CHARACTERIZATION AND ENVIRONMENTAL RISK ASSESSMENT OF A WASTEWATER TREATMENT LAGOON

Located at the Canadian Armed Forces
17 Wing Detachment Dundurn

CARACTÉRISATION ET ÉVALUATION DES RISQUES ENVIRONNEMENTAUX ASSOCIÉS À UNE LAGUNE DE TRAITEMENT DES EAUX USÉES

Située au Détachement Dundurn de la
17^{e} Escadre des Forces armées canadiennes

A Thesis Submitted to the Division of Graduate Studies
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by

Joseph Jean-Luc Armstrong, BEng, rmc, ing. jr
Captain

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Abstract

Stabilization of wastewater by wastewater treatment lagoon systems is popular across the world for use by small communities, including in Canada. According to Statistics Canada and Infrastructure Canada (2016), 49.7% (1244 facilities) of all publicly owned wastewater treatment facilities in Canada are lagoon systems. These types of systems are also used at several military bases within the Canadian Armed Forces (CAF). Lagoon systems do not require complex infrastructure and chemical additives needed in conventional treatment facilities and if operated effectively, result in low-maintenance and low energy requirements, whilst meeting current effluent discharge regulations. Despite their mechanical simplicity, there are complex chemical, biological, and physical processes which occur within lagoon systems that can be negatively influenced by site-specific factors including climatic elements, hydrogeological parameters, and inflow content & volume.

The research presented herein consists of an investigation of the CAF 17 Wing Detachment Dundurn's wastewater treatment lagoon system. This system was constructed in 1988 with selected components dating back to the original 1941 sewage treatment system and is approaching the end of its service life. The aim of the research was to characterize the facility and conduct an environmental risk assessment associated with its continued operation. The lagoon is situated on silty sand and the groundwater is under the direct influence of surface water at a depth of 6.5 m to 9.5 m below grade. The lagoon is only approximately 900 m from the existing source water wells. The methodology employed includes a holistic source water to effluent approach to examine the lagoon system with the intent of increasing the effectiveness of the effluent's treatment whilst also reducing the possibility of contaminants influencing the source water as well as migrating off-site. In this regard, numerical modelling of groundwater flow and effluent transport, a field study, and stakeholder consultations have been conducted. An assessment of possible environmental concerns associated with contaminating neighbours' nearby wellheads, a reassessment of current sampling requirements, an examination of the lagoon's self-containment, and an analysis of the overall effectiveness of the system were also undertaken. The proposed solutions outlined in this document aims to improve and/or optimize the lagoon's wastewater treatment performance and its reliability in producing an economical effluent of acceptable quality that meets or surpasses the regulatory environmental framework.

Résumé

La stabilisation des eaux usées par lagune est une méthode populaire pour les petites communautés à travers le monde, incluant au Canada. Selon Statistique Canada et Infrastructure Canada (2016), 49.7% (1244 installations) de toutes les installations de traitement des eaux usées publiques au Canada emploient des lagunes. Ces types de systèmes sont également utilisés dans diverses installations des Forces armées canadiennes (FAC). Le traitement des eaux usées par lagune ne requiert aucune infrastructure complexe ni des additifs chimiques typiquement nécessaires pour les usines d'assainissement conventionnelles. Si elles sont exploitées adéquatement, les lagunes nécessitent peu d'entretien et ont un besoin énergétique minime, tout en restant conforme aux exigences réglementaires actuelles. Malgré leur simplicité mécanique, plusieurs procédés chimiques, biologiques et physiques ont lieu dans les systèmes à lagune. Ces procédés complexes peuvent être négativement influencés par des facteurs propres au site tels que des facteurs climatiques, paramètres hydrologiques ainsi que la qualité et volume de l'eau brute.

La recherche présentée dans ce document porte sur une investigation du système de lagunes de traitement des eaux usées du détachement Dundurn de la 17^e^ Escadre des FAC. Ce système construit en 1988, avec certaines composantes datant du système d'assainissement original construit en 1941, approche la fin de sa durée de vie utile. L'objectif de cette recherche est de présenter les caractéristiques de l'installation et effectuer une évaluation du risque environnemental associé avec son exploitation continue. La lagune est située sur du sable silteux et la nappe phréatique a une profondeur de 6.5 m à 9.5 m. Cette nappe phréatique est directement influencée par les eaux de surfaces. De plus, une distance de seulement 900 m sépare la lagune des puits d'eau potable. La méthodologie employée inclue une approche de source à effluent pour l'étude du system avec l'intention d'évaluer l'efficacité du traitement ainsi que le risque d'infiltration de contaminant dans l'eau de source et leur mobilisation hors site. À cet effet, de la modélisation numérique, une étude sur le terrain et des consultations avec les parties intéressées ont été réalisées. De plus, une étude environnementale du risque de contamination des puits avoisinants, une réévaluation des besoins d'échantillonnages, un examen de la capacité de la lagune à contenir l'eau usée et une étude de l'efficacité globale de l'installation a également été réalisée. Les propositions présentées dans ce document visent a amélioré la performance et la fiabilité de la lagune ainsi que produire un effluent économique surpassant les exigences réglementaires.

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List of Abbreviations and Acronyms

ADM(IE)	Assistant Deputy Minister (Infrastructure and Environment)
AOI	Areas of Interest
APHA	American Public Health Association
AWWA	American Water Works Association
B Env O	Base Environmental Officer
BH	Bore Hole
BMP	Best Management Practices
BOD	Biochemical Oxygen Demand
BOD_5	5-day Biochemical Oxygen Demand
C	Column
CAF	Canadian Armed Forces
$CBOD_5$	5-day Carbonaceous Biochemical Oxygen Demand
CCME	Canadian Council of Ministers of the Environment
CFAD	Canadian Forces Ammunition Depot
CFB	Canadian Forces Base
CFM	Federation of Canadian Municipalities
CFS	Canadian Forces Station
COHNS	Organic matter (Carbon, Oxygen, Hydrogen, Nitrogen, and Sulphur)
DAOD	Defence Administrative Order and Directive
DCC	Defence Construction Canada
DEES	Defence Energy and Environment Strategy
DND	Department of National Defence
DO	Dissolved Oxygen
E	Cardinal point East
E. Coli	Escherichia Coli
EMS	Environmental Management System
ENE	Cardinal point East North East
ERRIS	Effluent Regulatory Reporting Information System
ESE	Cardinal point East South East
FAO	Food and Agriculture Organization of the United Nations
GUDI	Groundwater Under Direct Influence from Surface Water
GW	Groundwater
HAA	Halogenated Acetic Acids
HDPE	High-Density Polyethylene
HQ	Headquarters
ISO	International Standards Organization

K	Hydraulic conductivity
K_x, K_y, K_z	Hydraulic conductivity along axis x, y, and z respectively
K_{xy}	Hydraulic conductivity where (Kx = Ky)
L	Layer
LiDAR	Light Detection and Ranging
masl	Meter Above Mean Sea Level
MW	Monitoring Well
N	Cardinal point North; Nitrogen (context required for disambiguation)
NBOD	Nitrogenous Biochemical Oxygen Demand
NDMA	N-Nitrosodimethylamine
NE	Cardinal point North East
NNE	Cardinal point North North East
NNW	Cardinal point North North West
NW	Cardinal point North West
P	Phosphorus
PCB	Polychlorinated biphenyl
POL	Petroleum, Oils, and Lubricants
PPE	Personal Protective Equipment
PSB	Purple Sulphur Bacteria
PW	Production Well
R	Row
RC	Range Control
RP Ops	Real Property Operations
S	Cardinal point South, Sulphur (context required for disambiguation)
SCADA	Supervisory Control and Data Acquisition
SE	Cardinal point South East
SK	Saskatchewan
SOP	Standard Operating Procedures
SS	Suspended Solids
SSE	Cardinal point South South East
SSW	Cardinal point South South West
SW	Cardinal point South West
SWIM	Single Window Information Manager
T	Time
TDS	Total Dissolved Solids
THM	Trihalomethanes
TKG	Total Kjeldahl Nitrogen
TSS	Total Suspended Solids

USEPA	United Stated Environmental Protection Agency
USGS	United States Geological Survey
UV	Ultraviolet
VFA	Volatile Fatty Acids
W	Cardinal point West
WEF	Water Environment Federation
WNW	Cardinal point West North West
WSA	Water Security Agency
WSER	Wastewater Systems Effluent Regulations
WSW	Cardinal point West South West
WTP	Water Treatment Plant
WWT	Wastewater Treatment
.pdf	Portable Document Format file extension
.xls	Microsoft Excel file extension

Preface

The RMC Green Team was approached by the Commanding Officer of Real Property Operations Unit (RPOU) - West in 2016 to assess the management associated with water and wastewater facilities and systems for the Western Region. Currently the Department of National Defence (DND) Quality Management Programme for Water and Wastewater Facilities developed by RMC and the RMC Green Team includes eight (8) water treatment facilities and 10 wastewater treatment facilities; spanning seven (7) provinces, one (1) territory, and five (5) real property operations (RP Ops) regions. Since that time and based on the success of the programme, the investigation has expanded to cover all of the facilities in Canada.

The Quality Management Programme aligns itself with the proven methodology and rationale of the legacy, Area-Wide Sewage Treatment / Water Treatment Plant Optimization Programme (ST/WTPOP) which commenced in 1995 and involved the RMC Civil Engineering Department. The protocol adopted for plant evaluation was the two-step Composite Correction Programme (CCP), developed by the United States Environmental Protection Agency (USEPA 1998).

The mission of the Quality Management Program is to support DND bases and staff in achieving sustainable, optimized, and economical performance from water and wastewater treatment systems with a view to protecting the consumers of drinking water and the environment. Additional information of the Quality Management Program can be seen in Vlachopoulos and Pouliot (2002) and Vlachopoulos et al. (2003)

The objectives of the Quality Management Program include:

- Provision of Quality Management for the performance of Water and Wastewater facilities / systems;

- Ensure provision of safe, reliable drinking water for maximum public health protection and protection for DND users;

- Develop and implement a strategy that will ensure that optimization achievements are sustained within the Department of National Defence;

- Develop and sustain effective partnerships with the purpose of employing CCP tools on a DND - wide basis;

- Develop in-house expertise in applying the CCP;

- Promote DND as a leader amongst government departments in providing good, economical effluent from sewage treatment facilities;

- Promote DND as a leader amongst government departments in protecting water supplies;

- Enhance the skills and knowledge of staff and managers responsible for water treatment plants through on-site activities;

- Enhance the skills and knowledge of staff and managers responsible for sewage treatment plants through on-site activities; and

- Support the training and experience of the Water, Fuel and Environment Trade and related staff within the Canadian Armed Forces (CAF).

The Master's-level research project presented herein concerns itself with the site characterization and environmental risk assessment conducted at 17 Wing Detachment Dundurn with regard to the operation of the detachment's wastewater treatment (WWT) lagoon system. The research falls within the overall framework of the Quality Management Programme (as outlined above) and provides a detailed characterization and assessment of the detachment's WWT lagoon system. The research project resulted in the development of many recommendations and provided detailed, actionable items for the detachment RP Ops section.

1.0 Introduction

1.1 Purpose of Study

Stabilization of wastewater by wastewater treatment (WWT) lagoon systems is popular across the world for use by small communities, including in Canada. These types of systems are also used at several military bases within the Canadian Armed Forces (CAF). Lagoon systems provide significant advantages for small communities and bases, where land is more abundant and less expensive. Due to their reliance on natural processes for the stabilization of wastewater, lagoon systems do not require complex infrastructure and chemical additives needed in conventional treatment facilities. This results in lower capital and maintenance costs, and lower energy requirements. In addition, training required for the operator is less complex which is advantageous in remote locations where staffing can be an issue. The lagoon systems utilized at most military bases and wings within the CAF (including 17 Wing Detachment Dundurn) are unique in the fact that the population that is serviced on the bases and/or wings increases substantially in the summer months. This is not the case for similar lagoon systems that are owned and operated by municipalities across Canada.

Despite their mechanical simplicity, there are complex chemical, biological, and physical processes which occur within lagoon systems that can be negatively influenced by site-specific factors including climatic factors, hydrogeological parameters, and inflow content and volume. Due to the nature of WWT lagoon systems along with their low supervisory requirements, these facilities are often defaulted to a lower priority by municipalities. A similar phenomenon can be expected at military bases. This can be more apparent at smaller bases and detachments where personnel strength is minimal. With the lack of direct control of the wastewater treatment, WWT lagoon systems can be difficult to troubleshoot. Most solutions for the improvements of WWT lagoon systems have had mixed results in the past, demonstrating the need for site-specific solutions.

With the age of the facility, both the operators of the WWT lagoon system and the Real Property Operations (RP Ops) section of the detachment, have expressed concerns about possible containment issues. The operators have also reported issues of inconsistent effluent discharge quality, in the past. These issues may be further compounded by future plans for the detachment. Such changes include the installation of a vehicle wash facility in the near future and possible increased use of the training areas for large-scale exercises. Several of these plans may alter the water consumption habits and volumes of the detachment. The increase water use will, in turn, increase the generation of wastewater and put additional stresses on the WWT lagoon system.

Due to the unknowns associated with the WWT lagoon system at 17 Wing Detachment Dundurn and the possible future expansion of the role of the detachment for the CAF, the RMC Green Team has initiated research projects to address these knowledge gaps and support the detachment's continued use of the WWT lagoon system. These research projects are undertaken under the umbrella of the Water and Wastewater Quality

Management Programme. The project, herein, is the first project in this regard (i.e., related specifically, to the wastewater lagoons).

1.2 Research Goal and Objectives

The goal of this research project is to assess and quantify the effectiveness of the treatment and operational performance of 17 Wing Detachment Dundurn's WWT lagoon system using a source to effluent approach. To achieve this goal, the following objectives have been set:

1. Characterize the WWT lagoon system;

2. Evaluate the effectiveness of the WWT lagoon system (to include chemical, biological processes as well as other relevant factors. Also includes the assessment of the physical infrastructure, etc.);

3. Determine the environmental effect (if any) of the WWT lagoon on its surroundings; and,

4. Assess possible risk posed by the WWT lagoon to the detachment's drinking water supply.

1.3 Exclusions / Limitations

Although they may be referred to, the following elements are considered outside the scope of this thesis:

1. Assessment of the wastewater collection networks including the design of a new system, modification, or additions to the current network;

2. Assessment of appurtenances, including mechanical and electrical systems; and,

3. Optimization of the wastewater treatment process.

Several other exclusions to this research project were made and are mentioned throughout this document. Many of these exclusions were necessary due to lack of data, resources / equipment, or time.

1.4 Thesis Organization

This thesis document was written in the approved format following the Thesis Preparation Guidelines published by the Royal Military College of Canada in May of 2015. This thesis was organized into nine (9) chapters listed below and as seen in Figure 1.1:

1. Chapter 1 – Introduction: This chapter introduces the subject along with the aim and objectives of the research project. In addition the chapter presents the organization and framework of this thesis document.

2. Chapter 2 – WWT Lagoon Background: This chapter provides the background and literature review as it pertains to the fundamental concepts associated with this research study. Information regarding the performance and operation of WWT lagoon systems is included.

3. Chapter 3 – Regulatory Environment: This chapter outlines the various regulations that are imposed by all levels of government and from the DND that are related to WWT lagoon systems which are the subject of this research project.

4. Chapter 4 – Site Characterization: This chapter includes a site characterization of the WWT lagoon system of this research project. The condition of the infrastructure on the site as well as the historical practices is also included.

5. Chapter 5 – Dundurn Lagoon Management Review: This chapter assesses the various actions taken to operate 17 Wing Detachment Dundurn's WWT lagoon, and to collect and manage data. In addition, this chapter provides several recommendations to improve the overall performance of the WWT lagoon system or improve the detachment's understanding of the treatment provided.

6. Chapter 6 – Methodology: This chapter outlines the methodology (substantiated with references, approved practices and accepted scientific approaches) employed during the research project into the detachment's WWT lagoon system. The chapter details the field research and sampling programme conducted along with the management of the collected data.

7. Chapter 7 – Groundwater Modelling: This chapter includes a summary of the development of a hydrogeological model for the site of the detachment and its results. The chapter presents in detail all the steps taken into the development of the model from the collection of various data sets to the calibration of the model. The results from the model groundwater flow and particle analysis are also presented.

8. Chapter 8 – WWT lagoon Performance Analysis Results: This chapter reports the results of the analyses conducted on the various data sets obtained and developed as part of this research project into the detachment's WWT lagoon system. The data was obtained from multiple sources and includes but is not limited to: data from detachments, data obtained from a field investigation, and the results from testing conducted by an accredited

laboratory. The chapter also provides important conclusions and deductions uncovered from the data analyses.

9. Chapter 9 – Conclusions, Recommendations, and Implications: This chapter summarizes the contribution of this research project to the operation and management of the detachment's WWT lagoon by the operators and the RP Ops section. Furthermore, this chapter identifies possible areas for future work and research at the detachment's WWT lagoon.

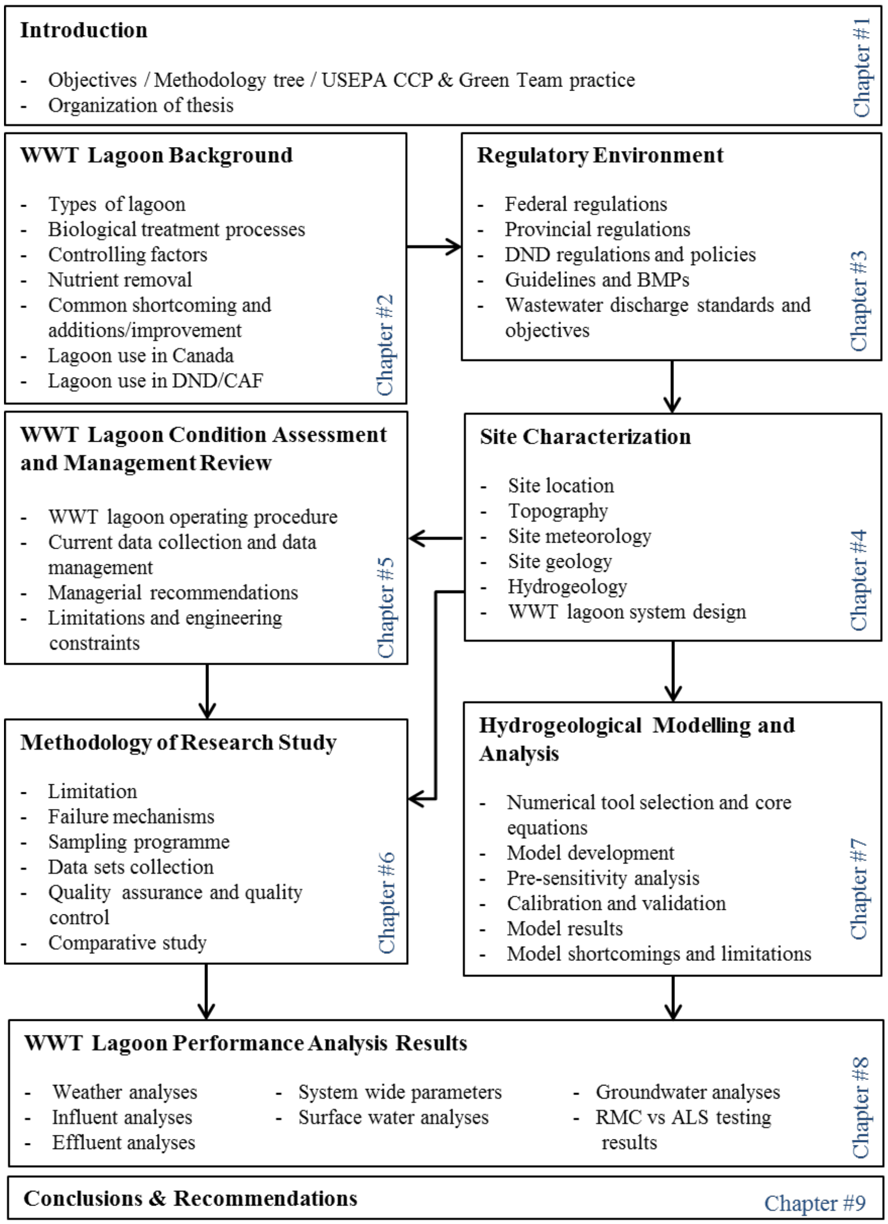

Figure 1.1 - Organization of thesis document

1.5 Relevance to Research

This chapter outlined the scope of this research study by identifying the goal and objectives along with major exclusions. In addition, the framework of this document was presented.

2.0 Wastewater Treatment Lagoon Background

2.1 Introduction

Wastewater treatment using lagoon systems is among the oldest method of managing wastewater from municipal sources. This treatment option is the most simplistic and cost-effective wastewater treatment options in areas where land is plentiful and available at reasonable cost (Pearson et al. 1987). Wastewater Treatment (WWT) lagoons operate by providing optimal conditions for naturally occurring wastewater stabilizing processes to occur. This treatment option is often favoured since it does not require the complex infrastructure and chemical additives that are needed with conventional municipal wastewater treatment plants. This simplicity results in low-energy requirements, low-maintenance requirements, and simplified operator knowledge requirements for the effective treatment of wastewater. Despite their mechanical simplicity, there are complex chemical, biological, and physical processes taking place in lagoons.

In this chapter, the background knowledge of the primary treatment processes of the wastewater in WWT lagoons is provided. In addition, common shortcomings and improvements are included along with a description of the adoption of WWT lagoons in Canada and the Canadian Armed Forces (CAF).

2.2 Types of Lagoons

WWT lagoon systems are normally composed of multiple reservoirs or cells. Cells are predominantly cut and fill reservoirs that employ a lining system to contain the wastewater. An example of a typical multi-celled municipal WWT lagoon system is given in Figure 2.1.

Figure 2.1 - Municipal WWT lagoon for Russell, Ontario (Imagery provided by Microsoft Corporation 2018)

Wastewater treatment lagoons can be classified in accordance with several characteristics. The USEPA (1983) classifies lagoons based on: dominant biological reaction, types of influent, and outflow conditions as it is believed to provide the most flexibility. This classification system can further be used to classify individual cells (also referred to as ponds) in multi-cell systems in which cells may be operated differently and promote different biological reactions.

2.2.1 Biological Reactions

Wastewater treatment lagoons are designed to promote the stabilization of the wastewater via natural processes. Four (4) types of lagoons exist with respect to biological reactions:

1. Aerobic lagoons;
2. Anaerobic lagoons;
3. Facultative (aerobic anaerobic) lagoons; and,
4. Aerated lagoons.

The following subsections will elaborate on each of these lagoon types and will include typical design parameters and their respective advantages and disadvantages.

2.2.1.1 Aerobic Lagoons

This form of lagoon relies exclusively on aerobic stabilization of the wastewater by the use of natural means (i.e. photosynthesis and surface reaeration). It is primarily used as a secondary treatment (Federation of Canadian Municipalities and National Research Council 2004). The lagoon is very shallow in comparison to other lagoon types to allow for light to penetrate throughout the water column. This allows for Dissolved Oxygen (DO) to be present throughout the pond. This light requirement limits aerobic lagoons to warmer environment where light is plentiful and there is little risk of ice forming at the surface of the pond. (USEPA 1983, 2011)

Aerobic lagoons have a typical depth of 0.18-0.45 m with a Five-day Biochemical Oxygen Demand (BOD_5) loading ranging from 85 to 170 kg/(ha·d). Mechanical mixing is often added to keep algae from settling to the bottom of the pond and create an anaerobic environment. Aerobic lagoons often require an additional step to remove algae from the effluent since this contributes to high (often unacceptable) Total Suspended Solids (TSS). Typical retention times are short (2-40 days) which limits the effectiveness of aerobic lagoons in treating for pathogens and coliforms. Additionally, fabricated pond lining is often required to prevent the growth of emerging vegetation (USEPA 1983, 2011, Federation of Canadian Municipalities and National Research Council 2004). Table 2.1 lists the main advantages and disadvantages associated with aerobic lagoons.

Table 2.1 - Advantages and disadvantages of aerobic lagoons (Adapted from Massoud, Tarhini, & Nasr, 2009; USEPA, 2000)

Main Advantages	Main Disadvantages
Effective removal of: BOD Nutrient removal (if algae are harvested)	Ineffective in removing heavy metals
Capable of handling heavy loading conditions	Higher climatic restriction (i.e. only suitable for warmer climates)
Easy to operate and maintain	Additional treatment required for disinfection and TSS requirements
Little energy requirement	Mechanical mixing often required
Lower land requirement when compared to most other types of lagoon	Energy requirement and associated cost increases with mixing
Cost-effective based on land expenses	

2.2.1.2 Anaerobic Lagoons

This form of lagoon is predominantly used for the pre-treatment of industrial or agricultural wastewater with high Biochemical Oxygen Demand (BOD) prior to discharge into municipal sewage systems. Anaerobic Lagoons manage influent with the highest organic loading of all lagoon types. As such, no aerobic zone is present and bacterial acid creation and methane fermentation provide the effective treatment (USEPA 1983, 2011, Federation of Canadian Municipalities and National Research Council 2004).

Aerobic lagoons have a typical depth of 2.5-5 m with BOD_5 loadings ranging from 160 to 800 $kg/1000m^3 \cdot d$ and a retention time of 5 to 50 days (USEPA 1983, 2011, Federation of Canadian Municipalities and National Research Council 2004). Odours are an important problem of anaerobic lagoons. Recirculating effluent from secondary facultative or aerated lagoons can create a thin aerobic layer at the surface of the lagoon. This layer is maintained to prevent odours from escaping the pond and is not intended to provide effective treatment. Naturally generated scum or man-made cover can also be effective in controlling odours (USEPA 1983, 2011). Table 2.2 lists the main advantages and disadvantages associated with anaerobic lagoons.

Table 2.2 - Advantages and disadvantages of anaerobic lagoons (Adapted from Massoud, Tarhini, & Nasr, 2009; USEPA, 2000)

Main Advantages	Main Disadvantages
Effective removal of: Pathogens and faecal coliform	Ineffective in removing heavy metals
Most effective for the treatment of heavy organic loading	Additional treatment required to meet discharge standards
Produces methane and less biomass per unit of organic loading	Objectionable odours are produced and require managing
Little energy requirement	Land area requirements are higher than for other treatment systems
Low sludge production	
Cost-effective	

2.2.1.3 Facultative Lagoons

This form of lagoon is the most frequently used and is well suited for use in treating municipal wastewater. It is suitable as a primary or secondary treatment process (USEPA 2011). In facultative lagoons, both aerobic stabilization and anaerobic fermentation takes place. The aerobic stabilization occurs in the upper layer of the pond where oxygen is introduced via algae photosynthesis and surface reaeration. Both of these processes will be elaborated in Section 2.3.3.1 and 2.3.3.3 respectively. In the lower layer of the pond, DO is absent and thus anaerobic conditions dominate (USEPA 1983). This layer also includes the sludge deposits. The thickness of each layer is dependent on loading rates. If lightly loaded, aerobic conditions may dominate throughout the water column (USEPA 2011). To facilitate both layers and to account for sludge accumulation, facultative lagoon depths are typically 0.9-2.5 m deep with a typical loading of BOD_5 ranging from 22 to 67 Kg/(ha·d) and retention time varying from 7 to 180 days (USEPA 1983, 2011, Federation of Canadian Municipalities and National Research Council 2004).

Facultative lagoons are favoured for they offer several advantages. They do, however, come with disadvantages. Table 2.3 lists the main advantages and disadvantages associated with facultative lagoons.

Table 2.3 - Advantages and disadvantages of facultative lagoons
(Adapted from Massoud, Tarhini, & Nasr, 2009; USEPA, 2000)

Main Advantages	Main Disadvantages
Effective removal of: BOD Settleable Solids Pathogens and faecal coliform Ammonia	Ineffective in removing heavy metals
Capable of handling both heavy and light loading conditions	Effluent ammonia levels are difficult to predict and control
Easy to operate and maintain	Sludge accumulation increases in cold climate and requires periodic removal
Little energy requirement	Mosquitoes and insect vectors may be an issue if emergent vegetation is not controlled
Cost-effective based on land expenses	Odour may be a problem
	Land area requirements are higher than other treatment systems

2.2.1.4 Aerated Lagoons

This form of lagoon is suitable for primary treatment of both municipal and industrial wastewater treatment. Aerated lagoons rely on aerobic stabilization to treat the wastewater. Unlike facultative and aerobic lagoons, oxygenation is not primarily supplied via the natural means (i.e. photosynthesis and surface reaeration). Instead, mechanical means are utilized such as motor-driven surface aerators or diffusers with blowers (USEPA 1983, Federation of Canadian Municipalities and National Research Council 2004). Aerated lagoons can be further characterized by the amount of mixing provided. As the name implies, the mechanical system utilized in partial mixing aerated lagoons only provide enough mixing for the upper layer of the pond. In contrast, complete mixing aerated lagoons provide mixing through its water column keeping all solids in suspension.

Aerated lagoons are often adapted from facultative lagoons as a solution for overloading where space for expansions is unavailable. In industrial settings, aerated lagoons are often utilized for pretreatment before discharge to municipal sewage treatment, where legislation requires it. These types of ponds are generally followed by facultative ponds to tackle settle able solids. Additionally, certain lagoons have been adapted to provide mechanical aeration only when needed (e.g. spring and autumn) and revert to a facultative mode of operation when not in need (USEPA 1983, Federation of Canadian Municipalities and National Research Council 2004).

To capitalize on the added oxygenation, aerated lagoons are typically 2-6 m in depth and can tackle a BOD_5 loading ranging from 8 to 320 $Kg/1000m^{3}\cdot d$. The typical retention times for such lagoons are between 7 and 20 days (USEPA 1983, Federation of Canadian Municipalities and National Research Council 2004). Table 2.4 lists the main advantages and disadvantages associated with aerated lagoons.

Table 2.4 - Advantages and disadvantages of aerated lagoons (USEPA, 1983)

Main Advantages	Main Disadvantages
Effective removal of: BOD Pathogens and faecal coliform Ammonia	Ineffective in removing heavy metals
Can provide high BOD and SS removal (if secondary clarification with sludge return is provided)	Secondary treatment is required for SS removal
Capable of treating some industrial waste	Operation and maintenance are more complex
Lower land requirement when compared to other types of lagoon	Energy requirement and associated cost increases significantly with the amount of aeration provided
Can be effective in the control objectionable odours	

2.2.2 Outflow Conditions

Another common classification for lagoons relates to the outflow conditions. Three (3) main conditions exist (USEPA 1983) in this regard:

1. Complete Retention (Zero-Discharge): In a complete retention lagoon, the wastewater is not released as effluent. Instead, the lagoon relies primarily on evaporation and, when environmental and legislative conditions permit it, percolation. The evaporation and percolation rates must be greater than or equal to the influent and precipitation rates for such a system to be viable. Zero discharge is only feasible where climatic and geological conditions are favourable (i.e. warmer and dryer climate) and in locations of low water use (Heinke et al. 1991). Zero discharge is vastly unsuitable for use in Canada;

2. Continuous Discharge: In a continuous discharge lagoon system, the influent and effluent are on average balanced. A natural body is constantly receiving the lagoon system's effluent. Many regions in Canada prohibit this discharge configuration due to effluent treatment efficiency during the winter and early spring (USEPA 2000a);

   Short circuiting, a condition in which part of the wastewater does not remain within a pond for the intended retention time, and thus is insufficiently treated prior to discharge is primarily a concern for this type of outflow configuration (Federation of Canadian Municipalities and National Research Council 2004); and,

3. Controlled (Discontinuous) Discharge: In a controlled discharge lagoon system, the effluent is discharged when the receiving natural water body conditions are favourable and the discharge will not cause undue environmental harm. Discharge is often limited to annual or seasonal discharge (Federation of Canadian Municipalities and National Research Council 2004). These long hydraulic retention times often require the use of storage cells in order to accommodate the increased effluent volume.

2.2.3 Influent Source

Wastewater is typically produced by two main sources: municipal and industrial sources. The following subsections will elaborate on characteristic of municipal and industrial wastewater.

2.2.3.1 Municipal Wastewater Source

Municipal wastewater is generated by everyday human tasks (e.g. lavatory needs, cooking, and household cleaning). Municipal wastewater is generally of consistent quality and is mostly comprised of water (99.9%) with low concentration organic and inorganic TSS and Total Dissolved Solids (TDS). Organics found in this form of wastewater include: carbohydrates, lignin, fats, soaps, synthetic detergents, proteins and their respective decomposition products (Food and Agriculture Organization of the UN 1992). Table 2.5 provides expected concentrations of the major constituents of wastewater from municipal sources. The concentrations are given for strong, medium, and weak wastewater concentrations. The concentration of the municipal wastewater is determined by the water consumption habits of the serviced population. A consumption of approximately 90 litres per person per day would result in a strong concentration in the wastewater. In accordance with Statistics Canada (2015), Canada consumed an average of 235 litres of potable water per person per day for residential uses. Although not a direct measurement of the wastewater production, potable water consumption provides reliable insight in the quality of the generated wastewater.

Table 2.5 - Concentrations of major constituents of municipal wastewater (Food and Agriculture Organization of the UN 1992)

Constituent	Concentration (mg/L)		
	Strong	Medium	Weak
Total Solids	1200	700	350
TDS	850	500	250
TSS	350	200	100
Nitrogen (as N)	85	40	20
Phosphorus (as P)	20	10	6
Chloride	100	50	30
Alkalinity (as $CaCO_3$)	200	100	50
Grease	150	100	50
BOD_5	300	200	100

2.2.3.2 Industrial source

Unlike municipal wastewater, wastewater generated from industrial sources has much greater variability in constituents and concentrations as a whole. Specific industrial sources may generate wastewater with specific pretreatment requirements not needed for municipal wastewater or may not be suitable for treatment via WWT lagoon systems. For this reason, the Ontario government published, in 1988, a guideline to control the quality of discharge of industrial wastewater into publicly owned municipal WWT systems. Table 2.6 list the quality parameters and their respective maximum concentration as stated by the guideline. In addition, several materials resulting from industrial/commercial processes are commonly prohibited from release in publicly owned WWT systems (Table 2.7).

Table 2.6 - Wastewater quality limitation as recommended by the Ontario Government guideline of 1988 (Modified from Hydromantis Inc. and University of Waterloo 2006)

Constituents	Concentration	Constituents	Concentration
pH	5.5-9.5	Cobalt	≤5 mg/L
Solvent extractable material (mineral or synthetic origin)	≤15 mg/L	Lead	≤5 mg/L
Solvent extractable material (animal or vegetable origin)	≤150 mg/L	Manganese	≤5 mg/L
BOD_5	≤300 mg/L	Molybdenum	≤5 mg/L
TSS	≤350 mg/L	Selenium	≤5 mg/L
Phosphorus (as P)	≤10 mg/L	Silver	≤5 mg/L
Total Kjeldahl Nitrogen (TKG)	≤100 mg/L	Tin	≤5 mg/L
Phenolic compounds	≤1 mg/L	Titanium	≤5 mg/L
Chlorides	≤1500 mg/L	Vanadium	≤5 mg/L
Sulphates	≤1500 mg/L	Copper	≤3 mg/L
Aluminium (as Al)	≤50 mg/L	Nickel	≤3 mg/L
Iron (as Fe)	≤50 mg/L	Zinc	≤3 mg/L
Fluoride	≤10 mg/L	Total cyanide	≤2 mg/L
Antimony	≤5 mg/L	Arsenic	≤1 mg/L
Bismuth	≤5 mg/L	Cadmium	≤1 mg/L
Chromium	≤5 mg/L	Mercury	≤0.1 mg/L

Any facilities intended for the treatment of wastewater from industrial sources or containing a significant portion of industrial wastewater will require individualized design (Water Security Agency 2012). Common examples include agricultural sectors such as cattle and swine farming which generate high concentrations of organic matter and thus high BOD. Pre-treatment via anaerobic lagoons are often required prior to release in the municipal sewage systems.

Table 2.7 - List of commonly prohibited materials for release in municipal WWT systems (Modified from Hydromantis Inc. and University of Waterloo 2006)

Common Prohibited Materials
Fuels
Polychlorinated biphenyl (PCB)s and PCB wastes
Pesticides
Severely toxic materials
Radioactive waste
Hauled sewage
Waste disposal site (landfill) leachate
Acute hazardous waste chemicals
Hazardous industrial wastes
Hazardous waste chemicals
Ignitable wastes
Pathological wastes

2.2.3.3 Military Sources

Wastewater generated at military establishments may vary from conventional municipal sources. In addition to the municipal wastewater, military establishments may contain constituents from light industrial sources based on the operations undertaken at the establishments. Unique to military establishments, is the potential of receiving wastewater with energetic constituents. These energetics are primarily the results of the use of explosive during military training.

2.2.4 WWT Lagoon System Layout

A single cell system is often not sufficient to treat wastewater to acceptable standards. To that effect, multiple cells, often with different dominant biological reactions, are combined to obtain the effluent quality standards as dictated by the regulatory agencies. Facultative cells are often preceded by aerated cells to manage the initial high BOD levels (Figure 2.1). Anaerobic cells are often needed when dealing with the very high BOD levels typical of some industrial sources. As seen in Figure 2.3, an anaerobic cell precedes the aerated cell to provide pre-treatment. The cell has a doted outline to indicate that the pre-treatment is conducted at the source, prior to discharging into the municipal infrastructure, and not at the WWT lagoon site.

Multiple cells can be used to perform the same role in the treatment train, as seen in Figure 2.2. The presence of multiple cells allows for greater operational flexibility. Cells can be operated in parallel operation where the influent is divided to reduce the BOD loading on each cell. Cells can also be positioned in series to allow for greater treatment of the wastewater prior to discharge. Such systems are often designed for both configurations to allow operators to alternate between configurations as needed. Such systems are beneficial when one cell needs to be taken offline for maintenance reasons (such as desludging), thus removing the need for a temporary packaged plant.

As seen in Figure 2.3, when the discharge of the WWT lagoon system is discontinuous, a storage cell is often needed. The primary function of storage cells is to manage the volumes in between discharges and are often not relied on to provide effective treatment. However, final polishing of the effluent can be conducted in such cells.

The ideal WWT lagoon configuration will largely be dictated by the discharge restrictions, effluent quality to be obtained, and influent source (Federation of Canadian Municipalities and National Research Council 2004).

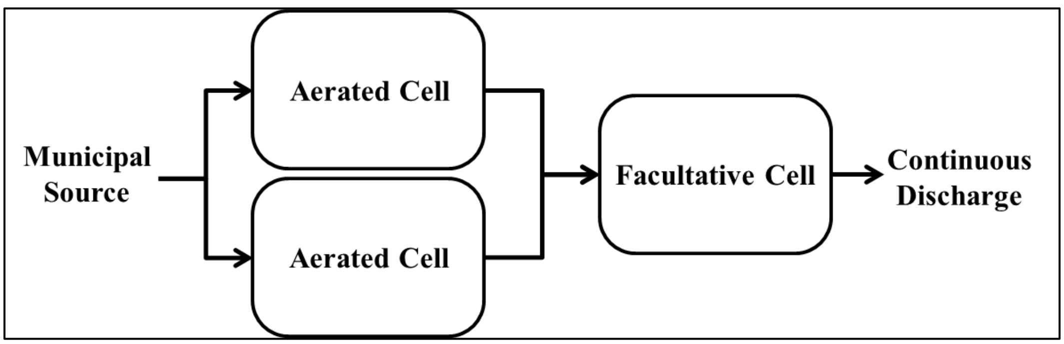

Figure 2.2 - Hypothetical WWT lagoon systems with continuous discharge.

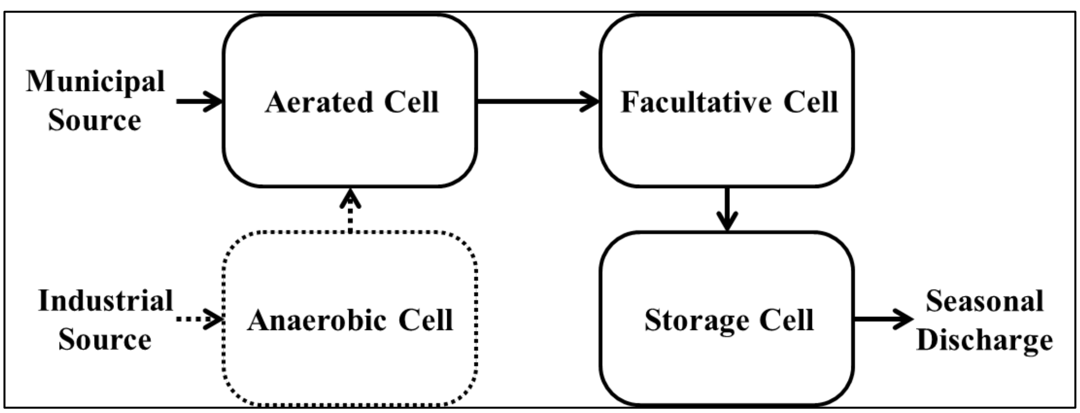

Figure 2.3 - Hypothetical WWT lagoon systems with discontinuous discharge receiving influent from both municipal and industrial sources. Dotted outline indicate that the cell consists of offsite pretreatment.

2.3 Biological Treatment Processes

There are three (3) main objectives in the treatment of municipal wastewater by biological means (Metcalf & Eddy 2013):

1. Oxidation: This process consists in the breakdown of biodegradable constituents (either in particle or dissolved forms) of the wastewater into simpler end products;

2. Biological Flocculation: Much like chemical flocculation, suspended colloidal particles can be grouped in floc by biological means. This floc allows for the settling of the particles that would otherwise not be settleable. In a similar process, particles can be grouped to form a film at the surface of the wastewater that can be skimmed and removed; and,

3. Nutrient Removal: This process consists in the removal of or the transformation of inorganic nutrients (i.e. Nitrogen (N), Phosphorus (P), and Sulphur (S)) and organic nutrient, taking the form of Carbon (C) compounds. The removal of nutrients from the wastewater is required due to concerns of eutrophication of the receiving natural ecosystem. Nutrient removal will be elaborated further in Section 2.5.

The biological stabilization of wastewater is primarily accomplished by two (2) groups of organisms, bacteria and algae (USEPA 1983). The following subsections will elaborate on each of these organisms and will include their roles in the treatment of municipal wastewater.

2.3.1 Bacterial Activity

Bacterial activity is essential to the stabilization of wastewater. Bacteria are microorganisms of lengths ranging for 0.5-5 μm. Municipal wastewater host a wide variety and concentration of such bacteria (Metcalf & Eddy 2013). The particular composition of bacterial life forms of any given lagoon systems will vary in accordance with several factors that include: the type of lagoon and its operation, influent wastewater characteristics, and climatic conditions (USEPA 1983). Knowledge of the exact composition of the bacterial community within the WWT lagoon at any given time is not necessary for proper lagoon operations.

Bacteria can be grouped to simplify and facilitate the understanding of bacterial processes within a lagoon system.

2.3.1.1 Aerobic Bacteria

A wide variety of bacteria can be found thriving within the aerobic layer of any given lagoon system. Some of the most studied include: *Beggiatoa Abla, Sphaerotilus Natans,* *Achromobacter, Alcaligenes, Flavobacterium, Pseudomonas*, and *Zoogloea* (USEPA 1983). Aerobic bacteria are heterotrophic and will consume and break down organic material into simple organic end products via oxidation. Aerobic bacteria are the primary consumers of the organic matter. The generalized aerobic oxidation stoichiometric equation is described below as presented by Metcalf & Eddy (2013):

$$\underset{(organic\ matter)}{COHNS} + O_2 + nutrients \xrightarrow{bacteria} CO_2 + NH_3 + \underset{(new\ cells)}{C_5H_7NO_2} + other\ end\ products \quad \textbf{[2- 1]}$$

As depicted in equation 2-1, COHNS (organic matter) present in the wastewater is oxidized by bacteria into carbon dioxide (CO_2), ammonia (NH_3) and other end products in the process of generating new cells ($C_5H_7NO_2$).

2.3.1.2 Anaerobic Bacteria

Anaerobic bacteria are heterotrophic and thrive in the anaerobic zone of lagoons by converting complex organic matter into alcohol, acids, and eventually methane (USEPA 1983). The breakdown of organic matter into methane is a four (4) step process that is described in Figure 2.4.

The first step in the conversion of the organic matter is hydrolysis. In this step organic matter is broken down into soluble compounds and further into sugars and acids usable by other bacteria for fermentation. Hydrolysis is carried out by several bacterial such as: *Butyrivibrio, clostridium, anaerovibrio lipolytica, clostridium proteolyticum, eubacterium,* and *peptococcus anaerobicus*. The end products of hydrolysis are: monosaccharides, amino acids, and low carbon fatty acids. The second step, acidogenesis or fermentation, converts the sugars and amino acids into Volatile Fatty Acids (VFA), CO_2, and hydrogen. The VFAs are propionate, butyrate, and valerate. In the third step, propionate and butyrate are fermented further into acetate, CO_2, and hydrogen in a process known as acetogenesis. The fourth and final step, methanogenisis, is carried out by a bacterial group known as the methanogens and transforms the acetic acid and hydrogen into methane and CO_2 at a typical ratio of 7:13 (Metcalf & Eddy 2013).

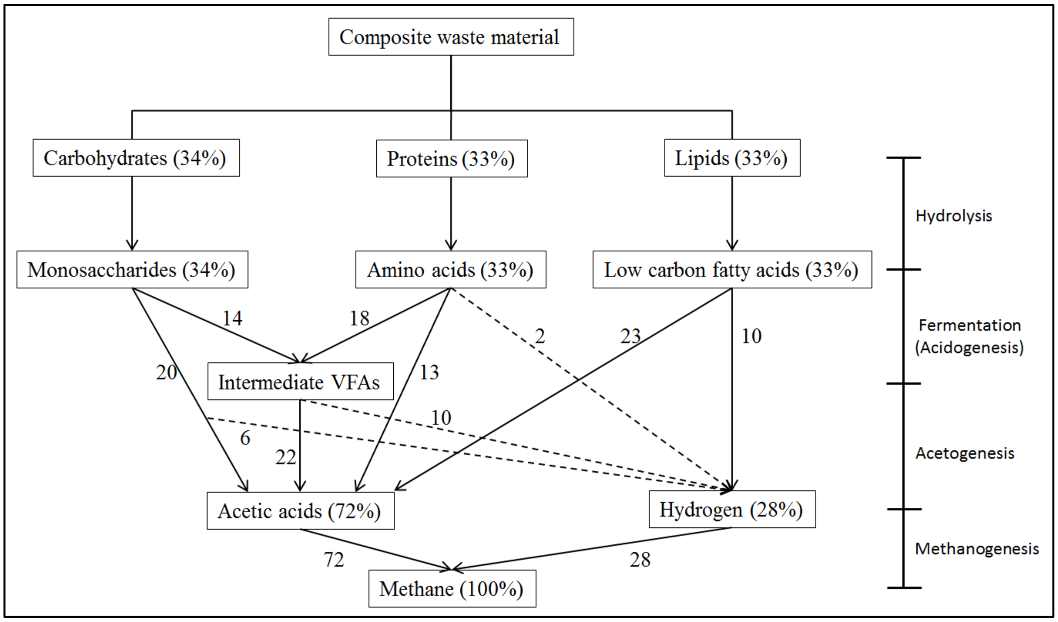

Figure 2.4 - Biodegradation of COD in anaerobic processing of waste solids (Modified after Metcalf & Eddy, 2013)

2.3.1.3 Other Commonly Isolated Bacteria

Several other bacteria are commonly isolated to assess and monitor the performance of the lagoons in the treatment of wastewater. Such bacteria include (USEPA 1983):

1. Cyanobacteria: Cyanobacteria (also known as blue-green algae) are both organoheterotroph, as well as photoautotroph and thus consume organic compounds and CO_2 as a source of carbon. As a result of photosynthesis, cyanobacteria releases O_2 that is used by other organisms within the lagoon;

2. Purple Sulphur Bacteria (PSB): PSB strive in anaerobic layers within a pond. They are valued for their ability to transform unwanted odorous sulphide compounds into inorganic sulphur and sulphate. This process is significant in the control of objectionable odours in lagoon systems that possess an anaerobic zone. Odour control is elaborated further in Section 2.6.1; and,

3. Pathogenic Bacteria: The wastewater environment is known for the presence of several pathogenic bacteria, most popular of which includes: Escherichia coli, Francisella, Leptospira, Salmonella, Shigella, and Vibrio. These pathogens' natural environments are the digestive tracks of infected humans and animals and thus they cannot survive for extended periods of time within the wastewater. As pathogenic bacteria are responsible for many waterborne diseases and have adverse effect on the natural ecosystem. Their concentrations, along with that of other pathogenic organisms (Protozoa,

Helminths, and Viruses) within municipal sewage effluent is frequently regulated (Metcalf & Eddy 2013, Government of Saskatchewan 2015, Government of Canada 2016).

2.3.2 Algae

The second essential component to the stabilization of wastewater is algae. Three (3) primary categories of algae are found in wastewater which are named according to their colour pigments: Green and Brown algae are the most common with Red algae blooming under more specific conditions. The exact constitution of the algae population within the wastewater varies with respect to temperature, predation, nutrient availability, and the presences of toxins (USEPA 1983). The effects of temperature on the biological activity within the wastewater are elaborated in more details in Section 2.6.4.

Algae are autotroph and have a symbiotic interaction with bacteria within the wastewater. Algae will consume inorganic nutrients (Carbon dioxide, phosphate, and nitrogen in the form of nitrate, ammonium, or ammonia) that are the by-products of bacterial breakdown of the wastewater organic matter, in order to replicate. The by-product of this reaction is DO which in turn is used to sustain the bacterial population (USEPA 1983).

Algae are capable of storing large quantity of nutrient present in the wastewater. Wastewater stabilization lagoons should be designed to favour the growth of algae as a treatment process and their removal from the effluent prior to discharge in order to reach nutrient removal targets.

2.3.3 Biochemical Interactions

The microorganisms that are present in the wastewater pond interact with chemical constituents to sustain their existence, reproduce, and in turn stabilize the wastewater. Biochemical interaction takes on many forms, the most basic of which includes: photosynthesis, respiration, and the dissolved oxygen cycle.

2.3.3.1 Photosynthesis

Photosynthesis is a process of converting solar energy and CO_2 into useful organic material for use by organisms. Within the wastewater pond, photosynthesis is performed by bacteria and certain algae, most notably: cyanobacteria and PSB. There exist two (2) types of photosynthesis: oxygenic and anoxygenic (USEPA 1983):

1. <u>Oxygenic Photosynthesis:</u> Oxygenic photosynthesis is the most commonly known form of photosynthesis. In wastewater, it is performed by bacteria, and some algae to a lesser extent. In this process, CO_2 and water are converted into sugar needed as a source of energy and more importantly O_2 that is required to sustain aerobic bacterial activity. The stoichiometric equation 2-2 represents the oxygenic photosynthesis process; and,

$$H_2O \xrightarrow{sunlight} \frac{1}{2}O_2 + 2H^+ + 2e^- \quad [2\text{-}2]$$

2. Anoxygenic Photosynthesis: Anoxygenic photosynthesis differs from oxygenic as it occurs in environment free of oxygen. This type of photosynthesis is conducted by anaerobic bacteria and utilizes sulphur compounds as the source of reducing power in accordance with stoichiometric equation 2-3.

$$H_2S \xrightarrow{sunlight} S^0 + 2H^+ + 2e^- \quad [2\text{-}3]$$

2.3.3.2 Respiration

Respiration is the process in which aerobic bacteria, protozoa and certain algae oxidize organic matter in the generation of new cells. Respiration undertakes several transformations, facilitated by enzymes within the organisms, and produces CO_2 and H_2O as end products. The stoichiometric equation 2-4 represents the generalized respiration process (USEPA 1983).

$$C_2H_{12}O_6 + 6O_2 \xrightarrow{enzymes} 6CO_2 + 6H_2O + new\ cells \quad [2\text{-}4]$$

In algae, both respiration and photosynthesis are undertaken simultaneously but with diurnal variations. When sunlight is available, the photosynthesis outpaces respiration resulting in a net contribution to DO into the wastewater. When sunlight is absent, photosynthesis ceases but respiration continues to occur, resulting in the consumption of DO and production of CO_2.

2.3.3.3 Dissolved Oxygen

DO is essential for the respiration of aerobic organisms. The solubility of O_2, however, varies in accordance with atmospheric pressure and temperature. The solubility of O_2 is directly proportional to pressure and inversely proportional to temperature. The concentration of impurities in the wastewater such as salinity and suspended solids is also a factor of O_2 solubility (Metcalf & Eddy 2013, Barlet 2017). According to the Water Security Agency (2004), DO level for wastewater treatment lagoon should fluctuate within 5 to 20 mg/L under normal operating conditions. Corrective actions are required if DO levels drop below 5 mg/L.

DO is generated naturally by two (2) mains processes photosynthesis and surface reaeration. DO can also be generated by mechanical methods:

1. Photosynthesis: As photosynthesis is a generated by microorganisms. The process of photosynthesis is elaborated in Section 2.3.3.1;

2. Surface Reaeration: Surface reaeration is the process in which O_2 is transferred to the wastewater pond by turbulences at the wastewater surface by wind action. Surface reaeration is influenced by meteorological and geographical factors and contributes to the generation of DO within the wastewater (USEPA 1983). When designing wastewater lagoon systems, the site's location, the system orientation, and pond width to length ration should consider prevailing wind direction, in order to maximize the wind's fetch (WHO 1987); and,

3. Mechanical Methods: Mechanical Methods such as motor-driven surface aerators or diffusers with blowers are employed in aerated pounds to augment the natural DO generation and improve performance. Aerated ponds are elaborated upon in Section 2.2.1.4.

Seasonal variation of DO concentration occurs in response to biological activity. In warm temperature associated with summer, biological activity increases consuming more DO and thus lowering its concentrations within the wastewater (Metcalf & Eddy 2013). DO is also a factor in the control of objectionable odours as it is essential for the sustainment of the aerobic layer within ponds. This layer, in turn, prevents the release of objectionable odours generated in the anaerobic zone.

2.4 Controlling Factors

As the stabilization of the wastewater within a lagoon system is conducted by biological processes, the rate and efficiency of these processes will vary in accordance with three (3) main factors: light, temperature and pH.

2.4.1 Light

As microbial life form requires the presence of DO, and DO is largely generated by photosynthesis, light (more often natural light) is of particular significance to microbial activity. Additionally, the intensity and spectral composition of the light will alter microbial activity (USEPA 1983).

1. Intensity: According to the USEPA (2011), O_2 production rates within a wastewater pond will level out between 5,380 to 53,800 lumens/m^2. Within this range, most microbial activity reaches its light saturation level. Light intensity outside of this range will adversely affect the production of O_2. Additionally, as sunlight undergoes diurnal variation, so does the microbial activity levels, thus directly impacting the wastewater treatment process.

   Care should be given when selecting a site in order to maximize sunlight on the pond surface in accordance to the site topography. Vegetation growth surrounding the pond should also be controlled to maximize sunlight. Inversely, shading or Lemna Duckweed can be used to control the algae population within a polishing pond in order to comply with effluent TSS limits; and,

2. Spectral Composition: The spectral wavelength needs of photosynthesis organisms vary according to its photosynthetic pigment (i.e. chlorophyll or phycobilins). The different absorption capacity of both differ, allowing for bacterial organisms, possessing chlorophyll pigment to thrive below algal organisms, employing phycobilins pigment, by absorbing light of different wavelengths (USEPA 2011). The penetration of sunlight is affected by the quantity of dissolved and suspended solids along with the quantity of organisms. Snow and ice cover, during winter conditions, also greatly impede sunlight penetration within the pond.

2.4.2 Temperature

Biological stabilization of wastewater is affected by the temperature of the treatment ponds. Microbial growth rates can withstand a range of temperature depending on their biological process type. Whilst microbial activity may take place within a relatively large range of temperatures, the optimum temperature ranges can be significantly smaller. Table 2.8 describes the temperature classification of different microbial families. As stated in Metcalf & Eddy (2013), below optimal temperatures have greater effect on microbial activity when compared with above optimal temperatures. In fact, for every increase of 10^{o}C increments until optimal temperature, biological activity will double.

Table 2.8- Temperature classification of biological processes (recreated from Metcalf & Eddy, 2013)

Type	Temperature Range (^{o}C)	Optimum Range (^{o}C)
Psychrophilic	10-30	12-18
Mesophilic	20-50	25-40
Thermophilic	35-75	55-65

The effect of low temperature along with ice and snow cover lowers the rate of bio-stabilization of the wastewater and allows pathogens to survive longer. In these conditions, lagoons acts more like storage and sedimentation cells than treatment lagoons (Tilsworth and Smith 1984). Despite the lower temperatures, anaerobic degradation may still occur as anaerobic bacteria are predominantly psychrophilic and can withstand colder environments (USEPA 2011). Additionally, lagoons operating in colder climates will observe higher sludge accumulation due to reduce degradation of settled organic matter (Federation of Canadian Municipalities and National Research Council 2004).

The thermal influence on biological reaction rate is often expressed as a modified Van't Hoff – Arrhenius equation (Tilsworth and Smith 1984):

$$\boldsymbol{k_t = k_{20}\theta^{(T-20)}} \quad \textbf{[2- 5]}$$

Where: k_t = reaction-rate coefficient at temperature T (^{o}C)
k_{20} = reaction-rate coefficient at 20^{o}C

θ = temperature activity coefficient (varies from 1.02 to 1.25)
T = temperature (^oC)

The major sources of heat introduced into wastewater ponds are: solar radiation and the influent wastewater. Ice and Snow cover will have major effects on the ability of ponds to utilize solar radiation. Although heating wastewater ponds can be a costly and impractical endeavour, studies have been conducted into preserving the heat introduced in the ponds by the influent. Sati et al. (2017) conducted a case study into the use of a floating geosynthetic insulated cover for such a purpose and found that effective heat retention was possible.

Seasonal temperature variation is often responsible for the creation of objectionable odours during the spring and autumn seasons. This phenomenon is elaborated further in Section 2.6.1.

Despite the issues of temperature on lagoon treatment rates, with proper modification, lagoons can be adapted to operate effectively in cold environments. Such modification includes: increased retention time, increase in dike height to accommodate for ice thickness, and smaller slenderness ratios (Tilsworth and Smith 1984).

2.4.3 pH

The pH level is an important factor that affects the rate of microbial activity. Most bacterial life present within wastewater ponds must remain between 4.0 and 9.5 in order to survive and with an optimum range varying from 6.5 to 7.5 (Metcalf & Eddy 2013). Wastewater with pH level on one of the extreme end of the scale will be difficult to treat by biological means alone and its release into the natural environment could cause deleterious effects on the receiving ecosystem.

In wastewater the concentration of H^+ ions is regulated by the equations below, representing the carbonate buffering system (USEPA 2011).

$$CO_2 + H_2O \leftrightarrow H_2CO_3 \leftrightarrow HCO_3^- + H^+ \quad \textbf{[2- 6]}$$
$$HCO_3^- \leftrightarrow CO_3^{-2} + H^+ \quad \textbf{[2- 7]}$$
$$CO_3^{-2} + H_2O \leftrightarrow HCO_3^- + OH^- \quad \textbf{[2- 8]}$$
$$OH^- + H^+ \leftrightarrow H_2O \quad \textbf{[2- 9]}$$

pH is tightly connected to photosynthesis and will observe the same diurnal variations. As such, pH will be at its lowest during the night and early morning when respiration is dominant, and reach its maximum during the late evening.

2.5 Nutrient Removal

The high concentration of nutrients, primarily in the form of Nitrogen (N), Phosphorus (P), and Carbon (C), within the wastewater is undesirable. If released into the environment, the high concentration of nutrients would cause environmental degradation and could also become a human health issue. These nutrients are often the limiting factors for biological growth in natural environments. Their introduction into the environment has led to eutrophication caused by excessive bacterial and algal activity. This excessive growth, often referred to as algal blooms, depletes DO levels which in turns leads to mass aquatic organisms' die-off (Hydromantis Inc. and University of Waterloo 2006, Mayo and Abbas 2014).

Due to the potential harm of the release of nutrient rich water into the environment, regulatory agencies across the world have implemented more stringent standards stipulating maximum nutrient concentration rates. Nutrient removal is also the subject of several papers in the academic world. The following subsections will cover each of these nutrients in turn.

2.5.1 Nitrogen

Nitrogen is essential to biological activity and can sometimes be the limiting factor. Nitrogen is needed for the biological treatment of wastewater to take place. However, its removal at the end of the treatment process may be necessary to avoid excessive algae blooms in the receiving waterbody. Nitrogen in wastewater is found in four (4) different forms as seen in Table 2.9 (Metcalf & Eddy, 2013).

Table 2.9 - Forms of Nitrogen found in Wastewater

Nitrogen Form	Definition
Ammonia	NH_3
Ammonium	NH_4^+
Nitrite	NO_2^-
Nitrate	NO_3^-

Nitrogen undergoes a complicated transformation cycle with many pathways that involve the wastewater, sludge, and atmospheric environments. The organic N found in the influent will undergo decomposition by bacterial activity and result in ammonia. As aerobic activity persists, ammonia will be further oxidized into nitrite and finally nitrate (Metcalf & Eddy 2013). This conversion process has been simplified in graphic form by USEPA (2011) (Figure 2.5), and results in a net N loss.

The primary nitrogen removal processes within wastewater stabilization ponds are: Gaseous ammonia volatilization, N assimilation in algal biomass, and biological nitrification and denitrification followed by sedimentation. Under favourable condition, ammonia may undergo volatilization. As reported by USEPA (2011), the fraction of N removal by ammonia volatilization can reach 90%. This may not always be the case as this level of removal is unobtainable in winter conditions (Federation of Canadian Municipalities and National Research Council 2004).

Mayo & Abbas (2014) determined in their study that a stabilization pond observed no significant N removal. In this study, sedimentation was the major removal mechanism

(74% in primary pond) followed by denitrification (26% in primary pond). In the maturation pond, the main N removal mechanism was denitrification with 89%. The final effluent's N fraction was present in the form of algal biomass (72.3%). Algae removal may be necessary to achieve adequate N removal.

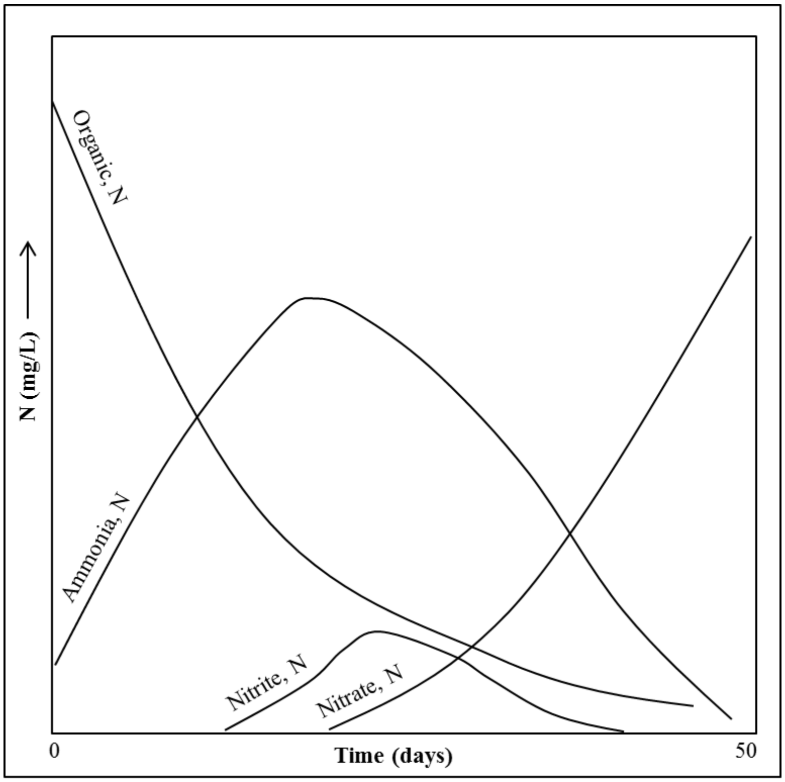

Figure 2.5 – Conceptual representation of changes occurring in forms of N present in a pond environment under aerobic conditions (Recreated from Sawyer et al., 1994 as depicted in USEPA 2011)

2.5.2 Phosphorus

Phosphorus is also an important requirement for organic life and it is most often the limiting nutrient. Phosphorus is present in wastewater in the three (3) forms: Organic phosphorus, orthophosphate (PO_4^{-3}), polyphosphate (Metcalf & Eddy 2013). The two main methods for phosphorus removal are: assimilation into algal and bacterial biomass and precipitation into the pond sludge in the form of a metal (Vijay and Yuan 2017). Algae will assimilate phosphorus in accordance with availability and the hydraulic residence time. Removal rates ranging from 30 to 95% have been reported (USEPA 2011). Algae removal may also be necessary to achieve adequate P removal. Research and experience have proven that the addition of metal salt (e.g. alum) is also effective a precipitating phosphorus from the effluent (Federation of Canadian Municipalities and National Research Council 2004).

2.5.3 Carbon

Carbon in wastewater is predominantly present in the organic matter of the influent. As demonstrated in equations [2-10] and [2-11], the organic matter (represented by COHNS which stands for carbon, oxygen, hydrogen, nitrogen, and sulphur) is oxidized by bacterial activity. Therefore, a relationship exists between the decomposable C content of organic matter and the DO within the wastewater (Metcalf & Eddy 2013).

$$COHNS + O_2 + bacteria \rightarrow CO_2 + H_2O + NH_3 + other\ end\ products + energy \quad \textbf{[2-10]}$$

$$COHNS + O_2 + bacteria + energy \rightarrow \underset{New\ cell\ tissue}{C_5H_7NO_2} \quad \textbf{[2-11]}$$

The standard method of measuring the C content is to measure the amount of O_2 that is consumed by aerobic bacteria in order to stabilize the organic matter under standardized conditions (USEPA 2011). Since the stabilization process can take approximately 20 days at 20°C, and since most of the organic matter stabilizes over the first few days (as can be seen in Figure 2.6), a five (5) day period corresponding to ~70% reduction in C content is standard. This test is known as the 5-day Biochemical Oxygen Demand (BOD_5) and serves as the primary criterion to measure treatment efficiency. Lagoon systems have reported 50-90% reduction BOD_5 (Xiang-Hua et al. 1994, USEPA 2011).

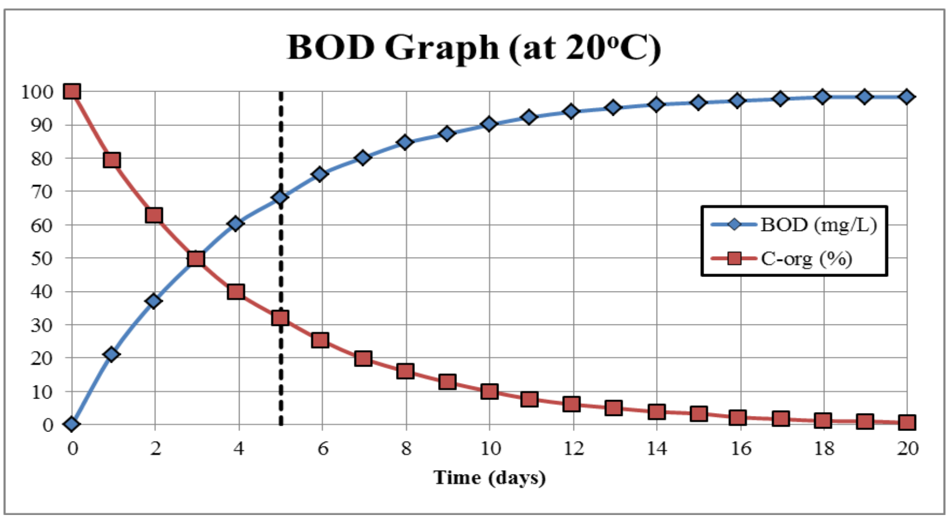

Figure 2.6 - Idealized BOD graph at 20°C superimposed with organic C reduction as a function of time (Recreated from Habeck-Tropfke, 1992 as referenced in Quantum Technologies Global n.d.)

2.6 Common Shortcomings and Improvements

Despite the lack of complex mechanical infrastructure of WWT plants, WWT lagoon systems do experience typical operational difficulties. As they rely on naturally occurring processes, the effectiveness of the treatment varies and the effluent quality may be hindered. These issues are further exacerbated by the increased awareness of the effects of anthropogenic activities on waterways and surrounding ecosystems, resulting in more stringent effluent standards. The following subsections will elaborate on common shortcomings and issues associated with WWT lagoon systems in addition to common upgrades to typical designs.

2.6.1 Odour Control

The release of objectionable gases from lagoon systems is the primary source of complaints from neighbours. The public's acceptance of wastewater treatment facilities can be impacted by the concern of odours (Metcalf & Eddy 2013). Therefore, odour control is an essential component of wastewater treatment. In addition, the presence of objectionable gases is generally a sign of operational issues.

The primary source of objectionable odours in wastewater ponds is the anaerobic digestion of organic matter present in the bottom anaerobic layers of facultative and anaerobic ponds. The process responsible for this is the reduction of sulphate to hydrogen sulphide in the sludge (Heinke et al. 1991). A list of the common odorous compounds and their thresholds are presented in Table 2.10.

In facultative ponds, the presence of a thin aerobic layer at the water and atmosphere interface acts as a barrier preventing the release of odours. It is for this reason that artificial covers or recirculation from aerobic ponds should be provided to anaerobic ponds (USEPA 1983, 2011).

Table 2.10 - Major odorous compounds and their corresponding thresholds associated with untreated wastewater (Metcalf & Eddy 2013)

Odorous Compound	Chemical formula	Molecular weight	Odour thresholds (typical), ppm_v
Ammonia	NH_3	17.0	0.035-53 (1.5)
Chlorine	Cl_2	71.0	0.0095-4.7 (0.15)
Crotyl mercaptan	CH_3-CH=CH-CH_2-SH	90.19	0.00003
Dimethyl sulphide	$(CH_3)2^s$	62	0.0001-0.02 (0.002)
Diphenyl sulphide	$(C_6H_5)2^s$	186	0.00005-0.005 (0.0004)
Ethyl mercaptan	$CH_3(CH_2)SH$	62	0.000009-0.03 (0.0002)
Hydrogen sulphide	H_2S	34	0.00007-1.4 (0.003)
Indole	C_8H_6NH	117	0.0001-0.0003 (0.0001)
Methyl amine	CH_3NH_2	31	0.02-8.7 (0.11)
Methyl mercaptan	CH_3SH	48	0.00002-0.04 (0.0007)
Skatole	C_9H_9N	131	0.00000007-0.05 (0.0002)
Sulphur dioxide	SO_2	64.07	0.009-5.0 (0.6)
Thiocresol	$CH_3(C_6H_4)SH$	124	0.00006-0.001 (0.0002)

Variations in temperature are an important factor for odour release. During transitional seasons (spring break up and autumn), the release of objectionable odours is more common. During the summer and winter months, the water column in the ponds stratifies, with colder and denser water at the bottom of the pond and warmer lighter water at the surface (Figure 2.7A&C). Once a pond stratifies, there is little interchange between the layers, this act as a barrier for the odorous compound in the anaerobic layer. However, during transitional seasons, the stratification weakens and the wastewater overturns (mixing of the layers) allowing for the release of odorous compounds into the air (Figure 2.7B).

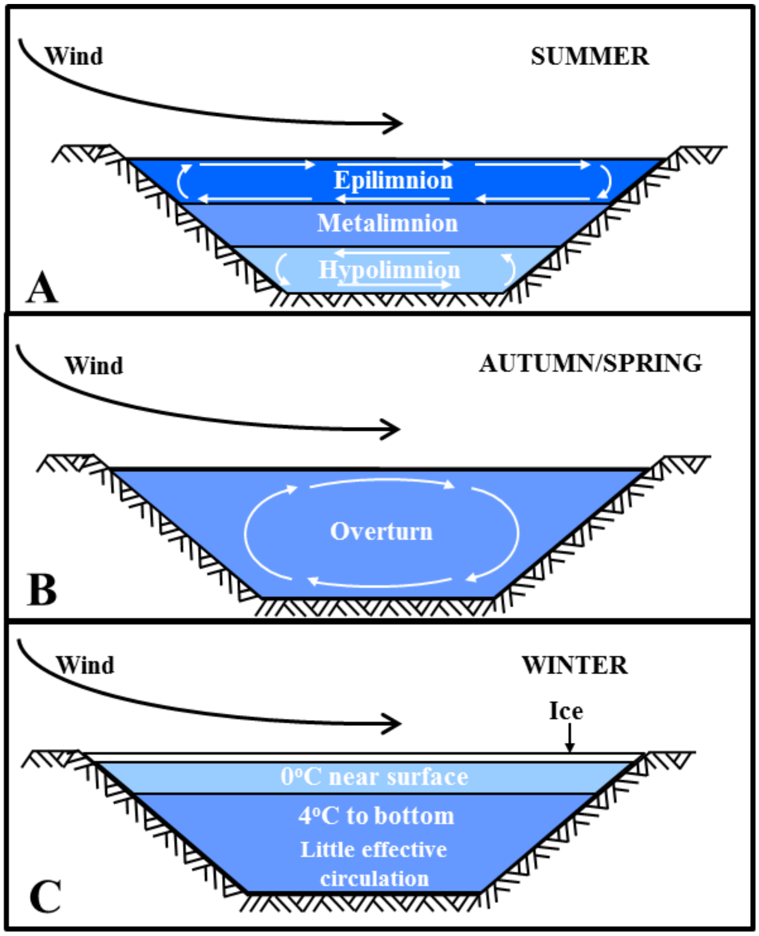

Figure 2.7 - Schematic representation of seasonal variation in pond stratification (Modified from Encyclopaedia Britannica Inc. n.d.)

Other reasons for the release of odours may be due to inappropriate operations of the lagoon systems which include (USEPA 2011):

1. Overloading: Overloading occurs when the pond receives influent of higher organic matter concentration than intended for or is capable of treating with current climatic conditions. In order to avoid this issue, pond should be designed to maximize their effective volume. If multiple ponds are present in the systems, operating in parallel as opposed to in series can alleviate overloading of the primary pond. Providing mechanical aeration, when needed, can also allow for higher loading rates without odour generations;

2. Excessive Surface Scum: Surface scum is the accumulation of floating debris and decaying algae. In sufficiently large quantities they may release noticeable odours. Breaking up scum clumps or harvesting scum can alleviate this issue. Mechanical agitation or recirculation is also effective at preventing scum build-ups; and,

3. Uncontrolled aquatic and slope vegetation: Vegetation on the surface and on the embankment of a pond can accumulate odorous scum. Proper maintenance of emerging vegetation will prevent this issue.

Temporary odour control can be achieved by the addition of sodium nitrate. The Federation of Canadian Municipalities and National Research Council (2004) recommends that 122 kg/ha of sodium nitrate be added to the influent or spread over the pond surface on the first day, with 56 kg/ha for every additional day as needed. Additionally, the use of enzymes has also been successful to reduce odours and sludge volume in lagoons. However, more research is needed to better understand their impact.

Odour generation should be considered when selecting a site for a new lagoon system. Lagoon should be installed down from the prevailing wind with respect to populated areas and a buffer zone should be maintained.

2.6.2 Pathogens and Disinfection

Disinfection of the effluent may be necessary in accordance with the sensitivity of the receiving ecosystem, uses of the waterway downstream, and regional regulations. The four (4) categories of enteric pathogens targeted by disinfection in wastewater are: bacteria, protozoan oocysts and cysts, viruses, and helminth ova (Metcalf & Eddy 2013).

Wastewater treatment by lagoon systems can achieve effective disinfection by natural means. Natural disinfection processes include: natural ultraviolet irradiation, temperature, adsorption to solids, settling, and predatory organisms. The Federation of Canadian Municipalities and National Research Council (2004) reports that 99.99% of Escherichia coli (E. Coli) deactivation by natural means has been reported in lagoons.

Although natural disinfection occurs, the variability of disinfection effectiveness is subject to diurnal and seasonal variation. Additional disinfection by chemical or physical processes is therefore often required. Metcalf & Eddy (2013) conducted a comparison of several common and well-documented method of wastewater disinfection. These methods include tradition chlorine variants and alternatives such as Ultraviolet (UV) radiation. Their findings are summarized in Table 2.11 and Table 2.12. Proper treatment of the wastewater is required prior to disinfection regardless of the disinfectant used. High levels of SS and BOD will interfere with the effectives of the disinfectant used (USEPA 2002).

Table 2.11 - Comparison of chlorine-based technologies used for the disinfection of treated wastewater (modified from Metcalf & Eddy, 2013)

Characteristic	Chlorine Gas	Sodium Hypochlorite	Combined Chlorine	Chlorine Dioxide
Availability / cost	Low	Moderately low	Moderately low	Moderately low
Deodorizing ability	High	Moderate	Moderate	High
Interaction with organic matter	Oxidizes organic matter	Oxidizes organic matter	Oxidizes organic matter	Oxidizes organic matter
Corrosiveness	Highly corrosive	Corrosive	Corrosive	Highly corrosive
Toxic to higher life forms	Highly toxic	Highly toxic	Toxic	Toxic
Penetration into particles	High	High	Moderate	High
Safety concern	High	Moderate to low	High to moderate	High
Solubility	Moderate	High	High	High
Stability	Stable	Slightly unstable	Slightly unstable	Unstable
Bacteria	Excellent	Excellent	Good	Excellent
Protozoa	Fair to poor	Fair to poor	Poor	Good
Viruses	Excellent	Excellent	Fair	Excellent
By-product formation	THMs and HAAs	THMs and HAAs	Traces of THMs and HAAs, cyanogen, NDMA	Chlorite and Chlorate
Increases TDS	Yes	Yes	Yes	Yes
Use as disinfectant	Common	Common	Common	Increasing slowly

Chlorine is the most common method employed (USEPA 2011) for disinfection. However, due to its high toxicity to higher life forms and its residual properties, it is now largely not permitted or otherwise discouraged in Canada (Federation of Canadian Municipalities and National Research Council 2004). The maximum allowable chorine residual in wastewater effluent is 0.02 mg/L (Government of Saskatchewan 2015, Government of Canada 2016).

Table 2.12 - Comparison of chlorine alternatives technologies used for the disinfection of treated wastewater (modified from Metcalf & Eddy, 2013)

Characteristic	Ozone	UV Radiation	Pasteurization
Availability / cost	Moderately high	Moderately high	Moderate
Deodorizing ability	High	NA	NA
Interaction with organic matter	Oxidizes organic matter	Absorbance of UV radiation	NA
Corrosiveness	Highly corrosive	NA	NA
Toxic to higher life forms	Toxic	Toxic	Toxic
Penetration into particles	High	Moderate	High
Safety concern	Moderate	Low	Low
Solubility	Moderate	NA	NA
Stability	Unstable	NA	NA
Bacteria	Excellent	Good	Excellent
Protozoa	Good	Excellent	Excellent
Viruses	Excellent	Good	Good
By-product formation	Bromate	None known in measurable concentrations	None known in measurable concentrations
Increases TDS	No	No	No
Use as disinfectant	Increasing slowly	Increasing rapidly	Increasing slowly

2.6.3 Short Circuiting

As previously stated in Section 2.2.2, short circuiting occurs when a preferential flow path exists in which part of the wastewater travels through the lagoon system in less time than intended. This occurrence is an issue for continuous discharge systems or any system in which the wastewater is expected to remain within a portion of the treatment train for a specified period of time (e.g. disinfection contact chamber). Short circuiting results in the discharge of untreated or partially treated wastewater. Short circuiting also creates dead zones in which the wastewater stagnates and treatment is ineffective reducing the overall lagoon treatment capacity. An example of short circuiting is given in Figure 2.8.

Short circuiting is most commonly created by improper cell inlet and outlet designs (Federation of Canadian Municipalities and National Research Council 2004, Water Security Agency 2004). Stratification of ponds as also been reported as a cause of short circuiting (Morgan 2010). A simple dye tracer study can be conducted to assess any component of a WWT lagoon system, where access points exist.

Several solutions exist to solve short circuiting issues such as (Federation of Canadian Municipalities and National Research Council 2004):

1. <u>Baffles:</u> Baffles can be introduced to control the flow of the wastewater within cells. Many low-cost and temporary systems are available

commercially for use in wastewater treatment ponds. Such system can be easily retrofitted to existing systems. Baffles have also been proven to increase biological activity by providing a substrate for attached growth (USEPA 2011);

2. Inlet and Outline Redesign: Inlets and outlets can be relocated to improve in-cell mixing and retention time. Alternatively, additional inlets or outlets may be installed;

3. Modifying System Operation: Short circuiting may be eliminated by simply altering the WWT lagoon system operation from a series to a parallel configuration. Alternatively, the addition of recirculation of part of the wastewater may be used to improve mixing;

4. Mixers and Aerators: The addition of or relocation of existing mixers and aerators can be used to modify the flow patterns and improve mixing; and,

5. Maintenance: In shallow cells, the presence of weeds or the accumulation of sludge may cause preferential flow patterns and dead zones. Regular maintenance of weeds and sludge may solve issues of short circuiting.

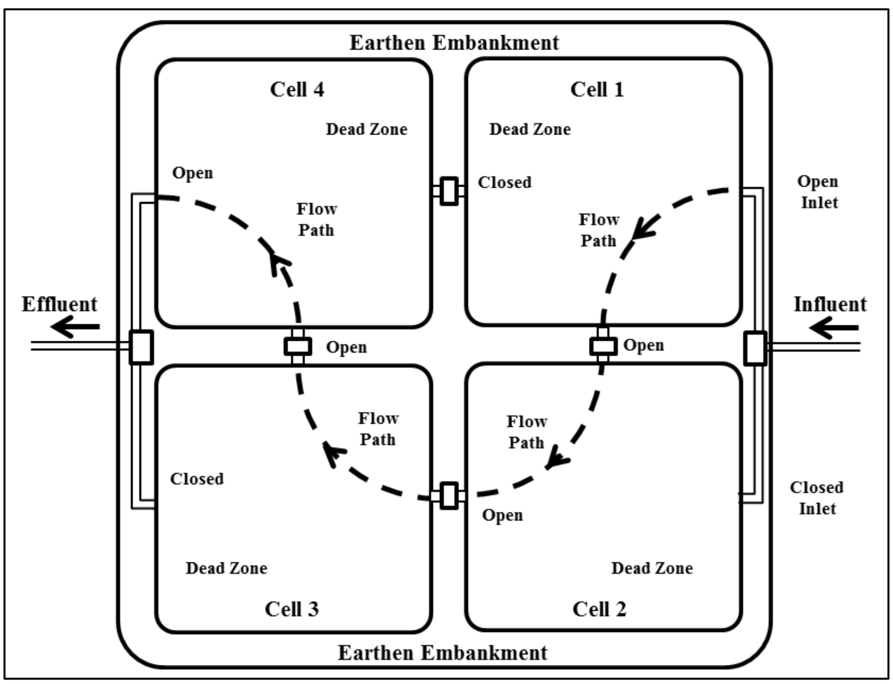

Figure 2.8 - Example of short circuiting occurring in at Whitehorse, YT wastewater treatment lagoon (Recreated from Whitley and Thirumurthi 1992)

2.6.4 Temperature Control

As stated in Section 2.4.2, temperature is a key controlling factor of the effectiveness of WWT lagoons. In cold climates, low temperature reduces biological activity, increase the generation of sludge, and lengthen the survival time of pathogens (Tilsworth and Smith 1984, Heinke et al. 1991). As active heating of the wastewater is largely considered prohibitively expensive, several actions can be taken for the WWT lagoon to retain the heat originating from the warmer influent:

1. Cell Design: Proper cell design can alleviate the effects of cold temperatures. Cells should be constructed with smaller slenderness ratios, with squared and circular shaped cells being preferable. Embankments should have increased freeboard (1 m to 2 m) to accommodate for ice thickness and be made of non-frost susceptible soils (Tilsworth and Smith 1984); and,

2. Modified Operation: WWT lagoon should be operated with controlled discharge to avoid discharge during colder periods. Supplemental aeration can be provided during the active treatment season to enhance treatment. Additionally, active disinfection efforts may be necessary prior to discharge. In their study, Sati et al. (2017) demonstrated the effectiveness of floating insulated covers to conserve the heat of WWT lagoons, allowing for longer treatment times.

2.6.5 Aeration

As stated in Section 2.2.1.4, the addition of mechanical aeration to a facultative cell (i.e. the conversion to an aerated cell) can greatly increase the BOD_5 loading capacity of the WWT lagoon system and increase the overall treatment of the wastewater prior to discharge (Federation of Canadian Municipalities and National Research Council 2004). Aeration provides the added benefit of preventing the formation of ice and controlling the wastewater flow.

Mechanical aeration can be generated by motor-driven surface aerators or by blowers with diffuser lines positioned at the bottom of the cell bed. Such systems are readily available commercially and many can operate with on-site generated renewable energy (i.e. solar or wind) (Jiang et al. 2018). Ewing et al. (2014) have even demonstrated the viability of utilizing a self-powered blower system utilizing the lagoon itself as a microbial fuel cell.

Aeration does not have to be continuous and can be provided to a cell intermittently or seasonally to obtain various desired effect and lower operating costs and maintenance requirements, whilst still providing some benefits of aeration.

2.6.6 Solid Removal

Excessive TSS has been reported as a common issue with WWT lagoons with effluent in exceedance of 100 mg/L (USEPA 2011). Algae are the main constituents of effluent TSS as opposed to organic waste matter in the influent. Several methods have been used to reduce the effluent TSS and meet compliance standards:

1. Intermittent Sand Filters: Intermittent sand filters operate by intermittently spreading the lagoon effluent over a sand bed. The effluent is allowed to percolate through the sand medium where TSS and organic matter are physically separated by the medium and the biologically active content is stabilized. Intermittent sand filters have been proven to be economical and simple to operate. The upper portion of the sand bed does require maintenance as clogging may occur overtime (Russell et al. 1984,USEPA 2000, USEPA 2011). Such system maybe gravity operated whenever possible to reduce operation costs;

2. Rock Filters: Rock filters operate in a similar fashion to sand filters, by allowing the effluent to percolate through a submerged rock filter media prior to discharge. Rock filters also have similar advantages to intermittent sand filter with the added advantage that they may be retrofitted within lagoon cells (USEPA 2011); and,

3. Coagulation Flocculation: The addition of chemical additives, most commonly ferric salts, alum, and lime have proven to be effective at settling suspended algae via a coagulation and flocculation process. The formation of flocs is sensitive to pH, alkalinity, turbidity, and temperature (USEPA 2011). This added operation process has seen much success with discontinuous discharge systems where the chemical is added prior to discharge. The chemical additive is most commonly dispensed via boat, removing the need for added mechanical infrastructure. In continuous discharge systems, the chemicals can be added on a regular interval at the access point of the final cell’s inlet. Reliance on this method does induce a need for added logistics and increases operational costs.

2.6.7 Wetlands

Wetlands can be used as a final polishing of WWT lagoon effluent prior to discharge. Constructed or engineered wetlands have a long-standing proof of effectiveness across various Canadian environments. Constructed wetlands can be defined as either Free Water Surface (FWS) wetland or Sub Surface Flow (SSF) wetlands.

1. Free Water Surface Wetlands: FWS wetlands are distinguishable by the water-atmosphere interaction. The most common types of vegetation used in FWS wetlands include: Cattail (Typha spp.), bulrush (Scirpus spp.), and

reeds (Phargmites spp.). In addition to the added treatment, FWS have been linked to added ecological benefits by providing a habitat for wildlife and communal green spaces. However, mosquitos and other insect disease vectors along with odours can become an issue (USEPA, 2000b; Massoud et al., 2009).

2. Sub Surface Flow Wetlands: SSF wetlands are mostly designed for the polishing of effluent from other treatment processes such as lagoon systems. SSF wetlands can provide an effective removal of BOD, TSS, metals, and some persistent organic content whilst eliminating the risk of public contact with partially treated wastewater (USEPA 2000c).

As stated by Wittgren & Maehlum (1997) and (Doku and Heinke 1995), several wetlands have been in operation in Canada (including as far north as Yukon and the NWT) and are capable of meeting effluent standards. Typical operation of a lagoon-wetland system in Canada (including in the province of Saskatchewan) is to store wastewater in lagoons during the winter period and discharge to the wetland during warmer periods. For this reason discharge may be conducted only over 6-8 months a year (Wittgren and Maehlum 1997, Ham et al. 2004, Water Security Agency 2012).

As wetlands operate mostly anaerobically, the removal of both ammonia and phosphorus is inefficient without long contact time resulting significantly large wetland areas. Common methods to tackle this issue are: integrated mechanical aeration by tubing in the wetland bed, integrated gravel trickling filters and vertical flow wetland beds (USEPA 2000c).

2.7 Lagoon Use in Canada

Treatment of municipal wastewater by WWT lagoon systems is popular across the world for use by small communities, including in Canada. According to Statistics Canada and Infrastructure Canada (2016), 49.7% (1244 facilities) of all publicly owned wastewater treatment facilities in Canada are lagoon systems. With the exception of the territories, lagoons are particularly favoured in the Prairie Provinces. 89.9% (179 facilities), 78.5% (124 facilities), and 80.9% (313 facilities) of the wastewater treatment facilities operating in Manitoba, Saskatchewan, and Alberta are lagoon systems. These percentages could be larger as the plants dedicated to the handling of sludge are included in these statistics. These statistics can be seen in Table A1 and Figure A1 of Appendix A.

As seen in Figure A2 of Appendix A, WWT lagoon systems are preferred in rural municipalities with the exception of the province of Prince Edward Island and Yukon Territory. 70.9% of all publicly owned municipal WWT lagoons are operating in rural municipalities. In the province of Saskatchewan, this percentage drops to 68% (Statistics Canada and Infrastructure Canada 2016b).

As part of *Canada's Core Public Infrastructure Survey: Wastewater and Solid Waste Assets 2016*, Statistics Canada and Infrastructure Canada (2016b) published an assessment of the physical conditions of all publicly owned wastewater assets which included lagoon systems. The report stated that 20.3% of all municipal WWT lagoon systems were in very good condition and were fit for the future. 40.4% were in good condition, meaning that the lagoons had reached the midpoint of their expected service life. 20.5% were characterized as being in fair conditions, meaning the lagoons showed deficiencies or signs of deterioration and are in need of remediation. 10.6% of lagoons were in poor condition, characterized by the presence of significant deterioration and operating below standards. 3.3% were in very poor conditions with advance deterioration and considered unfit for sustained service. 4.9% of lagoon systems could not be assessed and are of unknown physical condition.

The province of Saskatchewan ranked below the Canadian average with:

- 19.1% (1.2% below national average) in very good condition;
- 36.6% (3.8% below national average) in good condition;
- 25% (4.5% above national average);
- 11.7% (1.1% above national average); and,
- 3.5% (0.2% above national average).

2.8 Lagoon Use in DND/CAF

The Department of National Defence (DND) currently owns approximately 103 wastewater treatment assets, ranging from WWT plants, WWT lagoon, septic tanks, and holding tanks, located in 53 installations across the country from coast to coast to coast. The majority of these wastewater treatment assets are between 40 and 80 years old. This indicates that, according to Statistics Canada and Infrastructure Canada (2016c), the majority of the assets have surpassed the Canadian average expected useful life of wastewater assets. The Canadian average expected useful lives for WWT plants, WWT lagoon, septic tanks, and holding tanks are 28, 30, 42, 31, and 27 years respectively (Table 2.13).

In an effort to rationalize DND's real property portfolio, the Assistant Deputy Minister of Infrastructure and Environment (ADM(IE)) is seeking to divest from DND owned water and wastewater facilities through the Capital Assistance Programme (DND/CAF 2018), where neighbouring municipalities would be capable of providing such services. However, several wastewater treatment assets are located on remote and isolated bases/wings and stations where no neighbouring municipalities are present. Such locations include: Canadian Forces Station (CFS) Alert on Ellesmere Island and Canadian Forces Base (CFB) Suffield in the plain of Alberta. These locations will most likely not be subject to divestment. Much like the rest of Canada, these locations have a preference of using lagoon systems for the treatment of their wastewater. Many bases/wings and stations observe an increases in populations over the summer and early autumn period, primarily due to increases in military training. These increases can sometimes reach ten times the standing population in certain locations. This is a factor that makes the operation of WWT lagoons in the DND/CAF unique.

In summary, despite the overall reduction of DND wastewater assets as ADM(IE)'s divestment effort progress, DND will rely more heavily on their ageing WWT lagoon systems for the management of their wastewater across Canada.

Table 2.13 - Average expected useful life of major wastewater treatment assets by provinces/territories (Statistics Canada and Infrastructure Canada 2016c)

Geography	Average Expected Useful Life (years)				
	Treatment plants (includes sludge handling plants)	Lagoon systems	Pump stations	Lift stations	Storage tanks
NL	50	-	-	22	50
PE	-	-	-	22	-
NS	23	23	36	25	-
NB	-	-	15	22	-
QC	25	-	41	27	-
ON	37	25	50	43	28
MB	20	33	50	41	-
SK	27	38	15	38	-
AB	20	30	49	33	32
BC	37	25	42	26	15
YT	-	-	-	-	-
NT	-	-	-	25	-
NU	-	-	-	-	-
Canada	**28**	**30**	**42**	**31**	**27**

2.9 Relevance to Research

WWT lagoons are home to a complex physical, chemical, and biological dynamics. Extensive literature is available on many different aspects of WWT lagoon systems. This chapter provided the reader with the background associated with the definition of a sewage lagoon system and the relevant factors that influence the operation of such systems. This chapter elaborated on how WWT lagoon systems operate by expanding on: the various types of WWT lagoon systems, the biological treatment processes and their controlling factors, in addition to the basic chemistry of nutrient removal. Figure 2.9 provides a summary of these major functions. This chapter also provided information on common shortcomings and issues associated with lagoon system operations along with common modifications and retrofits. Lastly, statistics and observations were provided regarding the use of WWT lagoon across Canada and in the DND/CAF which supports the relevance of this research study.

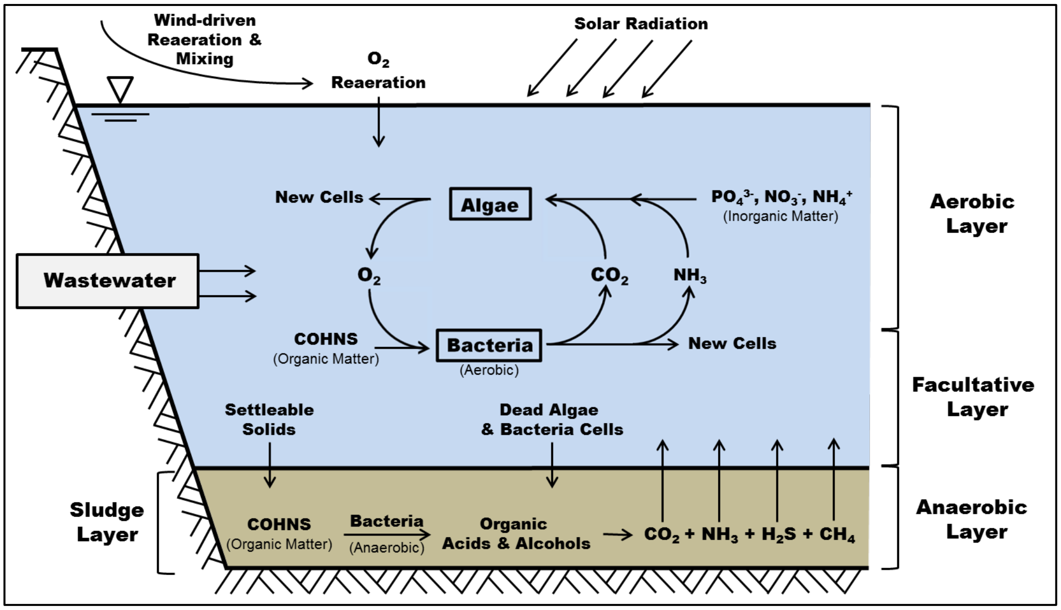

Figure 2.9 - Schematic summarizing the stabilization of wastewater in lagoon systems (Tchobanoglous and Schroeder 1985)

3.0 Regulatory Environment

3.1 Introduction

17 Wing Detachment Dundurn, being federal land and thus, under federal jurisdiction, is governed by two (2) principal bodies: Fisheries and Oceans Canada and the Department of National Defence (DND). Even though the detachment does not fall under the jurisdiction of the Government of Saskatchewan, it would be diligent to study (and also include) its regulations and guidelines as well as any site-specific considerations along with accepted best practices in this regard. These regulations and guidelines may differ from federal guidelines to account for regional specific needs and common issues. Additionally, as the effluent from the detachment may affect the adjacent land which is under provincial jurisdiction, observing both standards and respecting the more stringent requirement (where applicable) can avoid costly legal disputes and promote good environmental stewardship.

In this chapter, regulations on the use of Wastewater Treatment (WWT) lagoon systems from all levels of government and from DND are provided and compared. In addition, guidelines and Best Management Practices (BMPs) from prominent organizations and researchers will be included.

3.2 Federal Regulations

The federal government has published a series of regulations and guidelines design to provide Canadians with a supply of water of consistent quality and dispose of wastewater in a fashion that will not have negative impacts on the environment and human health. The following subsections will elaborate on some of the key documents provided by the federal government.

3.2.1 Wastewater Systems Effluent Regulations (SOR/2012-139)

The Wastewater Systems Effluent Regulations (WSER) is an annexe of the Fisheries Act published by the Minister of Justice that came into effect on 29 June 2012 via a phased approach. The WSER replaces the Effluent Quality and Wastewater Treatment at Federal Establishments (EPS 1-EC-76-1, 1976). The primary purpose of these regulations is to protect fish, fish habitats and human health as a result of fish consumption. These goals are obtained by regulating the release of deleterious substances from wastewater sources in natural waterways and waterbodies through a national effluent quality standard. These standards should be achievable via secondary wastewater treatment processes. The regulations apply to all WWT systems receiving an annual daily average of 100 m^3 or more and/or discharge to any surface water body connected to fish life. WWT systems had until 1 January 2015 to achieve the stipulated standards if no transitional authorization was given. The last set of transitional authorizations will conclude on 31 December 2040.

The regulations define and regulate the following substances or classes of substances as deleterious (Government of Canada 2017):

1. Carbonaceous biochemical oxygen demanding matter;

2. Suspended solids;

3. Total residual chlorine; and,

4. Unionized ammonia (NH_3).

The WSER specifies the legal requirement that must be adhered to by WWT systems owners/operators in order to safely discharge to the environment. The regulations not only include the effluent quality standards but also stipulate the proper sampling methodology and frequency as well as approved test methods. The regulations also dictate the reporting procedures and frequencies to be followed by WWT systems owners/operators (Government of Canada 2016). The effluent quality standards are further described in Section 3.6.1.

The regulatory requirements imposed on WWT systems owners/operators vary based on the type and size of WWT systems. The regulations groups WWT system types based on their discharge regime. WWT systems are either continuously or intermittently discharging. Intermittent WWT systems are defined as having retention time of 90 days or greater and discharges effluent to a maximum of four (4) occurrences with a minimum of seven (7) days between discharge events. All other WWT systems are considered continuous discharge WWT systems (Government of Canada 2016). The regulations further breakdown WWT systems by their sizes as defined by the annual average daily volume of influent wastewater they receive. There exists four (4) categories (Government of Canada 2016):

1. 100 to ≤ 2500 m^3;

2. >2500 to ≤ 17500 m^3;

3. >17500 to ≤ 50000 m^3; and,

4. >50000 m^3.

3.2.2 WSER Supporting Documentation

A variety of support documents are available on the Government of Canada website which accompanies the WSER (Government of Canada 2017b). The primary purpose of these documents is to provide guidance to WWT system owners and operators to better understand the WSER and their regulatory requirements. Such guidance includes the condensed versions of the WSER written in plain English or French (Government of

Canada 2013a, 2013b). Furthermore, information is provided regarding the timeline of enforcement of the WSER and a link to the reporting system is given. More information is provided on the reporting system in Section 3.2.3.

3.2.3 Effluent Regulatory Reporting Information System

The Effluent Regulatory Reporting Information System (ERRIS) was developed by Environment Canada to establish a database of the regulatory reporting information generated by WWT system owners and operators as part of the WSER. The ERRIS further assist Environment Canada with its monitoring, compliance, and enforcement duties (Environment Canada 2013).

The ERRIS is managed through Environment Canada's Single Window Information Manager (SWIM) on-line interface. SWIM allows for WWT system owners and operators to submit their reports (primarily: initial identification reports and ongoing effluent monitoring reports) and apply for temporary authorizations, in compliance with the WSER.

3.3 Provincial Regulations – Saskatchewan

As previously stated, Detachment Dundurn being an entity under the jurisdiction of the Department of National Defence, falls under federal jurisdiction, however, provincial regulation (Saskatchewan) should also be respected in order to align the overall regulatory framework with the most stringent of acceptable and best practices and to better adapt to regional specificities and avoid possible disputes with neighbours that reside in the province.

3.3.1 Environmental Management and Protection Act

The E-10.22 Environmental Management and Protection Act is a chapter of the Statutes of Saskatchewan 2010 last amended on 2018. This act provided the legal framework on all matters related to the environment and its protection along with the management of deleterious sources (Government of Saskatchewan 2018a).

Regulation 3 of the Environmental Management and Protection Act entitled: *The Waterworks and Sewage Works Regulations* is a document comparable to the WSER in that it stipulates the effluent qualities that must be adhered to, along with required sampling, testing, and certification (Government of Saskatchewan 2015). The effluent quality standards are further described in Section 3.6.1.

The Waterworks and Sewage Works Regulations separate WWT systems, or sewage treatment facilities, based on the presences of fish in the effluent receiving body, regardless of the volume of wastewater treated. WWT systems that discharges to waterbodies associated with fish life are required to adhere to more stringent and additional effluent standards (Government of Saskatchewan 2015).

