Final wetland samples had the lowest TSS measurements at 13 mg/L.

9.2 Water Quality Analysis Results Pond Inlet

Total P concentrations were significantly different between all combinations of pairs of months, raw wastewater samples, and decant samples at the Pond Inlet WSP

Table 5: Comparison of mean total P concentrations for water samples from the Pond Inlet WSP. BOD₅ and TSS are provided for wastewater characterization.

Sample	Average total P concentration in mg/L	Average BOD ₅ in mg/L dissolved oxygen	Average TSS in mg/L solids
Raw	20.93 ^a	490	320
June	8.88 ^b	191	46
July	10.20 ^c	177	22
September	11.41 ^d	113	56
39 Decant	11.46 ^e	103	65

Note: Means with differing superscript letters were significantly different ($p < 0.05$), and the means with the same superscript letters were not significantly different.

(Table 5).

The total P concentration in the lagoon at the end of the treatment season in September (11.41 mg/L P), and in the decant samples (11.46 mg/L), decreased from P concentration in the raw wastewater (20.93 mg/L P). The total P concentrations slightly increased over the treatment months within the WSP from June (8.88 mg/L P) to September (11.41 mg/L P).

Average BOD₅ decreased over treatment months going from 191 mg/L dissolved oxygen in June to 113 mg/L dissolved oxygen in September. Final BOD₅ measurements in decant samples (103 mg/L dissolved oxygen) were lower than those in the WSP (177 mg/L and 113 mg/L dissolved oxygen).

Average TSS first decreased then increased over the treatment months, going from 46 mg/L in June, to 22 mg/L in July, to 56 mg/L in September. TSS was highest in decant samples at 65 mg/L.

9.3 Kugaaruk Sediment Fraction Analysis

The largest fraction was the organic fraction comprising 49% of total P extracted (36% mobile organic and 13% immobile organic). The second largest fraction was from P bound in redox sensitive Fe compounds (21%) (Fig. 9).

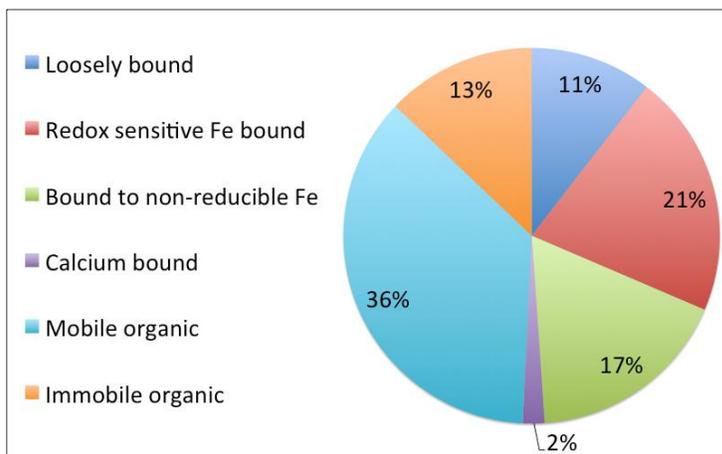


Figure 9: Sediment fractions as percentages of total phosphorus extracted from the Kugaaruk WSP sediment samples.

9.4 Pond Inlet Sediment Fraction Analysis

The largest fraction was the organic fraction comprising 43% of total P extracted (22% mobile organic and 21% immobile organic). The second largest fraction was from P bound in non-reducible Fe compounds (29%) (Fig. 10).

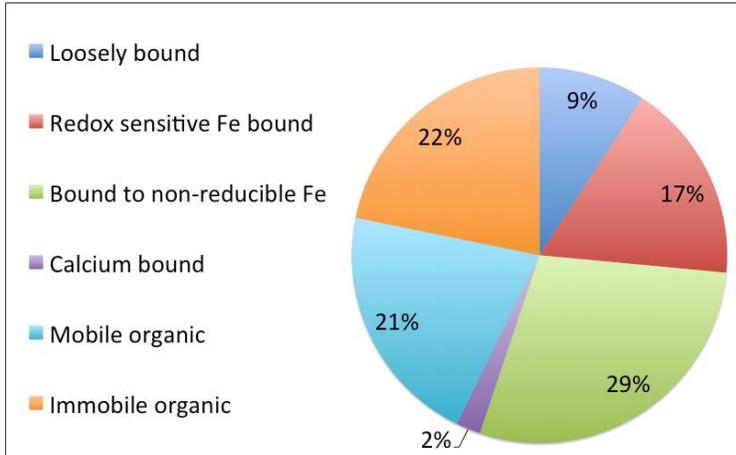


Figure10: Sediment fractions as percentages of total phosphorus extracted from the Pond Inlet WSP sediment samples.