3.3.2 Sewage Works Design Standards

The Water Security Agency (WSA) is a crown corporation established under the Water Security Agency Act (Government of Saskatchewan 2018b) and Saskatchewan's organization responsible for the management of all matters related to water within the province. The WSA manages and protects the province's water supply, regulate the quality of water for human consumption, and the quality of treatment provided to wastewater. The WSA also owns and operates 69 dams, regulates water supply channels, and protects aquatic habitats (Water Security Agency n.d.).

The Sewage Works Design Standards is a document provided by the Water Security Agency that stipulates the provincial code and standard that must be adhered to for the construction and maintenance of wastewater infrastructure. These standards include stabilization pond standards and lagoon monitoring requirements. Specific information regarding WWT lagoons systems (waste stabilization ponds) include (Water Security Agency 2012):

1. Siting;
2. Constructions requirements;
3. Monitoring requirements;
4. Facultative, aerated, and storage cell requirements; and,
5. Decommissioning.

3.3.3 Surface Water Quality Objectives

In addition to the Waterworks and Sewage Works Regulations, the WSA published the EPB 356 Surface Water Quality Objectives – Interim Edition in 2015. This document provides guidance on additional effluent quality objectives that should be met by WWT systems owners and operators if the effluent is intended for release in water bodies with aquatic life or for agricultural uses (Water Security Agency 2015).

These quality objectives are a direct adoption of the generic guidelines that were produced by the Canadian Council of Ministers of the Environment (CCME). Unlike the Waterworks and Sewage Works Regulations, these quality objectives are not legally binding but serve to protect water uses (Water Security Agency 2015). These quality objectives are presented in Section 3.6.2.

3.4 DND Regulations and Policies

3.4.1 Defence Administrative Order and Directive 4003-0

The Defence Administrative Order and Directive (DAOD) 4003-0, legally binds all employees of the Department of National Defence (DND) and Canadian Armed Forces (CAF) to follow proper environmental conduct during the fulfilment of their responsibilities. This policy states that DND and CAF personnel shall (DND 2004):

1. Adhere to the code of environmental stewardship;
2. Implement a sustainable development strategy;
3. Conduct environmental assessments;
4. Exercise due diligence;
5. Develop, operate and maintain an Environmental Management System (EMS) in accordance with the International Standards Organization (ISO) 14001 standards; and,
6. Commit to continual improvement.

Additionally, this policy established a Code of Environmental Stewardship that DND and the CAF will need to observe and define due diligence (DND 2004). This document provides the legal justification for the conduct of this research and, as a result of this thesis, Detachment Dundurn should be able to improve its environmental stewardship.

3.4.2 Defence Energy and Environment Strategy

As of November 2017, DND has published its latest strategy in its commitment to continuous improvement in energy and environmental management. Entitled: *Defence Energy and Environment Strategy* (DEES), this strategy encompasses four (4) goals and 18 targets to be accomplished within the next few years (DND 2017).

The efforts that will be conducted within the scope of this thesis will be in direct support of the sustainable real property goal of the DEES. More specifically, this thesis should support Detachment Dundurn in reducing its environmental footprint as described in section 5.1 – Reducing the environmental footprint of the infrastructure portfolio of the DEES. Additionally, this thesis will offer methods for the detachment to better manage its water and wastewater as described in section 5.3 – Managing water and wastewater sustainably of the DEES. The proposed modifications should reduce and optimize the use of potable water and production of wastewater, meet or exceed federal and provincial regulatory requirements and better manage and treat the wastewater discharged from the detachment.

This thesis aligns itself well with Target 18 of the DEES; Complete source water vulnerability assessments on all sites where DND supplies its own drinking water by 31 March 2020.

Finally, the DEES will be adhered to, whenever possible, during the development of solutions and recommendations within this thesis. In particular, principles of energy efficiency, green procurement, and the integration of sustainability principles within real property will be considered.

3.5 Guidelines and Best Management Practices (BMPs)

3.5.1 Canada-wide Strategy for the Management of Municipal Wastewater Effluent

The Canada-wide Strategy for the Management of Municipal Wastewater Effluent was developed by the CCME in 2009. This strategy was developed to provide a unified methodology to improve the management of wastewater across all levels of government within a 30-year timeframe. This strategy consists of the collective agreement of all 14 provincial and territorial ministers of the environment. With the goal of protecting the environment and human health, the strategy outlines the need for site-specific effluent discharge objectives in addition to the national performance standards regulated by the WSER. The second intended outcome of the strategy is to improve the clarity of the regulatory and management needs imposed on WWT facilities owners and operators. The Canada-wide strategy also states the importance for pollution source control and establishes an economic plan to achieve the outcomes desired by the strategy (Canadian Council of Ministers of the Environment 2003, 2014).

The CCME published a progress report on their Canada-wide Strategy for the Management of Municipal Wastewater Effluent in 2014. This report outlined the progress that was accomplished by signatory members of the strategy with their five (5) year commitments. The report also states issues and technical clarifications that have emerged since the ratification of the Canada-wide strategy (Canadian Council of Ministers of the Environment 2009).

3.5.2 National Guide to Sustainable Municipal Infrastructure

As part of their National Guide to Sustainable Municipal Infrastructure best practices documentation, the Federation of Canadian Municipalities (FCM) published in 2004: *The Optimization of Lagoon Operation – A Best Practice by the National Guide to Sustainable Municipal Infrastructure*.

This publication aims to assist WWT lagoon system owners and operators in optimizing their systems performance and capacity by providing design guidelines and performance expectation for various components of lagoon systems. This publication also provided possible approaches that can be used to enhance WWT lagoon systems (Federation of Canadian Municipalities and National Research Council 2004).

3.5.3 Principles of Design and Operations of Wastewater Treatment Pond Systems for Plant Operators, Engineers, and Managers

Published by the United Stated Environmental Protection Agency (USEPA, 2011), the *Principles of Design and Operations of Wastewater Treatment Pond Systems for Plant Operators, Engineers, and Managers* manual was developed to provide guidance to current and future WWT lagoon system owners and operators. This manual provides basic information on WWT lagoon operations and design recommendations, along with guidance on operations and maintenance (including troubleshooting). In addition, this manual also provides information on innovations that have been made prior to its publication.

3.5.4 Guideline for the Minimum Evaluation of the Performance of Full-Scale Waste Stabilization Pond Systems

This paper, written by Pearson et al. and published in 1987 in the journal of Water Research, proposes a sampling schedule for WWT lagoon system owners and operators. The recommended schedule allows for the acquisition of the minimum amount of data required to assess the performance of a WWT lagoon system. Additionally, the paper elaborates on low-cost methods of obtaining the samples and testing procedures. The proposed sampling schedule includes the collection of chemical and physical parameters of the individual ponds, and meteorological data, along with sludge properties (Pearson et al. 1987).

The recommended sampling schedule differs from the WSER requirements in that it allows for sufficient data for use in troubleshooting and correcting deficiencies within the system. In addition, the data allows for assessing the efficiency of the system with regard to its optimal operating conditions (Pearson et al. 1987).

3.6 Wastewater Discharge Standards and Objectives

3.6.1 Effluent Quality Standards

Both the Federal and Provincial governments provide effluent quality standard that must be respected by the owner and operators of WWT systems. These standards are listed below:

Federal regulations as stated in the *Wastewater Systems Effluent Regulations* (SOR/2012-139) Section 6:

1. CBOD ≤ 25 mg/L
2. TSS ≤ 25 mg/L
3. Residual Chlorine ≤ 0.02 mg/L
4. Unionized ammonia ≤ 1.25 mg/L as *N* at 15°C ± 1°C
5. No acute lethality

The province of Saskatchewan's regulations as stated in *The Waterworks and Sewage Works Regulations* (Chapter E-10.22 Reg 3) Section 11 – sewage treatment facilities:

1. BOD_5 ≤ 30 mg/L
2. $CBOD_5$ ≤ 25 mg/L
3. TSS ≤ 30 mg/L
4. Residual Chlorine ≤ 0.02 mg/L
5. Unionized ammonia ≤ 1.24 mg/L as *N* at 15°C ± 1°C
6. No acute toxicity at the point of discharge

For the purpose of this thesis, the more stringent standard between the Federal and Provincial regulation shall be used as the targeted standard for 17 Wing Detachment Dundurn's wastewater effluent. As such the targeted effluent quality is provided in Table 3.1.

Table 3.1 – Targeted effluent quality standards

Parameter	Targeted Standard	Standard Source
BOD	≤ 30 mg/L	Provincial
CBOD	≤ 25 mg/L	Both
TSS	≤ 25 mg/L	Federal
Residual Chlorine	≤ 0.02 mg/L	Both
Unionized ammonia	≤ 1.24 mg/L as *N* at 15°C ± 1°C	Provincial
Toxicity/Lethality	No acute toxicity/lethality at the point of discharge	Both

3.6.2 Effluent Quality Objectives

As stated in the WSA's *Surface Water Quality Objective – Interim Edition* (EPB 356) Section 4.1, the province of Saskatchewan had adopted objectives for the quality of the effluent that is being discharged to waterways and water bodies with aquatic life (Table 3.2 and Table 3.3).

The effluent quality and the surface water downstream from the discharge point at 17 Wing Detachment Dundurn will be compared with these objectives, where suitable data is available.

Table 3.2 – Surface water quality objective (Water Security Agency 2015)

Parameter	Objective (µg/L unless otherwise indicated)
Aluminium	5–100 (1)
Ammonia (mg/L)	See Table 3.3
Arsenic	5
Bromoxynil	5
Cadmium	0.017-0.10 (2)
Chlorine	0.5
Chlorpyrifos	0.0035
Chromium VI	1
Copper	2–4 (3)
Cyanide	5
Dicamba	10
Diclofop-methyl	6.1
Dimethoate	6.2
Glyphosate	65
Iron	300
Lead	1–7 (4)
Lindane	0.01
Mercury (inorganic)	0.026
Nickel	25–150 (5)
Oxygen, Dissolved (in mg/L)	5.5-9.5 (6)
Pentachlorophenol	0.5
Phenols (mono- and dihydric)	4
Phenoxy Herbicides (2,4-D)	4
Picloram	29
Selenium	1
Silver	0.1
Temperature	Narrative Statement (7)
Triallate	0.24
Trifluralin	0.20
Uranium	15 (8)
Zinc	30

1: Aluminium Objective: 5 µg/L at pH <6.5, Ca <4 mg/L and DOC <2 mg/L; 100 µg/L at pH ≥ 6.5, Ca ≥ 4 mg/L and DOC ≥ 2 mg/L

2: Cadmium Objective: 0.017 µg/L where hardness is 0 mg/L - 48.5 mg/L; 0.032 µg/L where hardness is 48.5–97; 0.058 where hardness is 97–194; 0.10 µg/L where hardness is >194

3: Copper Objective: 2 µg/L where hardness is 0 mg/L - 120 mg/L; 3 µg/L where hardness is 120 mg/L - 180 mg/L; 4 µg/L where hardness is >180 mg/L.

4: Lead Objective: 1 µg/L where hardness is 0 mg/L - 60 mg/L; 2 µg/L where hardness is 60 mg/L - 120 mg/L; 4 µg/L where hardness is 120 mg/L- 180 mg/L; 7 µg/L where hardness is >180 mg/L

5: Nickel Objective: 25 µg/L where hardness is 0 mg/L - 60 mg/L; 65 µg/L where hardness is 60 mg/L - 120 mg/L; 110 µg/L where hardness is 120 mg/L - 180 mg/L; 150 µg/L where hardness is >180 mg/L.

6: Dissolved Oxygen Objective: 6.0 mg/L for warm-water biota in early life stages; 5.5 mg/L for warm-water biota in other life stages; 9.5 mg/L for cold-water biota in early life stages; 6.5 mg/L for cold-water biota in other life stages.

7: Temperature Objective: Thermal additions should not alter thermal stratification or turnover dates, exceed maximum weekly average temperatures, nor exceed maximum short-term temperatures.

8: The objective was developed by the Industrial, Uranium and Hardrock Mining Unit of Saskatchewan Environment.

Table 3.3 – Surface water quality objectives for total ammonia (Recreated from CCME 1999, as seen in Water Security Agency 2015)

Temperature (^oC)	pH							
	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5
0	231	73	23.1	7.32	2.33	0.749	0.25	0.042
5	153	48.3	15.3	4.84	1.54	0.502	0.172	0.034
10	102	32.4	10.3	3.26	1.04	0.343	0.121	0.029
15	69.7	22	6.98	2.22	0.715	0.239	0.089	0.026
20	48	15.2	4.82	1.54	0.499	0.171	0.067	0.024
25	33.5	10.6	3.37	1.08	0.354	0.125	0.053	0.022
30	23.7	7.5	2.39	0.767	0.256	0.094	0.043	0.021

3.7 Relevance to Research

This chapter outlines the various regulations that are imposed by all levels of government and by the DND on CAF 17 Wing Detachment Dundurn's WWT lagoon system. The effluent quality standards along with effluent quality objectives were clearly stated and will be used as part of this risk assessment. In addition, this chapter presented several guidelines and BMPs from prominent Canadian & international organizations and researchers. These guidelines and BMPs will be essential in order to assess the state of Detachment Dundurn's WWT lagoon infrastructure along with its performance. These guidelines served as the overall regulatory framework within which the lagoon operations were evaluated and characterized. They also served to establish the metrics for the performance evaluation along with the limits of certain chemical constituents and/or indicator elements.

4.0 Site Characterization

4.1 Introduction

A site characterization is an essential step in any environmental risk assessment in order to establish the current infrastructure and/or environmental state or environmental benchmark / baseline of the specific site. A site characterization is designed to identify possible deficiencies and existing contaminations risk factors that are associated with any pre-existing or planned infrastructure projects. The site characterization described within this chapter was utilized in order to facilitate the investigation process of this research project and support any possible remediation recommendation.

In this chapter, the results of a site-specific desk study and site investigation are presented. The site of 17 Wing Detachment Dundurn's Wastewater Treatment (WWT) lagoon system was characterized by observing its topographical, meteorological, geological, and hydrogeological features. In addition, possible groundwater contamination threats, of which the WWT lagoon system is among, are described. Lastly, this chapter includes a detailed WWT lagoon design description conducted as part of this research study.

4.2 Site Location

CAF 17 Wing Detachment Dundurn, Saskatchewan is located SSE of the city of Saskatoon, approximately 30 km from the Saskatoon city limits and 50 km from the Saskatoon International Airport (YXE) along Louis Riel Trail (Highway 11). Figure 4.1 illustrates the approximate location in reference to the province of Saskatchewan and Canada as a whole. This figure in enlarged for clarity in Figure B1 of Appendix B. Figure B2 of Appendix B illustrates more specifically the location of Detachment Dundurn with regard to the cities of Saskatoon and Regina.

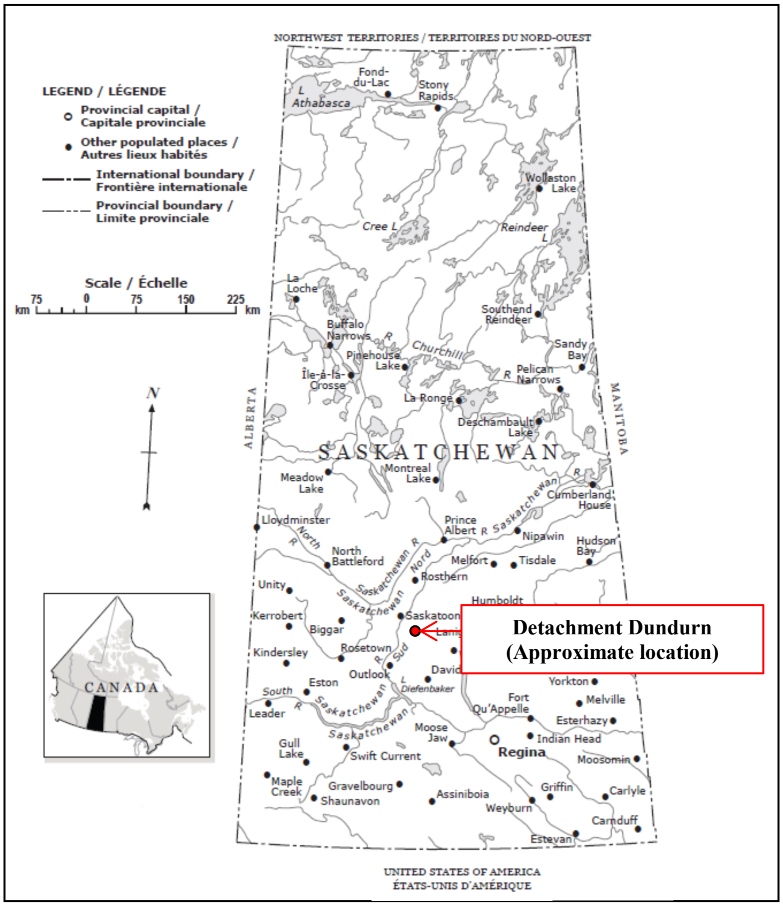

Figure 4.1 - Reference map of the province of Saskatchewan indicating the approximate location of Detachment Dundurn (Modified product from Natural Resources Canada, 2017)

4.3 Topography

The following subsections will cover various aspects of the topography of the Detachment Dundurn. The subsections will include: significant water features, vegetation profile, surface geometry, and manmade features.

4.3.1 Water Features

The main water features on or near Detachment Dundurn include:

1. Blackstrap Lake: Blackstrap Lake located approximately 12 km SE of Detachment Dundurn is an engineered lake linear in shape, 14.4 km long covering an area of 12.14 km^2. The mean depth is 5.15 m and a total water volume estimate at 61.5x10^6 m^3. The lake was constructed as a reservoir in

1967 for the Saskatoon South East Water Supply System. The lake is currently used for irrigation and recreational purposes (Google Map 2018).

2. South Saskatchewan River: The South Saskatchewan River is a major river flowing through both the provinces of Alberta and Saskatchewan and flows NW along the western border of Detachment Dundurn.

   The characteristics associated with the river near the detachment have not been investigated as it is considered outside the area of interest. However, according to Saskatchewan Watershed Authority's State of the Watershed report of 2010, the South Saskatchewan River and its associated watershed overall health are marked as stressed. This health rating indicates that the watershed has no degradation in its function or provided function but its ability to adapt to change is compromised (Saskatchewan Watershed Authority 2010). Among other condition indicators and stressors reported; 0–50% of groundwater wells were reported to exceed human-influenced maximum acceptable concentrations within the watershed. In contrast, the overall surface water quality was reported as good and municipal wastewater effluent discharge was considered as a low intensity stressor counting for less than 4% the watershed's recorded flow (Saskatchewan Watershed Authority 2010).

Several other small lakes and water bodies are present on the eastern side of the Detachment Dundurn. Marsh lands are present immediately along the western perimeter of the detachment and in the southern area along the creek. A map showing the major water features is given in Figure B3 of Appendix B.

4.3.1.1 Beaver/Brightwater Creek

One additional major water feature located at Detachment Dundurn, and of particular importance to the WWT lagoon system, is the Beaver/Brightwater Creek. This small heavily meandering creek flows through the centre of the site of interest. Despite its size near the Detachment Dundurn's WWT lagoon system, it is a major tributary to the South Saskatchewan River. The total length of the creek is reported to be 502.25 km with a watershed area of approximately 604.17 km^2 (South Saskatchewan River Watershed Stewards 2012). Approximately 74.22 km of the creek's total length is within 17 Wing Detachment Dundurn's administrative and training areas. Once out of the detachment, the creek continues to meander for an additional 11.12 km within the Beaver Creek Conservation Area prior to discharging in the South Saskatchewan River. Figure B4 of Appendix B presents a map of the Beaver/Brightwater Creek marked with the locations of significant features. South Saskatchewan River Watershed Stewards (2012) reported that the creek is inhabited by several species of fish throughout the tributary.

The flow volume of the Beaver/Brightwater Creek varies considerably seasonally and by location. Snow melt is a major contributor to annual flow resulting in high flows during spring runoff period. The Brightwater Reservoir is also responsible for the observed variations in flow rates. This reservoir located approximately 87 km upstream from Detachment Dundurn's WWT lagoon discharge point is used by the town of Hanley for the management of their water sources. Flow rates at the Detachment Dundurn's WWT lagoon have not been recorded. However, South Saskatchewan River Watershed Stewards (2012) reported that the mean annual flow rate downstream of the Brightwater Reservoir between 1967 and 1987 was 0.306 m^3/s.

A portion of approximately 7.5 km of the Beaver/Brightwater Creek has been straightened in order to accommodate for the detachment's administrative area. The work was conducted between 1928 and 1941. The exact date of construction was not discovered during the desk study. The creek is located between 15 m and 23 m away from the Western border of the WWT lagoon cells. The WWT lagoon discharges into this creek annually (mid to late summer when creek conditions are favourable) which flows NW and discharges into the South Saskatchewan River.

4.3.2 Vegetation Profile

Detachment Dundurn and the Canadian Forces Ammunition Depot (CFAD) are located in the Canadian Prairie Ecozone (Figure B5 of Appendix B). As seen in Figure B6 of Appendix B, Detachment Dundurn is surrounded by scattered pockets of forested areas with the densest zone surrounding the CFAD. This forested area extends northward. The training area, west of Detachment Dundurn's administrative area, is mostly covered in prairie grasslands of native mixed grass and fescue. The eastern part of the detachment is bordered by farm lands.

4.3.3 Surface Topography

As detailed in coloured shaded relief imagery seen in Figure B7 of Appendix B, Detachment Dundurn is located on relatively flat ground with a typical ground elevation of 520 m above main sea level (MSL). The highest elevated area is located at Blackstrap Lake, SE of the detachment with a typical elevation of 550 m above MSL. The plateau on which the detachment is located is scattered with gently rolling hills and drops gradually toward the South Saskatchewan riverbed and floodplain. The typical elevation of the floodplain is 490 m above MSL (Mapping and Charting Establishment DND, 2012).

4.3.4 Anthropogenic Features

With the noted exception of farm lands, the general area surrounding Detachment Dundurn is light in manmade features. The detachment is bordered to the east by Hwy 11, which provides the best means of accessing the detachment, and to the west by Hwy 219. There are three (3) settlements in proximity of the detachment:

1. <u>Whitecap Dakota First Nation reserve:</u> The reserve is located 12 km WNW of the detachment and has a population of 372 (last updated in 2017). Main

features of interests include: a casino and a golf course (Indigenous and Northern Affairs Canada 2017).

2. Town of Dundurn: The town of Dundurn is located 6 km SE of the detachment and has a population of 611 (last updated in 2016). A large portion of the detachment's personnel dwell in this town (Statistics Canada 2016a).

3. Village of Shields: The village of Shields is located 12 km ESE of the detachment and has a population of 288 (last updated in 2016). This resort town is situated on the western shore of Blackstrap Lake (Statistics Canada 2016b).

A map showing of the major anthropogenic features is given in Figure B8 of Appendix B.

4.4 Site Meteorology

As lagoon systems are biological treatment processes, their performance is impacted by climate conditions. Therefore, knowledge of the average climate condition is important to properly conduct an investigation into the detachment's lagoon system.

The closest weather station for which historical weather data is available is Saskatoon RCS. This weather station is located at the Saskatoon John G. Diefenbaker International Airport (YXE). Basic information related to the weather station is provided in Table 4.1.

Table 4.1 - Weather station identifying information (Government of Canada 2019)

Parameter	Value
Station Name	Saskatoon RCS
Station Operator	Environment and Climate Change Canada – Meteorological Service Canada
Latitude	52°10'25.000" N
Longitude	106°43'08.001" W
Elevation	504.10 m
Climate Identifier	4057165
World Meteorological Organization Identifier	71496
Transport Canada Identifier	POX

The averages extracted from Climate Canada are taken from 1981–2010 data. Selected climate data points may be missing from the databank due to various technical issues. No corrections were made to adjust for missing data points. The yearly average temperature is 3.3°C with the daily average temperature for the months of June to Aug being just below the 20°C and the months of November through March being below the freezing mark (0°C). The average yearly rainfall is 263.8 mm and snowfall is 76.6 mm for a total precipitation of 340.4 mm annually over an average period of 108.7 days. Monthly maximum and minimum temperature along with total precipitations are given in Figure 4.2. The yearly average degree days above 0, 5, and 18 ^{o}C are 2764, 1753, and 155.8 respectively (Government of Canada 2018).

The Saskatoon SRC weather station is approximately 58 km NNW of Detachment Dundurn. The extended distance between the detachment's WWT lagoon and the weather station is less than desirable and does not respect the guideline provided by Pearson et al. (1987). This guideline recommends that the weather station should be within 10 km. The guideline recommends that, when distance between WWT lagoon and weather station is greater than 10 km, at a minimum: maximum and minimum daily temperature, precipitation, and evaporation be taken at the WWT lagoon site. This extended distance established concerns that the weather data obtained from SRC station may not be fully representative of the true weather at the detachment. These concerns have been supported by anecdotal information provided by the detachment's personnel during the site investigation.

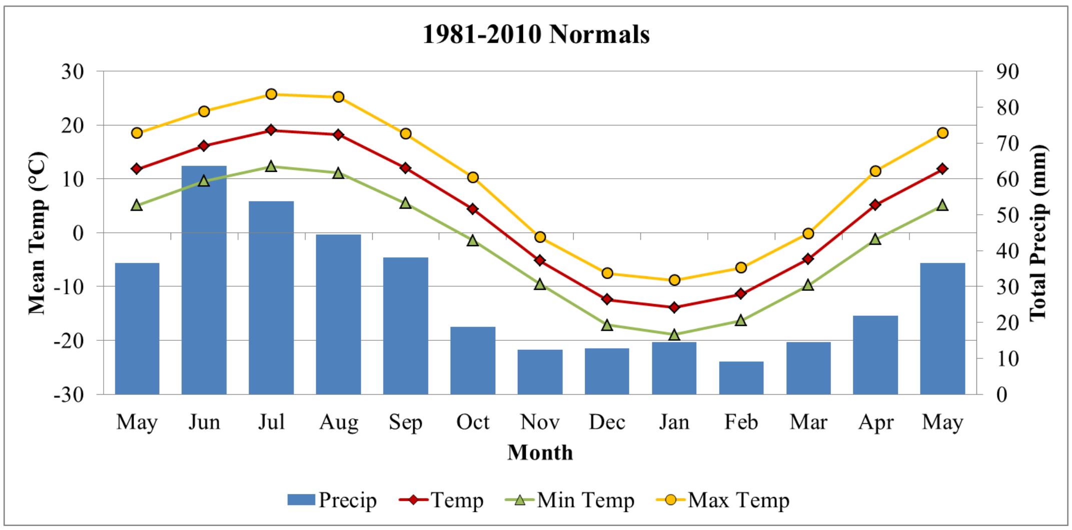

Figure 4.2 - Saskatoon SRC weather station 1981–2010 normals (Government of Canada 2018)

Range Control (RC) does operate a weather station (Vantage Pro 2 weather station provided by Davis Instruments) that is located within 2 km SSE of the WWT lagoon at the entrance to the training areas (Figure 4.3). This station is primarily used by RC for the prevention of forest/brush fires. All information is provided in real time and is not recorded and catalogued. Furthermore, RC operators reported, during the site investigation, that the readings are often not reliable. The maintenance and calibration schedule of the weather station systems and instruments is unknown and could not be provided by the RC operators during the site investigation. As a result of the unreliability of the weather station readings and the limitation imposed by the proprietary software, the modification of RC's weather station for use as part of this research project was not conducted.

Figure 4.3 - Range Control's A) Weather Station and B) Console

4.5 Site Geology

According to several geological site investigations conducted in the past and confirmed by multiple site visits by the author, the soil stratigraphy at 17 Wing Detachment Dundurn's location consists of the following: The overburden, approximately 30 m in thickness, is made up of calcareous tills upon which postglacial gravel, sand, silt, and clay have been deposited by the Battleford and Sutherland glacial formations. The bedrock, Bearpaw Formation, is composed of non-calcareous silty clays and shales. The Bearpaw Formation is a Mesozoic bentonitic sedimentary bedrock with concretionary zones (Wardrop Engineering Inc. 1996, Golder Associates 2007). These reports are in agreement with other sources obtained as part of the desk study which included publications from the Saskatchewan Industry and Resources and the South Saskatchewan River Watershed Stewards (Saskatchewan Industry and Resources - Saskatchewan Geological Survey 1999, Burke 2013).

4.5.1 Borehole Investigations

Although Monitoring Wells (MW)s have been installed around the WWT lagoon system and several other locations across the detachment, much of the BoreHole (BH) logs have been reported as lost or were otherwise not available at the time of the desk study and site investigation. However, a total of 59 BH logs were found from various projects that took place throughout the detachment as early as 1989, which includes:

1. Test drilling for production well (PW) #3 (Beckie Hydrogeologists Ltd. 1989);

2. Construction of the CFAD Headquarters (HQ) (1 Construction Engineering Unit 1994);

3. Environmental site assessment of the burn dump 1995 (MDH Engineered Solutions 2007);

4. Drilling of PW #4 (International Water Supply Ltd. 1995);

5. Construction of the detachment's gate house (1 Construction Engineering Unit 1995);

6. Soil and groundwater characterization study of the demolition site (Martel et al. 1998);

7. Environmental site assessment of the metal dump 2002 (MDH Engineered Solutions 2007); and,

8. Environmental site assessment of the Fire Fighter Training Area (FFTA) (Black et al. 2017).

In addition to the 59 BH logs mentioned above, four (4) additional BH logs were found directly on the WWT lagoon system's site. These logs were obtained from the 1988 upgrade of the 1941 septic system to the current WWT lagoon system. The logs were extracted from the drawing and can be seen in Appendix C.

The location of each of the aforementioned studies/construction sites are marked in Figure 4.4.

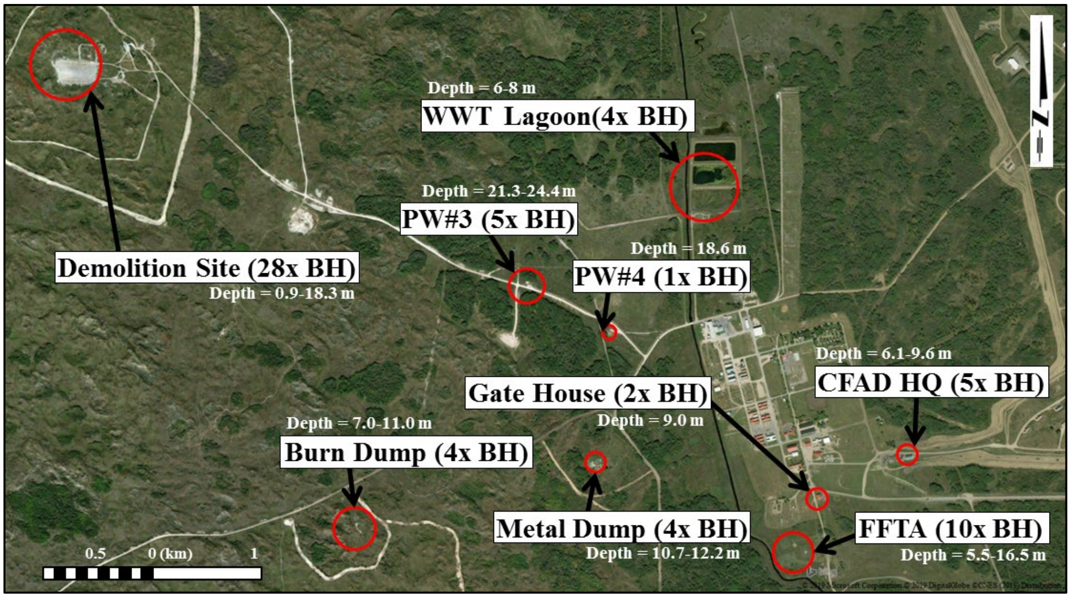

Figure 4.4 - Locations of sites for which BH logs were obtained.
(Imagery provided by Microsoft Corporation 2018)

Borehole data reveal that the first approximate 20 m depth consists of fine-grained silty sand overburden by 0.25 m to 0.5 m of top soil. The proportion of silt ranges from 1–10 % with higher silt concentrations seen with depth. The sand also contains iron with signs of environmental oxidation above the water table. Traces of clay and thin clayey sand layers are sporadically found between BH at depth between 6.25 m and 20 m. Silty clay is encountered below the 20 m depth and is expected to continue until bedrock (depth of approximately 30 m), although no BH were reported below 24.4 m (Beckie Hydrogeologists Ltd. 1989, International Water Supply Ltd. 1995, Martel et al. 1996, 2014, Wardrop Engineering Inc. 2002).

4.6 Hydrogeology

Glacial and post-glacial actions are responsible for the formation of the aquifer from which Detachment Dundurn currently draws its water. The aquifer is considered to be under direct influence of surface water (GUDI). The thickness of this unconfined aquifer varies within 10 m to 20 m. Ground water depth has been measured between 6.5 m to 9 m. Hydrogeological reports indicate that the groundwater generally flows toward the Beaver/Clearwater Creek at shallow depth and in a westerly direction at lower depth. There is a strong connection between surface (primarily Beaver/Clearwater Creek) and groundwater. The average hydraulic conductivity (K_{avg}) of the silty sand ranges from $5x10^{-5}$ to $3.9x10^{-4}$cm/s (Wardrop Engineering Inc. 1996, 2002, MEH 2001).

4.6.1 Potential Sources of Groundwater Contamination

As Detachment Dundurn is supplied from a GUDI source, every effort should be made to protect the aquifer from contamination. Previous hydrogeological reports have identified and assessed potential sources of groundwater contamination. Table 4.2 summarizes the possible contamination sources and was modified from MEH (2001) with notes taken during the preliminary site investigation. Imagery highlighting the location of the wellheads and the possible sources of contamination is presented in Figure 4.5.

The WWT lagoon system is a particular concern due to its nature, age, and its proximity to the nearest production well (approximately 900 m away). This research study will be limited to the risk posed by the WWT lagoon and will not be addressing any other possible contamination sources.

The risk of groundwater contamination is further exacerbated by the detachment's lack of a clearly defined and officialised wellhead protection programme. Several studies have assessed and even modelled individual contamination risk. However, no studies (available at the time of the desk study and site investigation) have modelled the groundwater flow at the WWT lagoon or holistically modelled the groundwater and the risks that it poses for the detachment. Such a model is necessary for the delineation of the wellhead protection areas.

Table 4.2 - Potential sources of groundwater contamination (modified from MEH, 2001)

Potential Source	Description	Concern
Metal dump	- Currently receives construction and demolition waste, primarily waste concrete and metal. - In operation for several decades and records of historical dumping practices are not available. - Anecdotal information indicates that municipal waste dumping, ash disposal, and waste burning was also practiced. - Excavation in progress for proper disposal of content. This would lead to the removal of sources but potential mobilize contaminants. - MWs have been installed.	- Site is up-gradient from water supply wells. - Uncertainty regarding past dumping practices.
Demolition site	- Excavated burn pit for controlled burns of waste material. - Site used for the disposal of explosive ammunition. - MWs have been installed.	- Site is up-gradient for water supply wells.

Potential Source	Description	Concern
Firefighting training area	- Site used for firefighting training activities. - MWs have been installed.	- Potential source of Petroleum, Oils, and Lubricants (POL) contamination. - Potential of firefighting foam contamination.
Underground and above-ground storage tanks	- Documentation regarding the removal, and associated soil remediation, of underground storage tanks isincomplete. - Some above ground fuel storage tanks have been reported by MEH (2001) to be lacking environmental safety measure associated with current standards (e.g. double-walled tanks, spill containment structures)	- Potential source of POL contamination.
CFAD area	- Large ammunition storage and maintenance area. - Considered to be a low risk by MEH (2001) assessment.	- Potential source of POL and explosive residue contamination.
Small arms range	- 100-500m firing range.	- Potential source of metal contamination.
WWT lagoon and sanitary collection system	- Lagoons systems with cell lining over 20 years old. - Annual discharge. - Sanitary collection system was installed in a common trench with the distribution system.	- Potential source of pathogens. - Effluent discharge to creek may infiltrate to groundwater supply.
Detachment's golf course	- Golf course located near the southern boundary of the detachment. - Not irrigated or fertilized at the time of MEH (2001) investigation.	- Potential source of herbicide and nutrient contamination (if maintenance practices change).
Cattle grazing area	- Land used is an open field located near wellheads.	- Potential source of pathogens.
Airfield training area	- Land used in an open field located near wellheads. - Training includes the establishment of temporary camps including the use of temporary fuelling stations, fuel cistern truck parking and use of petrol or diesel generators.	- Potential source of POL contamination.
Beaver / Clearwater Creek	- Habitat for a variety of wildlife including beavers. - Clear hydraulic connections exist between the creek and the shallow aquifer.	- Potential source of pathogens.

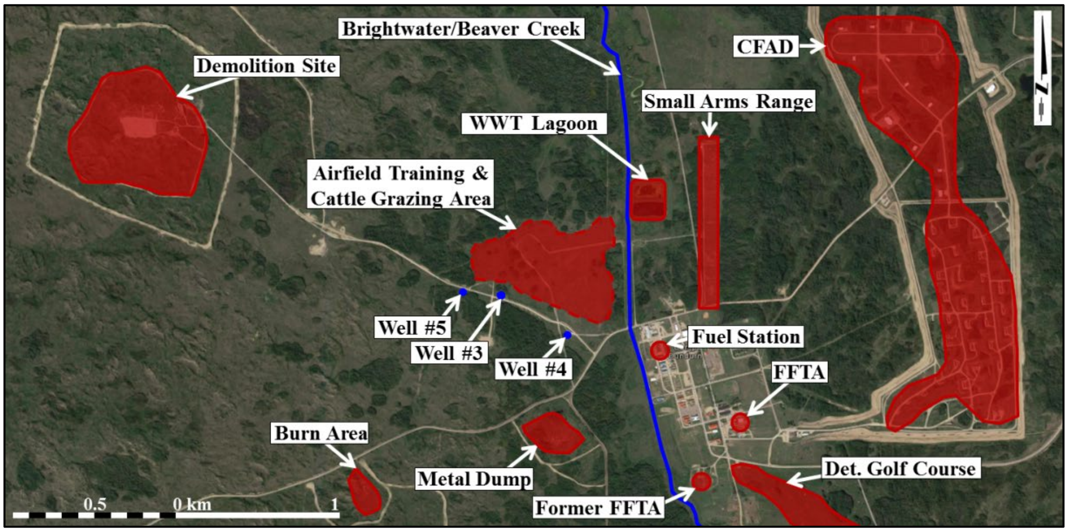

Figure 4.5 - Location of wellheads and possible sources of groundwater contamination (Imagery provided by Google Map, 2018)

4.7 WWT lagoon System Design

The current two (2) celled WWT lagoon system in operation at 17 Wing Detachment Dundurn was constructed in 1988 as an upgrade to the previous septic tank system installed in 1941. No significant upgrade retrofits, or maintenance has been reported since the 1988 upgrade by the system's operators and Real Property Operations (RP Ops) section during the site investigation. By the end of the site investigation portion of this research project, the WWT lagoon system life was 31 years old, one (1) year above the Canadian average expected useful and only seven (7) year under Saskatchewan's average with 38 years (Statistics Canada and Infrastructure Canada 2016).

The following subsections will cover the essential components of the design of the detachment's WWT lagoon. These subsections include an overview of the wastewater generation and quality, a breakdown of each of the current treatment components, the site's monitoring wells, and the derelict sludge drying bed.

4.7.1 Wastewater Generation and Quality

The following subsections will elaborate on the population serviced by detachment's WWT lagoon system along with the volumes and quality of the wastewater being generated by that population.

4.7.1.1 Serviced Population

17 Wing Detachment Dundurn has a permanent staff strength of 150–230 people and includes 27 private military quarters (single-family dwellings). A seasonal surge occurs yearly, increasing the strength size to 450 people (increase of nearly 100%). P. Machibroda Engineering Ltd. (2003) reported a population as high as approximately 1500 people in the past. This population surge is linked to an increase in military training exercises that typically take place in mid to late summer and autumn. Other governmental organizations such as the Royal Canadian Mounted Police, Corrections Canada, and local police forces are also known to make use of the facilities on the detachment, thus contributing to the high variability of the population serviced by the detachment (Royal Military College of Canada 2017). A detailed survey of the serviced population was not conducted during the time of the site investigation.

With an approximate water consumption of 1.0 m^3/capita/day, the detachment consumes over double the 2015 Canadian average of 0.447 m^3/capita/day (Statistics Canada 2015).

4.7.1.2 Wastewater Generation

Total wastewater received by the WWT lagoon system was obtained by the author during multiple site visits for the period of 2015 to 2018. The average accumulated volume of wastewater was 29908.62 m^3. The highest recorded annual accumulated volume was obtained in 2017 with 44524.37 m^3, as seen in Figure 4.6. The total variation in volume equate to 25150.64 m^3 which is higher than the total accumulated volume of 2015 with only 19373.73 m^3. This large variation is atypical of municipal wastewater treatment systems and is likely due to the variation in serviced population due to training exercises. Variation in annual system maintenance requirements may also help explain the variation in annual wastewater collection. For example, the detachment's water tower was undergoing cleaning on the 17–19 January 2018 and generated approximately 2 059.26 m^3 of wastewater. These three (3) days account for 7.49% of the total annual accumulated volume.

The data presented above was obtained from daily readings of the pumps which transfer wastewater from the septic tanks to the lagoon's Cell #1. These values reflect the wastewater captured by the WWT lagoon system and not the total wastewater generated by the detachment. These values do not account for losses do to leaks within the sanitary sewer network replaced in 2002. This network showed some sections of the 10500 m long network still using clay tiles and cast iron built, between 1934 and 1958. More importantly, the values do not account for the wastewater that is diverted by contracted latrine services and never reach the sewage network. This is a common practice when conducting military exercise in training areas where no facilities exist.

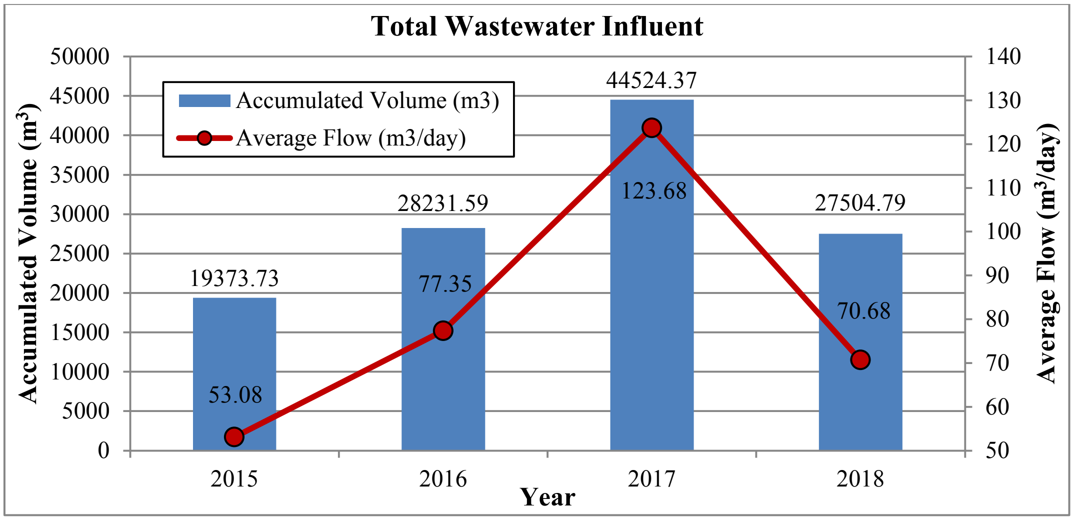

Figure 4.6 - Annual accumulated wastewater generation 2015–2018

4.7.1.3 Wastewater Quality

Table 4.3 provides the average wastewater influent quality as measured during the various sampling rounds conducted in this research study. The samples were obtained within the grit chamber (building 157) next to the inlet and prior to the filtering grate. No major industrial processes are undertaken on the detachment which would significantly alter the quality of the wastewater influent with regard to typical municipal sources.

Table 4.3 - Measured average wastewater influent quality

Influent Parameter	Average	Standard Deviation (σ)
Temperature (^oC)	10.6	2.5
pH (pH units)	7.68	0.48
DO (mg/L)	2.64	1.14
Conductivity (µS/cm)	1297	178
$CBOD_5$ (mg/L)	109	10
BOD_5 (mg/L)	120	28
TDS (mg/L)	725	66.1
TSS (mg/L)	86.6	31.2
Total Coliforms (MPN/100mL)	>2420	-
E. Coli (MPN/100mL)	>2420	-
Thermotolerant Coliforms (MPN/100mL)	>2420	-
Ammonia NH3 (mg/L)	19.9	1.8
Phosphorus (P)-Total (mg/L)	3.4	0.8
Nitrogen (N)-Total (mg/L)	33.3	8.6

4.7.2 WWT Lagoon System Breakdown

The detachment's wastewater treatment consists of a multistage treatment system based around two (2) lagoon cells. The WWT lagoon system is centred on MGRS grid 13UCT 921 465 which is located approximately 700 m north of the detachment's administrative area (as seen in Figure 4.4 and Figure 4.5). The wastewater is discharged once annually in the (mid- to late May weather permitting) aver a period of approximately 8–15 days. Appendix D marks the location of all the WWT lagoon components on satellite imagery. The following subsection will elaborate on each of the components of the WWT lagoon systems in order of treatment steps.

4.7.2.1 Treatment Train

The wastewater is pretreated in both a grit chamber and septic tanks operating in series prior to being pumped to the first lagoon cell where secondary level treatment is provided. The wastewater eventually progresses to the second lagoon cell where it is stored until discharge. No wastewater recirculation is provided at any point in the system. A schematic representation of the treatment train is depicted in Figure 4.7.

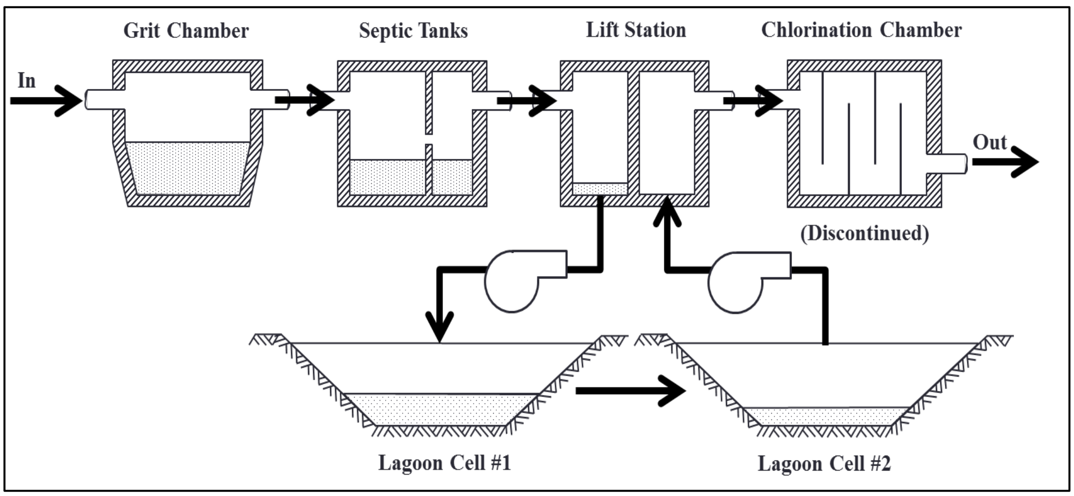

Figure 4.7 – Schematic representation of the detachment's wastewater treatment train

4.7.2.2 Grit Chamber

The grit chamber (building 157) is the first treatment step of the wastewater. The chamber's influent is supplied by a lift station (building 143) which is the collection point of the sewage network. The chamber is used to allow for the larger organic matter and foreign objects to settle out of the wastewater or to be filtered through a grate prior to its progression through the system.

The grit chamber was constructed as part of the original wastewater treatment system built in 1941. The 1941 wastewater system consisted of the grit chamber followed by the septic tanks. The wastewater would then be disinfected and discharged in the Brightwater/Beaver Creek. Excerpts from the site plan from the 1941 construction drawings are given in Figure E1 of Appendix E. The majority of the drawings detailing the design of the grit chamber were reported as lost or were otherwise unavailable at the time of the desk study and site investigation. However, some details remain and are presented in Appendix E.

The grit chamber is a 78 years old reinforced concrete tanks estimated to have a volume of approximately 44.67 m^3 with a footprint of 5.4 m x 3.5 m. The footprint was estimated by a light detection and ranging (LiDAR) survey of the above-ground section of the structure. The bottom profile of the tank was estimated based on the construction drawing and features a funnelled profile as a sludge collection system was once in operation. The grit chamber features a 1.37 m x 3.5 m angled grate made with 12.7 mm diameter bars with 25.4 mm openings between them. An approximate model was drawn in the Computer Assisted Design (CAD) software Google SketchUp Make (version 17.2.2555) and the limited information obtained in the construction drawing (see Appendix E). The result of the model is given in Figure 4.8.

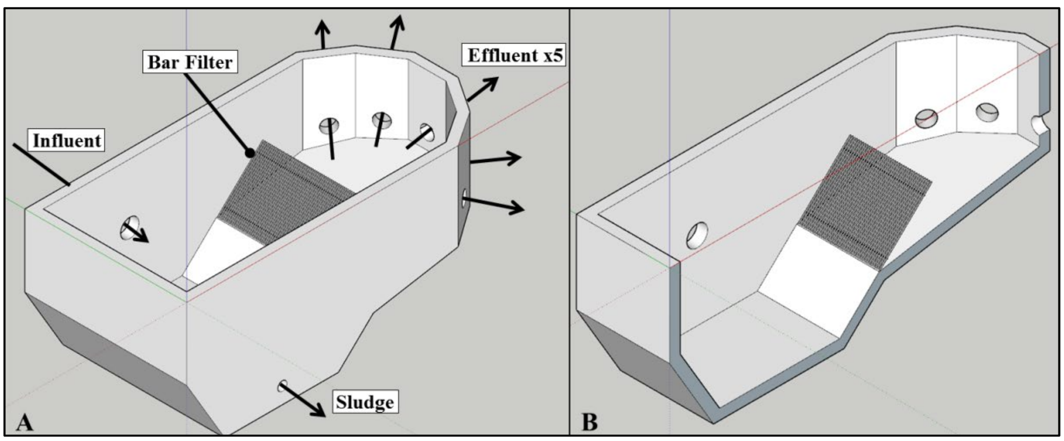

Figure 4.8 - Estimated design of the grit chamber A) Annotated isometric view B) Cross section. (Produced using SketchUp Make, Trimble Inc. 2016)

4.7.2.3 Septic Tank System

The septic tank system is the second treatment step of the wastewater. This system consists of five (5) double-celled septic tanks operating in parallel. The septic tanks are used to further clarify the wastewater by providing an environment favourable for the separation of the settleable material. The septic tanks thus assist in reducing the Biochemical Oxygen Demand (BOD) loading rate and reduce the generation of sludge in the lagoon cells. The septic tanks also support an anaerobic bacterial environment. The effluent from the septic tanks is then collected in the east chamber of the lift station (building 263) until the wastewater level is sufficient to activate the pump and transfer wastewater to the first lagoon cell. The pipework configuration does not allow for wastewater's flow path in the septic cells to be altered and are fixed in parallel configuration. Flow within the septic cells can be regulated using sluice gates.

The septic tank system is a reinforced concrete tank and was constructed as part of the original wastewater system built in 1941, at which time it was the main treatment process.

The drawing detailing the construction of the septic tank system was reported as lost or was otherwise unavailable at the time of the desk study and site investigation. However, selected, limited information remains and is given in Appendix E. As such, the exact dimensions could not be ascertained as part of this research study. The footprint of the septic tank system was estimated to be 49 m x 11.3 m and obtained from the distances between the above ground control and vents in the LiDAR survey. The volume of the total system is estimated to be 2739.2 m^3 with each primary and secondary cells estimated at 460.94 m^3 and 86.9 m^3 respectively.

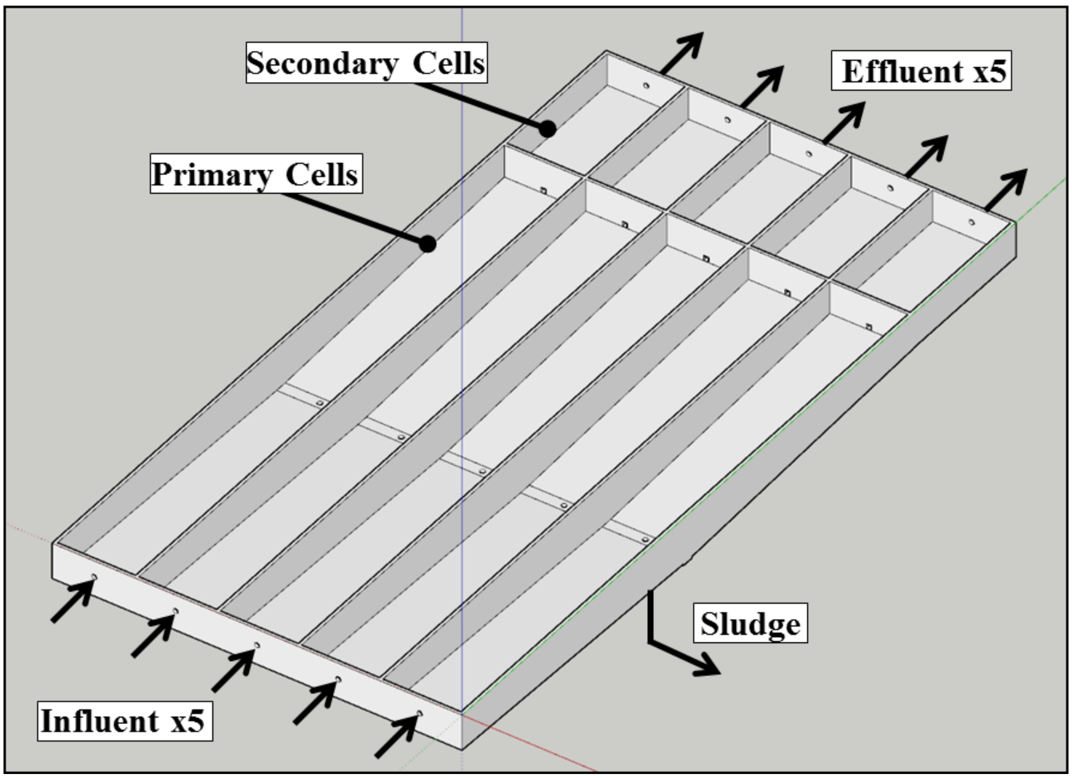

Figure 4.9 - Estimated design of the septic tank system (annotated)
(Produced using SketchUp Make, Trimble Inc. 2016)

The average retention time of the wastewater within the septic tank system was not determined during this research study. The bottoms of the tanks are funnelled since a sludge collection system was once in operation.

4.7.2.4 Lagoon Cells

The lagoon cells are the third and last treatment steps prior to effluent discharge. The two (2) cell system provides secondary level treatment and storage of the wastewater until the next discharge period. The cells both have a footprint that is right-angled trapezoidal in shape with the overall dimensions as seen in Figure 4.10. The basic properties of the WWT lagoon cells are given in Table 4.5. The maximum intended water column height for Cell #1 and Cell #2 are 1.5 m and 2.1 m respectively. These values are within the typical range of 0.9-2.5 m for facultative lagoons found in literature (USEPA 1983, 2011, Federation of Canadian Municipalities and National Research Council 2004) and are the maximum recommended by the Water Security Agency (2012). The increased depth in Cell #2 is consistent with its primary role as a storage cell and the elevation difference allows for the transfer of wastewater from Cell #1 to Cell #2 using only gravity. Both the max surface areas and volumes correspond to the maximum operating wastewater quantity. The minimum surface areas refer to the cells' floor surface (i.e. surface area whilst empty). All the values were calculated based on the original construction drawing which are given in Figure E2 of Appendix E. Calculations were verified by producing a CAD drawing of the lagoon cells in the Google SketchUp Make (version 17.2.2555) software.

Table 4.4 – Basic properties of the WWT lagoon's cells

Cell	WC* (m)	Surface Area				Volume (m^3)	Slenderness Ratio	Floor Elev. (masl)
		Max		Min				
		(m^2)	(ha)	(m^2)	(ha)			
1	1.5	21 896.20	2.19	18 314.74	1.83	30 212.69	2.164	516.200
2	2.1	22 120.85	2.21	17 077.27	1.71	41 059.12	1.950	515.600

*WC = Water column height

The volume of each cell has proven to be adequate to accommodate the past and current wastewater volumes generated by the detachment. No emergency discharges were reported by the operators and RP Ops during the site investigation. In addition, Cell #2 exceeds the minimum recommended 180 days storage volume of the Sewage Works Design Standards (Water Security Agency 2012). The slenderness (i.e. length-to-width) ratio of Cell #1 and Cell #2 are 2.164:1 and 1.950:1 respectively. These ratios are smaller than the 3:1 recommended by Heinke et al. (1991)

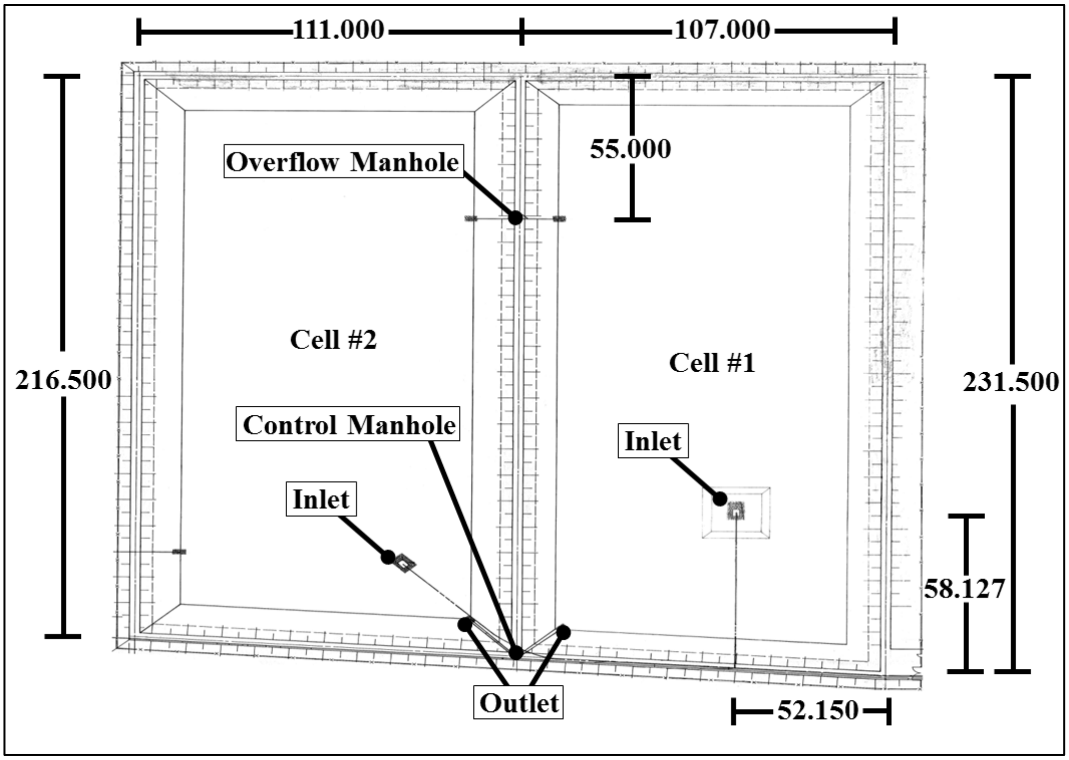

Figure 4.10 - Overall lagoon dimensions and inlet outlet positions
(dimensions are in meters and taken from centre of berms)
(Modified from Bullée Consulting Ltd. 1988)

4.7.2.4.1 Layout and Orientation

The WWT lagoon system is located within the training area 6, approximately 700 m north of the detachment's administrative area with the closest lagoon cells (Cell #1) an additional 300 m away (Mapping and Charting Establisment DND 2012). This is above the recommendation given by the Water Security Agency (2012). As seen in Figure D1 of Appendix D, the nearest infrastructure is the 900 m small arms range located approximately 300 m east of the lagoon cells. Suitable year-round access is available to the site via a two (2) lane wide compacted gravel road that connects the WWT lagoon's cells and remainder of the infrastructure to Strathcona Trail (one of the main supply roads) in the training areas.

As the prevailing wind blows SW and the second prevailing wind blows SE, the WWT lagoon system is not optimally positioned with regard to wind direction. However, no complaints of objectionable odours have been reported to the WWT lagoon operators or to RP Ops. Therefore, public acceptance of the WWT lagoon system with regard to its location in relation to the detachment's administrative area does not seem to be an issue.

All major components of the WWT lagoon system are nearly perfectly oriented E-W. This includes the grit chamber, septic tank, chlorination chamber, and discharge point which are in line with each other as seen in Figure D2 of Appendix D. An exception is the lift station and sludge pumping station which are directly north of the other components.

4.7.2.4.2 Pipework

The cells operate in series which is in compliance with the minimum cell requirements stated by the provincial regulations (Government of Saskatchewan 2015) and recommended by Heinke et al. (1991). However, the pipework support the reconfiguration of the lagoons as needed. Wastewater flow can be altered to change the sequence of the cells and could even allow for parallel operations if desired, which also complies with the Water Security Agency (2012). The added control on the wastewater flow allows for greater operational flexibility and facilitates maintenance tasks or possible future expansions. Details regarding the pipework of the WWT lagoon system can be seen in Figures E2-E3, E5-E7, and E11-E18 of Appendix E.

4.7.2.4.3 Berms

The wastewater is contained in the cells by a series of five (5) earthen berms. A central berm separates the two (2) cells. All berms are 3 m tall with a top elevation of 518.600 masl and have 4:1 slopes on both the internal and external slopes. These slopes are consistent with the recommendation of Heinke et al. (1991) to remain between 6:1 and 2:1 and the more stringent 6:1 and 3:1 recommendation of the Water Security Agency (2012). The 4:1 slopes allow for both the control of vegetation and ease of maintenance.

The top of the berms are 3 m wide, which complies with guidelines for maintenance vehicle access. These berms are built from compacted native fill, which consists of fine-grained silty sand. The berms are designed with a freeboard of 0.9 m. This value was measured as the difference between the max operational height of the wastewater and the top of the berms. However, as the top of the lining material is lower than the top of the berm by 0.2 m, the effective freeboard is only 0.7 m to accommodate for wind-driven wave and ice formation. Both values are below the 1 m minimum recommended by the Water Security Agency (2012). It should be noted that this only applies when the wastewater is at its maximum operating height. As the WWT lagoon system is operating with controlled discharge, the wastewater levels fluctuate and may only reach its maximum operational height for a limited time before discharge.

No special measures have been designed for the protection from wave or wind erosion on the berms with the exception of seeding. The top of the berms and the outside slopes are covered with 0.15 m and 0.2 m of seeded topsoil respectively. Details regarding the berms can be seen in Figures E2, E5, and E6 of Appendix E.

4.7.2.4.4 Lining

As seen in the construction drawings (Figure E5 and E6 of Appendix E), the cells are lined using a High-Density Polyethylene (HDPE) liner superimposed by 0.6 m of imported compacted clay till on the berms. At the top of the berms the clay till is reduced to 0.45 m and covered with 0.15 m of seeded topsoil. The HDPE liner on the beds of the cells is covered with 0.15 m of native sand. Details regarding the HDPE lining material's specifications including its thickness or manufacturer have been lost or were otherwise not available at the time of the desk study and site investigation. Additionally, no details were provided on the seams or the minimum expected seepage rate. The HDPE liner is anchored at the top of the outside berms using a trench cut and backfill method. The HDPE liner is continuous across the top of the central berm. The liner system terminates all around each cell at an elevation of 518.400 masl. The specifications on this anchoring and sealing method used at the top of the berms, the inlet pads, and around pipes can be found in Figure E19 of Appendix E.

4.7.2.4.5 Inlet, Outlet, and Overflow

As seen in Figure 4.10 and in more details in Figure E2 of Appendix E, the inlet of Cell #1 is positioned 58.127 m in from the western berm and 52.150 in from the southern berm. This indicated that the inlet is positioned approximately ¼ of the way in, along the longest length and just off centre along the shortest. The outlet of Cell #1 is positioned in the north-western corner of the cell near the control manhole. Due to the proximity of the inlet and outlet to each other and their position with respect to the cell's geometry, the design of the flow within Cell #1 does not appear to be optimized and seems vulnerable to short circuiting.

The inlet and outlet of Cell #2 are considerably close to each other near the south-western corner of the cell. As the WWT lagoon operates with controlled discharge and Cell #2 is primarily used as a storage cell, the configuration of the inlet and outlet is not as important as those of Cell #1.

An overflow manhole has been installed 55 m from the eastern berm within the central berm to prevent Cell #1 overtopping. The overflow from Cell #1 is discharged to Cell #2. No emergency overflow which would result in the uncontrolled discharge of the wastewater into the receiving creek exists. This measure is in line with the design guidelines provided by the Water Security Agency (2012). Pipework has been installed near the north-western corner of Cell #2 to facilitate future expansion.

4.7.2.4.6 Fence perimeter

A suitable perimeter is maintained using a 2 m tall chain linked fence with a three (3) barbwire strand cap. The perimeter fence is positioned between 5 m and 10 m away from the centreline of the top of the berms on the outside slopes. This fence helps prevent the intrusion of unwanted wildlife and potential vandalizers. Locked access points are present for both vehicles and on-foot operators. Warning signs are positions at regular intervals along the outside of the perimeter fence to inform personnel of the nature of the facility and the risks to intruders. The construction drawings of the perimeter fence were left out of the excerpts of Appendix E.

4.7.2.5 Chlorination Chamber

Prior to discharge, the wastewater once underwent chlorination as a post-treatment disinfection. The original 1941 chlorination system used a drip injection into the inlet of a below ground contact chamber. In 1960, the drip-injection system was replaced with Cl_2 gas for disinfection. The 1960 construction drawings of the Cl_2 gas disinfection system was omitted in the excerpts of Appendix E. The exact date of the decommissioning of the disinfection system was not ascertained during the desk study and site investigation. However, it is assumed that the decommissioning occurred sometime after 1992 as a prefabricated building (building 264) was added on site for chlorine storage.

Despite the decommissioning of the disinfection system, the chlorination chamber remains in the wastewater treatment flow path. During discharge, the wastewater is pumped from Cell #2 into the western chamber of the lift station (building 263) and flows into the contact chamber prior to discharging into the Brightwater/Beaver Creek. The discharge point is located directly west of the contact chamber at a distance of approximately 26 m (As seen in Figure D2 of Appendix D).

The reinforced concrete contact chamber has a footprint of 8.03 m x 4.06 m and is buried below a small structure (building 158). The chamber is designed to hold a volume of 40.36 m^3 of wastewater effluent. The chamber houses four (4) baffles to regulate the flow of wastewater effluent. Figures E21 and E22 of Appendix E provide all the details regarding the specifications of the contact chamber.

4.7.3 Monitoring Wells

A series of nine (9) monitoring wells (MW)s have been installed around the perimeter of the WWT lagoon system. The MWs have been re-labelled with the identification code SL#1 thought SL#9. Older reports utilized the identification code “Lagoon TH 1 through TH9". As seen in the image given in Figure F1 of Appendix F, three (3) MWs have been installed in the vicinity of the septic tanks and grit chamber (SL#1–3) and six (6) have been installed on the perimeter of the lagoon cells (SL#4–9).

The exact date of the MWs installation is unknown since the drilling and installation logs have been reported to be lost or were otherwise not available at the time of the desk study and site investigation. No current detachment personnel were capable of providing such information. However, the MW must have been installed prior to 2002 since sampling reports were obtained dating back to that year.

Based on the previous sampling reports, the wells are between 4.03 m and 5.90 m deep and have a diameter of approximately 63 mm. Additional information regarding the MWs is given in Table F1 of Appendix F.

4.7.4 Sludge Drying Beds

As seen in Figures E1 and E23 of Appendix E, the original 1941 wastewater treatment system included a sludge separation and disposal system. The sludge for both the grit chamber (building #157) and the septic tanks were extracted using a sludge pump housed in building #159. The sludge was pumped to three (3) unlined drying beds (referred to as: disposal ditches in the construction drawing) located approximately 100 m north from building #159 and fanning out from the discharge point. As can be seen in Figure 4.11 and Figure 4.12 remains of the drying beds can still be seen between the septic tank system and Cell #1. Detailed construction drawing of the sludge drying beds and the sludge collection system were reported to be lost or were otherwise not available at the time of the desk study and site investigation.

The use of the sludge collection system and drying bed has been disused. Records of the volume of sludge that was disposed of in the drying beds, what decommissioning process was undertaken (if any), and when the drying beds have stopped being used were not available. Contamination of the ground surrounding the drying beds has been reported in the borehole logs of the 1988 upgrade. As seen in Appendix C, discolouration due to the migration of waste from the sludge drying beds has been reported in all boreholes at a depth ranging from 3.0 m to 3.8 m below grade. The discolouration was seen for the remainder of the boreholes' depths. The current state of the waste has not been determined as part of this research study.

P. Machibroda Engineering Ltd (2003) reported that an estimated of 300-500 m^3 of sludge is generated in the grit chamber and septic tank annually. In addition, the report stated that testing of Cell #1 and annual inspection of Cell #2 revealed no significant accumulation of sludge.

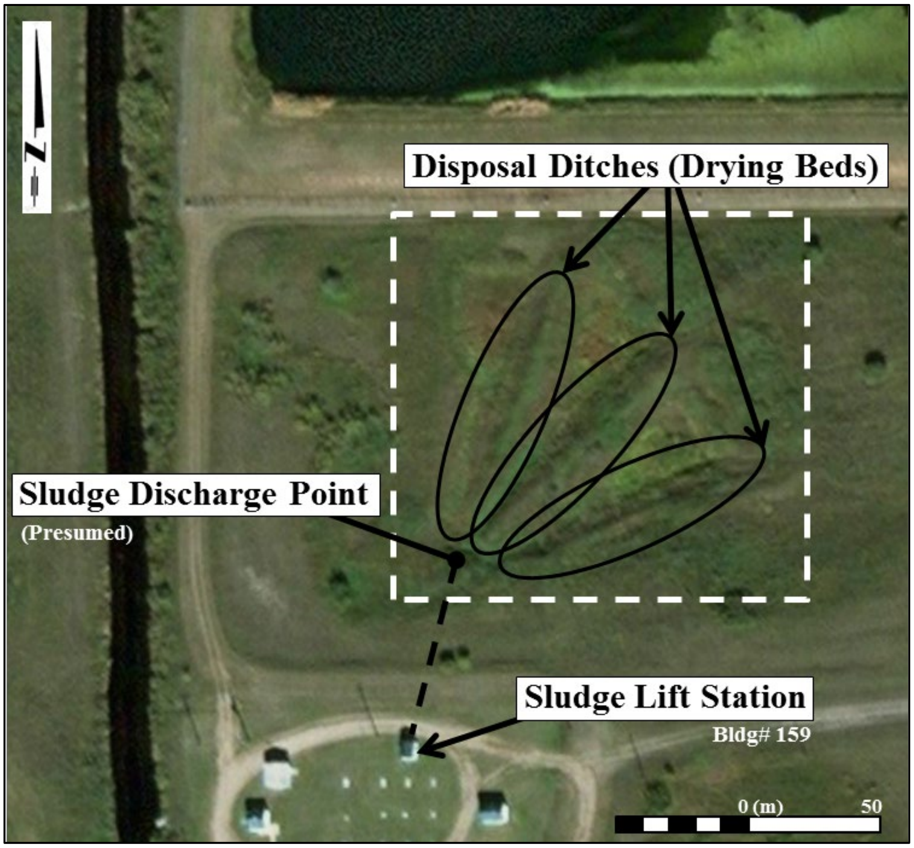

Figure 4.11 - Annotated sludge drying beds
(Imagery provided by Microsoft Corporation 2018)

Figure 4.12- Site condition of derelict sludge drying beds

4.8 Relevance to Research

This chapter characterized 17 Wing Detachment Dundurn's WWT lagoon site, its topography, geology, meteorology, and detailed each of the major components of the WWT lagoon system. Historical practices and infrastructure on the site of interest was also described. Proper understanding of the current system, its surroundings, and each of its components is essential to distinguish and eventually assess its performance and the environmental risk associated with its operation. An incomplete picture of the site could result in the omission of possible defects or contributing factures and thus underestimate the environmental risk of the WWT lagoon.

5.0 WWT Lagoon Condition Assessment and Management Review

5.1 Introduction

In order to adequately assess the environmental risk associated with a Wastewater Treatment (WWT) lagoon system, the operational procedures developed and used for its operation need to be reviewed. Any properly designed system may fail to provide adequate treatment if operated incorrectly and not properly maintained; this may adversely affect the operations of the entire detachment in addition to being a risk to the operators' health and safety.

In this chapter, the results from the author's assessment on the operational practices, data collection and record-keeping practices are presented. The information was gathered using a series of semi-structured interviews. The initial interviewing process was carried out using a questionnaire developed by the RMC Green Team for assessing WWT Lagoon systems. A copy of the questionnaire is available in Appendix G. Follow-on questions and interviews were carried out as needed. All possible stakeholders were interviewed. Stakeholders included: the system operators, the Real Property Operations (RP Ops) Section Commander and Requirements Officer, the detachment's Environmental Officer (B Env O), and local representatives of Defence Construction Canada (DCC).

Any recommendation provided within this chapter has the objective of providing the following benefits:

1. Management: Provide operators and the management staff with near-real time measurements of the WWT lagoon system in order to track system performance.

2. Troubleshooting: Allow for management and operators to fully understand the complex mechanism that determines the treatment's effectiveness. This knowledge will allow for troubleshooting to take place in a timely fashion should the effluent not meet the quality standards dictated by the regulatory agencies. In its current form, the operation of the WWT lagoon system does not permit the operators to understand the exact mechanisms that dictate treatment and thus, must rely on experience and best judgement when issues arise.

3. Improve future performance: Provide the ability to track long-term trends that are necessary for the proper planning of future improvement or modification. The trends will allow for the selection of the most appropriate improvement in the future based on data and facts as opposed to assumptions.

4. Environmental stewardship: Improve the environmental stewardship of the detachment and permit the detachment to lower its impact on the environment based on the environmental frameworks detailed in Chapter 3.

5. Real-property stewardship: Provide, in the short term, a detailed assessment of the current condition of the WWT lagoon's infrastructure (with the exception on the electrical and mechanical component along with the appurtenances). In the long term, the data collected will allow one to track the maintenance requirements and deterioration of the WWT lagoon and thus permit the RP Ops staff to optimize the maintenance plan and ensure needed maintenance is undertaken in a timely fashion.

6. Minimize operators' workload: Minimize the net workload on the operators whilst still meeting modern expectations of a WWT lagoon system.

5.2 WWT Lagoon Operation

The following subsections will elaborate on the procedures followed by the operators and other personnel with regard to the handling of wastewater and the detachment WWT lagoon system's infrastructure. Several recommendations are provided with regard to the procedures mentioned below.

5.2.1 Procedures

5.2.1.1 Wastewater Flow Control

Throughout the year, the wastewater is left to accumulate in Cell #1. The valves, connecting Cell #1 to Cell #2 are kept closed. Once annually (after spring break up), the wastewater is discharged into the Brightwater/Beaver Creek from Cell #2 through the discharge point until Cell #2 is completely drained. The time required to complete the discharge normally varies between 8 and 15 days. Discharge is discontinued during weekend days and statutory holidays as third party laboratories are not available to receive effluent samples and samples must be submitted within 24h.

Once Cell #2 is completely drained, the valve connecting the lift station (building 236) to Cell #2 located in the control manhole is closed. The valve connecting the two cells located in the overflow manhole is opened and the wastewater is allowed to transfer from Cell #1 to Cell #2. Approximately 10 days are required for the wastewater to reach equilibrium. Once equilibrium has been achieved, the valve connecting the two cells is closed and the discharge process has been completed. All valve controls are carried out manually. The overflow pipe remains open throughout the year to transfer the wastewater from Cell #1 to Cell #2 should Cell #1 overflow.

This modus operandi by the base is likely part of the reason that a high level of biological activity has been seen in Cell #2 during the course of the site investigation for this research project. During the transfer of wastewater, short circuiting is expected to occur in Cell #1; where new influent has a preferential path directly to Cell #2. Since a mixture of both old and new wastewater from Cell #1 is transferred into Cell #2, Cell #2 does not only acts as a storage cell but provide some level of treatment for the wastewater necessary to meet effluent quality standards. This level of treatment is expected to be greater than what is typically associated with tertiary treatment also known as polishing.

A tracer study is recommended to ascertain the effects of the short circuiting and assess the possibility of installing a retrofitted baffling system to reduce or eliminate short circuiting. Baffling may help to reduce the fraction of new influent reaching Cell #2, and may result in improved overall effluent quality.

5.2.1.2 Vegetation Growth and Animal Control

The vegetation on the berms is trimmed by the detachment's Roads & Ground section upon request by the WWT lagoon operators on an as needed basis. The WWT lagoon operators are diligent in inspecting the lagoon premises and submitting the work orders.

Several small patches of reeds grow around the cells at the water lines. At the time of the site investigation, Roads & Ground were unable to trim the vegetation along the inside slope of the cells' berms due to concerns with the load-bearing capacity of the berms and the associated risk to the machinery and the operator safety. It is recommended that the Roads & Ground section be equipped with a boom mower attachment to augment their current vegetation trimming capabilities. Such a tool would allow for the trimming of the inside slopes of the lagoon cells without endangering the heavy equipment or its operators.

Seasonal blooms of duckweed occur in both of the cells and often cover the majority of the cells surface area. Although duckweed may be advantageous under certain conditions, their presence in the detachment's WWT lagoon cells is not managed and hinders the performance of the treatment. Unless designed for, the presence of duckweed in WWT lagoon cells lowers Dissolved Oxygen (DO) levels and inhibits algal growth. In addition duckweed is effective at absorbing nitrogen, phosphorous, and toxins without processing them, and will eventually release them back into the wastewater once it dies. The extent of the duckweed problem should be investigated and harvesting or control measures should be put in place (USEPA 2011).

The fenced perimeter present on-site is effective in preventing the intrusion of larger animals in the WWT lagoon cells. Ducks, geese, and other birds regularly congregate at the lagoon cells. However, their presence does not impact the operational performance of the WWT lagoon System. Rodent intrusions have been reported in the past. At the time of the field investigation, at least one muskrat was spotted within the fenced perimeter. Muskrat and rodents in general are known to cause significant damage to infrastructure. Evidences of muskrat damage to the northern berm were seen during the field investigation. After discharge is complete, it is recommended that the liner be inspected for damage and repaired if needed. The liner cover material should then be replaced, the perimeter fence should be inspected for gaps, and a finer metal mesh should be installed on the perimeter fence where the fence meets the ground to deter further intrusions.

5.2.1.3 Desludging

There have been reports of desludging work conducted in the grit chamber (building 157), the septic tanks, and both cells in the past. However, desludging has not been completed since at least 2014. The date of the last desludging work was not known to the operators at the time of the interview process. Visual inspection of the accumulation on sludge in Cell #2 is conducted every year after discharge is complete. Operators have not seen any signs that indicate that desludging is required since the beginning of their employment at the base in 2014. Once desludging is required, the work will be contracted out by the RP Ops section.

5.2.2 Automated Systems

Little automation exists for both the operation and monitoring of the WWT lagoon system. The only automated systems are the pump controls located in the lift station (building 263) for both the influent pumps and effluent pumps. The pumps are set with staggered starts and stops based on the water levels in their respective collection chambers. An automated high water level alarm system is also associated with the pumps.

Since the mechanical components of the WWT lagoon system are minimal, the addition of a Supervisory Control and Data Acquisition (SCADA) system for the purpose of controlling the functions of the WWT lagoon system should be simple and not require major changes.

5.2.3 Additives

Little additives are used in the operation of the WWT lagoon system. Approximately 0.454 kg (1 lbs) of Acti-Zyme pellets is added to the sewage network at the detachment's sewage lift station (building 143) once a week (on Saturdays). Acti-Zyme is produced by Acti-Zyme Products Ltd. and consists of an enzymes blend in pellet form intended to assist in the degradation of solid organic matter, thereby reducing the generation of sludge and promoting good flow in the pipework.

Liquid chlorine and chlorine gas was once utilized to disinfect the effluent at discharge. However, their use has since been discontinued and only the contact chamber (building 158) remains.

5.3 Current Data Collection and Management

The following subsections will elaborate on the data being generated to track the performance of the WWT lagoon system and the procedures followed by the operators to collect, store, and process the data. These procedures are verified for regulatory compliance and recommendations are provided.

5.3.1 Data Collection

As part of the regular operations of the detachment's WWT lagoon system, data is generated and collected on a daily basis. In addition, sampling is conducted during the discharge period.

5.3.1.1 Daily Data Collection

On a daily basis, two sets of readings are taken from the WWT lagoon system. Readings are obtained from a sample obtained in the septic tank system and from the lift station pumps. The following subsections will elaborate on each of these elements in turn.

5.3.1.1.1 pH & Temperature Readings

As part of the morning routine, pH and temperature readings are taken from the septic tank system. The readings are taken from one (1) grab sample obtained in the secondary cell of the central septic tank in the system. As the grab sample is taken from one cell with a volume of 3.17% that of the whole septic tank system, the operators assume that it is representative of the whole, despite modification that could potentially alter the values. To facilitate sampling, the concrete lid of the septic cell has been removed and an insulated, operator-made, plywood box and lid has been installed. During the cold weather periods, a small submersible pump is installed in order to agitate the wastewater and prevent it from freezing (Figure 5.1).

The grab sample is obtained by an operator-made bailer and brought to the chlorination chamber building (building 158) approximately 29 m away where running water access is available. The readings are taken by hand using a hand-held sensION+ PH1 Portable meter and probe (product # LPV2550.97.0002) produced by Hach. The pH Combination Gel-filled probe has an accuracy of 0.02 pH units and also reads temperature within the range of 0 to 80^{o}C (Hach 2016). Readings are taken by hand and kept on log sheets within the chlorination chamber building (building 158). An example of the logging sheets can be seen in Appendix H.

Despite the presence of insulation in the fabricated wooden lid, it is expected that the cover does not insulate to the same degree as the access hatches for the other septic tanks. It is therefore expected that the temperature variation of the septic cell, including the wastewater contained within, would be greater than in the remainder of the septic cells. The grab sample taken from the accessible septic cell would therefore not be fully representative of the whole septic tank system.

Figure 5.1 – Septic tank sampling point with a submersible pump in operation

The logging sheets for the pH and temperature readings as seen in Appendix H seem to indicate that daily pH and temperature reading where once obtained for both the lagoon's Cell #1 and Cell #2 along with the effluent discharge (when discharging). However, from interviews with the WWT lagoon operators and an inspection of historical logging sheet, indicate that this sampling practice ended several years ago. The exact date for which the daily sampling of Cell #1 and Cell #2 stopped was not ascertained during the author's desk study and site investigation.

5.3.1.1.2 Flow Readings

In addition to the daily sampling of the septic tank system, daily readings are taken from the control panels of the two (2) pumps in the WWT lagoon lift station (building 263). The volume of wastewater that is pumped to Cell #1 is obtained by reading the volume meter at each pump. The meters display the total pumped volume since the meter was re-initialized. The meter reading from the previous day must be subtracted to obtain the wastewater volume pumped in the previous 24h. The meters display volumes in x1000 gallons. The runtime of each pump is also displayed and recorded daily (in hours). The readings from each pump must be summed up to obtain the total volume of wastewater that was sent to the Cell #1 along with the total runtime.

In a similar fashion to the pH and temperature readings of the septic tanks, all readings obtained from the pumps are taken by hand and kept on log sheets within the WWT lagoon lift station (building 263). The calculations are also done manually, which introduces additional possibilities for blunders. An example of the logging sheets can be seen in Appendix H.

5.3.1.2 Effluent Discharge Sampling

The following data are collected annually as part of the WWT lagoon discharge. Discharge durations are variable but will last on average between 8 and 15 days. All grab samples are taken manually and sent to an accredited third party laboratory for analysis in the city of Saskatoon. Samples are analysed for a large array of parameters. A total of 88 parameters, listed in Table 5.1, are tested as part of the effluent discharge process. Recommendations regarding the testing parameters are given in Section 5.3.3.4. Figure 5.2 depicts the relative locations of the sampling points.

1. Sampling prior to discharge: Before discharging, water samples are taken from the following seven (7) points: Creek north and south boundary, Creek north and south of lagoon, Septic cell, and both lagoon cells;

2. Daily during discharge: Lagoon effluent is sampled daily at the discharge point;

3. Mid-discharge: At midway thought discharge, water samples are taken from the creek at the northern and south boundary; and,

4. Post discharge: Once discharge has been completed, the final samples are taken from the creek at the north and south boundary.

The laboratory results and reports are obtained via e-mail directly from the third party laboratory. The results are given in both portable document format (.pdf) and in Microsoft Excel spreadsheet format (.xls or .xlsx).

Table 5.1 – Tested parameters during wastewater discharge

Parameters		
Conductivity	pH	Volatile Suspended Solids
Fixed Suspended Solids	Total Suspended Solids	Total Dissolved Solids
Alkalinity, Total (as CaCO3)	Ammonia, Total (as N)	Bicarbonate (HCO3)
Carbonate (CO3)	Chloride (Cl)	Hardness (as CaCO3)
Hydroxide (OH)	Nitrate+Nitrite-N	Nitrate-N
Nitrite-N	Total Kjeldahl Nitrogen	Total Nitrogen
Orthophosphate-Dissolved (as P)	Phosphorus (P)-Total	TDS
Cation – Anion Balance	Dissolved Organic Carbon	Escherichia Coli
Faecal Coliforms	Total Coliforms	Aluminium (Al)-Total
Antimony (Sb)-Total	Arsenic (As)-Total	Barium (Ba)-Total
Beryllium (Be)-Total	Bismuth (Bi)-Total	Boron (B)-Total
Cadmium (Cd)-Total	Calcium (Ca)-Total	Caesium (Cs)-Total
Chromium (Cr)-Total	Cobalt (Co)-Total	Copper (Cu)-Total
Iron (Fe)-Total	Lead (Pb)-Total	Lithium (Li)-Total
Magnesium (Mg)-Total	Manganese (Mn)-Total	Mercury (Hg)-Total

Parameters		
Molybdenum (Mo)-Total	Nickel (Ni)-Total	Phosphorus (P)-Total
Potassium (K)-Total	Rubidium (Rb)-Total	Selenium (Se)-Total
Silicone (Si)-Total	Silver (Ag)-Total	Sodium (Na)-Total
Strontium (Sr)-Total	Sulphur (S)-Total	Tellurium (Te)-Total
Thallium (Tl)-Total	Thorium (Th)-Total	Tin (Sn)-Total
Titanium (Ti)-Total	Tungsten (W)-Total	Uranium (U)-Total
Vanadium (V)-Total	Zinc (Zn)-Total	Zirconium (Zr)-Total
Biochemical Oxygen Demand	Oil and Grease	
Phenols (4AAP)	Benzene	Ethylbenzene
Toluene	O-xylene	M+p-Xylene
Xylenes	F1(C6-C10)	F1-BTEX
4-Bromofluorobenzene	3,4-Dichlorotoluene	1,4-Difluorobenzene
F2 (C10-C16)	TEH (C11-C22)	F3 (C16-C34)
TEH (C23-C60)	F4 (C34-C50)	Total Hydrocarbons (C6-C50)
2-Bromobenzotrifluoride		

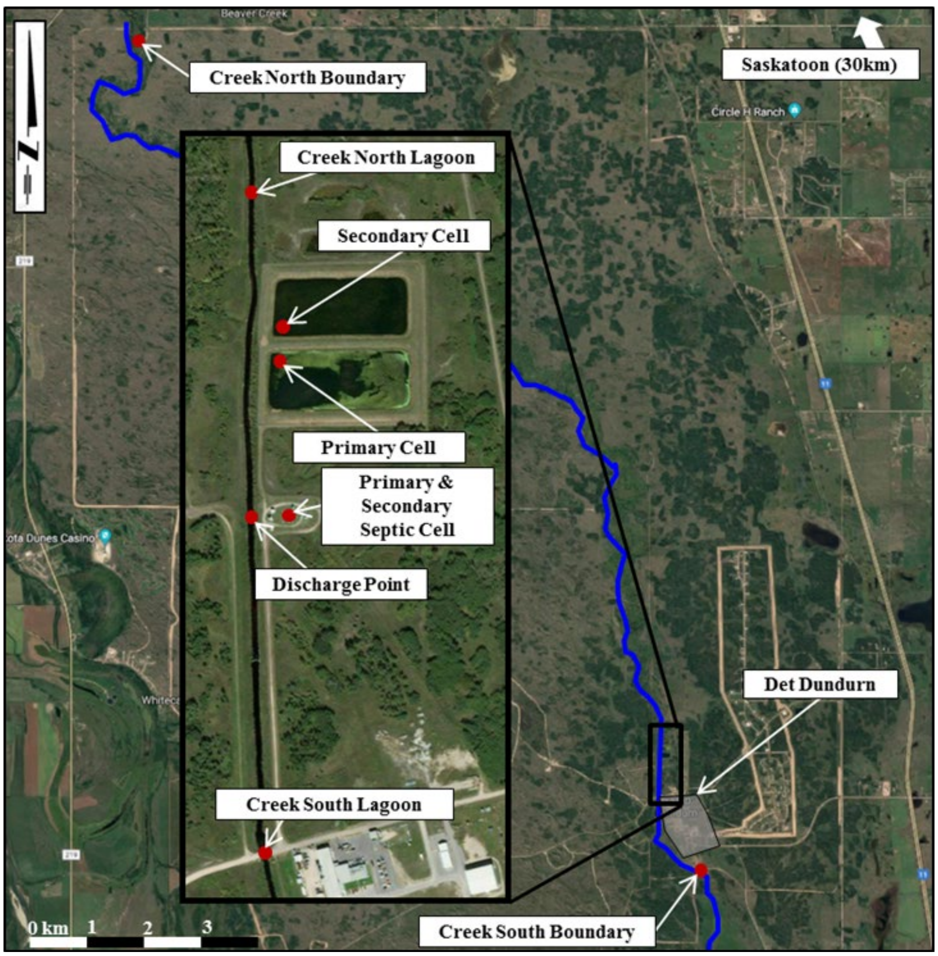

Figure 5.2 – Map of relative sampling location conducted as part of the WWT lagoon discharge procedure (Imagery provided by Google Map 2018, Microsoft Corporation (2018)

5.3.1.3 MW sampling

As detailed in Appendix F, a series of nine (9) Monitoring Wells (MW)s have been installed around the WWT treatment lagoon. The MWs are typically sampled once annually as part of the groundwater monitoring programme which has been in place, in various forms since 2003. The management of the MWs and the sampling programme fall under the purview of the B Env O and not the WWT lagoon operators. In recent years, the sampling programme has been carried out by DCC. All samples are tested by an accredited third party laboratory for analysis in the city of Saskatoon. The groundwater is typically tested for 26 parameters listed in Table 5.2. Some of the 26 parameters have been omitted during certain years of the groundwater monitoring programme.

Table 5.2 – Groundwater testing parameters

Parameters		
Ionic Balance	Bicarbonate	Carbonate
Chloride	Hydroxide	P. alkalinity
pH	Specific conductivity	Sum of ions
Total alkalinity	Total hardness	Nitrate (calc. from NO2+NO3-N)
Nitrite+Nitrate nitrogen	Fluoride	Total dissolved solids
E. coli.	Total coliform	Calcium
Magnesium	Potassium	Sodium
Sulphate	Iron	Manganese
Dissolved Organic Carbon	Groundwater Level	

5.3.2 Sampling/Recoding Compliance with Regulatory Requirements

The sampling and recording practices were compared with the regulatory requirements in order to assess for compliance. The assessment of the current monitoring programme determined the following:

1. The monitoring programme meets the minimum requirement as dictated by the Wastewater Systems Effluent Regulations (WSER) section 6, 7, 10, and 11 (Government of Canada 2016) along with the requirements of provincial regulations part II, division 2, paragraph 11 (Water Security Agency 2012).

2. The current monitoring parameters does not include, in contradiction to regulations, the monitoring of the effluent's five (5) days Carbonaceous Biochemical Oxygen Demand ($CBOD_5$). The monitoring of $CBOD_5$ should be included in the list of tested parameters.

5.3.3 Monitoring Recommendation

In addition to the lack of $CBOD_5$ monitoring, the monitoring programme is incapable of determining the mechanisms or the performance of the wastewater's treatment as it progresses over the treatment period. The following subsection will cover a variety of parameters that should be monitored as part of the detachment WWT lagoon operation.

These parameters are based on the minimum guidelines established by Pearson et al. (1987).

5.3.3.1 Meteorological Parameters

As WWT lagoon systems operate using natural treatment processes, they are highly dependent on meteorological factors. Currently, meteorological parameters are not being tracked as part of the WWT lagoon operations. The meteorological parameters listed in Table 5.3 should be monitored.

Table 5.3 – Recommended meteorological parameters monitoring

Meteorological Conditions			
Air temperature	Precipitation	Evaporation	Wind speed
Wind direction	Relative humidity	Solar radiation intensity	Daily sunshine hours

All the listed parameters, with the exception of solar radiation intensity, are within the capabilities of the weather station currently employed by Range Control. The weather station should be repositioned where its instruments can accurately and reliably obtain readings. Ideally, the weather station should be reinstalled at the WWT lagoon system's location. This location should be ideal for all the organizations that require the information from the weather station. In this location, the station would be installed in an open area with low traffic and well away from interference from the administrative area of the detachment. Despite its relative remoteness, the site is readily accessible via an all season road facilitating calibration and maintenance and power from the detachment's grid is available to run the instruments and is within 2 km from its original location at Range Control.

A proper maintenance and calibration schedule will need to be established based on the manufacturer's recommendations to ensure accurate readings. In addition, the current instrument set-up will need to be modified to allow for the recording of the readings to be stored in a usable format. The weather instruments could be connected to a SCADA system to automate post-processing of the data.

5.3.3.2 Wastewater Parameters

In addition to the pH and temperature readings, several other wastewater parameters should also be monitored. The list of parameters varies based on the location in the treatment train. Table 5.4 provide the recommended parameters to be monitored in the grit chamber and septic tank. All of these parameters should be monitored using in-situ probes and sensors with adequate specification to monitor the full range of values and obtain readings. The reading frequency should be at least 1/hours for temperature, pH, conductivity, and wastewater flow. Daily readings of TSS, nitrogen, ammonia, and phosphorus should be sufficient.

Table 5.4 – Recommended wastewater parameter monitoring in grit chamber and septic tanks

Wastewater Conditions (Grit chamber & Septic tanks)			
Wastewater Temperature	pH	Conductivity	TSS
Nitrogen	Ammonia	Phosphorus	Wastewater flow

For the grit chamber (building 157), the instruments should be placed within the main chamber, prior to the grates and be easily retrievable via the access hatch or through a new access port for maintenance and calibration purposes. Since access to the septic tanks is more restrictive, the instruments should be located immediately after the septic tanks and in the east chamber of the lift station (building 263). An access port should be installed for ease of access to the instruments.

The current practice of measuring the wastewater flows via the influent pumps is adequate. However, pump readouts should be changed to metric units (i.e. m^3) and connected to a SCADA system to avoid manual note keeping.

Due to their nature, Cell #1 and Cell #2 require more parameters to be monitored to adequately assess the effectiveness of the wastewater treatment. Table 5.5 provide the recommended parameters to be monitored in both cells. However, all parameters can still be monitored via in-situ instrumentation. Readings should be ideally taken from several points throughout the wastewater column to capture variation throughout the column.

Table 5.5 – Recommended wastewater parameter monitoring in Cell #1 and Cell #2

Wastewater Conditions (Cell #1 & Cell #2)			
Wastewater Temperature	pH	Conductivity	DO
Nitrogen	Phosphorus	TSS	Algal biomass
Total alkalinity	Wastewater levels		

Piezometers should to be installed in each of the cells to measure the wastewater elevations. These piezometers will be located as close to the edge as possible whilst still remaining above the bed and near the north-eastern corner to minimize the influence of wind-driven waves. To provide redundancy and to ensure reading correctness, an incremented rod should also be installed in each cell.

A proper maintenance and calibration schedule will need to be established for all instruments. The schedule will need to be based on the manufacturer's recommendations to ensure accurate readings. The use of in-situ probes and sensors would also eliminate the need for operators to conduct daily sampling for testing via hand-held probes, provided that a SCADA system is put into place. This would reduce the daily work load on the operators and the risk of contamination.

5.3.3.3 Sludge Depth

The accumulation of sludge throughout the WWT lagoon system should be monitored on a regular basis. If left unchecked, the accumulation of sludge would gradually reduce the effective volumes of all treatment components (i.e. grit chamber, septic tanks, and both cells). The sludge accumulation would result in a higher effective BOD loading rate, reduced wastewater capacity, and the possibility of obstructed pipes. As recommended by Pearson et al. (1987), the sludge depth should be measured once annually to adequately assess the need and prepare for desludging.

One measurement should be taken from the same location every time in the grit chamber located in building #157. As accessing all five (5) septic tanks is difficult and all tanks operate in parallel, one measurement taken in the current sampling point can be assumed to be representative of all tanks. However, the current sampling point is located in the second cell and a greater accumulation of sludge is expected in the first cell. Therefore, a measurement taken from the first cell is also necessary and an established measuring point should be installed.

The measurement of sludge depths in both Cell #1 and Cell #2 is also required. As sludge can be unevenly distributed in the bed of each cell, multiple measuring points are required to adequately assess sludge levels. 10 points in each cell are proposed to accomplish the assessment. Figure 5.3 presents the approximate location of each measuring point and includes a naming convention. The measurement of the sludge in Cell #2 can easily be accomplished on foot by the operators once the cell has been drained during annual wastewater discharge. As wastewater is perpetually present in Cell #1 whilst the WWT lagoon system is in operation, measurements will need to be taken from a sampling boat or barge.

Figure 5.3 – Proposed sludge measuring locations

The measurement of the sludge can be made using the “White Towel Test” as described by Pearson et al. (1987). This testing method consists of lowering a rod with a white tower wrapped on one end. The wrapped towel once inserted to the bottom of the cell bed or bottom of a tank will discolour where it is in contact with the sludge. The depth of the sludge can then be reliably measured from the towel. Alternatively, a dedicated sludge sampling device, such as a Sludge Judge produced by Nasco, can economically accomplish the same task but with greater ease of operation and would reduce the possibility of operators getting in contact with wastewater.

5.3.3.4 Sample Testing Parameters

All samples taken as part of the discharging process of the WWT lagoon are analysed by an accredited third party laboratory. As seen in Section 5.3.1.2, these samples are tested for 88 parameters. The large amount of testing parameters results in a large amount of data to process. Additionally, this contributes to the $85,000.00 annual cost in sampling for the detachment as part of the operation of both the Water Treatment Plant (WTP) and WWT lagoon system. This figure was reported by the RMC Green Team (Royal Military College of Canada 2017).

The need for each parameter should be reassessed with the objective of removing any parameters that are needlessly tested. The need for a specific parameter should be determined based on the regulatory requirements of the WSER and the parameters recommended by the Canadian Council of Ministers of the Environment (CCME)’s water quality guidelines for the protection of aquatic life (Canadian Council of Ministers of the Environment 2014). The CCME’s guideline also provided a methodology to establish site-specific quality objectives (Canadian Council of Ministers of the Environment 2003). Once both the parameters and their site-specific objectives have been established, the list of sampling parameters may be further refined to exclude parameters for which historical testing has demonstrated consistently below detection concentrations.

Any parameter tested should be adequately tracked and plotted (or otherwise processed) to facilitate future referral or analysis. If data tracking and processing are not completed, the testing for that parameter is of little to no benefit to the operations of the WWT lagoon system.

As the testing parameters of the groundwater samples is part of a larger project (i.e. detachment-wide groundwater monitoring programme), judgement on the relevance of each parameter has not been completed and is considered outside the scope of this project.

5.3.4 Data Management

The following subsections will elaborate on the current procedure used in the management of collected data/readings and provide both long-term and interim recommendations.

5.3.4.1 Current Data Management Practice

With the lack of a SCADA system, the management of the data collected by the operators is rudimentary. In its present form, the daily log sheets are retrieved at the end of each month for both the septic tank readings and the pump readings. The retrieved log sheets are kept loose in a filing cabinet. The data from the log sheets are not digitized for future manipulation.

The laboratory reports are kept within the e-mail system (Microsoft Outlook) of each operator's personal mail box. These files are not extracted to a common location and the data from the reports are not extracted to a common system for data storage and handling.

As the collected data is not centralized in one file or software, such as a Microsoft Excel spreadsheet or even digitized and little to no data manipulation in undertaken, its usefulness to the operation of the WWT lagoon is severely limited. Considerable time must be taken to digitize, centralize, and organized the data prior to any plotting and analysis to take place. As such, the WWT lagoon operators currently rely on their experience with the specific system and data at their disposal to assess the performance of the system.

The current method of operation coupled with the lack of collection of vital data, severely limits the ability of the operators to assess the effectiveness and compliance of the WWT lagoon as treatment progresses. Higher order assessments, such as observing seasonal variations and comparing treatment across many years, are nearly impossible to complete accurately.

Due to the ownership of the groundwater monitoring programme and its associated data set, the management of the data obtained from the MWs located at the WWT lagoon site was not assessed during this research project. However, it was determined that the data was kept in a centralized location on the detachment's servers and in the form of annual reports in .pdf file format.

The current data management programme meets the minimum requirements for record keeping and record retention as set out in WSER section 17 and section 22 respectively (Government of Canada 2016). However, due to the lack of any redundant system, the ability of the current data management programme to continue meeting the record retention requirement can be potentially problematic.

5.3.4.2 Recommendation for Data Management

The following subsections will cover both long-term and short-term recommendations or objectives with regard to the management of data generated as part of the operation of Detachment Dundurn's WWT lagoon.