9.5 Kugaaruk WSP Characterization

9.5.1 Temperature and pH

The pH range was pH 6.57-7.44. The temperature range was 0.42 – 18.73 °C (Fig. 11).

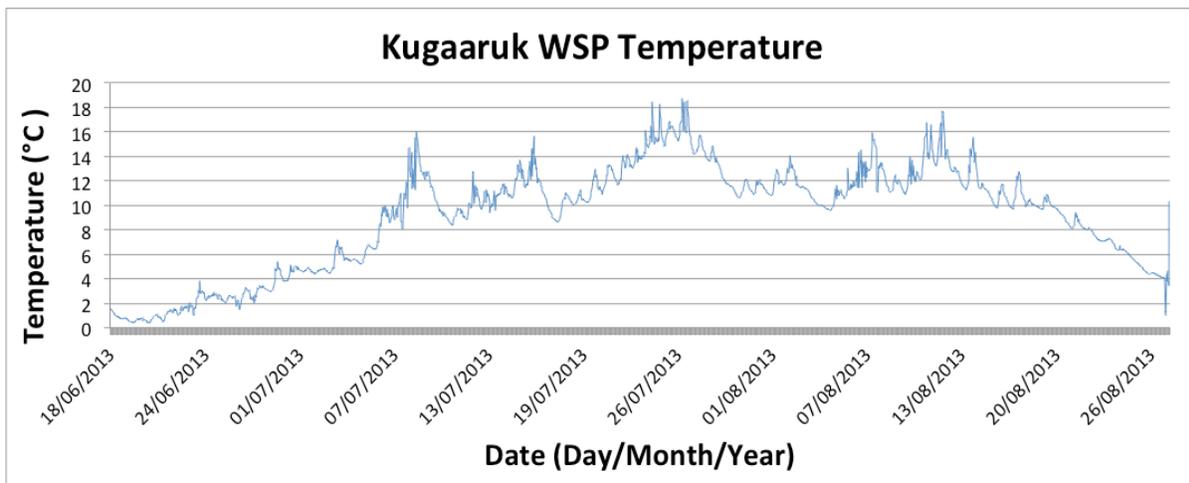


Figure 11: Plot showing the variation of temperature (°C) over the course of the treatment season (dates are in day/month/year) in the Kugaaruk WSP, from mid June to late August.

9.5.2 Solar Radiation

The majority of solar radiation in Kugaruuk was 200-600 W/m². The overall range for solar radiation was 0.6-786 W/m² (Fig. 12).

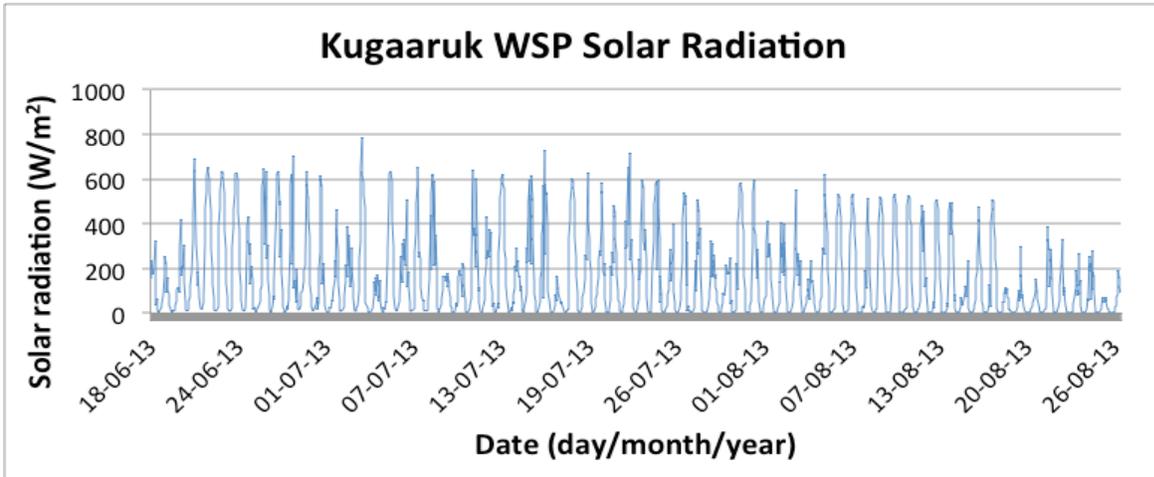


Figure 12: Plot showing the variation of solar radiation (W/m²) over the course of the treatment season (dates are in day/month/year) in the Kugaruuk WSP, from mid June to late August.

9.6 Pond Inlet WSP Characterization

9.6.1 Temperature and pH

The pH range for the Pond Inlet WSP was pH 7.1-7.63. The temperature range was 0.92 – 18.84 °C (Fig. 13).

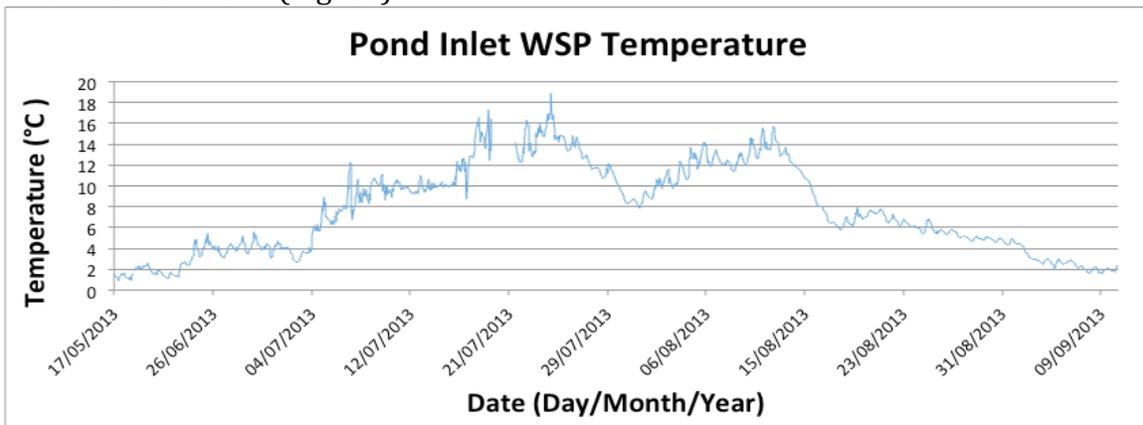


Figure 13: Plot showing the variation of temperature (°C) over the course of the treatment season (dates are in day/month/year) in the Pond Inlet WSP, from early June to early September.

9.6.2 Solar Radiation

The majority of solar radiation in Pond Inlet was 200-600 W/m². The overall range for solar radiation was 0.6 - 942 W/m² (Fig. 14).

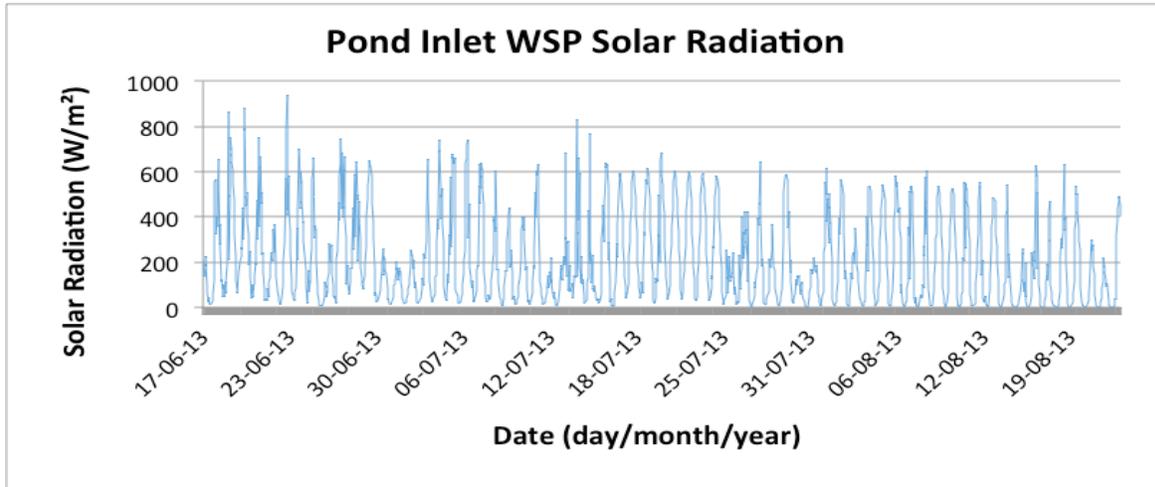


Figure 14: Plot showing the variation of solar radiation (W/m²) over the course of the treatment season (dates are in day/month/year) in the Pond Inlet WSP, from mid June to late August

10 Discussion

10.1 Water Quality Analysis

10.1.1 Phosphorus in the water column

Total and dissolved P within the WSP in Kugaaruk and total P within the WSP in Pond Inlet increased over the treatment season. A small concentration effect may have contributed to this increase in P due to a decrease in the volume of water in the WSPs through evaporation. The increase in P concentrations in the WSPs may have also been caused by solubilisation of P from the sediment as the temperature in the pond increased and the sediment in the pond thawed. Changing redox conditions in

the pond may have also released bound or trapped P. The mobile P fractions that can undergo such mobilization and release due to changing physical conditions are: loosely bound P, redox sensitive P, and mobile organic P (Lukkari et al., 2007). Mobilization of these mobile P fractions (which composed over 50% of P extracted from sediment at both WSP locations) from the sediment over the course of the treatment season may have caused the observed increase in P in the water column.