5.3.4.2.1 Long Term Recommendations

The long-term goals should be to have a SCADA system in place. One of the major advantages of SCADA systems is the ability to automate the capture and archival processes for a vast amount of data along with displaying data in near-real time. SCADA systems are also capable of automatically plotting data to establish trends and assess the performance of a particular system. The following should be considered when selecting a SCADA software for use with the Detachment Dundurn's WWT Lagoon system:

1. Interface: The interface of the SCADA software should be intuitive and user-friendly. The interface should not be fixed but allow to be adapted to the operators' needs as they may change over time;

2. Data processing: The selected SCADA software should be capable of processing data automatically without being prompted by the users. The SCADA system should be able to generate daily/weekly/monthly/yearly reports in a flexible format defined by the user and should be adjustable overtime using any archived data.

3. Data display: The SCADA software should be capable of easily plotting trend lines on adjustable scales for various parameters in accordance with the needs of the operators;

4. Library: The SCADA software should have an integrated indexed library for operators to access and consult instruments' user manual, Standard Operating Procedures (SOP)s, training material, and inspection records of various components. The users should be able to add and remove files; and,

5. Data backup: Data generated and managed by the SCADA software should have both on-site backup drive(s) dedicated to the WWT lagoon SCADA system along with off-site drive.

It is essential that, once a SCADA system has been installed, the operators are adequately trained in the management and manipulation of the software and the data bank.

Despite the presence of a SCADA software, measures should be in place for manual data collection and storage. These measures are intended to allow for the collection of needed data when technical difficulty (e.g. power outages, network crash, and software glitches) occurs. The measures should also allow for the integration of manually obtained data to the data bank once systems have been restored. Any paper records should be adequately archived.

5.3.4.2.2 Interim Recommendations

The change from the current modus operandi to the full adoption of a SCADA system will require both a monetary and time commitment. A phased transition process could be adopted to facilitate the transition on the operators and provide more immediate benefits.

As a temporary measure, an automated spreadsheet (such as a Microsoft Excel file) can be developed and employed. The automated spreadsheets should:

1. Allow the operators to easily input the data on a daily basis;

2. Allow the operators to easily input the results from the laboratory testing;

3. Plot the collected data automatically;

4. Display and track inspection and calibration records for various components of the lagoon system (e.g. pumps, liner, sensors)

5. Be formatted to easily extract or print out reports as desired by the operators or the detachment's RP Ops section; and,

6. Allow for multiple users to access the file simultaneously.

To facilitate the work of the operators and reduce blunders inherent in the manual digitization of data, operators should be capable of directly inputting their recordings in the spreadsheet whilst at the WWT lagoon. To accomplish this, operators should be equipped with ruggedized tablets, laptops, or personal digital assistant devices with internet connectivity or automatic synchronization software when reconnected to the DWAN network. Additionally, a quality management programme should be developed in order for the operators to check each-others work and to facilitate the verification of the work by the system's supervisor and the detachment's RP Ops section. The laboratory results should be sent to a common e-mail box and not the operator's personal boxes to avoid losses during personnel turnovers. The reports should be extracted from the e-mail network and placed in a common location. The generated data bank should be placed in a networked location for easy access by all stakeholders and should be backed up (preferably automatically) on a regular basis on a local drive.

The operators should be ready to revert to the manual recording of the data when encountering technical difficulties. This can be accomplished by having pocket books in their possession whilst on duty. The recording from the pocket books will need to be manually transferred to the spreadsheet as soon as possible. Once filled, pocket books will need to be adequately archived.

Current paper records should be properly organized, indexed and filed. An adequate filing system should be established and maintained until the current paper records have been digitized, backups have been made, and the entire data management system has transitioned to a paperless system (i.e. SCADA system).

5.4 Additional Managerial Recommendations

Several other points have been brought to light when conducting the interview process with regards to the operation and management of the WWT lagoon system. At the time of the interview process, no SOPs regarding the operation of the WWT lagoon system was available in written form for review. The current practice for the operators is to learn whilst on the job. This poses obvious continuity issues and renders the assessment of the system more difficult. SOPs need to be developed and tailored for the detachment's infrastructure. These SOPs should be based on the best management practices available along with manufacturer instructions of individual components of the system. The SOPs need to cover all aspects of the lagoon operations both regular and irregular operations. Irregular operations should include the desludging process, liner inspections, and any other operations as deemed fit by the operators. All SOPs should be approved by RP Ops staff and available in both electronic and paper format to facilitate the operation of the WWT lagoon system in any operating condition. These SOPs will require revision on a regular basis (e.g. 3-5 years), when parts are replaced, and the system is upgraded.

Although the minimum required level of Personal Protective Equipment (PPE) is being used by the operators for their personal protection when operating the WWT lagoon system, additional measures can be taken. With the nature of other responsibilities that are not associated with the operation of the WWT lagoon (further explained in Section 5.6), operators should take some additional protective measure when in direct contact with the wastewater (i.e. when conducting sampling) or when working around the lagoon cells. Such measures should include: either having a separate set of work attire, including boots, dedicated for working at the WWT lagoon site, or using reusable splash-proof coveralls (e.g. Tyvek coveralls). These measures would serve primarily to ensure the prevention of the contamination of water samples taken daily with wastewater (sampled every morning) and during the discharge process. In addition, some of the requirements provided above require the need for additional PPE. Since boating operations are needed, an adequate size boat or barge should be used to provide a suitable working platform and all operators should have access to life-jackets or other suitable floatation devices. Additionally, since there is a risk of falling in the wastewater, an emergency shower should be available on-site along with spare work attires for each operator.

As part of the sampling programmes for both the WWT lagoon system and WTP (further explained in Section 5.6), the operators conduct a large amount of sampling and are required to manually label all the sample bottles. Arrangements should be made with the third party laboratory to provide the detachment with blank labelling papers and an electronic template instead of partially pre-labelling the sample bottles with fill-in fields, which is the laboratory's standard practice. Equipped with both labelling paper and template, the detachment would be able to print their own label using a fully or partially automated process. This would result in significantly less time consumed in labelling bottles by hand and reduce the risk of mislabelling samples due to the menial and repetitive nature of the work.

5.6 Limitations & Engineering Constraints

The following subsections will elaborate on certain limitations and engineering constraints that are imposed on the detachment's WWT lagoon systems and its operators.

5.6.1 Staff Strength & Responsibilities

One of the more significant limitations on the WWT lagoon system operation is the size of the staff operating the system. The WWT lagoon system is operated with a staff strength of three (3); which includes one (1) level II supervisor and two (2) apprentice operators. For a period of approximately six (6) months, staff strength was reduced to the two (2) apprentice operators due to a turnover.

The operators are also responsible for the management and operation of the detachment's WTP, the management of the three (3) production wells, the water quality control sampling programme, and the detachment's swimming pool. The WTP was constructed in 1957 and, much like the WWT lagoon system, it does not feature any SCADA system and very little automation. The WTP require at least one (1) operator on call and ready to respond to issues 24/7. Certain tasks such as replacing the chlorine gas bottles of the WTP chlorination system require a minimum of two (2) operators to complete. All these factors results in a high workload for all operators and little flexibility. The detachment has expressed difficulty in sending their operators on training programmes or continuing education venues for extended periods of time due to its small staff strength.

As the WTP and the water quality control sampling programme have a direct impact on the detachment's personnel and operations, they are the main focus of the operators. In addition, the small staff strength also means that any irregular maintenance tasks that fall outside the operators routine need to be contracted out. This process increased the complexity and time requirement of any maintenance project.

Many recommendations made as part of this research project has been made with the intent of reducing or limiting the workload on the operators whilst still meeting modern expectations for WWT systems. This is why many recommendations rely on a high level of automation. This level of automation is regularly included in modern municipal WT and WWT system and has proven its reliability and usefulness over the years.

5.6.2 Historical Record Keeping

With the original wastewater treatment system built in 1941 and the current WWT lagoon system built 1988, much of the original documentation regarding the infrastructure has been lost over the years. These documents include: construction drawing and plans, reports, and manufactures' instructions. It is also possible that certain documents/records never existed as regulations were less stringent at the time. These lost documents pose obvious challenges for the management of the WWT lagoon as it ages and for the conducting the assessment of the WWT lagoon system and proposing relevant site-specific recommendation.

5.6.3 Limited Cells

As the detachment's WWT lagoon system only has the two (2) cells which is the minimum required by provincial regulation, the system does not provide flexibility in flow management. This lack of flexibility is particularly evident when conducting maintenance of cells. When such maintenance is required, the detachment must resort to the use of a temporary packaged plant to treat the wastewater whilst repairs are being carried out. Otherwise, the wastewater from one cell must be transferred to the other and the system must operate with only one cell for the duration of the maintenance project, therefore risking the discharge of effluent of unsatisfactory quality levels at the end of the treatment period. There is an opportunity for maintenance to be carried out in Cell #2 once discharge has been completed and before equalization of the wastewater between the cells. However, no such opportunity exists for Cell #1. If the system operated with three (3) or more cells, maintenance of any one cell could be done without the need of a packaged plant, or risk unsatisfactory effluent quality. This would greatly simplify the maintenance process. This will be significant as the WWT lagoon system is approaching the average expected useful life of lagoon systems in Saskatchewan and has already exceeded the national average (Statistics Canada and Infrastructure Canada 2016) and will most likely require significant maintenance work in the near future.

5.7 Relevance to Research

This chapter summarized the various activities associated with the operation of 17 Wing Detachment Dundurn's WWT lagoon (i.e. data collection, operations and management). These actions were compared with their regulatory requirements when applicable and several recommendations were made that should improve the overall performance of the WWT lagoon system or improve the detachment's understanding of the treatment provided. In addition, several important limitations and engineering constraints were identified. Proper knowledge of the procedures used by the operators is essential to the proper assessment of the environmental risk associated with the operation of the WWT lagoon system. Proposed alteration of procedures currently followed may be beneficial to the overall performance of the system in meeting and possibly exceeding the regulatory requirements. Additional recommendations were made to facilitate the operation of the WWT lagoon system whilst still collecting the data required for the proper operation of the system.

6.0 Methodology of this Research Study

6.1 Introduction

Properly developed research procedures with an adequate field study is the foundation for the production of quality data; data that will be representative of actual site conditions and allow for the creation of accurate and reliable deductions and recommendations. As such, a logical and detailed methodology was employed for the assessment of 17 Wing Detachment Dundurn's Wastewater Treatment (WWT) lagoon system.

In this chapter, the procedure of this research project is provided along with the limitations imposed on this specific research endeavour by the author. The sampling programme that was developed and employed is detailed along with the data set. Measures utilized to control and ensure the quality of the data collected are also included.

6.1.1 Research Procedure

In order to conduct this research study, the procedure depicted in the flow chart of Figure 6.1 was developed and followed. The procedure, which emulates the procedure for a typical field investigation, included the elements presented in the following subsections.

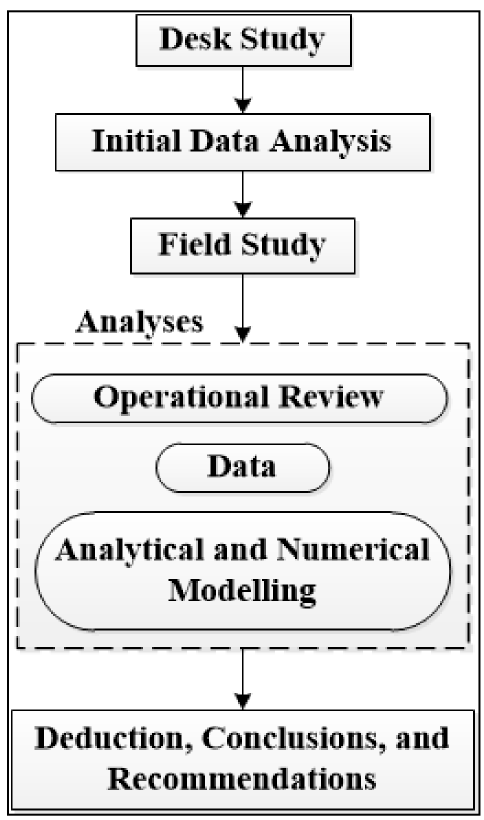

Figure 6.1 - Research procedure

6.1.1.1 Desk Study

The first step in the research project was to conduct a desk study. The primary purpose of this study was to collect all the information that may be relevant from the detachment's WWT lagoon and the detachment itself. The information was collected using a macro to micro procedure, i.e. relevant information from a global or general perspective was obtained first followed by more relevant, site-specific information regarding 17 Wing Detachment Dundurn and its WWT lagoon system.

The majority of the information utilized during this project was collected during a two (2) day preliminary site visit which was conducted on the 15–16 February 2018. The purpose of the initial site visit was to establish contact and build professional relationships with the owners and operators of the detachment's water and wastewater works, obtain a better understanding of the initial site conditions, and obtain relevant data. In order to accomplish this goal, the following objectives were determined prior to the site visit:

1. Know the Real Property Operations (RP Ops) section's priorities and concerns related to the detachment's wastewater works;

2. Learn of any planned upgrades to the Water Treatment Plant (WTP) or WWT lagoon;

3. Learn of any planned or ongoing environmental studies;

4. Learn of the current state of the Assistant Deputy Minister (Infrastructure and Environment) (ADM(IE)) source water vulnerability study for 17 Wing Detachment Dundurn;

5. Obtain data and details related to the monitoring wells programme;

6. Obtain detailed site photos of all relevant waterworks and wastewater work infrastructure;

7. Identify and obtain data related to source water vulnerability issues;

8. Obtain a better understanding of the treatment process in both the WTP and WWT lagoon, including objectives, known issues, and operator schedules;

9. Obtain the WTP and WWT lagoon data logs and reports; and,

10. Obtain WTP and WWT lagoon infrastructure drawings.

A large number of reports and a large amount of data was collected during the visit which allowed for the successful completion of the desk study and the orientation of the remainder of the research project.

6.1.1.2 Initial Data Analysis

The second step in the research programme that was undertaken by the author was to conduct an initial analysis on all the available data, both publicly available data and data obtained during the site visit. This step provided an understanding of what data was produced from past studies and what data was/is being generated by the operators.

This initial data analysis along with the desk study led to further refinements of the objectives of this research project, based on the site conditions, data availability, and limitations identified in Section 6.2.

6.1.1.3 Field Study

A field study was developed and executed by the author in order to complement already available data, in order to accomplish the aim and objectives of this research project. The field study also provided a detailed understanding of the site condition and the operational environment at the WWT lagoon's infrastructure. The field study consisted of a series of site visits spaced out throughout the active portions of the 2018–2019 treatment period. Three (3) separate visits were conducted during: 13–16 Aug 2018, 09–12 Oct 2018, and 16–19 Apr 2019. All of these site visits had to be planned and co-ordinated by the author in order to ensure that the site visit activities were effective in the fulfilment of the objectives of this study.

The site visits were conducted with the following three (3) objectives:

1. Conduct an assessment of the WWT lagoon system's operations;

2. Conduct an assessment of the WWT lagoon system's infrastructure condition; and,

3. Conduct a water and wastewater sampling programme.

To accomplish some of these objectives and to complement the desk study, a series of semi-structured interviews using the RMC Green Team's questionnaire for the assessment of WWT lagoon systems (Appendix G) were conducted during the initial site visits. Follow-on interviews were conducted, as needed, throughout the remainder of the field study.

6.1.1.4 Follow-on Research

With the information and data collected, a series of tasks could be conducted simultaneously. The primary tasks consisted of:

1. <u>Data analysis:</u> The analysis of the various data sets collected was conducted to characterize the site, assess the performance of the WWT lagoon system

and to look for signs of leaks. The data analysis conducted can be broken down into the major components listed in Table 6.1.

Table 6.1 - Major components of the data analysis

Data Analysis	
Weather	Influent volumes and quality
Effluent volumes and quality	Wastewater quality (system wide)
Surface water quality	Groundwater elevations and quality

2. Numerical modelling: A numerical model was developed to understand the groundwater (GW) flows and to determine how the detachment's production wells and the WWT lagoon system interacts with the GW. In addition, the model simulates the conditions required for the GW located at the WWT lagoon to migrate to the productions wells.

3. Operational review: A review of both the WWT lagoon's infrastructure and the operational procedures followed by the operators was conducted. The information for the review was obtained: from the interview process, from conducting an inspection of the infrastructure, and from conducting a Light Detection and Ranging (LiDAR) survey of the infrastructure. The report on the LiDAR survey can be seen in Appendix I. An example of the LiDAR results can be seen in Figure 6.2.

With the completion of the data analysis, GW numerical model, and the operations review; deductions and recommendations could be made. Recommendations include changes to the design of the detachment's WWT lagoon along with changes to their operations and maintenance practices.

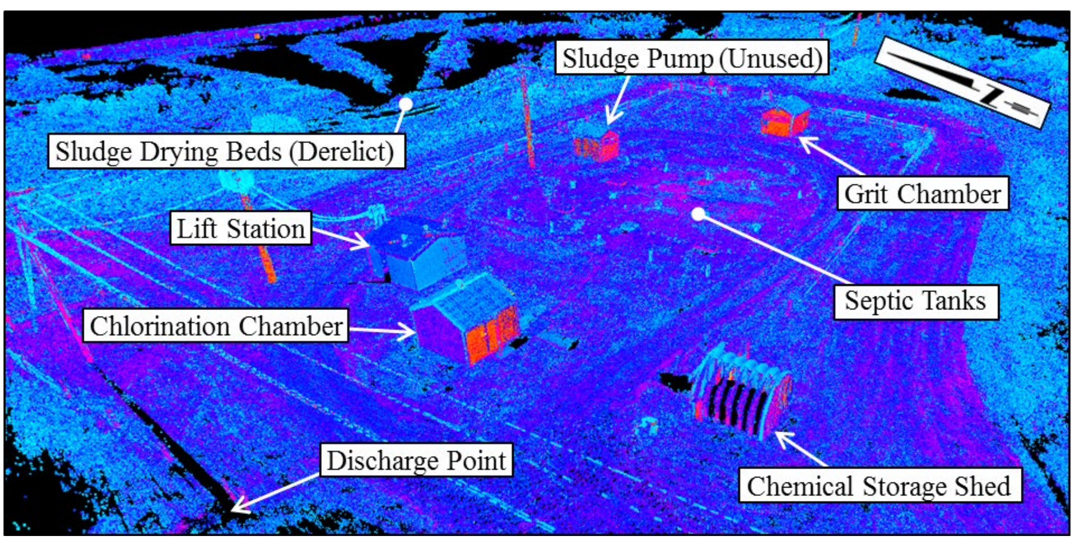

Figure 6.2 - Annotated LiDAR point cloud of septic tank site (Oct 2018)

6.2 Site Visits

To conduct this research study, a total of 4 visits were conducted. Table 6.2 provide the detail regarding each site visits including: dates, personnel attending, detachment personnel supporting the visits, and the main activates accomplished. Figure 6.3 depict various activities that were conducted during the site visits.

Table 6.2 - Detachment Dundurn site visits information

Trip & Dates	Participant	Supporting Detachment Personnel	Activities
Preliminary site visit 15-16/02/2018	-Capt Jean-Luc Armstrong (Researcher) -Ms Maame Addai (Researcher)	-Mr Dwayne Crawford (WWT Plant Operator) -Mr Kevin Seivewright (WWT Plant Operator) -Ms Cheryl-Ann Beckles (Environmental O) -Mrs Evelyn Jackson (RP Ops Drafting)	-Initial interviews -Initial site visit -Initial data collection
Field visit #1 13-16/08/2018	-Capt Jean-Luc Armstrong (Researcher) -Ms Maame Addai (Researcher) -Mr Robert Bogle (Researcher)	-Mr Dwayne Crawford (WWT Plant Operator) -Mr Kevin Seivewright (WWT Plant Operator) -Ms Cheryl-Ann Beckles (Environmental O)	-Sampling programme round #1 -Follow-up interviews #1 -Data collection #1
Field visit #2 23-26/10/2018	-Capt Jean-Luc Armstrong (Researcher) -Mr Adam Watson (Technologist)	-Mr Dwayne Crawford (WWT Plant Operator) -Mr Kevin Seivewright (WWT Plant Operator) -Ms Cheryl-Ann Beckles (Environmental O)	-Sampling programme round #2 -LiDAR survey and initial infrastructure assessment -Data collection #2
Field visit #3 16-19/04/2019	-Capt Jean-Luc Armstrong (Researcher) -Ms Maame Addai (Researcher)	-Mr Dwayne Crawford (WWT Plant Operator) -Mr Kevin Seivewright (WWT Plant Operator) -Ms Cheryl-Ann Beckles (Environmental O)	-Final sampling programme round -Final follow-up interviews -Follow-up infrastructure assessment -Final Data collection

Figure 6.3 – Various activities conducted during site visits:
A) Infrastructure assessment B) Field testing C) Groundwater sampling D) LiDAR survey

6.3 Limitation

Several limitations were imposed on the research project. These limitations were either imposed by outside organizations or due to the nature and location of the study. Limitations included the following:

1. Time constraints: A period of 24 months was allotted for this project. In this period of time, the research project needed to be conceptualized, a minimum of one (1) full treatment period needed to be monitored (~12 months), and the project needed to be concluded and a report produced. In addition, all other academic requirements for the successful completion of a master's degree of applied science in civil engineering needed to be completed.

2. Budget: The research project was completed with a limited budget. Funds for the operation of the WWT lagoon system could not be utilized.

3. Site location: Since the site was located on a relatively remote location 3166 km from RMC, equipment selection had to be limited to tools that may be easily shipped from RMC, handled by the author during transport to the site or otherwise available at the detachment.

4. Operator burden: As the detachment's WWT lagoon operator strength size was quite limited and considering their other responsibilities and workload, the research project needed to be completed with little to no added burden on the operators. As such, the research required to be completed remotely or feasible in a series of short 4–5 days field visits.

5. Non-destructive & disruptive testing: All task completed as part of this research project needed to be completed without inducing damage to the WWT lagoon system (e.g. perforating the cell's geomembrane liner). In addition, no task necessitating that part or all of the WWT lagoon system be brought off-line were authorized, thereby limiting the testing possibilities.

6.4 Failure Mechanisms of Wastewater Treatment Lagoon Systems

The treatment of the wastewater at 17 Wing Detachment Dundurn is primarily undertaken in two (2) cut-and-fill reservoirs which are subject to a variety of issues that may affect their ability to retain the wastewater. For this research project, failure mechanisms associated with WWT lagoons were divided into two (2) categories. These failure mechanisms are containment failure and treatment failure as defined by the following:

1. Containment failure: These types of failures are associated with the support structure (i.e. berms), the lining systems or how the lagoon is being operated. Containment failure is defined as the involuntary discharge of wastewater in sufficiently large quantity to have deleterious effects on the surrounding ecosystem and/or on the groundwater. Table 6.3 provides a list of failure mechanisms that are associated with cut-and-fill reservoir. This table was modified from USEPA municipal wastewater stabilization pond design manual (USEPA 1983) to adjust for site-specific conditions.

Table 6.3- Possible containment failure mechanisms associated with WWT lagoons (Modified from USEPA, 1983)

<table>
<tr><th>Support Structure Problems</th><th>Lining Problems</th><th>Operating Problems</th></tr>
<tr><td>Under draining</td><td rowspan="6">Mechanical difficulties:
Failed seams
Fish mouths
Structural Seals
Bridging
Porosity
Holes
Pinholes
Tear strength
Tensile strength
Extrusion and extension
Rodents, birds, other animals
Insects
Weed growths</td><td>Excessive hydraulic loading</td></tr>
<tr><td rowspan="5">Substrate:
Compaction
Texture
Voids
Subsidence
Holes and cracks
Groundwater
Grassing
Slope anchor stability
Mud
Frozen ground and ice</td><td>Cavitation</td></tr>
<tr><td>Impingement</td></tr>
<tr><td>Maintenance cleaning</td></tr>
<tr><td>Reverse hydrostatic uplift</td></tr>
<tr><td>Vandalism</td></tr>
<tr><td>Seismic activity</td><td>Weathering</td><td>Health and safety of operators</td></tr>
</table>

2. Treatment failure: these types of failure are associated with the weather conditions in which the wastewater is being treated along with certain characteristics of the wastewater itself. Treatment failure is defined by the voluntary release of effluent that has not met the regulatory quality standards (both provincial and federal). In addition, a treatment failure is also deemed to have occurred if emissions from the WWT lagoon system exceed the Canadian Ambient Air Quality Standards (CAAQS). However, emissions from the WWT lagoon system have not been measured as part of this research project. Table 6.4 provides a list of failure mechanisms that are associated with wastewater treatment.

Table 6.4 - Possible treatment failure mechanisms associated with WWT lagoons (Modified from USEPA, 1983)

<table>
<tr><th colspan="2">Treatment Failure Mechanisms</th></tr>
<tr><th>Treatment Problems</th><th>Odour Problems & Emissions</th></tr>
<tr><td>Insufficient light (solar radiation)</td><td>Overloading of ponds</td></tr>
<tr><td>Insufficient dissolved oxygen (DO)</td><td rowspan="2">Excessive accumulation of surface scum</td></tr>
<tr><td>Temperature too low</td></tr>
<tr><td>Excessive nutrient concentrations</td><td rowspan="2">Uncontrolled aquatic and embankment weeds</td></tr>
<tr><td>Excessive suspended solids concentrations</td></tr>
</table>

The monitoring and sampling programme developed for this research project was designed to address the two (2) types of failure mechanisms presented above.

6.5 Sampling Programme

In order to properly assess the effectiveness of 17 Wing Detachment Dundurn's WWT lagoon system and determine if there is a concern over possible leaks, additional data was required to augment the data generated by the detachment on a routine basis. Water-quality data are a major component of the required data. In order to adequately obtain there additional and complimentary water-quality data a sampling programme was developed by the author. The following subsections will cover various aspects of the sampling programme and include: parameter selection, sampling location, sampling protocol, analysis protocol, and equipment selection.

6.5.1 Sampling Parameters

The parameters selected for analysis of water samples taken as part of this research project are listed in Table 6.5. These parameters were selected since they address the two (2) possible failure mechanisms identified in Section 6.3 which are: containment and treatment failure.

Table 6.5 - Selected parameters for analysis

Parameters	Primary Purpose
pH	Effectiveness indicator
Conductivity	Effectiveness indicator
Temperature	Effectiveness indicator
Dissolved Oxygen (DO)	Effectiveness indicator
Total Suspended Solids (TSS) & Turbidity	Effectiveness indicator
Total Dissolved Solids (TDS)	Effectiveness indicator
5 Day Biochemical Oxygen Demand (BOD_5)	Effectiveness indicator
5 Day Carbonaceous Biochemical Oxygen Demand ($CBOD_5$)	Effectiveness indicator
Thermotolerant Coliforms	Leak indicator
Total Coliforms	Leak indicator
E. Coli.	Leak indicator
Elevations (Groundwater only)	Modelling

6.5.2 Sampling Site Selection

As part of the sampling programme developed for this research project, 18 locations of interest were identified and selected for sampling. The locations, as seen in Figure 6.4 included:

1. Monitoring well: All nine (9) monitoring wells (MW)s present in the vicinity of the WWT lagoon cells and the septic tanks were selected for sampling. The MWs (ID SL#1–9) were sampled to obtain background groundwater quality and to look for signs of possible leaks from any part of the WWT lagoon systems. Pictures of all the MWs can be seen in Appendix F.

2. Creek: The Brightwater/Beaver Creek was sampled at two separate locations. Creek-S is located approximately 200 m upstream from the discharge point and Creek-N is located approximately 300 m downstream from the northern berm of Cell #2. These locations were sampled to obtain background surface water quality and to look for signs of possible leaks from any part of the WWT lagoon systems. The condition of the sampling sites of the creek can be seen in Appendix J.

3. Stagnant waterbody: An unnamed stagnant surface water body is present approximately 20 m north of the northern berm of Cell #2. This water body's size varies but was present throughout the field study period. This water body was sampled at two (2) locations identified as SW-1 and SW-2. These locations were sampled for signs of possible leaks in the WWT lagoon cells.

   A small creek/stream bed was identified approximately 250 m north of the northern berm of Cell #2 in satellite imagery. The desk study reviled that this steam bed is the remanence of the meandering Brightwater Creek prior to the construction of the diversion ditch and its renaming. The work was carried out between 1928 and 1941. This location is considerably humid, evident by the presence of dense vegetation on the banks and high moisture in the creek bed. However, the presence of free water was discontinuous and sampling could not be carried out during the August and October 2018 sampling round. This creek bed is therefore seasonal and maybe ephemeral as no rain was recorded for several days prior to any of the field visits. This location (ID SW-3) was sampled to obtain background surface water quality. The condition of the sampling sites of the stagnant water bodies can be seen in Appendix J.

4. Wastewater: Four (4) locations within the detachment's WWT lagoon system were selected for sampling. The locations included: the grit chamber, the septic tank, Cell #1 and Cell #2 and were identified as WW-IN, WW-S, WW-1, and WW-2 respectively. The sampling locations for the grit chamber and the septic tank were restricted to their respective access hatches as seen in Appendix J. The sampling locations from Cell #1 and Cell #2 were selected based on the capabilities of the sampling equipment available. The lack of boating equipment restricted the possibilities of the sampling locations. Based on these restrictions, the sampling locations were positioned approximately 11 m within each cell from the wastewater's edge along the central berm and centred on each cell's E-W dimension. Figure 6.4 depicts the approximate locations of these sampling points. Since the water level in Cell #1 increases as the treatment season progresses, the sampling location varied between sampling rounds. Regardless of the final sampling locations, all samples were obtained from positions over the bed of the cells and not the berms.

   These locations were selected to ascertain the spatial and temporal variation in the treatment of the wastewater and to assess the overall treatment performance.

Coordinates for the all the sampling locations are given in Table 6.6.

Table 6.6- Sampling location - basic information

Location ID	Location Grid	Location Description
SL#1	13U CT 0391992 5746308	Monitoring well
SL#2	13U CT 0391981 5746351	Monitoring well
SL#3	13U CT 0392029 5746331	Monitoring well
SL#4	13U CT 0392096 5746456	Monitoring well
SL#5	13U CT 0392196 5746457	Monitoring well
SL#6	13U CT 0392196 5746577	Monitoring well
SL#7	13U CT 0392190 5746711	Monitoring well
SL#8	13U CT 0392078 5746702	Monitoring well
SL#9	13U CT 0391968 5746700	Monitoring well
Creek-S	13U CT 0391943 5746052	Brightwater/Beaver Creek upstream
Creek-N	13U CT 0391950 5746870	Brightwater/Beaver Creek downstream
SW-1	13U CT 0392048 5746718	Surface water
SW-2	13U CT 0392113 5746712	Surface water
SW-3	13U CT 0392076 5746958	Surface water

Location ID	Location Grid	Location Description
WW-1	13U CT 0392070 5746569*	Cell #1
WW-2	13U CT 0392069 5746592*	Cell #2
WW-S	13U CT 0391980 5746328	Septic tank
WW-IN	13U CT 0392020 5746322	Intake (Grit Chamber)

*Indicate the coordinate of the sampling equipment setup (samples were obtained 11 m South for Cell #1 and 11 m North for Cell #2 from indicated grid coordinate)

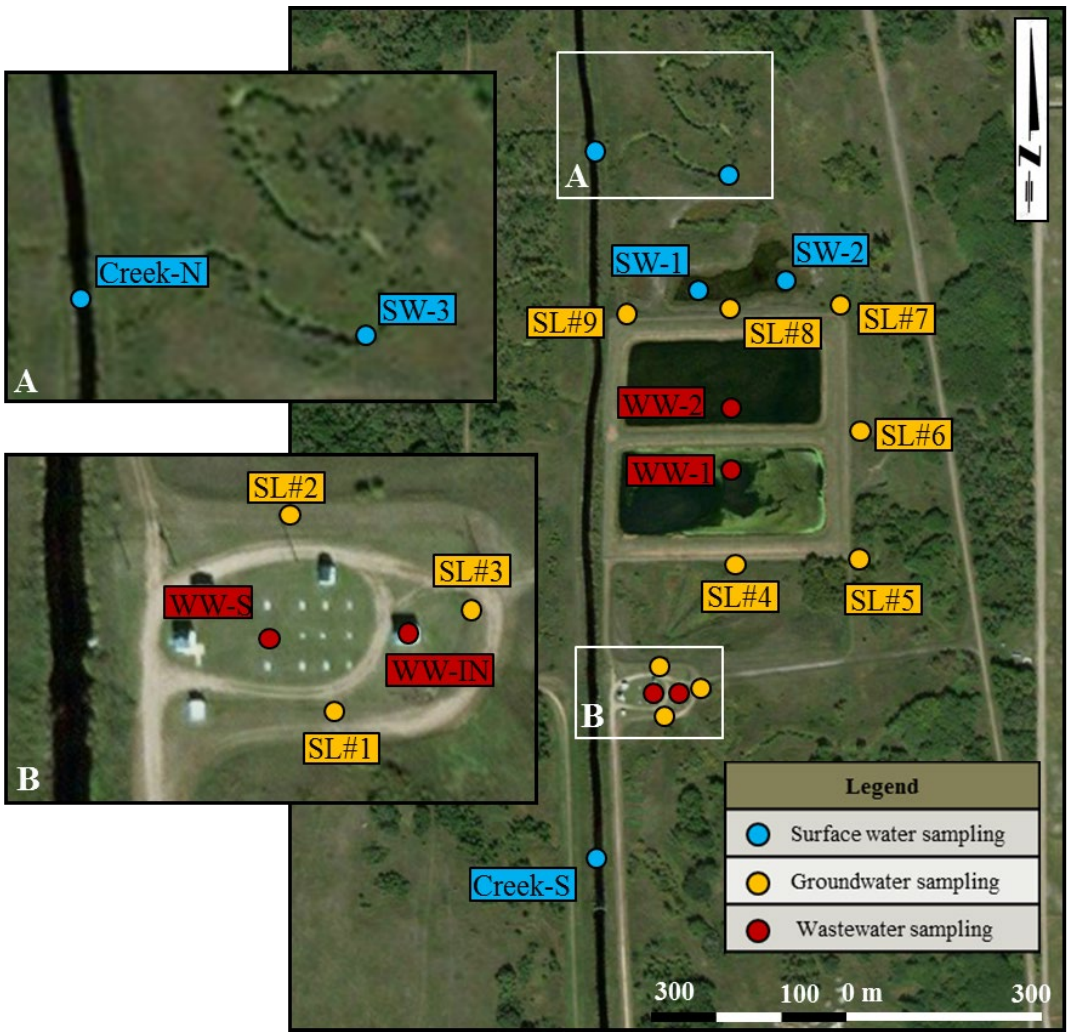

Figure 6.4 – Approximate sampling locations (Imagery provided by Microsoft Corporation 2018)

6.5.3 Sampling Protocols

A series of sampling protocols was observed during the sampling programme associated with this research project. These sampling protocols were developed, based on recommended guidelines, from various prominent authorities. The guidelines included the CCME's *Protocols for Water Quality Sampling in Canada*, the USEPA's *Operating Procedures for Surface Water Sampling*, and the USGS's *Field Manual for the Collection of Water-Quality Data* (Canadian Council of Ministers of the Environment 2011, USEPA 2013, USGS 2015). These guidelines were respected for all aspects of the sampling programme and included:

1. Sampling procedures;

2. Record keeping measures; and,

3. Health and safety measures.

Three (3) sets of sampling protocols were developed based on the water sources and are described in the following subsections. All samples obtained as part of this research project were grab samples.

6.5.3.1 Groundwater Sampling

The procedure followed for the measurement of the groundwater levels inside all the MW was the GWPD 4 published by the United States Geological Survey (Cunningham and Schalk 2011). The USGS also published a step-by-step procedure video detailing the procedure (Petersen 2014) including the record-keeping process. The record keeping for the groundwater was loosely replicated for use in this research project as seen in Appendix K.

Once the groundwater levels have been measured, the sampling tubing was cut to measure and the peristatic sampling pump prepared. A full flush of the well was carried out by letting the sampling pump run and discarding the water discharged for several minutes. Samples were then taken and immediately refrigerated. Records were kept of the site conditions (e.g. weather and water condition), sampling time and equipment used on a field form. The template for this field form is presented in Appendix K.

6.5.3.2 Surface Water Sampling

Surface water samples obtained from Brightwater/Beaver Creek and all other surface water bodies were obtained by wading into the surface water bodies and using the dip-sampling method. This method consists of obtaining the water sample by submerging the sample bottle directly into the source. An exception was made for BOD_5 and $CBOD_5$ sample bottle which contained additives. A single-use plastic container was used to transfer the water sample from the source to the sample bottle. The template for the field form is presented in Appendix K.

6.5.3.3 Wastewater Sampling

Two (2) separate methodologies were used to collect wastewater samples based on the source. Due to the lack of boating equipment and restrictions on the installation of any semi-permanent structures at the WWT lagoon site, a sampling protocol was developed to collect the grab samples from, as close to the centre of each of the cells as the pump system would allow without the need to wade. The procedure developed by the author and employed on-site is described in detail in Appendix L and is depicted in Figure 6.5.

The sampling of wastewater from the septic tank and the grit chamber (WW-S and WW-IN) was considerably simpler. Samples were obtained by lowering the sampling tube in the tanks at a depth of approximately 50–60%. A full flush of the tubing was carried out by letting the sampling pump run and discarding the water discharge back into the tank for several minutes. Once completed, samples were then taken and immediately refrigerated. The template for this field form is presented in Appendix K.

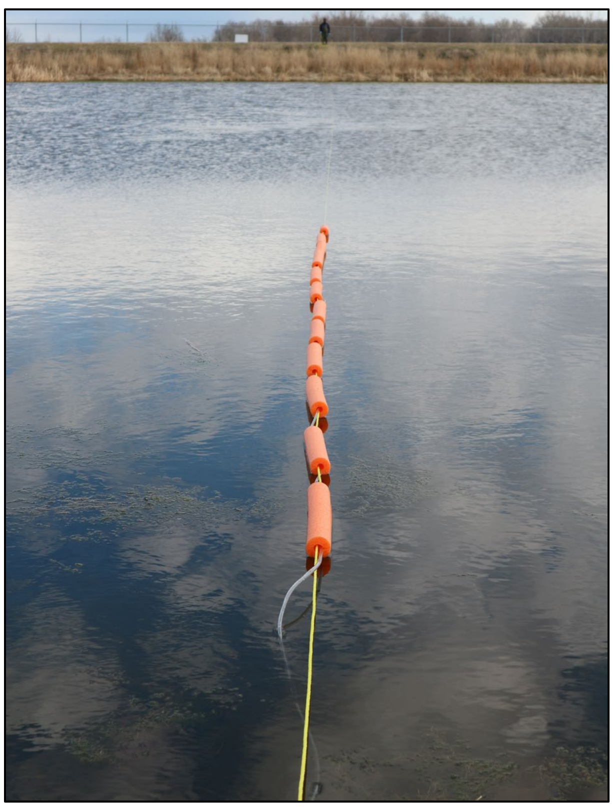

Figure 6.5- Sampling setup in Cell #2
(25 October 2018)

6.5.3.4 General Sampling Information

The following is a series of general measures that were observed for all samples regardless of the source:

1. Whilst on site, all sampling bottles were kept in refrigerated coolers in a vehicle with air conditioning (when needed). The bottles and samples were carried to and from the sampling site and vehicle in a portable cooler with icepacks;

2. All samples destined for ALS environmental laboratory were delivered within 12 hours of sampling. Since the field analysis of some samples were conducted up to 48 hours after sampling, these samples were kept in an off-site refrigerator until analysis;

3. A sample was taken from all sampling locations using a single-use plastic container for DO and temperature readings immediately prior to the collection of other samples;

4. The sampling procedures were conducted using a minimum of two (2) samplers. This allowed for the use of the clean hands, dirty hands procedure. One sampler conducted all the tasks in which exposure to the source water and the risk to contamination is likely, such as wading (i.e. dirty hands) and one sampler conducted the remainder of the tasks such as managing and labelling sampling bottles, prepping tubing, etc. (i.e. clean hands);

5. The sampling sequence was conducted from the cleanest sources to the dirtiest sources. As such, groundwater samples, which are expected to be the cleanest, were sampled first, followed by surface water sources. Wastewater sources were the last to be sampled and were sampled in the following sequence: WW-2, WW-1, WW-S, and WW-IN. This procedure reduced the possibilities of accidental cross contamination of samples whist sampling and the contamination of the groundwater;

6. All sample bottles were pre-labelled and grouped in bags for each sampling locations to avoid contamination of the bottles whilst handling them on site;

7. All samplers wore a fresh pair of powder-free nitrile gloves for each sampling site and re-gloved if touching any part of the vehicle of other non-sampling related equipment; and,

8. An emergency response plan and risk assessment associated with sampling activities was developed and respected for the duration of the field study.

6.5.4 Analysis Protocols

Several test methods were used to analyse the water samples for the various parameters of interest. These methods were established in the Standard Methods for the Examination of Water and Wastewater 23rd edition published by the APHA, AWWA, and WEF (American Public Health Association et al. 2017). The exact methods used are listed in Table 6.7.

Appendix M details the other field laboratory procedures utilized during the sampling programme and include the preparation, handling of the various meters and probes (as per manufactures specifications), and clean-up. Figure 6.6 depicts the laboratory set up used during the field analysis.

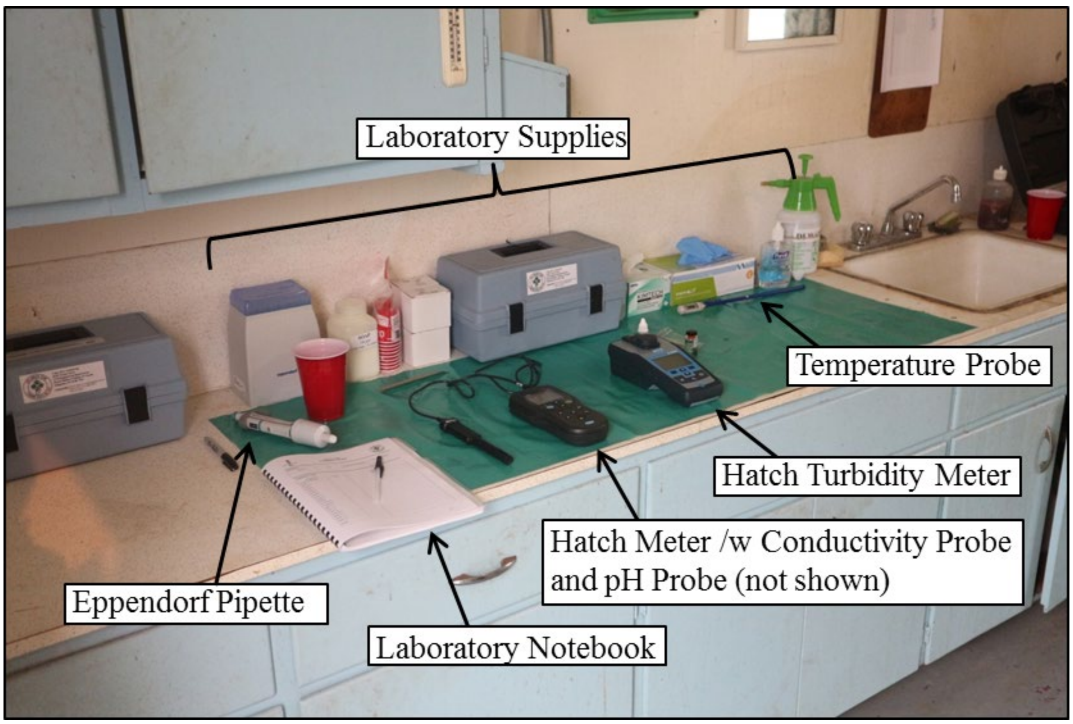

Figure 6.6 - Field laboratory set up by author in building 158 at 17 Wing Detachment Dundurn

Table 6.7 - Test methods used for the analysis of samples
(methods refer to American Public Health Association et al. 2017)

Parameter	Analysis Method	Testing Organization
pH	APHA 4500-H pH Value	RMC & ALS
Conductivity	APHA 2510	RMC & ALS
Temperature	APHA 2550B	RMC
Dissolved Oxygen (DO)	APHA 4500-O H	RMC
Total Suspended Solids (TSS)	APHA 2540D	ALS
Total Dissolved Solids (TDS)	APHA 2540C	ALS
Turbidity	APHA 2130B	RMC
5 Day Biochemical Oxygen Demand (BOD_5)	APHA 5210B	ALS
5 Day Carbonaceous Biochemical Oxygen Demand ($CBOD_5$)	APHA 5210B	ALS
Thermotolerant Coliforms	APHA 9223B	ALS
Total Coliforms	APHA 9223B 2B	ALS
E. Coli.	APHA 9223B 2B	ALS

6.5.5 Equipment Selection

The selection of the equipment used for both the sampling and analysis of the various water sources was conducted with care. The selected equipment needed to be easily transportable to and from the detachment and whilst on the site of the detachment's WWT lagoon system. More importantly, the selected equipment must not alter the chemical and physical properties of the samples obtained and must not have deleterious effects on their sources. In particular, the equipment should not cause the contamination of any MWs. To that effect, the USGS's *National Field Manual for the Collection of Water-Quality Data* and in particular Chapter A2 was consulted (USGS 2015).

The following major pieces of equipment were used during sampling:

1. Electric dip meter: The groundwater level in all wells was measured using an electric dip meter model CPR6-50PM manufactured by Roctest. Technical difficulties were experienced during the second sampling round due to damages sustained during transport. To carry on, the detachment's H.Oil Sm.Oil electric dip meter produced by Heron Instrument Inc. (Serial #01–5621) was borrowed;

2. Sampling pump: All groundwater and wastewater samples were extracted via a portable peristaltic sampling pump model Masterflex E/S portable sampler manufactured by Cole-Parmer Instrument Company. Since the selected pump is peristaltic, no part of the samples was in contact with the pump's mechanism. This reduced the possibilities of cross contamination and allowed for the pump to be used for all samples without cleaning and disinfection between sampling. A Waterra foot valve was also available for the manual extraction of samples should the sampling pump failed;

3. Tubing: Three (3) types of tubing were used in the collection of groundwater and wastewater samples.

   Small segments of approximately 40 cm of 4.8 mm internal diameter Masterflex platinum-cured silicone tubing produced by Cole-Parmer were used in the peristaltic pump mechanism. All segments were pre-cut and placed in sealed individual bags in the laboratory facilities at RMC prior to the field visits.

   Groundwater samples were obtained using 6.35 mm (1/4”) outer diameter polyethylene tubing. This tubing was kept on a reel and cut on site once the distance from the well casing to the groundwater was known, thereby reducing waste. No fittings were needed between this tubing and the peristaltic tubing since this tubing could be forced inside the peristaltic tubing with a proper seal for the operation of the pump.

   For the sampling of wastewater, a length of approximately 12 m of 6.35 mm (1/4”) internal diameter clear vinyl tubing was used. Fittings were required to connect this tubing to the peristaltic tubing. In addition, a series of galvanized steel washers and pipe clamps were used as a tubing weight.

   All tubes was treated as single use only and was discarded after use at each sampling locations in order to avoid cross contamination of the samples and the sources. An exception was made for the vinyl wastewater tubing and its fittings. Since the risks associated with cross contamination of the wastewater sources were considered negligible and the reuse of this tubing would not alter the properties, the reuse of this tubing was deemed acceptable with thorough rinsing using DI water and source water between sampling; and,

4. Sample bottles: A variety of single use sampling bottle was provided by ALS Environmental Saskatoon, SK which was the accredited third party laboratory contracted to conduct the analyses of the obtained samples. All sample bottles were provided ready for use. Additionally, a series of 1L FEP Teflon bottles manufactured by Nalgene were used to collect additional samples for field analysis. These bottles were thoroughly cleaned and autoclaved in laboratory facilities at RMC prior to each field visits.

The following major pieces of equipment were used during the field analysis of samples:

1. Dissolved oxygen probe: DO was measure using a Luminescent dissolved oxygen sensor with integrated stirring system model: LBOD10101 produced by Hach. This sensor was used in conjunction with Hach’s HQ11d Portable meter to display the measurements;

2. pH probe: pH was measured using a refillable pH probe for low ionic strength samples model: PHC28101 produced by Hach. This sensor was used in conjunction with Hach's HQ11d Portable meter to provide readouts of the readings;

3. Conductivity and temperature probe: Conductivity and temperature measurements were taken using a graphite, 4-pole conductivity probe Model: CDC401 produced by Hach. This sensor was also used in conjunction with Hach's HQ11d Portable meter to provide readouts of the readings; and,

4. Turbidity meter: Turbidity readings were obtained using a Hach's 2100Q turbidity meter kit #02398.

6.6 Data Sets Collection

Data sets were collected from various sources in order to have sufficient data to accomplish the aim and objectives of this research project. The data sets are listed in Table 6.8 along with their date ranges. The majority of these data sets have been generated by the WWT lagoon operators and have been defined in detail in Section 5.3.1. These data sets include wastewater pumping rates, septic tank pH and temperature readings, and water quality data from the annual effluent discharges. In addition, the pumping rates from the production wells of the WTP were also collected. These data are also generated by the operators on a daily basis. Groundwater quality data from the groundwater monitoring programme were also extracted for use in the research project.

Weather data and discharge flows from the Brightwater Creek were extracted from Climate Canada and the Water Survey of Canada respectively (Government of Canada n.d., Environment Canada and Water Survey of Canada 2019). These sources are publicly available online databanks.

The last data set includes the data generated from this research project's sampling programme as described in Section 6.4.

Table 6.8 - Data sets utilized for analysis

Data Set	Data Range
WWT influent pumping rate	01/01/2015 – 12/05/2019 (daily)
WWT effluent pumping rate	2010 – 2019 (daily)
Septic tank pH & temperature readings	01/01/2018 – 12/05/2019 (daily)
Groundwater quality data (groundwater monitoring programme)	2003 – 2018 (annually / biannually)
Water quality data (effluent discharge)	2015 – 2019 (annually)
Water Treatment Plant pumping rates	01/01/2015 – 31/03/2017 (daily)
Weather data (Saskatoon SRC)	01/05/2015 – 12/05/2019 (hourly) 01/01/2015 – 12/05/2019 (daily) 1981–2010 normals
Brightwater Creek discharge	1960–2016 (daily averages) & 2015 (daily)
RMC sampling programme results	August 2018, October 2018, and April 2019

All of the data from these resources were extracted and combined into one master Microsoft Excel spreadsheet (.xlsx) file for ease of storage and handling. Many sources required the data to be manually transcribed by the author into the spreadsheet from paper records and photos. This was a non-trivial undertaking. A total of 258,815 data points was collected by the author to conduct this research project. Of those data points, 33,155 data points were manually transcribed by the author into a workable format (.xlsx file). Table 6.9 through Table 6.11 provide general statistics on the collected data.

Table 6.9 - Statistics on operators logs used for research

Log	Pages	Parameter	Data Entry	Data Points
Influent Pumping Rates	53	6	1593	9558
Septic Tank pH & Temp	17	3	497	1491
Effluent Pumping Rates	6	6	36	216
WTP Pumping Rates	42	11	1263	10959

Table 6.10 - Statistics on laboratory and groundwater monitoring reports used for research

Reports	Reports	Parameter	Samples	Data Points
Historical Groundwater	14	26	123	3198
Groundwater	3	9	27	243
Historical Water	46	123	80	7274
Water	6	8	27	216

Table 6.11 - Statistics on online databases used for research

Online Databases	Reports	Parameter	Data Entry	Data Points
Weather (Daily)	5	7	1593	11151
Weather (Hourly)	56	6	35567	213402
Weather Normals	1	48	12	624
Creek Monthly Mean Discharge	1	12	63	483

6.7 Quality Assurance & Quality Control

Several measures were taken throughout the field sampling programme and during the post processing of the collected data to insure and confirm the quality of the data. The following subsections will cover quality assurance measures and quality control measures in turns.

6.7.1 Quality Assurance

Data quality measures were considered and incorporated whilst developing the field sampling programme and included the following:

1. All procedures and equipment selection for the proper collection of samples as recommended by the three (3) sources referred to in Section 6.4.3 were strictly respected to minimize the potential of cross contamination of any samples and to insure that samples were representative of their sources;

2. Detailed records were kept of the site conditions during sampling and any deviations from the developed protocols were recorded along with the justification for the deviations;

3. A local accredited laboratory (ALS Environmental, Saskatoon) was contracted to perform the testing of all samples to ensure that testing was conducted following only approved standard methods by experienced technicians;

4. An appropriate number of trip and field blanks were used for all types of samples taken to validate the collection and handling procedures of the samples;

5. Chain of custody procedures were respected and records were kept during all sampling rounds; and,

6. Duplicate testing was conducted during each field visit to support the validity of obtained data.

Several data quality measures were also taken during the collection of third party data:

1. Operators were thoroughly questioned on the methodology that was employed for the collection of routine readings and sampling in order to assess their protocols and the validity of the data collected;

2. Any data set which predates the employment of the current operators and for which the collection methodology could not be ascertained was rejected;

3. The history of the WTP and WWT lagoon systems were obtained from the operators and RP Ops and any data which predates significant changes to the system (where applicable) were rejected (e.g. WTP pumping rates prior to the 2011 installation of production well #5);

4. Any data sets from questionable sources or for which the source could not be determined was rejected; and,

5. Data sets in which data conflicted with data obtained from reputable sources or in which data were obtained by unclear methods were rejected.

6.7.2 Quality Control

The following measures were followed to verify the validity of the data analysed as part of this research project:

1. Manually transcribed data were verified on three (3) separate occasions by multiple individuals to ensure no blunders that may have occurred during the transfer process remained;

2. When applicable, data sets were verified for atypical values using various statistical and graphical means;

3. Atypical data and data with unanticipated values were verified with the original source. The operators were consulted when atypical data in the original source were encountered, to ascertain the reason for the unusual value (when possible);

4. Duplicated water quality data between ALS and RMC were compared for fit with each other; and,

5. Data were submitted on multiple occasions to supervisors and thesis advisor in order to review and to provide expert comment.

6.8 Comparative Study

As part of this research project, other wastewater treatment facilities owned and operated by the Canadian Armed Forces were also visited in order to obtain a better understanding of these processes and related topics. These facilities vary in types and sizes. The visited facilities included:

- CFB Cold Lake Wastewater Treatment Plant: This treatment plant with a design capacity of 4500 m^3/d was built between 1951 and 1954 and services a population of 2800. The wastewater undergoes oxidation, clarification and UV disinfection. Sludge is collected and undergoes digestion prior to being dried and disposed of in an on-site land farm. Effluent for the plant is discharged to a nearby creek.

- Primrose Lake Evaluation Range WWT lagoon (near Cold Lake, Alberta): This small isolated two (2) 4000 m^2 celled facultative lagoon system services a population of approximately 20. The effluent is continuously discharged via land spreading.

- CFB Suffield WWT Lagoon: Wastewater at CFB Suffield is treated in a six (6) celled lagoon system. The wastewater is pretreated via four (4) 4225 m^2 anaerobic cells before being treated in a 206400 m^2 facultative cell and a 179800 m^2 settling cells operating in series. This facility services a population of 700 with seasonal surges to 15000. The effluent is discharged to a pond which is used by a local farm for field spreading.

The listed facilities were used to provide a frame of reference when assessing the design, operation, and record keeping of the WWT lagoon system at 17 Wing Detachment Dundurn.

6.9 Relevance to Research

This chapter outlined the methodology employed during the research project associated with 17 Wing Detachment Dundurn’s WWT lagoon system. The overall procedure of the research was presented along with the limitation imposed. In addition, details regarding the author’s sampling programme, the data collected, and the measures that were taken to ensure and control the quality of the data obtained were provided. This chapter established the framework for the collection of data and validated the results and deductions presented in subsequent chapters of this research project.

7.0 Hydrogeological Modelling and Analysis

7.1 Introduction

As stated in Section 4.6, the hydrogeological characteristics of 17 Wing Detachment Dundurn renders it vulnerable to potential sources of contamination. Additionally, the lack of a formalized wellhead protection programme further increases the risk of contamination of the detachment water supply by various possible sources including the Wastewater Treatment (WWT) lagoon system.

Several studies conducted in the past have modelled sites of individual contamination risks. However, no studies available at the time of the desk and field studies of the author, have holistically modelled the groundwater and the possible sources of contamination, including the WWT lagoon system, which may impact the quality of the water extracted by the production wells (PW)s. As such, better knowledge of the groundwater at the production wells and at the WWT lagoon system will help assess the risk associated with the continued operation of the detachment's WWT lagoon system.

In this chapter, the steps taken to develop a hydrogeological model for 17 Wing Detachment Dundurn are presented in detail. These steps include:

1. Selecting of the numerical tools;

2. Developing of the model space;

3. Conducting a pre-sensitivity analysis; and,

4. Conducting model calibration and validation.

In addition, the results from the model are also detailed along with its shortcomings and limitations.

7.1.1 Numerical Modelling - Aim & Objectives

Considering the risk associated with groundwater contamination and the vulnerability of the source water, the aim of the present hydrogeological model is to produce a steady-state model of the groundwater flow in the area surrounding the production wells of the detachment and identify the risks of source water contamination by the WWT lagoon system. The modelling considerations for this project included the following:

1. Selecting appropriate analytical and numerical tools to develop the model based on the data amassed;

2. The availability, ease of use and cost of a suitable numerical modelling package;

3. Whether or not the numerical modelling software was an industry standard;

4. Developing the model using retrieved field data and/or reasonable assumptions based on the literature;

5. Performing a pre-sensitivity analysis of the model;

6. Calibrating and validating the model and its results; and,

7. Applying the model to identify the general provenance of the detachment's source water and identify groundwater flow patterns originating from the WWT lagoon system's site.

Although the following may be mentioned in this report, they are considered to be outside the scope of this project:

1. Modelling the mobilization of leachate from the possible sources of groundwater contamination; and,

2. Providing a draft for a wellhead protection programme or proposing policies for the safeguard of source water at the detachment.

7.1.2 Variables of Interest & Data Set

The data used for developing the model were obtained from multiple sources. The data set includes:

1. Aerial photography: Aerial photography produced by Microsoft Corporation (2018) was used and edited using the QGIS software (QGIS Development Team 2018). This photograph, as seen in Figure N1 of Appendix N, was used as the base map for the model.

2. Groundwater elevation data: Groundwater elevation data were obtained from the groundwater monitoring programme of which data dating back to 2003 was available. All data obtained prior to July 2011 were rejected. This date corresponds to the installation of the newest PW (Well #5). Any data prior to this date would not reflect the current situation. Groundwater elevation data for the September 2015 groundwater monitoring programme were selected, over the 2016 and 2017, for use in this model as they provided the greatest number of observations and have the best spatial coverage (Banilevic 2015). A total of 67 data points was available for use in this model as seen in Figure N2 through Figure N8 of Appendix N.

3. Production well data: The pumping rates of the three (3) PWs applied to this model were obtained from the Water Treatment Plant (WTP) logs.

   The elevation of the PWs' screens were obtained from the wells installation reports (Crowther and Partners 1989, International Water Supply Ltd. 1995). The elevations of all PW screens are within the top layer of the model.

4. Model elevation data: The elevation and geometry of the top layer of the model were made to conform to actual ground elevation data. The data were obtained from the open source Canadian Digital Elevation Model produced by Natural Resources Canada (2016).

5. Geological data: The geological property (i.es. soil composition, depths, and hydraulic conductivity) were obtained from borehole logs and several geological site investigations that were conducted in the past. The available borehole logs have reported an appreciable consistency in soil characteristic. A detailed geological description is given in Section 4.5.1.

6. Brightwater/Beaver Creek data: The water elevation of the creek was estimated to be approximately 514.15 meters above mean sea level (masl). This information was taken from the construction drawing for the wastewater treatment lagoon built in 1988 (Bullée Consulting Ltd. 1988) and the results of the Light Detection and Ranging (LiDAR) survey conducted by the author.

7. Watershed recharge and limits: groundwater recharge was estimated based on the discharge flow of the Brightwater Creek watershed and its catchment area. This data was obtained from the Water Survey of Canada's online databank (Environment Canada and Water Survey of Canada 2019).

7.2 Numerical Tool Selection and Core Equations

This section will elaborate on the numerical tools used for the development of the model.

7.2.1 MODFLOW

MODFLOW 2005 version 1.12.00 produced by the United States Geological Survey (USGS) was selected as the groundwater flow numerical tool for this model. MODFLOW 2005 is an open source three-dimensional finite difference numerical tool written in FORTRAN 90. The code was not modified for the development of this model (Harbaugh 2005a).

This numerical tool was selected for the following reasons; MODFLOW 2005 is the 5^{th} version of MODFLOW originally developed in 1984. This numerical tool is specifically designed for groundwater flow processes. MODFLOW has been proven effective and is widely used in the industry. This tool is open sourced and well documented. Its popularity has resulted in a large community of users that could be consulted for assistance, thus facilitating the development and possible re-use of the model. Additionally, the available data, described in Section 7.1.2, were sufficient to conduct a steady-state analysis.

The governing finite-difference approximation equations used by MODFLOW describe the groundwater flow in cell i,j,k and is defined as follows (Harbaugh 2005b). The nomenclature is described in Figure 7.1.

$$\boldsymbol{q}_{i,j-\frac{1}{2},k} + \boldsymbol{q}_{i,j+\frac{1}{2},k} + \boldsymbol{q}_{i-\frac{1}{2},j,k} + \boldsymbol{q}_{i+\frac{1}{2},j,k} + \boldsymbol{q}_{i,j,k-\frac{1}{2}} + \boldsymbol{q}_{i,j,k+\frac{1}{2}} + \boldsymbol{P}_{i,j,k}\boldsymbol{h}_{i,j,k} + \boldsymbol{Q}_{i,j,k} = \boldsymbol{SS}_{i,j,k}\left(\Delta \boldsymbol{r}_j \Delta \boldsymbol{c}_i \Delta \boldsymbol{v}_k\right)\frac{\Delta \boldsymbol{h}_{i,j,k}}{\Delta \boldsymbol{t}} \quad \textbf{[7- 1]}$$

Where: $\boldsymbol{q}$ = Flow from the six adjacent cells (indicated by their respective subscripts) to cell i,j,k (L^3T^{-1})

$\boldsymbol{P}_{i,j,k}\boldsymbol{h}_{i,j,k} + \boldsymbol{Q}_{i,j,k}$ = Sum of flow from external sources (e.g. well, seepage, rivers, drains, areal recharge) (L^3T^{-1})

$\boldsymbol{SS}_{i,j,k}$ = Specific storage of cell i,j,k (L^{-1})

$\Delta \boldsymbol{r}_j \Delta \boldsymbol{c}_i \Delta \boldsymbol{v}_k$ = Volume of cell i,j,k (L^3)

$\frac{\Delta \boldsymbol{h}_{i,j,k}}{\Delta \boldsymbol{t}}$ = Finite difference approximation for the derivative of head with respect to time (LT^{-1})

L = unit of length and T = unit of time. All units are defined by the user and must remain consistent throughout the model. For this model, L is given in metres and T is given in days.

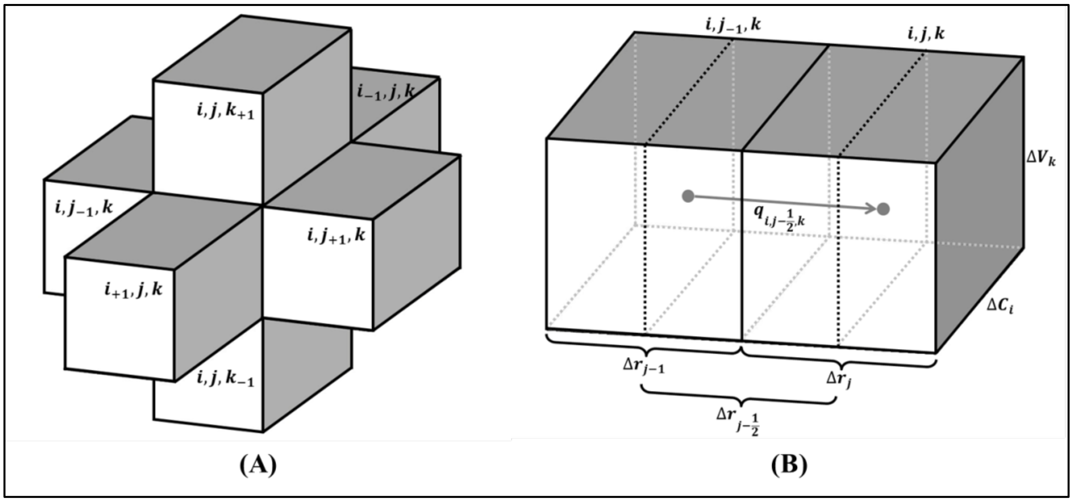

Figure 7.1 - A) Nomenclature of the six adjacent cells surrounding cell i,j,k (hidden), (B) Convention for positive flow from cell i,j-1,k to cell i,j,k. Subscript i,j-1/2,k is used to indicate the distance between nodes (Originally produced by McDonald and Harbaugh (1988) retrieved and modified from A. W. Harbaugh, (2005))

7.2.2 MODPATH

MODPATH version 7.2.001 also produced by the USGS is a particle-tracking post-processing program that is designed to operate with MODFLOW. MODPATH 7 is the fourth major release of this open-source software since its conception in 1989.

This numerical tool was selected since it is specifically designed to conduct water drop analysis and for its seamless interaction with MODFLOW. This open sourced tool is well documented and is widely used in the industry alongside MODFLOW. This tool was also selected since it does not require any additional input than those needed for MODFLOW.

The governing particle-tracking equations for MODPATH are based on the groundwater velocity distribution generated from the flow budget provided by MODFLOW. The x, y, and z coordinates of a particle as a function of time in a structured grid are described in the following equations (Pollock 2016). The nomenclature is described in Figure 7.2.

$$x_t = x_1 + \frac{1}{A_x}\left[(v_x)_{t_1} e^{A_t(t-t_1)} - v_{x_1}\right] \quad \textbf{[7.1A]}$$

$$y_t = y_1 + \frac{1}{A_y}\left[(v_y)_{t_1} e^{A_t(t-t_1)} - v_{y_1}\right] \quad \textbf{[7.1B]}$$

$$z_t = z_1 + \frac{1}{A_z}\left[(v_z)_{t_1} e^{A_t(t-t_1)} - v_{z_1}\right] \quad \textbf{[7.1C]}$$

Where: $\boldsymbol{v}$ = velocity components which are independent of one another. The velocity components within the cells are computed by MODPATH using linear interpolation:

$$v_x = A_x(x - x_1) + v_{x_1} \quad \textbf{[7.2A]}$$

$$v_y = A_y(y - y_1) + v_{y_1} \quad \textbf{[7.2B]}$$

$$v_z = A_z(z - z_1) + v_{z_1} \quad \textbf{[7.2A]}$$

$\boldsymbol{A}$ = velocity gradients within the cell:

$$A_x = \frac{(v_{x_2} - v_{x_1})}{\Delta x} \quad \textbf{[7.3A]}$$

$$A_y = \frac{(v_{y_2} - v_{y_1})}{\Delta y} \quad \textbf{[7.3B]}$$

$$A_z = \frac{(v_{z_2} - v_{z_1})}{\Delta z} \quad \textbf{[7.3C]}$$

t_1 refers to the known location (i.e. coordinates) and velocity component of a particle at the stated time value (user imputed); t refers to a desired time step.

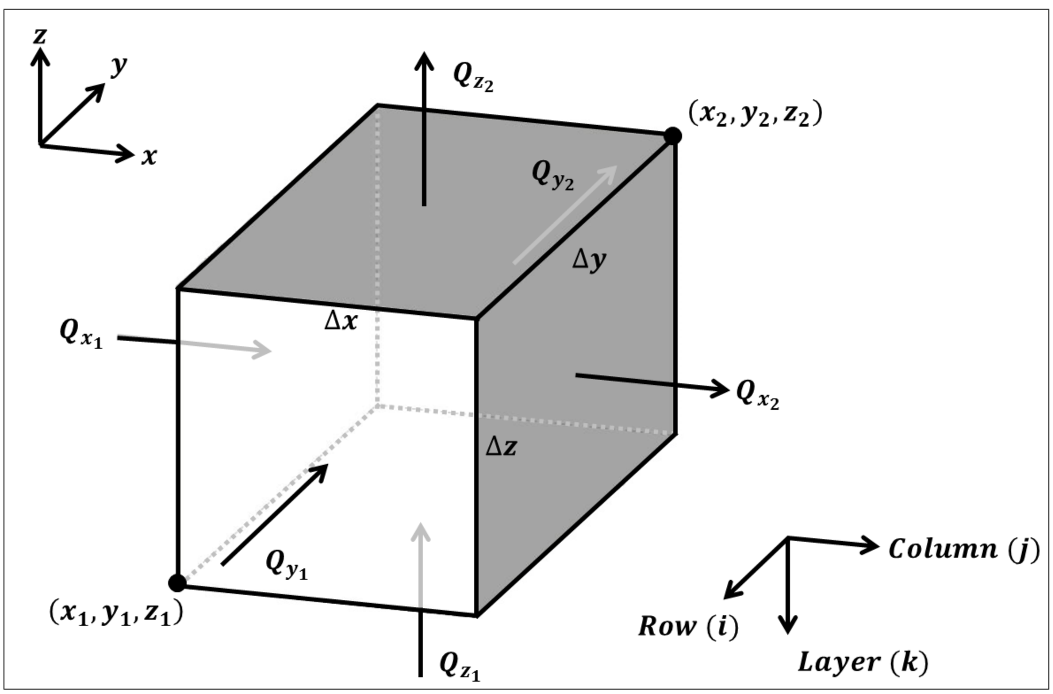

Figure 7.2 – Nomenclature and schematic representation of a finite-difference cell with volumetric flow components of the faces (Modified from Pollock 2016).

7.2.3 Groundwater Vista

As MODFLOW, and by extension MODPATH, do not have a user interface, Groundwater Vistas version 6.96 Build 49 (GWV 6) was used to facilitate the development of the model and to interpret the results (Rumbaugh and Rumbaugh 2017). This licenced software was made available via RMC resources.

In addition to model development, GWV 6 was used to perform sensitivity analysis and calibration. Both were completed using tools integrated into GWV 6.

7.3 Model Development and Checks

The following section will cover the steps that were taken in the development of the hydrogeological model for 17 Wing Detachment Dundurn, specifically.

7.3.1 Optimization of Model Mesh

Once the base map was imported into GWV 6, geo-located, and sized; a mesh was established over the modelled area. The mesh consists of 100 rows (R) x 110 columns (C) x 2 layers (L). All rows and columns are uniform in dimensions (45 m and 62.5 m respectively) and cover a total area of 30.9375 km^2. The origin point (SW corner) was positioned at the grid: -11868 664; 6771 699 (NAD 83). The model mesh when applied to the model can be seen in Figure N9 of Appendix N.

The mesh layers were created based on the boreholes data and geological reports obtained during the desk study. The bottom layer was set at 490 masl (meters above mean sea level) and is 10 m high. This layer was assigned an initial hydraulic conductivity along the x and y axis (K_{xy}) of 0.079 m/d and K with depth (K_z) of 0.0079 m/d. These K values were estimated based on typical values for silty clay soil found in literature (Natural Resources Conservation Service Soils n.d.).

The top layer's bottom elevation was set at 500 masl and had a variable top elevation that conformed to actual ground elevation obtained from the Canadian Digital Elevation Model (CDEM). The data, obtained in the form of an image file, was imported and converted into a surfer file that could be read by the GWV 6 using QGIS (QGIS Development Team 2018) and applied to the top. The variation in elevation can be seen in Figure N10 and Figure N11 of Appendix N. This layer was assigned initial K values of K_{xy} = 0.19 m/d (Wardrop Engineering Inc. 1996, 2002, MEH 2001) and K_z = 0.019 m/d (estimated). These values are consistent with a silty sand material.

As the layers' soil composition was assumed to be homogenous, no variations in K values were applied. K values were later used as calibration variables.

7.3.2 Boundary Conditions

Constant head boundary conditions were established using nine (9) monitoring wells (MW)s. These MWs were selected for their proximity to the four (4) boundaries of the mesh. The spatial distribution of the MWs is presented in Figure N12 of Appendix N. The exact use of the MWs is listed below. The translation of the MW head data to boundary condition into the model (as see in GWV 6) can also be seen in Figure N13 of Appendix N.

1. P9 & P22: MW P9 and P22 were used to establish a constant head gradient along the northern boundary of the mesh. The gradient varies linearly from 516.80 masl (cell R:01 C:24 L:01) to 515.00 masl (cell R:01 C:01 L:01).

2. P25 & P11: MW P25 and P11 were used to establish a constant head boundary of 515.00 masl along the entire western boundary of the mesh (from cell R:01 C:01 L:01 to cell R:100 C:01 L:01).

3. BD#01, BD#05, FFTA#01, SL#5, and SL#7: The five (5) remaining MWs were used to establish a constant head boundary at each of their respective mesh cells as presented in Table 7.1.

Table 7.1 - MWs used as point boundary conditions and their corresponding values

Monitoring Well	Location		Constant Head Value (masl)
	(x,y)	Mesh Cell	
BD#01	2643.87, 0551.67	R:88 C:43 L:01	516.53
BD#05	2787.55, 0108.67	R:98 C:45 L:01	516.67
FFTA#01	6156.69, 0202.06	R:96 C:99 L:01	516.94
SL#5	5608.33, 2948.62	R:35 C:90 L:01	515.10
SL#7	5593.97, 3355.69	R:26 C:90 L:01	514.97

In addition to the MWs, the Brightwater/Beaver Creek was simplified as a constant head boundary condition. This simplification was deemed acceptable as a steady-state analysis was conducted and thus water levels along the creek would remain constant for this model. The affected cells that correspond to the creek can be seen in Figure N13 of Appendix N. The head values during September 2015 groundwater sampling were unknown and were therefore estimated from the values obtained in the WWT lagoon construction drawing (Bullée Consulting Ltd. 1988) and the results from the LiDAR survey. The head value was set to vary linearly with the value listed in Table 7.2. The slight gradient was established to simulate water flow. Head value for the creek was later adjusted to improve the model's fit.

Table 7.2 - Initial and adjusted values for Brightwater/Beaver Creek

Description	Location		Initial Head (masl)	Adjusted Head (masl)
	(x,y)	Mesh Cell		
Entry	5883.23, 0	R:100 C:95 L:01	514.20	514.50
Exit	5075.69, 4499.18	R:01 C:82 L:01	541.00	514.30

7.3.3 Production Wells

The PW #3, #4, and #5 were introduced to the model as analytical elements at their respective location as seen in Table 7.3. Pumping rates were set as constant and were assigned negative values to follow MODFLOW convention in which flow leaving the model is assigned a negative value. The assigned pumping rates correspond to the average rates for the Sep 2015. In addition, the screen elevations obtained from the PWs' construction logs were inputted into the model to set the elevation from which the groundwater was extracted.

Table 7.3 - Production well used as analytic elements

Production Well	Location		Screen Elevation (masl)		Pumping Rate (m^3/d)
	(x,y)	Mesh Cell	Top	Bottom	
3	3969.52, 2222.46	R:51 C:64 L:01	508.311	500.691	-27.67
4	4588.96, 1834.97	R:60 C:74 L:01	505.760	502.710	-38.73
5	3615.57, 2255.89	R:50 C:58 L:01	506.190	499.94	-38.73

7.3.4 Model Properties

7.3.4.1 Groundwater Recharge

As the groundwater recharge for the area of 17 Wing Detachment Dundurn is unknown, approximation was done using the recorded discharge flows for the Brightwater Creek upstream from the detachment and near Kenaston, recording station ID 05HG002 located at 51° 33' 44" N, 106° 30' 03" W. The average for the months of September was calculated from the recorded data and divided over the gross drainage area to estimate recharge. September data was available for a total of eight (8) years between 1960 and 2016.

7.3.4.2 MODFLOW & MODPATH Parameters

MODFLOW parameters were established as part of the final steps prior running the analysis. The following parameters were set in the MODFLOW package (using GWV 6 interface):

1. Units: The time unit was set to days and the length unit to meters;

2. Simulation type and stress period: A steady-state simulation was selected with only one (1) stress period;

3. Layer types: Both layers (Top and Bottom) were set as unconfined; and,

4. Initial head: initial head was set to be 520 masl for both layers.

Evapotranspiration and precipitation were omitted from this model.

7.4 Pre-Sensitivity Analysis

The following section will elaborate on the methodology and the result of the pre-sensitivity analysis that was conducted prior to the model's calibration.

7.4.1 Calibration Variables

The hydraulic conductivity in all directions (K_x, K_y, and K_z) of both layers and the groundwater recharge rate were selected as the variables to be used for calibration. These parameters were selected due to their uncertainty. Head values for the Brightwater/Beaver Creek were also used to manually improve the model's fit.

An acceptable range of value for each of these parameters was set to the values as seen in Table 7.4. The range of value was determined to remain within plausible values. The K upper and lower bound values were selected based on values as seen in literature for the soil type found in each layer (Natural Resources Conservation Service Soils n.d.). As each soil layer was assumed to be homogenous, K_x and K_y were of equal value throughout the calibration process. Groundwater recharge was assigned a range of value of 0.1 to 3.0 times the initial value. Section 7.3.4.1 provides more details on the initial groundwater recharge value.

Table 7.4 - Calibration variables and their acceptable range of values

Variable	Value Range (m/d)	
	Min	Max
GW Recharge	0.1x initial value	3.0x initial value
Top Layer K_{xy}	0.365	1.22
Top Layer K_z	0.0365	1.22
Bottom Layer K_{xy}	0.0363	0.122
Bottom Layer K_z	0.00363	0.122
Creek Head*	514.00 masl	515.50 masl

*Only used for manual adjustment during calibration

Initial value for the groundwater recharge was set, based on the calculated estimate using the procedure detailed in Section 7.3.4.1. To obtain reasonable initial values for the hydraulic conductivity of the top and bottom layer, several iterations were conducted by manually altering the K values. The initial K values were deemed acceptable if the model resulted in no flooded or dried cells and if production wells were able to extract water. These conditions were based on observations of site conditions in September 2015 from the detachment personnel and from the pumping logs.

As a result of the manual trail-and-error iteration process, the initial values presented in Table 7.5 provided acceptable results and were used as the initial state for calibration. The results of this analysis can be seen in Appendix O.

Table 7.5 - Initial values for calibration parameters

Variable	Value (m/d)
GW Recharge	$1.22e^{-5}$
Top Layer K_{xy}	1.00
Top Layer K_z	$1.00e^{-1}$
Bottom Layer K_{xy}	$7.90e^{-2}$
Bottom Layer K_z	$7.90e^{-3}$

7.5 Calibration and Validation

The following section will elaborate on the methodology utilized to calibrate and validate the result obtained from the model.

7.5.1 Calibration Targets

In order to utilize the auto calibration function integrated in GWV 6, calibration targets had to be established. These head targets were obtained from field measurements of groundwater elevation and were compared with the model's result in order to determine suitability. A total of nine (9) MWs were used as calibration targets. These MWs and their values are listed in Table 7.6 and visually represented in Figure N14 of Appendix N.

Table 7.6 - Monitoring wells used as calibration targets and their respective values

Monitoring Well	Location		Head Value (masl)
	(x,y)	Mesh Cell	
P07	0925.62, 3728.85	R:18 C:15 L:1	516.05
P14	0452.97, 4098.16	R:10 C:8 L:1	515.78
POL	5431.31, 1756.71	R:61 C:87 L:1	515.81
MD1	4286.44, 1202.74	R:74 C:69 L:1	515.97
MD2	4308.60, 0722.64	R:84 C:69 L:1	515.12
MD4	4663.14, 0663.55	R:86 C:75 L:1	516.00
MD9	4692.69, 1121.49	R:76 C:76 L:1	515.89
BD3	2535.89, 0338.55	R:94 C:41 L:1	516.62
SL3	5359.32, 2726.51	R:40 C:86 L:1	514.81

7.5.2 Sensitivity Analysis

Following the establishment of calibration targets, a sensitivity analysis was conducted using the automated sensitivity tool integrated in GWV 6. The sensitivity analysis tool runs the MODFLOW analysis through a fixed number of iterations as set by the user. Each iteration introduced a different multiplier to a user defined variable and compares the model's computed results with the calibration targets. The sensitivity tool then plots the sum of squared residuals.

For this model, the sensitivity analysis tool was used with groundwater recharge, K_{xy} for Layer 1 & 2, and K_z for Layer 1 & 2. One run was required per calibration parameter resulting in a total of five (5) runs. The sensitivity tool was set to conduct 36 iterations with multipliers ranging from 0.5 to 4.0 and increments of 0.1. The resulting sums of squared residuals were plotted on Figure 7.3.

As seen in Figure 7.3, the model was noticeably more sensitive to changes in recharge. The model is also sensitive to variations in K_{xy} in Layer 1, to a lesser extent. Only negligible changes occur to variations to K_z in Layer 1, along with K_{xy} and K_z in Layer 2.

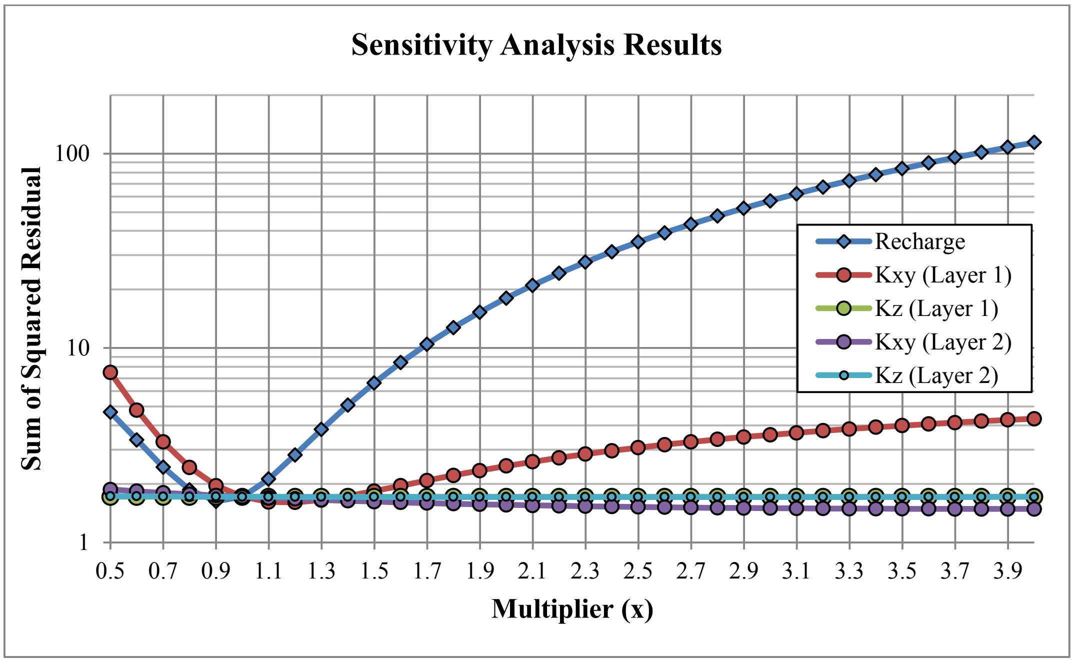

Figure 7.3 - Results from the model sensitivity analysis

7.5.3 Calibration

Pre-calibration was conducted by verifying the model's fit. This step was done by comparing the targets with the computed results at their respective locations and performing statistical analysis. The results from the pre-calibration are presented in Table 7.7.

Table 7.7 - Pre-Calibration Results

Target Name (MW ID)	Target Value (masl)	Computed Results (masl)	Residual (masl)
P07	516.05	516.148	-0.098
P14	515.78	515.504	0.275
POL	515.81	514.400	1.409
MD1	515.97	515.204	0.765
MD2	515.12	515.584	0.535
MD4	516.00	515.276	0.723
MD9	515.89	514.920	0.970
BD3	516.62	516.764	-0.144
SL3	514.81	514.473	0.337
Sum of Squared Residuals		4.542	
Residual Mean		0.530	
Absolute Residual Mean		0.584	
Residual Standard Deviation		0.472	

As clearly seen in Appendix O, targets located to the South and East of the production wells have a poorer fit. The overall fit of the model's values to the target values is more easily seen in Figure 7.4. Ideally all points should be placed on the 45^{o} line indicating a perfect fit. As seen in Figure 7.4, the model's return values are below the fit line (resulting in a positive residual) with the exception of values corresponding with target P07 and BD3. The residual sum of squares for the model prior to calibration equated to 4.542.

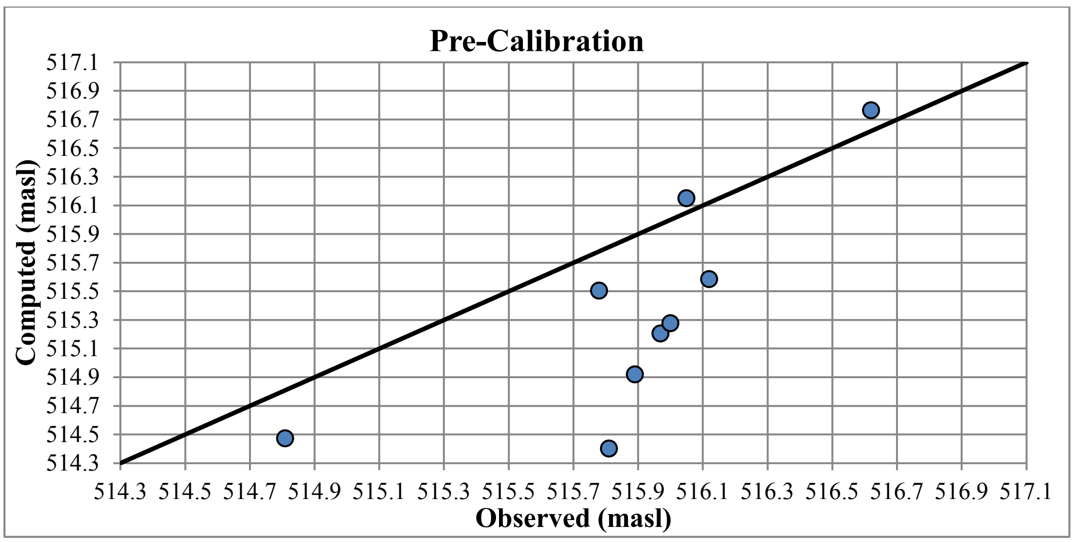

Figure 7.4 - Model fit prior to calibration

Calibration was completed using the integrated calibration tool of GWV 6. The calibration was done with Levenberg-Marquardt's nonlinear least squares curve-fitting method (Rumbaugh and Rumbaugh 2017) using the MWs location assigned as calibration targets. Similarly to its auto sensitivity tool, GWV 6 is capable of automating this process and produce plots. Unlike the auto sensitivity tool, the calibration tool is capable of manipulating up to 50 parameters per run and the user does not have to specify the multiplier for each iteration.

The calibration tool was set to perform 100 iterations with a maximum of three (3) Marquardt iterations and using a parameter multiplier of 0.8. The residuals were not weighted for this calibration process. In an attempt to further increase the fit of the model, the boundary conditions which correspond to the Brightwater/Beaver Creek was manually adjusted within the range of acceptable water levels as seen in Section 7.4.1. This range is based on field observations and LiDAR data.

7.5.4 Validation

Once the calibrated results were obtained, a new MODFLOW analysis would be conducted with the new values applied to the parameters of the model. To validate the model's results, the final calibrated model results needed to meet all criteria listed below and would be rejected if any of the criteria were not met.

1. New values for the calibration parameters need to be within their respective ranges of allowable values as determined in Section 7.4.1;

2. MODFLOW analysis with the new values must not result in any flooded cells;

3. MODFLOW analysis with the new values must not result in any dry cells;

4. MODFLOW analysis with the new values results in operational PW (i.e. drawing water); and,

5. MODFLOW analysis with the new values must provide the lowest sum of squared residuals when comparing to the targets' value.

7.5.5 Particle Tracking Setup

In order to identify the provenance of the detachment's source waster and flow patterns originating from the WWT lagoon system's site, two separate particle tracking analysis were conducted using MODPATH. For the particle tracking to work a properly fitted MODFLOW analysis was conducted with the calibrated parameters and its results inputted into the model.

The first particle tracking analysis was conducted in order to identify the provenance of the detachment's water supply. In order to do so, particles were added as analytical elements using GWV 6. Three (3) circular particle sets, 27 m in radius, were placed centred on each of the PWs. Each set contained 100 particles evenly distributed along their perimeter of the circles. 100 particles were found to fully identify the area affected by each well without overcrowding the model and obscuring the base map underneath, thereby facilitating the analysis of the results. This analysis was set for reverse particle tracking in order to trace the particle path from their unknown origin points to the PWs.

The second particle tracking analysis was done to trace the path of the groundwater originating from the site of the WWT lagoon system. This analysis was carried out in order to identify the path that a theoretical contamination plume would follow if released from the WWT lagoon system. In order to do so, two (2) sets of particles were inputted into the model. The first set consists of four (4) straight segments of 100 evenly distributed particles tracing the perimeter of Cell #1 and Cell #2. The second set consists of 100 particles positioned along the perimeter circle with a 75 m radius centred on the septic tanks and grit chamber. This analysis was set to conduct forward particle tracking.

The particle tracking setup is detailed in Figure N15 of Appendix N and the results from both analyses are detailed in Section 7.6.3.

7.6 Modelling Results

The following subsection will elaborate on the final results of the numerical analysis that was conducted as part of this research endeavour.

7.6.1 Calibrated Results

The model resulted in the best obtained fit using the final variable values listed in Table 7.8. In addition, the Brightwater/Beaver Creek constant head boundary condition was adjusted to the adjusted values presented in Table 7.2. The model results are also visually represented in Appendix O.

Table 7.8 - Comparison of final and initial calibration parameter values

Variable	Acceptable Range	Initial Value (m/d)	Final Value (m/d)
GW Recharge	$1.71e^{-6}$ - $5.13e^{-5}$	$1.22e^{-5}$	$1.95e^{-5}$
Top Layer K_{xy}	0.365 – 1.22	1.000	1.157
Top Layer K_z	0.0365 – 1.22	0.100	1.000
Bottom Layer K_{xy}	0.0363 - 0.122	0.079	0.154
Bottom Layer K_z	0.00363 – 0.122	0.0079	0.001

Table 7.9 - Post-Calibration Results

Target Name (MW ID)	Target Value (masl)	Computed Results (masl)	Residual (masl)
P07	516.05	516.502	-0.453
P14	515.78	515.633	0.147
POL	515.81	514.764	1.046
MD1	515.97	516.111	-0.141
MD2	515.12	516.390	-0.270
MD4	516.00	515.998	0.002
MD9	515.89	515.677	0.213
BD3	516.62	517.126	-0.506
SL3	514.81	514.762	0.048
Sum of Squared Residuals		1.718	
Residual Mean		0.010	
Absolute Residual Mean		0.314	
Residual Standard Deviation		0.437	

7.6.2 Comparison of Initial versus Calibrated Results

7.6.2.1 Fit Comparison

As seen in Table 7.10, the calibration of the hydrogeological model resulted in overall improvements. The sum of squared residuals was reduced from 4.542 to 1.718 resulting in a 62% improvement from initial values. The reduction in overall residual may be more clearly seen in Figure 7.5. Calibrated results improved the fit on all targets with the exception of target well P07 and BD3 which are located in the demolition range and burn dump respectively. The residual for both wells P07 and BD3 increased by 0.355 m and 0.362 m respectively. These values are seen in Table 7.11 which compares the computed results and the residuals for both the initial and calibrated model to the target values.

The spatial distribution of residuals (as seen in Appendix O) indicates that the worst fit is obtained in targets located near boundary conditions with suspicious values. This is the case for wells POL and BD3 which have the greatest residual with 1.046 m and -0.506 m. Well POL is positioned one (1) cell away from the Brightwater/Beaver Creek which was assigned approximate constant head values based on inferred data. Similarly, well BD3 is approximately six (6) cells away from two (2) constant head boundaries which are exhibiting depression cones without cause. The presence of the depression cones at these MWs without an obvious reason cast doubt in the validity of those boundary conditions despite being measured readings.

Table 7.10 - Model calibration improvement

Parameter	Results (masl)		Improvement	
	Initial	Calibrated	Value (m)	$\%_{initial}$
Sum of Squared Residuals	4.542	1.718	2.824	62.171
Residual Mean	0.530	0.010	0.521	98.178
Absolute Residual Mean	0.584	0.314	0.270	46.236
Residual Standard Dev.	0.472	0.437	0.036	7.586

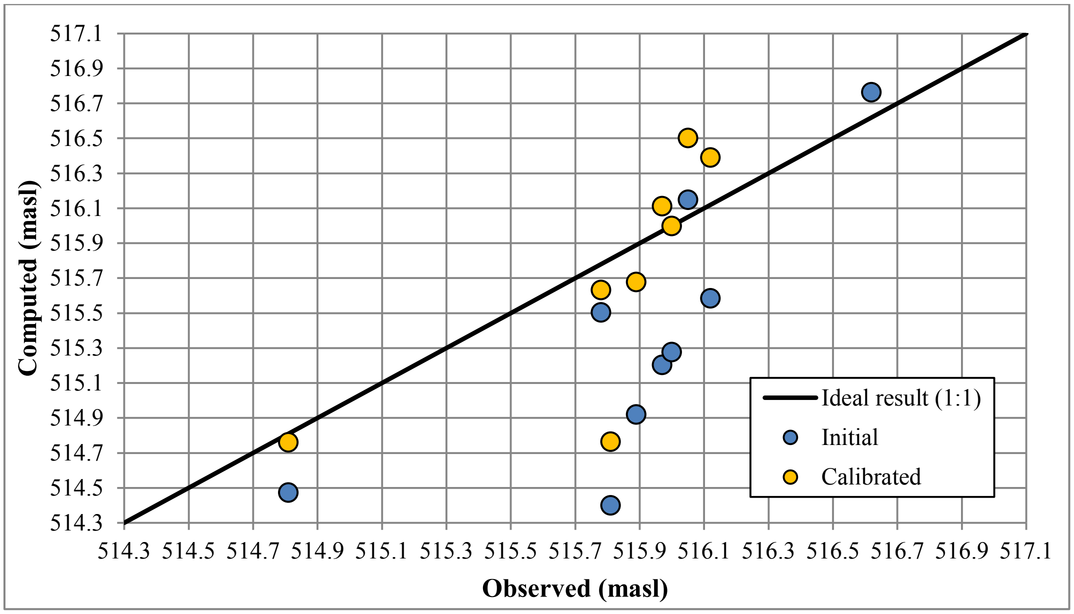

Figure 7.5 - Comparison of models fit pre- and post-calibration

Table 7.11 - Comparison of residual between initial and calibrated results

Target Name (MW ID)	Target Value (masl)	Initial (masl)		Calibrated (masl)	
		Computed	Residual	Computed	Residual
P07	516.05	516.148	-0.098	516.503	-0.453
P14	515.78	515.504	0.276	515.633	0.147
POL	515.81	514.401	1.409	514.764	1.046
MD1	515.97	515.205	0.765	516.111	-0.141
MD2	515.12	515.585	0.535	516.390	-0.270
MD4	516.00	515.277	0.723	515.998	0.002
MD9	515.89	514.920	0.970	515.677	0.213
BD3	516.62	516.764	-0.144	517.126	-0.506
SL3	514.81	514.473	0.337	514.762	0.048

The model residual mean was lowered from 0.530 to 0.010 with calibration, resulting in an improvement of 98%. This is supported by Figure 7.6 which compares the cumulative sum of squared residuals for both pre- and post-calibration result. In the curve associated with the initial results, the majority of the residual error is shared between 5/9 targets. In contrast, the majority of the residual error for the calibrated curve is shared between 3/9 targets. In addition, the calibrated curve is lower than the initial curve. This indicates that the calibrated model has an overall better fit and that most of the targets have good fit (within 0.3 m as seen in Table 7.11). If the three (3) targets mainly responsible for the error (POL. P07, and BD3) were omitted, the sum of squared residuals would be further reduced to 0.162 which would correspond to a 96% reduction from the initial sum of squared residuals.

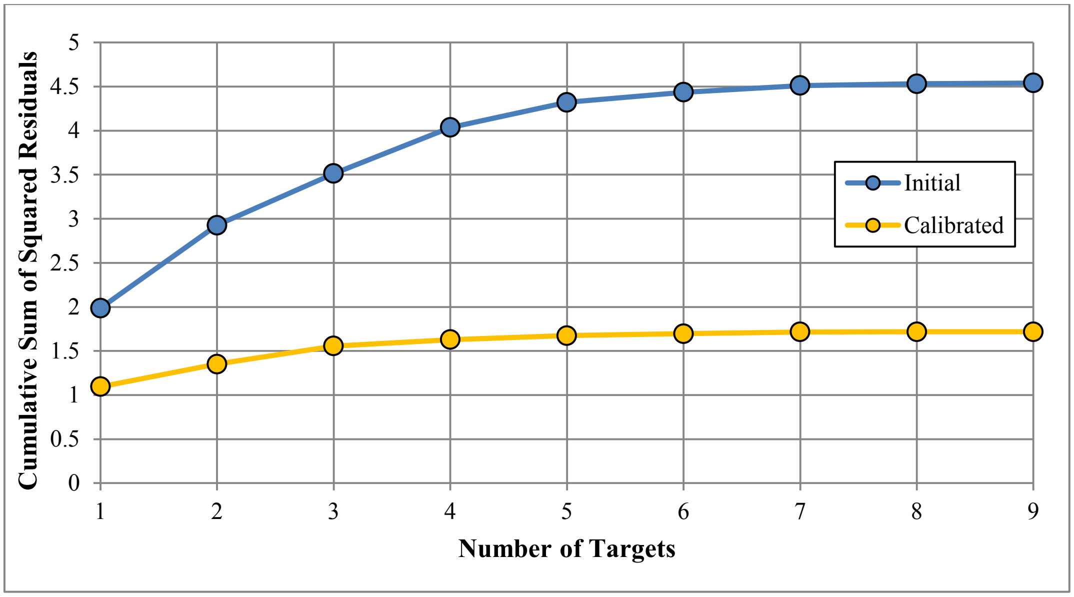

Figure 7.6 - Comparison of models cumulative sum of squared residuals pre- and post-calibration

7.6.2.2 Head Profiles and Drawdown

As seen in both initial and calibrated head profiles of Figure 7.7, groundwater head varies over several metres along its East-West cross-section. When observing the curves along the cross-sections at rows 50, 51, and 60 which correspond to PW #5, #3, and #4 respectively, the depression cones from the PWs can be clearly seen. The locations of rows 50, 51, and 60 can be seen in several figures of Appendix N. A drawdown from the creek is also apparent (at approximately 5200 m). It is consistent with the head contour lines seen in Figures O1 and Figures O5 of Appendix O. The increase in both groundwater recharge and K_{xy} for both layers during calibration resulted in overall higher head elevation throughout the model, with the exception of the western border due to a constant head boundary condition. The changes in calibration also resulted in a decrease in the depression cone from the PWs. These changes, which are consistent with literature, are seen by the transition from the dotted to the solid lines in Figure 7.7.

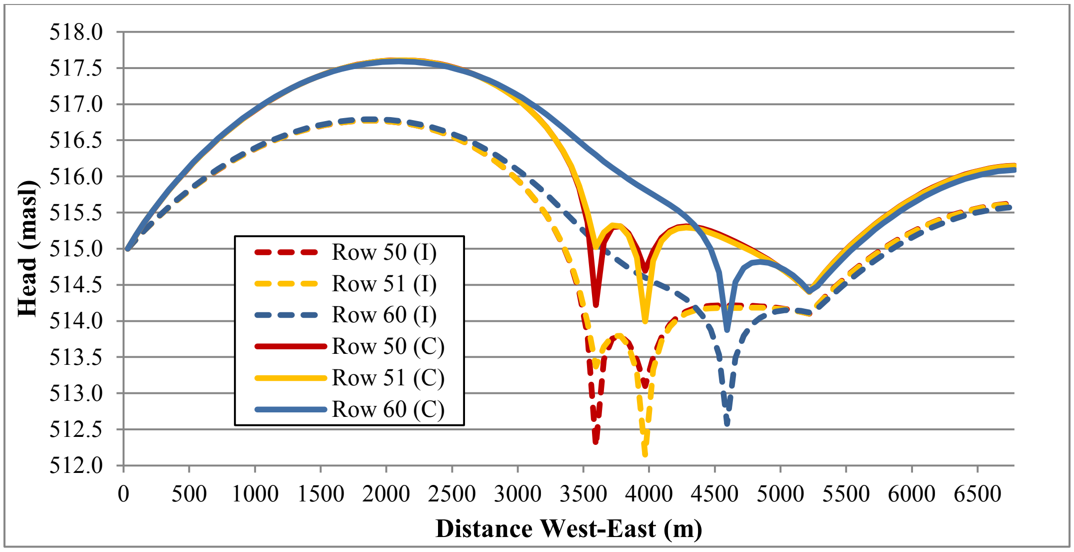

Figure 7.7 - Head Profile along rows 50, 51, and 60. (I) initial and (C) calibrated results

7.6.2.3 Mass Balance

A water mass balance analysis was performed on the model. The results are presented in Figure 7.8. In this model, only three sources of inflow or outflow are present and that includes the constant head boundaries applied along the periphery. These boundaries are primarily allowing for water to leave the model space. Another obvious source for water leaving the model consists of the production wells. The primary inflow source consists of groundwater recharge. The overall balance approached zero (0), as is expected of a steady-state model, with only a small error resulting in a net increase of water despite the model not being assigned any storage functions. No other sources of inflow or outflow to the model exists including evapotranspiration, leakage, precipitation, and storage which have not been included within the current model.