Despite an increase in P in the WSPs over the course of the treatment season, the P in decant samples from the Pond Inlet WSP, and in wetland samples from the Kugaaruk WSP, was significantly lower than in the original raw samples obtained from each location, indicating that P removal did occur. Pond Inlet decant samples had a P content of 11.46 mg/L total P compared to 20.93 mg/L total P in the raw wastewater samples, which indicates a 45% decrease in total P after the treatment of raw wastewater. Kugaaruk wetland samples had an average total P content of 6.09 mg/L and an average dissolved P content of 4.88 mg/L compared to raw samples which had 15.05 mg/L average total P and 9.42 mg/L average dissolved P. This indicates a 60% decrease in total P and nearly a 50% decrease in dissolved P after treatment of raw wastewater. In Pond Inlet we can speculate that the P removal occurred in the WSP, as the comparison between P concentrations was made between raw sewage and decant wastewater, just before it enters the receiving wetland. In Kugaaruk it can only be assumed that P removal occurred at some point in the WSP or wetland, because P concentrations were compared between raw sewage and wetland water samples.

10.1.2 Biological oxygen demand (BOD₅)

BOD₅ was lower in the Kugaaruk WSP (121 mg/L and 162 mg/L dissolved oxygen) than in raw wastewater samples (398 mg/L dissolved oxygen) indicating the WSP provided removal of carbonaceous materials from the wastewater. The BOD₅ did, however, increase between June and August, going from 121 mg/L to 162 mg/L dissolved oxygen. This could be due to increased biological activity in the WSP causing an increase in oxygen demand. The final BOD₅ in wetland samples was much lower (25 mg/L dissolved oxygen) indicating the wetland provided efficient removal of carbonaceous materials.

BOD₅ in the Pond Inlet WSP decreased consecutively from June samples (191 mg/L), July samples (177 mg/L), September samples (113 mg/L), and final decant samples (103 mg/L). This sequential decrease in BOD₅, compared to the increase in BOD₅ in the WSP in Kugaaruk, may be due to the shallower structure of the Pond Inlet WSP, which is about 1.5 m deep, compared to the Kugaaruk WSP, which is about 5 m deep. The deeper structure of the Kugaaruk WSP can vertically support more algae and bacteria, possibly contributing to an increase in biological activity over the course of the treatment season.

10.1.3 Total suspended solids (TSS)

In Kugaaruk, TSS concentrations were over 90% lower in WSP samples (29 mg/L and 28 mg/L) and in wetland samples (13 mg/L) compared to raw wastewater samples (294 mg/L), indicating adequate solids removal from the pond.

By contrast, TSS results from Pond Inlet show an initial decrease in TSS from raw wastewater (46 mg/L) to WSP June samples (22 mg/L), followed by an increase in September samples (56 mg/L), and another increase in final decant samples (65 mg/L). The increased TSS concentrations in September at Pond Inlet may have been due to the higher solar radiation range at the Pond Inlet WSP compared to the Kugaaruk WSP, which may have led to better algal growth at the Pond Inlet WSP. Consequently, greater amounts of algae could have contributed to the higher concentration of suspended solids in the Pond Inlet WSP. As a possible explanation for increased TSS concentrations in Pond Inlet decant samples, sediment at the bottom of the WSP may have become uplifted during the decanting process, creating more suspended solids in the water being released. The decanting process requires the use of a pump, which could easily disturb the sediment at the bottom of the WSP. Additionally, sediment disturbance is more likely in the shallower WSP of Pond Inlet (about 1.5 m deep), than the Kugaaruk WSP (about 5 m deep).

10.2 WSP Characterization

10.2.1 Algal growth

Solar radiation at both locations (Kugaaruk: 0.6-786 W/m², Pond Inlet: 0.6 - 942 W/m²) was in the range to support algal growth. The majority of solar radiation in both Kugaruuk and Pond Inlet was 200-600 W/m². *Chlorella Vulgaris* has been grown under radiation ranging from 20 W/m² to 110 W/m² (Ahn et al., 2012; Belotti et al., 2013) and *C. Reinhardtii* has been show to grow at 306–357 W/m² (Janssen et al.,

2000). As such, both species of algae are able to grow within the solar radiation range observed at both WSP locations.

The temperatures at both locations were also in the appropriate range to support algal growth. *C. vulgaris* has optimal growth at about 25-30 °C (Sharma et al., 2012) but can grow at temperatures as low as 4 °C (Ahn et al., 2012), and *C. reinhardtii* has been observed to grow at temperatures ranging 15–37°C (Vitova et al., 2011). The temperature ranges observed at both WSPs (Kugaaruk: 0.42 – 18.73 °C, Pond Inlet: 0.92 – 18.84 °C) coincide with temperature ranges found to support growth for both species of algae. Therefore, the two WSP locations can support algal growth and the mechanism of P removal by algal assimilation.

10.2.2 Precipitation with Cations

The lower pH range in the Kugaaruk WSP (pH 6.57-7.44) was optimal for P removal by precipitation with Fe (Peng et al., 2007), while the higher pH range in the Pond Inlet WSP (pH 7.6 - 7.11) was optimal for P removal by precipitation with Ca (Peng et al., 2007; Shilton, 2005). Sediment fractionation data from Kugaaruk showed 38% of P extracted was bound to Fe (non-reducible + redox sensitive Fe). This fraction was the second highest extracted, and corresponds to the observed pH range at this WSP, as it was optimal for formation of Fe-bound P. Although the pH range at Pond Inlet was optimal for formation of Ca-bound P (Peng et al., 2007; Shilton, 2005), surprisingly, Ca-bound P was only 2 % of total P extracted from sediments from this WSP. This finding is not consistent with the results of previous

studies such as the one by Peng et al., (2007), who found that removal by precipitation with Ca was dominant at higher pH ranges.

10.3 Sediment Analysis

The organic fractions in the sediment were the largest in both Kugaaruk (49%) and Pond Inlet (43%), which is evidence supporting P removal by deposition of organic P as one of the dominant removal mechanisms (algal or bacterial assimilation contributes to this dominant removal mechanism). The second largest fractions in both locations were P-bound to Fe compounds. In Pond Inlet this was the non-reducible Fe fraction (29%) and in Kugaaruk this was the redox sensitive Fe fraction (21%). These results indicate that precipitation with Fe was another dominant removal mechanism.

The mobile P fractions at both locations were over 50% of the total P extracted, and may have become mobilized over the treatment season causing the increases in P that were observed in both locations. The mobile fractions (redox sensitive Fe-bound P, mobile organic P, and loosely bound P) are the P species that can become solubilized when physical conditions in the WSPs change: such as pH and redox potential (E_h) (Lukkari et al., 2007). In particular, the P bound to redox sensitive Fe can be mobilized when redox conditions within the WSP change (Lukkari et al., 2007). Redox potential (E_h) is a measurement of the tendency of a species to become reduced by gaining electrons. A high E_h indicates that a species has a high tendency to become reduced, and the reverse is true for a low E_h . In WSPs, the redox conditions can change due to changing concentrations of dissolved oxygen via chemical

reactions (e.g.,oxidation,) and aerobic respiration (Gomez et al., 1999; Reed et al., 2011). Under low E_h conditions, Fe-bound P becomes more soluble, which mobilizes the P, leading to higher concentrations of P in the water column. Higher E_h conditions are associated with lower P concentrations in the water column because Fe-bound P is more stable under these conditions (Gomez et al., 1999; Peng et al., 2007). The mobile P was 52% of P extracted in Pond Inlet and 60% of P extracted in Kugaaruk. Therefore, over 50% of P in sediments at both locations could have become solubilized from the sediment layer and resulted in the higher P concentrations observed in the water column over the treatment season.

11 Conclusion and Recommendations

Research on arctic WSPs is limited, thus with the release of new federal Wastewater Systems Effluent Regulations, the territory of Nunavut was given a 5-year timeframe to conduct further research into these systems to optimize treatment and to create unique standards and regulations specific to the North (Environment Canada, 2013; Krkosek et al., 2012). This study aimed to examine the forms of and amounts of P in water and sediment samples taken from two arctic climate WSPs located in Kugaaruk, and Pond Inlet, Nunavut. The findings of this study contribute to the body of knowledge surrounding arctic WSPs and provide areas for wastewater treatment improvement as well as direction for future research. The following research questions were examined:

1. Does P decrease in the water column over the treatment season?

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2. Do the WSP physical parameters support the P removal mechanisms hypothesized?
3. Is P predominantly removed in organic materials or through precipitation with cations?
4. Which P fractionation method is most time efficient and has the highest percent recovery: Golterman (1996) or Lukkari et al., (2007)?

11.1 Main Findings

Through the analysis of P concentrations in water samples obtained from the WSPs over the course of the treatment season, it was found that P concentrations increased in the Pond Inlet WSP and did not significantly change in the Kugaaruk WSP. However, P concentrations in final effluent samples at both locations were significantly lower than P concentrations in raw wastewater, which indicated adequate removal of P from the sewage.