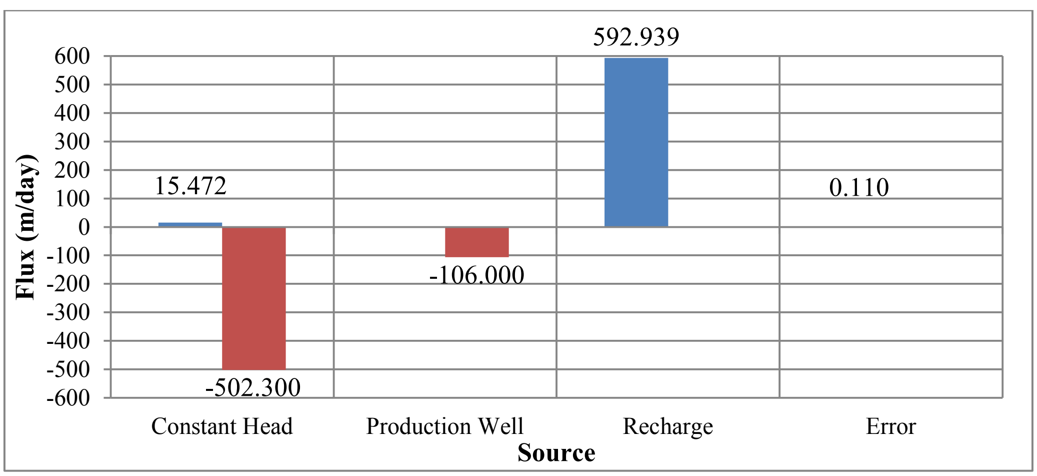

Figure 7.8 - Inflows and outflows to the model space divided by sources

7.6.3 Particle Tracking Results

Figure O11 of Appendix O presents the results of the reserve particle tracking analysis using MODPATH 7 at the site of the PWs. The analysis indicates that, with the groundwater conditions and production well draws of September 2015, the detachment's potable water was sourced from an area extending approximately 1.5 km to the West of the well field.

Figure O12 of Appendix O presents the results of the forward particle tracking analysis using MODPATH 7 at the site of the WWT lagoon system. Based on this analysis, groundwater at the site of the WWT lagoon system flows directly to the West and is fully captured by Brightwater/Beaver Creek.

Based on the two (2) particle tracking analysis, the conditions of September 2015 are such that the detachment's source water is not at risk of contamination from the WWT lagoon system. The creek is acting as an effective barrier that would capture any possible contamination leaks from the WWT lagoon system from migrating west of the creek and into the well field. In addition, particle tracking analysis #1 indicates that the detachment's source water is more likely at risk from the detachment's metal dump and to a lesser degree from the burn dump sites.

A small parametric study was conducted on the production wells pumping rates in order to determine their effects on the provenance of the sourced water. This study was conducted by progressively increasing the draw from each production wells by 10%, 25%, 50%, and 75%. The respective values are given in Table 7.12. As seen in Figure 7.9 and enlarged in Appendix O, all increases did not alter the shape of the particle paths for both Well #5 and Well #3 but merely increase the overall impacted area. With an increase of 10% draw in Well #4, water began being sourced from a narrow band north of the well as well as increasing the particle paths in the south. In addition, the particle path to the south began to encompass the area of the detachment's metal dump. A 25% increase resulted in no alteration in the shape from the 10% increase but enlarged the impacted areas; further encroaching in the area of the metal dump. At 50% and 75% increases, the water was obtained from a new area, in addition the other two (2) areas. This new area was located east of the production well and reached past the creek and well into the administrative area of the detachment. Therefore, an increase of 50% and more would put the detachment's water supply at risk from contamination sources originating from the northern section of the detachments, which include the detachment's fuel station. Figure O14 of Appendix O provides details on the possible contamination sources of the water supply. Figure O14 of Appendix O present the envelopes for each production well overlaid by the various possible contamination sources. The envelopes were created with the results of the parametric study.

Increases in draw above 75% could not be adequately captured by the model and resulted in unrealistic results. This limitation is expected to be due to boundary condition, applied to the model, being no longer appropriate for such draw rates. This indicates that draws above 75% of the ones used in the model would result in a significant impact of the groundwater at the site of the detachment. Increases of 75% did occur periodically between 16 Oct 2013 and 31 Mar 2017 reaching the maximum draw rates shown in Table 7.12.

Table 7.12 - Draw values from parametric study

Draw Factor	Draw Rate (m^3/day)*		
	Well #3	Well #4	Well #5
Original	-27.67	-38.73	-38.73
+10%	-30.44	-42.60	-42.60
+25%	-34.59	-48.41	-48.41
+50%	-41.51	-58.10	-58.10
+75%	-48.42	-67.78	-67.78
Max*	-313.00	-687.00	-730.00

* Draw attributed negative values to comply with GWV 6 conventions

** Maximum recorded draw (16/10/2013-31/03/2017)

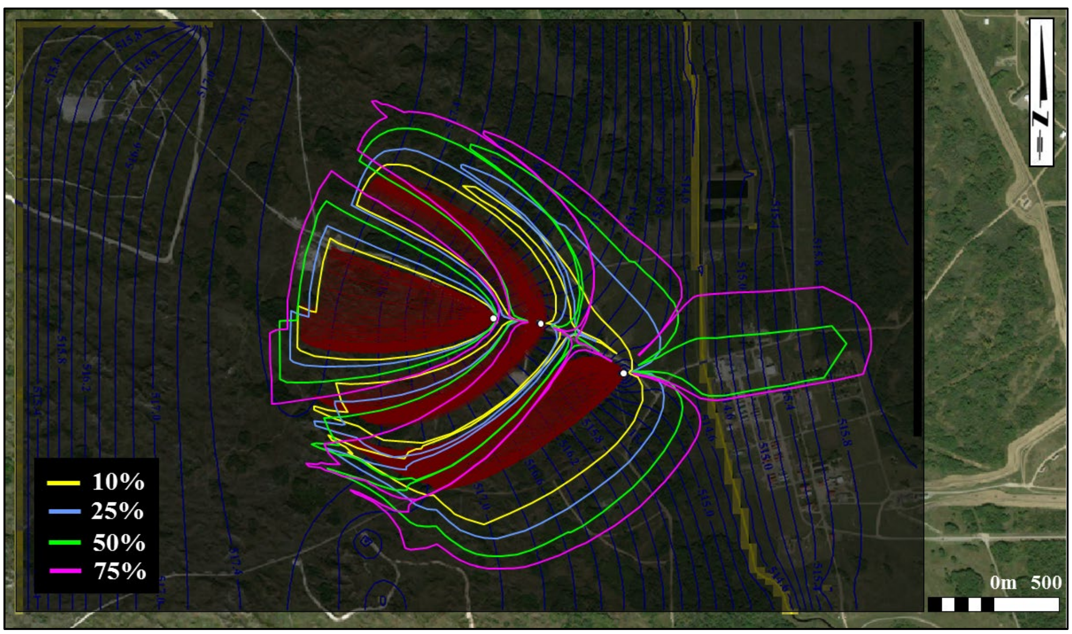

Figure 7.9 - Results of production well pumping rates parametric study

As the current model is only a steady-state analysis with the recorded conditions of September 2015, the results of the particle tracking are only representative for that time period. These particle paths most likely vary seasonally and from year to year. The current model fails to capture such changes.

7.7 Limitations of Current Numerical Model

The hydrogeological model of 17 Wing Detachment Dundurn, presented above, does have shortcomings, in its current form. The limitations include:

1. <u>Creek approximations:</u> The primary limitation of the model is the lack of details regarding the Brightwater/Beaver Creek. No information regarding water elevations and flow rates in the creek near the detachment's WWT lagoon system were available at the time of the desk and field study. The lack of information on these parameters and their seasonal variation prevented the modelling of the creek as an analytical element within the numerical model. In order to compensate for the lack of data and obtain a functional model, the creek was simplified to a constant head boundary condition estimated based on field observation. As an estimated constant head boundary condition, the creek may not be precisely representative of actual field conditions and prohibited the development of a transient analysis. This issue is further complicated by the presence of a beaver dam which was not accounted for in this model;

2. <u>Steady-state analysis:</u> The current models consist of a steady-state analysis only. As such the model is only representative of the groundwater conditions for September 2015. The groundwater does observe seasonal variation and variations over the years due to precipitation and snow melt. Such variations are apparent, based on recorded observations of the creek. In addition the water draw from the PWs also varies seasonally to accommodate the demands of the detachment further altering the condition of the groundwater and may also alter the risk of contamination from the various potential sources. All these variations could not be accounted for in a steady-state analysis; and,

3. <u>Residual error:</u> Despite the improvement made to the model during calibration, large discrepancies still remain between computed and observed target values. Discrepancies as large as 0.453 m to 1.046 m were observed. These discrepancies generate uncertainty on the validity of the MODFLOW analysis result. Such residual errors are unacceptable for many applications.

Despite the limitations presented above, the model in its current state was deemed acceptable for the objective of this research project. As the objectives of the model was to identify the general provenance of the detachment's source waster and ascertain its risk of contamination from the WWT lagoon system, perfect or near-perfect model results are not necessary.

The model would need to be further upgraded and refined by addressing the limitations listed above if it intended to be used for other tasks, such as the development of a wellhead protection programme, which requires more precise model results to adequately accomplish.

7.8 Relevance to Research

This chapter reported on the development of a hydrogeological numerical model for 17 Wing Detachment Dundurn and its results. The chapter presented in detail all the steps taken to develop the model from the collection of various data sets to the calibration of the model. The results from the model groundwater flows and particle analysis were also presented. This model is a significant contribution to this research project as it assisted in determining the risks associated with the contamination of the detachment's source water from the WWT lagoon system. Despite not being explicitly stated as one of the main objectives of this research project, the numerical model created for this purpose by the author identified possible risk to the detachment's source water from other possible contamination source.

8.0 Wastewater Treatment Lagoon Performance Analysis Results

8.1 Introduction

A large sum of data was collected from various sources as part of the desk study into 17 Wing Detachment Dundurn's Wastewater Treatment (WWT) lagoon system. The data was further complemented by data collected during the sampling rounds conducted in Aug 2018, Oct 2018, and Apr 2019. The analysis of the data is the core portion of this research project. The analysis seeks to establish trends as well as interpreting the results considering: treatment processes, the chemistry at play, time and space, climate conditions, influencing factors and process control. The various analyses presented below accomplished the aim of the research project which consists of characterizing the WWT lagoon system, assess the effectiveness of the wastewater's stabilization, and assess for possible containment issues. This section will provide the majority of the deliverables for the detachment and the remainder of the Canadian Armed Forces (CAF).

In this chapter, the results from the analyses of the data collected as part of this research study are presented in detail. The analyses include: weather, influent quantities and qualities, effluent quantities and qualities, study of selected parameters systemwide, surface water quality, groundwater elevation and quality, and comparison of results from RMC and ALS testing.

8.2 Treatment and Discharge Periods

As part of the research project, sufficient data was obtained to cover the five (5) discharge and four (4) treatment periods listed in Table 8.1. The 2018-2019 treatment and 2019 discharge periods are the primary subjects of this research project. The other periods were obtained for the basis of comparison and to establish trends.

The 2018-2019 treatment period lasted for a total of 331 days which is the shortest treatment period observed during this research project. This treatment period is 7% shorter than the average since the 2015-2016 treatment period.

Table 8.1 – Observed treatment and discharge periods

Periods	Total Days	Start Date	End Date
2015 Discharge	10	19 May 2015	28 May 2015
2015-2016 Treatment	353	29 May 2015	16 May 2016
2016 Discharge	15	17 May 2016	31 May 2016
2016-2017 Treatment	350	01 June 2016	16 May 2017
2017 Discharge	8	17 May 2017	24 May 2017
2017-2018 Treatment	367	25 May 2017	05 June 2018
2018 Discharge	10	06 June 2018	15 June 2018
2018-2019 Treatment	331	16 June 2018	12 May 2019
2019 Discharge	8	14 May 2019	21 May 2019

8.3 Weather

As the stabilization of wastewater within lagoons is conducted via biological processes, the rate and efficiency of the treatment is weather dependant. The following subsections will elaborate on temperature and precipitation along with wind speed and orientation.

8.3.1 Temperature and Precipitation

In order to more adequately assess the effects of air temperature at the site of Detachment Dundurn's WWT lagoon system, daily mean temperature readings obtained from the Saskatoon RCS weather station were converted to degree days above various thresholds. This method not only accounts for the number of days for which the threshold was reached or surpassed but for the number of degrees Celsius above the threshold. The sum of degree days is an effective method of assessing biological activity.

The detachment's climate normal from 1981 to 2010 was compared with various other Canadian locations which operate WWT lagoon systems at various latitudes ranging from 45^o to 72^o. As seen in Table 8.2, the detachment climate ranked as the fifth coldest when comparing accumulated degree days above 10^{o}C which is considered the lower threshold for the effective stabilization of wastewater by aerobic bacterial means. All data was obtained from the Canadian Climate Normals databank published by the Government of Canada (2019).

Table 8.2 - Degree days of various Canadian locations operating WWT lagoon system (Government of Canada, 2019)

Name	Location		Accumulated Degree Days Above					
	Latitude	Elevation (masl)	0°C	5°C	10°C	15°C	18°C	24°C
Pond Inlet, NU	72°41'22"	61.6	473.0	99.0	7.1	0.1	0.0	0.0
Kugaaruk, NU	68°32'26"	15.5	660.3	243.2	56.4	5.1	0.9	0.0
Cold Lake, AB	54°25'00"	541.0	2454.7	1469.2	714.3	212.7	64.2	1.1
Dundurn, SK	51°51'35"	504.1	2764.0	1753.0	945.3	366.3	155.8	9.8
Brandon, MB	49°52'00"	362.7	2729.9	1740.9	942.7	367.0	155.3	8.8
Russell, ON	45°15'46"	76.2	3289.9	2127.3	1212.1	529.0	249.4	14.7
Suffield, AB	50°16'00"	769.6	3032.2	1885.6	1006.7	396.3	176.6	10.9

As wastewater temperature data of the lagoon cells was limited to three (3) days corresponding to the sampling periods (i.e. August 2018, October 2018, and April 2019), air temperatures were used as a substitute to assess the effect of temperature on the various treatment periods. As such, the accumulated degree days above 0^{o}C, 5^{o}C, 10^{o}C, 15^{o}C, 18^{o}C, and 24^{o}C were calculated for the four (4) treatment periods listed in Table 8.3. This analysis revealed that the 2017-2018 treatment period received the highest number of accumulated degree days above all thresholds with the exception of the 18^{o}C and 24^{o}C thresholds for which the 2015-2016 treatment period ranked highest. The 2018-2019 treatment period which was the subject of this research project had the lowest accumulated degree days above the 0^{o}C to 15^{o}C thresholds. In contrast, this treatment period ranked second highest for accumulated degree days above the 24°C. These results can be partially explained by the reduced treatment period as seen in Section 8.2.

A breakdown of the average monthly temperature for all four (4) treatment periods can be seen in Appendix P. the monthly averages are compared with the 1981-2010 normal mean, minimum, and maximum.

As seen in Figure P5 of Appendix P, the 2018-2019 treatment period experienced mean temperatures consistently below normals for the Jul 2018 to Jan 2019 with the majority of mean temperatures below the normal minimum. Mean temperature for Feb and Mar 2019 were above the normal maximums.

The monthly breakdown of total precipitation, by treatment period, is also presented in Appendix P, along with daily accumulation of precipitation. The 2018-2019 treatment period experience the lowest precipitation and accumulated only 139.9 mm which consists of only 41% of the 1981-2010 normals and 47% of the average of the remaining treatment periods.

Table 8.3 - Degree Days and Accumulated Precipitation per treatment periods

Treatment Period	Days	Accumulated Degree Days Above						Accumulated Precipitation (mm)
		0°C	5°C	10°C	15°C	18°C	24°C	
2015-2016	355	2683.8	1669.4	904.7	351.1	147.5	2.8	305.6
2016-2017	351	2546.0	1571.4	826.8	286.0	84.4	0.0	352.2
2017-2018	378	2933.1	1927.5	1038.6	379.6	134.2	0.7	239.0
2018-2019	331	1925.7	1189.8	653.8	259.1	113.2	1.9	139.9
1981-2010 Normals	N/A	2764.0	1753.0	945.3	366.3	155.8	9.8	340.4

8.3.2 Wind

Dissolved Oxygen (DO) is an essential component for the stabilization of wastewater in facultative lagoons. The natural reaeration of lagoons is generated by wind turbulence. As such, the prevailing wind direction and speeds were calculated and compared with the orientation of the detachment's WWT lagoon cells. The effect of wind speed, orientation and its associated fetch to DO levels in both cells were not investigated during this research project.

8.3.2.1 Speed and Orientation

Hourly wind speed and direction data were obtained for the Saskatoon RCS station for the period of 01 January 2015 to 12 May 2019. The hourly data were averaged to obtain daily averages. The data, which presents wind speeds in kilometres per hours and wind directions in 10s of degrees, was subsequently converted to metres per seconds and to the 16 cardinal points. The 16 cardinal points were determined by dividing a circle into 16 wedges of 22.5° as depicted in Figure 8.1. The data was then divided into the respective treatment periods and plotted on wind rose diagrams. These diagrams are presented in Appendix P.

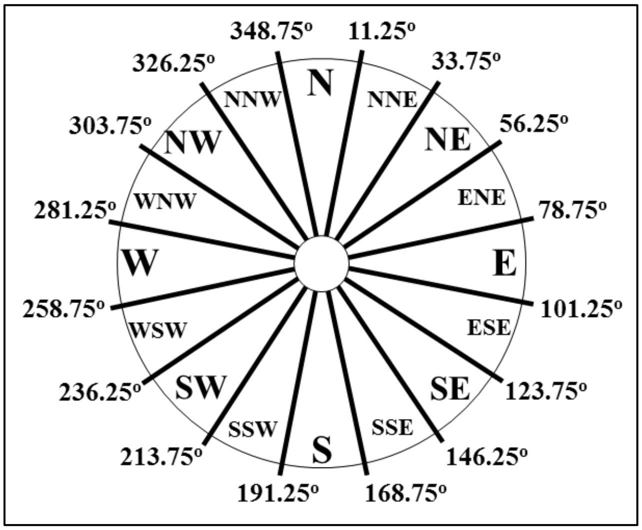

Figure 8.1 – 16 cardinal point divisions in degrees

The wind rose diagrams were further refined by excluding the winter month (November to March) in which ice covers are expected to be present and no wind-driven reaeration is possible. Additional wind rose diagrams were generated to plot the cumulative number of days in which wind was present by directions (as seen in Appendix P) during the expected active treatment periods.

As seen in Table 8.2 and as depicted in Appendix P, the SSW, SW, and WSW wind orientations are most common, accounting for an average of 35% of all windy days. The prevailing wind originates from the SW direction, alone, accounts for 13% of all windy days on average. The second most dominant wind directions included the ESE, E, and SSE accounting for an average of 26% of all windy days.

Table 8.4 - Wind direction by treatment periods in the percentage of recorded windy days

Period	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW
15-16	0	1	2	3	4	6	6	9	8	15	17	8	10	10	3	1
16-17	0	1	2	1	7	11	11	10	8	9	11	14	10	5	3	1
17-18	0	1	0	3	3	4	12	9	10	12	14	12	9	6	4	0
18-19	0	0	4	7	4	12	18	18	15	15	17	21	33	12	2	0
Average (days)	0	2	5	10	15	24	35	34	31	41	48	41	39	25	11	1
Average (%)	0	0	2	3	4	7	10	9	9	11	13	11	12	7	3	0

As seen in Table 8.3 and as depicted in Appendix P, the majority of recoded wind speeds are between 2 m/s and 6 m/s accounting for 83.2% of all windy days. Of these, wind speeds of 3 m/s to 4 m/s are dominant, accounting for 24.5% of all windy days.

Table 8.5 - Wind speeds by treatment periods in the percentage of windy days

Wind Speeds (m/s)	15-16	16-17	17-18	18-19	Average
1-2	4.0	3.0	3.0	4.5	3.6
2-3	27.5	21.0	16.7	21.2	21.6
3-4	24.0	24.5	24.9	24.6	24.5
4-5	21.5	23.5	20.2	19.6	21.2
5-6	13.5	15.0	18.9	16.2	15.9
6-7	5.5	7.5	7.3	7.3	6.9
7-8	2.0	3.5	5.6	5.0	4.0
8-9	1.0	0.5	1.7	1.1	1.1
9-10	1.0	1.0	0.0	0.6	0.6
10-11	0.0	0.0	0.9	0.0	0.2
11-12	0.0	0.5	0.9	0.0	0.3

8.3.2.2 Fetch

In order to quantify and compare fetch between various wind orientations, the surface of both lagoon cells were divided into 10 equal with slices along a specified orientation as seen in Appendix P. The length of all 10 slices were summed to obtain a fetch distance in metres. The obtained fetch distance value was compared to the optimal fetch based on the cells slenderness and orientations. The optimal fetch was obtained from a western or eastern wind due to the near perfect alignment of the cells along the E-W orientations.

As presented in Table 8.6, the optimal fetch distances estimated by the methodology presented above were 3275.59 m and 3088.96 m for Cell #1 and Cell #2 respectively. Additionally, the fetch estimations determined that the detachment's WWT lagoon cells are not optimally oriented, based on dominant winds directions. The dominant winds SW, WSW, and SSW only provide between 40% and 61% of optimal fetch as seen in Table 8.6. Optimal fetch with an E or W wind occur for, on average, 14% of windy days during the active treatment period.

Table 8.6 - Fetch estimations by wind orientation

Cell #	Optimal Fetch Length (m)	SW (225°)		WSW (247.5°)		SSW (202.5°)	
		(m)	$\%_{(optimal)}$	(m)	$\%_{(optimal)}$	(m)	$\%_{(optimal)}$
1	3275.59	1440.80	43.99	1918.06	58.56	1310.70	40.01
2	3088.96	1402.34	45.40	1881.27	60.90	1292.64	41.85

8.3.2.3 Wind Obstacles

The obstacles to the wind's approach to the WWT lagoon cells were identified within a radius of approximately 600 m from the centre point of the southern berm of Cell #1 between the 292.5° (WNW) and 67.5° (ENE) arcs as seen in Figure 8.2. The identified obstacles consist of the following natural and manmade features:

1. Sand borrow pit: Sand borrow pit (identified in red) with an approximate footprint of 120 m x 45 m and 5 m tall, located 20 m east of the perimeter fence;

2. 900 m range buts: Range buts (identified in red) with an approximate footprint of 150 m x 50 m and 10 m tall, located 530 m NE of the perimeter fence; and

3. Dense wood patches: Various dense wooden patches (identified in green) of approximately 10 m to 15 m tall trees, 0.1 m to 0.3 m in diameter, located 140 m or more from the perimeter fence on all sides.

All the obstacles, identified above, are minor and are not expected to cause significant restriction to the wind flow at the WWT lagoon cells and thus do not restrict the cells' wind-driven reaeration. Installation of any new vertical infrastructure within less than 140 m in the north of the lagoon cells (NW through NE) should be avoided. In addition, the vegetation within that same area should also be controlled.

Figure 8.2 - Obstacles to wind

8.4 Influent

The following subsections elaborate on analyses conducted on the influent wastewater. The primary objective of these analyses was to characterize the influent and obtain a baseline for the assessment of the wastewater stabilization provided by the detachment's WWT lagoon system. The data were obtained at the nearest access point which consists of the grit chamber in building #157. The subsections cover volumes, wastewater quality parameters, BOD loading rates, along with pH and temperature.

8.4.1 Influent Volumes

The detachment's wastewater influent volumes were obtained from the daily pumping logs of both pumps located in building 263 transferring the wastewater to Cell #1. The obtained data include the period of 01 Jan 2015 to 12 May 2019. Some gaps in the data of no longer than three (3) days exist due to technical issues. No corrections were made to address these gaps. The total influent volume by treatment period along with the average daily flow can be seen in Figure 8.3. A variation of 19291.32 m^3 was recorded between all treatment periods with the 2017-2018 treatment period reaching a total accumulated volume of 41098.57 m^3. The volume for the 2017-2018 treatment period greatly exceeds the total accumulated volume of the 2015-2016 treatment period which only accumulated 21807.75 m^3. The observed variation cannot be explained purely by the different treatment period lengths as seen by the differences in average flows presented in Figure 8.3.

Cell #1 can only contain a maximum volume of wastewater of 30212.69 m^3 based on construction drawings and assuming a negligible amount of sludge accumulation. The accumulated volumes seen in Figure 8.3 indicate that overflow occurred during the 2016-2017 and 2017-2018 treatment periods. Each treatment period begins with an unknown residual amount of wastewater in Cell #1. The difference between the maximum capacity of Cell #1 and the accumulated volume of 2015-2016 and 2018-2019 treatment periods is only 8405.44 m^3 and 7186.04 m^3 respectively. These differences represent 27.8% and 23.8% of Cell #1's maximum capacity. Although overflowing could not be confirmed for the 2015-2016 and 2018-2019 treatment periods, the differences were minimal. These deductions do not account for the added volume generated by precipitation. Due to the lack of information regarding the initial volumes in Cell #1 at the beginning of each treatment period, the overflow volumes could not be calculated.

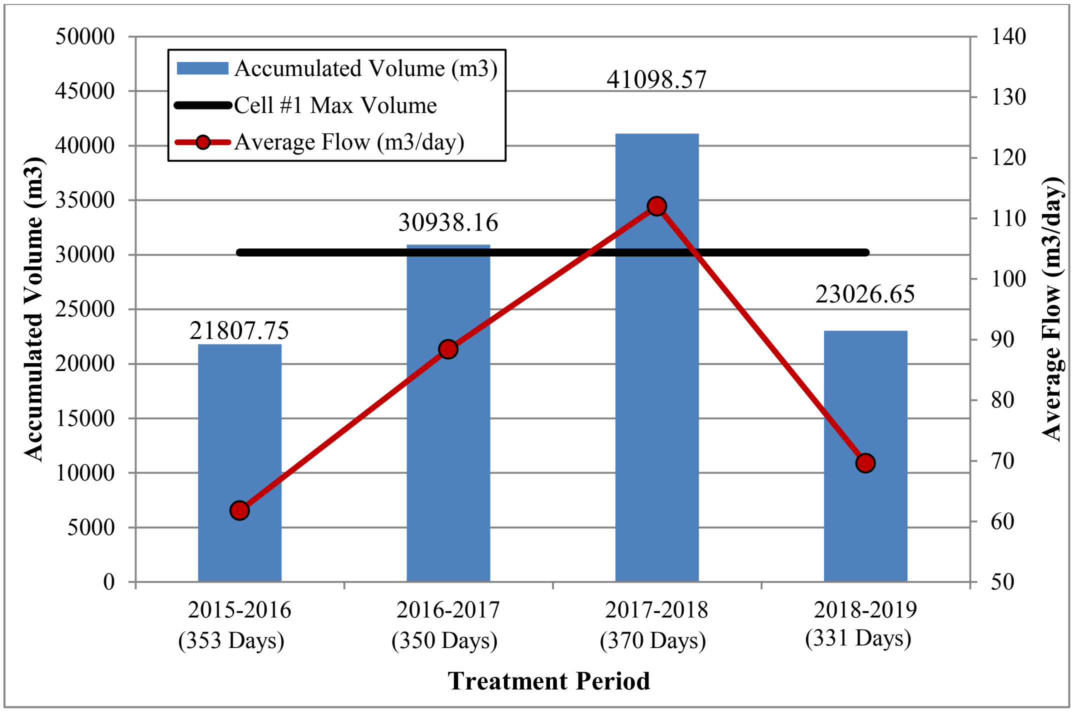

Figure 8.3 - Influent volume and flows by treatment periods

A monthly breakdown of wastewater influent for January 2015 through May 2019 can be seen in Appendix Q. The seasonal increases in influent generation are reported in Table 8.7. The seasonal increases last for a period of 3-4 months and normally occur between the months of May and September. The peak results in an average increase of 25.14% in accumulated volume and 22.54% increase in daily flow. These increases are less than what could be predicted from the expected seasonal increases in population approaching or surpassing 100%. The relatively low increase can be partially explained from the standard practice of employing contracted latrine for the collection of waste for all training and operations in the training area. The waste collected in such a way never reaches the detachment's WWT lagoon system and is treated at a separate facility that is not operated by the CAF.

Table 8.7 - Annual and peak months averages by years

Year	Annual Standard			Peak Months (May-Sept)			
	Average Flow (m^3/day)	SD (σ)	Average Monthly Volume (m^3)	Average Flow		Average Monthly Volume (m^3)	
				(m^3/day)	$\%_{annual}$	m^3	$\%_{annual}$
2015	47.98	8.20	1456.84	60.00	25.04	1835.17	25.97
2016	70.52	14.49	2147.41	86.85	23.15	2639.94	22.94
2017	89.07	23.66	2688.72	175.69	97.26	5140.66	91.19
2018	65.46	3.09	1891.08	78.18	19.43	2392.38	26.51

A graph of the daily influent volumes from 01 Jan 2015 through 12 May 2019 can be seen in Figure Q6 of Appendix Q. An annotated version of this plot can be seen in Figure 8.4 which is enlarged for clarity in Figure Q7 of Appendix Q. Four (4) events, marked by the "1" indicator, have significantly higher influent volume than the overall 82.47 m^3/day average. These events, which reached one order of magnitude higher, were all confirmed by the operators as being the result of maintenance events conducted on the detachment's water distribution system. For example, cleaning of the detachment's water tower was conducted on the 17-19 Jan 2018. These three (3) days were responsible for 7.5% of the total accumulated volume of 2018. Whilst not confirmed, other visible spikes in daily volume are suspected to be the result of other, more minor, maintenance events to the water distribution system.

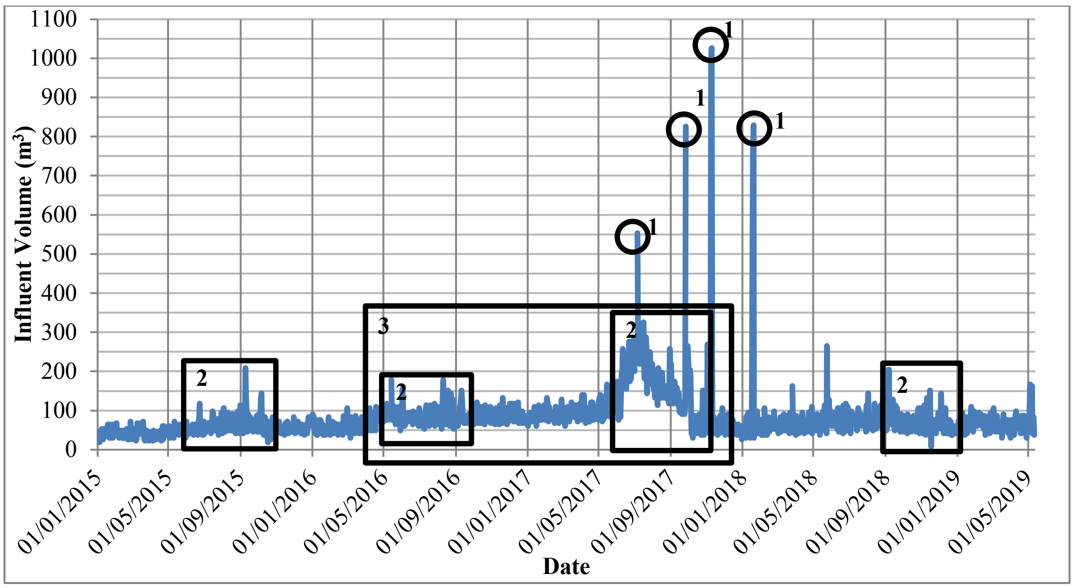

Figure 8.4 - Annotated daily influent volume between 01 Jan 2015 and 12 May 2019

The seasonal increase in volume can be also be seen on this plot in the areas marked by the "2" indicator. In addition, a distinct increase in the average daily influent volumes can be seen between 01 May 2016 and 15 Oct 2017 in the areas marked by the "3" indicator. The cause for this increase was not ascertained, but is expected to be due to an increase in serviced population.

The collected data reflect only the wastewater that was pumped from the lift station (building #236) and directed to the Cell #1 and does not account for possible leaks in the sewage collection network or in the grit chamber (building #157) and any of the septic tanks. As such, the data is not a direct measure of the wastewater generated by the detachment but the fraction captured by Cell #1 (assuming no significant leaks in the pipes between the lift station and Cell #1).

The analysis revealed that the WWT lagoon system's volume is sensitive to small fluctuations in serviced population, changes in the water uses at the detachment, and to the maintenance of the detachment's water treatment plant and water distribution network. This sensitivity is due to the detachment's small size and the relatively large impact caused by any one individual. Additionally, the large portion of water utilized during maintenance events is expected to have an effect on the performance of the WWT lagoon system. The large fraction of clean water added to the regular wastewater influent is expected to cause noticeable dilution. The residual chlorine could also negatively impact the biological activity occurring in the septic tanks. The effects of dilution and residual chorine concentration from water utilized during maintenance events were not ascertained during this research project.

8.4.2 Influent Quality

Table 8.8 presents the average wastewater influent concentration for the parameters that were selected for this research project. The majority of the parameter values were averaged from grab samples of the grit chamber (building #157) obtained during the three (3) sampling rounds conducted in August 2018, October 2018, and April 2019. An exception exists for Ammonia, Total Phosphorus, and Total Nitrogen which were obtained from sampling conducted by the operators on 21 Apr 2015, 27 Apr 2016, and 02 May 2017. Excluding maintenance events, which would alter the concentrations of the influent and introduce chlorine, the influent concentrations are assumed to be relatively constant as supported by the relatively low standard deviations for most parameters.

As seen in Table 8.8, the parameters were compared with the concentration categories established by the FAO (Food and Agriculture Organization of the UN 1992). As expected, the influent concentration proved to be weak, with the exception of Total Dissolved Solids (TDS) with has a medium concentration. All coliform parameters exceeded the detection limit of the testing protocol with an upper limit of 2420/100 mL. The actual concentrations could, therefore, not be determined.

Table 8.8 - Average Wastewater Influent Quality

Parameter	Average	SD (σ)	FAO Category
$CBOD_5$ (mg/L)	109	10	N/A
BOD_5 (mg/L)	120	28	Weak
Thermotolerant Coliforms (MPN/100 mL)	>2420	-	N/A
TDS (mg/L)	725	66.1	Medium
TSS (mg/L)	86.6	31.2	Weak
Total Coliforms (MPN/100 mL)	>2420	-	N/A
E. Coli (MPN/100 mL)	>2420	-	N/A
pH (pH Units)	7.68	0.48	N/A
Conductivity (μS/cm)	1297	178	N/A
Ammonia NH_3 (mg/L)	19.9	1.8	N/A
DO (mg/L)	2.64	1.14	N/A
Temperature (^oC)	10.6	2.5	N/A
Turbidity (NTU)	88.5	34.1	N/A
Phosphorus (P)-Total (mg/L)	3.4	0.8	Weak
Nitrogen (N)-Total (mg/L)	33.3	8.6	Weak

8.4.2.1 BOD Loading Rate

As an essential component for the assessment of a WWT lagoon system, the BOD loading rate was calculated. As the closest data point from the influent of Cell #1, the average BOD_5 concentration for the septic tank system was calculated. Three (3) data points were available from the sampling rounds conducted as part of this research project. The average BOD concentration was valued at 75.3 mg/L. This concentration was assumed to be constant and was attributed to the daily influent volume to obtain a loading rate. The surface area of Cell #1 was assumed to be constant at the cell's maximum operating elevation of 518.600 masl resulting in its largest surface area. The results were plotted for the 01 Jan 2015 to 12 May 2019 period as seen in Appendix Q. The plot was corrected by removing days with extreme wastewater volume as a result of known maintenance days. Additional spikes seen on the graph are expected to be associated with unconfirmed maintenance days and would not represent true BOD loading rates.

Based on the procedure above, the overall average BOD loading rate was 2.79 Kg/(ha·d) and reaching a maximum value of 11 Kg/(ha·d) and a minimum of 0.26 Kg/(ha·d). Table 8.9 provides the BOD lading rate by years between 2015 and 2018. Whilst the BOD loading rate is expected to be slightly higher during the beginning of each treatment due to the reduced surface area of Cell #1, the BOD loading rates are significantly lower than typical BOD for facultative lagoons with ranges of 22 Kg/(ha.d) to 67 Kg/(ha·d). As such, the current WWT lagoon system is not at risk of being overloaded and should be capable of treating wastewater with a higher concentration of waste than what it is currently treating.

Table 8.9 - BOD loading rate by year (2015-2018)

Year	Daily Flow (m3/Day)				BOD Loading Rate (Kg/(Ha*day))			
	Average	SD (σ)	Lowest	Highest	Average	SD (σ)	Lowest	Highest
2015	53.08	19.67	18.93	208.20	1.83	0.68	0.65	7.16
2016	77.35	23.51	30.28	177.91	2.66	0.81	1.04	6.12
2017	123.68	100.81	26.50	1025.85	4.25	3.47	0.91	11.20
2018	78.20	6.01	30.28	829.00	2.43	0.89	1.04	9.11

8.4.2.2 pH and Temperature

As daily readings are not taken from the grit chamber, daily influent pH and temperature values were approximated from readings taken from the septic tanks. These daily readings were extracted for 01 Jan 2018 through 12 May 2019. The results are plotted in Figure Q9 of Appendix Q. An annotated version of this plot can be seen in Figure Q1 of Appendix Q.

The overall pH average was 8.4. With the highest reading of 9.3 and the lowest reading of 7.2, the pH varied around the upper limit of the optimal range of 6.5 to 8.5. Issues were encountered with the pH probe during the timeframe marked by the "1" indicator. The pH readings for this period were obtained via a colorimeter instead of the usual probe. pH readings experienced high variability during this period with the highest readings also occurring during this period.

Due to the readings not being taken immediately at the intake point but from the septic tank with an improvised access hatch, the temperature of the wastewater experiences seasonal variations. The periods marked by the “2” indicator indicate periods in which an agitation pump was in operation in the septic tank as a preventative measure for freezing. This practice accounts for the high variability in the temperature reading obtained during these periods. Based on the information obtained, the average temperature of the influent entering Cell #1 is 11.2^{o}C.

8.5 Effluent

The following subsections elaborate on the analyses conducted for the effluent discharge. The primary objective of these analyses was to characterize the effluent from the WWT lagoon system and to compare it to regulatory standards and guidelines. The data were obtained from the daily grab samples of the 2015 through 2019 discharge periods. The subsections cover effluent volumes, effluent quality, and removal rates.

8.5.1 Effluent Volume

Effluent discharge volumes were obtained from the discharge pump reading taken daily during discharge periods. The discharge pumps (Pump #3 and #4) are located in the WWT lagoon system’s lift station (building #263). Data were obtained for the 2015 through 2019 discharge periods. Table 8.10 present the average daily flow and total effluent discharge volumes for each discharge period. Key data points were missing from the 2015 log which prevented the calculation of flow and total volumes. The overall average daily flow of effluent is 1387.81 m^3/day with an average standard deviation of 246.55 m^3/day and an average total volume of 9762.67 m^3. As seen in Figure R1 of Appendix R, the daily flows observed high variations throughout the discharge periods with the exception of the 2016 discharge which remained remarkably constant. The daily flows for the 2016 to 2019 discharge period were superimposed on the 2010 to 2014 periods, as seen in Figure R2 of Appendix R. Comparison indicated that the average daily flow discharge lowered from 1651.67 m3/day to 1387.81 m3/day from 2010-2014 to 2015-2019. Additionally, the total number of discharge days also reduced from an average of 10 days to 7 days. The effect of current discharge pattern on the environment and the migration of possible contaminants were not investigated in this research project. Such an investigation could be beneficial to the detachment and validate the current discharge practice or proposed alterations. Such an investigation could also benefit from modelling the groundwater during discharge from the WWT lagoon system.

Table 8.10 - Effluent discharge flow and volumes by year

Discharge Period	Days	Average Flow (m^3/day)	SD (σ)	Total Volume (m^3)
2015	8	Missing Data		
2016	10	1088.31	10.13	10883.05
2017	6	1405.65	266.60	8433.89
2018	8	1482.46	248.93	11859.69
2019	5	1574.81	460.53	7874.03

8.5.2 Effluent Quality

The effluent quality data was obtained from laboratory reports of daily grab samples for each discharge period from 2015 through 2019. The discharge averages are presented in Table 8.11. All testing was conducted by ALS Environmental located in Saskatoon with the exception of 2015 testing which was completed by Saskatchewan Research Council (SRC) Environmental Analytical Laboratories.

The daily concentrations for the regulated parameter for each discharge periods were plotted and compared. These graphs can be seen in Figure 8.4 through Figure 8.6. Enlarged versions of these graphs can be seen in Appendix R for legibility. Effluent quality analysis revealed the following:

- <u>5-Day Biochemical Oxygen Demand:</u> BOD_5 is general well below both the legal limit of 30 mg/L and the 25 mg/L guidelines. An exception exists for the 2018 discharge which experience high variability, three (3) exceedances to the guideline concentration of 20 mg/L and one (1) legal limit exceedance with a concentration higher than 30 mg/L was recorded.

- <u>Total Suspended Solids:</u> TSS is highly variable throughout each discharge period. All discharge periods experienced exceedances of either the legal limit of 25 mg/L and/or the guideline of 20 mg/L.

- <u>Un-ionized ammonia:</u> NH_3 is generally below the legal limit of 1.24 mg/L at the beginning of each discharge period. However, NH_3 concentrations generally increase significantly towards the end of the discharge periods. These increases resulted in the 2015 concentrations being dangerously close to the legal limit and exceedance of over 100% in 2016. The 2018 concentrations remained above the legal limit throughout the discharge period reaching a peak concentration of 5.85 mg/L which consists of 472% of the legal limit.

- <u>Concentration increase at end of discharge period:</u> All parameters concentrations consistently increase towards the end of the discharge period resulting in an effluent of inferior quality. The increase in concentration is probably due to the capture of sludge from the bottom of Cell #2 in the effluent as the water column in Cell #2 decreases.

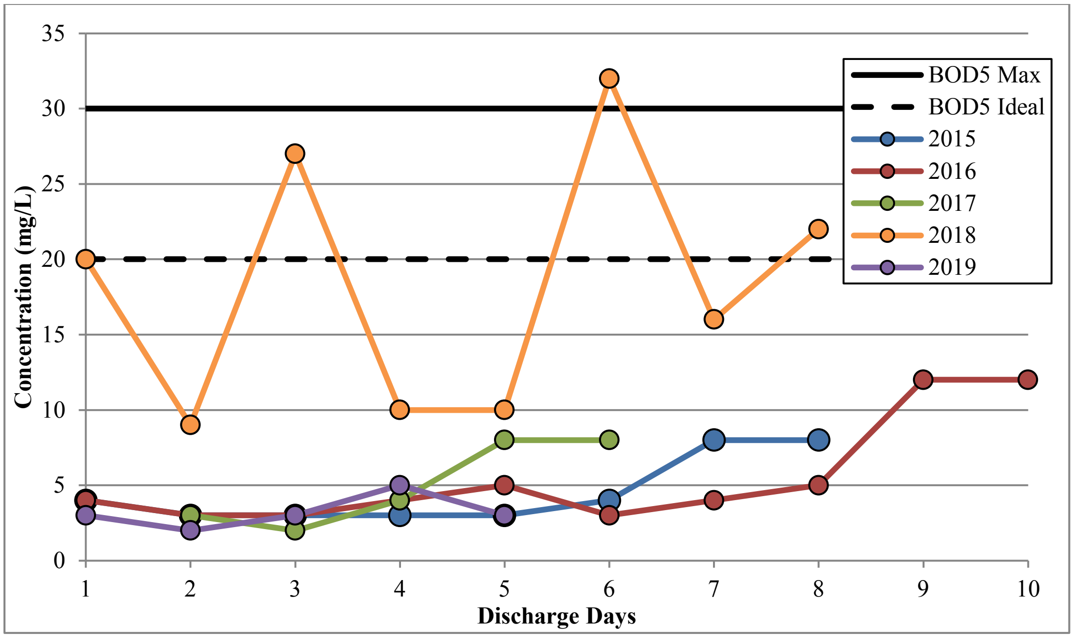

Figure 8.5- Effluent BOD_5 concentrations by discharge days

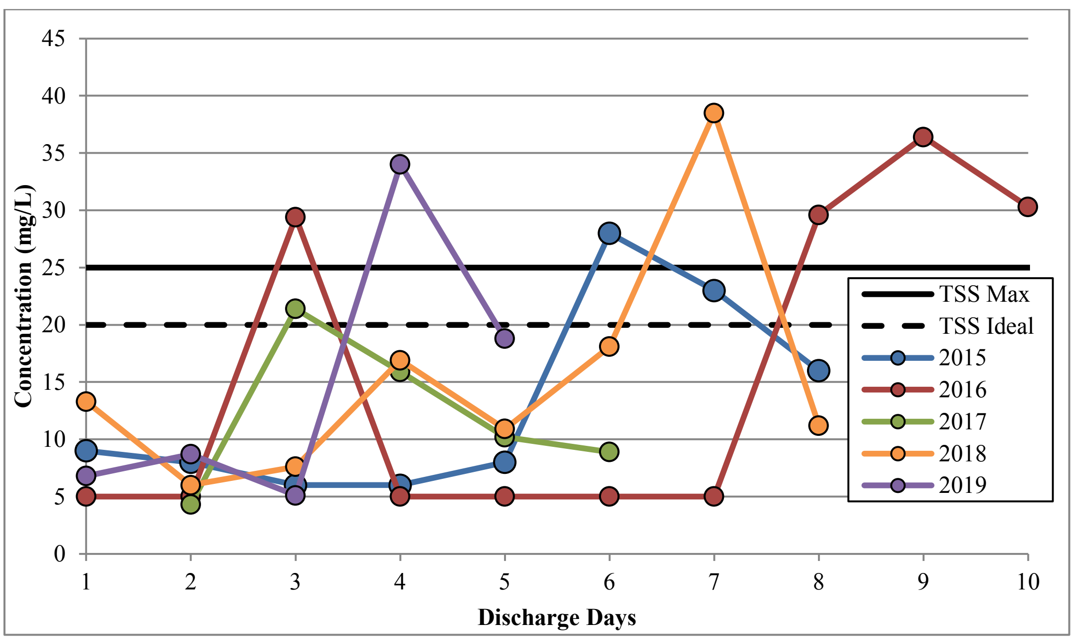

Figure 8.6 - Effluent TSS concentration by discharge days

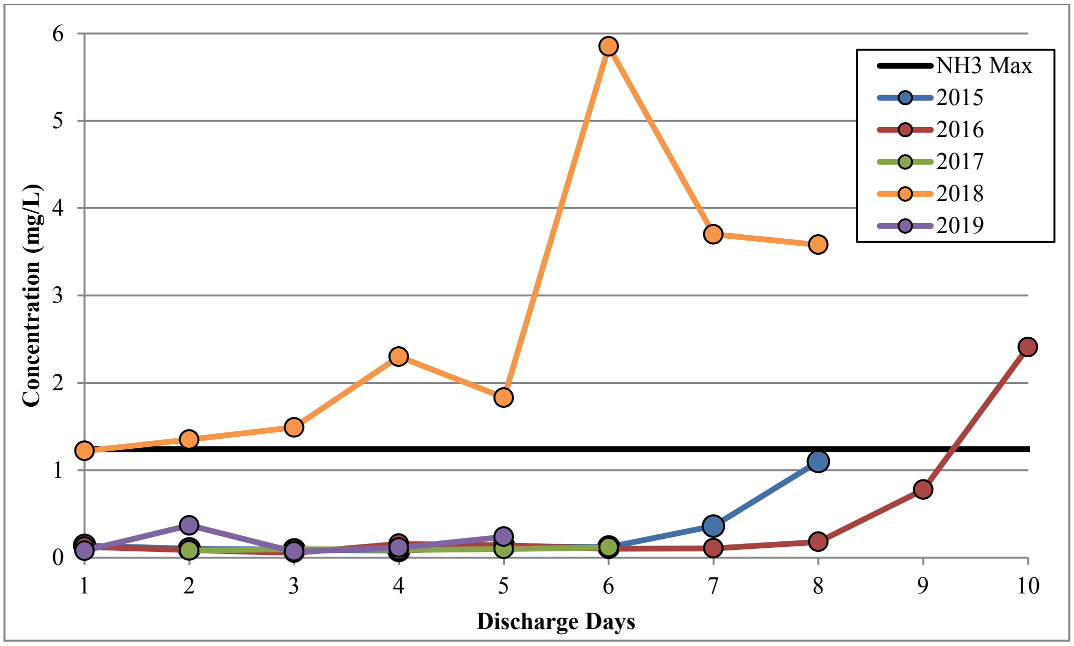

Figure 8.7 - Effluent un-ionized ammonia (NH3) concentration by discharge days

$CBOD_5$ and residual chlorine were not plotted since these parameters were not tested. As chlorine disinfection is not practiced, this parameter is not a concern. Since CBOD is a subset of BOD (i.e. BOD = CBOD + NBOD), $CBOD_5$ concentration will always be inferior BOD_5 concentration. Additionally, $CBOD_5$ regulations are more stringent than BOD_5 and the recorded BOD_5 concentration were inferior to the $CBOD_5$ regulations for the majority of discharge periods. Therefore, it can be concluded that the effluents met the $CBOD_5$ discharge standards despite not being specifically tested for the majority of discharge periods. However, this deduction can't always be utilized, which was the case for the 2018 discharge. As such, $CBOD_5$ should be added to the testing parameters.

As seen in Table 8.11 and in the regulated parameter plots of Appendix R, the 2018 effluent was overall inferior in quality to the remainder of the discharged periods observed during this research project. The logs for the 2017-2018 treatment period recorded an influent volume of 41098.57 m^3. This volume is 136% of Cell #1's capacity, indicating that Cell #1 reached its maximum volume and overflowed for the remainder of the treatment period. A minimum of 10885.88 m^3 of wastewater overflow was transferred to Cell #2 without accounting for initial volume and precipitation. Therefore, the poor quality of the 2018 effluent is expected to be the result of the large volume of untreated or partially treated wastewater that was transferred to Cell #2 during the 2017-2018 treatment period.

Table 8.11 - Average effluent quality by discharge periods

Parameter		Discharge Period				
		2015	2016	2017	2018	2019
$CBOD_5$ (mg/L)	Concentration	-	-	-	-	-
	SD (σ)	-	-	-	-	-
BOD_5 (mg/L)	Concentration	5	6	5	18	3.2
	SD (σ)	2	4	3	9	1.1
Thermotolerant Coli. (MPN/100mL)	Concentration	6	885	70	1740	3
	SD (σ)	8	1143	84	945	1
TDS (mg/L)	Concentration	3185	2927	2448	1053	2578
	SD (σ)	162	289	157	1453	292
TSS (mg/L)	Concentration	13.0	15.6	12.1	15.3	14.7
	SD (σ)	8.4	13.8	6.6	10.2	12.0
Total Coli. (MPN/100mL)	Concentration	15384	409	169	>2420	56
	SD (σ)	38368	707	132	-	81
E. Coli. (MPN/100mL)	Concentration	1	124	32	22	2
	SD (σ)	3	307	27	41	2
pH (pH units)	Value	8.81	9.00	9.10	8.21	9.33
	SD (σ)	0.45	0.37	0.17	0.11	0.32
Conductivity (µS/cm)	Concentration	5434	5326	4512	5153	4788
	SD (σ)	298	320	247	247	409
Ammonia NH3 (mg/L)	Concentration	0.27	0.414	0.096	2.67	0.174
	SD (σ)	0.35	0.732	0.014	1.61	0.128
Nitrogen (N) (mg/L)	Concentration	2.3	2.64	1.68	7.60	2.64
	SD (σ)	0.9	1.81	0.29	4.93	0.82
Phosphorus (P) (mg/L)	Concentration	0.68	1.20	0.53	3.10	0.57
	SD (σ)	0.33	0.69	0.10	0.63	0.11

Additional parameter plots for parameters of interests are presented in Appendix R and include the plots for daily discharge concentrations of nitrogen and phosphorus.

8.5.2.1 Removal Rates

The removal rates were calculated by comparing the average effluent quality with the influent quality obtained during the field study. The removal rates are presented in Table 8.12. As seen in this table, the overall average removal of BOD_5 and TSS for the 2014-2015 to 2018-2019 treatment periods was 94.3% and 83.7% respectively. The removal of Ammonia and Nitrogen was 96.4% and 94.7% respectively. Phosphorus removal was significantly less than all other parameters with a removal rate of only 64.5%. These results are unsurprising since no effluent polishing or chemical additives are used that would improve phosphorus removal. Some values in Table 8.12 could not be computed due to differences in detection limits between various sampling rounds.

Table 8.12 - Average removal rates by treatment periods

Parameters	14-15	15-16	16-17	17-18	18-19	Overall Average
$CBOD_5$ (%)	-	-	-	-	-	-
BOD_5 (%)	96.3	95.4	95.8	84.8	97.5	94.3
Thermotolerant Coliforms (%)	99.8	63.5	97.1	28.1	99.9	77.7
TSS (%)	85.0	82.0	86.0	82.3	83.0	83.7
Total Coliforms (%)	-	83.1	93.0	-	97.7	91.3
E. Coli (%)	99.9	94.9	98.7	99.1	99.9	98.5
Ammonia NH3 (%)	98.7	97.9	99.5	86.6	99.1	96.4
Nitrogen (N) (%)	97.3	94.6	99.1	85.2	97.6	94.7
Phosphorus (P) (%)	80.2	65.1	84.6	9.5	83.2	64.5

8.6 System Wide Parameters

Concentrations from various parameters were obtained from all major components of the detachment's WWT lagoon system which consist of the grit chamber (building #157), the septic tanks, Cell #1, and Cell #2. The primary objective of this analysis was to characterize the performance of the wastewater stabilization. The data originate from grab samples taken during the field investigation of this research project undertaken during the 2018-2019 treatment period. The data were augmented with data from samples taken by the operators prior to the 2019 effluent discharge.

The results were plotted by parameters in order to see both spatial and temporal variation, as seen in Appendix S. The system-wide parameter analysis revealed the following:

- Conductivity: Conductivity remained relatively consistent over time for all locations with the exception of the septic cell which experienced a variation of 3880 µS/cm. Spatial variation indicates that conductivity gradually increase at the wastewater progresses through the system.

- pH: pH experienced little spatial and temporal variation in the system and varied between 7.51 and 9.82. A slight increase in pH can be seen as the wastewater progresses through the system. Cell #2 experience the highest variation with a range of 0.81.

- Dissolved Oxygen: Consistent with expectations, DO concentrations are at their lowest in the septic cell with a concentration of 1.41 mg/L. This is a slight decrease from the grit chamber which had an average concentration of 2.64 mg/L. Due to their environmental exposure; the cells have higher average concentrations with 13.97 mg/L and 13.53 mg/L for Cell #1 and Cell #2 respectively. The two (2) cells also experience the highest variations.

- Total Suspended Solids: Consistent with expectations, TSS concentrations are reducing with the wastewater's progression through the system. The grit chamber is effective pre-treatment of TSS with an average reduction of 83%. The septic cell, Cell #1, and Cell #2 remain relatively constant with average

TSS concentrations of 14.6 mg/L, 18.2 mg/L, and 10.6 mg/L respectively. However, a large increase in TSS was obtained in Cell #1 on the 30 April 2019. This concentration of 85.9 mg/L was 472% the average concentration for all other sampling periods. This result could be due to sediment disturbance during the time of sampling.

- Total Dissolved Solids: TDS concentrations are increasing until the wastewater reaches the lagoon cells. The average concentration for the grit chamber, septic cell, Cell #1, and Cell #2 are 725 mg/L, 1803 mg/L, 1995 mg/L, and 2080 mg/L respectively. The highest variation has been seen in the septic cell which varied within a range of 1652 mg/L.

- Escherichia Coli: Consistent with expectations, the E. coli concentrations decreased once the wastewater reached the lagoon cells. This is due to the long residency time of the wastewater in the cells and their exposure to ultraviolet radiation. The testing protocol was unable to capture the exact concentration in the grit chamber and septic cell which exceeded 2420/100mL.

- Total Coliform: The assessment of total coli. is nearly impossible due to the testing protocol's detection limit of 2420/100mL. Both lagoon cells experienced some variation with values below 950/100mL. Cell #2 experienced the lowest values reaching 20/100mL. Total coliform test results for the 30 April 2019 sampling were not included due to unacceptable detection limit.

- 5-Day Biochemical Oxygen Demand: Consistent with expectations, BOD_5 gradually decreases with the wastewater's progression through the system. The average concentration for the grit chamber, septic cell, Cell #1, and Cell #2 are 129 mg/L, 44 mg/L, 18 mg/L, and 5 mg/L respectively. Concentrations of BOD_5 obtained on the April 2019 sampling round were higher in the septic cell and both lagoon cells than previous rounds. This increase could be due to the reduced biological activity of the winter period. The winter period would reduce the algal biomass and reduce the rate of treatment of influent; thereby increasing BOD_5 concentrations.

- 5-Day Carbonaceous Biochemical Oxygen Demand: $CBOD_5$ experienced a similar behaviour to BOD_5, as can be expected. $CBOD_5$, on average, accounted for 76% of BOD_5 values.

The biology of the wastewater in the WWT lagoon cells were not investigated as part of this research project. In order to fully assesses and characterize the WWT lagoon system, volatile suspended solids and other parameters indicative of biological treatment should be investigated.

8.7 Surface Water

The following subsections elaborate on the analyses conducted for the various surface water sources. The data were obtained from the grab samples taken during the 2015 through 2019 discharge periods in addition to grab samples taken during the field investigation of this research project. The primary objective of these analyses was to identify the effect of effluent discharge on the receiving creek and to identify possible signs of containment failure from any part of the WWT lagoon system. The subsections cover quality analysis of Brightwater/Beaver Creek both during and outside of discharge periods, along with the quality of stagnant water bodies located immediately north of the detachment's WWT lagoon system.

8.7.1 Discharge Creek Quality

The concentrations of various selected parameters were plotted for all pre-, mid-, and post-discharge grab samples for the locations where Brightwater/Beaver Creek meets the southern and northern boundaries of the detachment. These plots, as seen in Figure T1 trough Figure T5 of Appendix T, cover the 2015, 2016, 2017, 2018, and 2019 discharge periods. Due to missing data, pre-discharge concentrations for the 2015 and mid-discharge concentrations for 2018 periods could not be plotted.

Given that the meandering creek flows for 74.22 km between the southern and northern boundary sampling locations, the analysis of the result may be challenging and over interpretation may lead to erroneous deductions. However, when comparing concentrations between pre-, mid-, and post-discharge, the TSS and E. coli have shown the highest variability in all discharge periods and at both sampling locations, with the exception of the 2015 and 2019 discharge periods which experience higher variation in Total coliform then a E. coli. Ammonia has also shown to be variable but to a lesser extent. The remainder of the parameters of interest have remained comparatively consistent.

To facilitate the comparison of the two (2) sampling locations over the discharge periods, the variation, expressed as a percentage of the initial concentrations (i.e. concentration located at the southern sampling point), was plotted before and after each discharge period. Due to missing data, the 2018 discharge period could not be plotted in this way. The plots can be seen in Figure T6 through Figure T9 of Appendix T.

Based on recorded flow rates for Brightwater/Beaver Creek obtained from Water Survey of Canada (2019), the effluent can take between 18 h and 97 h to reach the sampling location at the northern boundary. Given the time delay observed before conducting the post-discharge sampling, as seen in Table 8.13, post 2016 and post 2018 discharge sampling may not be representative of the creek's condition after discharge as intended. A minimum period of five (5) days should be observed in order to ensure that effluent has fully flowed out of the detachment's training area in order to assess for lingering effects.

The waiting period could be refined based on flow calculation at various points in the creek between the northern boundary.

The creek's post discharge resulted in a drastic reduction in TSS concentration change for all the recorded discharge periods and even resulted in lower TSS concentrations. Post discharge concentration for 2016 and 2017 observed an 87.6% and 17.0% reduction respectively. E. coli concentration changes decreased on average by 215.3% with the exception of 2015 which has seen an increase of 420.3%. Total coliform concentration change increased by 420.3% and 21.6% for 2015 and 2016. In contrast, the concentration lowered by 210.1% in 2017. Ammonia and TDS concentration changes consistently lowered for all observed years.

Table 8.13 - Pre- and post-discharge sampling dates

Discharge Period	Pre-Discharge Sampling		Post-Discharge Sampling	
	Date	Days Before Discharge	Date	Days After Discharge
2015	21/04/2015	28	16/06/2015	19
2016	27/04/2016	20	01/06/2016	1
2017	02/05/2017	12	09/06/2017	16
2018	-	-	19/06/2018	4
2019	30/04/2019	14	27/05/2019	6

Due to the lack of data, the comparison of the creek's quality a location near the discharge points could not be undertaken during the discharge periods. Such analysis could only be conducted whilst the WWT lagoon system was not discharging.

8.7.2 Non-Discharge Creek Quality

The concentrations of various selected parameters were analysed for Brightwater/Beaver Creek during various days when no discharge was occurring. The data correspond to the sampling rounds conducted in Aug 2018, Oct 2018, and Apr 2019 augmented by pre-discharge data collected from the operators for the 2016, 2017, and 2019 discharge periods. The results were plotted as the variation between concentrations at the south sampling point (upstream) and the north sampling point (downstream) from the detachment's WWT lagoon system expressed as a percentage of the upstream values. The distance between sampling points was approximately 1 km for the samples collected during the field study of this project and 1.6 km for the samples collected by the operators. The results can be seen in Figure 8.8. An enlarged version of the plot is provided in both graph and table formats in Figure T10 of Appendix T for legibility.

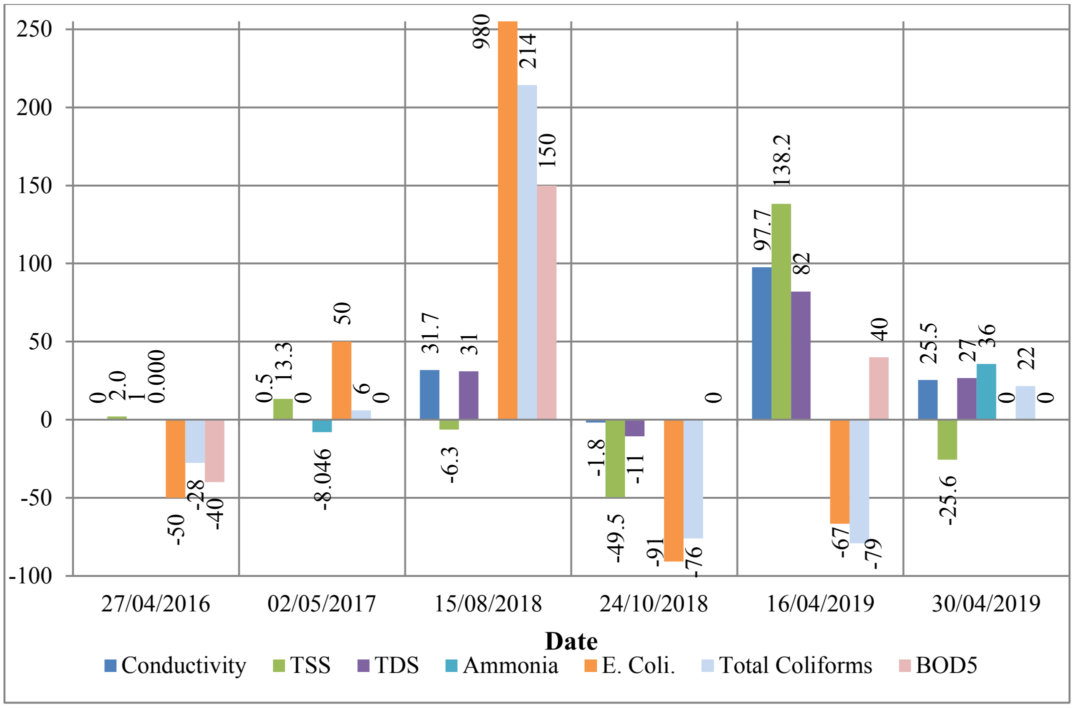

Figure 8.8 - Change in parameter concentrations up & down the stream from WWT Lagoon (all values in %)

As seen in Figure 8.8, days associated with high water levels (i.e. spring melt and autumn precipitations) see a general reduction in parameter concentrations. The reduction in concentrations for 27 Apr 2016 and 24 Oct 2018 is most likely due to dilution. During these periods, the creek is expected to be recharged by groundwater resulting in the observed reductions in concentrations of all parameters with the exception of the slight increase in TSS and TDS in the 2016 samples. This minimal increase could be due to disturbances of creek sediments at the time of sampling. Whilst the results of the 16 Apr 2019 samples indicate a reduction of E. coli and Total coliform, Conductivity, TSS, TDS, and BOD_5 have all experienced increases. Similar results were seen for 30 Apr 2019 with only TSS experiencing a reduction in concentration.

Days associated with lower water levels may provide more information on the state of the lagoon's containment system. As the creek recharge rates by the groundwater is reduced, any possible leaks from the lagoon's cells would be more prominent. The data from 02 May 2017 and 15 Aug 2018 indicated an overall increase of concentrations for most parameters. More importantly, the 15 Aug 2018 sampling, which was conducted during the period with the lowest water level, resulted in an increase of the original E. coli from 5/100mL to 54/100mL. In addition, the Total coliform concentration increased from 770/100mL to over the detection limit of 2420/100mL. The BOD_5 concentration also increased from 4 mg/L to 10 mg/L. The results from the 15 Aug 2018 and 02 May 2017 may indicate that the detachment's WWT lagoon system could have issues in its containment system in sufficient quantities to cause deterioration on the

Brightwater/Beaver Creek during periods of low water levels. However, the leaks would not be sufficiently large to cause deterioration of the creek year round at the time, based on data obtained during sampling. More data points would be required to assess the extent of the lining system's failure and its rate of deterioration.

8.7.3 Stagnant Water Bodies Quality

Data obtained from two (2) stagnant water bodies located approximately 60 m and 260 m north of the WWT lagoon cells during the field study were plotted for various parameters as seen in Figure T11 of Appendix T. The sampling point SW-1 and SW-2 are both within the same water body and have recorded E. coli, Total coliform, BOD_5 and $CBOD_5$ values. The presence of these values could not be solely attributed to leaks in the WWT lagoon cells as wildlife regularly access the water body as evident by field observations and the lack of controlled access. However, as seen in Figure T12 of Appendix T, SW-1 is consistently of inferior quality than SW-2 with the exception of E. coli concentration on 24 Oct 2018. As seen in the particle tracking analysis of Chapter 7, SW-1 is located along the flow path of the groundwater originating from the WWT lagoon site. As such, the consistent increased in concentrations of parameters indicative of wastewater contamination could be the result of leaks in the WWT lagoon cells' lining system. The data therefore support the conclusions, obtained in Section 8.7.2 that the lagoon lining system may have failed and leaks are occurring.

8.8 Groundwater

The following subsections elaborate on the analyses conducted on the groundwater obtained from the nine (9) MWs located around the WWT lagoon system. The data were obtained from grab samples from the 2003 to 2017 groundwater monitoring programme and the field study portion of this research project conducted during the 2018-2019 treatment period. The primary objective of these analyses was to identify possible signs of containment failure from any part of the WWT lagoon system. The subsections cover groundwater elevation and groundwater quality.

8.8.1 Groundwater Elevation

During the field study conducted in the 2018-2019 treatment period, the depth to groundwater was measured using an electric dip metre. The measured readings were corrected to account for tape elongation based on the manufacturer's specifications. The elevation of the groundwater was then calculated using the known elevation of the ground and the height of the well casing protruding from the ground. A similar procedure was employed by Defence Construction Canada (DCC) and the various other organizations contracted to carry out the sampling for the detachment's groundwater monitoring programme.

In order to determine the variability of the groundwater elevation over time, the average groundwater elevation of all nine (9) MW was plotted for each sampling round from 2003 to 2019. The plots included the range of values via high-low lines, as seen in Figure U1 and Table U1 of Appendix U. The results indicate that the average groundwater elevation normally varies between 514.64 masl and 515.10 masl with individual well elevation within 0.40 m from each other. However, the Oct 2014 and May 2015 sampling rounds resulted in significantly lower averages of 513.94 masl and 513.75 masl respectively. These values do not reflect the trends of the other samples taken during the same months of the year. The groundwater at those dates also experience much wider disparity between individual well with a range of 1.08 m and 1.21 m for Oct 2014 and May 2015 respectively. These levels may be partly due to the low monthly precipitation when compared to the 1981-2010 normals. Similarly, the results from the Aug 2003, Aug 2004, and Jul 2005 also resulted in large disparity between individual well with ranges of 1.61 m, 1.57 m, and 1.45 m respectively.

The historical groundwater elevation was also plotted for each well as seen in Figure U2 and Table U1 of Appendix U. The plot features the average groundwater elevation along with the range of values via high-low lines. The plot was also marked with the bottom elevation of each MW. The results indicate that the average elevation of the groundwater in all MWs is relatively constant ranging from 515.03 masl and 514.48 masl. The groundwater in MWs SL#5 through SL#9 varied within a range of 1.59 m on average. SL#1 and SL#2 experience relatively little change with groundwater elevation varying within 0.51 and 1.07 m respectively. The full range of variation for both SL#3 and SL#4 could not be ascertained as both MWs dried in the past. These MWs are therefore not sufficiently deep enough. Once SL#3 and SL#4 require significant maintenance or need to be rebuilt, the wells should be dug deeper in order to capture the full range of groundwater level depth. A similar consideration should be considered for SL#5 which had recorded groundwater levels of only 0.06 m above the bottom of the MW.

In an attempt to determine the seasonal variations of the groundwater, the average monthly groundwater elevation was plotted for each MW as seen in Figure U3 of Appendix U. The plot was overlaid by a chart indicating the amount of data points available for averaging by months. No data was available for the months of January, February, March, April, and November. As the groundwater monitoring programme is generally undertaken in the August to October timeframe, four (4) data points were available for averaging for those months. Only one (1) data point was available for the months of April through July, and December. The averages for all MWs during the month of May are considerably lower than the other recorded months as the data correspond to the May 2015 sampling round. May 2015 levels were noted to be considerably low and may not be representative of actual averages for the month of May. Additionally, the average groundwater elevation for SL#9 is considerably lower than the remainder of the MWs for the months of July and August. Whilst the July average is based on a single data point, the August averages four (4) data points which provided more validity to the results. SL#9 is 1.16 m and 0.62 m below the average of the other MWs for the months of July and August respectively. The large discrepancy may be due to the proximity (approximately 23 m) of SL#9 to the Brightwater/Beaver Creek. The seasonal variations in the MWs at the site of the WWT lagoon system could be improved with the addition of new data points for the first seven (7) months of the year.

In order to estimate the groundwater flow path at the site of the detachment's WWT lagoon system, the groundwater elevations obtained during the Aug 2018, Oct 2018, and Apr 2019 sampling rounds were placed on satellite imagery. The maps can be seen in Figures U4 through Figure U6 of Appendix U. The overall trends in all three (3) maps are consistent with expectations; with the groundwater flowing westwards towards the creek. In contrast, the MWs located around the grit chamber and septic tanks indicate the groundwater flowing SE away from the creek. The reason for the change in the groundwater flow direction at the site of the grit chamber and septic tanks was not ascertained during this research project.

8.8.2 Groundwater Quality

The values/concentrations of various parameters of interest in the groundwater grab samples obtained during the Aug 2018, Oct 2018, and Apr 2019 sampling rounds were analysed and plotted, as seen in Figure U7 through Figure U9 of Appendix U. Due to the inability of extracting sufficient groundwater for analysis, groundwater quality from SL#4 could not be conducted for the Aug 2018 sampling round.

The analysis results indicated that overall SL#4, SL#5, and SL#9 are consistently of inferior quality. All three (3) MWs have elevated conductivity concentrations with an average concentration of 2174 µS/cm, 1727 µS/cm, and 1601 µS/cm above the remaining MWs' average respectively. These values are supported by field observations of the groundwater samples. In particular, all samples extracted from SL#9 had a rusty colour, which could be indicative of high iron content. SL#7 also experience elevated conductivity during the Aug 2018 and Apr 2019 sampling rounds. The metal content of the groundwater was not analysed. In addition to the elevated conductivity, all three (3) MWs had detectable concentrations of $CBOD_5$ and BOD_5 during at least one sampling round. SL#5, in particular, had consistent BOD_5 and $CBOD_5$ concentrations between 26 mg/L and 40 mg/L. These results are supported by the presence of septic odours that emanated from the well at the time of the field study. SL#7 also returned BOD_5 and $CBOD_5$ concentrations of 3 mg/L and 2 mg/L respectively during the Aug 2018 sampling round. During the Apr 2019 sampling round, SL#9 returned a Total coliform concentration of 1/100mL.

The results from SL#4, SL#5, SL#7, and SL#9 indicate that contamination of the groundwater is occurring from a persistent source. The conditions of the MWs at the time of the field study were not ideal. As seen in Appendix F, many of the well caps were not properly fastened, sampling equipment left in the wells had rope or tubing protruding, none of the protective casings were locked to prevent unauthorized access and SL#5's casing was broken. These factors allow for the possibility of contamination from other sources than the wastewater from the WWT lagoon system. The lack of E. coli contamination also indicates that the source of contamination may not be from the wastewater in the WWT lagoon cells. Whilst not a direct indication of containment failure of the WWT lagoon cells by themselves, the results obtained from the MWs support the results from the surface water analysis with regard to leaks in the WWT lagoon cells. As such, breaches of the liner system are expected to be occurring in the NW and SE corners of the WWT lagoon cells resulting in the consistent inferior quality of the groundwater obtained from these MWs. In order to validate the results of this analysis, the MW should be cleaned and inspected to eliminate the effects of possible outside contamination sources, then resampled.

To analyse the spatial distribution of the results presented in Figure U7 through Figure U9 of Appendix U, the temperature, conductivity, and pH data was georeferenced on satellite imagery as seen in Figure U10 through Figure U18.

The results from the 2003 to 2017 groundwater monitoring programme were analysed for E. coli and total coliform contamination. E. coli contamination was only recorded in SL#4 during the Oct 2013 sampling round. As seen in Figure U19 of Appendix U, all MWs have a record of total coliform contamination hits since 2011. Several reports prior to 2011 were not included due to their unacceptable detection limits. The results also indicate that the contamination from total coliform is most frequently reported in SL#2 and SL#7. The highest concentration levels have been reported in SL#1 and once in SL#7 with concentrations over 200/100mL. In addition, the frequency of hit seems to be increasing over the seven (7) year period observed as seen in Figure 8.9. If the contamination is originating from the WWT lagoon system, these results would indicate that the condition of the WWT lagoon system is deteriorating. This would be consistent with the age of the system approaching the end of its useful service life as stated in Chapter 4.

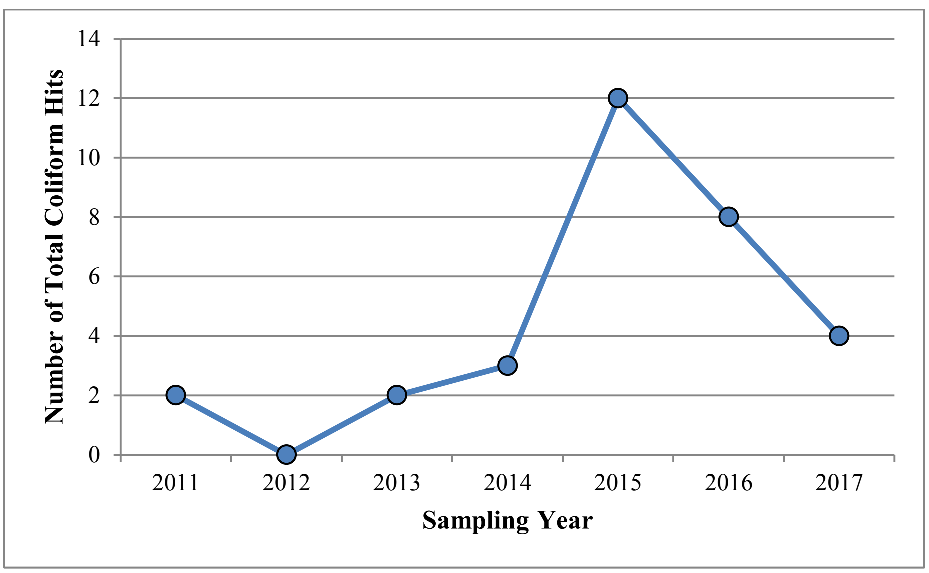

Figure 8.9 - Number of total coliform hits reported in the groundwater monitoring programme (2011-2017)

8.8.3 Monitoring Well

As detailed in Appendix F, the Monitoring Wells (MW)s located at the site of the WWT lagoon system (SL#1 through SL#9) are in various levels of disrepair. MWs SL#1, SL#2, SL#4, and SL#8 were considered to be in good condition, necessitating only minor maintenance such as repainting of the MWs protective casings and the addition of locks. MWs SL#6 and SL#7 were considered in fair condition due to obstructions in the well casing rendering the sampling more difficult. MWs SL#3, SL#5, and SL#9 were considered to be in poor condition. SL#3 was heavily obstructed at a depth of approximately 3.95 metres below the top of the casing. The lid for the MW was also missing during the last sampling round (April 2019). A consistent sewage odour was emanating from SL#5 throughout all sampling rounds (Aug 2018, Oct 2018, and Apr 2019). The MW's casing was also cracked near the top and the lid of the protective casing was broken and could not be repositioned. Due to the nature of the damage sustained by the MW and its locations next a bend in a black track along the WWT lagoon perimeter fence, it is speculated that the MW was subject to a collision with a motor vehicle. SL#9 was considered to be in poor condition due to the presence of an obstruction within the MW and due to the discolouration of the groundwater samples and the sampling equipment that was left within the MW.

All MWs are located in close proximity of the WWT lagoon system's component. SL#1 through SL#3 are within approximately 20 m of either the grit chamber (building #264) or the septic tanks. SL#4 through SL#9 are all on the slope or at the toe of the two cells' berms and within approximately 50 m of the water's edge. Due to their proximity to the WWT lagoon systems and the type of soils present on site, all MWs have the potential of being contaminated by wastewater. This results in the inability of the detachment to determine the background groundwater condition at the site and fully assess the impact of the WWT lagoon system on the groundwater. The installation of a new MW should be considered up-gradient from the WWT lagoon system. The location of this well the proposed name SL#12 can be seen in Figure 8.10. The depth of SL#12 should be assessed based on site conditions but should be no less than 4.20 m below the ground surface.

As detailed in Section 7.6.3, the forward particle tracking analysis indicated that the groundwater flow at the site of the WWT lagoon generally flows eastwards toward Brightwater/Beaver Creek. Only one (1) MW (SL#9) is located along the eastern 400 m border of the cells. The addition of two additional MW with the proposed name SL#10 and SL#11 should be considered in order to better capture possible wastewater seepage along the eastern berm. The proposed location for both SL#10 and SL#11 can be seen in Figure 8.10.

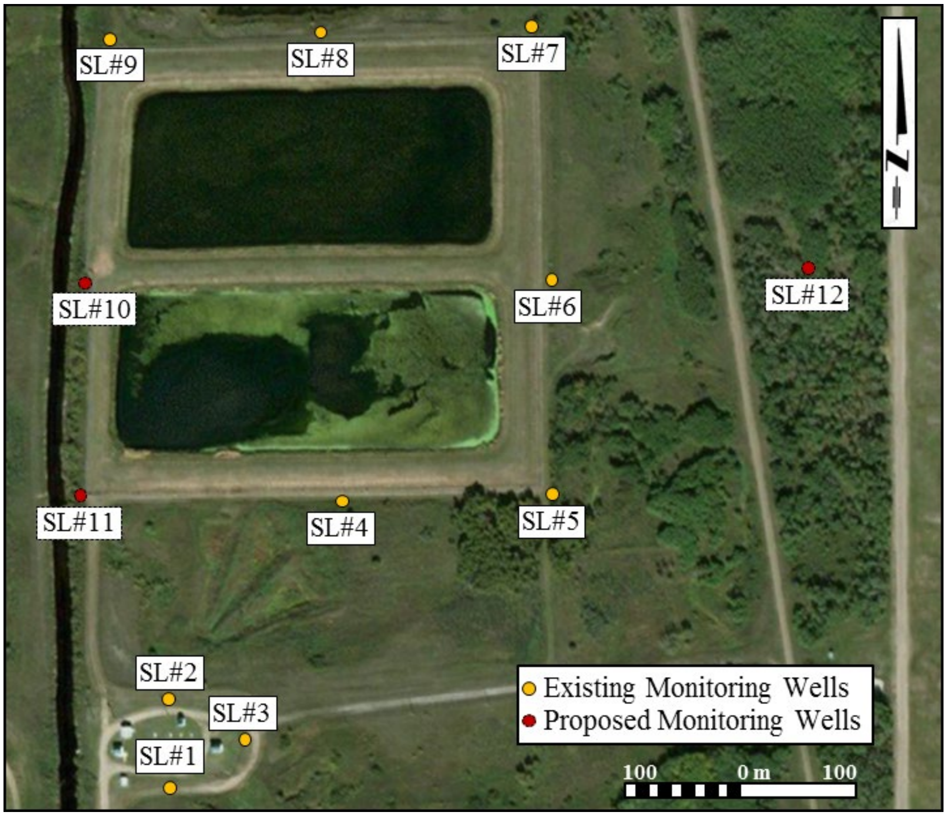

Figure 8.10 - Location of proposed new monitoring wells (Imagery obtained from Microsoft Corporation 2018).

8.9 RMC vs ALS Testing Results

In order to provide redundancy and to validate the field sampling procedures employed, duplicate field testing of certain parameters was conducted during each sampling. These tests were conducted on separate samples collected at the same time as samples sent to ALS for analysis. Redundant testing was conducted from both pH and conductivity. Turbidity was also tested but could not be directly compared with ALS results. Where disparity existed between RMC and ALS values, ALS results were considered correct used for all analysis. These values were considered more reliable as they were obtained in ideal conditions in an accredited laboratory as opposed to field conditions with portable equipment.

RMC ALS results for pH and conductivity were compared for fit on 45^{o} graphs as seen in Figure V1 and Figure V2 of Appendix V. The comparison of the conductivity resulted in good fit for all sampling rounds. All results were within 20% of ALS results with the exception of one (1) data point for the Oct 2018 which had a 63.6% (508 µS/cm) difference and was interpreted as a blunder. The comparison of pH results showed progressively wort fit with each sampling round. The pH values for the Aug 2018 and Oct 2018 sampling round were considered to be in good agreement with ALS value. However, pH values for the Oct 2018 were showing degreased fit. Apr 2019 values were not coherent with high disparities and no apparent trend. The average disparity was equal to 1.30 with the greatest disparity of 1.55. These results are considered to have an unacceptable fit with ALS results. Post-field work check of the sampling equipment revealed that the pH 4 standard, which was used to calibrate the probe in the field, was contaminated and bacterial growth had developed in the standard fluid. This issue deregulated the calibration curve for the pH meter and resulted in the inconsistent and poor results obtained.

The precision of the equipment and the testing methodology employed for the analysis of the samples during field study was assessed by conducting duplicate testing. Duplicate testing was possible for the pH, conductivity, and turbidity tests. The results from the duplicate comparison are shown in Figure V3 and Figure V4 of Appendix V. The results were plotted as the residual over the original values. The results indicate that overall good precision was achieved. However, the residual progressively increased with each sampling round. This increase is apparent when observing the sum of squared residual in Table 8.14.

Table 8.14- Sum of squared residual by parameters

Parameter	Aug-18	Oct-18	Apr-19
pH	0.0005	0.0101	0.0293
Conductivity	104	4100	20129
Turbidity	1.48	4.28	361.12

8.10 Relevance to Research

This chapter reported on the results of the analyses conducted on the various data sets obtained and developed as part of this research project into 17 Wing Detachment Dundurn's WWT lagoon system. The chapter presented in detail: the weather conditions analyses, wastewater influent volumes and quality analyses, along with the effluent volumes and quality analyses. The chapter also reported on the progress of the treatment systemwide and looked for signs of containment failure via analyses of the various surface water bodies and the groundwater on site. The analyses were essential to this research project and uncovered important deductions that were once only speculated with regards to the characterization of the site, the performance of the WWT lagoon system and its impact on the surrounding environment.

9.0 Conclusions & Recommendations

9.1 Introduction

This final chapter will summarize the major conclusions, recommendations, and contributions that were obtained from or developed as part of this research project. Recommendations for possible future work or studies are also given throughout this chapter.

9.2 Treatment Performance

9.2.1 Influent Quality

As detailed in Section 8.4.2 wastewater influent quality was determined based on the average of grab samples of the grit chamber (building #157) obtained during the three (3) samples rounds conducted by the author in August 2018, October 2018, and April 2019. The effluent concentration proved to be predominantly weak.

As detailed in Section 8.4.2.1, the BOD loading rate was calculated from BOD_5 concentrations of grab samples obtained during the three (3) samples rounds conducted in August 2018, October 2018, and April 2019. These samples were taken from the septic tank system. The average BOD loading rate was calculated to be 2.79 Kg/(ha·d) with maximum and minimum values of 11 Kg/(ha·d) and 0.26 Kg/(ha·d) respectively. These BOD loading rates are significantly lower than typical values for facultative lagoons with ranges of 22 Kg/(ha·d) to 67 Kg/(ha·d). The WWT lagoon system was thereby determined not to be at risk of being overloaded and should be capable of treating wastewater with a higher concentration of waste than what it is currently treating.

9.2.2 Effluent Quality

The results from analysis of effluent quality (Section 8.5.2) indicate that the WWT lagoon system has issues obtaining the regulated concentrations for both Total Suspended Solids (TSS) and ammonia on a regular basis. In addition, removal rates of phosphorus (P) are low averaging at 59.9%. Since chlorine disinfection has been discontinued, the 40.36 m^3 chlorine contact chamber is underutilized and may provide the detachment an opportunity for improving effluent quality.

It is recommended that a pilot study be performed to investigate the possibility of using the pre-existing chlorine contact chamber to house a filter medium, such as sand or activated charcoal, in order to polish the effluent prior to discharge. The addition of this step could potentially produce an effluent with TSS and ammonia concentrations consistently below legal limits and increase the P removal with little added costs to the detachment's exploitation of the WWT lagoon system.

It is recommended that the effect of current discharge pattern on the environment and the migration of possible contaminants be investigated in order to validate or adjust the detachment's current discharge practises. A hydrogeological model should be developed for this effect.

9.2.3 Effect of Influent Volume on Effluent Quality

As detailed in Section 8.5.2, the 2018 effluent was distinctively of inferior quality to all other discharge periods. The 2018 effluent observed exceedances in all regulated parameters studied in this research project. The inferior quality is expected to be due to the higher influent volumes obtained in the 2017-2018 treatment period. The accumulated influent volume for 2017-2018 treatment period was 136% bigger than the Cell #1's capacity resulting in a significant overflow volume to Cell #2 (as detailed in Section 8.4.1). Whilst not a containment risk, the effluent quality results indicate that the WWT lagoon system is incapable of adequately treat the wastewater volumes obtained during the 2017-2018 treatment period. This indicated that the system's rate of treatment is the limiting factor and not its storage capacity. In addition, the results from the other treatment year indicate that the WWT lagoon seems to be regularly operating at or near its upper volume limit.

It is recommended that the wastewater volume in Cell #1 be monitored. The data collected from this monitoring should allow for the determination of the full extent of the overflow issue and the subsequent short circuiting issue.

It is recommended that a baffling system be installed to mitigate the negative effect of overflow from Cell #1 on the final effluent quality. In addition, an adequately designed aeration system may be beneficial to accelerate the rate of wastewater stabilization in Cell #1. Such a system should be considered for continuous or intermittent use.

As detailed in Section 8.4.1, the WWT lagoon system is sensitive to surge in wastewater generation due to maintenance and cleaning of the water distribution system. Maintenance and cleaning can represent a large fraction of the wastewater being collected and thus dilute the influent and can exacerbate overflow of Cell #1.

It is recommended that measures for the reduction of the water consumed for the cleaning and maintenance of the water distribution system be employed. Alternatively, the water consumed during cleaning and maintenance should be disposed of in open fields as instead of the sewage system whenever possible. The water distribution system and the WWT lagoon system should be considered intimately linked. The effect on the WWT lagoon system should be considered whilst operating the water distribution system.

It is recommended that the addition of a third lagoon cell be considered. This third cell, which should be located immediately north of Cell #2, would act as a storage cell. In its current form, the WWT lagoon system does not have such a storage cell since Cell #2 is actively participating in the treatment process whilst overflow of Cell #1occures. The addition of this cell would increase the overall retention time of the wastewater and should eliminate the effluent quality issues associated with the overflow of Cell #1.

It is strongly recommended that all future plans for the detachment consider the increase in wastewater that will be generated and the ability of the WWT lagoon system to manage the influent and produce effluent of adequate quality. Changes such as the installation of a vehicle wash facility and the possible increased use of the training areas for large-scale exercises can be expected to deteriorate the performance of the WWT lagoon system. Transitioning from an annual to a biannual discharge regime would also deteriorate the effluent quality due to lower retention time. The addition of a third lagoon cell may be necessary in order to have adequate wastewater retention times and should be considered if large changes to the detachment are expected.

9.2.4 Short Circuiting

Despite the WWT lagoon system operating with controlled discharge, short circuiting was determined to be an issue during two (2) instances. Short circuiting occurs during the equalization of the wastewater between Cell #1 and Cell #2, as described in Section 5.2.1.1. The second occurrence of short circuiting is seen when the wastewater volume capacity of Cell #1 is exceeded and the overflow is being transferred to Cell #2, as described in Section 8.4.1.

It is recommended that a properly designed baffling system be installed in Cell #1 to eliminate short circuiting and to maximize the residency time of the wastewater in Cell #1 prior to its transfer to Cell #2 in both occurrences. The baffling system should consider the position of the inlet of Cell #1 and the two (2) different outlet positions. In addition, the inlet and outlet of Cell #1 should be repositioned to a more optimal position at the earliest opportunity. As indicated in Section 4.7.2.4.5, this reconfiguration would allow the maximization the cell's residency time when coupled with an adequate baffling system.

9.2.5 Natural and Mechanical Aeration

As detailed in Section 8.3.2, the WWT lagoon cells are not optimally oriented, based on dominant winds directions. Calculations indicated that approximately only 40% to 61% of optimal fetch, and its associated wind-driven reaeration was obtained. No major obstacles to wind flow at the WWT lagoon cells were found.

It is recommended that the installation of any new vertical infrastructure within less than 140 m in the north of the lagoon cells (NW through NE) be discouraged and that vegetation within that same area be controlled.

Seasonal blooms of duckweed occur in both of the cells and often cover the majority of the cells surface area. Such blooms were observed during the August 2018 and April 2019 visits conducted by the author. The presence of duckweed in the WWT lagoon cells lowers Dissolved Oxygen (DO) concentration and lower ultraviolet light availability within the cells, thereby inhibits algal growth.

It is recommended that the cells be monitored for duckweed blooms in order to determine the extent of the duckweed problem and harvesting or control measures be used.

It is recommended that an adequately designed mechanical aeration system be employed in Cell #1. The addition of mechanical aeration during the active treatment period would address the losses of natural aeration due to less than optimal cell orientation and would prevent the growth of duckweed by agitating the surface of the wastewater. In addition, mechanical aeration would help reduce the negative effects of Cell #1's overflow by accelerating the wastewater's stabilization whilst it is in Cell #1 and could possibly extend the active treatment period.

9.3 Containment Performance

9.3.1 Containment Failure

The analysis of Brightwater/Beaver Creek sample obtained during the 2018-2019 treatment period resulted in increased concentration of parameters indicative of wastewater contamination. These results, as detailed in Section 8.7.2, indicate that the lining system is possibly leaking at a sufficient rate to cause degradation of the creek during low flow periods. These results are likely considering that the HDPE and clay liner system is over 31 years old. This conclusion is further supported by the analysis of the stagnant water bodies north of the WWT lagoon cells. The analysis found, as detailed in Section 8.7.3, that the sampling locations in the expected down gradient from the WWT lagoon cells had consistently higher concentration for parameters indicative of wastewater contamination. Furthermore, groundwater quality analysis of the monitoring wells (MW)s also supports the conclusion that the WWT lagoon cells have leaks. This analysis, as detailed in Section 8.8.2, seems to indicate that the possible breaches of the liner system are expected to be occurring in the NW and SE corners of the WWT lagoon cells resulting in the consistent inferior quality of the groundwater obtained from MWs in these corners. Although none of the analyses presented above prove without a doubt the presence of leaks, the balance of probability support this conclusion.

It is recommended that an assessment be conducted on the WWT lagoon cells' lining system and the HDPE liner in particular. The assessment should also seek to determine the rate of deterioration.

It is also recommended that the resilience of the ecosystem and the impact of the contamination from the WWT lagoon system on the ecosystem be evaluated.

9.3.2 Monitoring Wells

As stated in Section 8.8 and in Appendix F, the MWs located at the site of the WWT lagoon system experience several issues and are in various states of disrepair.

It is recommended that a detailed structural health assessment of the monitoring well be conducted to determine the nature of the obstructions, where reported, and the casings be repaired. The next available opportunity should be taken to increase the depth of MWs SL#3, SL #4, and SL#5. MWs should be cleaned to remove possible outside sources of contamination and monitored. Re-contamination would further validate the conclusions of this research project regarding containment failures in the WWT lagoon cells.

The current configuration of the MWs results in the inability of the detachment to determine the background groundwater condition at the site and fully assess the impact of the WWT lagoon system on the groundwater. Additionally, the forward particle tracking analysis indicated that the groundwater flow at the site of the WWT lagoon generally flows eastwards toward Brightwater/Beaver Creek. Only one (1) MW (SL#9) is located along the eastern 400 m border of the cells.

It is recommended that three (3) new MWs be installed as detailed in Section 8.8.3.

The assessment of the MWs, reported in Section 8.8.3, has revealed several issues with the use of the MWs.

It is recommended that sampling equipment be removed from the wells and stored off-site in order to reduce the possible avenues for contamination and to avoid obstructing the MWs. In additions the wells' metal protective housing should be locked to avoid unauthorized access.

9.3.3 Groundwater Flow

The hydrogeological model developed during this research project was capable of determining the groundwater flow in the area of approximately 31 km^2 centred on the detachment's production wells (PW)s and the general provenance of the detachment's water supply. As detailed in Section 7.6.3, the model determined that, based on the conditions of September 2015, the detachment's source water is not at risk of contamination from the WWT lagoon system. Additionally, particle tracking indicates that the source water is more at risk from the detachment's metal dump, Airfield training/ cattle grazing area, fuel station, small arms range, and burn dump. The creek is acting as an effective barrier that would capture any possible contamination leaks from the WWT lagoon system from migrating west of the creek and into the well field. A 50% increase in the September 2015 draw rates would result in groundwater on the north section of the detachment's administrative area to be drawn by the PWs.

It is recommended that a refined transient model be developed with the objective of more thoroughly identifying the possibility of contamination from the WWT lagoon system and of developing a formal wellhead protection programme for the detachment. In order to develop such a model, critical information, such as flow and elevations, of Brightwater/Beaver Creeks needs to be obtained. Furthermore, groundwater elevation readings from the detachment's MWs would need to capture seasonal variations.

9.4 WWT Lagoon Management

9.4.1 Standard Operating Procedures

As detailed in Section 5.4, the interview process uncovered that no Standard Operating Procedures (SOP)s regarding the operation of the WWT lagoon system exist in written form. The current practice for the operators is to learn the procedures for the operation of the WWT lagoon system whilst on the job.

It is strongly recommended that detailed SOPs be written and approved by RP Ops. The SOPs should be based on current best management practices and manufacturers' recommendations on the equipment utilized. The SOPs must cover all aspects of operations of the WWT lagoon system including both routine and occasional procedures. All SOPs should be approved by RP Ops staff and available in both electronic and paper format and revised on a regular basis (e.g. 3-5 years).

9.4.2 Personal Protective Equipment

As stated in Section 5.4, the operators have and utilize the minimum required level of Personal Protective Equipment (PPE). However, given their additional responsibilities with the detachment's water treatment plant and the water quality control sampling programme, additional measures can be put in place to enhance the protection of the operators and lower the risks of cross contamination.

It is recommended that additional PPE be made available to the operators. Due to their work in or around the lagoon cells, the operators should have access to life jackets or other suitable floatation devices. Additionally, since there is a risk of falling in the wastewater, an emergency shower should be available on-site along with spare work attires for each operator. Operators should have access to telescopic sampling rods or other remote sampling equipment in order to remove the need for wading in the wastewater lagoon cells.

It is also recommended that either a separate set of work attire, including boot, be dedicated for working at the WWT lagoon site, or that the operators use reusable splash-proof coveralls (e.g. Tyvek coveralls) whilst at the WWT lagoon site.

9.4.3 Monitoring Programme

The current monitoring practices are sufficient to meet the Wastewater Systems Effluent Regulations, with the exception of Carbonaceous Biochemical Oxygen Demand ($CBOD_5$). Whilst sufficient, the current monitoring practices do have limitations as stated in Section 5.3.3.

It is strongly recommended that $CBOD_5$ be included in the list of tested parameters.

Currently the wastewater and surface water are sampled and tested for over 92 parameters. The need for each parameter should be reassessed with the objective of removing any parameters that are needlessly tested in order to reduce costs and the post processing of the data. This reassessment should be conducted following the various requirements and guidelines as stated in Section 5.3.3.4.

Based on recorded flow rates for Brightwater/Beaver Creek the effluent can take between 18 h and 97 h to reach the sampling location at the northern boundary. It is therefore recommended that a minimum period of five (5) days should be observed in order to ensure that effluent has fully flowed out of the detachment's training area in order to assess for lingering effects.

As recommended in the Section 5.3.3.2, several wastewater parameters should be monitored using in-situ probes and sensors in the grit chamber (building 157) and in the east chamber of the lift station (building 263). Monitoring of the east chamber of the lift station (building 263) would act as a substitute to the current monitoring of the septic cell. The operator-made sampling port could them be removed and the cell properly closed. Similarly, it is recommended that Cell #1 and Cell #2 be monitored for all the parameters listed in Table 5.5 of Section 5.3.3.2 using in-situ probes and sensors.

It is also recommended that a detailed monitoring programme be developed based on best practices and equipment manufacturers' specifications. The monitoring programme should include all the parameters and sampling/reading locations recommended in Section 5.3.3. The monitoring programme should be approved by RP Ops staff and available in both electronic and paper format.

9.4.4 Weather Station

The environmental data used during this research are obtained from the Saskatoon SRC weather station is approximately 58 km NNW of this is far greater distance of less than 10 km that is recommended by Pearson et al. (1987). The detachment's range control section does have a weather station within 2 km of the WWT lagoon system. The station also measure more than the recommended minimal parameters. However, the station is known to provide inaccurate readings and the readings are not recorded and catalogued.

It is recommended that the detachment relocate the weather station where its instruments can accurately and reliably obtain measurements. As recommended in Section 5.3.3.1, the repositioning of the station in the relatively open area approximately 200 m south of the Cell #1 and approximately 150 m from the grit chamber (building #157) should be considered.

It is recommended that, as stated in Section 5.3.3.1, additional equipment be added to the weather station in order to record and store weather readings in a usable format for all organization on the detachment. In addition, a proper maintenance and calibration schedule should be established based on the manufacturer's recommendations to ensure the accuracy of the readings, if such a maintenance programme does not current exists. Provisions should be made for the inclusion of the weather station to a future Supervisory Control and Data Acquisition (SCADA) system.

9.4.5 Data Management and SCADA System

The WWT lagoon system is currently operated manually with minimal automation. Automation is only present in the lift station (building #263)'s pump controls.

It is recommended that a SCADA system be installed at the detachment's WWT lagoon system. Due to the simplicity of the WWT lagoon system, the SCADA's primary purpose would be for the collection of a larger set of data whilst reducing the daily workload on the operators. This could eliminate the need for operators to have daily contact with wastewater. The added data would allow for better assessment of the wastewater's stabilization to be done in near-real time. The SCADA system should be capable of collecting data from all mechanical components of the WWT lagoon system, collect weather data, and wastewater quality parameters from all major components of the system. Recommendations for such a SCADA system are detailed in Section 5.3.4.2.1.

It is recommended that the interim measure for data management listed in Section 5.3.4.2.2 be followed until such time as a SCADA system is implemented. However, good progress has been noted between the start and end of the field study, in this regard.

9.4.6 Maintenance Operations

As described in Section 5.2.1.2, the RP Ops section had expressed concerns with the vegetation along the inside slopes of the lagoon cells' berms. Due to safety concerns associated with the current equipment availability and the bearing capacity of the slopes, the along the inside slopes of the lagoon cells' berms was not controlled.

It is recommended that the Roads & Ground section be equipped with a boom mower attachment to augment their current vegetation trimming capabilities. Such a tool would allow for the trimming of the inside slopes of the lagoon cells without endangering the heavy equipment or its operators.

During the infrastructure assessment, at least one muskrat was spotted within the fenced perimeter and evidences of muskrat/rodent damages to the northern berm were seen.

It is recommended that the liner be inspected for damages and repaired if needed. The liner cover material should then be replaced and the perimeter fence should be inspected for gaps and a finer metal mesh should be installed on the perimeter fence where the fence meets the ground to deter further intrusions.

It is recommended that the addition of a third lagoon cell be considered. This third cell, along with the required controls to reconfigure the flow between cells, would provide flexibility to the WWT lagoon system during future maintenance events requiring a lagoon cell to be brought offline. The WWT lagoon system does not currently have such flexibility, as described in Section 5.6.3. The third cell may also remove the need of a temporary packaged plant during maintenance events.