The physical parameters (temperature, solar radiation, and pH) examined at both WSP locations were in the appropriate ranges to support the mechanisms hypothesized for P removal: algal assimilation contributing to formation of organic P, and precipitation with cations contributing to formation of inorganic P. The ranges recorded for temperature and solar radiation were consistent with previously observed ranges that allowed for the growth of *C. vulgaris* and *C. reinhardtii* (Ahn et al., 2012; Belotti et al., 2013; Janssen et al., 2000; Sharma et al., 2012; Vitova et al., 2011).

The ranges recorded for pH were appropriate for P precipitation with cations, as observed and documented in the literature (Peng et al., 2007; Shilton, 2005).

The Lukkari et al., (2007) method provided the highest percent recovery, and the data obtained with this method was therefore chosen for analysis. Sediment fractionation data obtained with the Lukkari et al., (2007) method also supported the hypothesized P removal mechanisms as both organic P fractions (created through the deposition of organic materials) and inorganic P fractions (created by P precipitation with cations) were extracted. The organic P fraction was the largest P fraction extracted from both locations, suggesting that P removal through deposition of organic materials is a dominant removal mechanism, and P assimilation with algae or bacteria has contributed to the formation of this P fraction. Precipitation with Fe was indicated as the second most dominant removal mechanism as Fe-bound P was the second largest fraction extracted from both locations.

11.2 Recommendations

The data collected from this study highlights areas where wastewater treatment performance can be improved for the locations under study. Firstly, it was observed that P concentrations in both WSP locations were lower at the beginning of the treatment season in June compared to the end of the treatment season in August (Kugaaruk) and September (Pond Inlet), which is when the WSPs were decanted. In order to minimize P released into the receiving water bodies, it is recommended that the WSPs are decanted when P concentrations are lowest: in June.

Secondly, the sediment data indicates that deposition of organic-bound P was the dominant removal mechanism at both locations, and assimilation with algae or bacteria contributed to the formation of this P fraction. In order to improve P removal within the WSPs, it is recommended that assimilation with algae be facilitated. One way to improve algal growth is to design shallower WSPs so that light intensity reaching the full vertical depth of the water column is maximized, and thus algae will have maximized sunlight for growth.

In order to incorporate both recommendations (minimize P released in effluent and maximize algal growth in the WSPs), a two-part WSP system is ideal. The first WSP would be anaerobic (the WSP would have no oxygen and thus no algal growth would occur in this WSP) and would serve to reduce BOD₅ levels in the sewage by settling out a majority of the suspended solids (Shilton, 2005). The secondary, shallower WSP would serve to remove P through algal assimilation by facilitating algal growth (Shilton, 2005). The final treated effluent could then be released at the beginning of the treatment season in June when P concentrations in the current WSPs were recorded as the lowest out of the entire treatment season. In this two-part WSP system, BOD₅, TSS and P concentrations in the effluent would be minimized through the facilitation of settling solids in the first WSP, and through facilitation of P removal by algal assimilation in the second WSP (Shilton, 2005).

11.3 Limitations

Despite the important contributions of the present study to the WSP literature, some limitations do exist. For example, data collection was limited to the summer

season. This is because during the winter period there is limited biological and chemical activity in the lagoons (Shuter et al., 2012), making it difficult to measure removal mechanisms and to obtain samples due to ice cover. However, the purpose of this study was to contribute to the knowledge of P cycling in arctic lagoons so that treatment can be optimized. Since the majority of treatment occurs over the summer months, the focus of this study was therefore during the summer season.

Due mainly to time and financial constraints the scope of this study was also limited in terms of the quantity of data and the number of samples collected. Firstly, there are only two WSPs that were analyzed in this study, from which sediment samples and water quality data were collected. Secondly, due to the focus on the summer season, options for when sediment and water sampling could be conducted were limited, and therefore sampling was only conducted over a few days during the treatment season. This limited the amount of data available for analysis and could have affected the representativeness of the actual conditions in the ponds. It would have been beneficial to the study to have sediment samples and water quality data that were collected over a longer timespan and across more locations within the lagoons so that the data would be more representative temporally as well as spatially. However, due to time and financial constraints of sending researchers to the remote communities of Kugaaruk and Pond Inlet, only the sediment and water samples collected were available.

Limitations associated with speculations of the main P removal mechanisms occurring in the WSPs were also present within this study. The hypothesis of what the main removal mechanism is in the lagoons was based on an observation of the

sediment fractionation data. The fractions extracted were hypothesized to have formed through the proposed removal mechanisms. However, this process was only speculative as it could not be determined for certain that the fractions extracted were formed through to the process of the main removal mechanism since there may have been other mechanisms involved.