9.5 General Observation

The following observations were made by the author as a result of the research project:

1. The design of infrastructure at 17 Wing Detachment Dundurn is adequate and follows guidelines, with the expiration of the lagoon cells' orientation and the position of the intake and outflows of Cell #1;

2. Given the current equipment, supplies, and infrastructure condition; the operators are employing the best possible procedure whilst operation the WWT lagoon system. Improvements can be made regarding data management as previously stated; and,

3. 17 Wing Detachment Dundurn should employ measure in order to reduce their water consumption per capita. In addition to lowering the demand on the water treatment plant and its associated cost, reduction of water consumption would extend the serviceable population of the WWT lagoon system.

9.6 Research Contributions

This research project provided the following contributions for the management of the detachment's WWT lagoon system:

1. The creation of a sampling and analysis database tailored for Dundurn's WWT lagoon system;

2. An evaluation and assessment of the historic sampling protocols and current SOPs;

3. Recommendations on sampling locations, methods, and testing parameters based on guidelines and legal regulations;

4. An assessment of the potential risks to the source water and the environment obtained through a hydrogeological model of the detachment;

5. An environmental site characterization for the WWT lagoon system and the environment;

6. An evaluation and assessment of the physical condition and functionality of the WWT lagoon system and its design; and,

7. Recommendations on design, operation and maintenance practises.

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Appendix A – Statistics of Lagoon Use in Canada

This appendix contains statistics on the use and state of publicly owned municipal wastewater treatment lagoons in Canada. All data was obtained from *Canada's Core Public Infrastructure Survey: Wastewater and Solid Waste Assets* published in 2016 by Statistic Canada and Infrastructure Canada.

Table A1 compares the number of publicly owned conventional wastewater treatment plants (all types) with WWT lagoon systems used to treat municipal wastewater across all provinces and territories. For ease of comparison across all provinces and territories, Figure A1 plots WWT lagoon systems as a percentage of wastewater treatment facilities. Figure A2 provides further breakdown and compares the distribution of all WWT lagoon facilities between urban and rural municipalities.

Figure A3 plots the quantitative assessment of all publicly owned WWT lagoon systems per provinces. The facilities are characterized according to the following assessment scheme provided by Statistics Canada and Infrastructure Canada (2016c):

1. *Very Poor: The asset is unfit for sustained service. Near or beyond expected service life, widespread signs of advanced deterioration, some assets may be unusable.*
2. *Poor: Increasing potential of affecting service. The asset is approaching end of service life; condition below standard and a large portion of systems exhibits significant deterioration.*
3. *Fair: The asset requires attention. The assets show signs of deterioration and some elements exhibit deficiencies.*
4. *Good: The asset is adequate. Acceptable, generally within mid stage of expected service life.*
5. *Very Good: Asset is fit for the future. Well maintained, good condition, new or recently rehabilitated.*

Table A1 - Composition of all publicly owned municipal wastewater treatment facilities per province/territory (Statistics Canada and Infrastructure Canada 2016b)

Geography	Wastewater treatment plants (includes sludge handling plants)	Lagoon systems	
		#	$\%_{facilities}$
NL	32	15	31.9
PE	4	11	73.3
NS	107	42	28.2
NB	26	59	69.4
QC	477	171	26.4
ON	334	218	39.5
MB	20	179	89.9
SK	34	124	78.5
AB	74	313	80.9
BC	150	89	37.2
YT	0	3	100
NT	0	7	100
NU	1	14	93.3
Canada	1259	1244	49.7

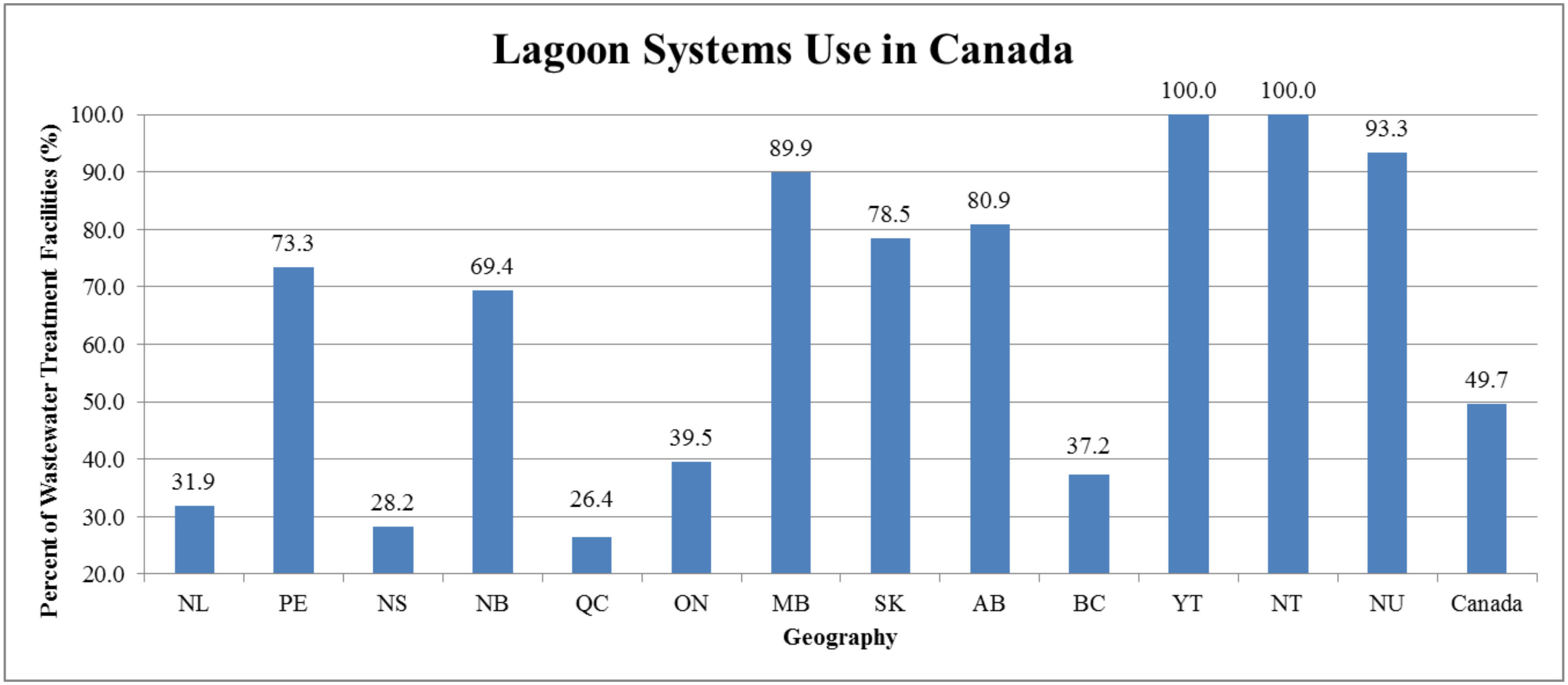


Figure A1 - Lagoon systems as a fraction of all publicly owned municipal wastewater treatment facilities per province/territory (Statistics Canada and Infrastructure Canada 2016b)

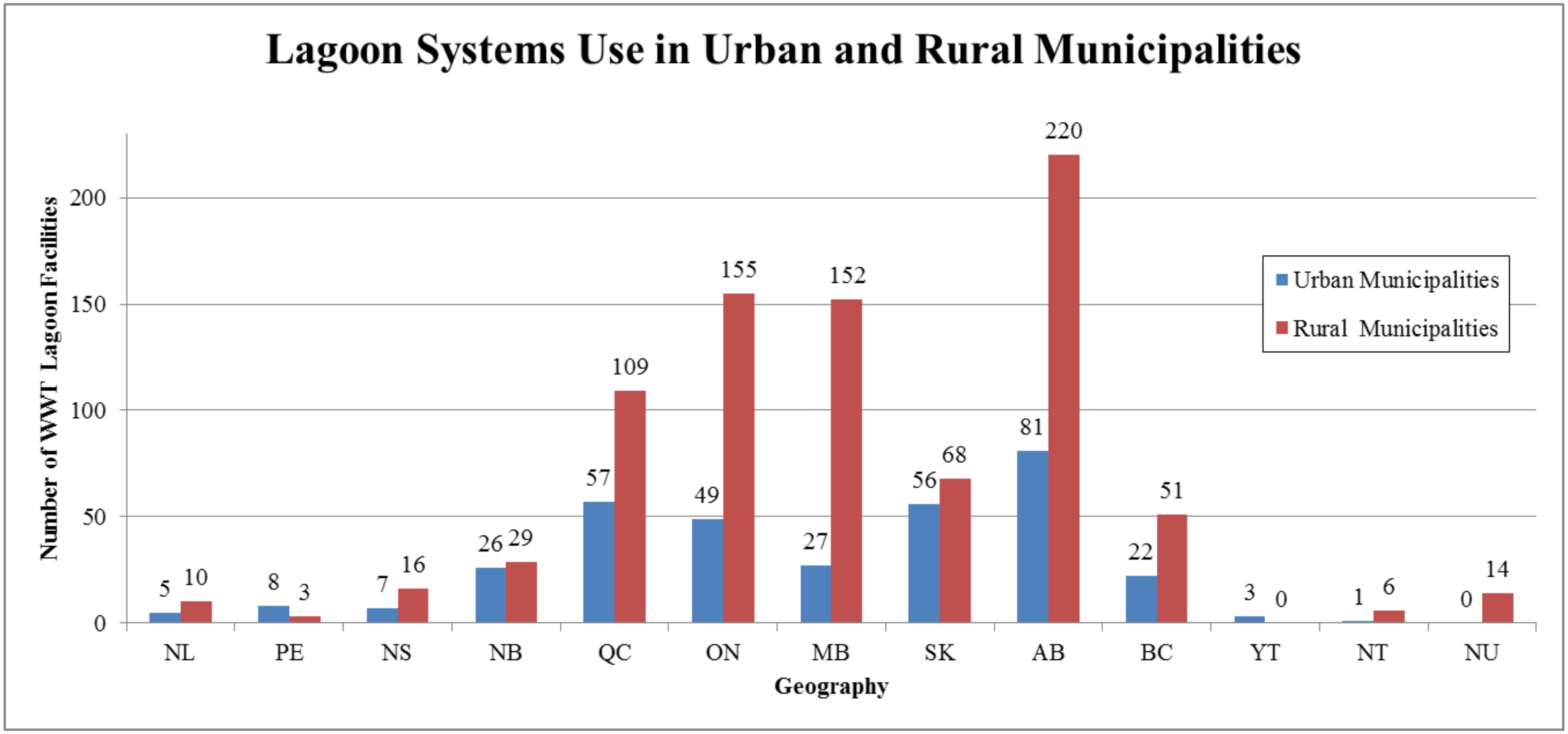


Figure A2 - Inventory of all publicly owned municipal wastewater treatment lagoon systems by population centres per province/territory (Statistics Canada and Infrastructure Canada 2016c)

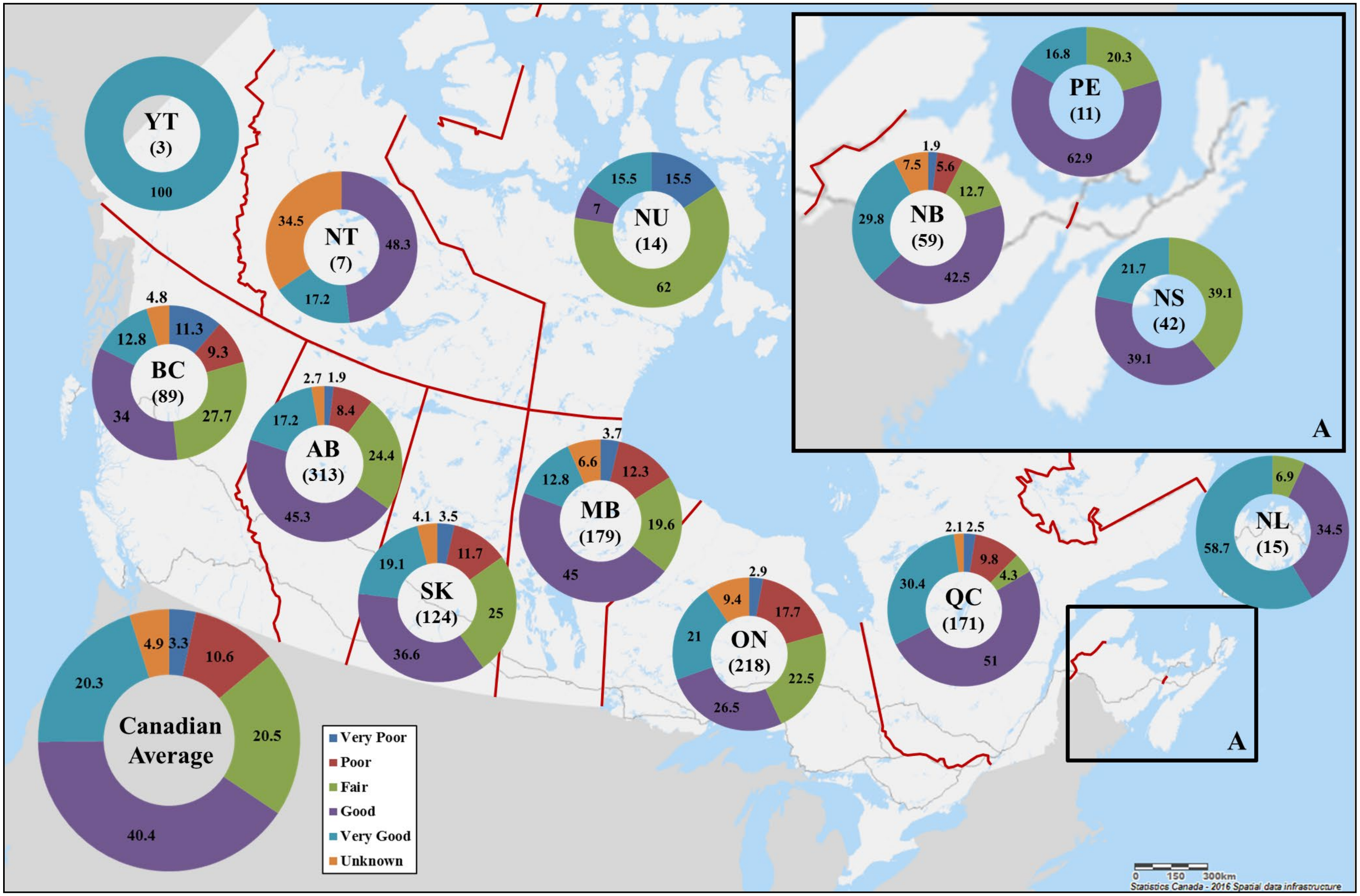


Figure A3 - Physical assessment of all publicly owned municipal wastewater treatment lagoon systems per province/territory (Statistics Canada and Infrastructure Canada 2016a). All data within rings are percentages (%). Data in brackets ( ) denotes the total numbers of WWT lagoon systems.

Appendix B – Site Location and Topographical Analysis

The following appendix presents the figures produced by the author during the topographical analysis conducted during the desk study. The topographical analysis covers an area of approximately 40x50 km centred on 17 Wing Detachment Dundurn's administrative area.

Figure B1 and Figure B2 locate 17 Wing Detachment Dundurn with regard to Canada, the province of Saskatchewan and more specifically Saskatchewan's major cities. Figure B3, Figure B4,Figure B5, and Figure B6 highlight the major water features, the vegetation profile, the surface geometry, and anthropogenic feature surrounding Det. Dundurn respectively.

Site Location:

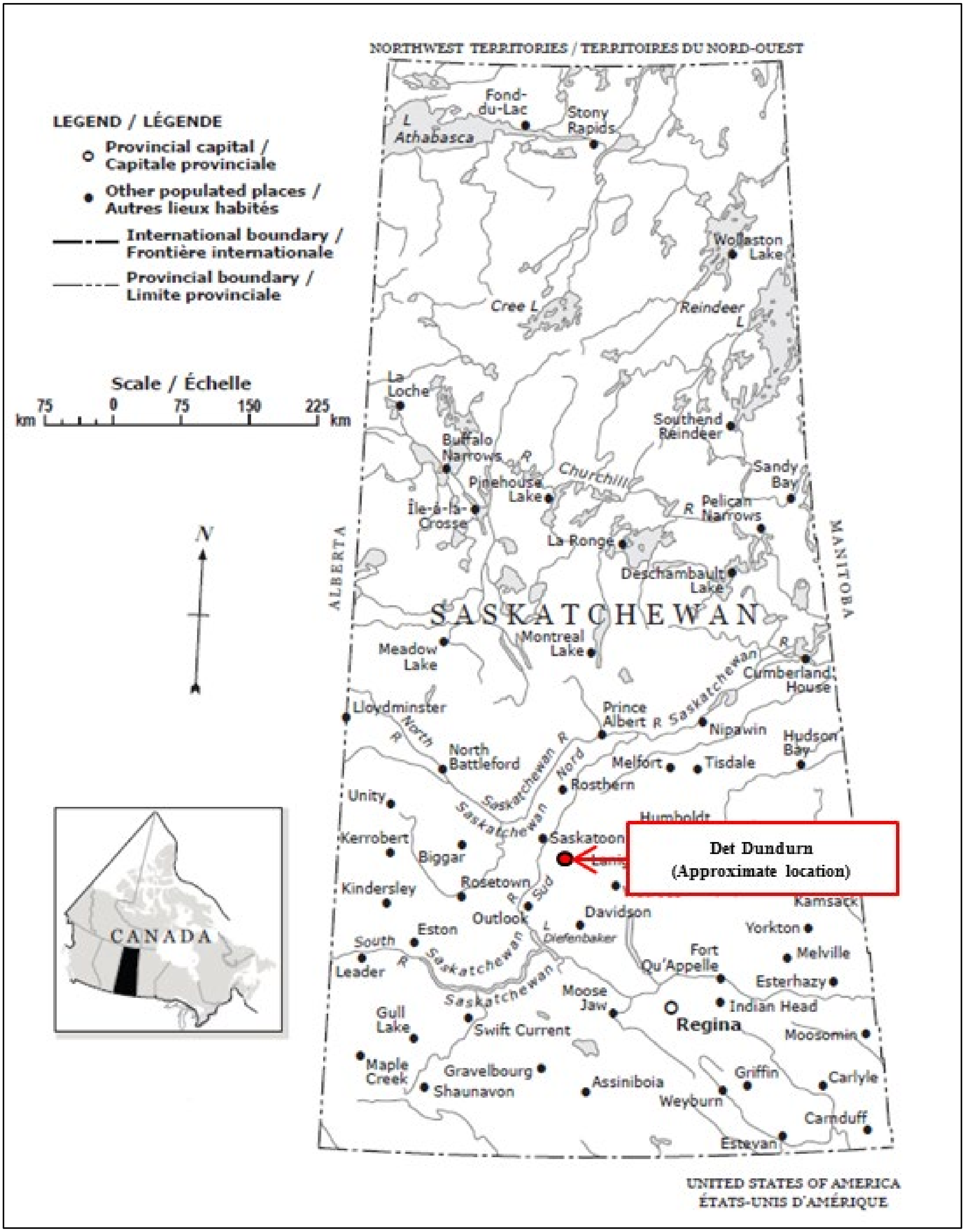


Figure B1 - Reference map of the province of Saskatchewan indicating the approximate location of Detachment Dundurn (Modified product from Natural Resources Canada, 2017)

Figure B2 - Location of 17 Wing Detachment Dundurn with regard to Saskatoon, SK and Regina, SK (Microsoft Corporation 2018)

Water Features:

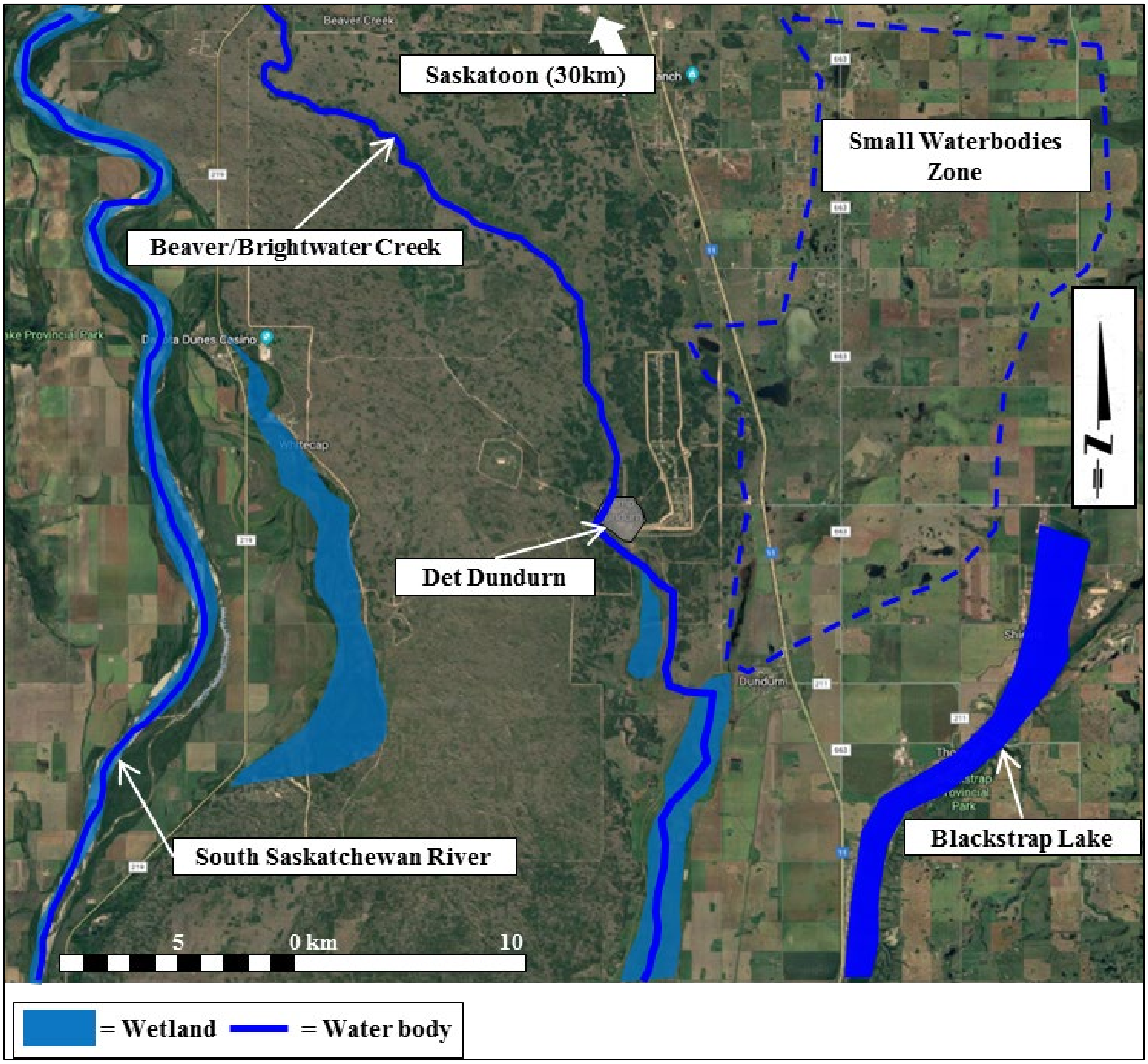


Figure B3 - Major water features near Detachment Dundurn (Imagery provided by Google Map, 2018)

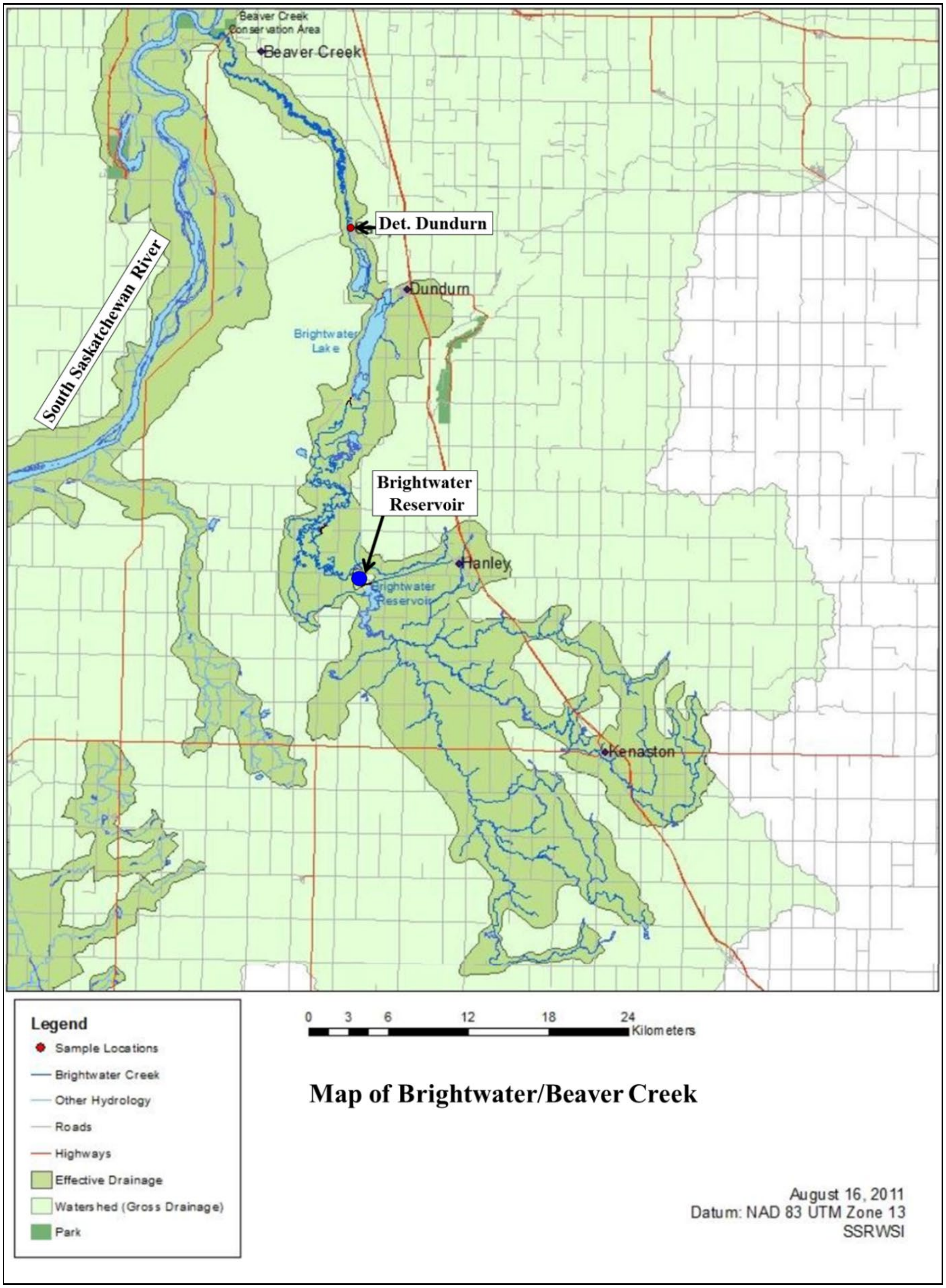


Figure B4 - Map of Brightwater/Beaver Creek Watershed
(Modified from South Saskatchewan River Watershed Stewards 2012)

Vegetation Profile:

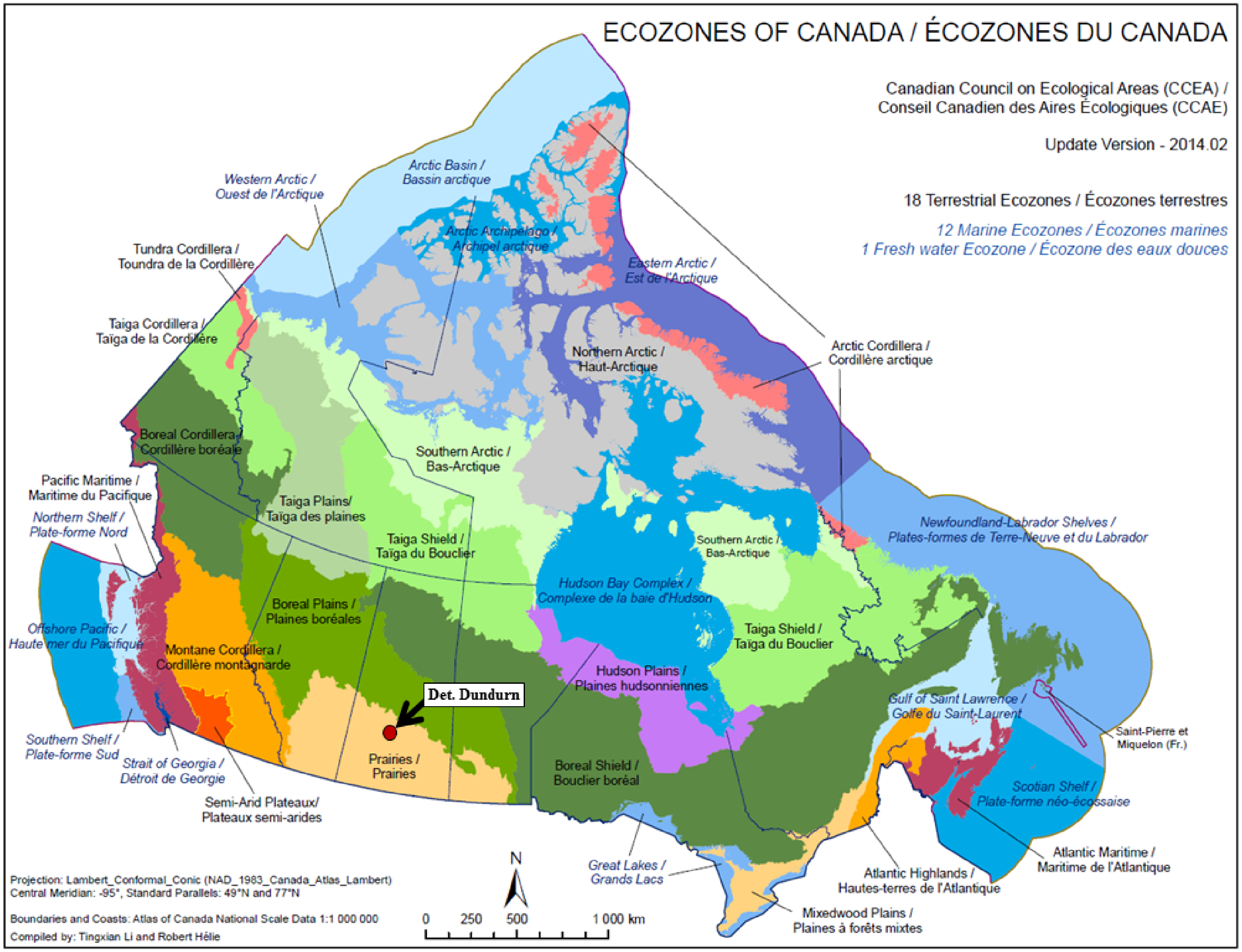


Figure B 5 - Ecozone map of Canada marked with the approximate location on 17 Wing Detachment Dundurn. (Modified from Canadian Council on Ecological Areas 2014)

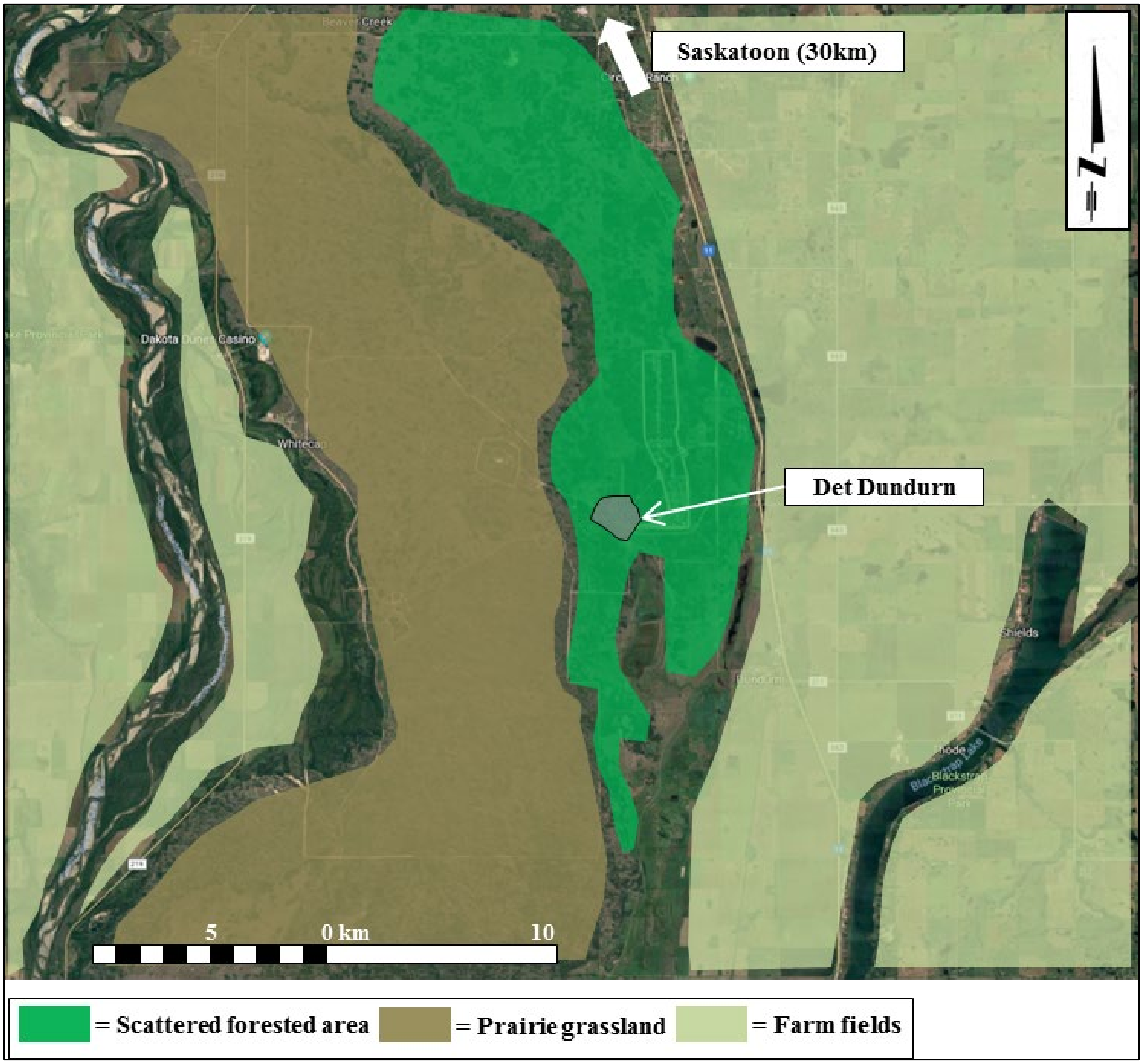


Figure B6 - Vegetation profile of Detachment Dundurn and surrounding area (Imagery provided by Google Map, 2018)

Surface Geometry:

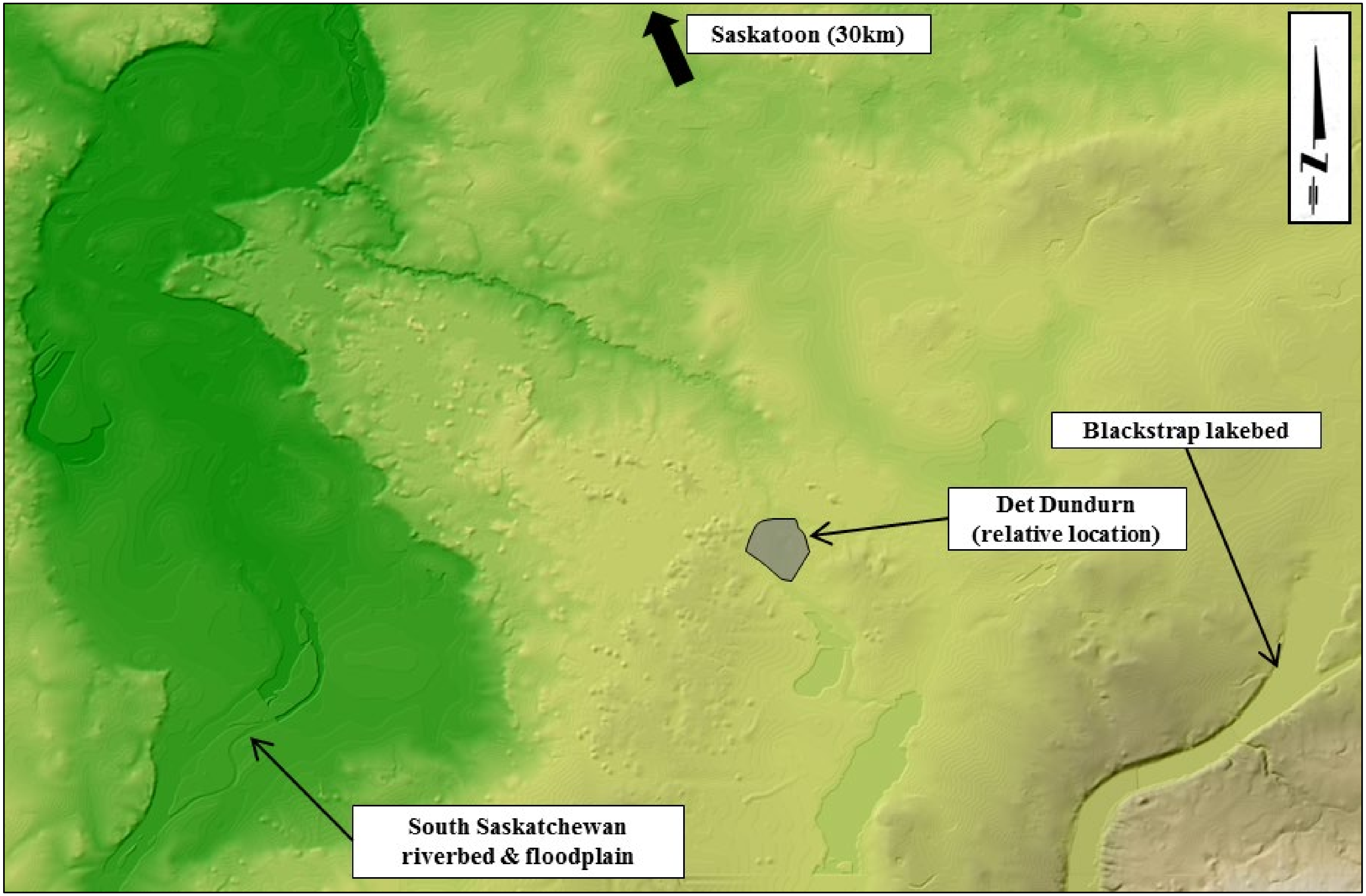


Figure B7 - Colour shaded relief imagery of Detachment Dundurn and surrounding area (modified product of Natural Resources Canada, 2016)

Anthropogenic Features:

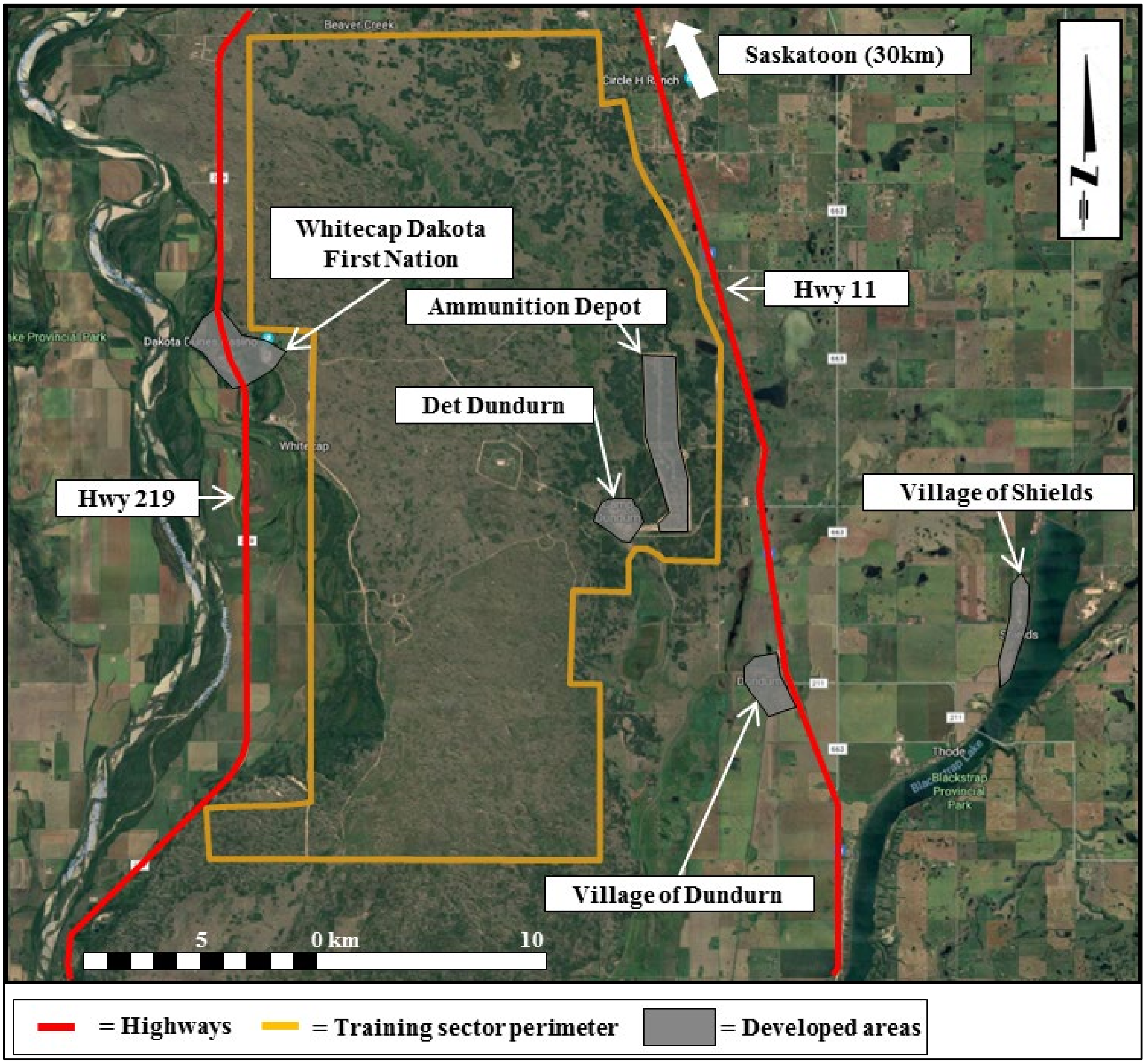


Figure B8 - Major anthropogenic features near Detachment Dundurn (Imagery provided by Google Map, 2018)

Appendix C – Borehole Data

The following appendix highlights the boreholes (test holes) information that was extracted from the construction drawings of the WWT lagoon system drawn by the Bullée Consulting Ltd. in 1988. In accordance with the drawings (Figure C1), the bore holes were drilled on 01 September 1988. The detailed subsurface investigation report mentioned by the drawings was not available at the time of the desk study and the site investigation and has been reported as lost.

Figure C2 provided the legend used in the test holes graphs. The locations of the test holes have been highlighted in Figure C3 and Figure C4. The location of Test Hole 2 was not found. The data for Test Hole 1, 2, 3, and 4 are given in Figure C5, Figure C6, Figure C7, and Figure C8 respectively.

NOTE

ANY INFORMATION PERTAINING TO SOILS AND ALL TEST HOLE LOGS ARE FURNISHED BY THE ENGINEER AS A MATTER OF GENERAL INFORMATION ONLY AND TEST HOLE DESCRIPTIONS OR LOGS ARE NOT TO BE INTERPRETED AS DESCRIPTIVE OF CONDITIONS AT LOCATIONS OTHER THAN THOSE DESCRIBED BY THE TEST HOLES THEMSELVES. DETAILED SUBSURFACE INVESTIGATION REPORT IS AVAILABLE FOR INSPECTION AT OFFICE OF DCEO, DETACHMENT DUNDURN. THESE TEST HOLES WERE DRILLED ON 1st. SEPTEMBER 1988.

Figure C1 - Notes associated with the borehole data (Modified from Bullée Consulting Ltd. 1988a).

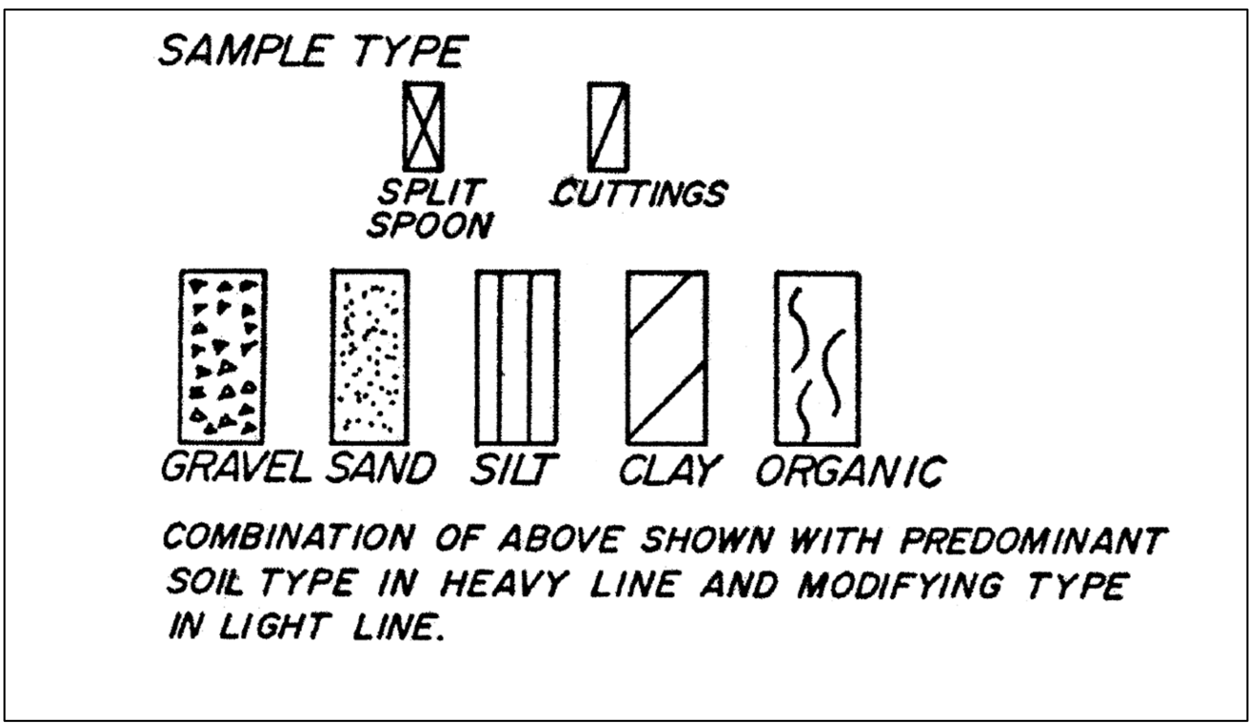


Figure C2 - Legend used in the borehole logs (Modified from Bullée Consulting Ltd. 1988a)

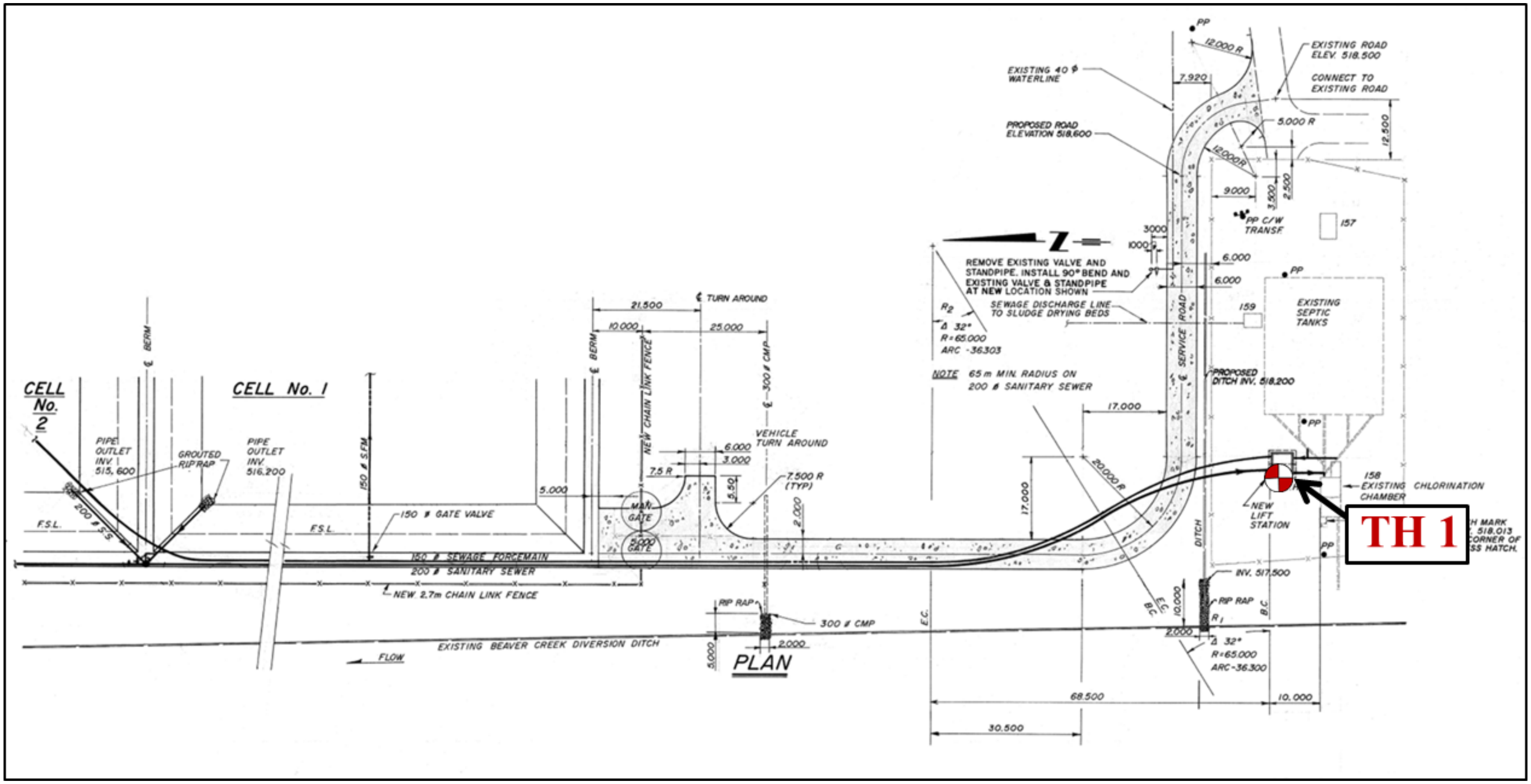


Figure C3 - Location of test hole 1 (Modified from Bullée Consulting Ltd. 1988b).

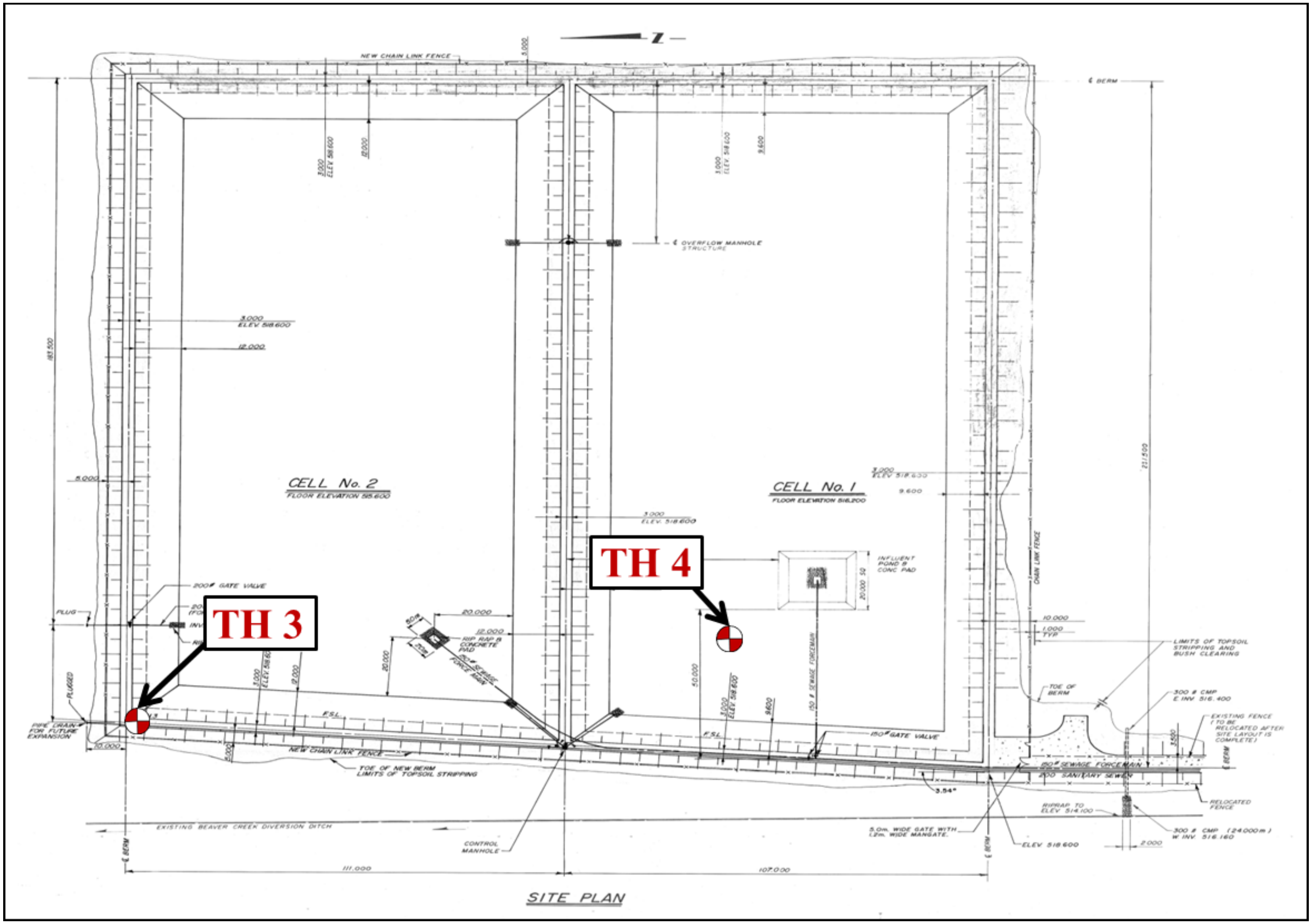


Figure C4 - Location of test holes 3 and 4 (Modified from Bullée Consulting Ltd. 1988a).

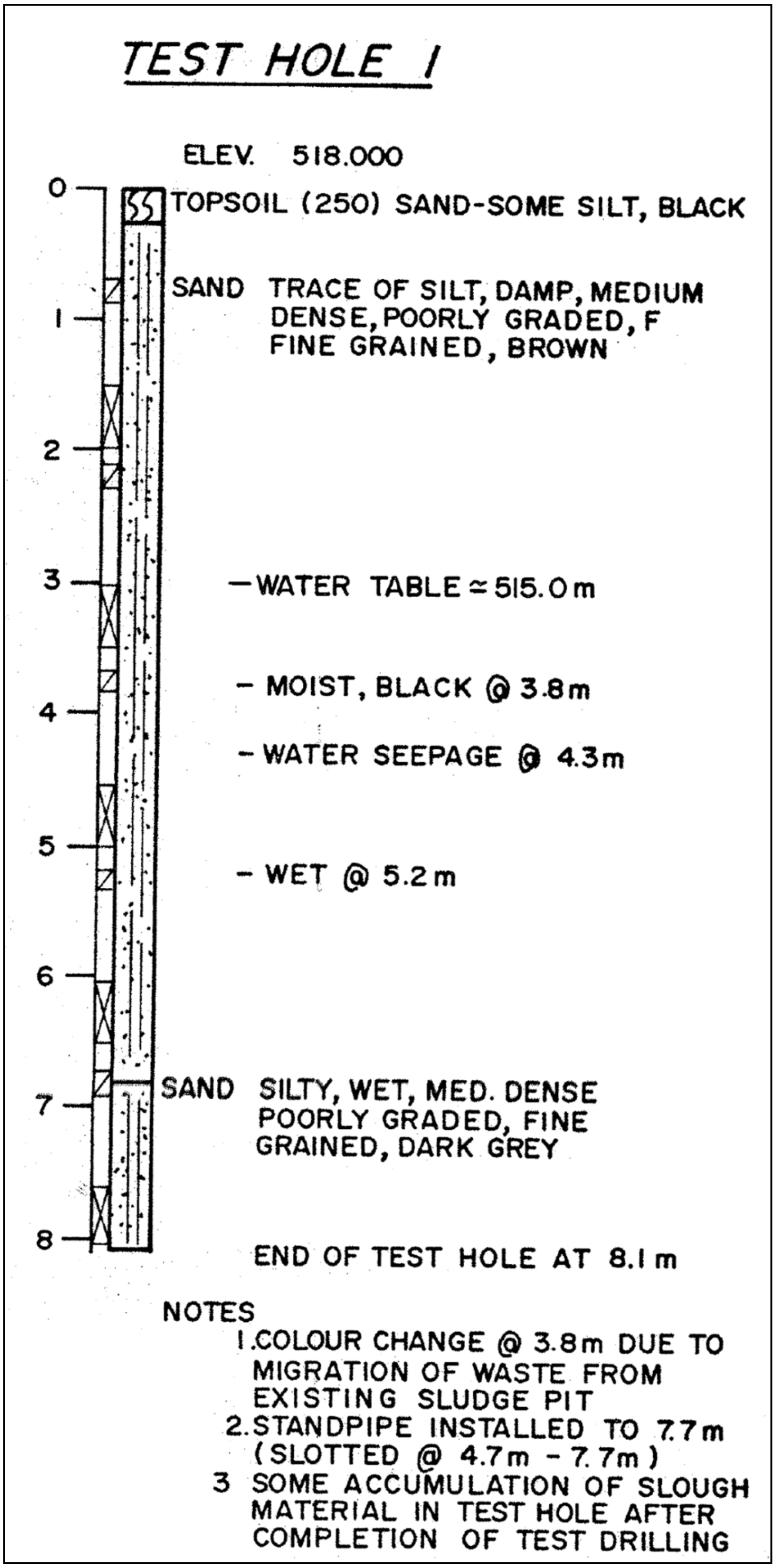


Figure C5 - Test Hole 1 data (Modified from Bullée Consulting Ltd. 1988a).

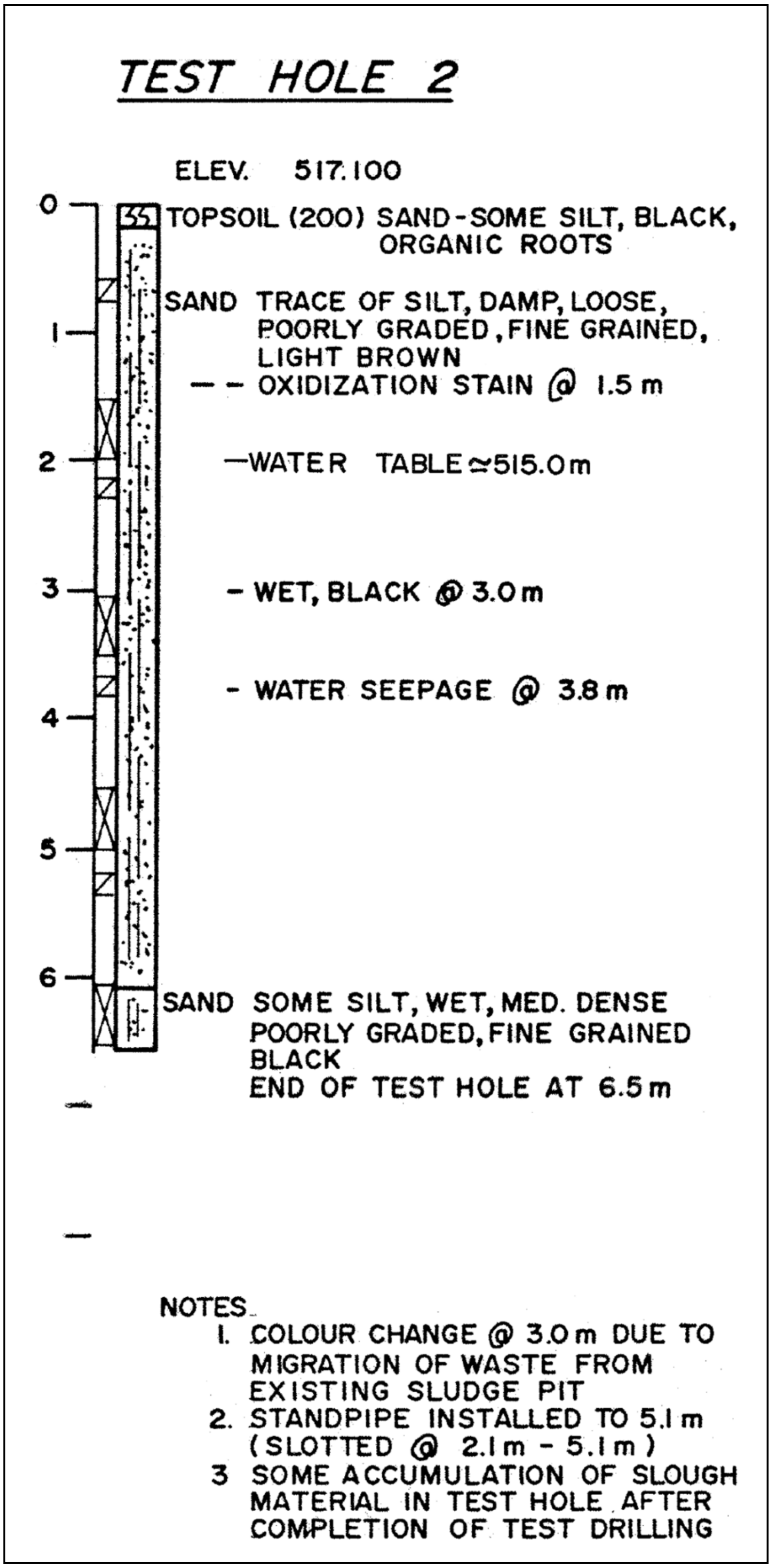


Figure C6 - Test Hole 2 data (Modified from Bullée Consulting Ltd. 1988a).

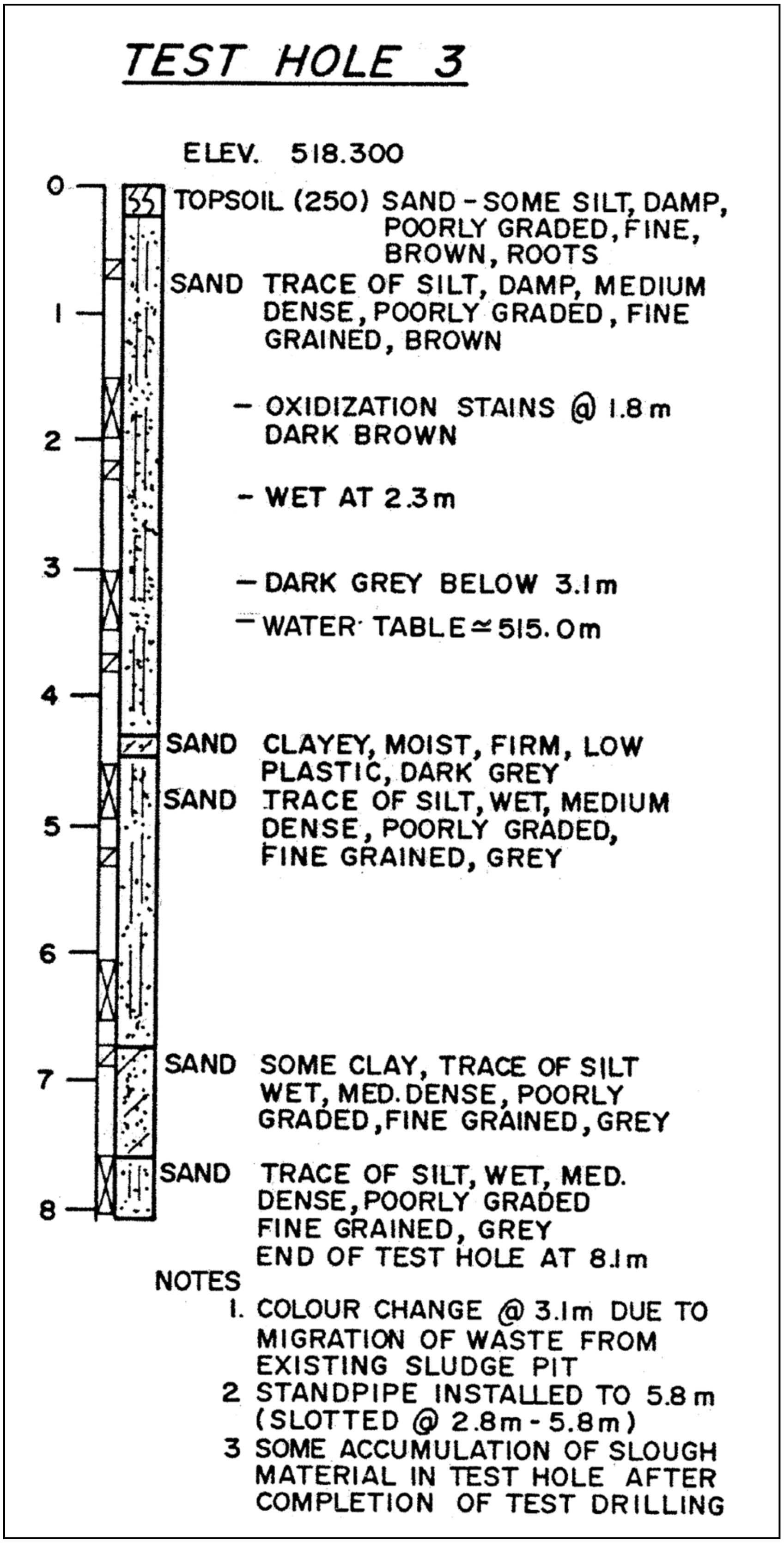


Figure C7 - Test Hole 3 data (Modified from Bullée Consulting Ltd. 1988a).

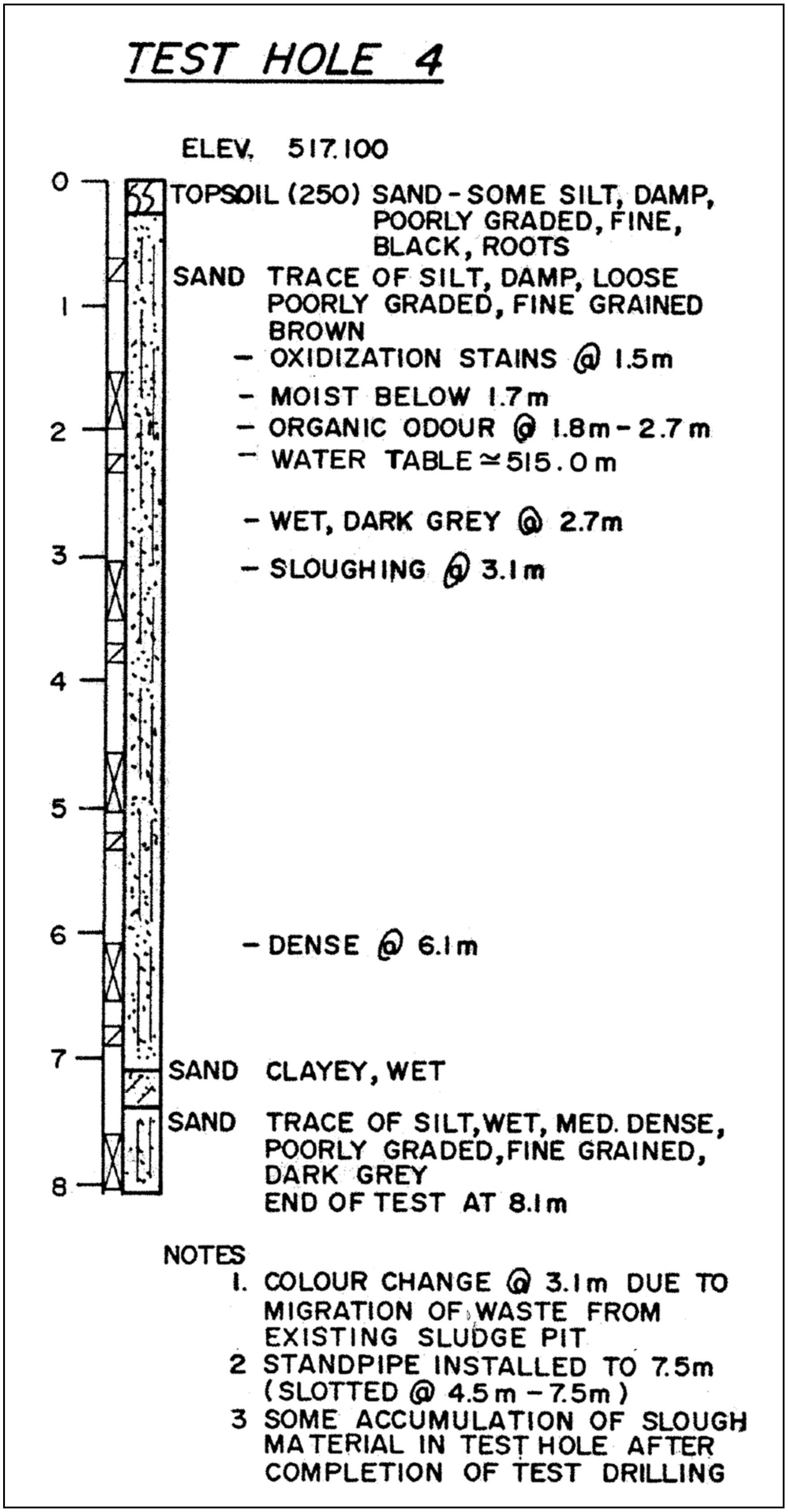


Figure C8 - Test Hole 4 data (Modified from Bullée Consulting Ltd. 1988a).

Appendix D – Detachment Dundurn WWT Lagoon Site Layout

The following appendix presents the points of interest located at 17 Wing Detachment Dundurn's WWT lagoon site. These points of interest are commonly referred to throughout this thesis.

Figure D1 presents the entirety of the site location with large points of interest marked. Figure D2 present all the points of interest that surrounds the septic tanks (Box A).

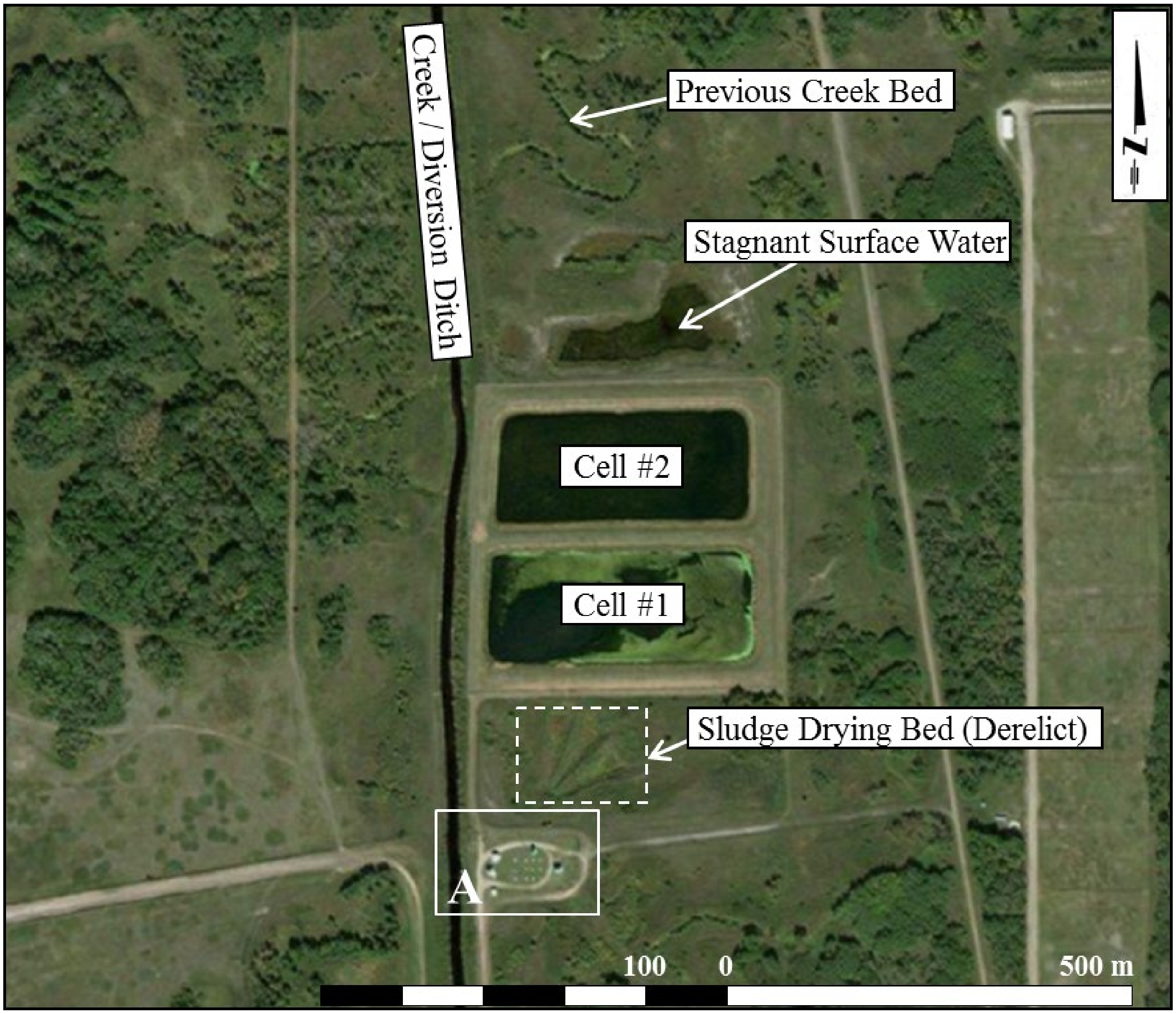


Figure D1 - Points of interest at the WWT lagoon site (Imagery provided by Microsoft Corporation 2018)

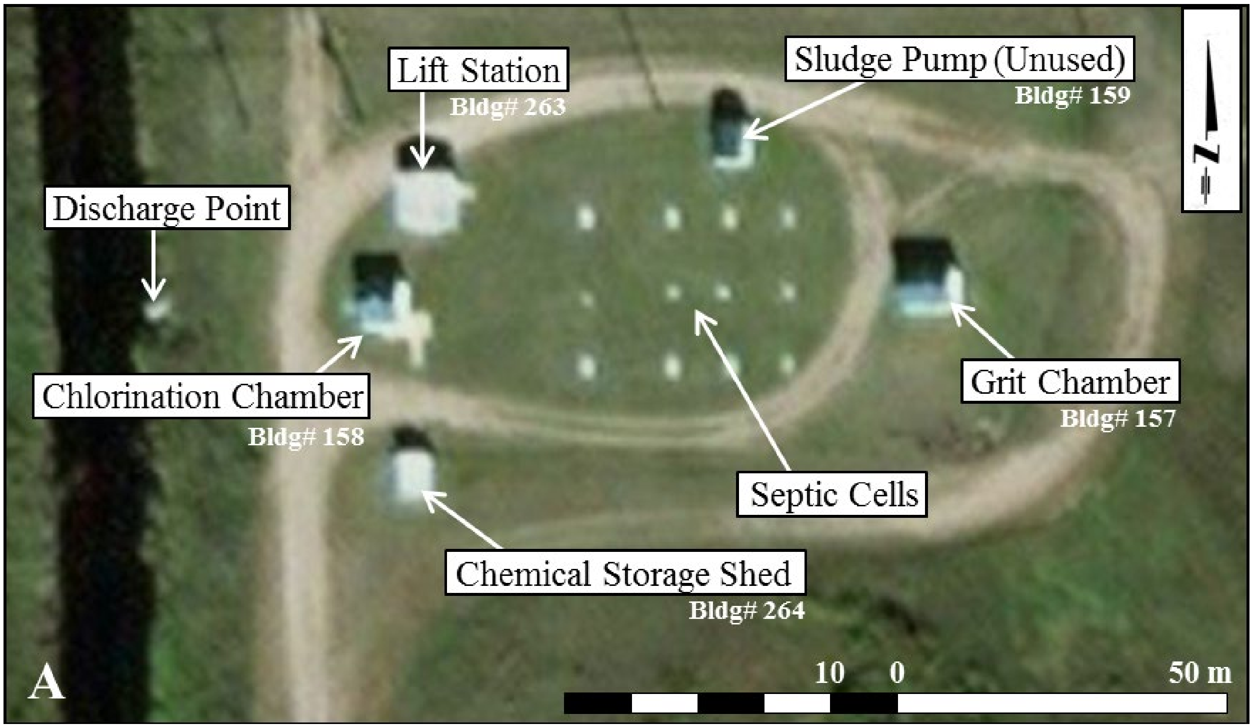


Figure D2 - Points of interest located inside Box A of Figure D1 (Imagery provided by Microsoft Corporation 2018)

Appendix E – Construction Drawings

The following appendix present excerpts of construction drawings from the original 1941 drawings to the latest modifications conducted in 1992. These construction drawings were obtained as part of the site investigation and represent the totality of the construction records available at Real Property Operations Detachment Dundurn; with the exception of a 1960 drawing for the renovation of the chlorination system which has since been removed and therefore not included in this appendix.

The modified drawings excerpts presented in Figure E1 through Figure E23 depict drawings of interest to this research study and were obtained from the construction drawings sets listed below. All measurements in the construction drawings are meters and degrees unless otherwise indicated. Other drawings were obtained during the site investigation but were omitted.

1. Original 1941 sewage disposal system: Construction drawing of the original sewage disposal system which consisted of a septic tank system with a grit separation as pretreatment and effluent chlorination. A sludge separation system was included for the removal of sludge from the grit chamber and septic tank system.

    a. Site Plan L-D125-5822-101;

    b. Disposal Filed Site Plan L-D125-5822-102;

    c. Chlorination and Distribution Chambers L-D125-5822-203; and,

    d. Gates, Valves and Access Hatch Details L-D125-5822-204.

2. 1964 construction drawings: Incomplete set of drawings of unknown modifications conducted on the sewage disposal system. The only remaining drawing depicts the sludge suction line connected to the grit chamber and septic tank system.

3. 1988 WWT lagoon installation: Construction drawing of the current wastewater treatment system. Upgrade of the original sewage system consisted of the addition of a two celled lagoon system prior to chlorination.

    a. Title Page C-D125-5825-000;

    b. Building Elevations and Details & Mechanical C-D125-5825-001;

    c. Sewage Lagoon Site Plan C-D125-5825-101;

    d. Structural Plan, Sections and Details C-D125-5825-201;

    e. Site Plans & Electrical Details C-D125-5825-501;

    f. Force Main and Sanitary Sewer Plan and Profile & Sewage Lagoon Sections C-D125-5825-601; and,

    g. Sewage Lagoon Sections and Details C-D125-5825-602.

4. 1992 chemical storage building: Construction drawing (L-D125-8219-001) for the addition of a chlorine storage building to the WWT lagoon.

Site Plans:

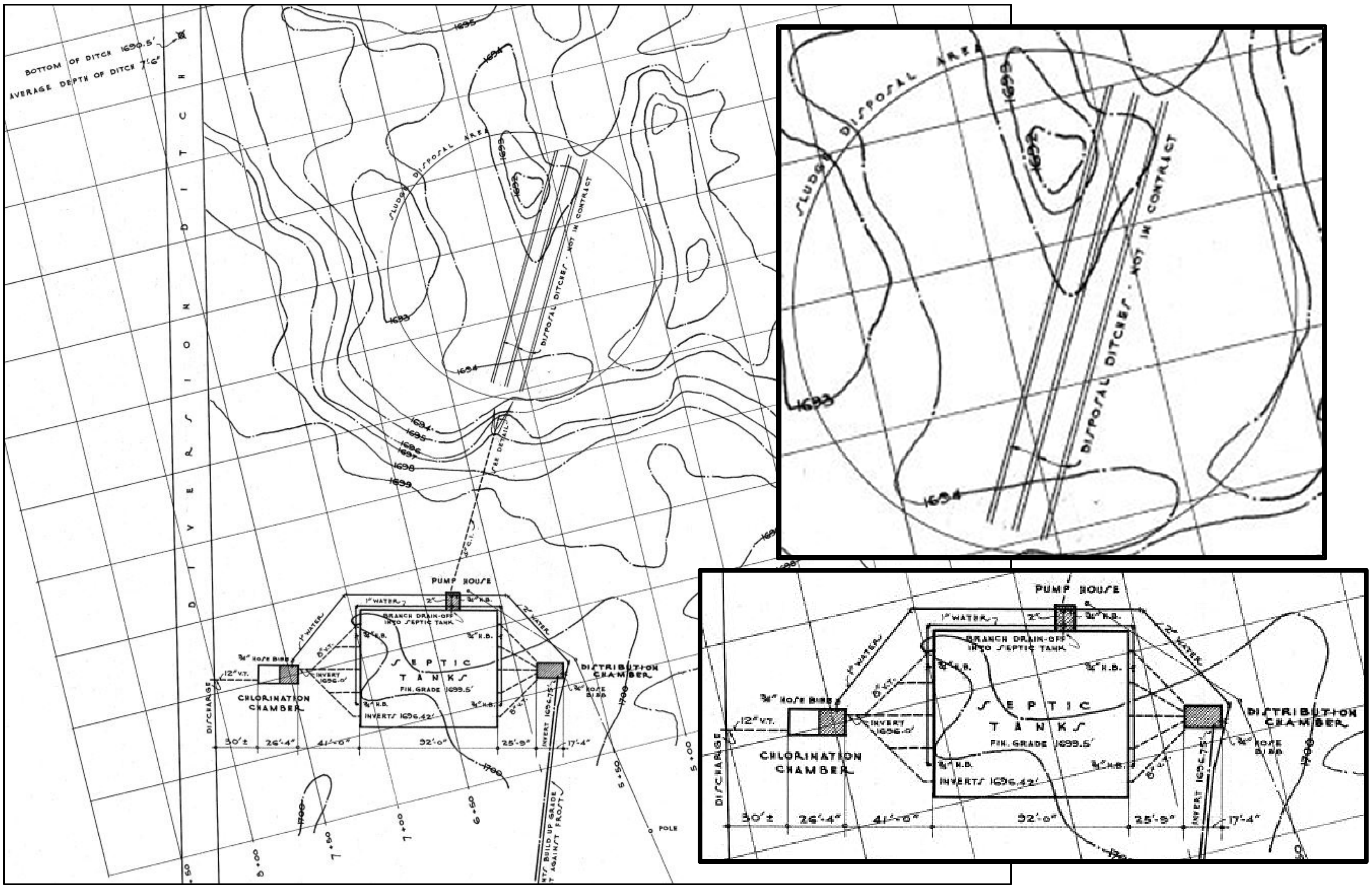


Figure E1 - 1941 Construction drawing - Site plan of septic system and sludge disposal ditches (measurements in feet and inches)
(Modified from DND Engineer Services Branch 1941)

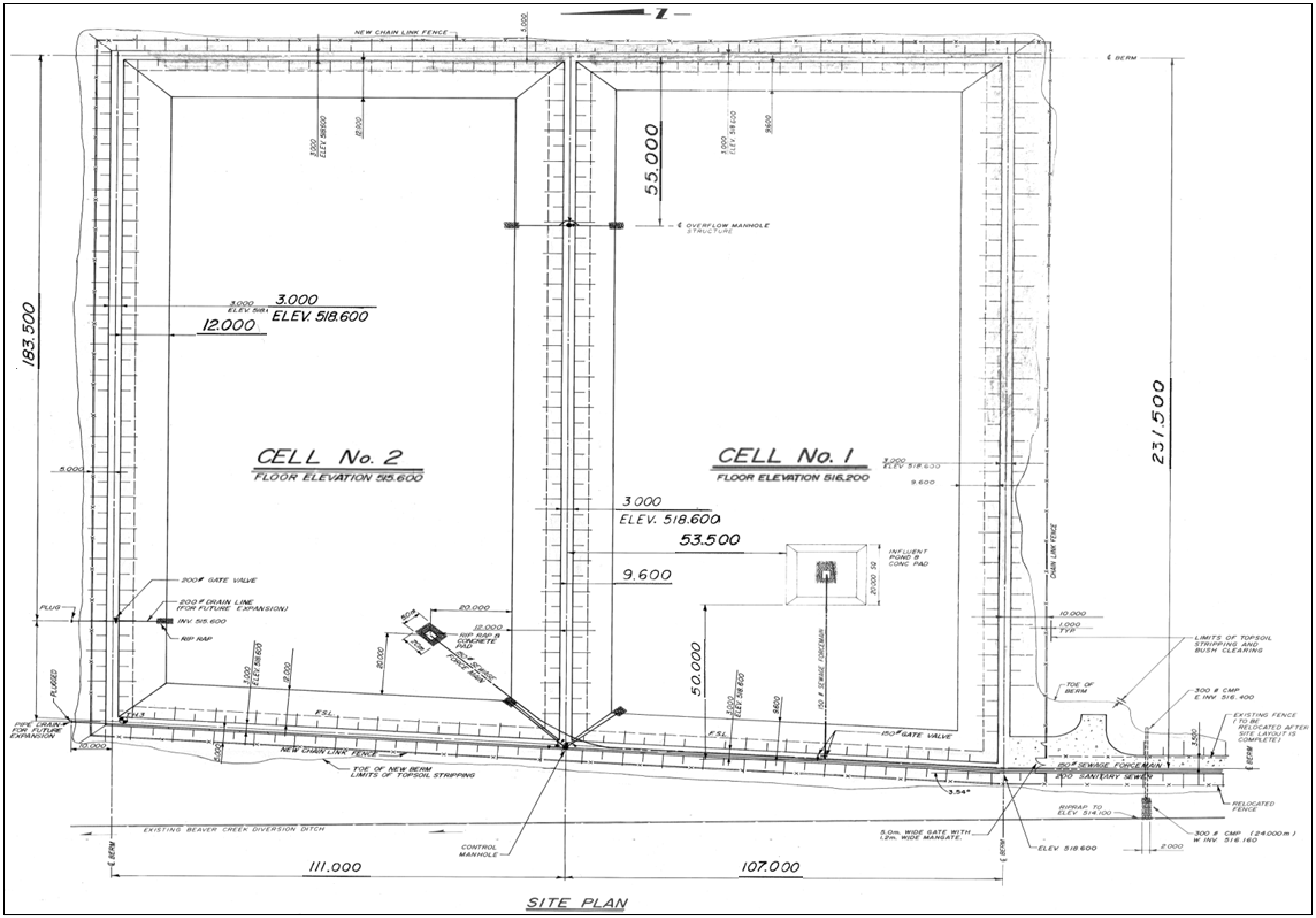


Figure E2 - 1988 Construction drawing - Site plan of lagoon cells area. Major dimensions have been enlarged. (Modified from Bullée Consulting Ltd. 1988)

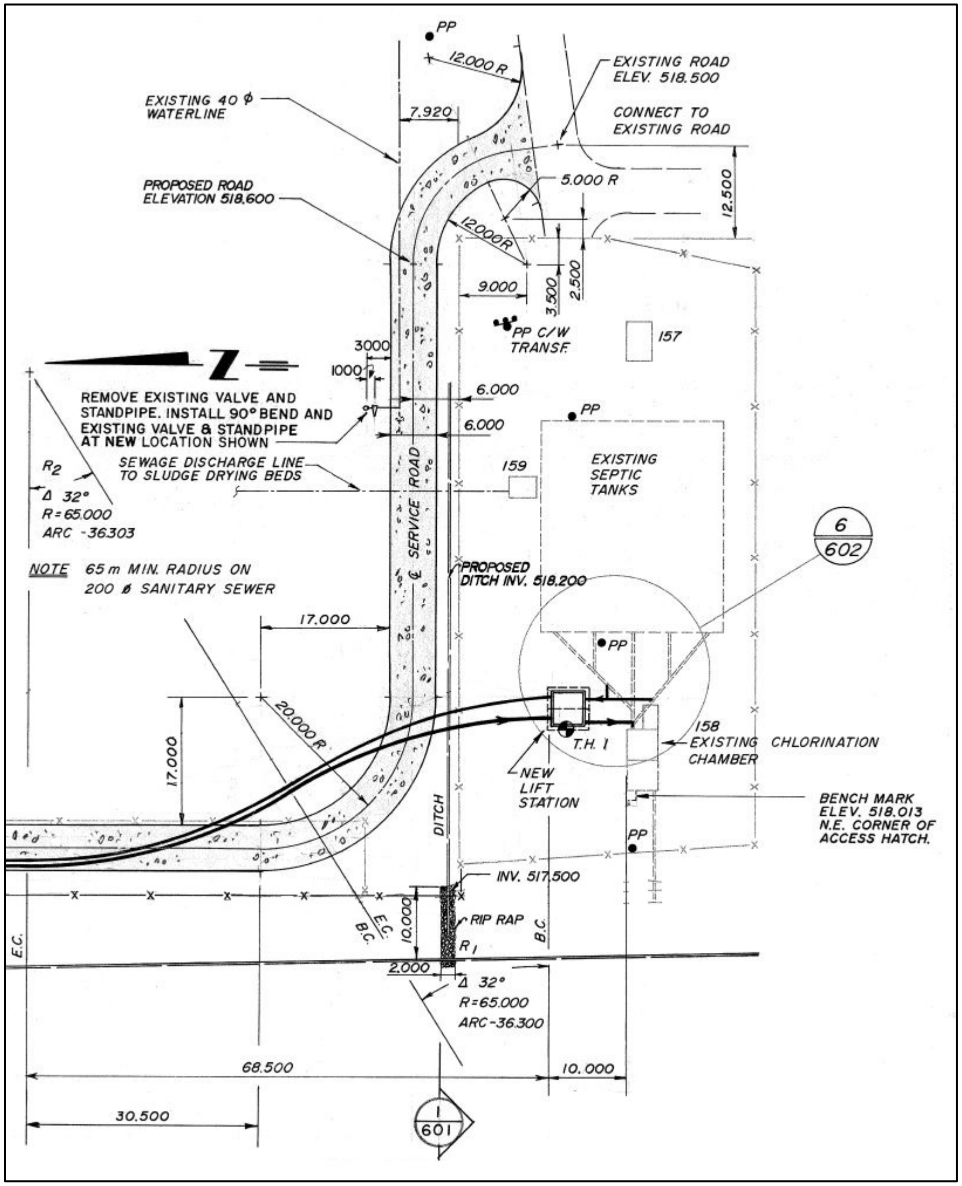


Figure E3 - 1988 Construction drawing - Site plan of lift station area
(Modified from Bullée Consulting Ltd. 1988b)

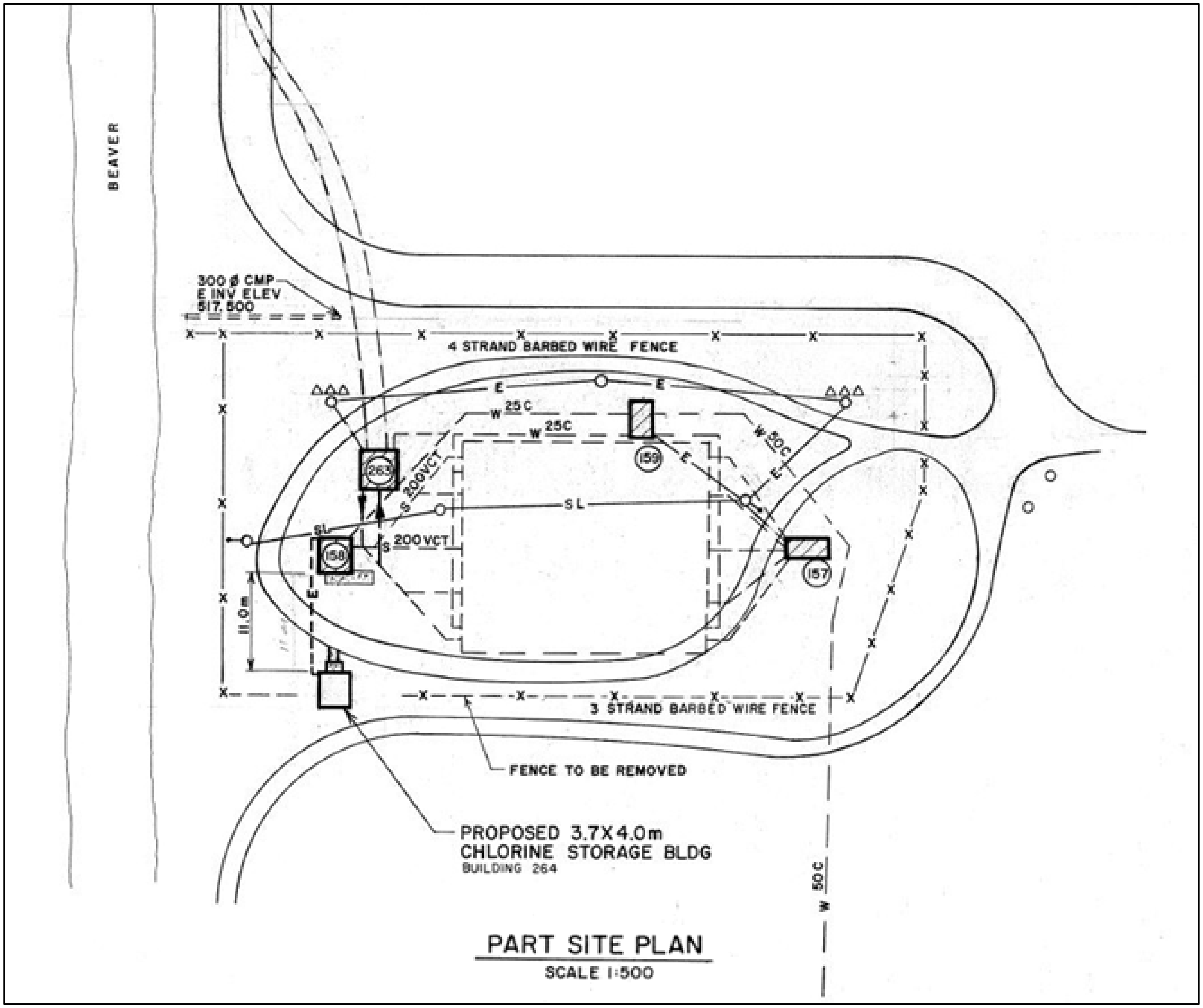


Figure E4 - 1992 Construction drawing - Site plan of lift station area. Note: Addition of chemical storage shed (Modified from BCEO CFB Moose Jaw 1992)

Lagoon Cells Cross Sections:

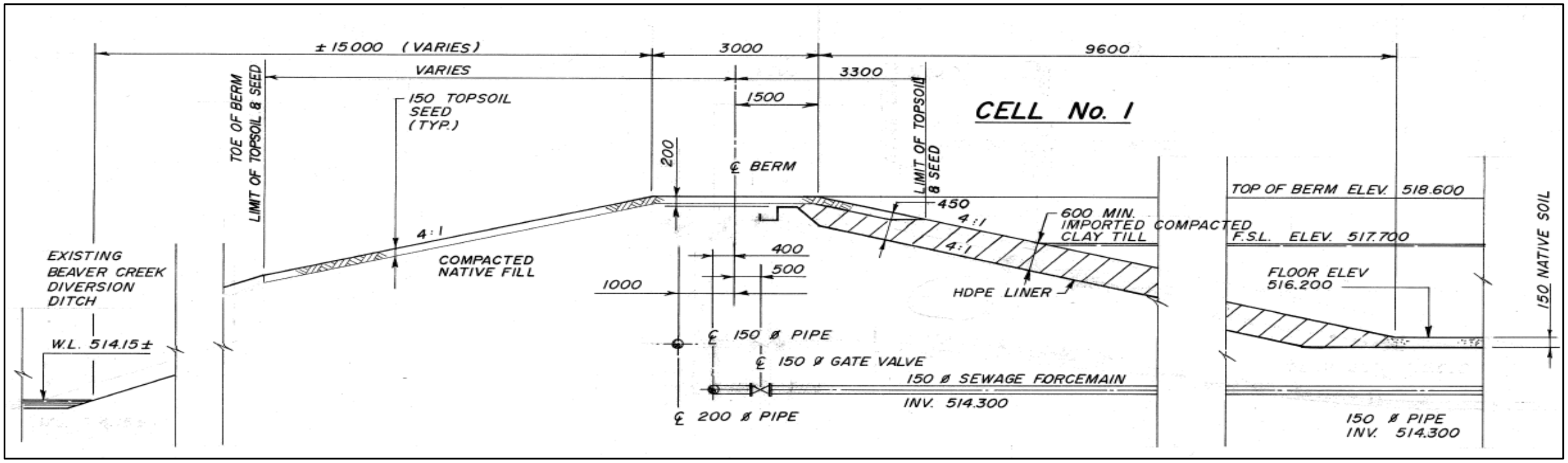


Figure E5 - 1988 Construction drawing - Western berm cross section at cell #1 (Modified from Bullée Consulting Ltd. 1988b)

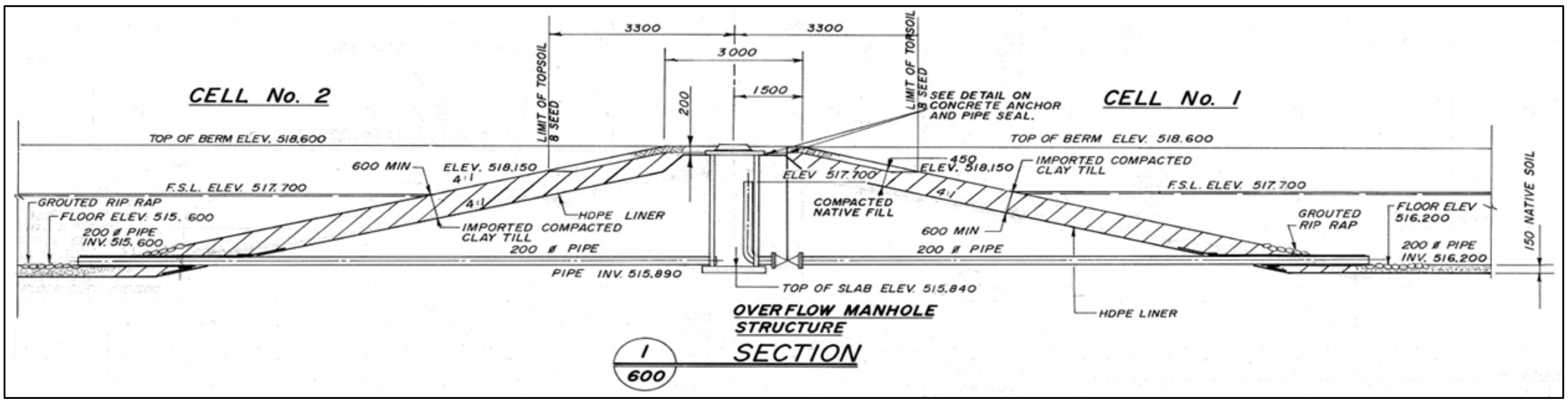


Figure E6 - 1988 Construction drawing - Cross section of central berm (Modified from Bullée Consulting Ltd. 1988b)

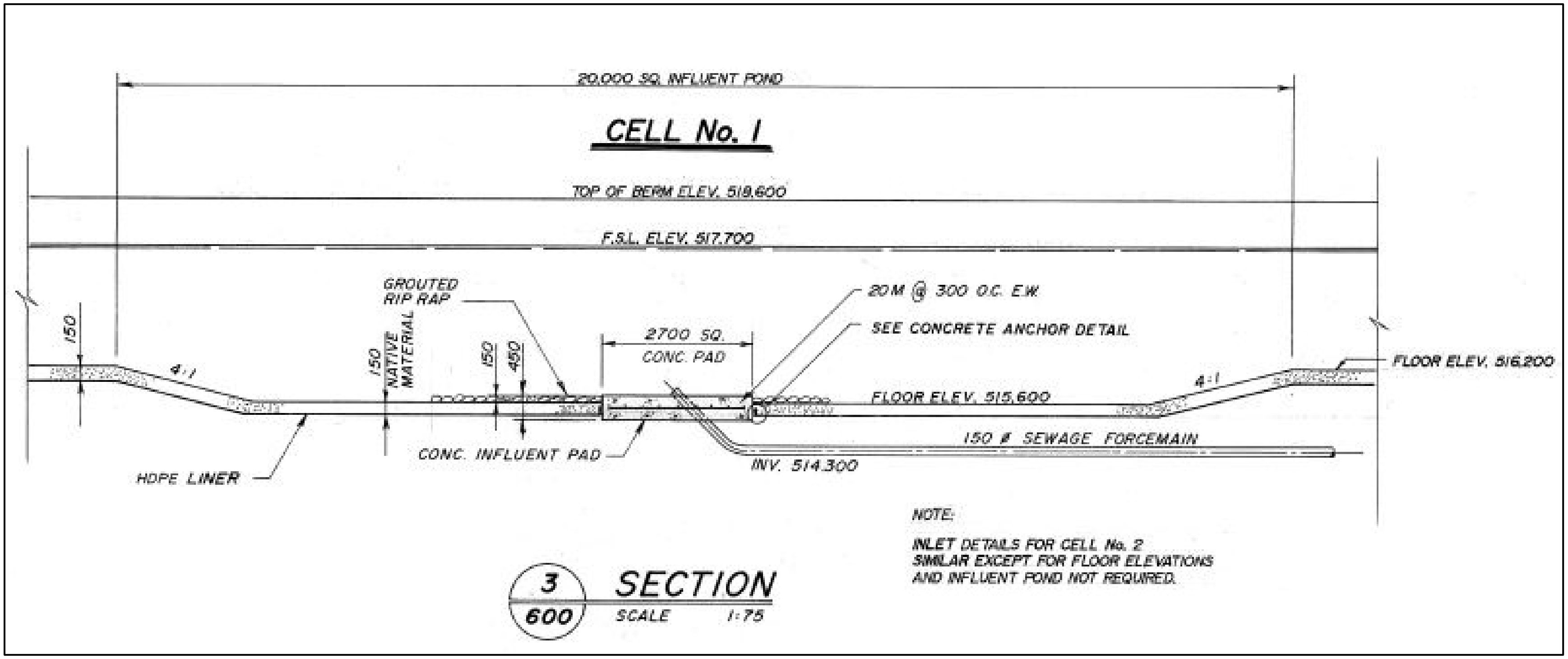


Figure E7 - 1988 Construction drawing - Cross section of Cell #1 at intake pipe (Modified from Bullée Consulting Ltd. 1988c)

Grit Chamber, Septic Tanks, and Pipework Details:

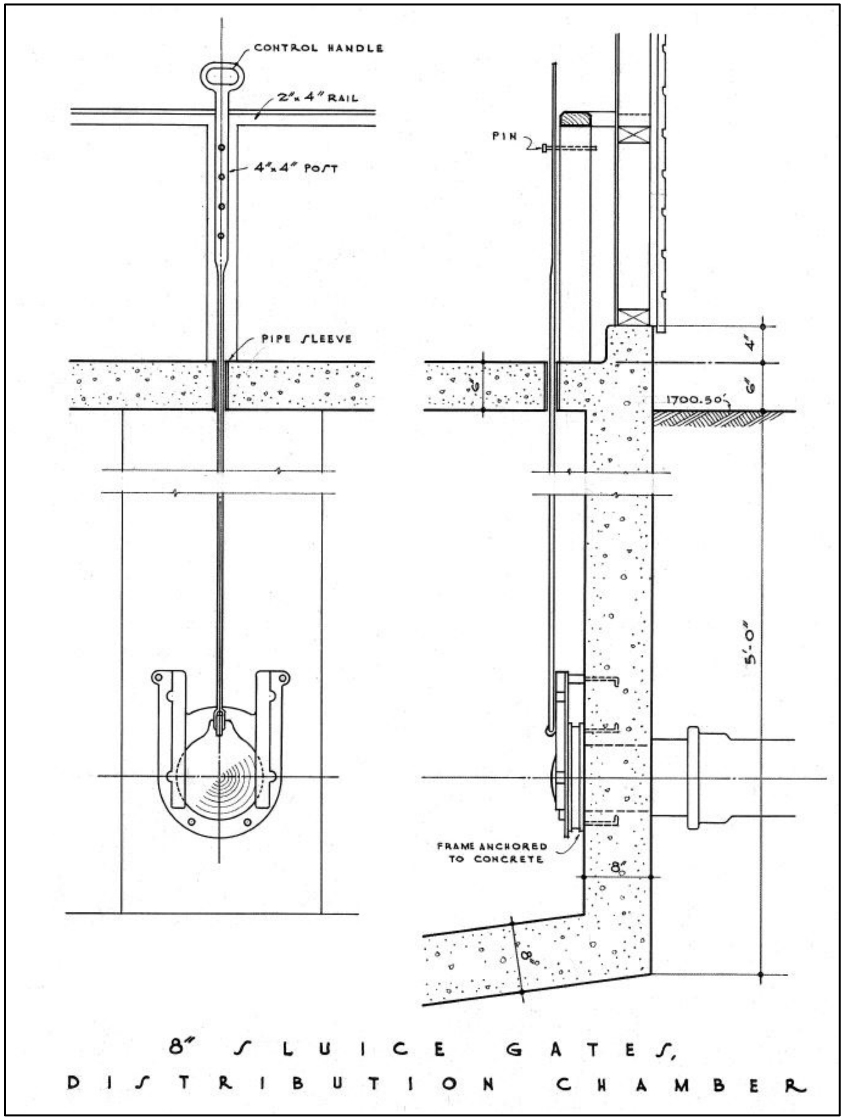


Figure E8 - Grit (distribution) chamber sluice gate detail (measurements in feet and inches) (Modified from DND Engineer Services Branch 1941b)

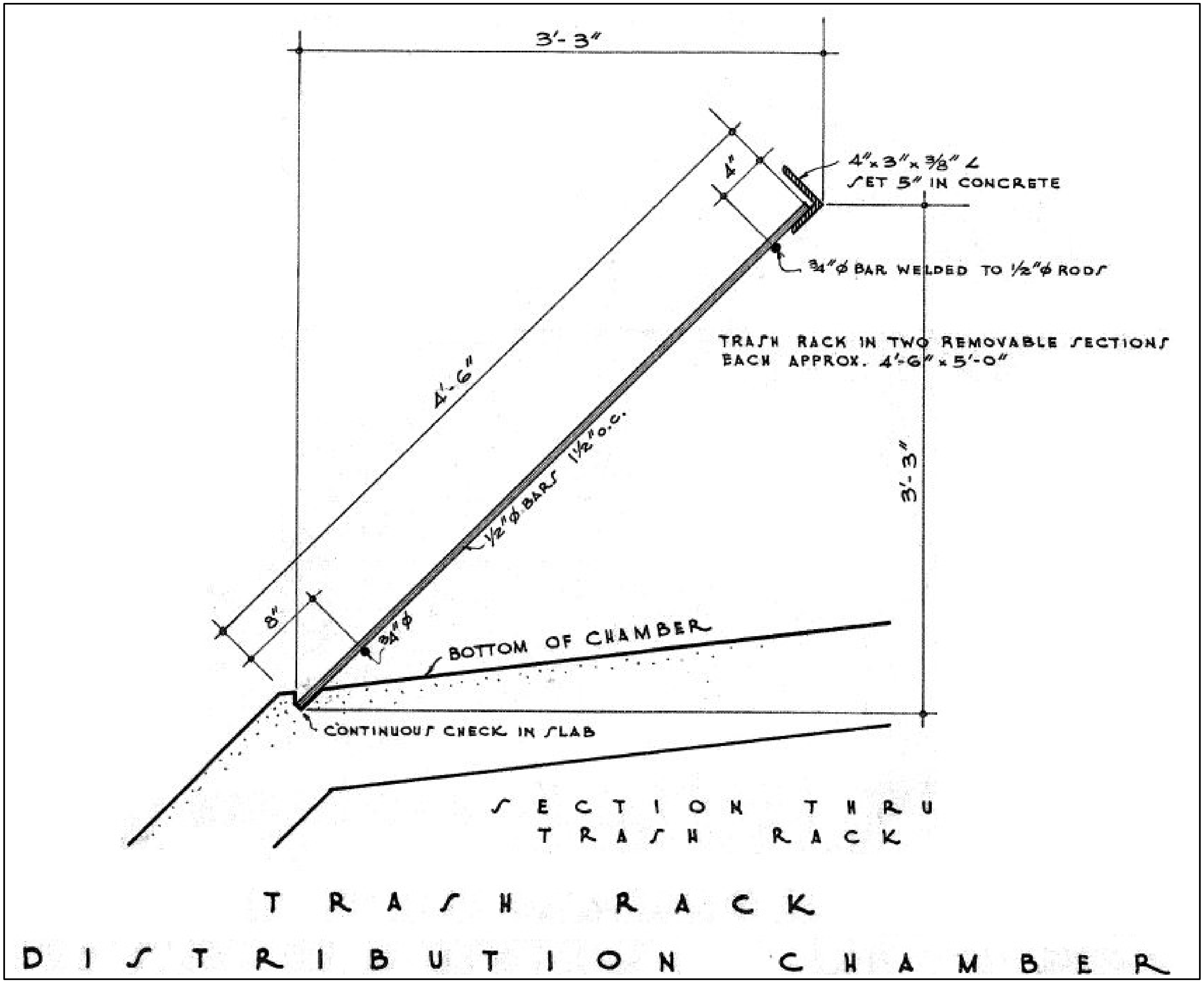


Figure E9 - Trash rack in grit chamber detail (measurements in feet and inches) (Modified from DND Engineer Services Branch 1941b)

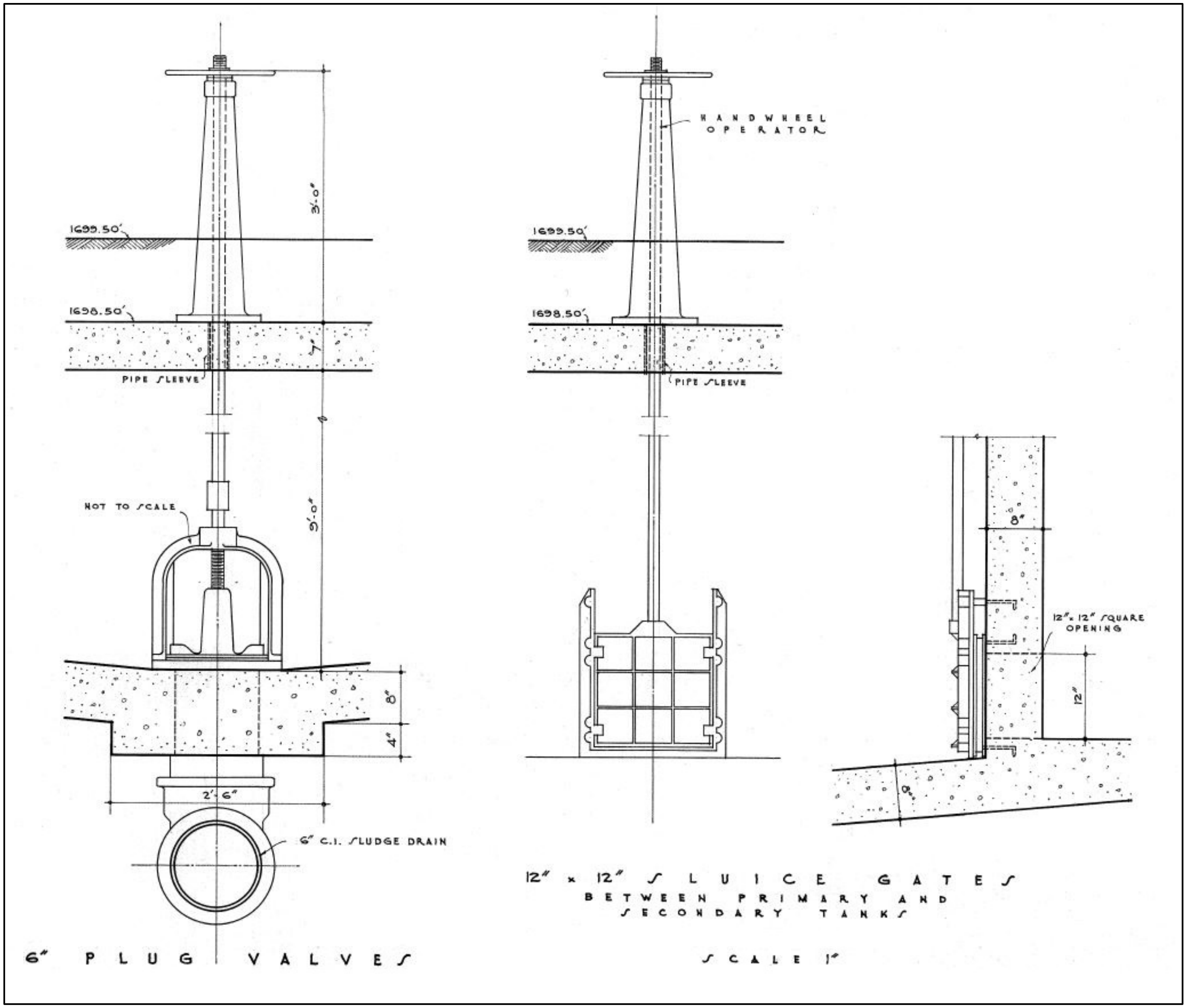


Figure E10 - Septic tanks plug valves and sluice gates detail (measurements in feet and inches)
(Modified from DND Engineer Services Branch 1941b)

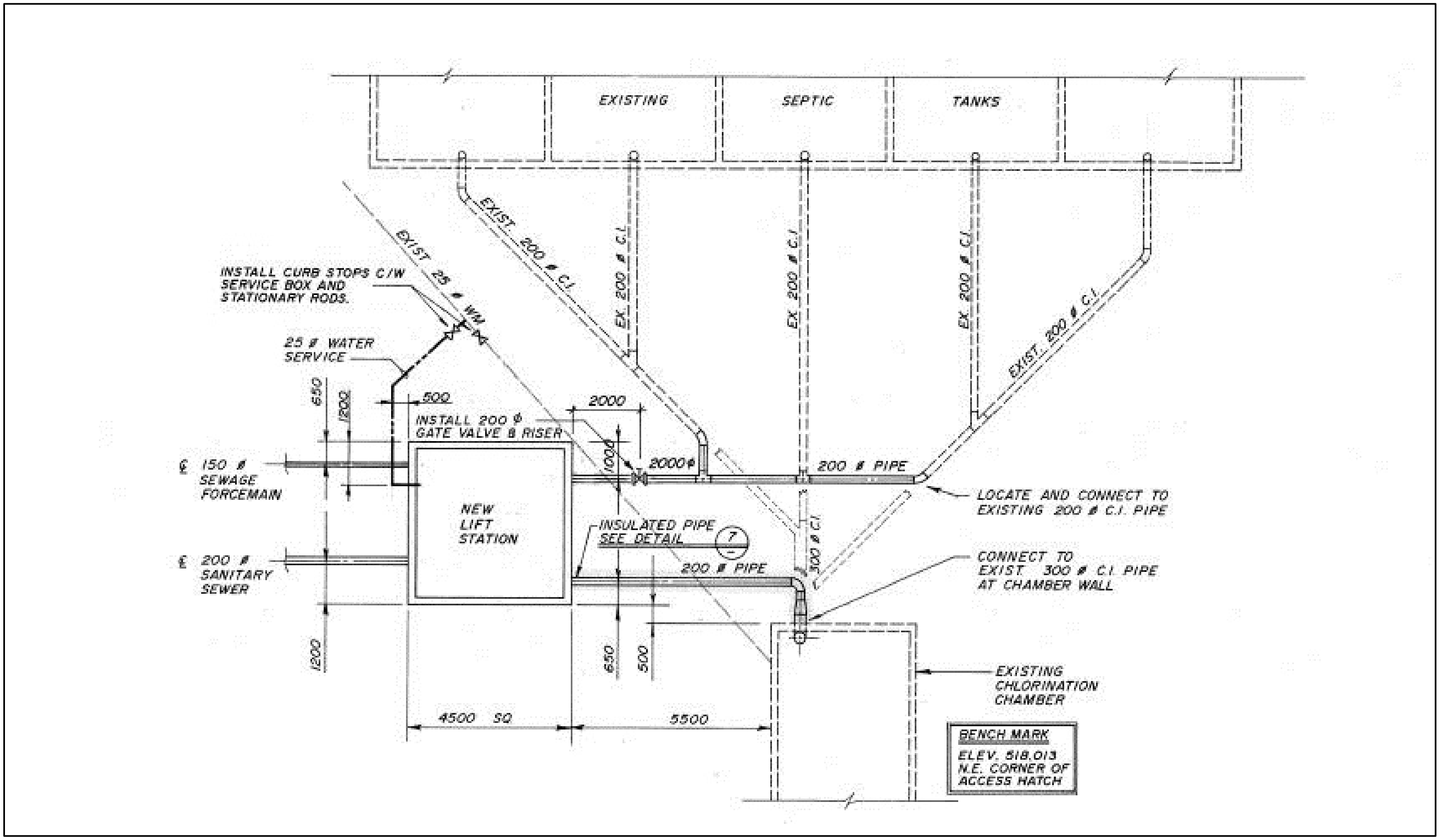


Figure E11 - 1988 Construction drawing - Pipework of lift station connection to the septic tank and chlorination chamber (Modified from Bullée Consulting Ltd. 1988c)

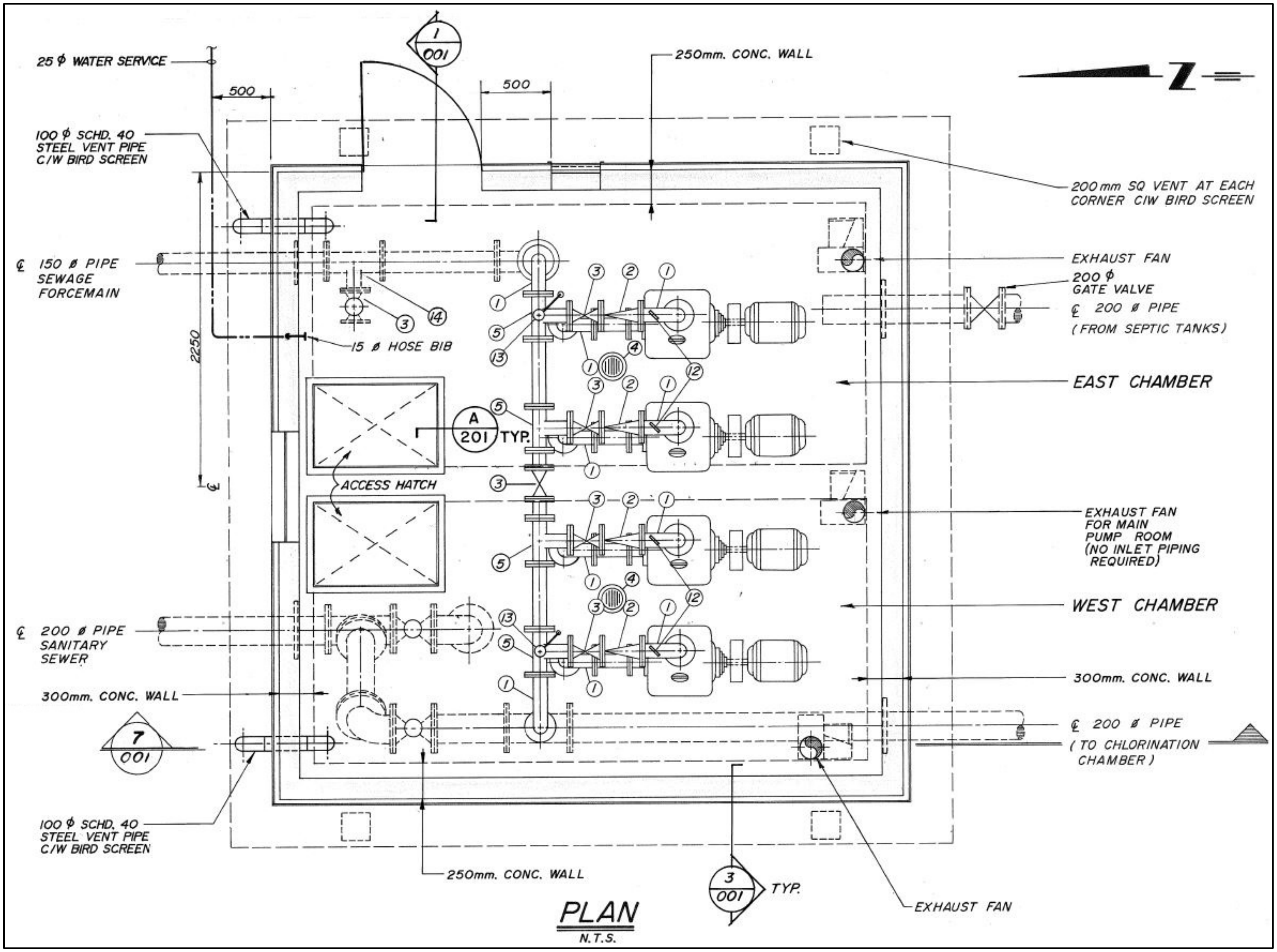


Figure E12 - Lift station floor plan (Bullée Consulting Ltd. 1988d)

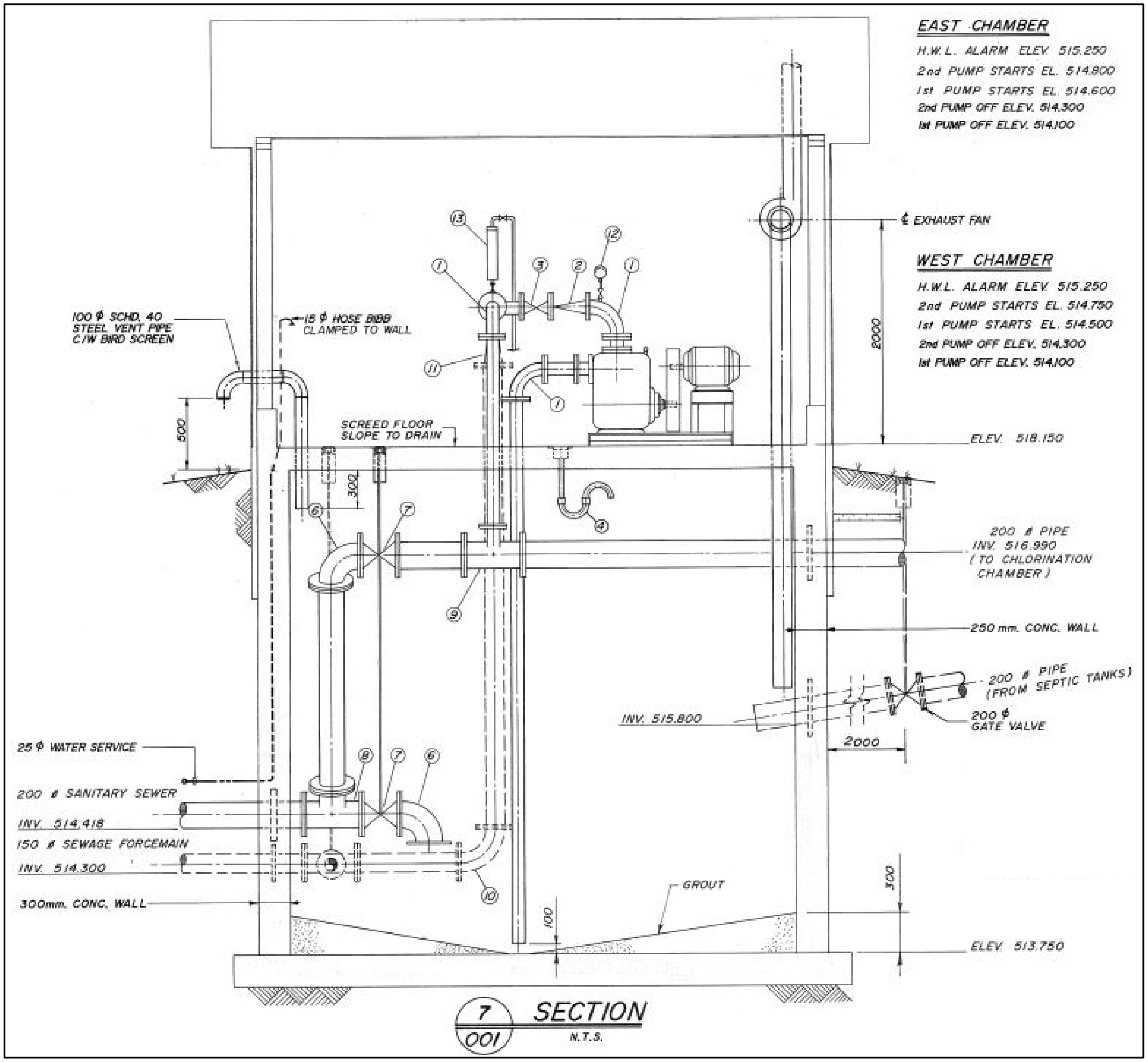


Figure E13 - Lift station cross section (Bullée Consulting Ltd. 1988d)

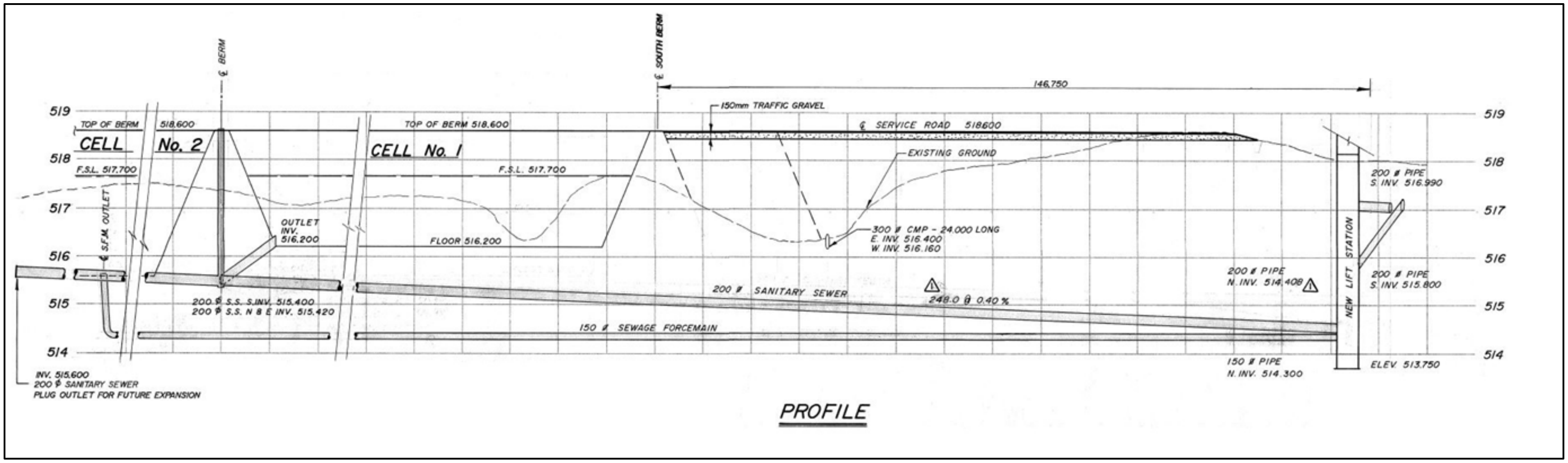


Figure E14 - 1988 Construction drawing - Elevation profile of sewage force main and sanitary main lines (Modified from Bullée Consulting Ltd. 1988b)

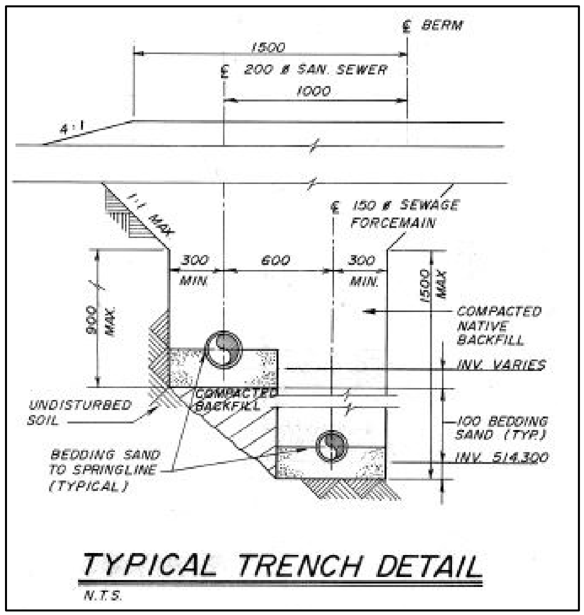


Figure E15 - 1988 Construction drawing - Force main and sanitary main trench details (Modified from Bullée Consulting Ltd. 1988b)

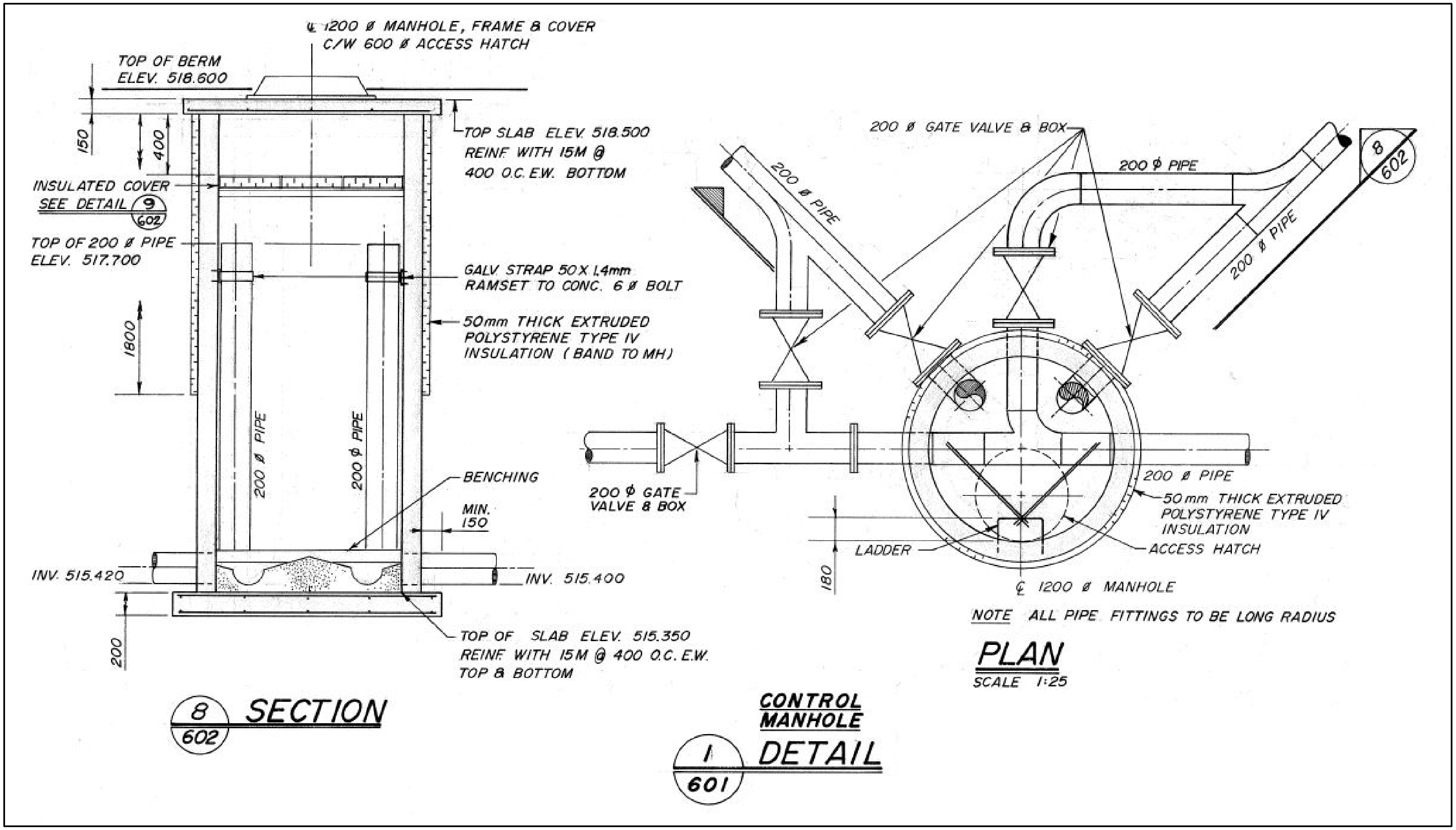


Figure E16 - 1988 Construction drawing - Control manhole details (Modified from Bullée Consulting Ltd. 1988c)

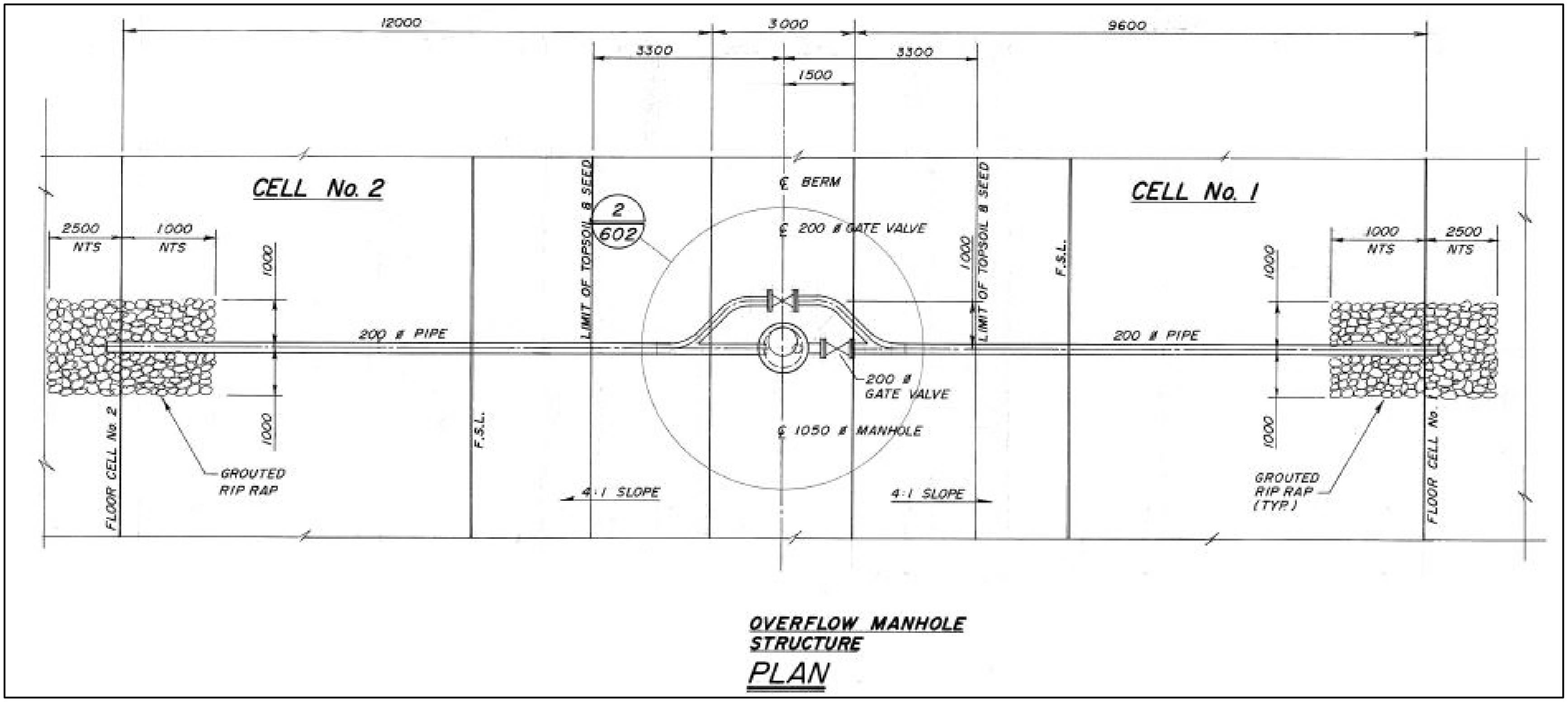


Figure E17 - 1988 Construction drawing - Plan view of overflow manhole structure (Modified from Bullée Consulting Ltd. 1988b)

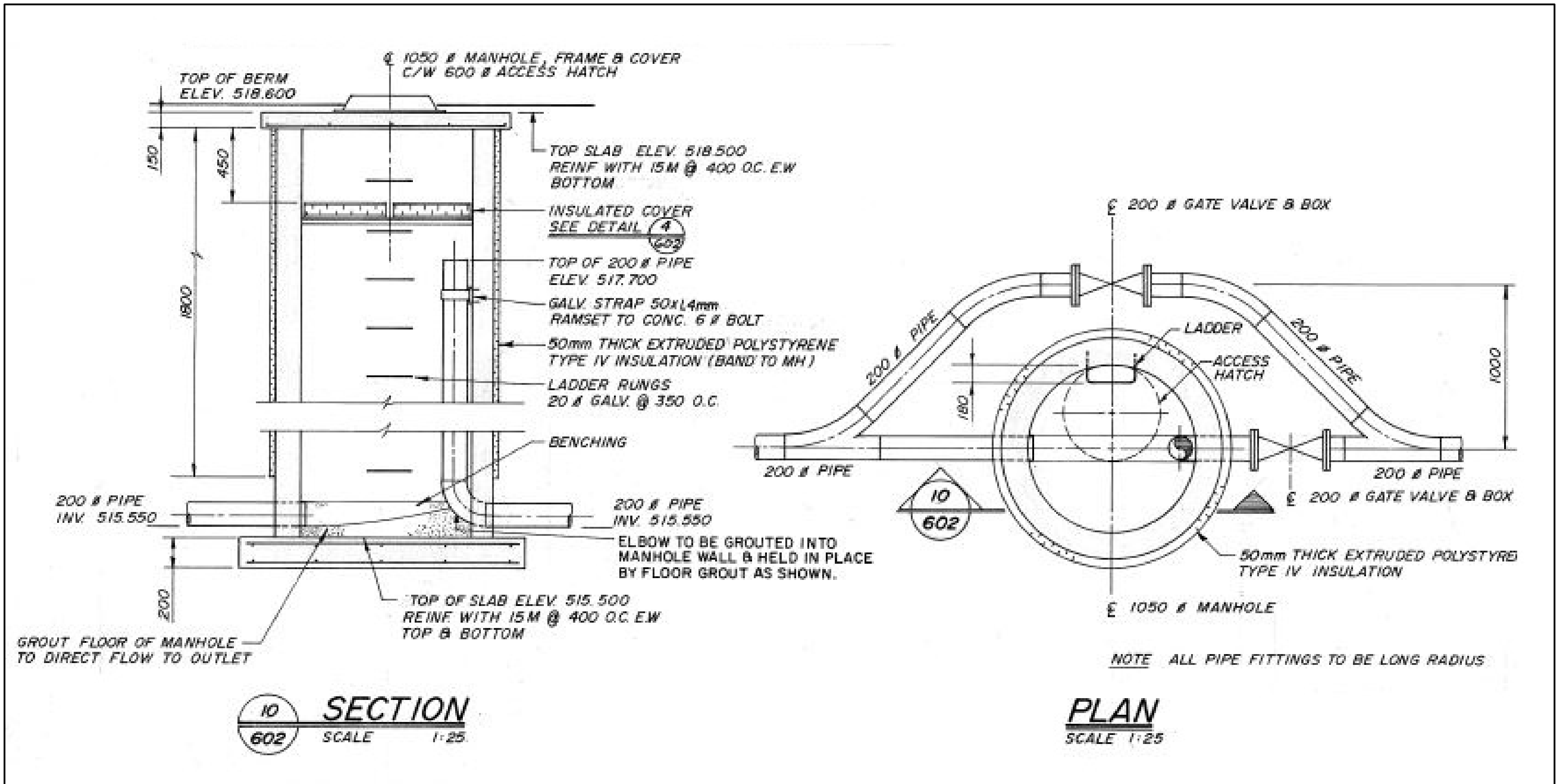


Figure E18 - 1988 Construction drawing - Overflow manhole details (Modified from Bullée Consulting Ltd. 1988c)

Lagoon Lining Details:

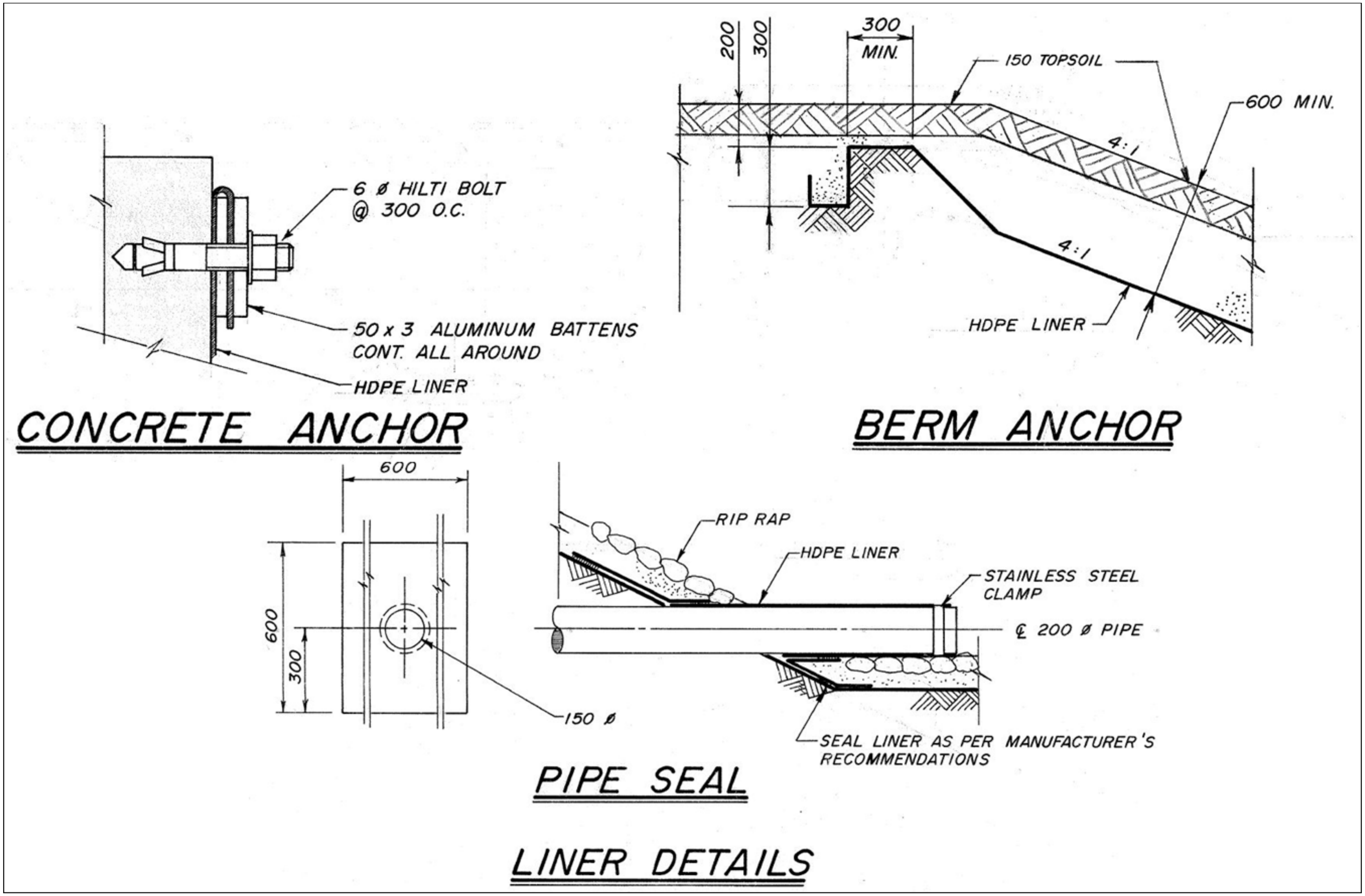


Figure E19 - 1988 Construction drawing - Liner details (Modified from Bullée Consulting Ltd. 1988c)

Discharge Point Details:

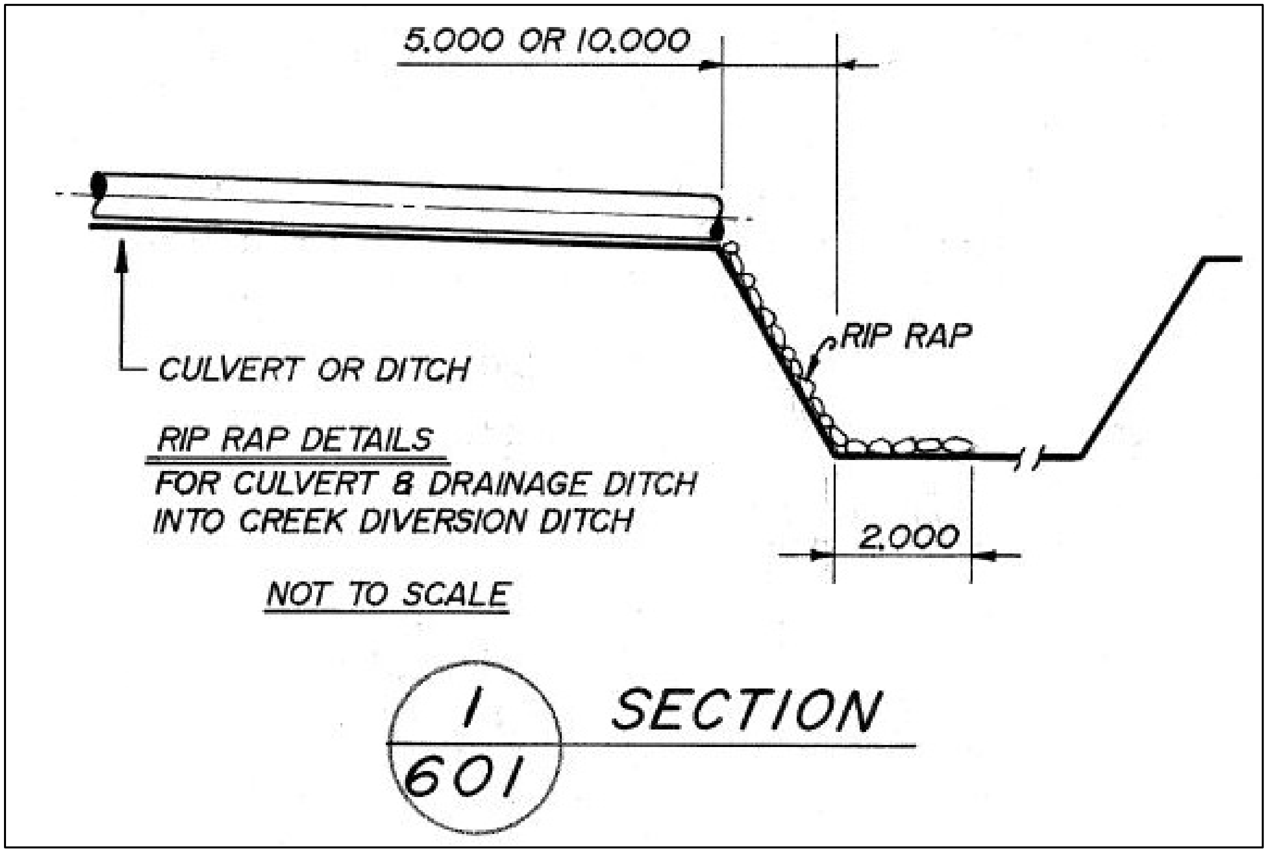


Figure E20 - 1988 Construction drawing - Discharge ditch cross section (Modified from Bullée Consulting Ltd. 1988b)

Chlorination Chamber Details:

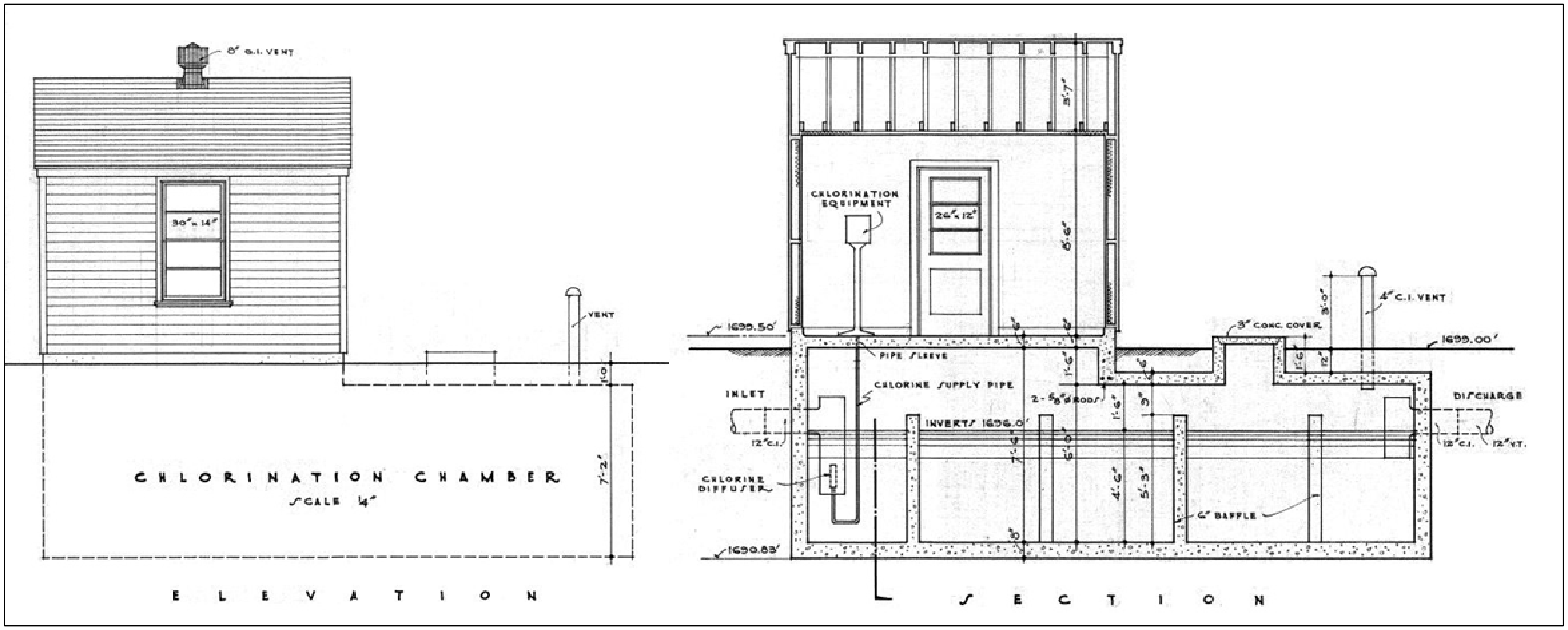


Figure E21 - 1941 Construction drawing - Chlorination chamber side view and cross section 1 (measurements in feet and inches) (Modified from DND Engineer Services Branch 1941b)

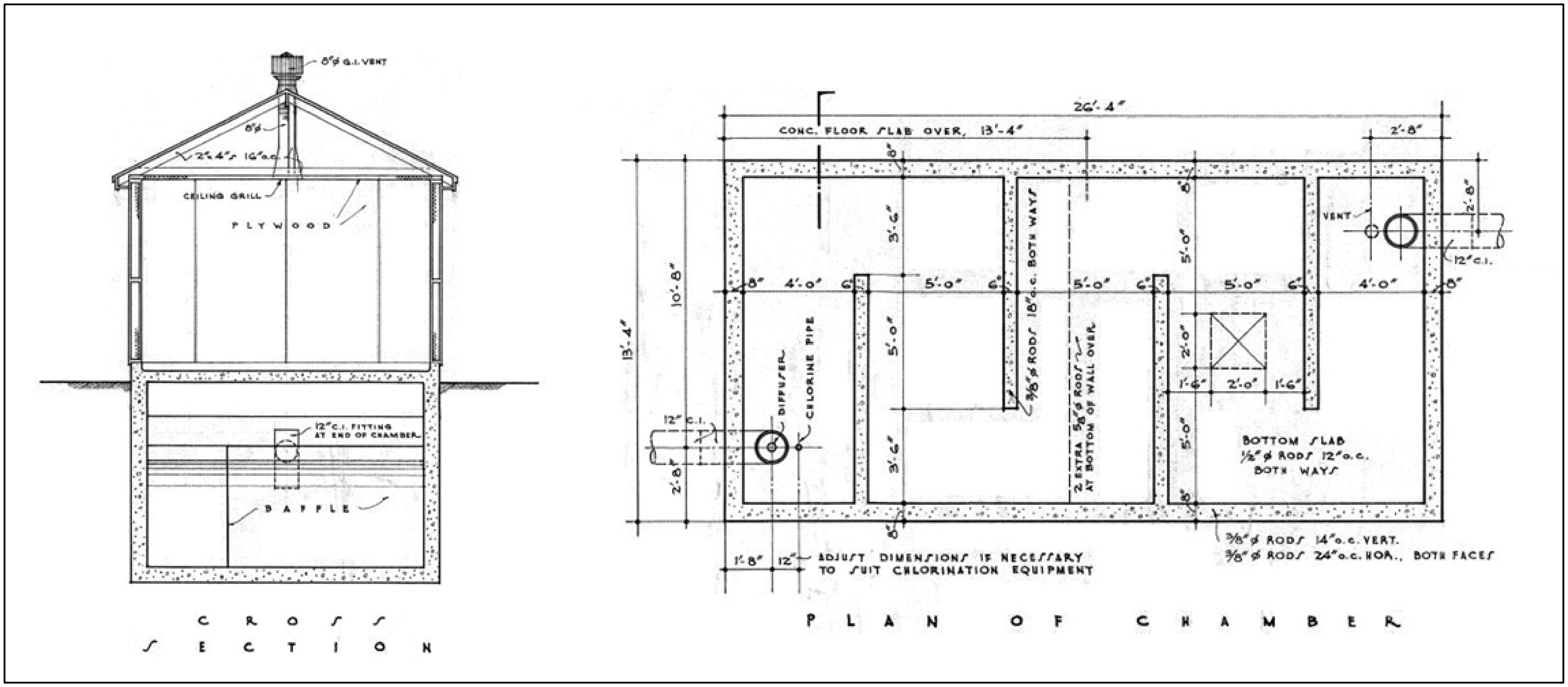


Figure E22 - 1941 Construction drawing - Chlorination chamber cross section 2 and plan view (measurements in feet and inches) (Modified from DND Engineer Services Branch 1941b)

Sludge Pump Details:

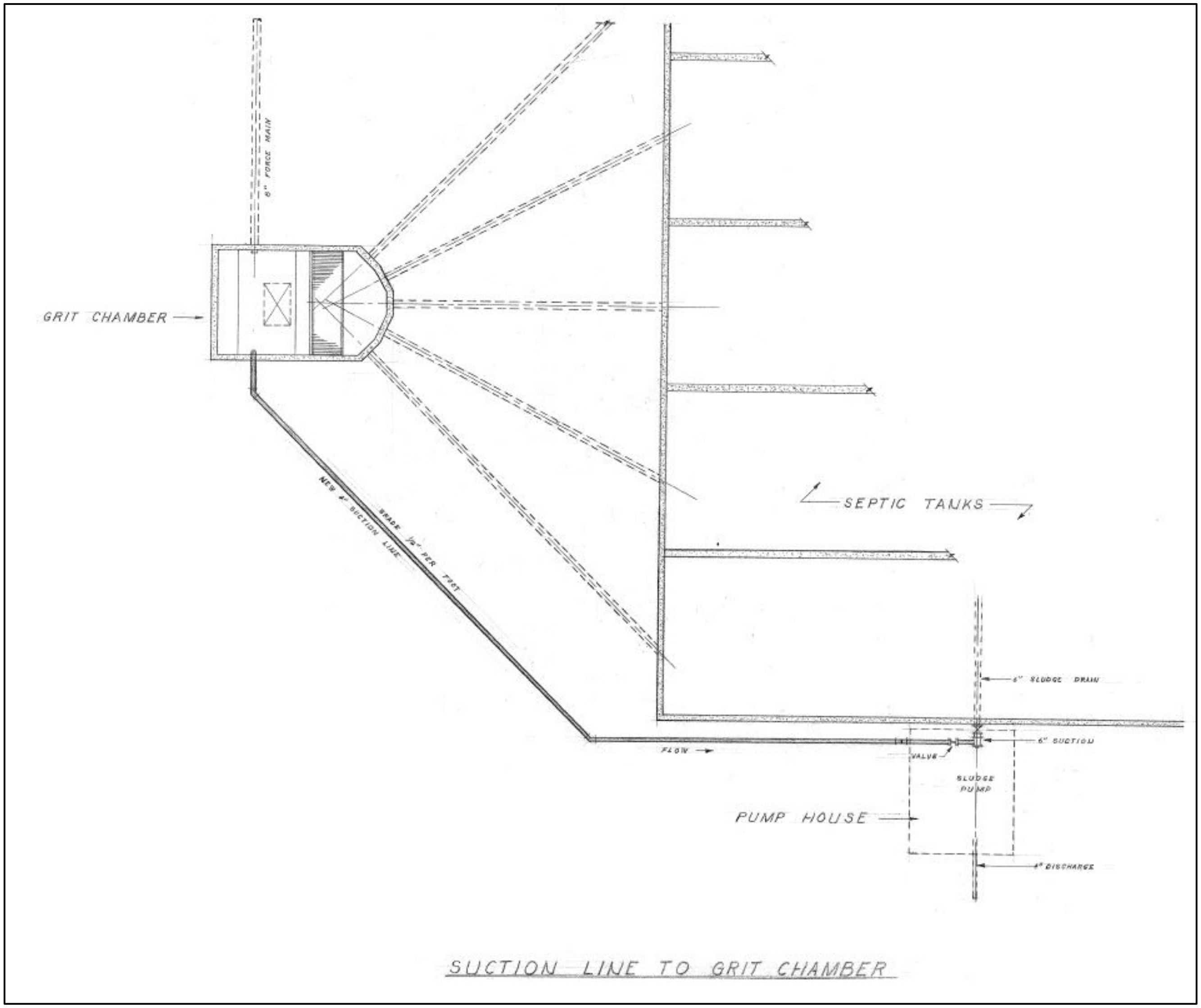


Figure E23 - 1964 Construction drawing - Sludge suction line details (measurements in feet and inches) (Modified from "CFD Dundurn Sewage Treatment Facilities - Dwg. No. 402" 1964)

Appendix F – Monitoring Wells

The following appendix highlights the basic information regarding the nine (9) monitoring wells (MW) located within the proximity of 17 Wing Detachment Dundurn's Wastewater Treatment (WWT) lagoon system. The MWs have been installed prior to 2002 as part of a detachment-wide groundwater monitoring programme. MW installation logs have been reported to be lost or where otherwise not available at the time of the desk study and site investigation.

Table F1 presents the basic information regarding the MW. All the information presented in this table have been obtained from previous groundwater monitoring programme reports and verified, where possible, during the sampling undertaken as part of this research project. Information regarding the total depth of the wells has differed between reports with variations of up to 1 m. Table F2 provides observations that were taken during the each of the sampling rounds of this research project. In addition, observations taken by Defence Construction Canada in 2015 are included. All MW had bailers or Waterra pumps stored within them. The presence of these sampling devices within the MWs often prevented the lid of the wells to be properly secured. The paint on all MW casings was worn and surface rust was visible in certain areas. All MW were not locked to prevent unauthorized access.

Figure F1 presents areal imagery of the WWT lagoon site marked with the locations of the MWs. Figure F2 through Figure F10 are photos of the MWs. Figure F11 through Figure F13 show typical examples of well conditions within once the casing lid was opened.

Table F1 - Basic information of monitoring wells located at the WWT lagoon (Jacques Whitford 2005, MDH Engineered Solutions 2006, WorleyParsons Canada 2011).

ID	Location (Coordinates)		Ground Elevation (masl)*	Stickup (m)	Total Depth (mbgs)**
	Easting & Northing NAD83	MGRS NAD83			
SL#1	391992.856; 5746307.838	13UCT 91990 46309	518.58	0.90	4.89
SL#2	391982.276; 5746349.457	13UCT 92030 46332	518.67	1.05	5.37
SL#3	392031.423; 5746331.564	13UCT 91981 46349	518.43	1.15	5.68
SL#4	392099.102; 5746454.440	13UCT 92095 46459	517.13	0.70	4.03
SL#5	392197.093; 5746454.474	13UCT 92198 46455	517.51	0.75	4.13
SL#6	392193.854; 5746573.764	13UCT 92193 46575	517.64	0.70	4.49
SL#7	392190.812; 5746706.785	13UCT 92195 46713	516.94	0.50	4.08
SL#8	392080.033; 5746704.422	13UCT 92078 46706	517.37	0.80	4.70
SL#9	391967.054; 5746700.667	13UCT 91976 46704	518.18	1.20	5.90

* Meters above mean sea level
** Meters below ground surface

Table F2 - Observations made by the author during sampling of MW. Observations from the 2015 groundwater monitoring programme is also included (Banilevic 2015).

Location	Date	Report	Well Condition	Comments
SL#1	03/09/2015	2015 GW Monitoring Programme Memorandum	Good	- Bailer in well.
	14/08/2018	Sampling Round 1	Good	- Tubing and Bailer left in well. - Well lid not properly secured and bailer rope protruding from well. - Well casing not locked. - Worn casing paint.
	23/10/2018	Sampling Round 2	Good	- No change from 14/08/2018 observations.
	16/04/2019	Sampling Round 3	Good	- No change from 23/10/2018 observations. - Ice formation present on equipment in well.
SL#2	03/09/2015	2015 GW Monitoring Programme Memorandum	Good	- Waterra tube in well.
	14/08/2018	Sampling Round 1	Good	- Waterra tube and pump left in well. - Well lid not properly secured. - Well casing not locked. - Worn casing paint.
	23/10/2018	Sampling Round 2	Good	- No change from 14/08/2018 observations.
	16/04/2019	Sampling Round 3	Good	- No change from 23/10/2018 observations.
SL#3	03/09/2015	2015 GW Monitoring Programme Memorandum	Good	- Waterra tube in well. - Well pipe separated in two spots.
	14/08/2018	Sampling Round 1	Fair	- Waterra tube and pump left in well. - Well casing damaged or obstructed. - Sampling tube was difficult to lower. - Well casing not locked. - Worn casing paint.
	23/10/2018	Sampling Round 2	Fair	- No change from 14/08/2018 observations. - Well obstruction located at approximately 3.95 mbtoc.
	16/04/2019	Sampling Round 3	Poor	- No change from 23/10/2018 observations. - Well lid missing
SL#4	03/09/2015	2015 GW Monitoring Programme Memorandum	Good	- Bailer in well.
	14/08/2018	Sampling Round 1	Good	- Bailer and tubing left in well. - Well lid not properly secured and bailer rope protruding from well. - Well casing not locked. - Worn casing paint. - Well dry at time of sampling. - Dipmeter reaches bottom at approximately 4.20 mbtoc. No alarm. - Partial samples extracted and heavily sedimented.

Location	Date	Report	Well Condition	Comments
	23/10/2018	Sampling Round 2	Good	- Bailer and tubing left in well. - Well lid not properly secured and bailer rope protruding from well. - Well casing not locked. Worn casing paint.
	16/04/2019	Sampling Round 3	Good	- No change from 23/10/2018 observations. - Well lid was properly secured.
SL#5	03/09/2015	2015 GW Monitoring Programme Memorandum	Poor	- Bailer in well. - Lid damaged. - Sewage odour from well.
	14/08/2018	Sampling Round 1	Poor	- Bailer left in well. - Casing lid broken and Casing damaged. - Well lid not properly secured and bailer rope protruding from well. - Well casing not locked. Worn casing paint. - Sewage odour emanating from well.
	23/10/2018	Sampling Round 2	Poor	- No change from 14/08/2018 observations.
	16/04/2019	Sampling Round 3	Poor	- No change from 23/10/2018 observations. - Well lid was properly secured.
SL#6	03/09/2015	2015 GW Monitoring Programme Memorandum	Good	- Bailer in well.
	14/08/2018	Sampling Round 1	Good	- Bailer and rope left in well. - Well lid not properly secured. - Well casing not locked. - Worn casing paint.
	23/10/2018	Sampling Round 2	Good	- No change from 14/08/2018 observations.
	16/04/2019	Sampling Round 3	Fair	- Bailer and tubing left in well. - Obstruction in well detected.
SL#7	03/09/2015	2015 GW Monitoring Programme Memorandum	Good	- Bailer in well.
	14/08/2018	Sampling Round 1	Good	- Bailer and tube left in well. - Well lid not properly secured and bailer rope protruding from well and casing. - Well casing not locked. - Worn casing paint.
	23/10/2018	Sampling Round 2	Fair	- No change from 14/08/2018 observations. - Slight obstruction at approximately 2.40 mbtoc.
	16/04/2019	Sampling Round 3	Fair	- No change from 23/10/2018 observations. - Well lid was properly secured.
SL#8	03/09/2015	2015 GW Monitoring Programme Memorandum	Good	- Waterra tube in well.
	14/08/2018	Sampling Round 1	Good	- Waterra tube and pump left in well. - Well casing not locked. - Worn casing paint.

Location	Date	Report	Well Condition	Comments
	23/10/2018	Sampling Round 2	Good	- No change from 14/08/2018 observations. - Sampling tube too low for manual retrieval.
	16/04/2019	Sampling Round 3	Good	- No change from 23/10/2018 observations.
SL#9	03/09/2015	2015 GW Monitoring Programme Memorandum	Good	- Bailer in well.
	14/08/2018	Sampling Round 1	Fair	- Bailer and tubing left in well. - Well lid not properly secured and bailer rope protruding from well and casing. - Well casing not locked. - Worn casing paint. - Obstruction in well. - Extracted water samples have a rusty colour. - Bailer and tubing are stained with rusty colour.
	23/10/2018	Sampling Round 2	Fair	- No change from 14/08/2018 observations.
	16/04/2019	Sampling Round 3	Poor	- No change from 23/10/2018 observations. - Obstruction in well detected. - Well lid was properly secured.

Figure F1 - Locations of MW at the WWT lagoon system (Imagery obtained from Microsoft Corporation 2018).

Figure F2 - MW SL#1

Figure F3 - MW SL#2

Figure F4 - MW SL#3

Figure F5 - MW SL#4

Figure F6 - MW SL#5

Figure F7 - MW SL#6

Figure F8 - MW SL#7

Figure F9 - MW SL#8

Figure F10 - MW SL#9

Figure F11 – Example of a Waterra pump and tubing found within some of the MWs (SL#1).

Figure F12 - Example of sampling equipment found preventing the lid of the MWs to be properly secured (SL#4).

Figure F13 - Bailer rope obstructing a MW lid and filling the casing cavity (SL#8).

Appendix G – RMC Green Team Lagoon Systems Questionnaire

The following appendix outlines the questionnaire that is used by the RMC Green Team when conducting initial site visits or phone interviews with Wastewater Treatment (WWT) lagoon systems operators and managers. This questionnaire was used as part of the semi-structured stakeholder interview process conducted in this research project at 17 Wing Det. Dundurn. Further questions were asked based on the information provided by the interviewees.

Figure G1- RMC Green Team Logo

Source/Collection System:

1.1. What is the population served (size/residential or day workers)?

1.2. Provided/described the lagoon system flow diagram (pictures if available).

1.3. Described the collection system.

1.4. Are there any lift stations? If yes, described it/them (e.g. location, size, and age)

1.5. Are there other wastewater sources (e.g. equipment wash stations, swimming pools, and storage tanks of any other deleterious substances)? If yes, described it/them.

1.6. Is preliminary treatment provided (e.g. pre-screen, interceptors, and oil & grease separators)? If yes, described it.

1.7. What is the inflow volume (m^3/day)?

1.8. Is the lagoon protected/restricted access?

1.9. Are there any known issues with the wastewater sources or collection systems?

Design:

2.1. Provided/described the lagoon system flow schematic.

2.2. Described the lagoon system (e.g. number of cells, dimensions, surface area, depth, total volume, retention time)?

2.3. Is aeration provided? If yes, what type?

2.4. Is the lagoon lined/insulated (e.g. membrane, clay)? If yes, described it (type, age, inspections, maintenance undertaken).

2.5. How is the sludge managed? If the sludge is periodically removed from the lagoons, how is it disposed of?

2.6. Are there any known issues with the lagoon system design?

Operation:

3.1. Who is involved in the operation of the lagoon system (e.g. plant personnel, contractors)?

3.2. Define the effluent receiving body (e.g. surface water, irrigation pond, and wetlands)

3.3. What effluent guidelines/regulations are followed (e.g. Provincial, area specific restrictions, etc.)

3.4. What is the typical effluent discharge quality (i.e. laboratory results)?

3.5. Are there any compliance issues? If yes, described it/them.

3.6. Where is the effluent discharge location (i.e. exit point)?

3.7. What is the effluent discharge frequency (i.e. continuous or scheduled)?

3.8. Who is the approval authority for treated effluent discharges?

3.9. Are there any monitoring wells located on site? If yes, describe (e.g. How many? Is there a monitoring programme in place for the wells? Are there any exceedances? Are laboratory results available?)

3.10. Are there any known infiltrations from the lagoons?

3.11. Are there any known operational issues?

Maintenance:

4.1. What maintenance work is conducted regularly?

4.2. Are there any large maintenance work carried out or pending for the lagoon system (e.g. desludging, liner replacement, etc.)?

4.3. Are there any known maintenance problems?

Sampling:

5.1. Is there a written sampling protocol available for perusal?

5.2. Are operators following an approved sampling protocol?

5.3. What are the sampled parameters: (underline the applicable ones)

Table G1 – List of Sampled Parameters

Parameters		
Alkalinity	BOD	Cd
Free Chlorine	Chloride	COD
Dissolved Oxygen	Conductivity	Glycol
Sulphide	Hardness	Heavy Metal (total/dissolved)
Ion Balance	Ammonia	Nitrite
Nitrate	Nitrogen	pH
Phenol	Sulphide	Sulphate
TDS	Phosphorus (P)	TSS (fixed and volatile)
Turbidity	UV absorbance	

5.4. What is the frequency of the sampling for each of the tested parameters? (e.g. weekly, monthly, quarterly, annually, at the time of discharging)

5.5. Where are the sampling points (e.g. influent, lift station, grab samples from the lagoons, effluent discharging, from the receiving water body)?

5.6. How are the samples analysed (i.e. in house staff, accredited laboratory)?

5.7. Are laboratory results available for the past year?

Interviewee Provided Information:

6.1. Is there any other information the interviewee is willing to provide?

Appendix H – Log Sheets

The following appendix provides example photos of the manual logging sheets as utilized at the WWT lagoon site. An entry is produced every day into the monthly logging sheet and is filed offsite at the end of every month. The logs are produced and kept by the WWT lagoon operators. Each of these logging sheets were taken and inputted into an electronic database by the author as part of this research endeavour. Table x provides statistics on the data collected from the manual log sheets.

Table H1- Log sheet statistics

Log	No. Pages	No. Parameters	No. Data Entry	No. Data Points
WWT Pumping Rates	53	6	1593	9558
Septic Tank pH & Temp.	17	3	497	1491
Total	70	9	2090	11049

Figure H1 provides an example of the pump readings log sheet for the month of February 2018. These logging sheets are kept within the WWT lagoon's lift station (building 263). Figure H2 provides an example of the readings that are obtained from the septic cell system for the month of October 2018. These logging sheets are kept within the WWT lagoon's chlorination chamber building (building 158) until completed and filed.

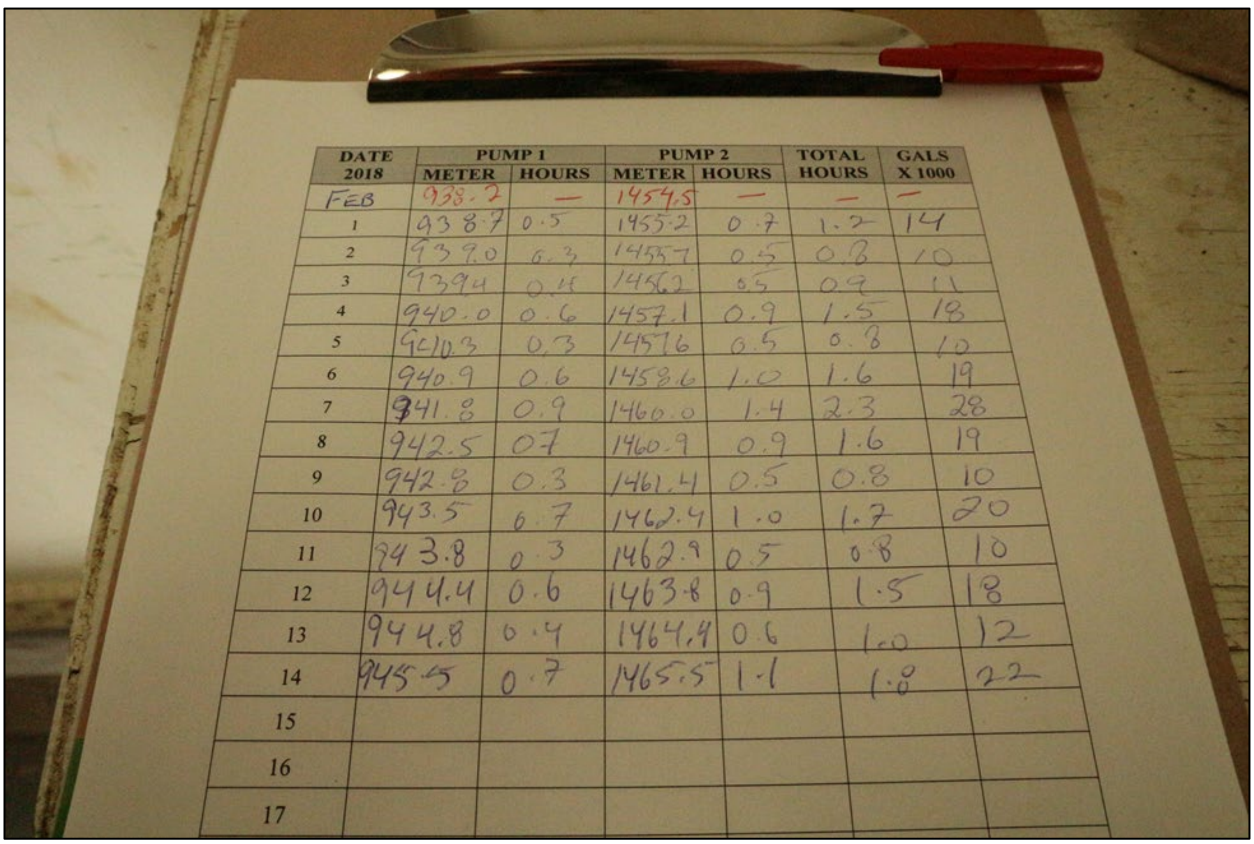
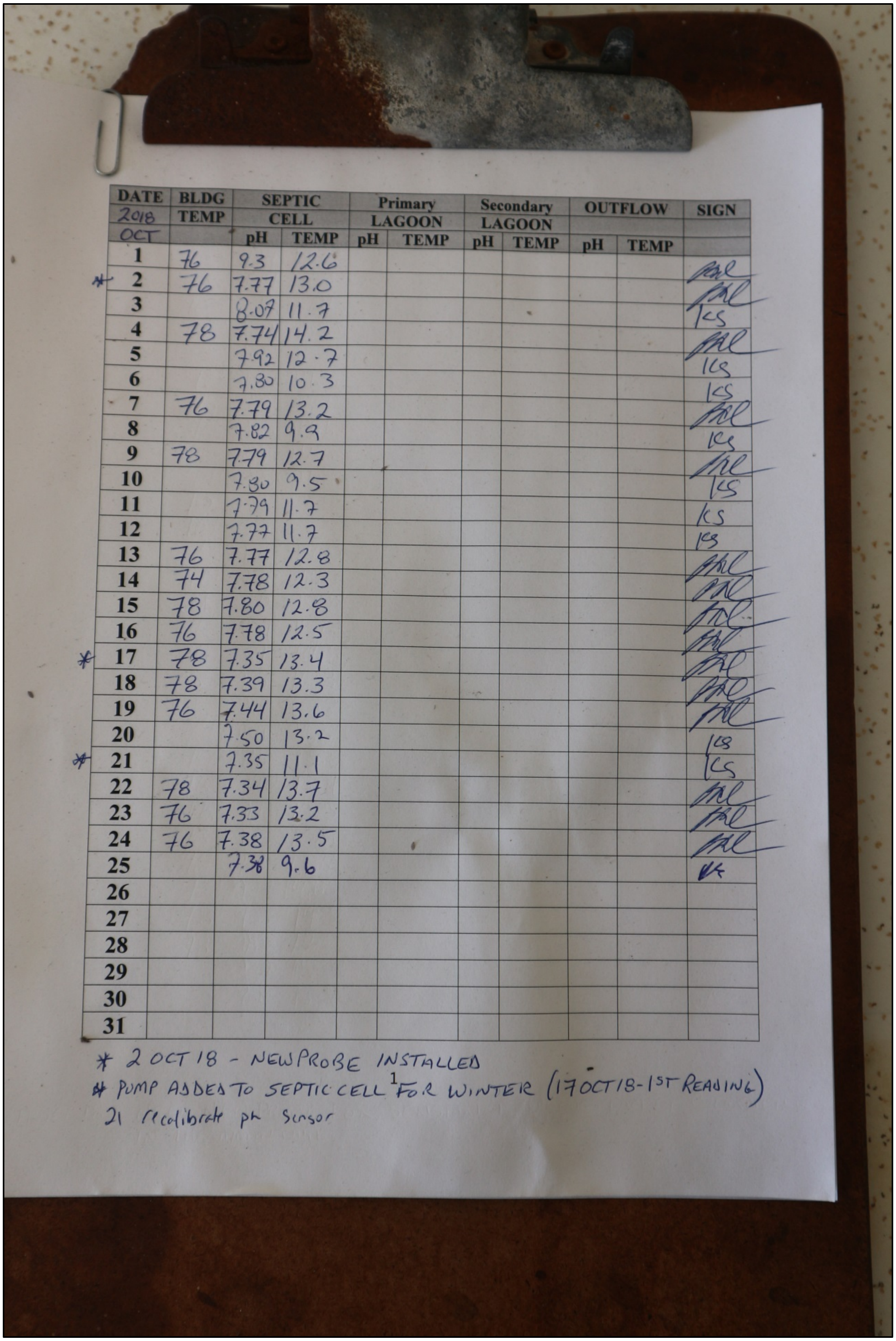


Figure H1 – Example of a WWT lagoon pump reading logging sheet



DATE 2018 OCT	BLDG TEMP	SEPTIC CELL		Primary LAGOON		Secondary LAGOON		OUTFLOW		SIGN
		pH	TEMP	pH	TEMP	pH	TEMP	pH	TEMP	
1	76	9.3	12.6							[signature]
* 2	76	7.77	13.0							[signature]
3		8.07	11.7							[signature]
4	78	7.74	14.2							[signature]
5		7.92	12.7							[signature]
6		7.80	10.3							[signature]
7	76	7.79	13.2							[signature]
8		7.82	9.9							[signature]
9	78	7.79	12.7							[signature]
10		7.80	9.5							[signature]
11		7.79	11.7							[signature]
12		7.77	11.7							[signature]
13	76	7.77	12.8							[signature]
14	74	7.78	12.3							[signature]
15	78	7.80	12.8							[signature]
16	76	7.78	12.5							[signature]
* 17	78	7.35	13.4							[signature]
18	78	7.39	13.3							[signature]
19	76	7.44	13.6							[signature]
20		7.50	13.2							[signature]
* 21		7.35	11.1							[signature]
22	78	7.34	13.7							[signature]
23	76	7.33	13.2							[signature]
24	76	7.38	13.5							[signature]
25		7.38	9.6							[signature]
26										
27										
28										
29										
30										
31										

* 2 OCT 18 - NEW PROBE INSTALLED

* PUMP ADDED TO SEPTIC CELL FOR WINTER (17 OCT 18 - 1ST READING)

1

21 recalibrate pH sensor

Figure H2 – Example of Septic Cell pH and temperature logging sheet

Appendix I – LiDAR Report & Results

The following appendix includes reports on the Light Detection and Ranging (LiDAR) survey that was conducted 24-26 Oct 2018 as part of the research project at 17 Wing Detachment Dundurn, SK. The LiDAR scan was conducted in order to provide a condition survey of the lagoon at the time of the scan. The LiDAR survey was largely executed by Mr Adam Watson, technologist for RMC's Civil Engineering Department

Area of Interest:

As part of this research project, three (3) Areas of Interest (AOIs) were identified:

1. AOI 1: AOI 1 consists of a zone of approximately 500x500 m which encompasses the two cells of the WWT lagoon system. The northern, eastern, and southern border of the AOI were delineated by the perimeter fence with an additional 3-5 m in order to capture the outer slopes of the berms of the two cells. The western border was marked by the western bank of the Brightwater/Beaver Creek;

2. AOI 2: AOI 2 consists of a zone of approximately 200x200 m which is centred on the septic cell and encompasses the WWT lagoon system's pump house and appurtenances. The limit of the AOI 2 was marked by the outer edge of the gravel road on the perimeter; and,

3. AOI 3: AOI 3 consists of a zone of 250x100 m which includes both the derelict sludge drying bed and the access road. AOI 3 overlaps both AOI 1 and AOI 2.

All AOIs are indicated in Figure I1 by the red-shaded zones. AOI numbers represent the order of priority for the study.

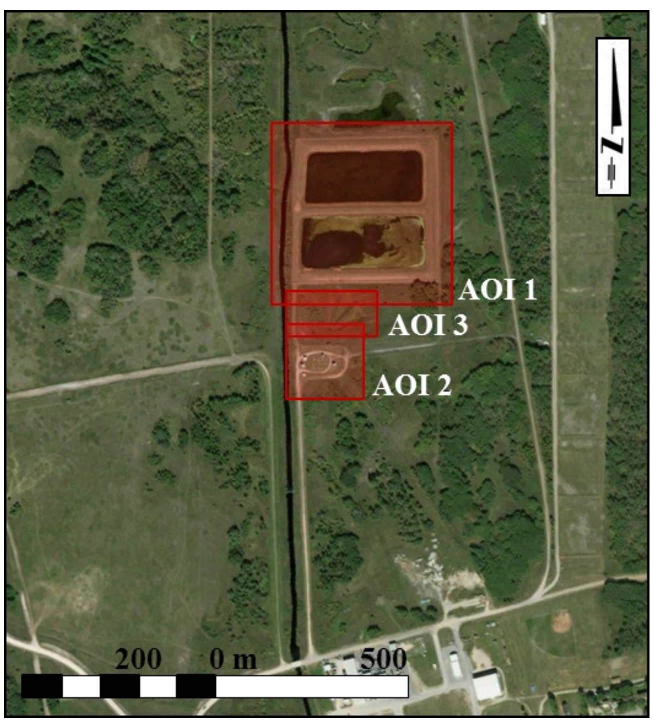


Figure I1 - Areas of interest for LiDAR survey
(Imagery provided by Microsoft Corporation 2018)

Data Acquisition:

The LiDAR data was acquired using a Leica ScanStation P40 laser scanner as seen in Figure I2. This scanner, with a max rang of 270 m and user define resolution settings, utilizes a laser with a wavelength of 1550 nm and is capable of obtaining photo for stitching over the point cloud. The camera feature of the scanner was only used for certain scans of this LiDAR survey. Whilst the LiDAR scans are a true representation of the dimensions and arrangements on-site, there were no survey-grade reference points within the vicinity of the lagoon and as such, were not georeferenced. Differential scans were obtained with the first scan (SW-001) of AOI 1 & 2 as the origin point.

Figure I2 - Leica ScanStation P40 in operation at Dundurn WWT lagoon

The scanner was mounted on a tripod system. In total, 23 separate 360^{o} scans were required to adequately cover all AOIs and minimize shadows (i.e. areas of missing data). A set of four (4) 152.4 mm (6") tilt-and-turn black and white survey targets were used to facilitate the stitching of the individual scans during post processing. These targets were positioned on survey poles driven into the ground or positioned on the perimeter fence with magnetic bases. Targets were repositioned as needed for each scan.

AOI 1 required 18 scans to cover including one obtained from the western bank of the Brightwater/Beaver Creek as seen in Figure I3. AOI 2 required 5 scans to adequately cover as seen in Figure I4. No dedicated scans were made for AOI 3 as adequate coverage was obtained from the scans for AOI 1 & 2. Broad shadows were unavoidable for AOI 3 as the area is fully covered with 1 m to 1.5 m tall vegetation and due to the lack of vantage points. However, the data retrieved from AOI 1 & 2 scans was deemed adequate for the needs of this research project. Information regarding each scan's station position is given in Table I1 and Table I2 for AOI 1 and AOI 2 respectively.

Table I1 - Positions of scanning stations in AOI 1

#	Station	Differential Position (m)		
		X	Y	Z
1	SW-001	0.000	0.000	0.000
2	SW-002	-101.145	34.727	0.083
3	SW-003	-143.213	47.614	0.130
4	SW-004	-208.961	64.154	0.221
5	SW-005	-239.814	-30.832	0.469
6	SW-006	-179.989	-50.163	0.452
7	SW-007	-133.046	-67.040	0.592
8	SW-008	-75.925	-85.463	0.550
9	SW-009	-35.756	-98.491	0.618
10	SW-010	-54.060	-148.414	0.445
11	SW-011	-77.233	-197.741	0.652
12	SW-012	-135.195	-180.063	0.594
13	SW-013	-187.963	-162.215	0.561
14	SW-014	-232.586	-147.360	0.521
15	SW-015	-274.725	-129.725	0.770
16	SW-016	-261.945	-82.750	0.570
17	SW-017	-15.308	-48.976	-0.197
18	SW-018	-19.647	-154.564	-0.624

Table I2 - Positions of scanning stations in AOI 2

#	Station	Differential Position (m)		
		X	Y	Z
1	SW-001	0.000	0.000	0.000
-	SW-002 Omitted			
2	SW-003	71.421	-29.277	-0.090
-	SW-004 Omitted			
3	SW-005	56.661	6.860	-0.394
4	SW-006	108.670	1.225	-0.138
5	SW-007	46.148	58.150	0.168

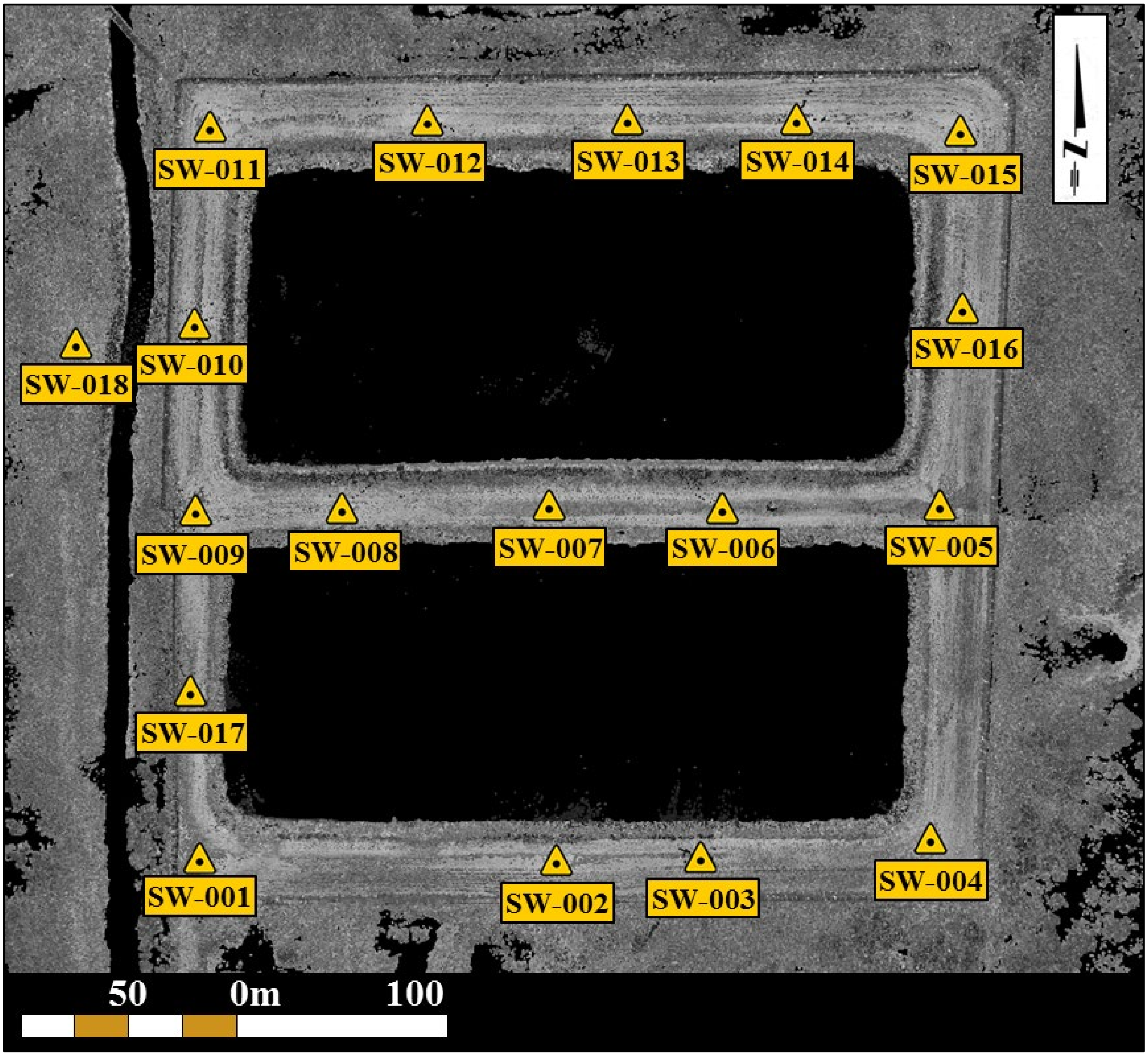


Figure I3 - Scan station layouts conducted in AOI 1

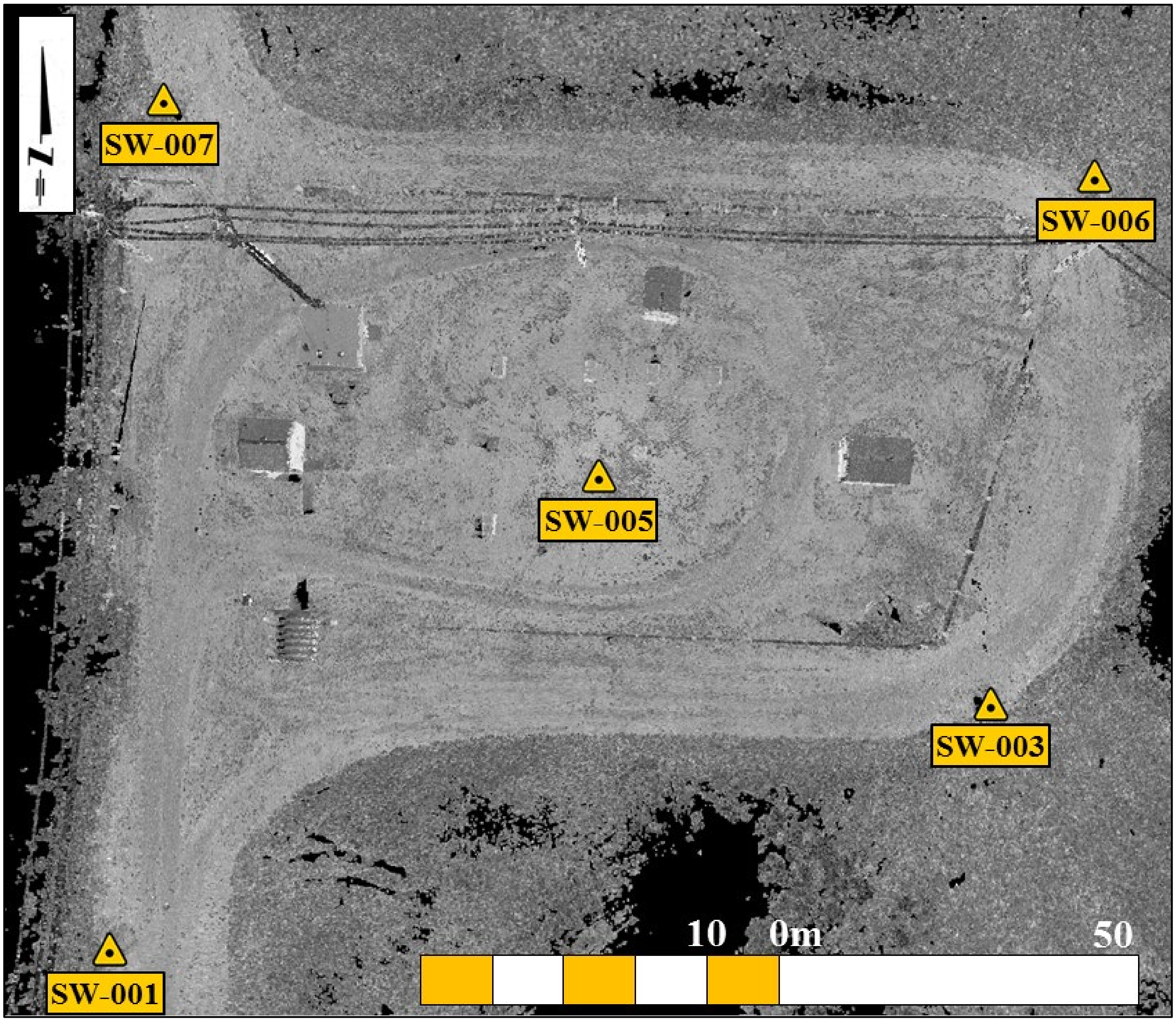


Figure I4 - Scan station layouts conducted in AOI 2

AOI 1 scans were mostly obtained on the 25th of October 2018 with only scan 18 obtained on the 26th of October 2018. Weather conditions at the time of capture was overcast with light wind and temperature ranging from 0°C to 12°C. Scan 18 was obtained at midday due to heavy fog. AOI 2 scans were obtained on the 24th of October 2018. Weather conditions at the time of capture was sunny with light wind and temperature ranging from -2°C to 17°C. Table I3 provides details regarding the types of scans and their point cloud densities.

Table I3 - Scan details

AOI 1			
Scan	Station	Scan Type	Point Cloud Density
1	SW-001	Range	1.66 mm at 10 m
2	SW-002	Range & Imagery	1.66 mm at 10 m
3	SW-003	Speed	3.10 mm at 10 m
4	SW-004	Range & Imagery	1.66 mm at 10 m
5	SW-005	Range & Imagery	1.66 mm at 10 m
6	SW-006	Speed	3.10 mm at 10 m
7	SW-007	Range & Imagery	1.66 mm at 10 m
8	SW-008	Speed	3.10 mm at 10 m
9	SW-009	Range & Imagery	1.66 mm at 10 m
10	SW-010	Speed	3.10 mm at 10 m
11	SW-011	Range & Imagery	1.66 mm at 10 m
12	SW-012	Speed	3.10 mm at 10 m
13	SW-013	Range & Imagery	1.66 mm at 10 m
14	SW-014	Speed	3.10 mm at 10 m
15	SW-015	Range & Imagery	1.66 mm at 10 m
16	SW-016	Speed	3.10 mm at 10 m
17	SW-017	Speed	3.10 mm at 10 m
18	SW-018	Speed	3.10 mm at 10 m
AOI 2			
Scan	Station	Scan Type	Point Cloud Density
1	SW-001	Speed	3.10 mm at 10 m
2*	SW-001	Speed & Imagery	3.10 mm at 10 m
3	SW-003	Speed	3.10 mm at 10 m
4*	SW-003	Speed & Imagery	3.10 mm at 10 m
5	SW-005	Speed & Imagery	3.10 mm at 10 m
6	SW-006	Speed & Imagery	3.10 mm at 10 m
7	SW-007	Speed & Imagery	3.10 mm at 10 m

* Duplicate scan

Data Post Processing:

The point clouds and imagery obtained from the LiDAR scans were imported into Cyclone version 9.1.5 (Build 5387) produced by Leica Geosystems where they were stitched together (i.e. cloud to cloud unification). Stitching resulted into two (2) clouds covering AOI 1 and AOI 2 separately.

The point clouds were converted into a file format that can be imported into JetStream Viewer version 1.3.2 also produced by Leica Geosystems. In this software, the data could be manipulated.

Results:

As a result from the LiDAR survey and data post-processing, two (2) files that can be imported into JetStream Viewer were produced. The resulting point clouds had minimal shadows within the AOIs with the exception of AOI 3 due to unavoidable blind spots. The point clouds were manipulated within the JetStream Viewer to obtain accurate distances and elevation measurements as needed. In addition, the LiDAR survey provided site imagery of higher resolution that all available open sourced satellite imagery available at the time of the desk and field studies. Figure I5 through Figure I7 provides examples of obtained imagery from various angles. Additionally, fly through video footage was also produced.

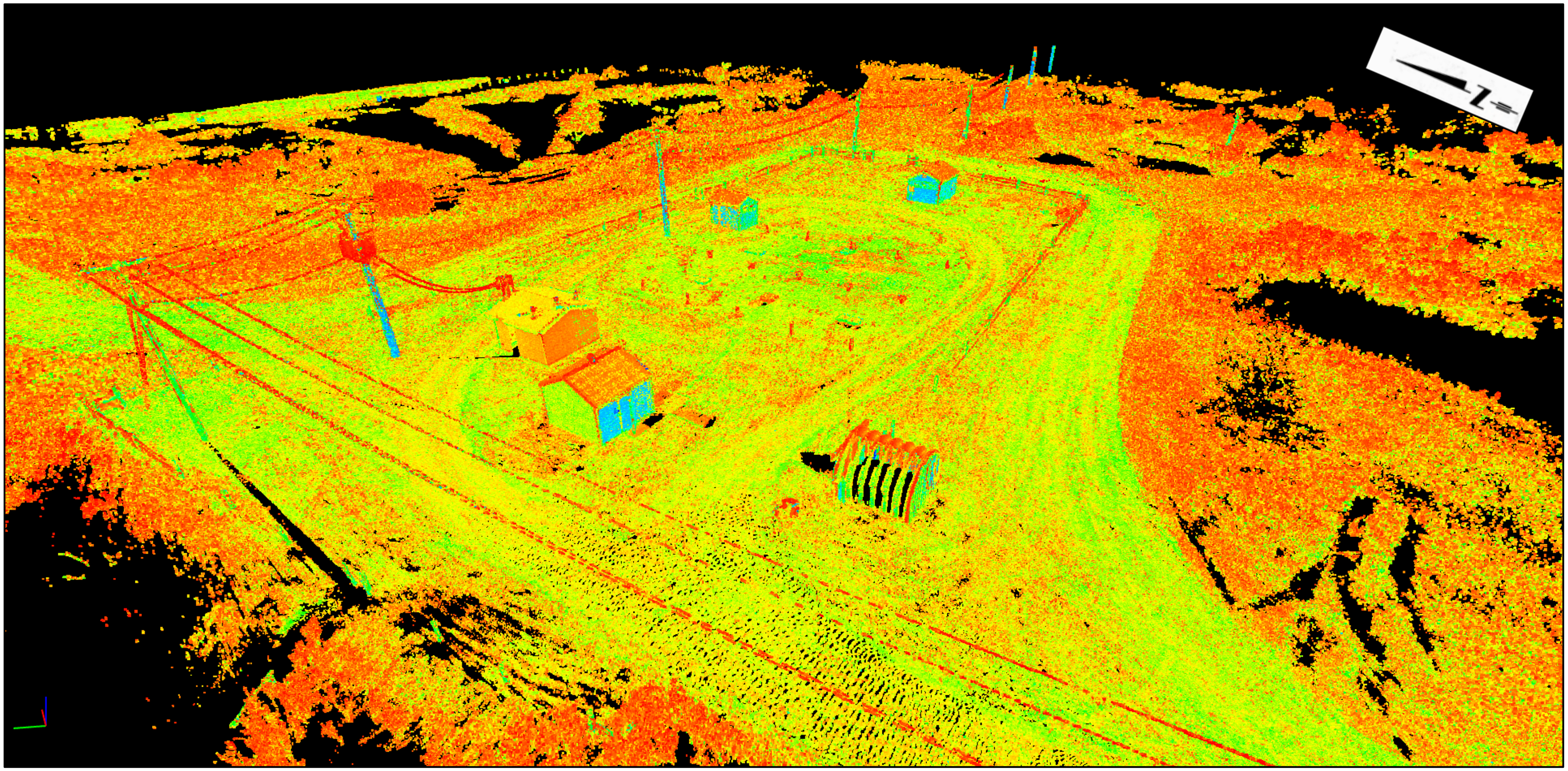


Figure I5 - Final result of point cloud covering AOI 2 and AOI 3.

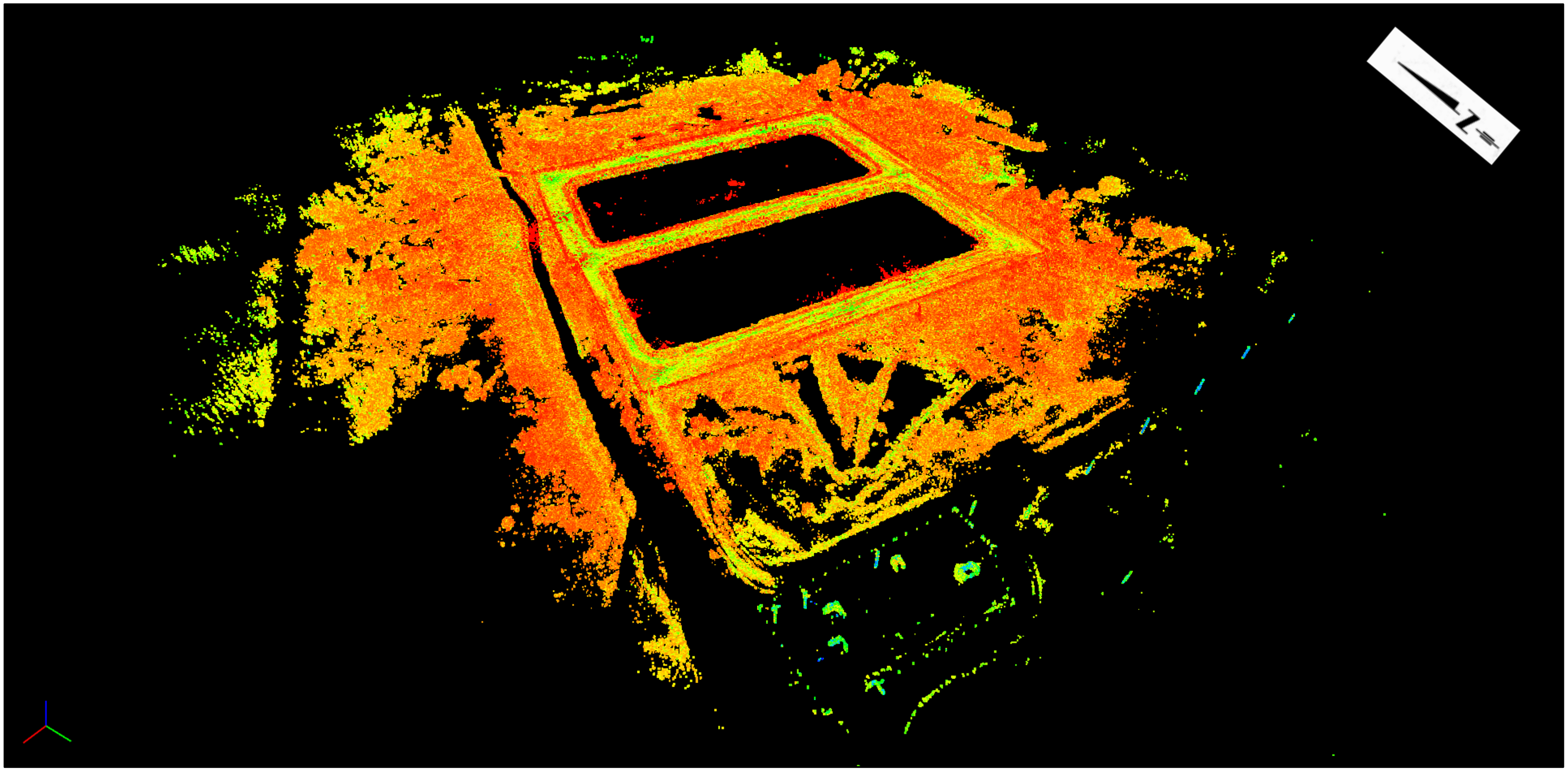


Figure I6 - Final result of point cloud covering AOI 1 and AOI 3.