Human error, as well as error due to equipment problems can occur during laboratory procedures, data collection, and data analysis. Attempts to minimize human and equipment error were made by analyzing triplicates of the sediment samples to ensure consistency when performing the procedure and to ensure reliability of results. In addition, the fractionation methods were pilot-tested on samples from the Halifax Wastewater Treatment Facility in order to familiarize the researchers with the methods and to limit human error. The pilot testing also revealed any problems that may arise with equipment and the preparation of solutions so that these problems could be resolved before the analysis of the Nunavut samples.

11.4 Direction for Future Research

To improve on the limitations of the present study, future research could span over a longer time frame and sampling could take place at more communities utilising WSP wastewater treatment. For example, future studies should aim to cover multiple summer seasons, as well as to collect samples from more communities. This would improve the representativeness of results for P cycling within arctic WSPs. There is also a need to further investigate P removal by deposition of organic

material (and the mechanism of algal assimilation that contributes to the formation of this fraction), as the sediment fractionation data indicated it was a dominant removal mechanism. Further research could focus on improving P removal by algal assimilation through the examination of various WSP designs and through the identification of the most effective designs that improve overall wastewater treatment.

11.5 Conclusion

Phosphorus cycling in arctic climate WSPs was examined through the analysis of water quality data and sediment fractionation data obtained from two WSPs located in Nunavut. This study succeeded in identifying areas for treatment improvement and directions for future research so that wastewater treatment in arctic climates can be improved. The territory of Nunavut can utilize this information in the process of creating their unique standards and regulations for wastewater effluent.

12 Appendix A

Contents and preparation instructions for solutions of both methods are listed below.

Lukkari et al. (2007) Method

0.11 M NaBD solution:

0.11 M sodium dithionite ($\text{Na}_2\text{S}_2\text{O}_4$) in 0.11 M sodium bicarbonate (NaHCO_3) under N_2 atmosphere

Golterman (1996) Method

0.05 M Ca-EDTA solution:

Dissolve 18.6 g $\text{Na}_2\text{-EDTA}\cdot 2\text{H}_2\text{O}$ and 7.35 g $\text{CaCl}_2\cdot 2\text{H}_2\text{O}$ in 1 L H_2O

Add Tris to adjust pH to ~ 9

Add 1% $\text{Na}_2\text{S}_2\text{O}_4$ under N_2 atmosphere

Before using solution for extraction pH must be adjusted to pH 7-8

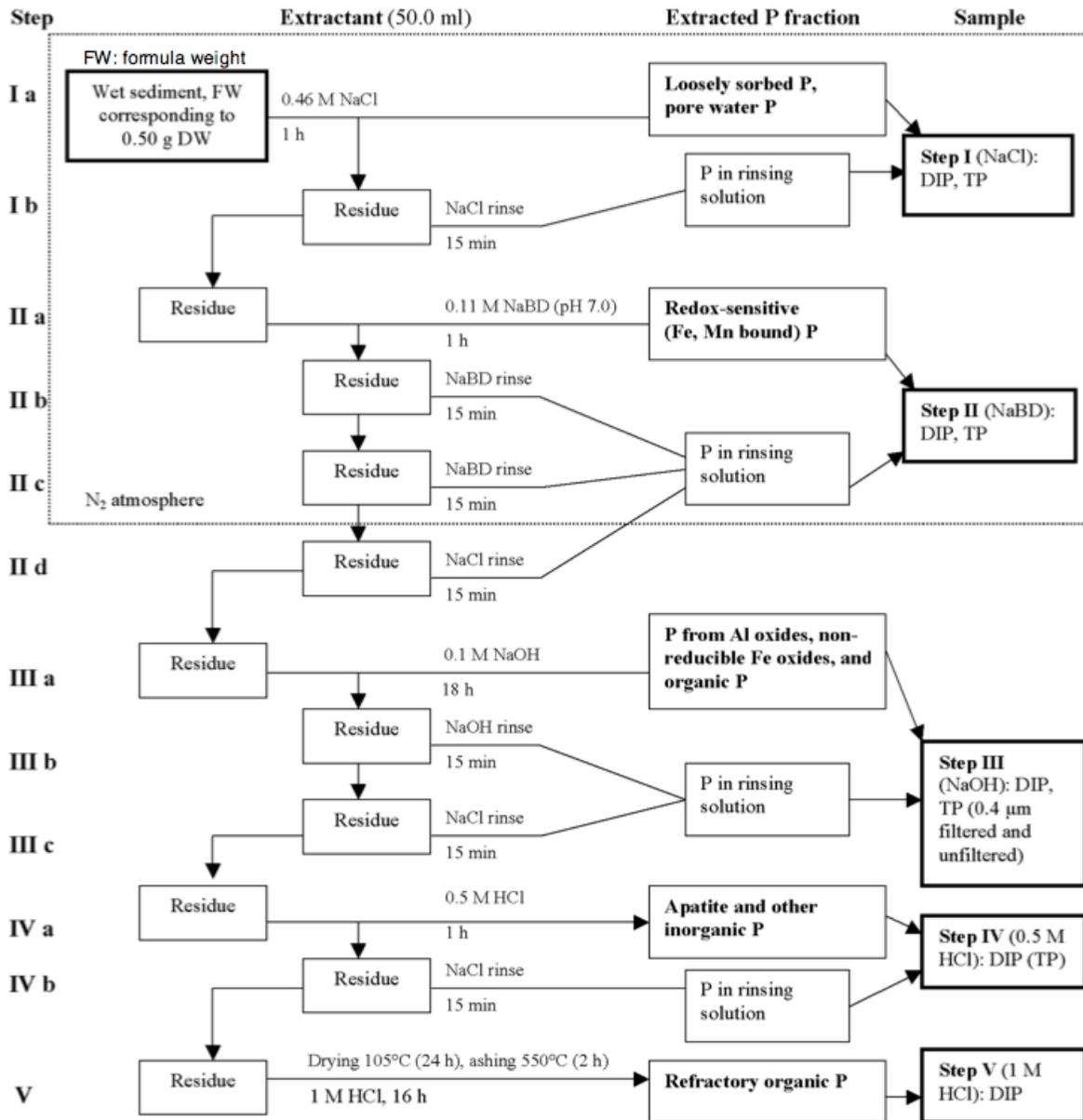
0.1 M $\text{Na}_2\text{-EDTA}$ solution:

Dissolve 37.2 g $\text{Na}_2\text{H}_2\text{EDTA}\cdot 2\text{H}_2\text{O}$ in 1L H_2O

Adjust pH to ~ 4.5

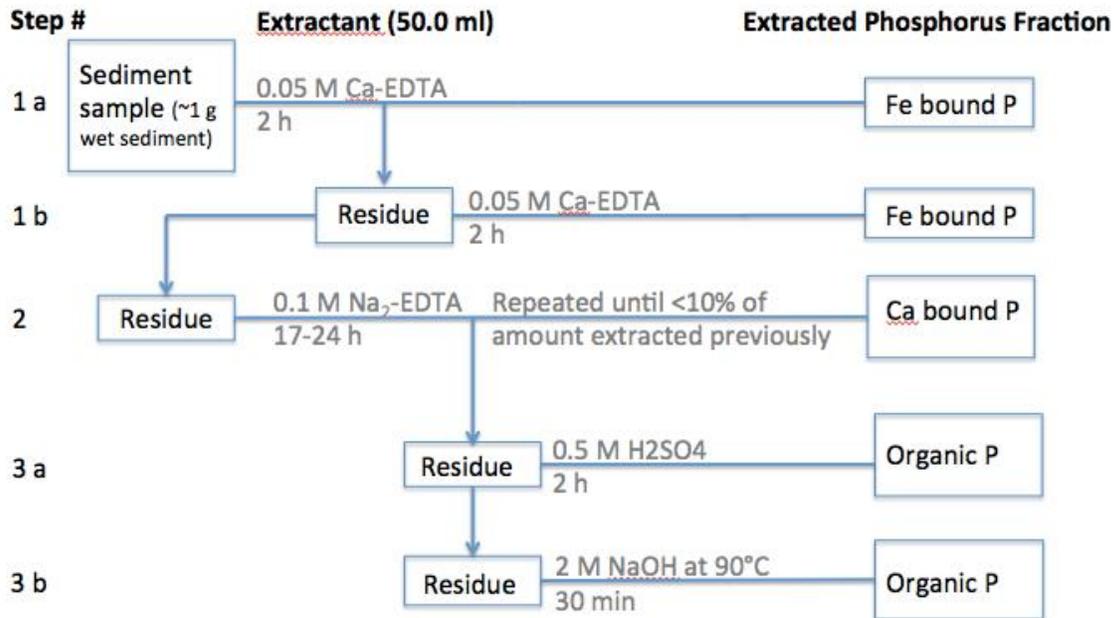
13 Appendix B

The P fractionation scheme for the Lukkari et al. (2007) method. Step numbers and extractants are listed in sequence.



14 Appendix C

The P fractionation scheme for the Golterman (1996) method. Step numbers and extractants are listed in sequence.



(Golterman, 1996; Gomez et al., 2000)

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