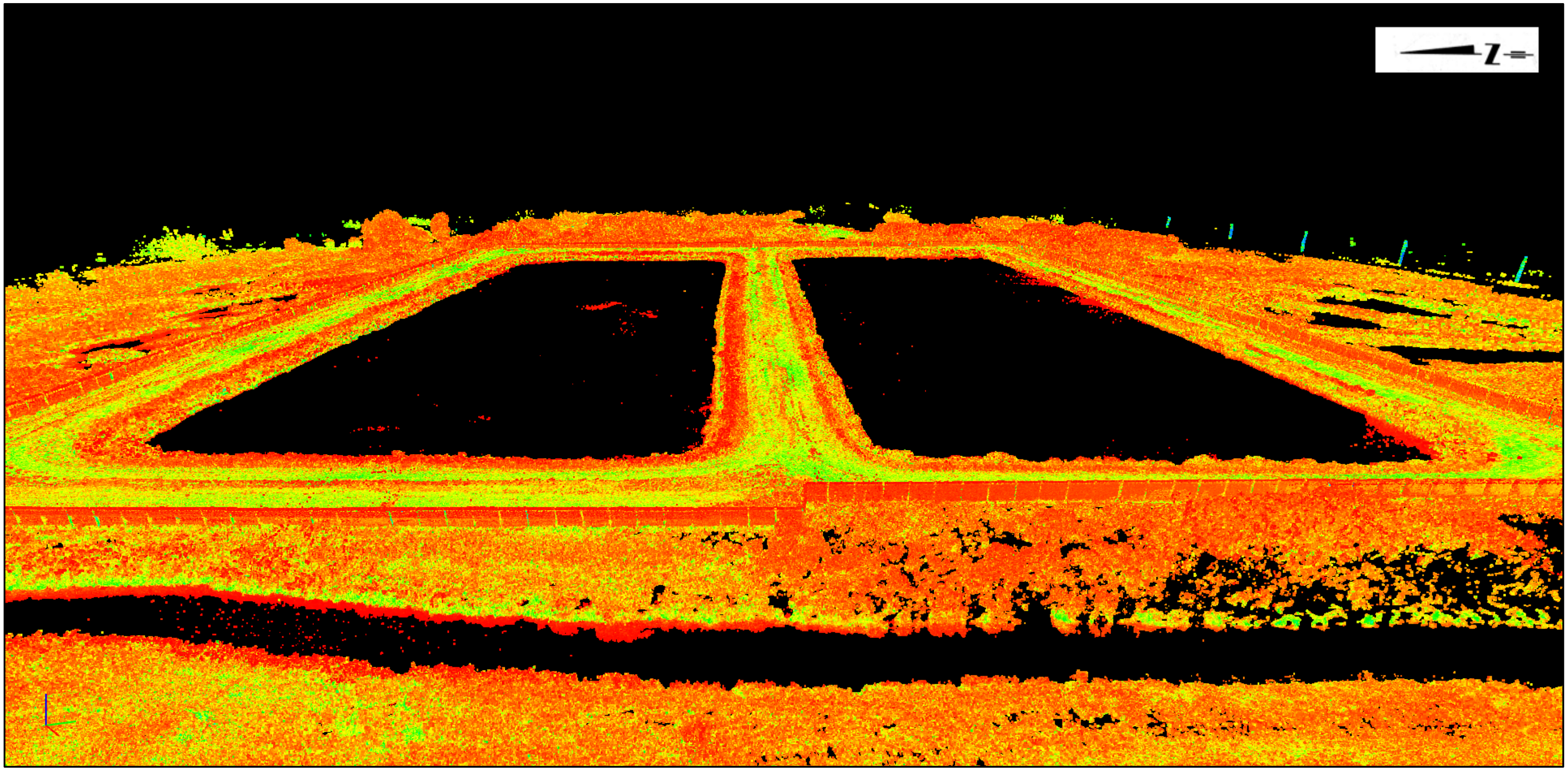


Figure I7 - Close up view of AOI 1 point cloud with vantage point along the western perimeter.

Appendix J – Sampling Locations

The following appendix presents photos depicting the conditions of the sampling locations identified as part of the research project at 17 Wing Detachment Dundurn's WWT lagoon site. Pictures were obtained from each of the 3 sampling rounds in order to record the seasonal variations. An exception was made for SW-IN which is located inside a temperature-controlled building and does not see seasonal variations and SW-S which is located at the septic tank which also sees little variations. In addition, the monitoring wells (SL#1-9) have been omitted from this appendix as they are documented in detail in Appendix F. All picture locations referred to the locations ID as described in Figure J1.

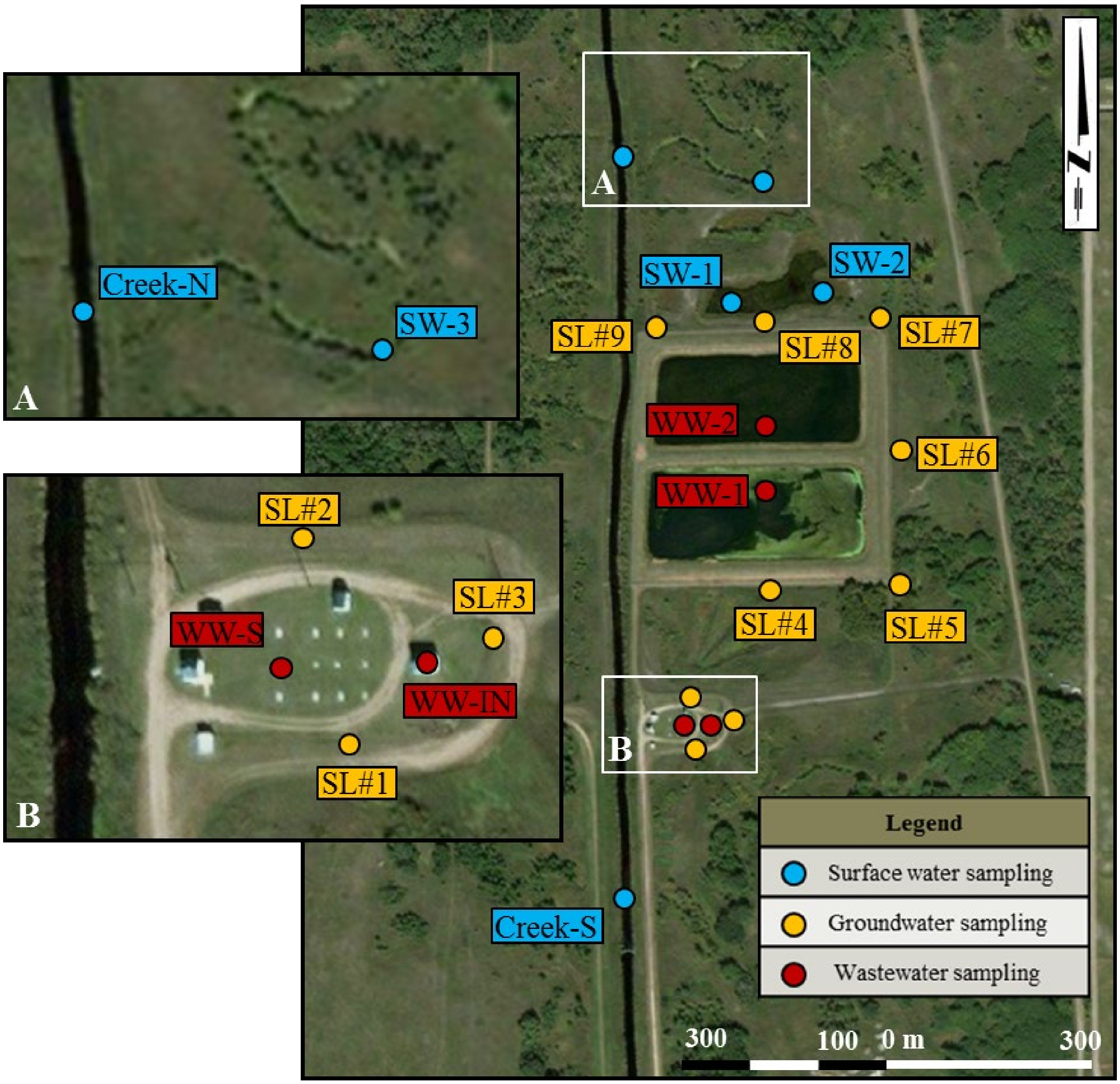


Figure J1 - Approximate sampling locations (Imagery provided by Microsoft Corporation 2018)

Figure J2 to Figure J7 depicts the conditions of Brightwater/Beaver Creek at Creek-S and Creek-N locations. A noticeable marked increase in the water column was observed between August and October of 2018. During the second sampling round conducted on 23 October 2018, the creek was covered by a thin sheet of ice. This thin ice sheet had melted by midday and was not present for the remainder of the field visits. The highest water level for the Brightwater/Beaver Creek was observed during the final sampling round on the 16 April 2019.

Figure J8 to Figure J16 depicts the conditions of the stagnant water body north of the lagoon cells (at SW-1 and SW-2) and the previous creek bed (SW-3). Much like Brightwater/Beaver Creek, the stagnant water body observed an increase in free water between August and October of 2018. During sampling on 23 October 2018, this water body was covered by a thin ice sheet which disappeared by midday. During the first and second sampling rounds (August and October 2018), the previous creek bed was dry and sampling was impossible. A thin sheet of ice was observed over the shaded portion of the water at SW-3. The ice sheet quickly disappeared when exposed to direct sunlight.

Figure J17 and Figure J18 depict the conditions of the sampling locations WW-IN and WW-S respectively. Figure J18 was obtained during the second sampling round on 24 October 2018 whilst the agitation pump was in operation. This pump is added during the cold months in order to prevent freezing.

Figure J19 to Figure J24 depicts the conditions of the lagoon Cell #1 and Cell #2 (sampling points WW-1 and WW-2). As predicted, the water column in Cell #1 increased between August 2018 and April 2019. In addition, Cell #1 was 80% covered in duckweed during the first sampling round (15 August 2018). This duckweed was not present during second sampling round (24 October 2018) and a small concentration of duckweed was observed within the vegetation on the periphery of Cell #1 during the third sampling round (16 April 2019). Cell #2 observed little to no variations.

Figure J2 - Sampling location Creek-S (14 August 2018)

Figure J3 - Sampling location Creek-S (23 October 2018)

Figure J4 - Sampling location Creek S (16 April 2019)

Figure J5 - Sampling location Creek-N (14 August 2018)

Figure J6 - Sampling location Creek-N (23 October 2018)

Figure J7 - Sampling location Creek N (16 April 2019)

Figure J8 - Sampling location SW-1 (14 August 2018)

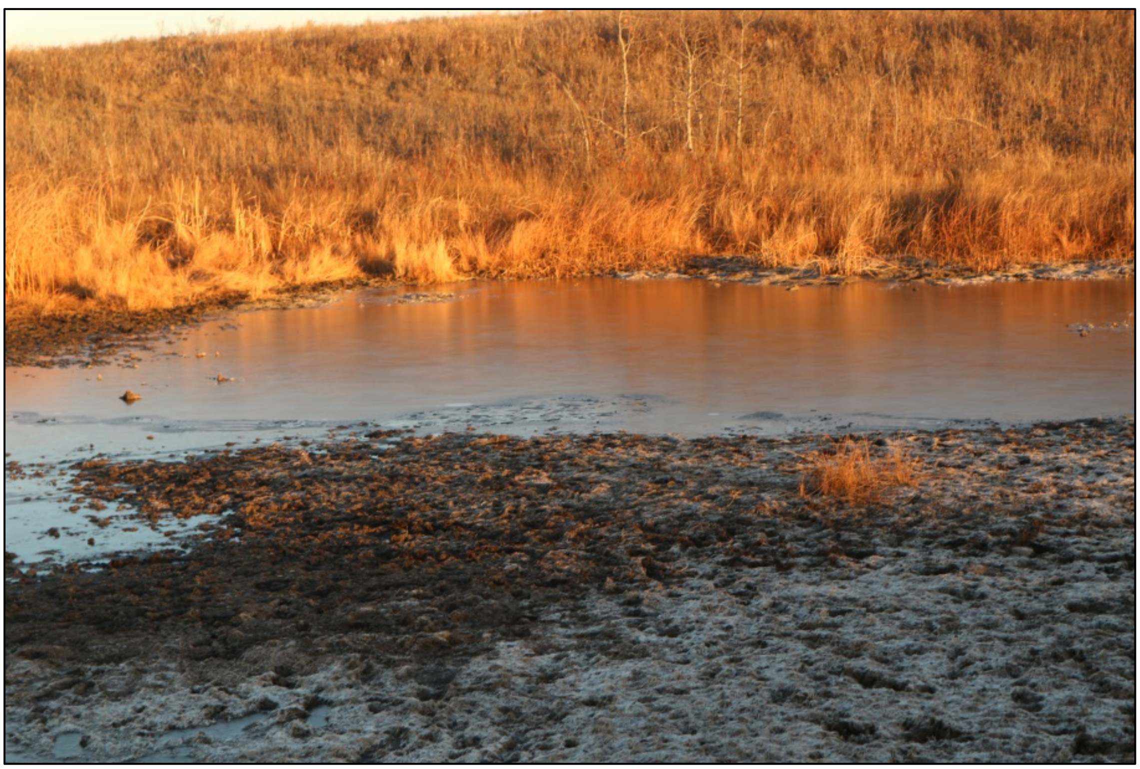


Figure J9 - Sampling location SW-1 (23 October 2018)

Figure J10- Sampling location SW-1 (16 April 2019)

Figure J11 - Sampling location SW-2 (14 August 2018)

Figure J12 - Sampling location SW-2 (23 October 2018)

Figure J13- Sampling location SW-2 (16 April 2019)

Figure J14 - Sampling location SW-3 (14 August 2018)

Figure J15 - Sampling location SW-3 (23 October 2018)

Figure J16- Sampling location SW-3 (16 April 2019)

Figure J17 - Sampling location WW-IN


Figure J18 - Sampling location WW-S (24 October 2018)


Figure J19 - Sampling location WW-1 (15 August 2018)

Figure J20 - Sampling location WW-1 (24 October 2018) (obtained from the south bank)

Figure J21- Sampling location WW-1 (16 April 2019)


Figure J22 - Sampling location WW-2 (15 August 2018)


Figure J23 - Sampling location WW-2 (24 October 2018)

Figure J24- Sampling location WW-2 (16 April 2019)

Appendix K – Field Notebook

The following appendix includes the templates of the field and laboratory templates / forms developed for the sampling programme undertaken in the research project for 17 Wing Detachment Dundurn's Wastewater Treatment (WWT) lagoon system. Multiple copies of each form were printed in quantities sufficient for all sampling points (when applicable) and to have additional backup copies. Together all the forms made the field notebook. A copy of the notebook was developed for each sampling rounds. The following figures provide the template for the second sampling round as an example and consist of the following:

- Figure K1 provides the template used for recording the measured groundwater levels within the monitoring wells;

- Figure K2 provides the template used for recording the dissolved oxygen and temperature readings and site condition of all water samples;

- Figure K3 provides the template used for recording the calibration verifications for all the equipment utilized during the field analysis of samples; and,

- Figure K4 to Figure K9 provides an example of the recoding form for conductivity, temperature, pH, and turbidity used during the field analysis portion of the second sampling round.

WATER LEVEL MEASUREMENT FIELD FORM

SITE INFORMATION

Site ID	Equipment ID	Date of Field Visit
Ground Elevation (masl)	Stickup (m)	Elevation Top of Casing (masl)

WATER LEVEL DATA

	1	2	3	4	5
Time					
Hold					
Tape Correction					
WL below MP					
MP Correction (Stickup)					
WL below LSD					

Comments:

Comments should include quality concerns and changes in: access, locks, measuring problems, etc.

FINAL MEASURMENT DATA

Day	Month	Year	Time	Water Level (masl)
Date WL Measured				

Measured By	Signature

Figure K1- Template of the groundwater level measurement record form

RMC CMR

WATER SAMPLING FIELD FORM
DISSOLVED OXYGEN & TEMPERATURE

RMC GREEN TEAM L'ÉQUIPE VERTE DU CMR

SITE INFORMATION

Site ID		Date of Field Visit
Sample ID	Equipment ID	Grid Coordinates

□ Site Photos Taken

SITE CONDITION

Weather	
Water	
Comments	

WATER SAMPLE INFORMATION

Sampling Time	DO Reading	Water Temperature (°C)

Measured By

Signature

Figure K2 - Template of the water sampling record form

RMC CMR

FIELD LAB
CALIBRATION VERIFICATION FORM

RMC GREEN TEAM L'ÉQUIPE VERTE DU CMR

GENERAL

Instrument	Date & Time of Verification
DO Probe	
Turbidity Meter	
Conductivity Probe	
pH Probe	

DISSOLVED OXYGEN PROBE

Probe #	Standard	Reading	Delta	Calibration Verification
	8.00			

TURBIDITY METER

Meter #	Standard	Reading	Delta	Calibration Verification
	10 NTU			

CONDUCTIVITY PROBE

Probe #	Standard	Reading	Delta	Calibration Verification
	1413 µS/cm			

PH PROBE

Probe #	Standard	Reading	Delta	Calibration Verification
	4.00			
	7.00			

Figure K3 - Template of the calibration verification record form

FIELD LAB
CONDUCTIVITY & TEMP FORM

GENERAL

Probe #	Meter #	Date	Ambient Temperature

☐ Calibration Verified

CONDUCTIVITY & TEMPERATURE TEST

Sample ID	Time	Conductivity (µS/cm)	Temperature (°C)
1413 µS/cm Standard			
SL#1-2			
SL#2-2			
SL#3-2			
SL#4-2			
SL#5-2			
SL#6-2			
SL#7-2			
SL#8-2			
SL#9-2			
Creek-S-2			
Creek-N-2			
SW-1-2			
SW-2-2			
SW-3-2			
WW-2-2			
WW-1-2			
WW-S-2			
WW-In-2			
Blank			

Figure K4 - Example of the conductivity and temperature measurement form (page 1/2)

FIELD LAB
CONDUCTIVITY & TEMP FORM

Sample ID	Time	Conductivity (µS/cm)	Temperature (°C)
Duplicate 1			
Duplicate 2			

Measured By ______________________ Signature ______________________

Figure K5 - Example of the conductivity and temperature measurement form (page 2/2)

RMC CMR

FIELD LAB
PH FORM

RMC GREEN TEAM L'ÉQUIPE VERTE DU CMR

GENERAL

Probe #	Meter #	Date	Ambient Temperature

☐ Calibration Verified

PH TEST

Sample ID	Time	Value (pH units)
4 pH Standard		
7 pH Standard		
SL#1-2		
SL#2-2		
SL#3-2		
SL#4-2		
SL#5-2		
SL#6-2		
SL#7-2		
SL#8-2		
SL#9-2		
Creek-S-2		
Creek-N-2		
SW-1-2		
SW-2-2		
SW-3-2		
WW-2-2		
WW-1-2		
WW-S-2		
WW-In-2		

Figure K6 - Example of the pH measurement form (page 1/2)

RMC CMR

FIELD LAB
PH FORM

Sample ID	Time	Value (pH units)
Blank		
Duplicate 1		
Duplicate 2		

Measured By

Signature

Figure K7 - Example of the pH measurement form (page 2/2)

RMC CMR

FIELD LAB
TURBIDITY FORM

RMC GREEN TEAM · L'ÉQUIPE VERTE DU CMR

GENERAL

Meter #	Date	Ambient Temperature

☐ Calibration Verified

TURBIDITY TEST

Sample ID	Time	Value (NTU)
10 NTU Standard		
SL#1-2		
SL#2-2		
SL#3-2		
SL#4-2		
SL#5-2		
SL#6-2		
SL#7-2		
SL#8-2		
SL#9-2		
Creek-S-2		
Creek-N-2		
SW-1-2		
SW-2-2		
SW-3-2		
WW-2-2		
WW-1-2		
WW-S-2		
WW-In-2		
Blank		

Figure K8 - Example of the turbidity measurement form (page 1/2)

FIELD LAB
TURBIDITY FORM

Sample ID	Time	Value (NTU)
Duplicate 1		
Duplicate 2		

Measured By ______________________

Signature ______________________

Figure K9 - Example of the turbidity measurement form (page 2/2)

Appendix L – Wastewater Lagoon Sampling Procedure

The following appendix presents the procedures that were developed and followed for the sampling of wastewater from 17 Wing Detachment Dundurn's Wastewater Treatment (WWT) lagoons. This procedure was used for the sampling locations WW-1 and WW-2. The procedure described below was developed in compliance with the guidelines stated in Section 6.4.3.

Positioning the Sampling Equipment:

1. Preposition all necessary sampling equipment (e.g. peristatic pump, sample bottles, DO and temperature sensors) at the sampling location on clean plastic bags.

2. Fill 2x sand bags and position them at the sampling location and directly across the cell on the opposite berm.

3. With both samplers positioned at one corner cell, walk the 6.35 mm (1/4") polypropylene rope to the other corner of the cell on the same berm as seen in Figure L1A. Ensure that the majority of the slack remains with the sampler on the sampling point side of the cell (i.e. sampler 1).

4. Walk both end of the polypropylene rope to the centre of the cell, keeping the rope relatively perpendicular whilst suspending it over the wastewater as seen in Figure L1B.

5. Secure the vinyl sampling tube to the polypropylene rope using a hose clamp, leaving enough of the sampling tube to hang from the secure point in order to sample at a depth of approximately 50-60% the depth of the water column.

6. Insure the weights at the end of the sampling tube are properly secured and will not slip off during use. Insure the other end of the sampling tube is properly secured to the sampling pump and will not accidentally fall in the lagoon cell.

7. Slowly pull the polypropylene rope from the end of the lagoon cell opposite to the sampling point.

8. As the polypropylene rope is being pulled, ensure the sampling tube is straightened and follows the rope, securing floaters to both the rope and tube periodically.

9. Stop pulling the polypropylene rope once the sampling tube has reached its maximum length as seen in Figure L1C.

10. Secure both end of the polypropylene rope by tying them to the sand bags.

Sampling:

1. Field rinse the tubing by letting the peristatic sampling pump run and discarding the water discharge back into the cell for several minutes.

2. Fill a single-use plastic container with wastewater and obtain a DO and temperature reading.

3. Fill all remaining sample bottle to the indicated marking with wastewater without letting the pump tubing contact the rim of the sample bottles.

4. Secure lid on all bottles immediately after filling and finish filling in the labels.

5. Refrigerate the samples and secure them for transport.

6. Record site conditions on the site's field form.

Sampling Equipment Removal:

1. Release the polypropylene rope from the end of the lagoon cell opposite to the sampling point.

2. Pull the polypropylene rope and sampling tube back toward the sampling point removing the floaters when reachable.

3. Thoroughly clean the outside of the sampling tube with DI water using the hand-pumped sprayer.

4. Thoroughly clean the inside of the sampling tube by pumping DI water thought it.

5. Place sampling tube in a clean plastic bag to avoid contamination until the next use or marked for return to RMC for thorough cleaning.

6. At the end of the sampling round, place the rope to hand dry for several days prior to storage for next sampling round and discard floaters.

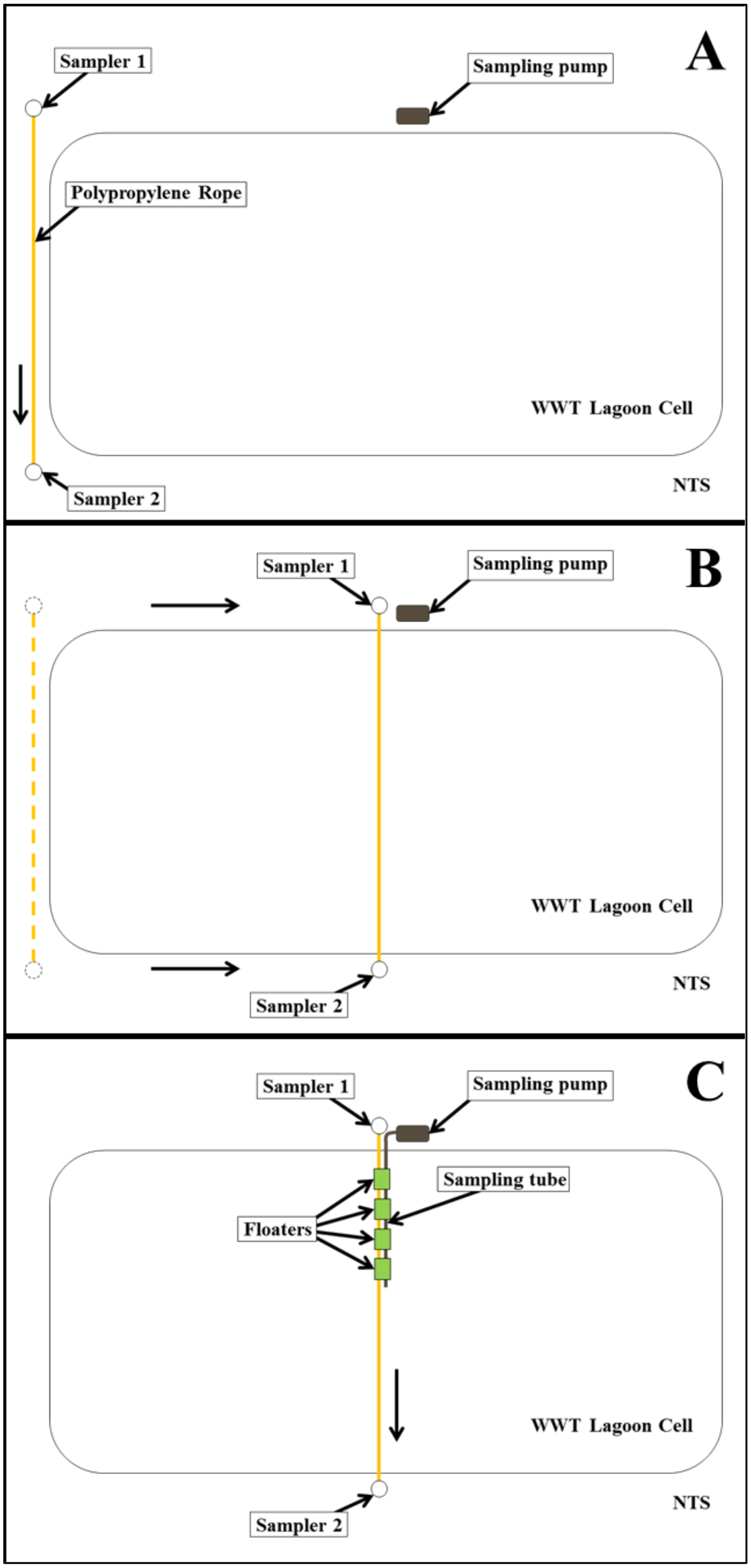


Figure L1 - Schematic representation for the positioning of the sampling equipment at a lagoon cell

Appendix M – Field Laboratory Procedures

The following appendix presents the laboratory procedures that were developed and followed for the field analysis of water samples. These water samples were taken during the sampling rounds of this research project into 17 Wing Detachment Dundurn's Wastewater Treatment (WWT) lagoon system. As stated in Section 6.4.4, the procedures comply with the Standard Methods for the Examination of Water and Wastewater 23rd edition published by the APHA, AWWA, and WEF (American Public Health Association et al. 2017) and the testing equipment manufacturer.

Preparations:

1. Wash hands / put on gloves (double) / put on eye protection.

2. Wash work surface and layout equipment on disposable work surface cover. (Dust control procedures: keep container lids on until needed / place disposable cups upside down until needed / keep probes in travel case until needed.)

3. Prep bucket with bleach-water solution.

Turbidity Test:

1. Set out turbidity meter and test vials.

2. Verify calibration with the 10 NTU vials (as prompted).

3. Remove 1x sample bottle from cooler and shake thoroughly for 3x mins.

4. Empty test vials of DI water and rinse 3x using sample water using a pipette.

5. Transfer water sample to test vial using pipette. The water line should be above the marking on the vial (~2.5 pipette volume). Dispose of pipette tip in the rubbish bin. Rinse pipette tips that handled wastewater in bleach solution prior to disposal.

6. Close lid on sample bottle and return to cooler.

7. Close lid on test vial and clean outer surface with 2x DI water.

8. Dry off test vial outer surface.

9. Thoroughly mix sample by tilting vial repeatedly (No shaking).

10. Apply silicone to the outer surface of vial and place in metre. Silicone film must not have streaks or "look wet".

11. Take reading and record data in lab book.

12. Set test vial aside for cleaning.

13. Repeat steps 3-12 for all 18 samples, 2x duplicate selected randomly, and 1x blank.
    Sequence: GW – SW – WW.

14. Re-glove.

15. Replace turbidity meter in travel case.

Conductivity & Temperature Test:

1. Set out meter and conductivity probe.

2. Clean probe head using DI water (3x).

3. Verify calibration using the 1413 µS/cm standard (Standard should be in cooler with samples).

4. Remove 1x sample bottle from cooler and shake thoroughly for 3x mins.

5. Pour water sample into clean disposable cup (~20ml).

6. Close lid on sample bottle and return to cooler.

7. Place probe in sample, take a reading and record data in lab book.

8. Dispose of water sample and placed disposable cup in the rubbish bin.

9. Clean probe head using DI water (3x).

10. Repeat steps 3-14 for all 18 samples, 2x duplicate selected randomly, and 1x blank.
    Sequence: GW – SW – WW.

11. Clean probe head with bleach-water solution.

12. Re-glove.

13. Replace conductivity probe in travel case.

pH Test:

1. Set out pH probe.

2. Remove probe cover and clean probe head using DI water (3x).

3. Verify calibration using the pH4 and pH7 standards (Standards should be in cooler with samples).

4. Remove 1x sample bottle from cooler and shake thoroughly for 3x mins.

5. Pour water sample into clean disposable cup (~20ml).

6. Close lid on sample bottle and return to cooler.

7. Place probe in sample, take a reading and record data in the lab book.

8. Dispose of water sample and placed disposable cup in the rubbish bin.

9. Clean probe head using DI water (3x).

10. Repeat steps 3-14 for all 18 samples, 2x duplicate selected randomly, and 1x blank. Sequence: GW – SW – WW.

11. Clean probe head with bleach-water solution.

12. Re-glove.

13. Replace conductivity probe in travel case.

Data Collection:

1. Connect USB port connector to meter and connect USB.

2. Transfer data to USB.

3. Verify that data transferred properly.

4. Transfer data from lab book to electronic format.

Cleanup:

1. Empty all water sample bottles and rinse using the bleach-water solution.

2. Dispose of water sample in the turbidity test vial.

3. Rinse vial with bleach-water solution and DI water.

4. Place vial aside and mark it for return to RMC.

5. Dry all bottles and mark them for return to RMC.

6. Pack all equipment.

7. Dispose of surface cover in the rubbish bin.

8. Clean work surface.

9. Remove PPE.

10. Dispose of rubbish.

Appendix N – Hydrogeological Model Development

The following appendix presents various figures associated with the development of a hydrogeological model at 17 Wing Detachment Dundurn. The hydrogeological model was developed using MODFLOW 2005 version 1.12.00 finite difference numerical tool along with the MODPATH version 7.2.001 particle-tracking post-processing program both produced by the USGS. Groundwater Vistas version 6.96 Build 49 was used as a user interface. Figures include the following:

- Figure N1 provides the aerial photo that was used as a base map for the groundwater model;
- Figure N2 through Figure N8 provides the locations of all the monitoring wells that were available for the development of the groundwater model;
- Figure N9 depicts the groundwater model's mesh;
- Figure N10 and Figure N11 provided details regarding the ground elevation of the site once imported into the model;
- Figure N12 and Figure N13 provide details regarding the various boundary conditions applied to the groundwater model;
- Figure N14 provides details with regard to the calibration targets; and,
- Figure N15 provides details with regard to the particle tracking analyses.

Aerial Photography & Base Map:

Figure N1 - Aerial photography of Det. Dundurn used for the model's base map (Imagery provided by Microsoft Corporation 2018)

Groundwater Monitoring Well Locations:

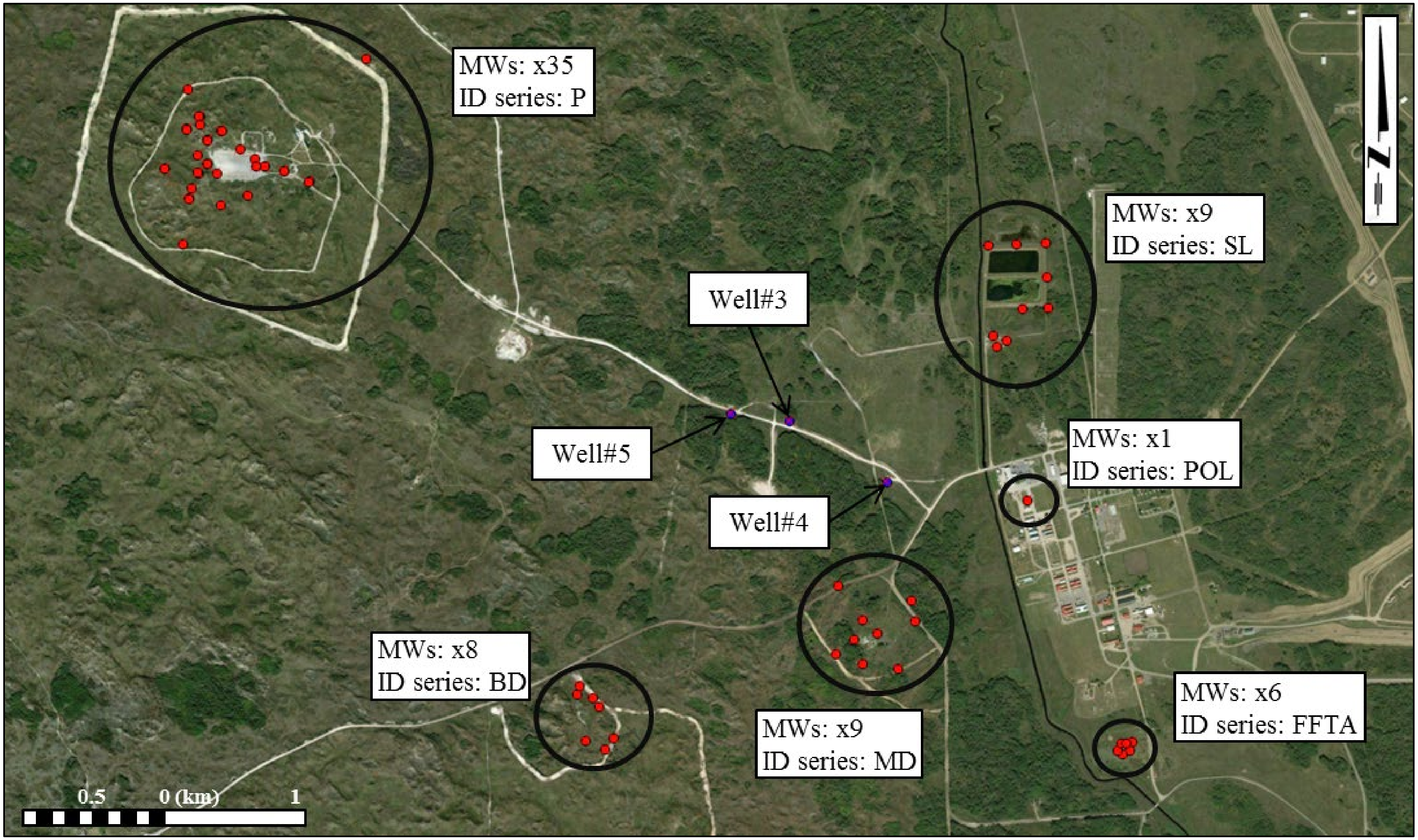


Figure N2 - Aerial photography depicting the location of all monitoring wells and production wells (Imagery provided by Microsoft Corporation 2018)

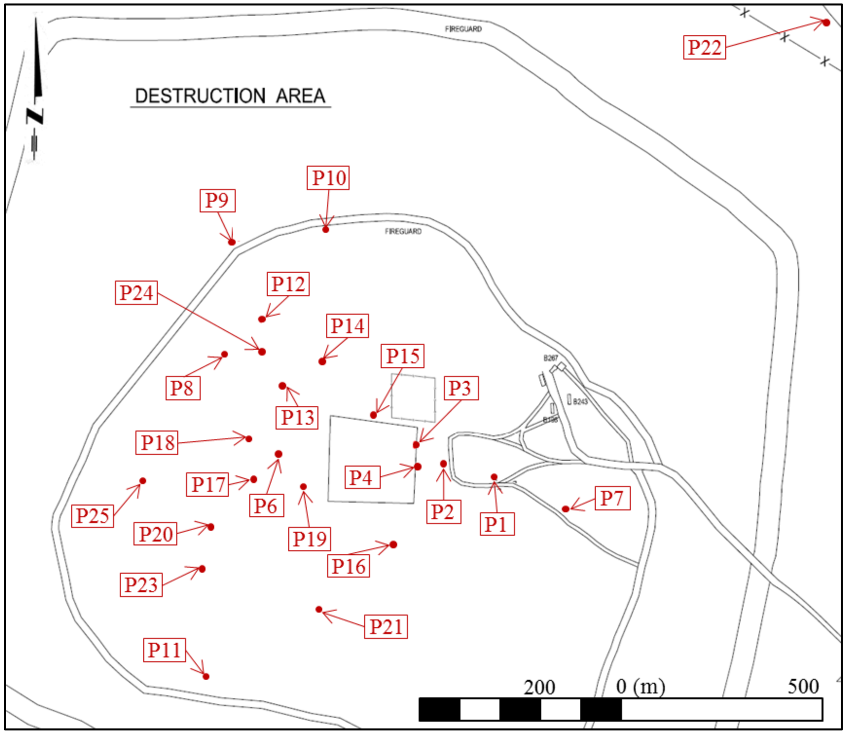


Figure N3 - MW locations and ID in the destruction area (Modified from 17 Wing Construction Engineering Squadron, 2014)

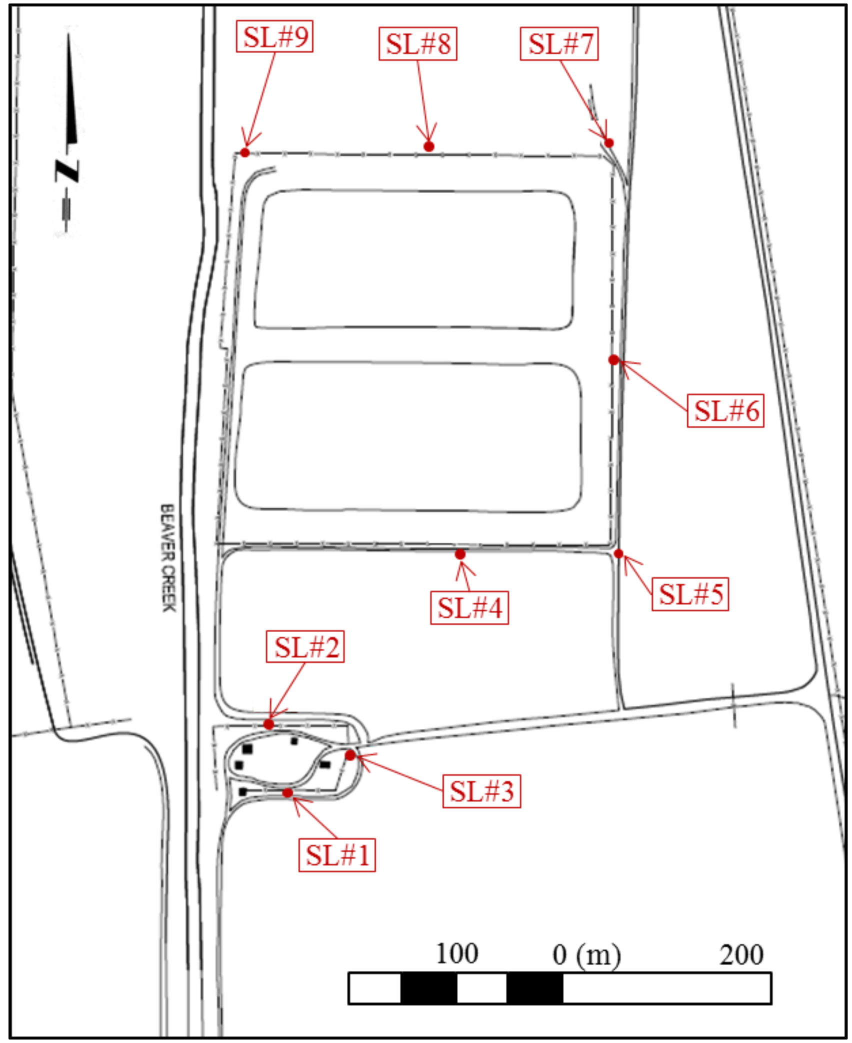


Figure N4 - MW locations and ID at the wastewater treatment lagoon (Modified from 17 Wing Construction Engineering Squadron, 2014)

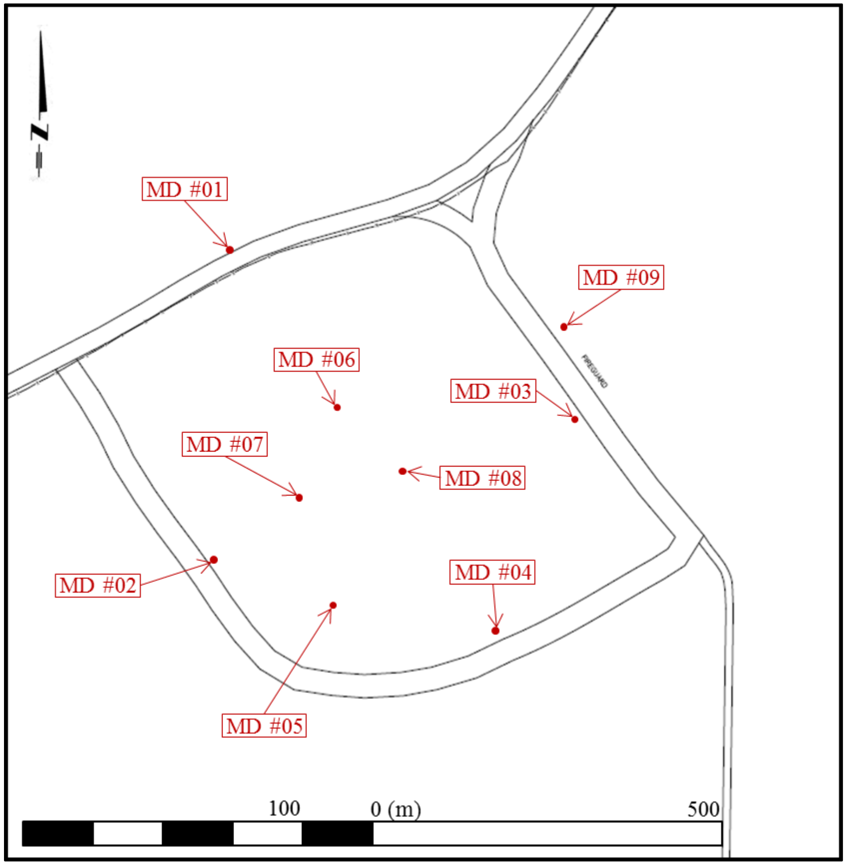


Figure N5 - MW locations and ID near the metal dump
(Modified from 17 Wing Construction Engineering Squadron, 2014)

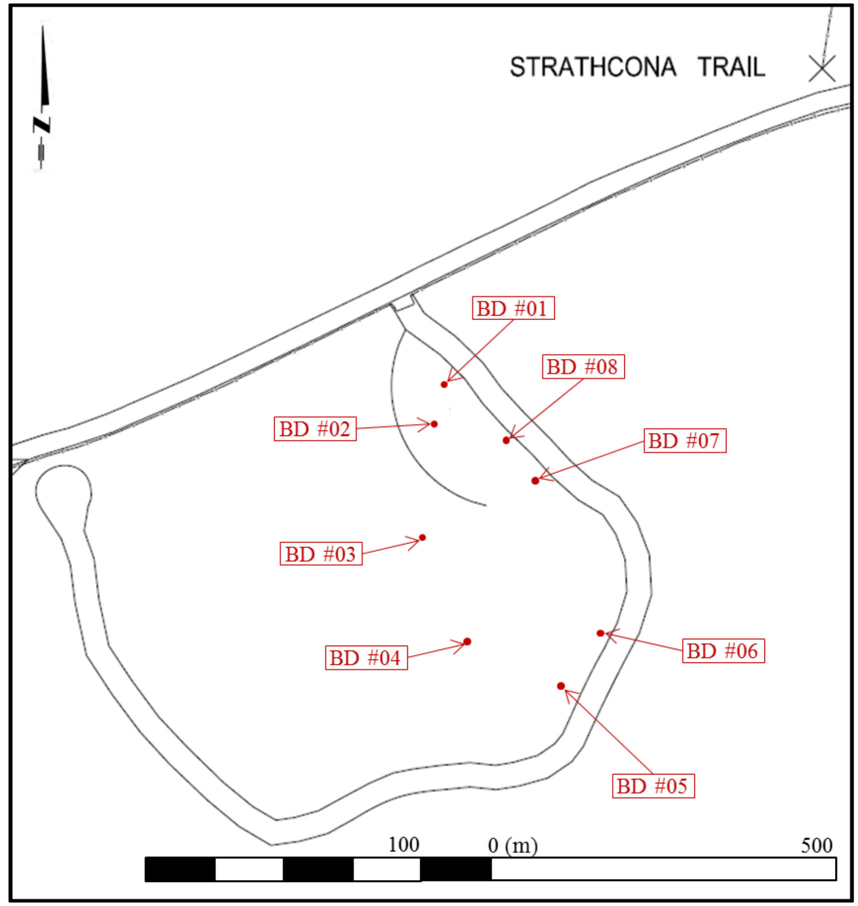


Figure N6 - MW locations and ID near the burn dump
(Modified from 17 Wing Construction Engineering Squadron, 2014)

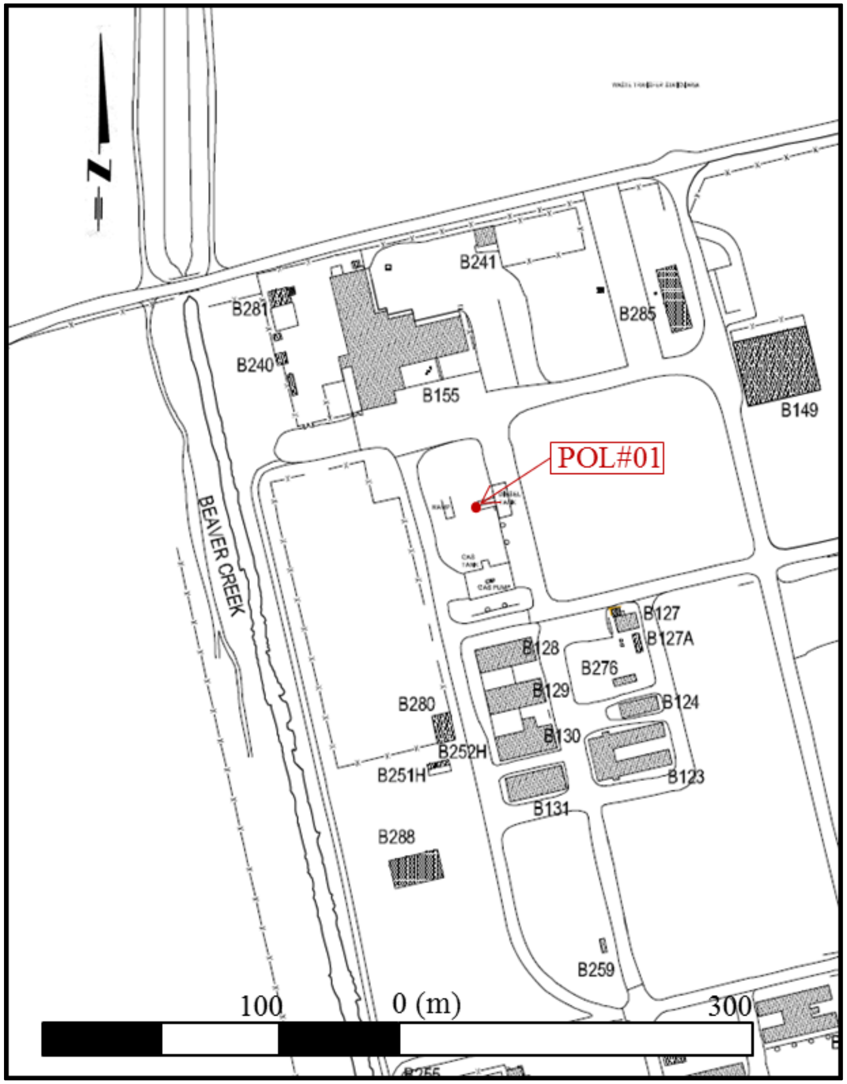


Figure N7 - MW location and ID near the current service station (Modified from 17 Wing Construction Engineering Squadron, 2014)

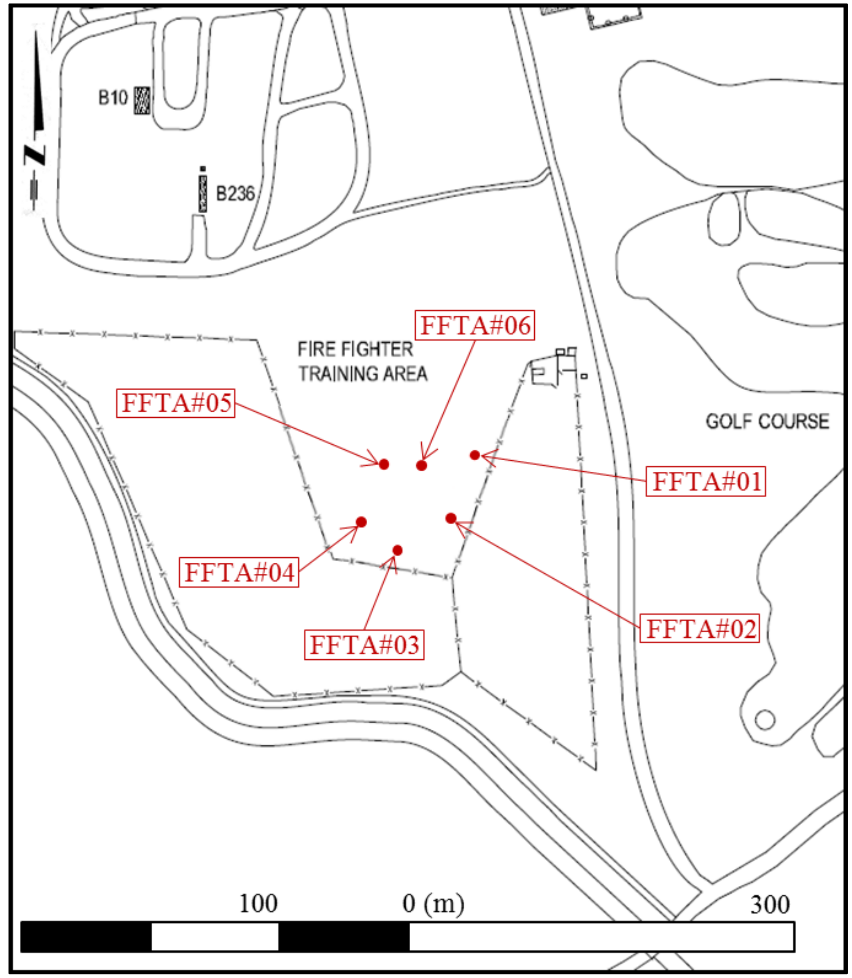


Figure N8 - MW locations and ID near the former firefighting training area (Modified from 17 Wing Construction Engineering Squadron, 2014)

Model Mesh:

Figure N9 - Model mesh positioned on the base map

Ground Elevation Layer:

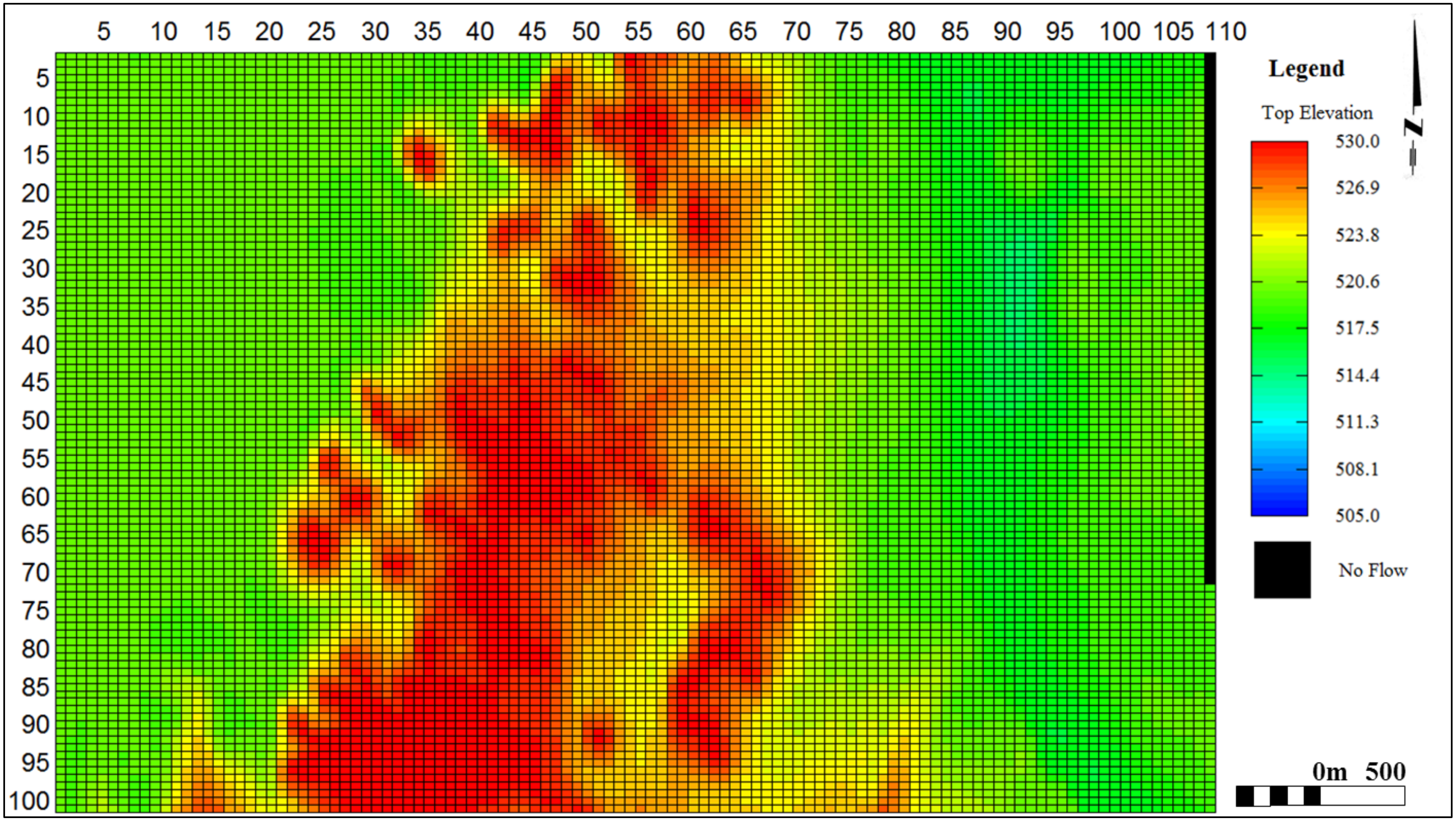


Figure N10 - Ground elevation (elevation of the top layer) as integrated in Groundwater Vistas 6

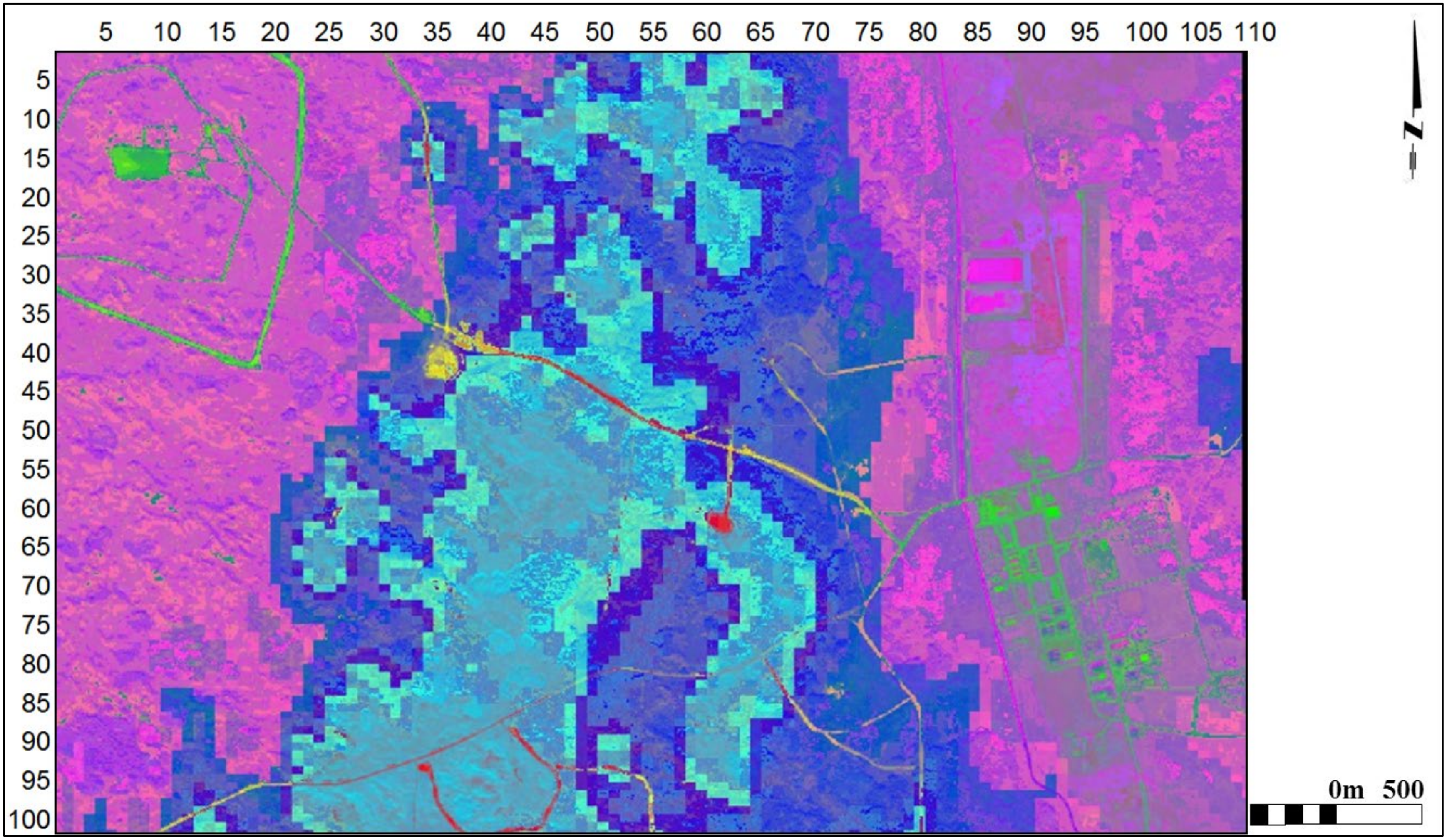


Figure N11 - Ground elevation (elevation of the top layer) overlaid on the base map as a negative image

Boundary Conditions:

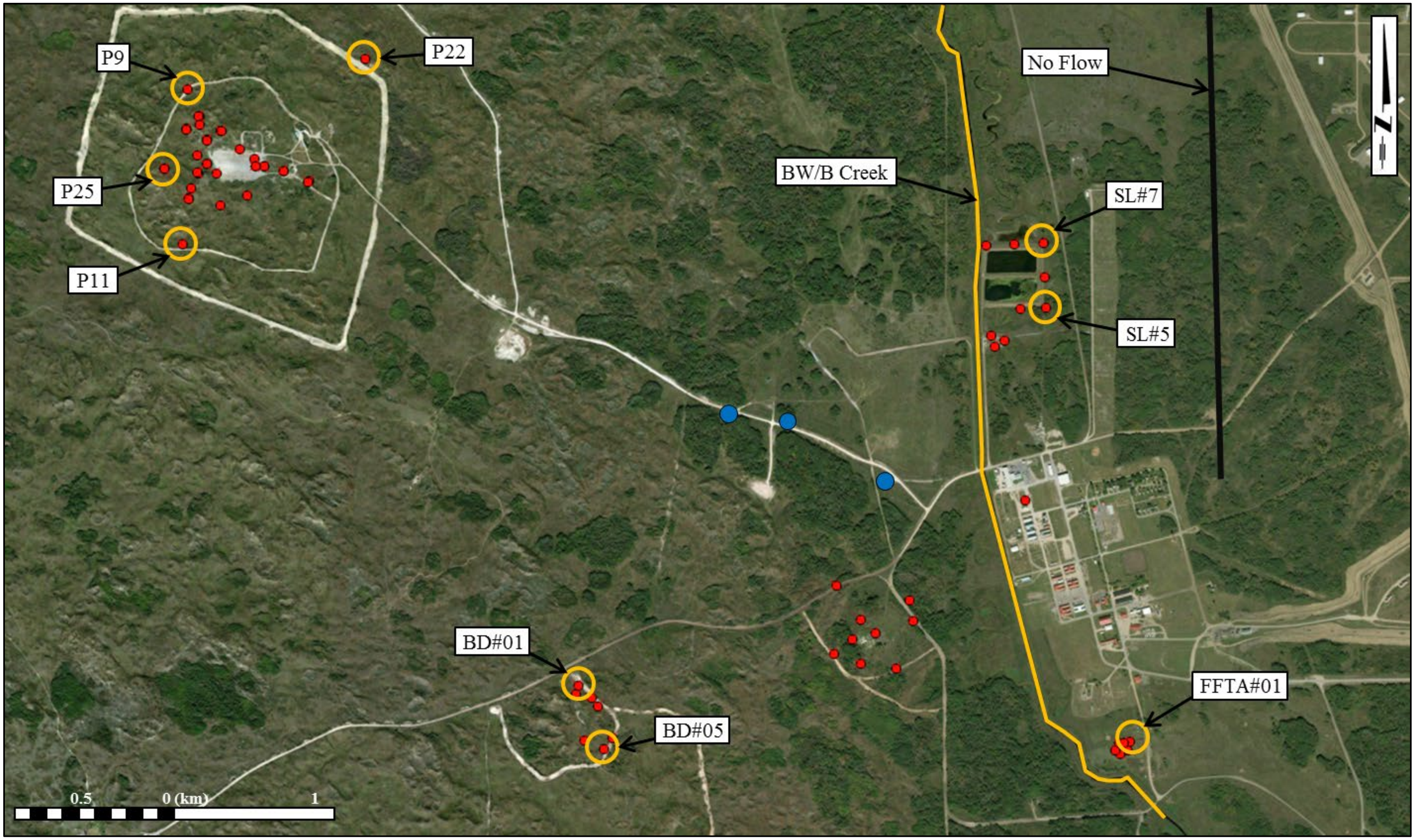


Figure N12 - Data points (i.e. MWs and Brightwater/Beaver Creek) used as boundary conditions (Imagery provided by Microsoft Corporation, 2018)

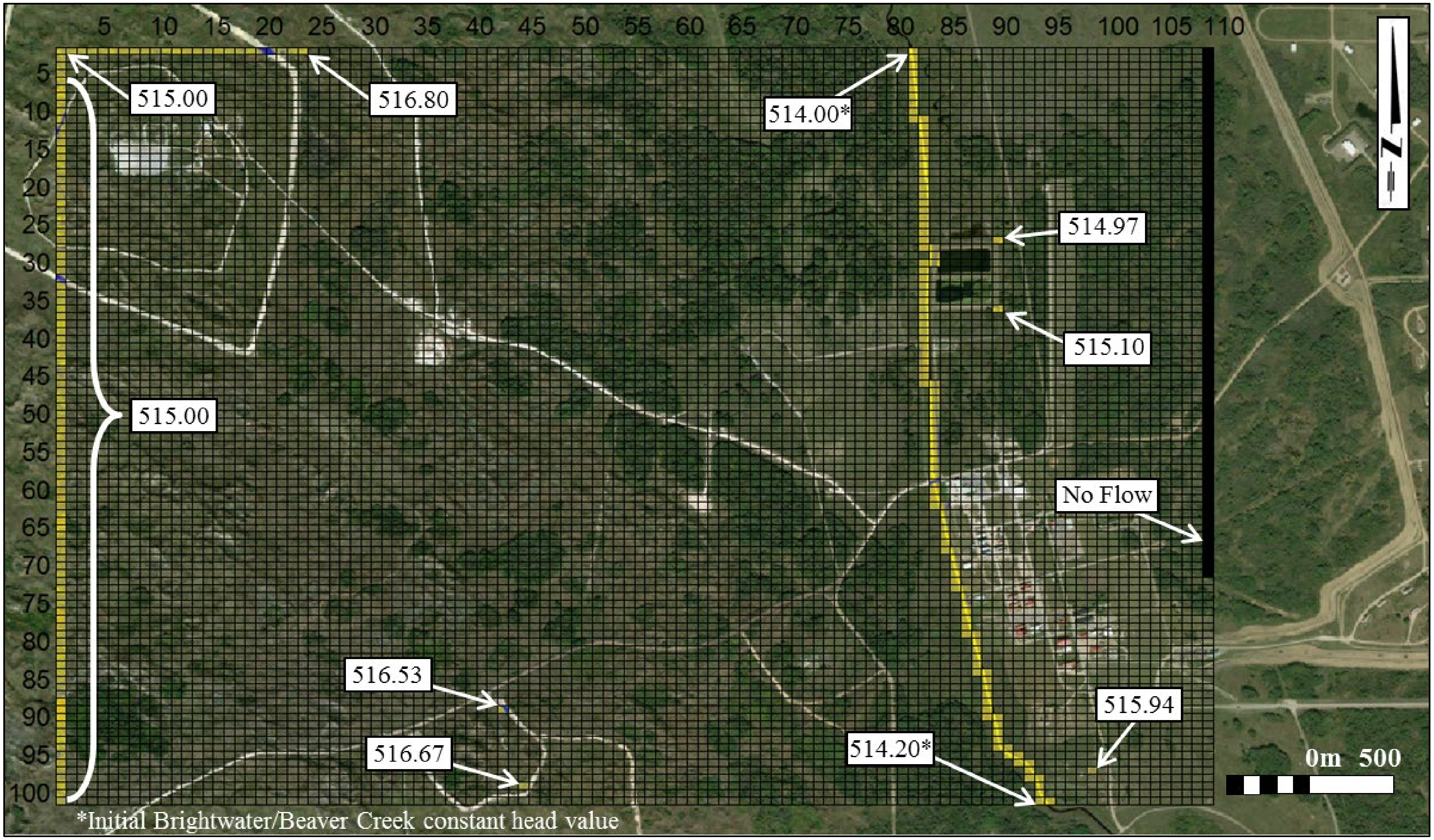


Figure N13 - Boundary condition when applied to the model as seen in GWV 6 with head values (All values are in masl)

Calibration Targets:

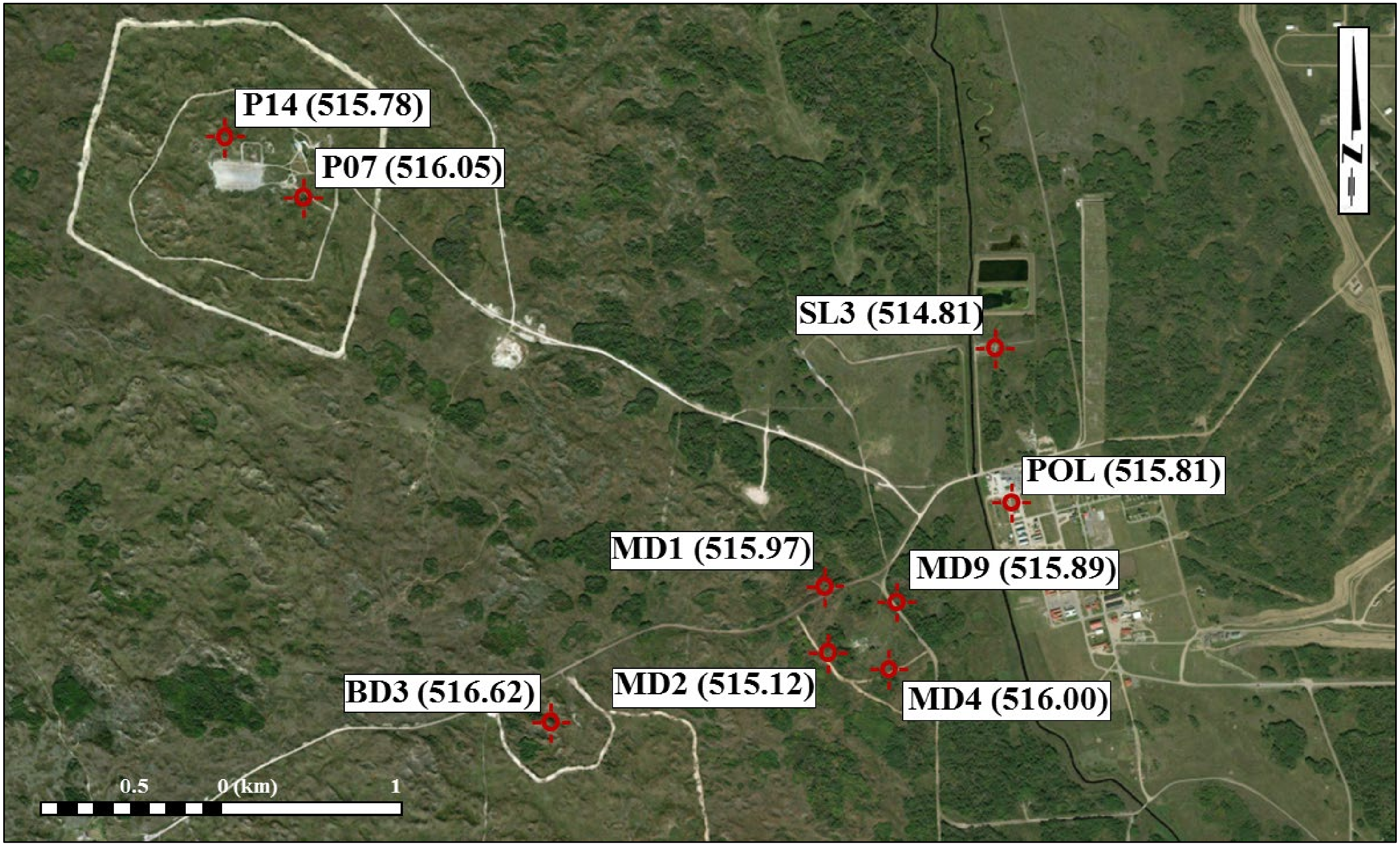


Figure N14 - Calibration targets' locations and values (Imagery provided by Microsoft Corporation, 2018)

Particle Tracking Setup:

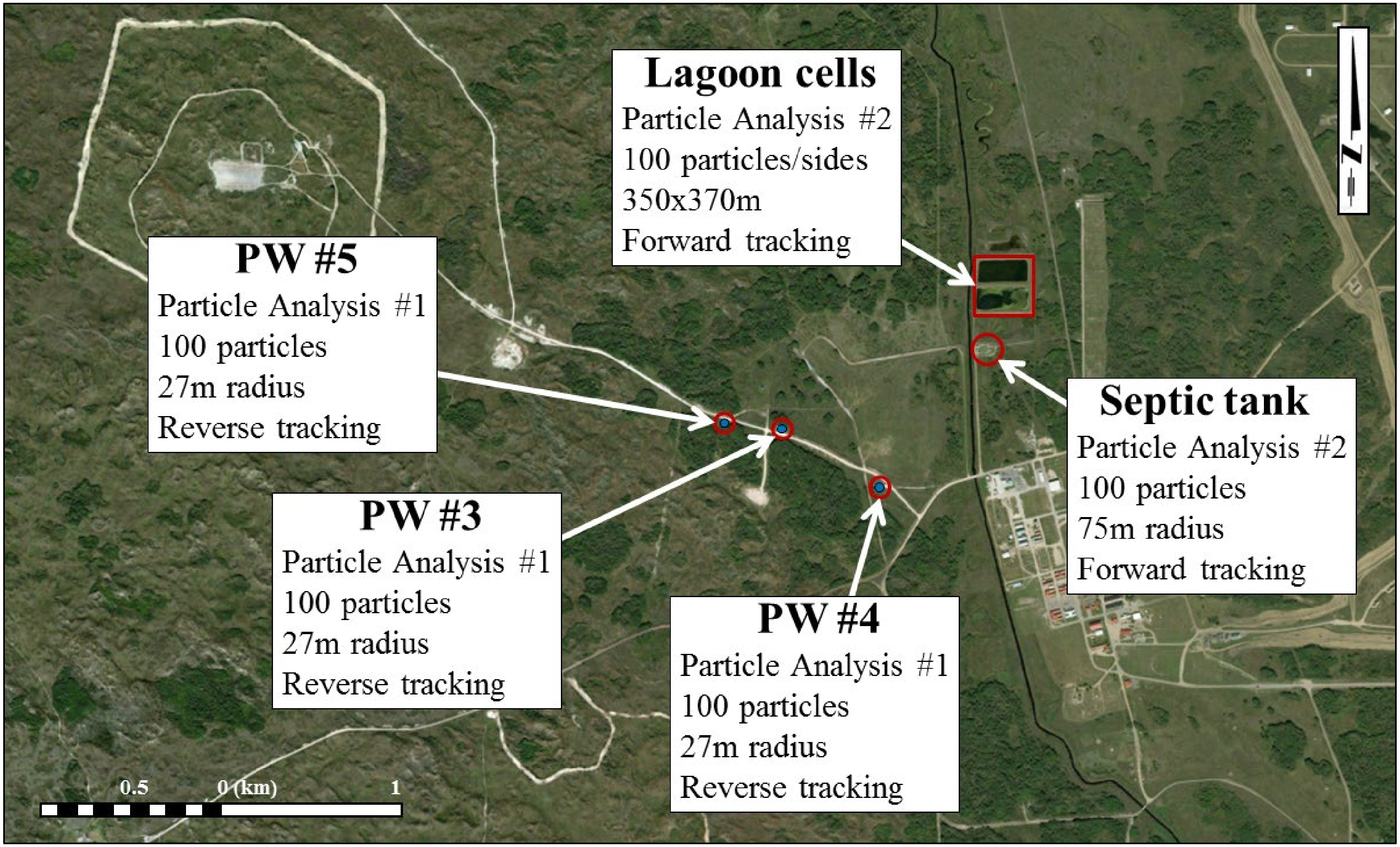


Figure N15 - Particle tracking positions, quantities, and analyses (Imagery provided by Microsoft Corporation, 2018)

Appendix O – Hydrogeological Model Results

The following appendix presents various figures associated with the results of the hydrogeological model at 17 Wing Detachment Dundurn. The hydrogeological model was developed using MODFLOW 2005 version 1.12.00 finite difference numerical tool along with the MODPATH version 7.2.001 particle-tracking post-processing program both produced by the USGS. Groundwater Vistas version 6.96 Build 49 was used as a user interface. Figures include the following:

- Figure O1 presents the initial uncalibrated model results superimposed on the base map. The contour lines represent head elevation assisted by a colour gradient;

- Figure O2 through Figure O4 provides cross-sections of the initial uncalibrated model results along rows 50, 51, and 60 which correspond to the rows of the production wells;

- Figure O5 presents the calibrated model results superimposed on the base map. The contour lines represent head elevation assisted by a colour gradient;

- Figure O6 through Figure O8 provides cross-sections of the initial uncalibrated model results along rows 50, 51, and 60 which correspond to the rows of the production wells;

- Figure O9 and Figure O10 provide the results of the comparison of the computed model results with the observed target values both pre- and post-calibration;

- Figure O11 and Figure O12 provide the results from the particle tracking analyses;

- Figure O13 presents the results of production well pumping rates parametric study; and,

- Figure O14 presents the results of the production well pumping rates parametric study as envelopes for each well. The envelopes are overlaid by the possible sources of groundwater contamination.

Initial Results

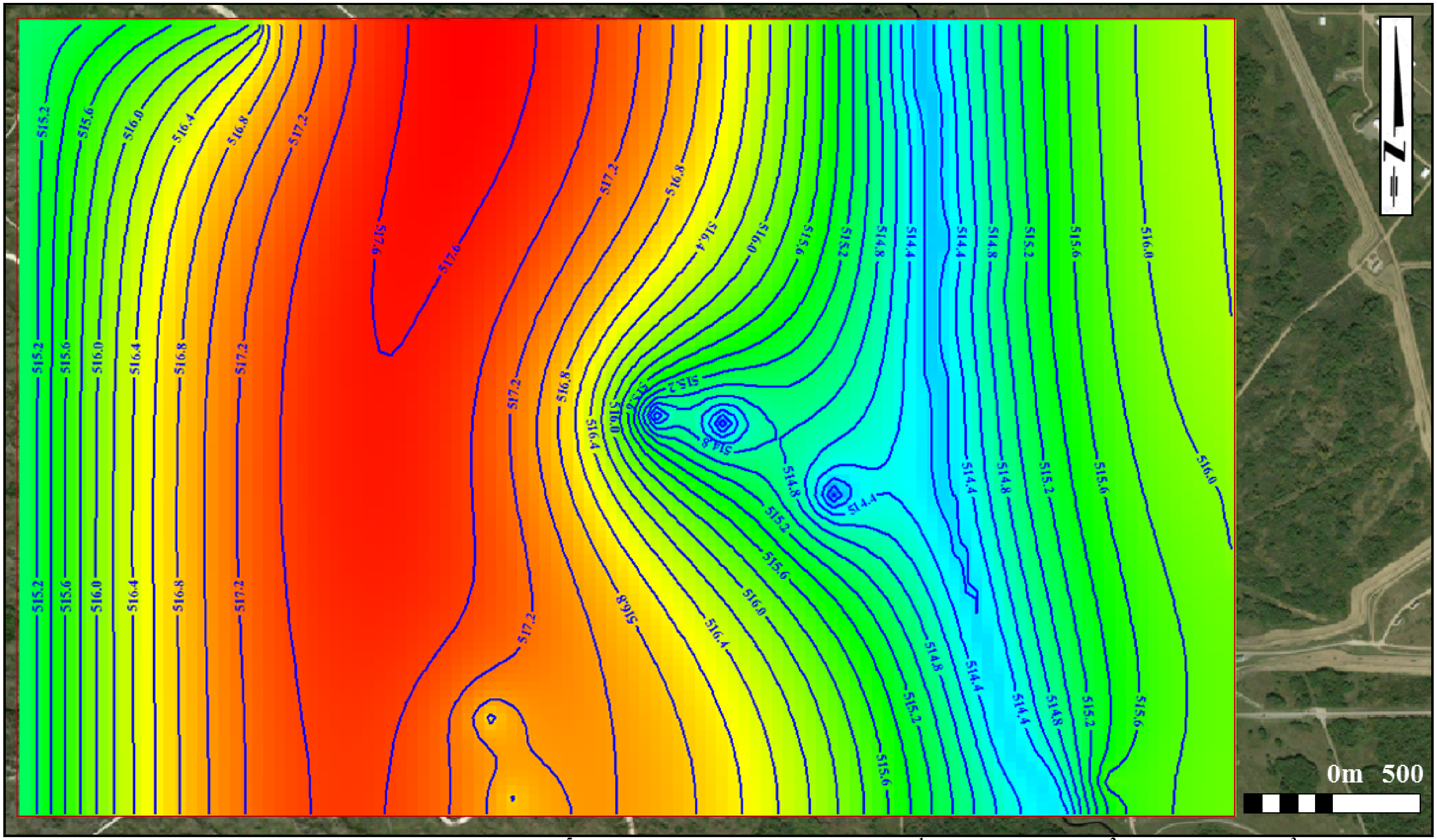


Figure O1 - Initial model results (Recharge = $1.22e^{-5}$, Layer 1 Kxy = 1.00, Layer 1 Kz = $1.00e^{-1}$, Layer 2 Kxy = $7.90e^{-2}$, Layer 2 Kz = $7.90e^{-3}$)

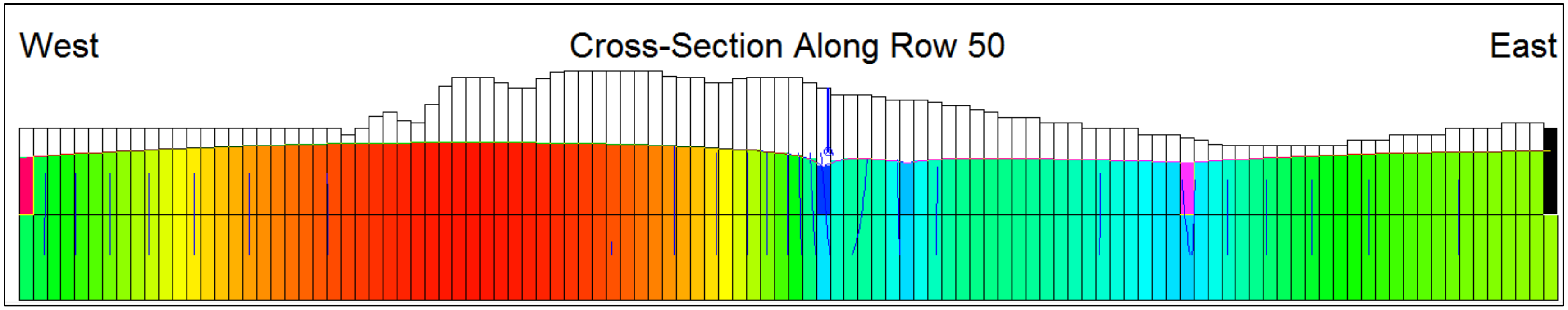


Figure O2 - Initial cross section of row 50 (Well #5)

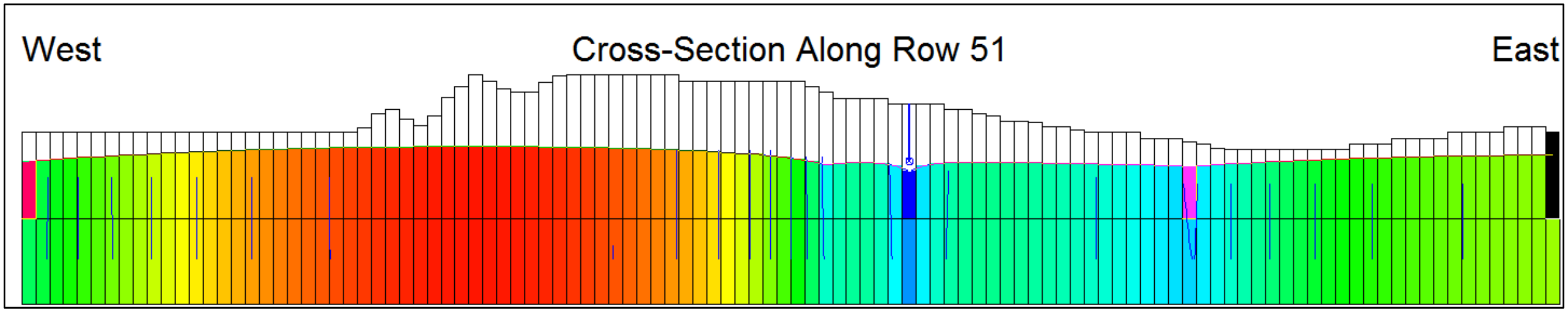


Figure O3 - Initial cross section of row 51 (Well #3)

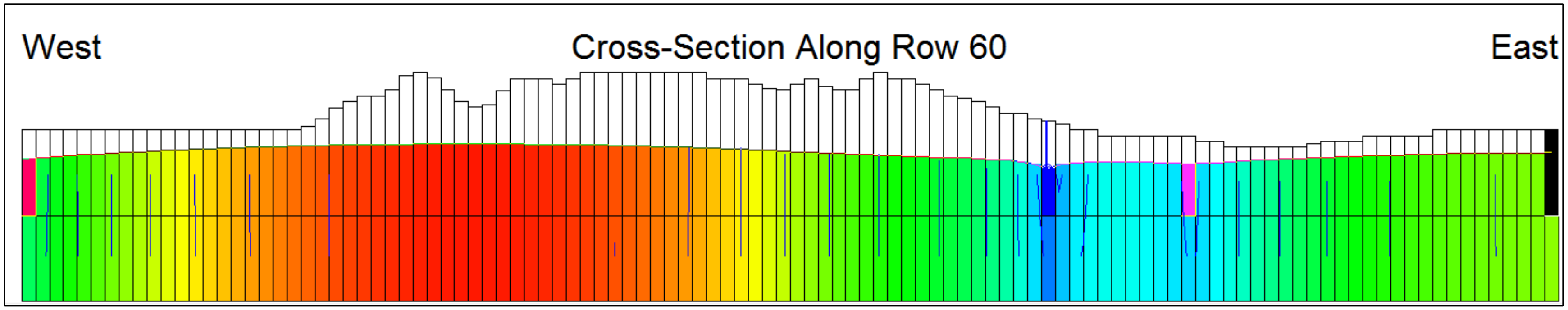


Figure O4 - Initial cross section of row 60 (Well #4)

Final Results

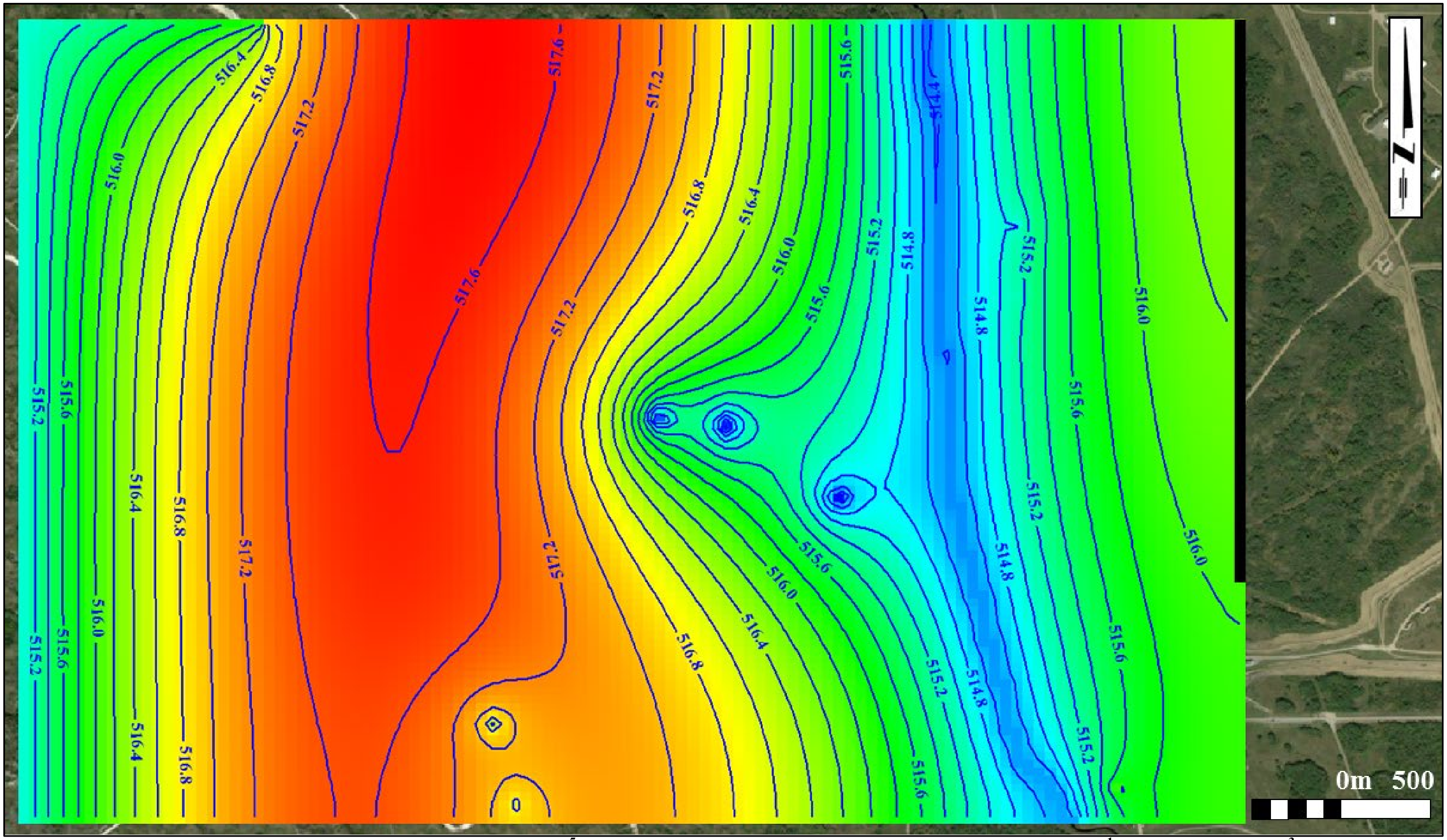


Figure O5 - Final model results (Recharge = $1.95e^{-5}$, Layer 1 Kxy = 1.157, Layer 1 Kz = 1.00, Layer 2 Kxy = $1.54e^{-1}$, Layer 2 Kz = $1.00e^{-3}$)

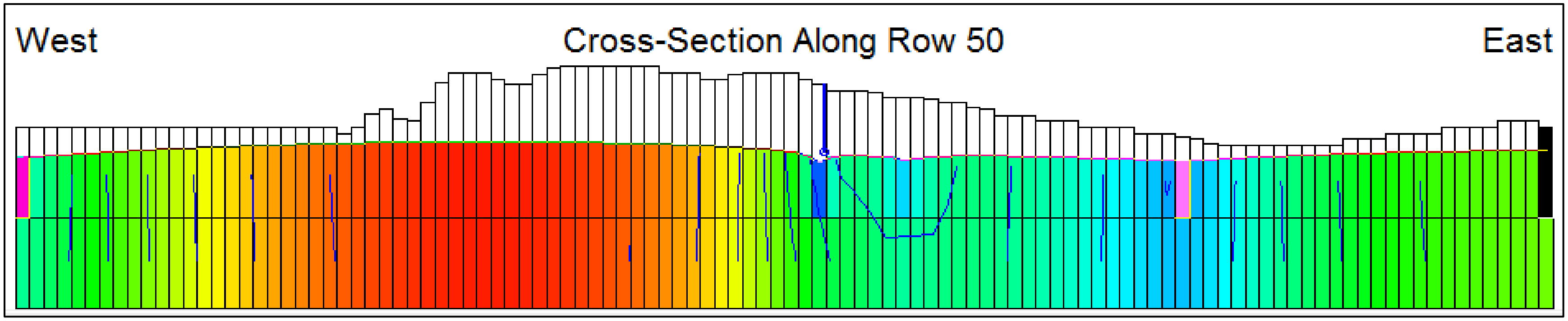


Figure O6 - Final cross section of row 50 (Well #5)

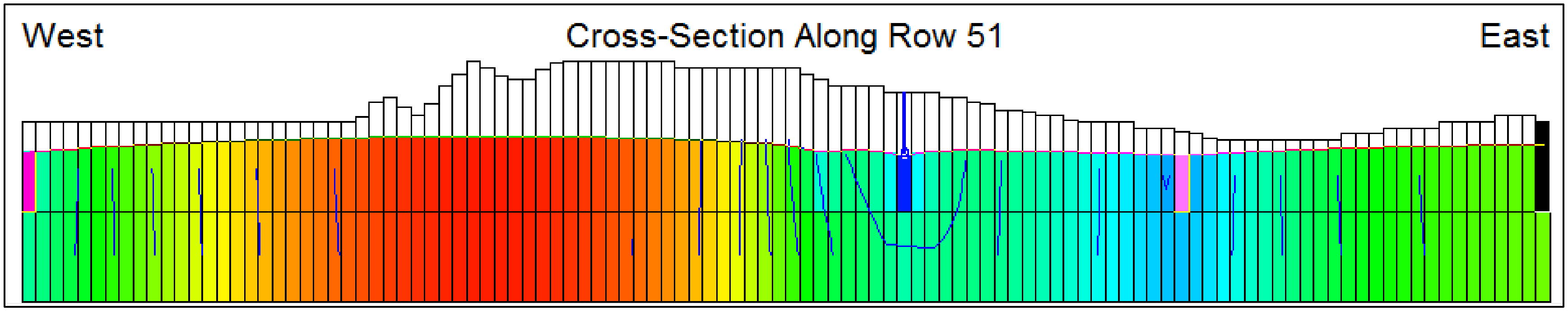


Figure O7 - Final cross section of row 51 (Well #3)

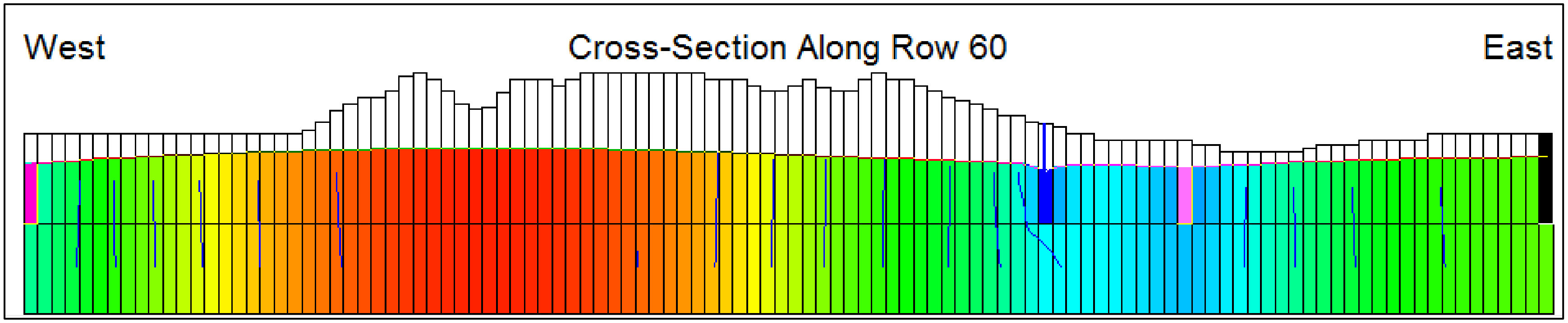


Figure O8 - Final cross section of row 60 (Well #4)

Calibration Results

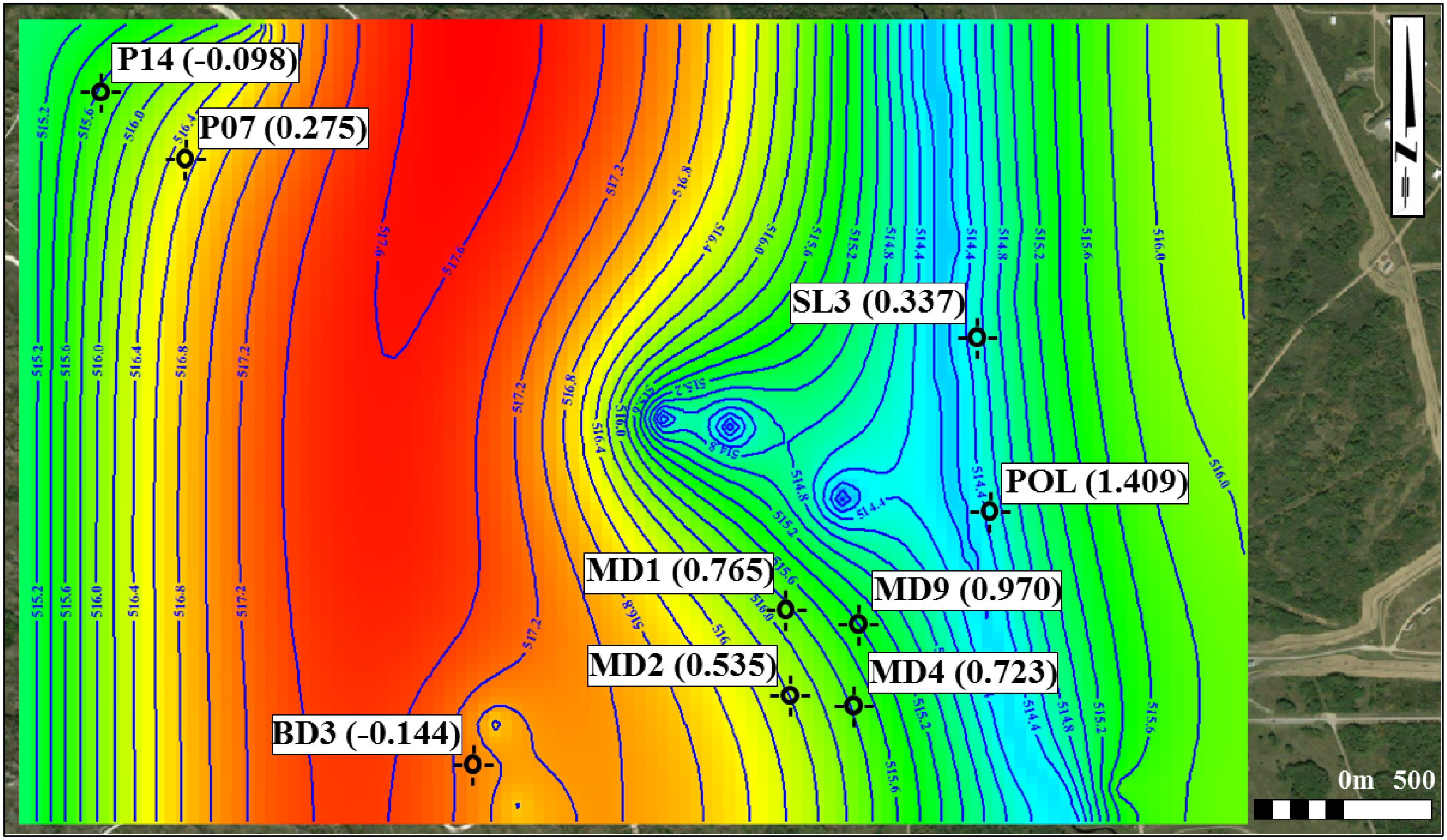


Figure O9 - Pre-calibration residuals errors by targets (all values are in metres)

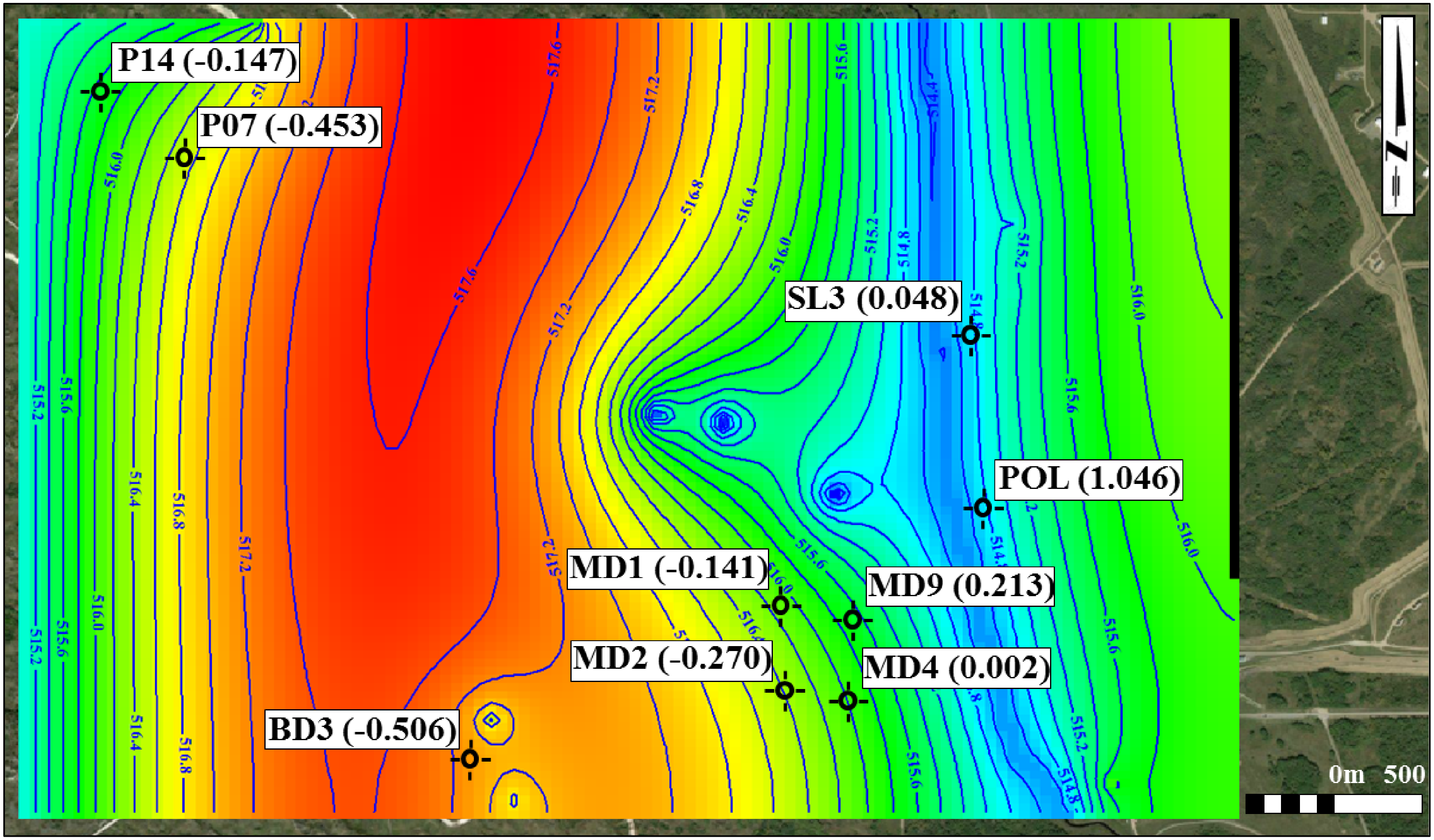


Figure O10 - Post-calibration residual errors by targets (all values are in metres)

Particle Tracking Results

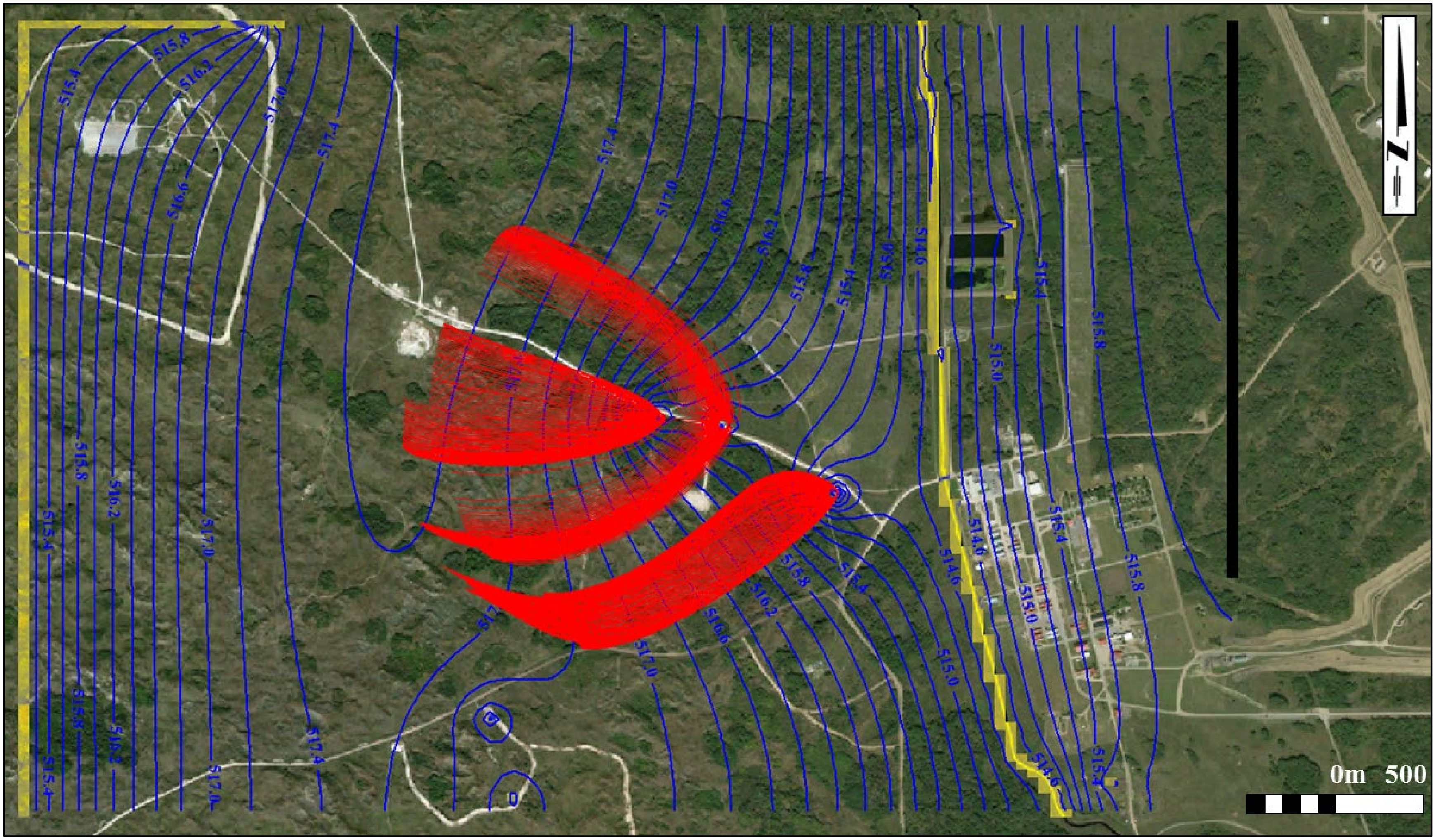


Figure O11 - Analysis #1 (Reverse particle tracking of production wells)

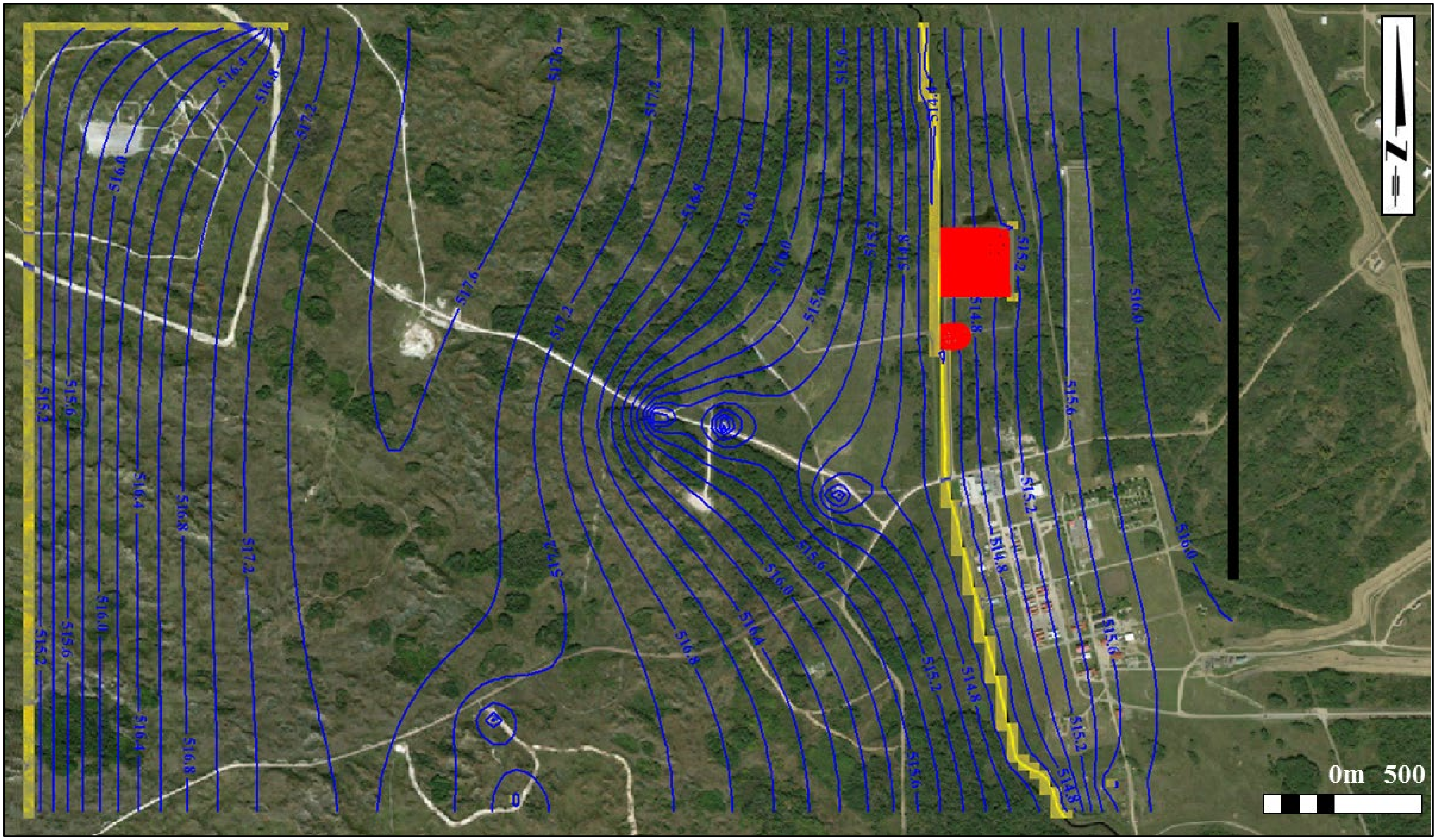


Figure O12 - Analysis #2 (Forward particle tracking of WWT lagoon site)

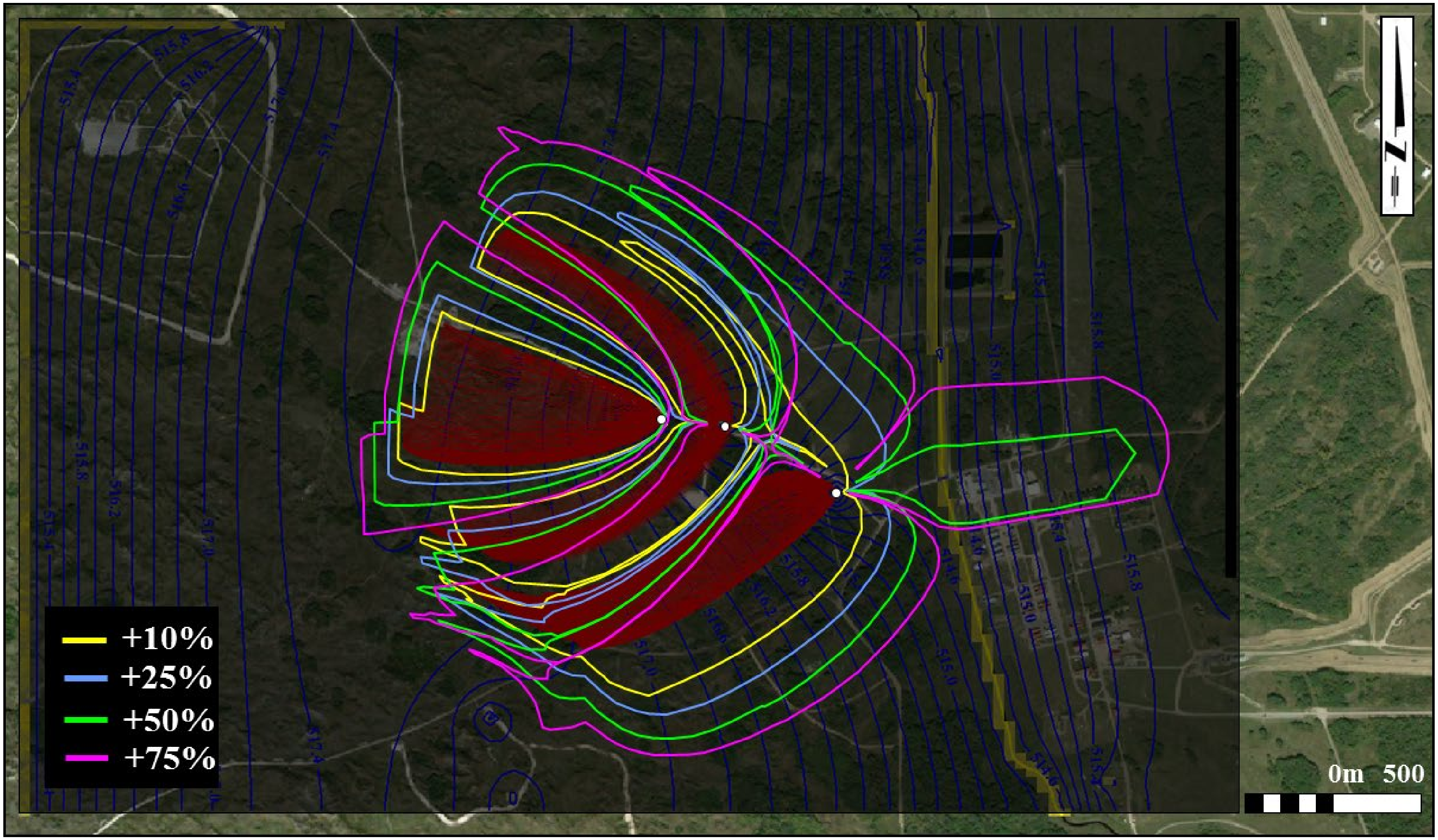


Figure O13 - Results of production well pumping rates parametric study

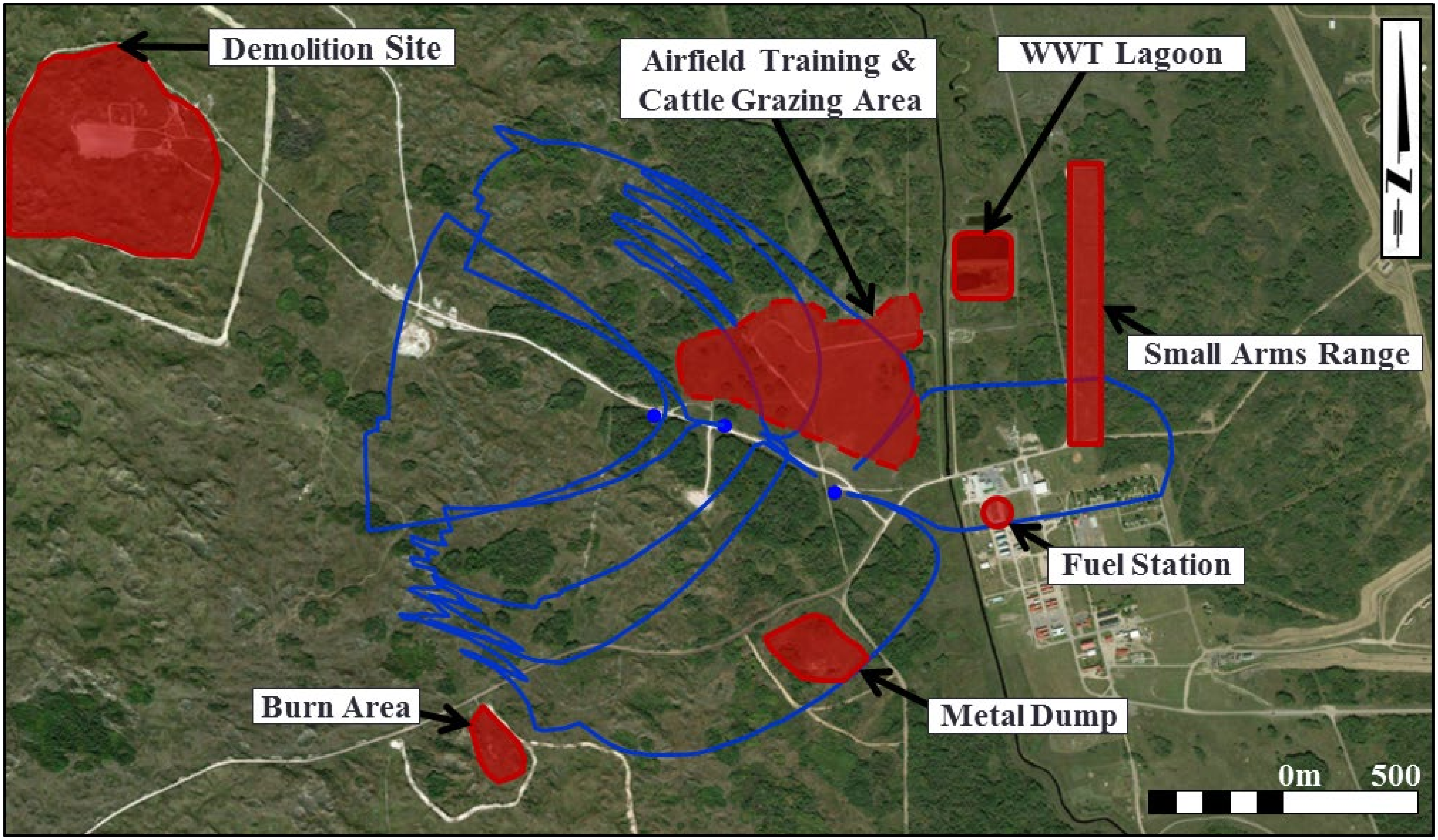


Figure O14 – Production well envelopes with possible sources of contamination overlay

Appendix P – Weather Data Analysis

The following appendix presents various figures associated with the results of the analysis on recorded weather at 17 Wing Detachment Dundurn. Figures include the following:

- Figure P1 through Figure P4 plots the monthly average temperatures and precipitation accumulation by treatment periods;
- Figure P5 plots the average monthly temperature of each treatment period over the 1981-2010 normals. Months marked by an asterisk (*) indicate months in which treatment period start or end, thereby effecting the monthly average;
- Figure P6 plots the average monthly temperature of each treatment period over the 1981-2010 normals. Months marked by an asterisk (*) indicate months in which treatment period start or end, thereby effecting the monthly average;
- Figure P7 plots the daily accumulation of precipitation by treatment periods;
- Figure P8 through Figure P11 plot recorded wind speeds and direction by treatment periods;
- Figure P12 through Figure P15 plot recorded wind speeds and direction for the periods of expected active treatment (i.e. May-Oct) of each treatment period;
- Figure P16 through Figure P19 plot the windy days and direction for the periods of expected active treatment (i.e. May-Oct) of each treatment period; and,
- Figure P20 through Figure P24 present various figures used to approximation calculation of fetch.

Weather Summaries

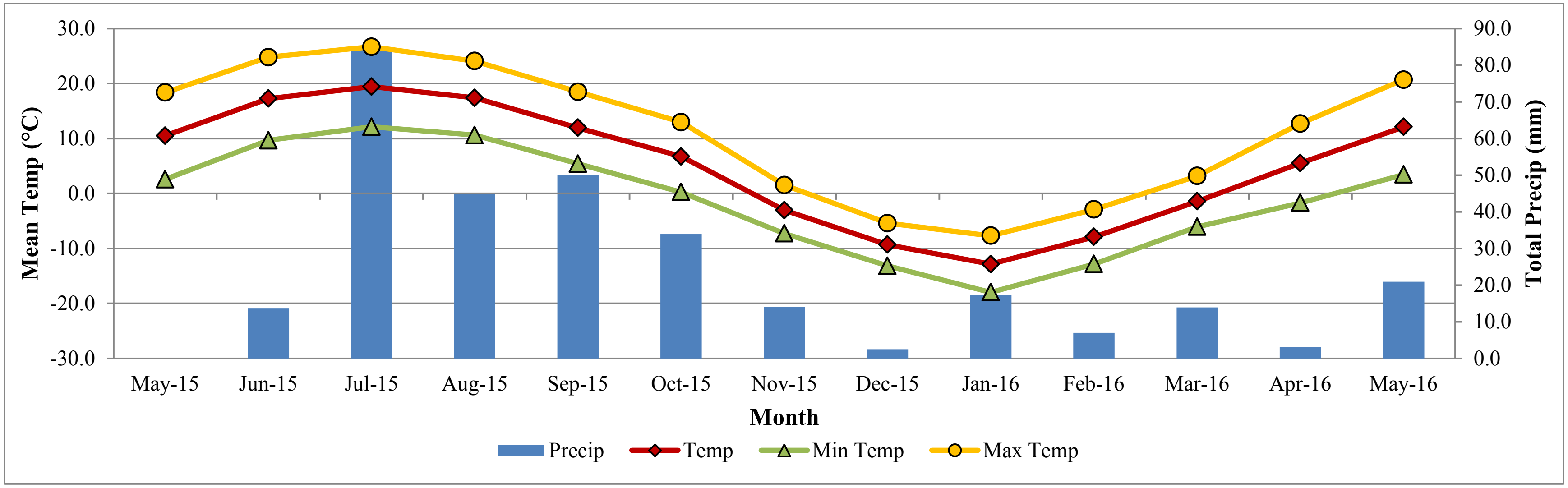


Figure P1 - Monthly temperature and precipitation for the 2015-2016 treatment period

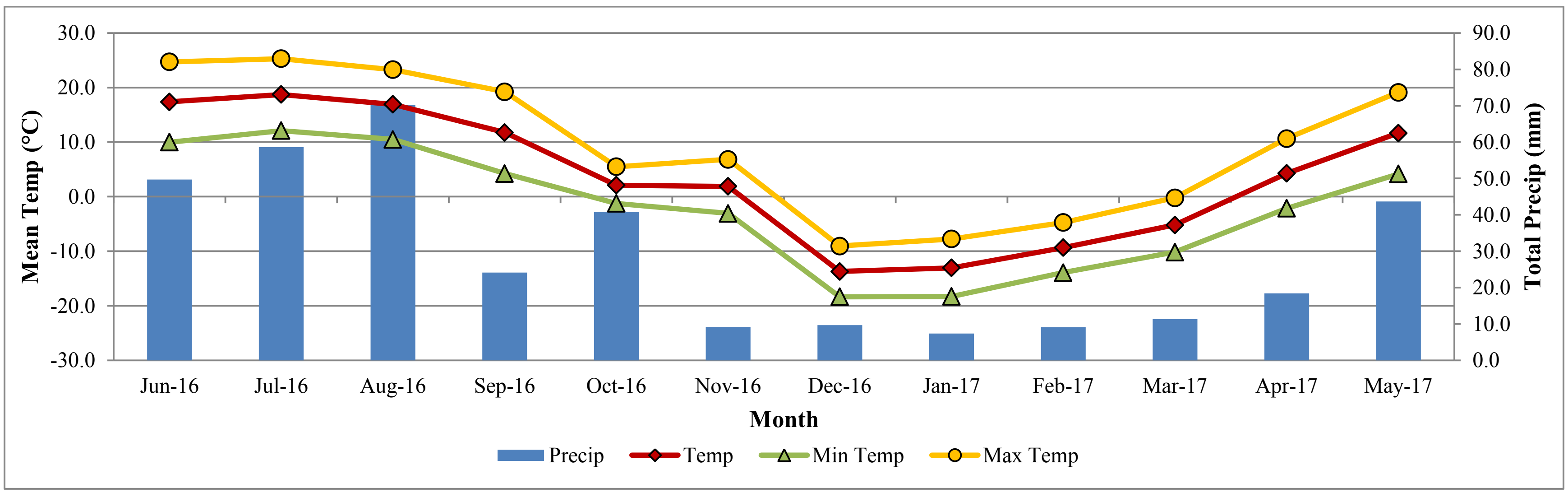


Figure P2 - Monthly temperature and precipitation for the 2016-2017 treatment period

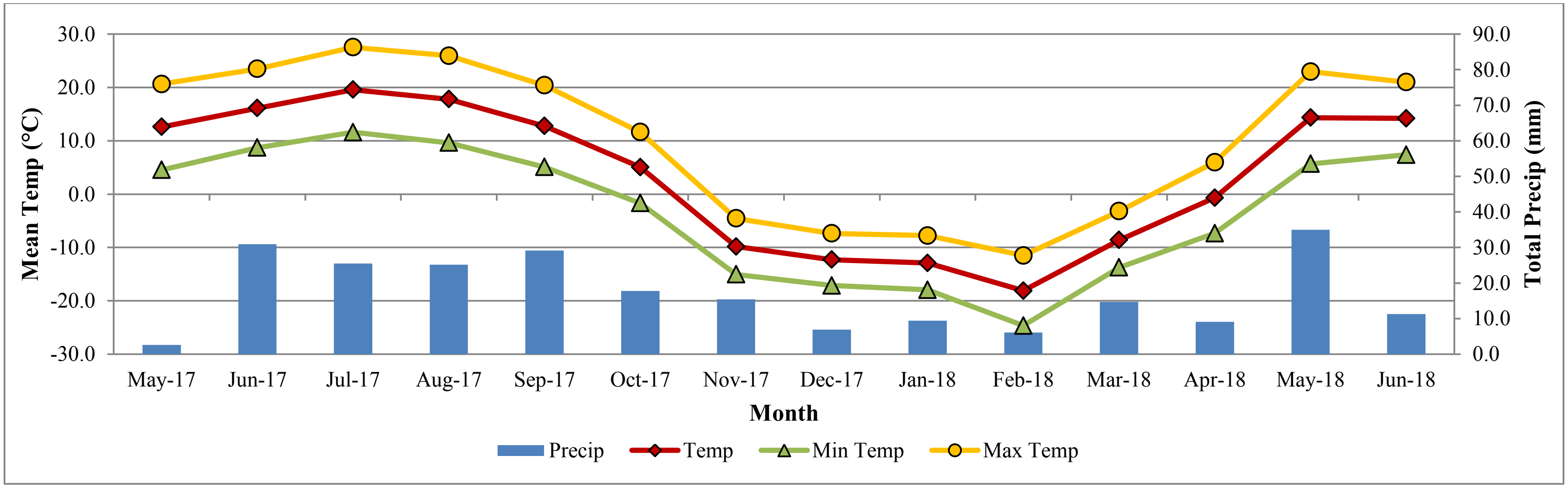


Figure P3 - Monthly temperature and precipitation for the 2017-2018 treatment period

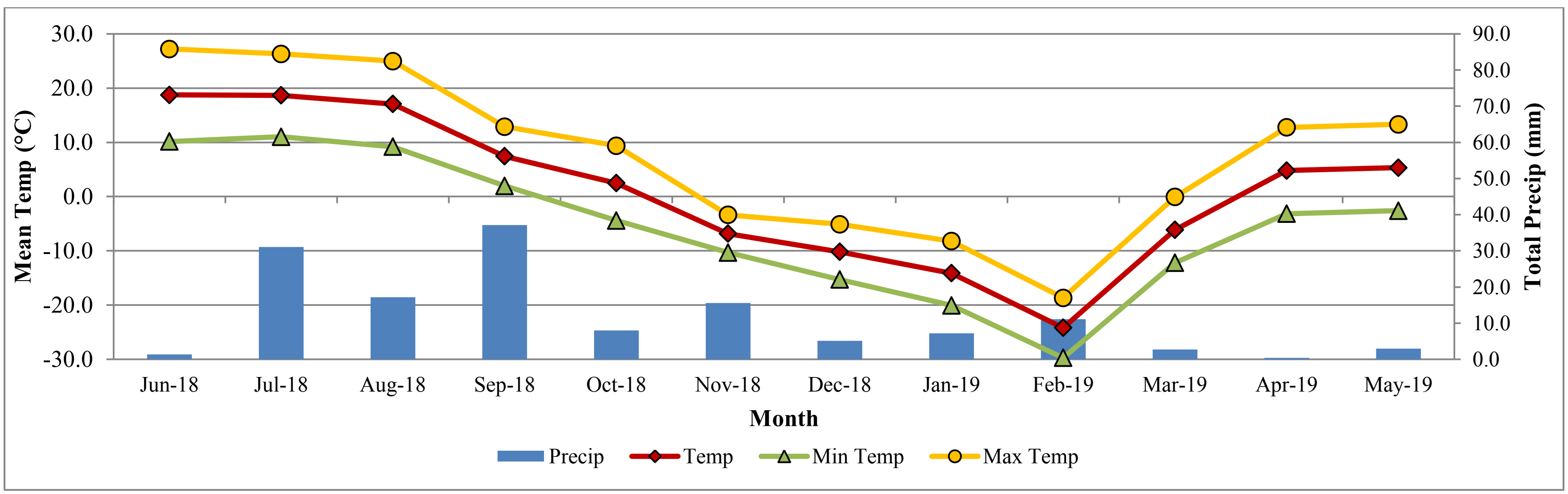


Figure P4 - Monthly temperature and precipitation for the 2018-2019 treatment period

Temperature Comparison

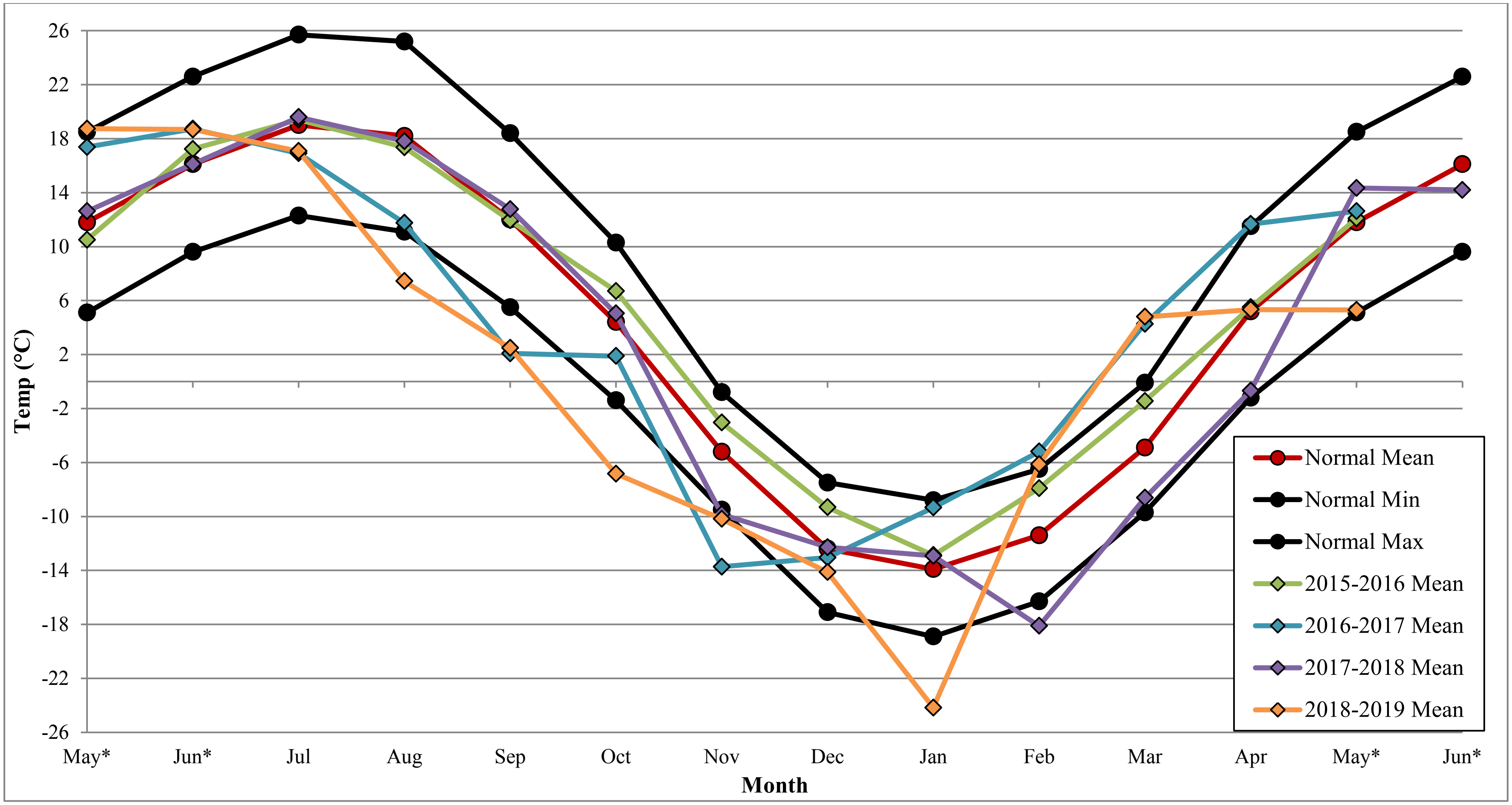


Figure P5 - Average monthly temperature of each treatment period superimposed on the 1981-2010 normal mean, minimum, and maximum

Precipitation Comparison

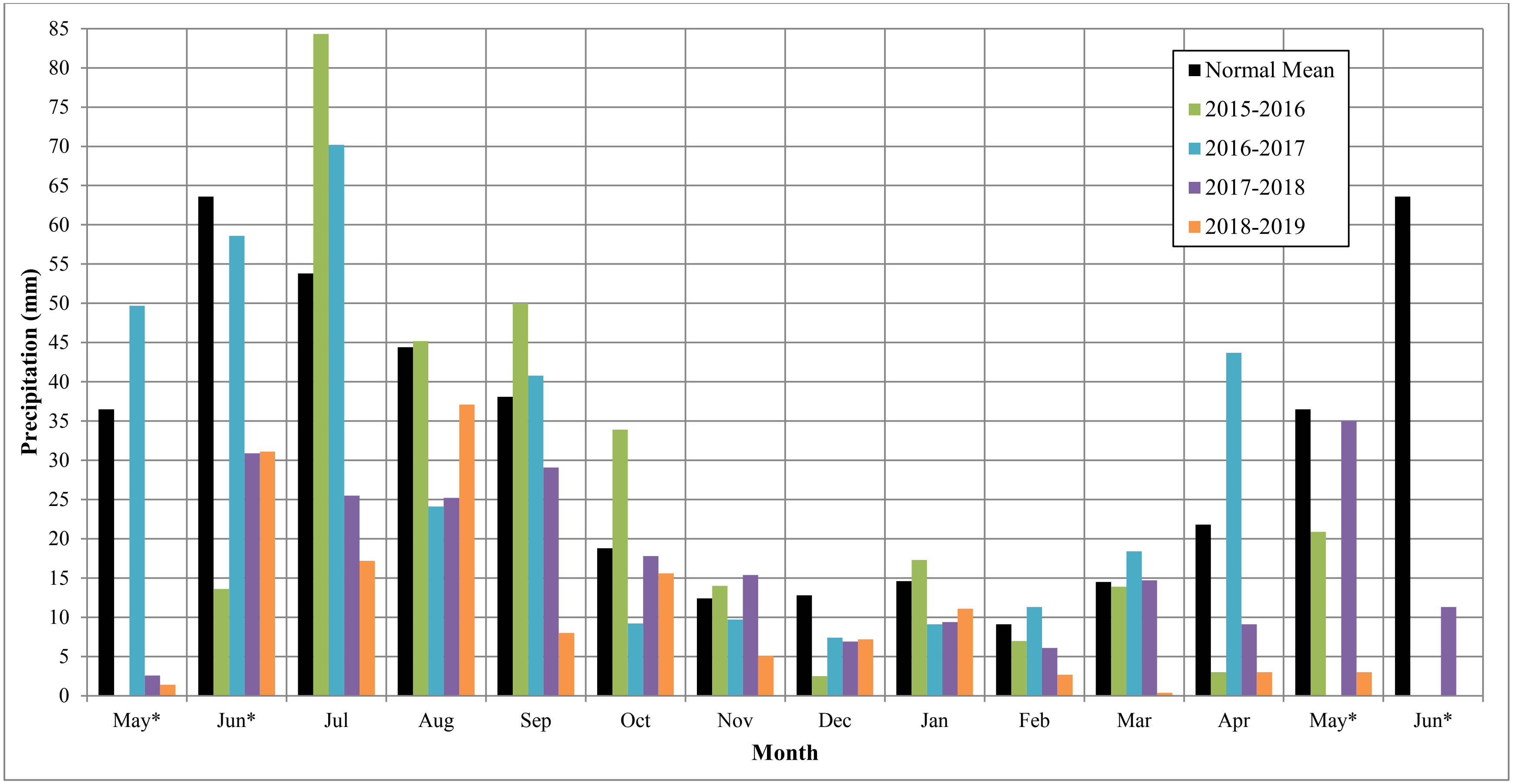


Figure P6 - Monthly precipitation by treatment period superimposed on 1981-2010 normals

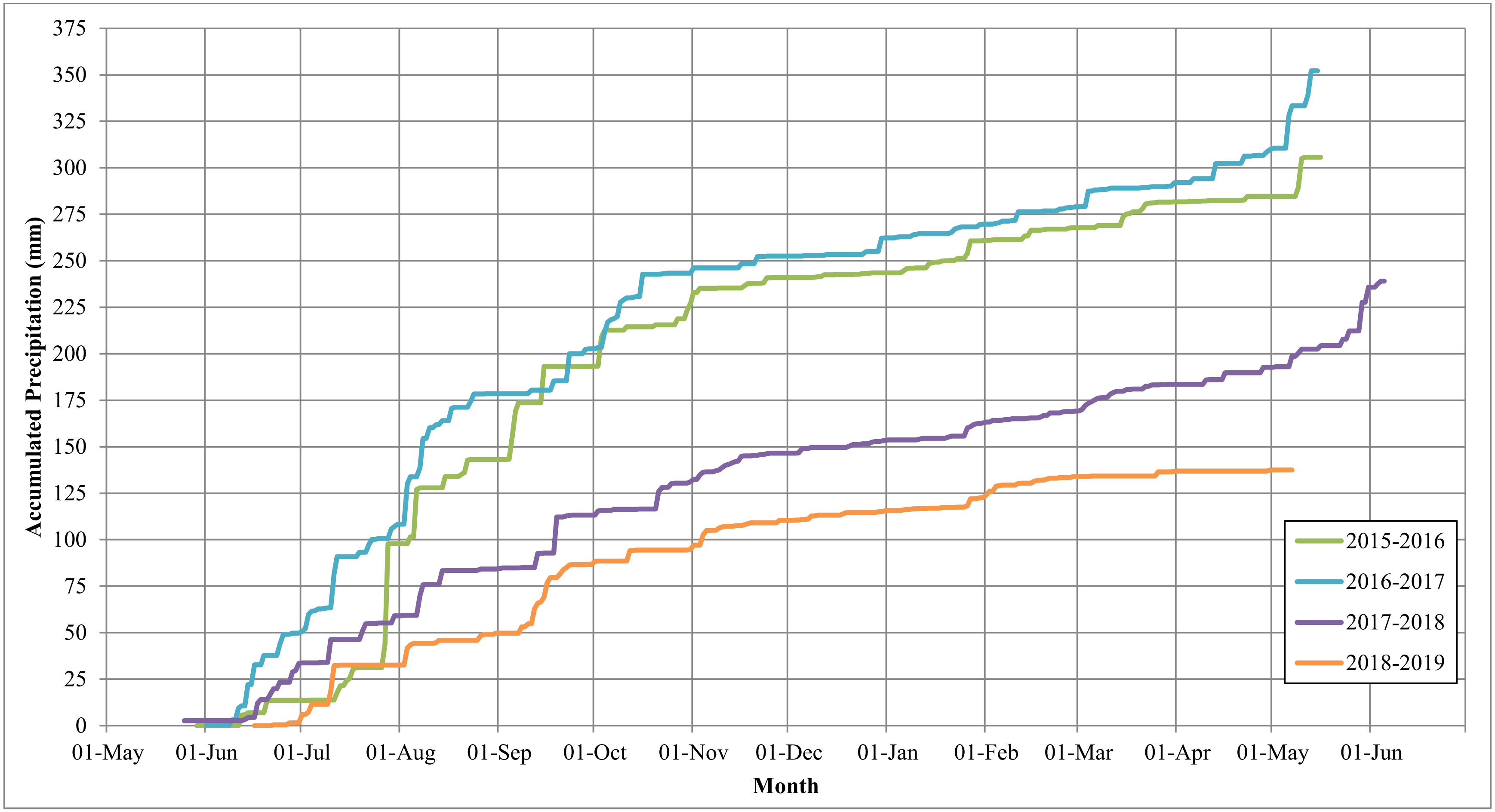


Figure P7 - Total accumulated precipitation by treatment periods

Wind

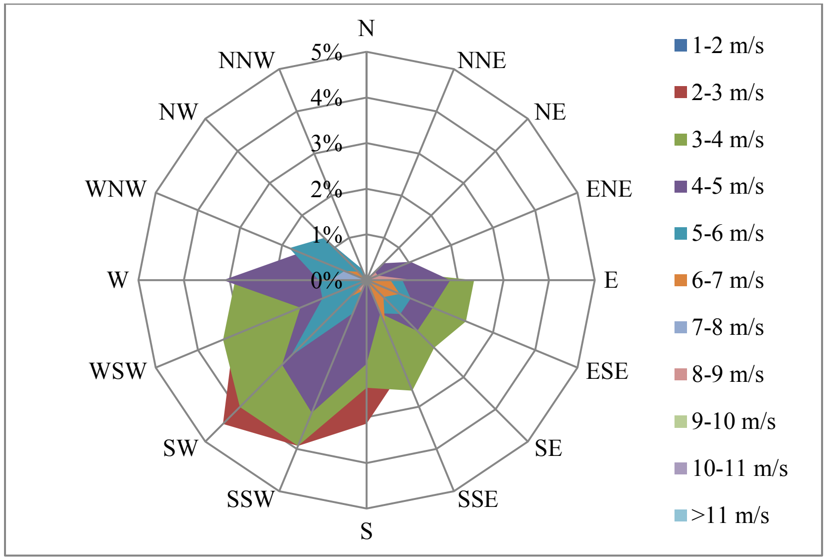


Figure P8 – Wind speed and direction for the 2015-2016 treatment period

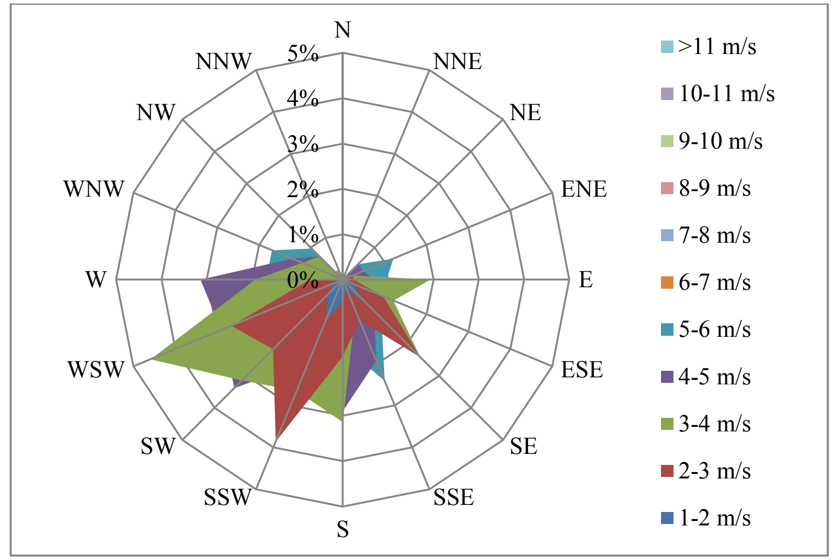


Figure P10 - Wind speed and direction for the 2017-2018 treatment period

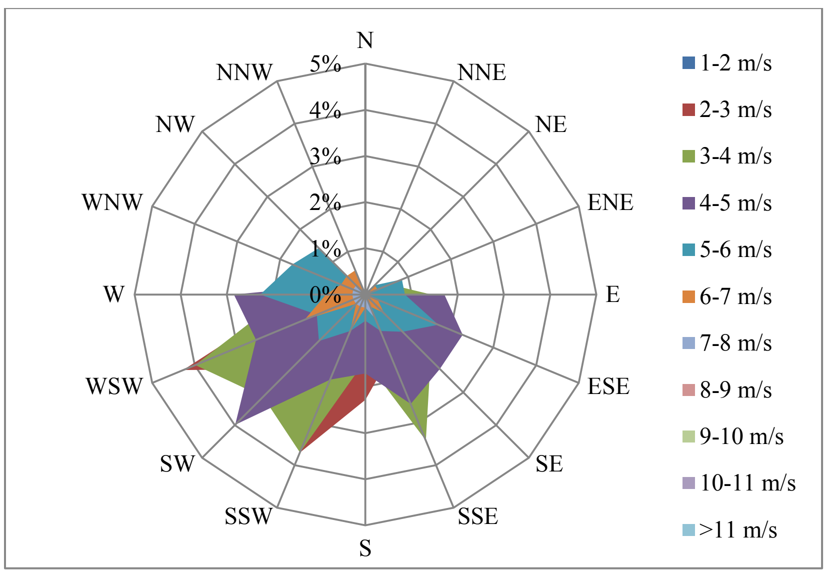


Figure P9 - Wind speed and direction for the 2016-2017 treatment period

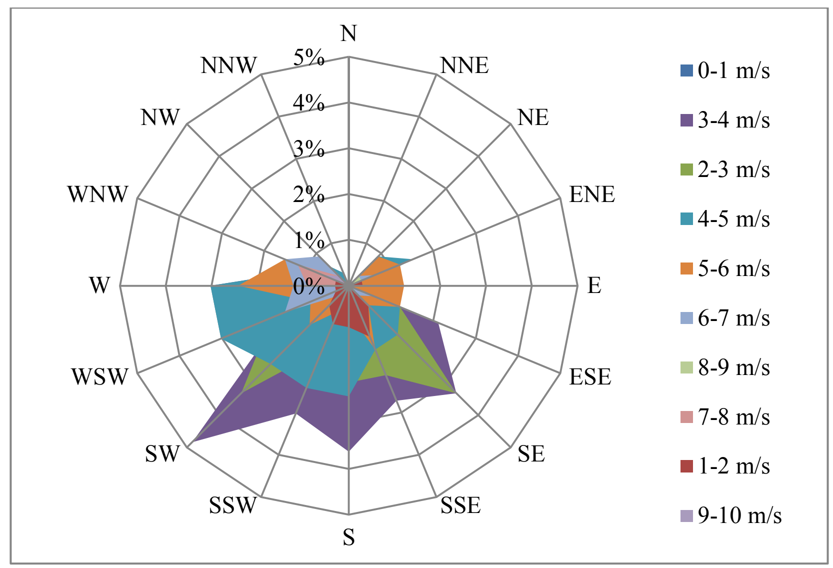


Figure P11 - Wind speed and direction for the 2018-2019 treatment period

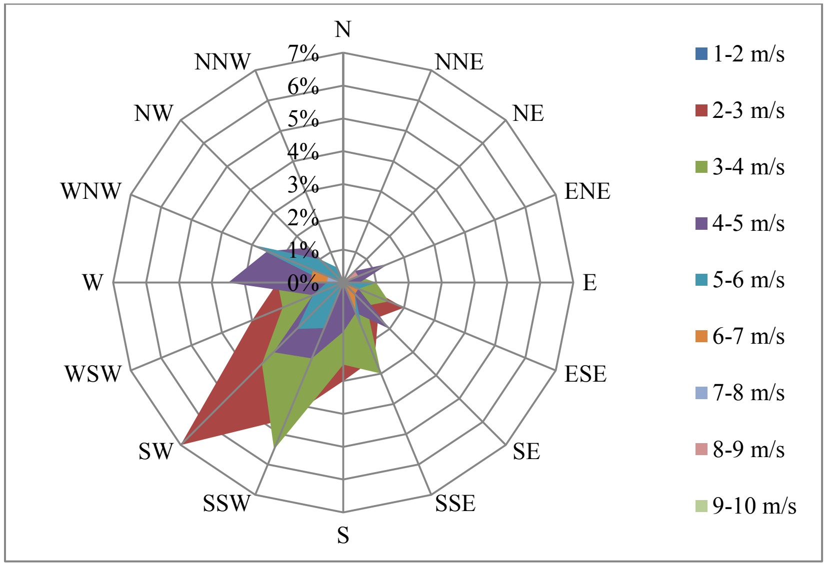


Figure P12 Wind spd & dir - 2015-2016 treatment period (May-Oct)

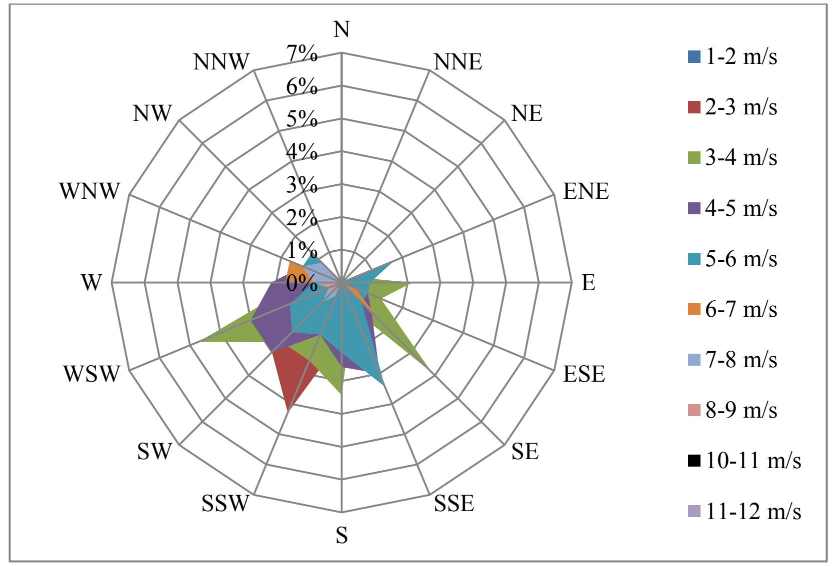


Figure P14 - Wind spd & dir - 2017-2018 treatment period (May-Oct)

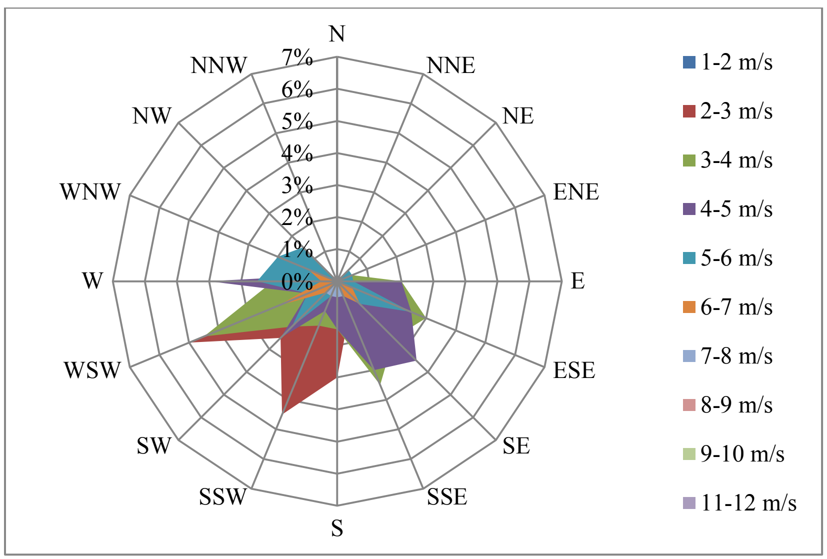


Figure P13 - Wind spd & dir - 2016-2017 treatment period (May-Oct)

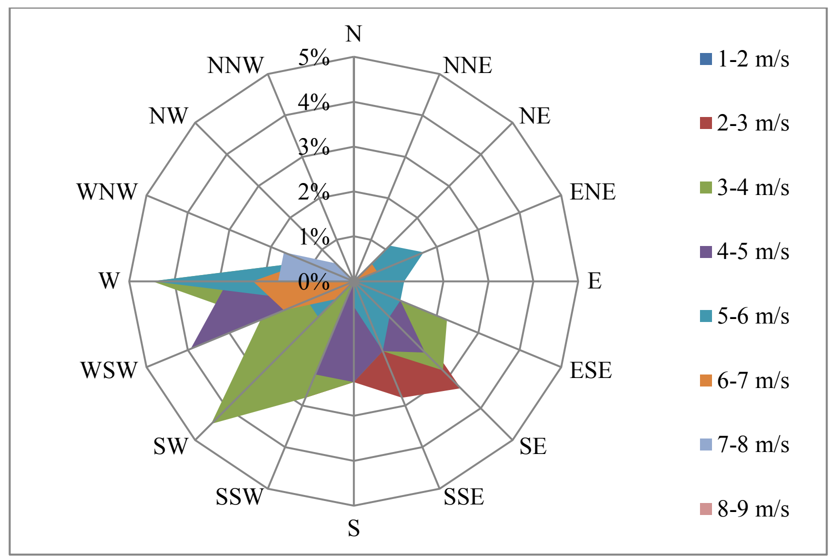


Figure P15 - Wind spd & dir - 2018-2019 treatment period (May-Oct)

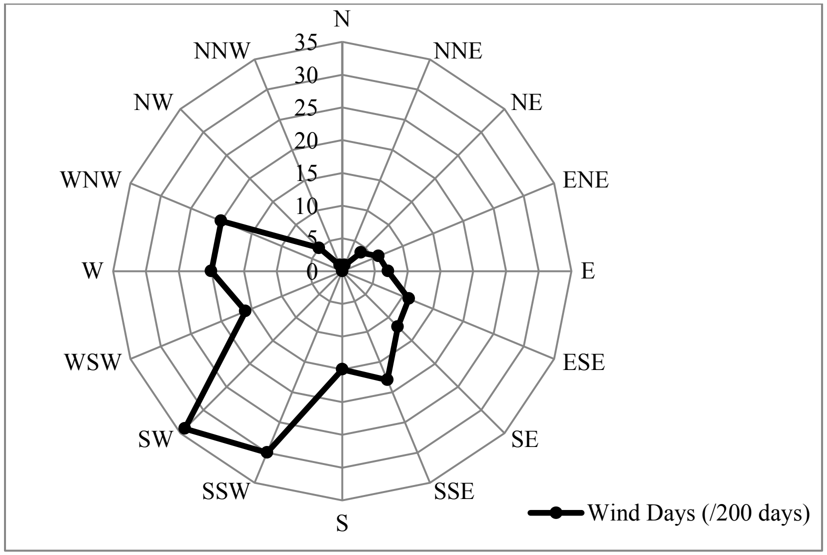


Figure P16 - Wind days - 2015-2016 Treatment period (May-Oct)

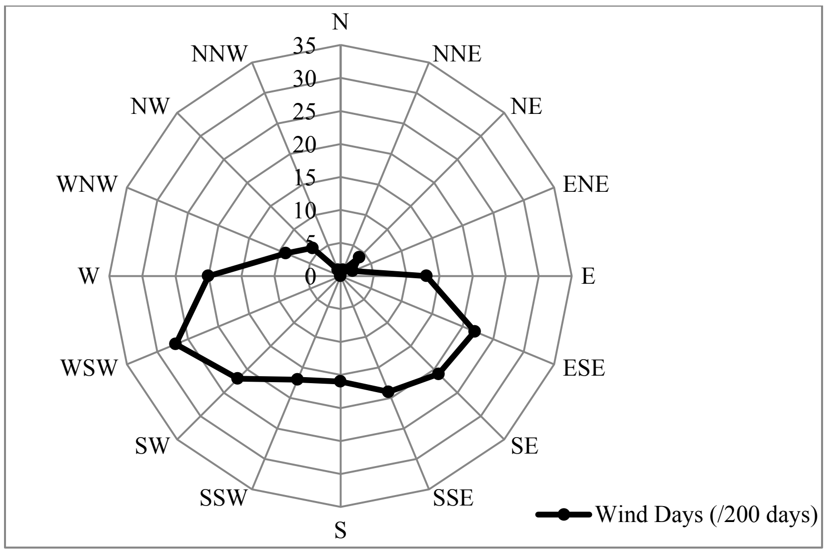


Figure P17 - Wind days - 2016-2017 Treatment period (May-Oct)

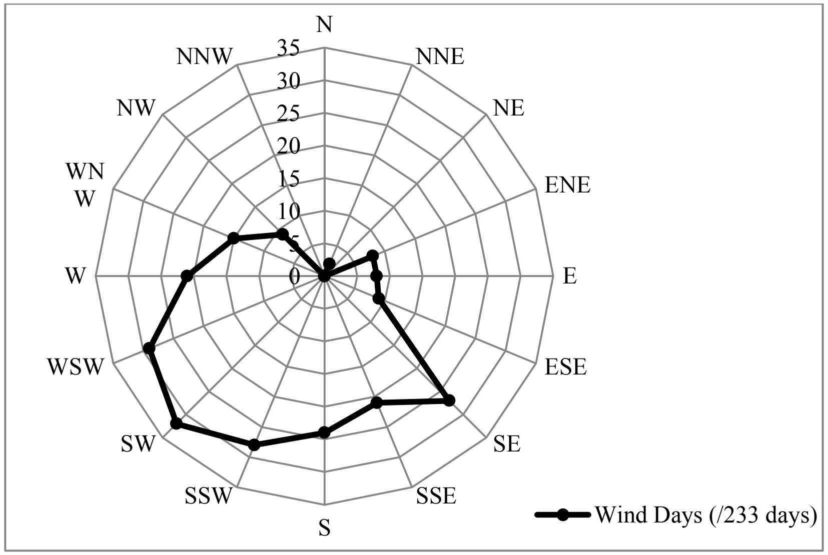


Figure P18 - Wind days - 2017-2018 Treatment period (May-Oct)

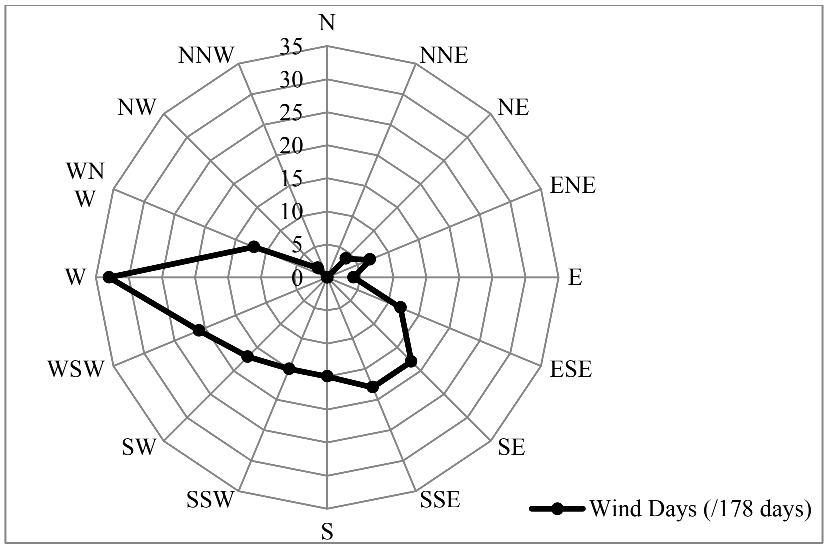


Figure P19 - Wind days - 2019-2018 Treatment period (May-Oct)

Lagoon Cell Fetch Calculations

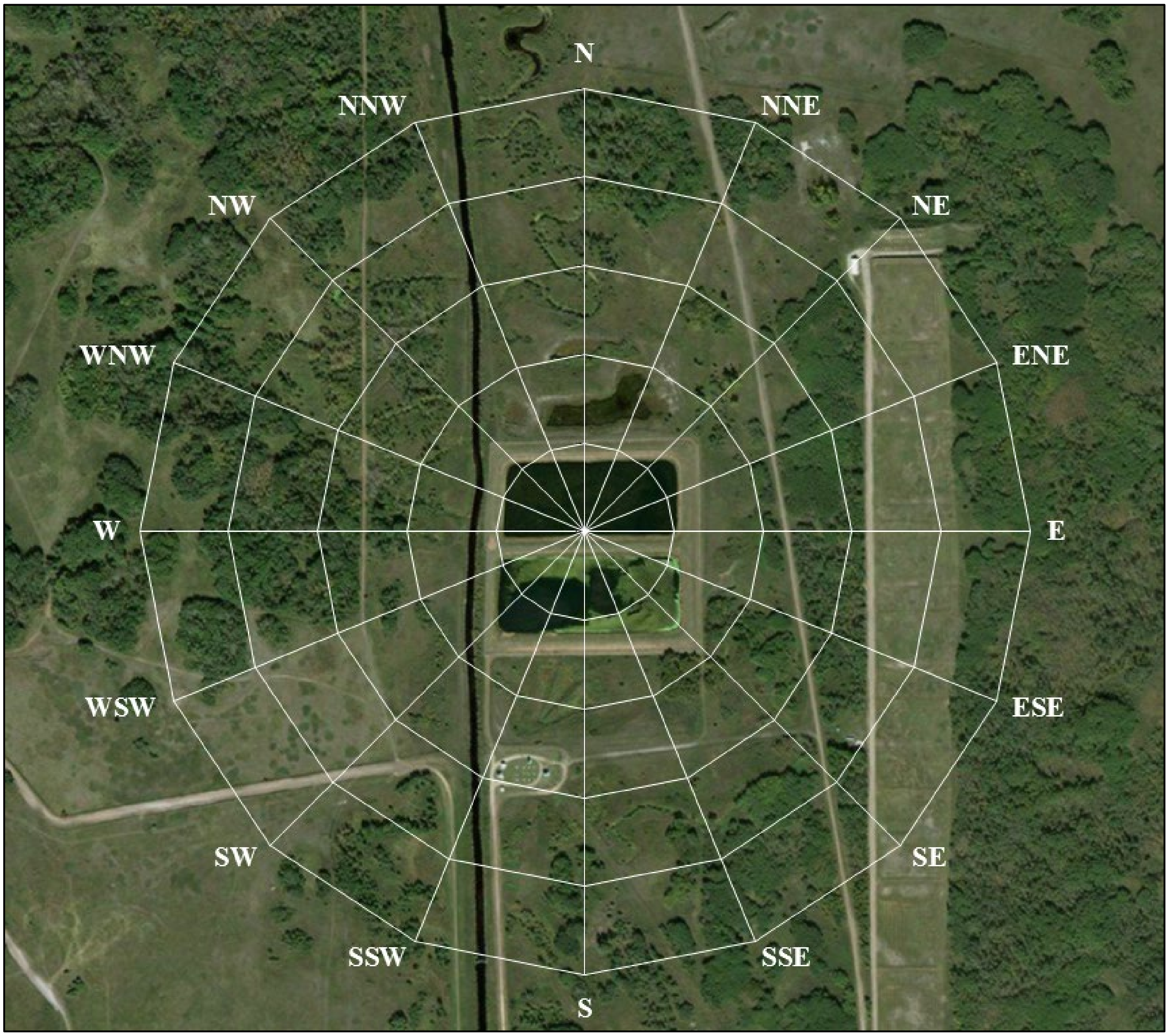


Figure P20 - WWT lagoon cells with wind rose overlay

Figure P21 - Fetch slices at 225º (SW) wind orientation

Figure P22 - Fetch slices at 247.5º (WSW) wind orientation

Figure P23 - Fetch slices at 202.5° (SSW) wind orientation

Figure P24 - Fetch slices at 270° (W) wind orientation

Appendix Q – Influent Data Analysis

The following appendix presents various figures associated with the results of the analysis on wastewater influent at 17 Wing Detachment Dundurn's wastewater treatment lagoon system. Figures include the following:

- Figure Q1 through Figure Q5 plots the influent for the year: 2015, 2016, 2017, 2018, and the first four (4) months of 2019;

- Figure Q6 and Figure Q7 plot the daily influent volumes for the period of 01 Jan 2015 to 12 May 2019;

- Figure Q8 plots the daily BOD loading rates for the period of 01 Jan 2015 to 12 May 2019; and,

- Figure Q9 and Figure Q10 plot the daily pH and temperature reading for the septic tank for the period of 01 Jan 2018 to 12 May 2019.

Influent Volumes

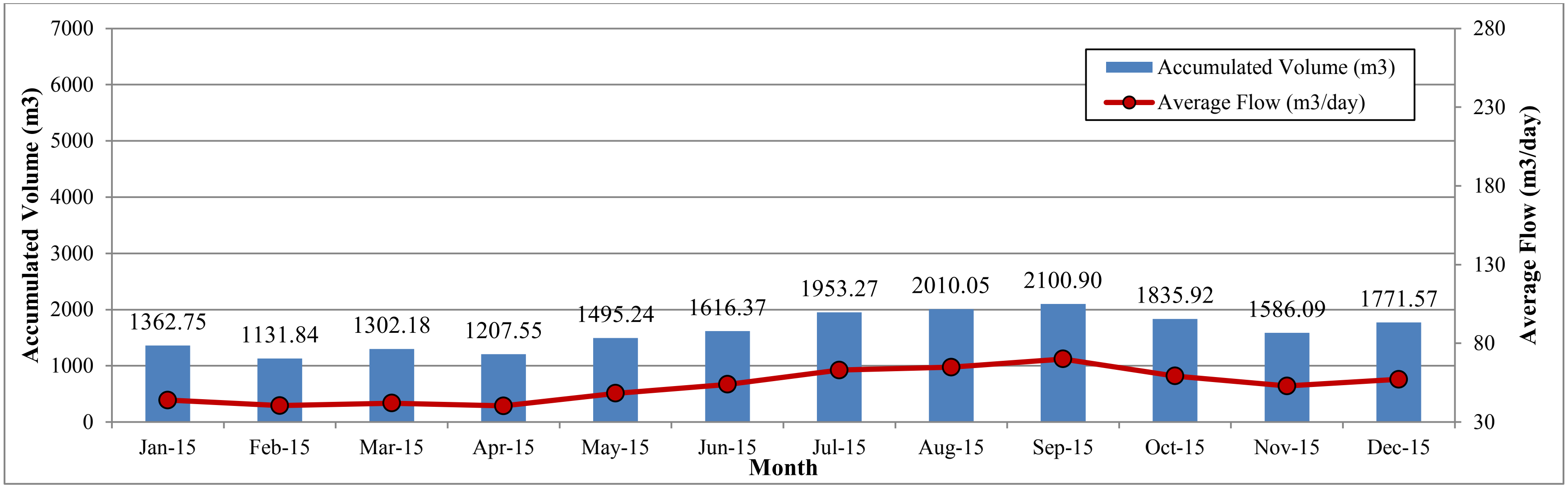


Figure Q1 - Monthly influent volumes and flows for 2015

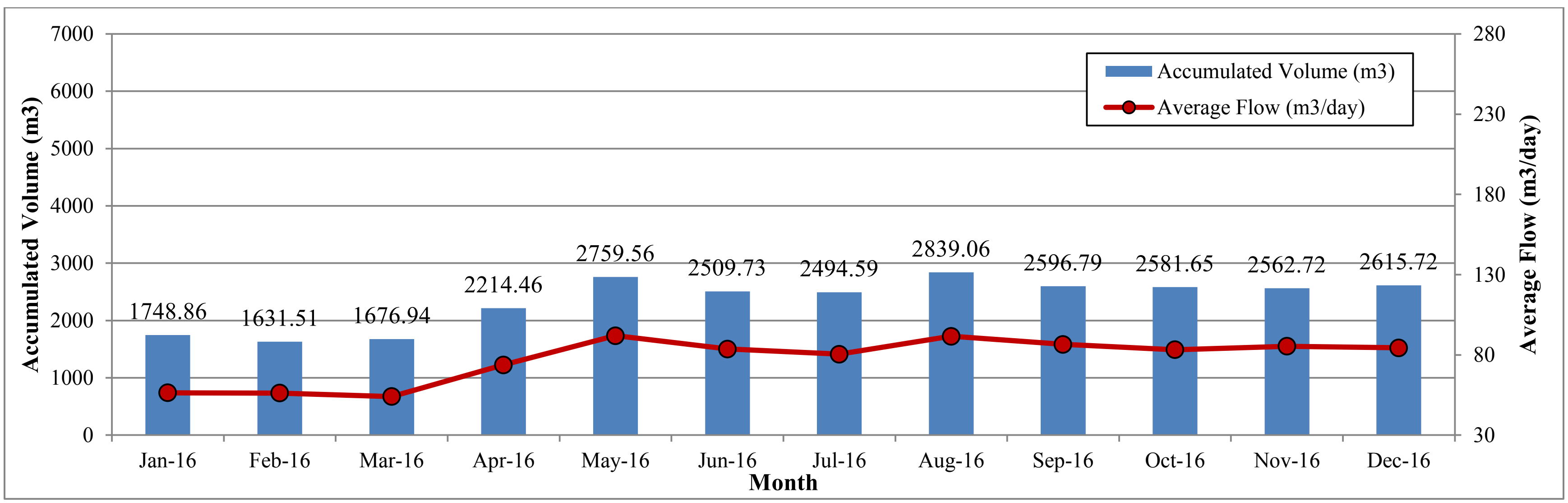


Figure Q2 - Monthly influent volumes and flows for 2016

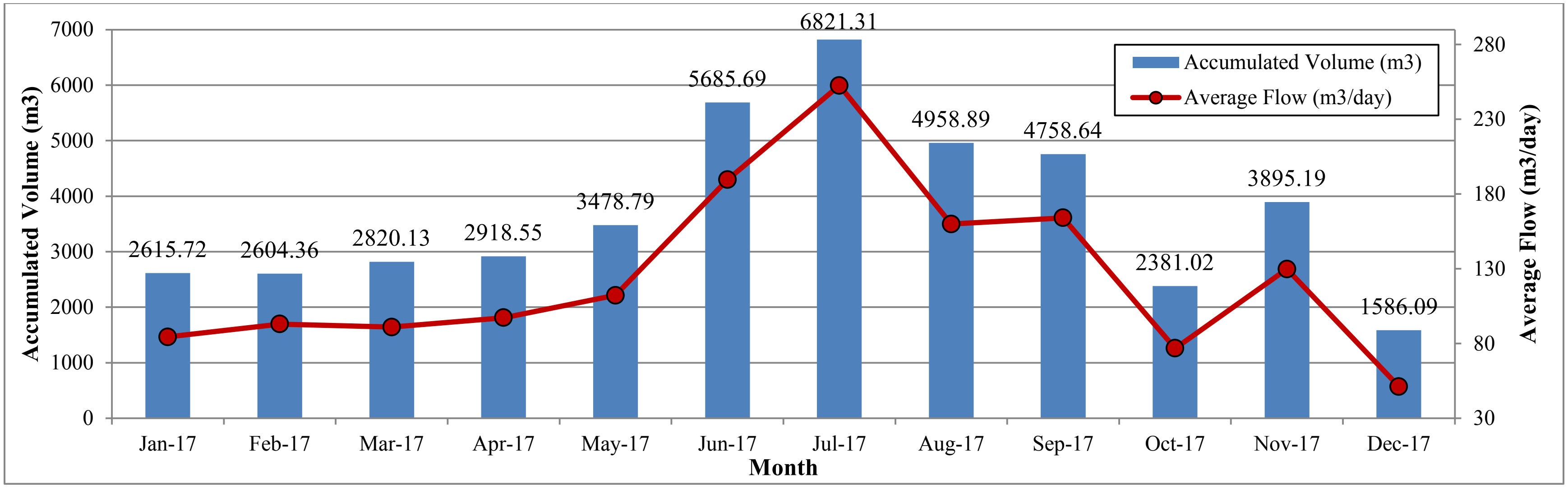


Figure Q3 - Monthly influent volumes and flows for 2017

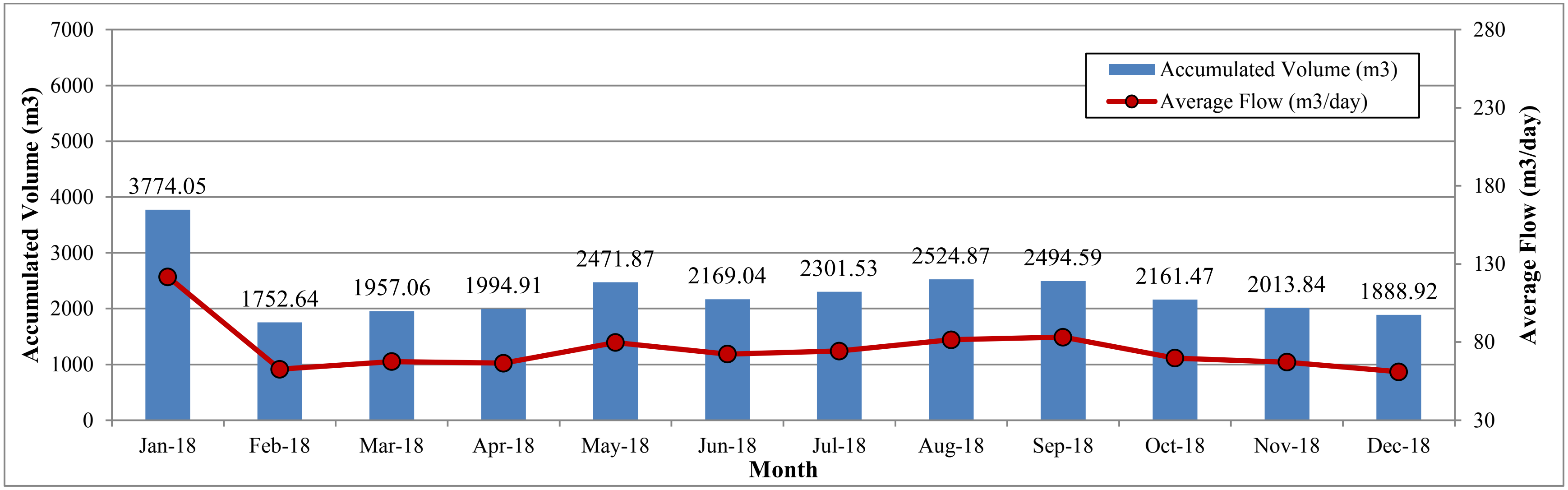


Figure Q4 - Monthly influent volumes and flows for 2018

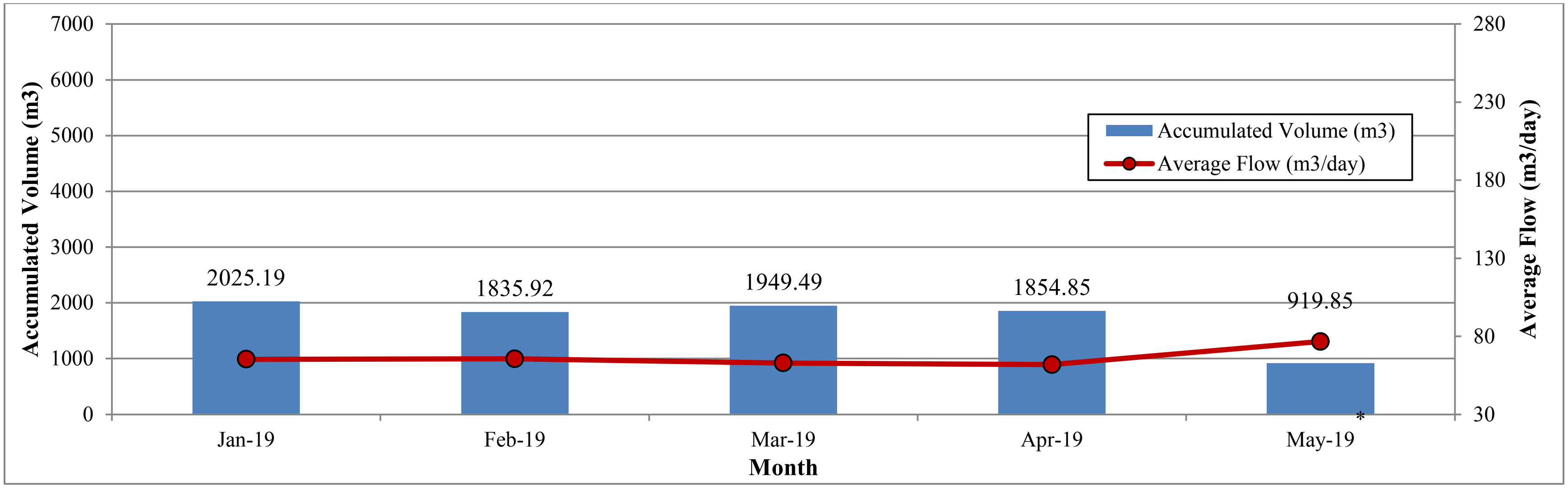


Figure Q5 - Monthly influent volumes and flows for Jan-Apr 2019 (*May data only reflect first 12 days).

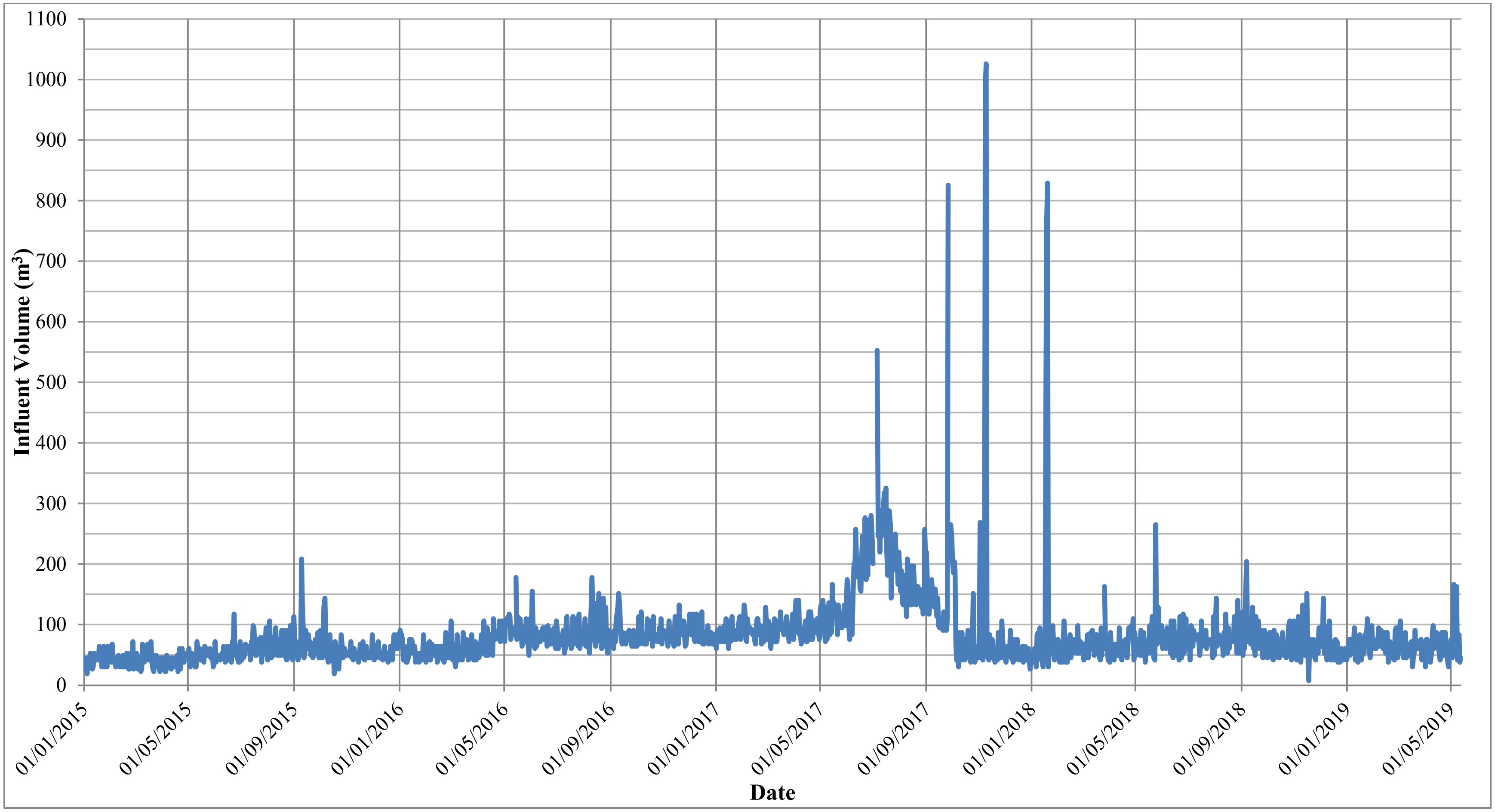


Figure Q6 - Daily influent volume between 01 Jan 2015 and 12 May 2019

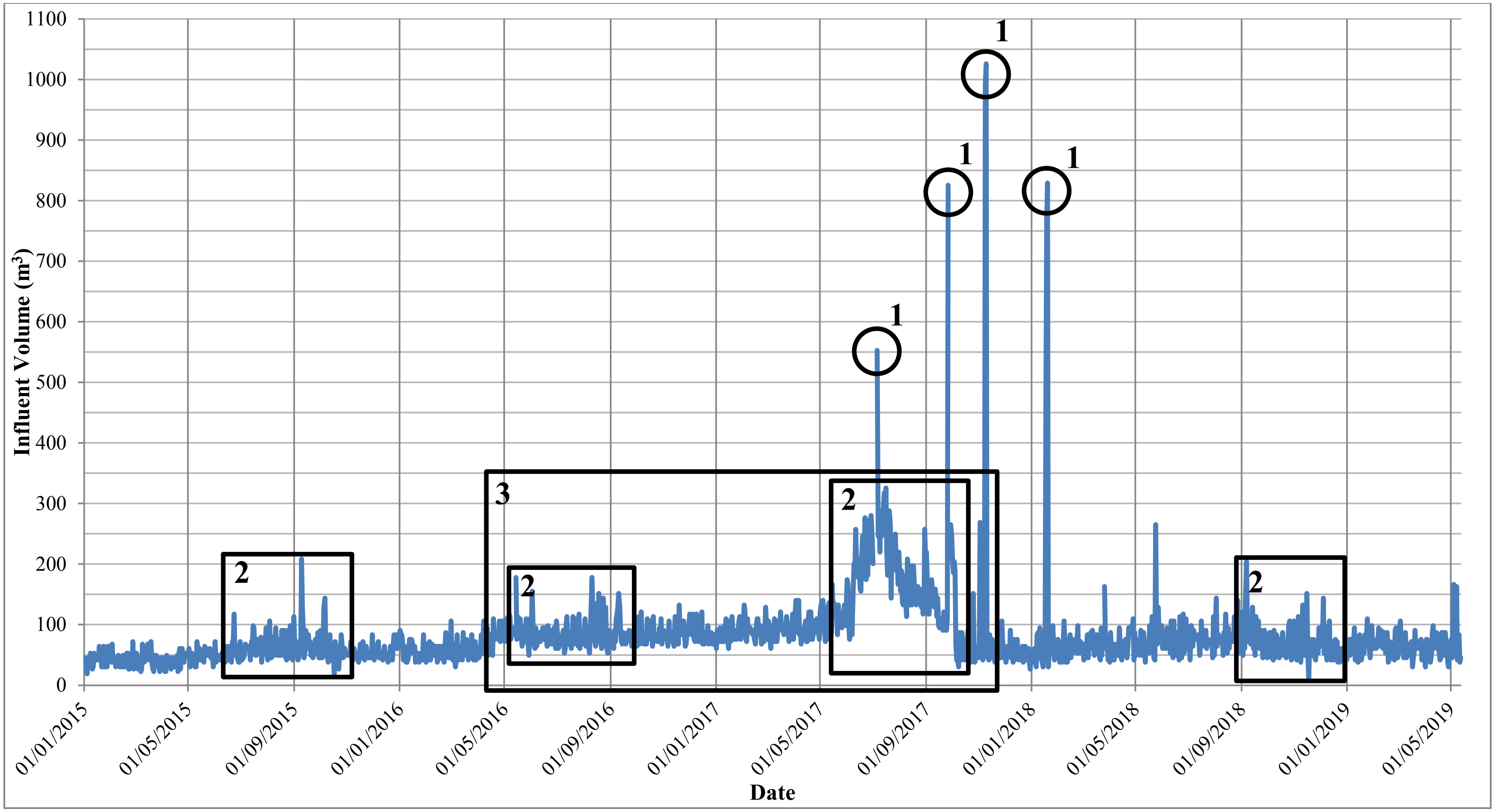


Figure Q7 – Annotated daily influent volume between 01 Jan 2015 and 12 May 2019

BOD Loading

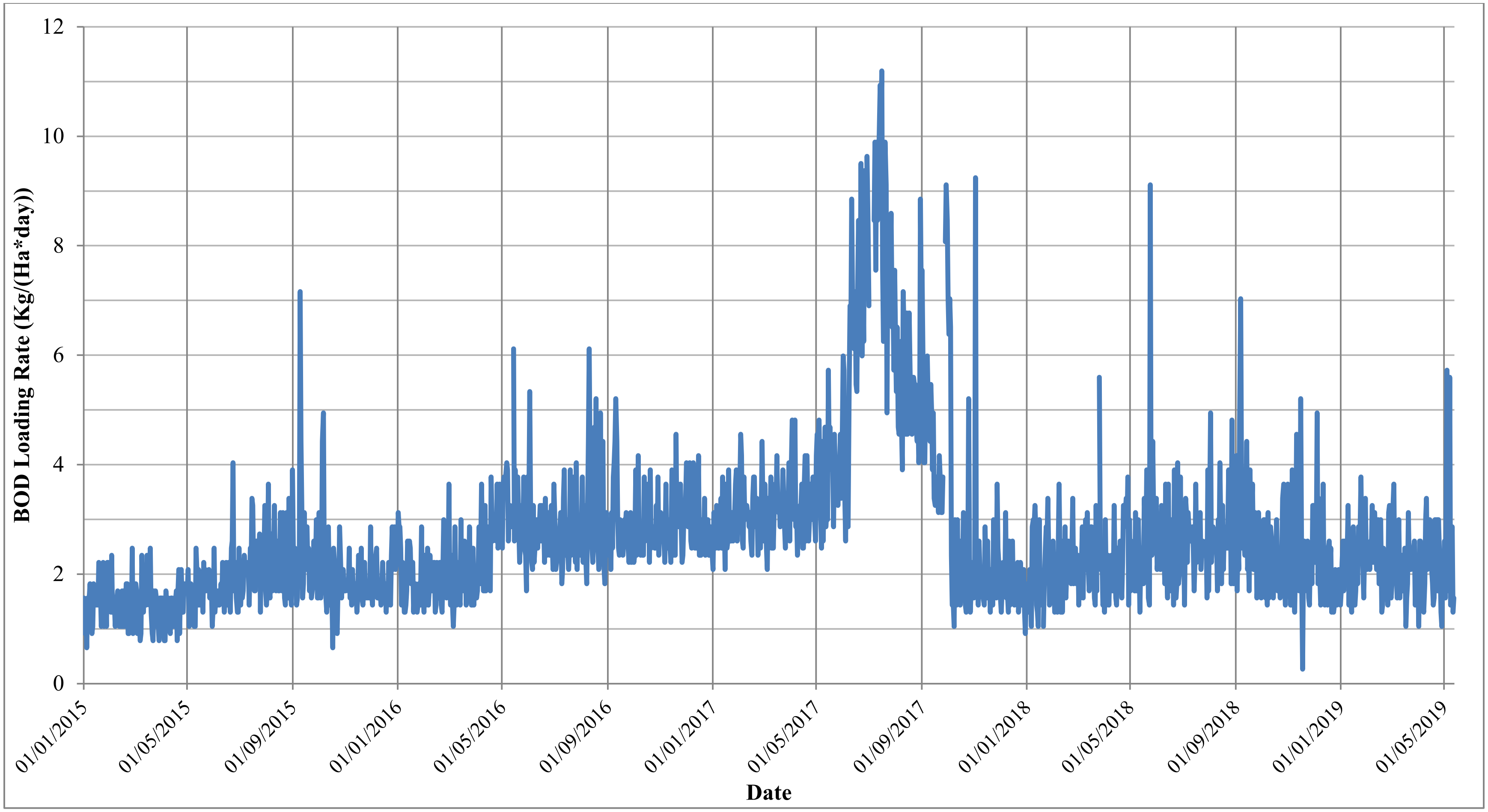


Figure Q8 - Daily BOD loading rate from 01 Jan 2015 to 12 May 2019

pH and Temperature

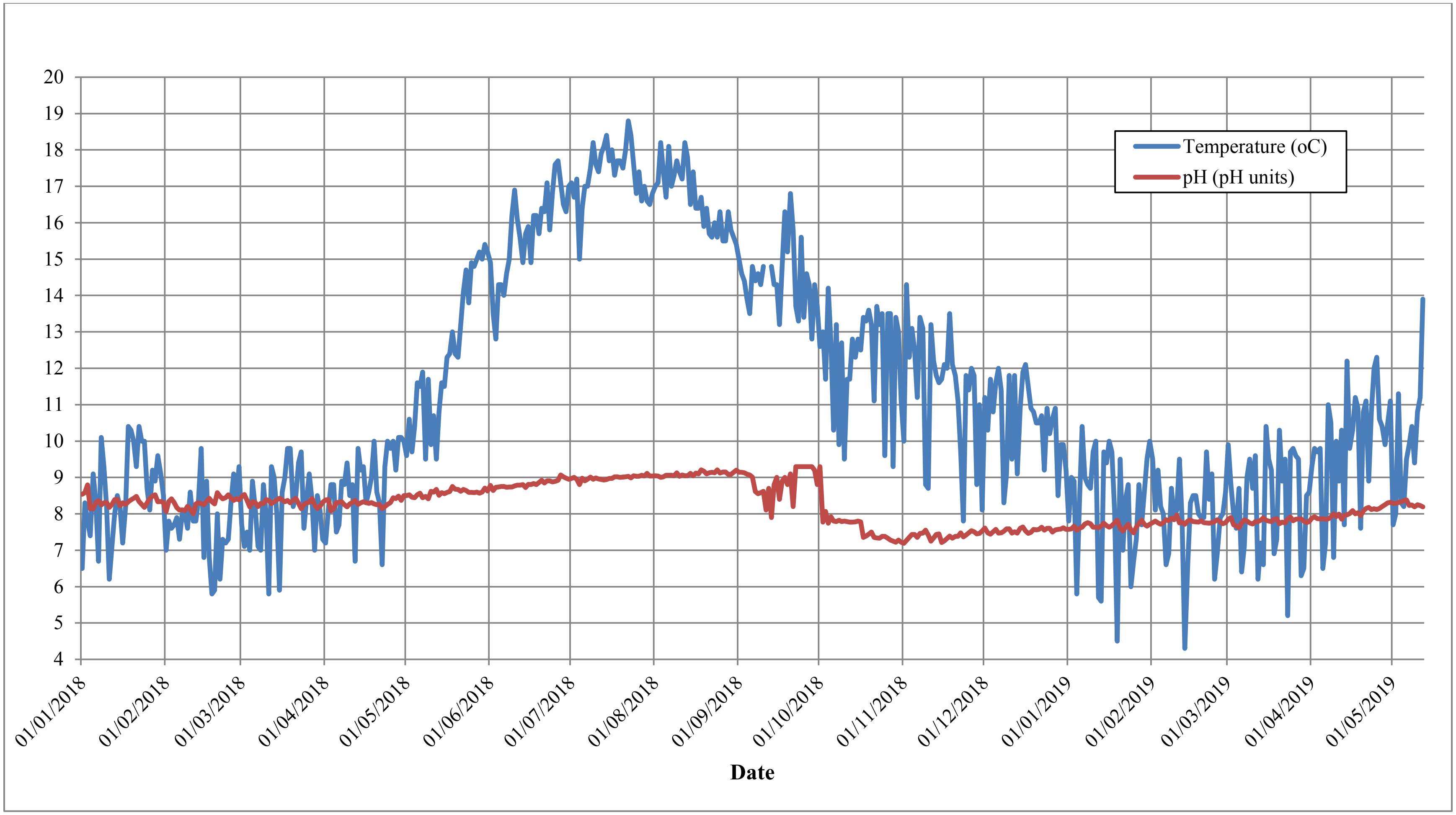


Figure Q9 - Septic tank daily pH and temperature from 01 Jan 2018 to 12 May 2019

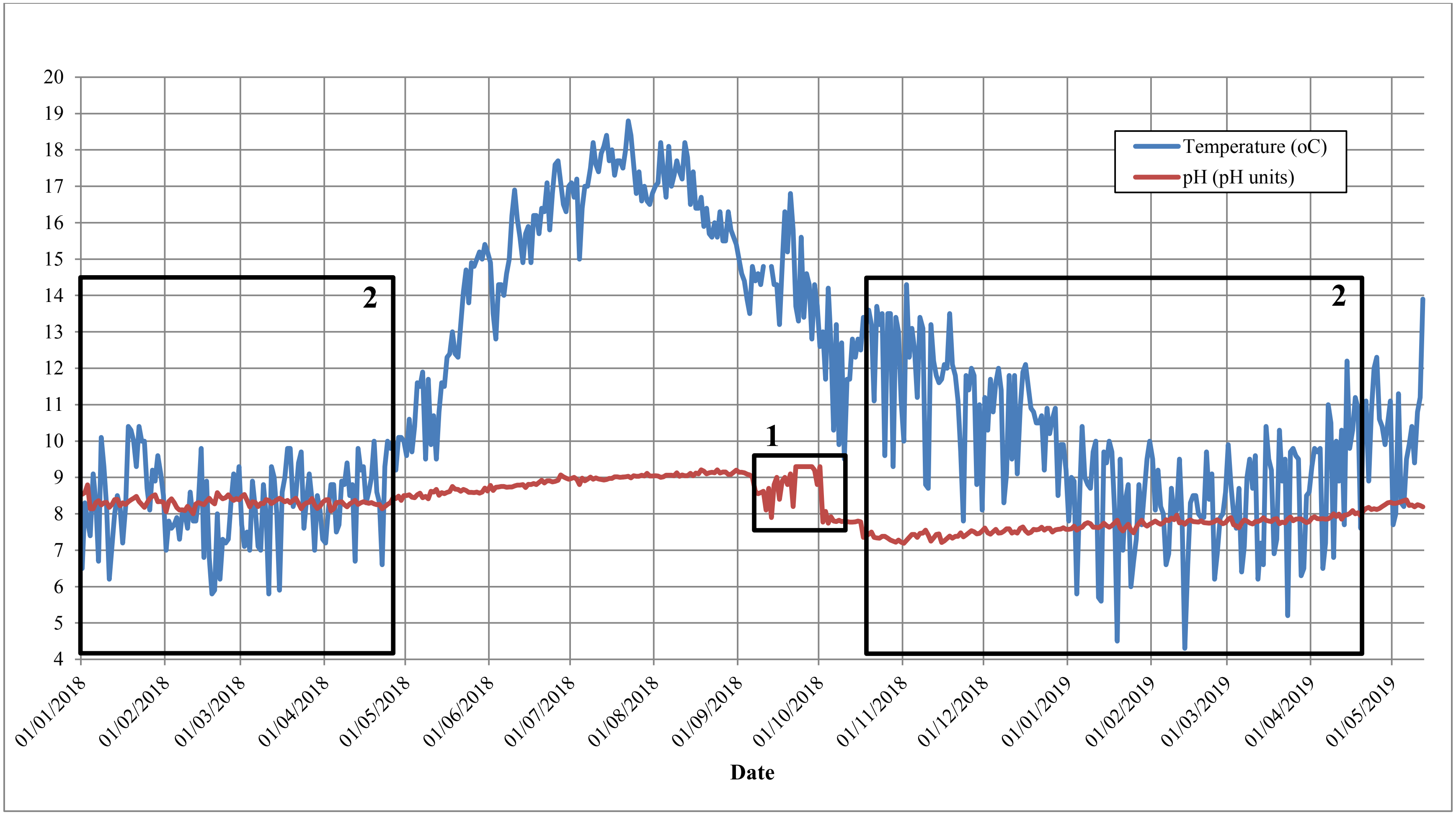


Figure Q10 – Annotated septic tank daily pH and temperature from 01 Jan 2018 to 12 May 2019

Appendix R – Effluent Data Analysis

The following appendix presents various figures associated with the results of the analysis on effluent discharge from 17 Wing Detachment Dundurn's wastewater treatment lagoon system. This appendix includes the following:

- Figure R1, Figure R2, and Table R1 present the details regarding the effluent discharge volumes for 2016 through 2019 discharge periods;

- Figure R3 through Figure R5 plot daily effluent concentrations for regulated parameters for the 2015 to 2019 discharge periods;

- Figure R6 and Figure R7 plot daily effluent concentrations of nitrogen and phosphorus respectively for the 2015 to 2019 discharge periods; and,

- Table R2 provide details on daily effluent concentrations for most parameters of interest in this research project for the 2015 to 2019 discharge periods.

Effluent Volumes

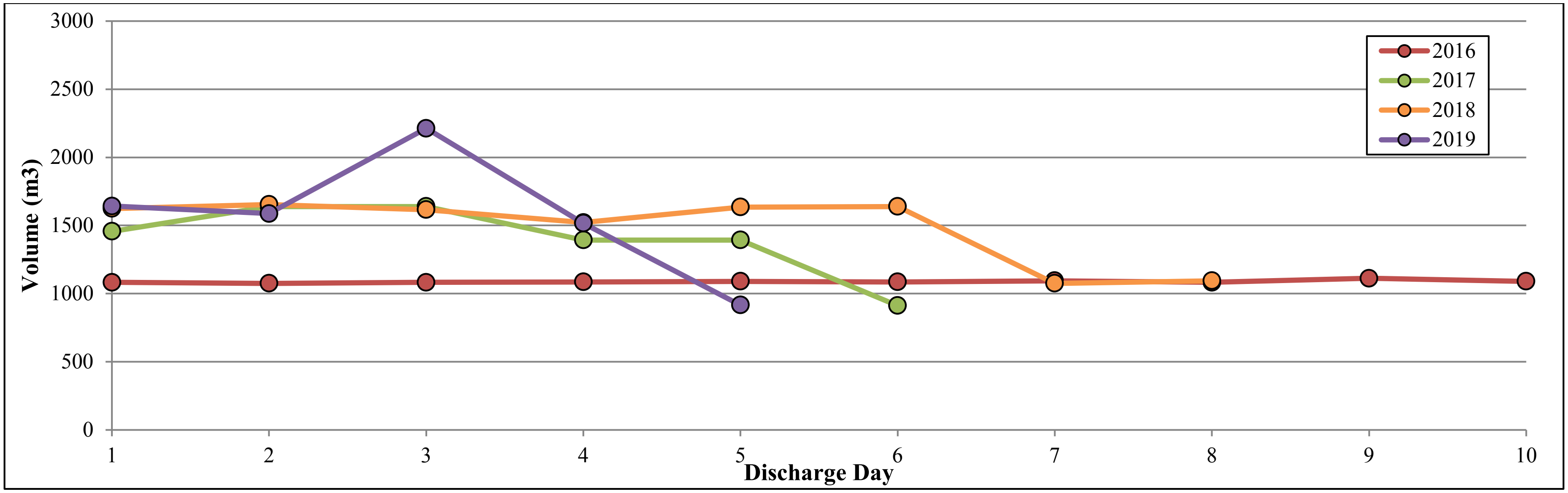


Figure R1 - Daily effluent flow by discharge periods

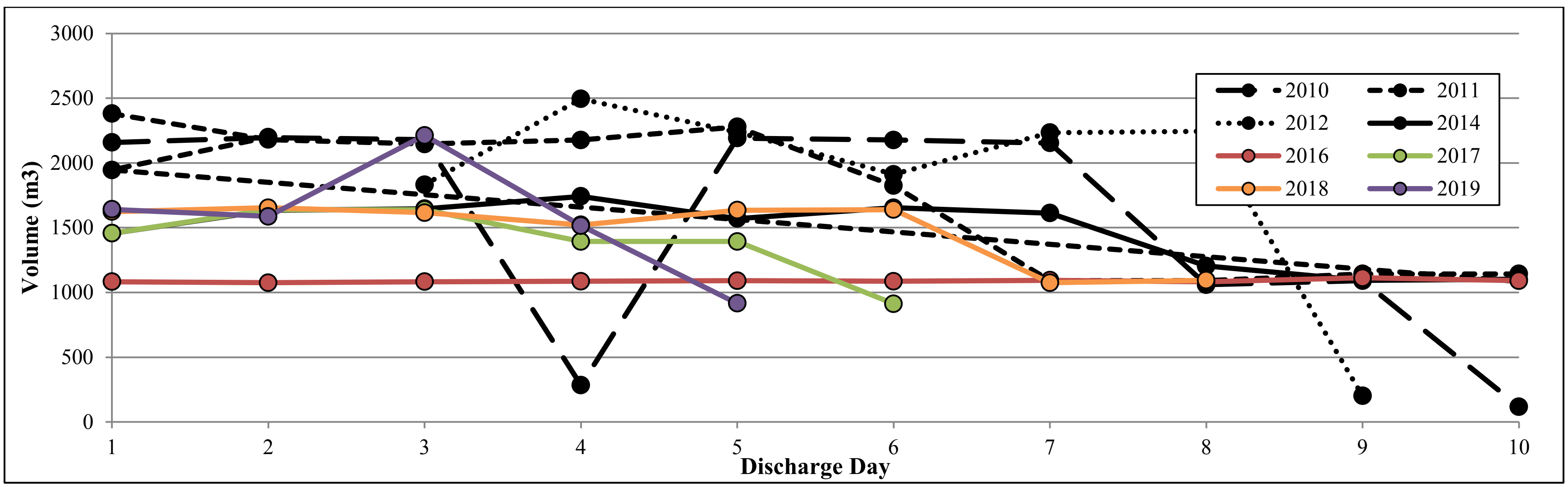


Figure R2 - Daily effluent flow by discharge periods superimposed on 2011 to 2014 discharge

Table R1- Daily discharge flow rates by discharge periods

Discharge Period	Day	Date	Flow (m3/day)
2010	1	19/05/2010	2157.684
	2	20/05/2010	2195.538
	3	21/05/2010	2180.396
	4	25/05/2010	283.9058
	5	26/05/2010	2191.752
	6	27/05/2010	2176.611
	7	28/05/2010	2153.898
	8	31/05/2010	1059.915
	9	01/06/2010	1090.198
	10	02/06/2010	117.3477
2011	1	07/06/2011	2381.023
	2	08/06/2011	2180.396
	3	09/06/2011	2146.327
	4	10/06/2011	2176.611
	5	13/06/2011	2278.817
	6	14/06/2011	1824.568
	7	15/06/2011	1090.198
	8	16/06/2011	1090.198
	9	17/06/2011	1143.194
	10	20/06/2011	1143.194
	11	21/06/2011	987.992
2012	1	19/06/2012	1945.701
	2	20/06/2012	2199.323
	3	21/06/2012	1832.138
	4	22/06/2012	2494.585
	5	25/06/2012	2237.177
	6	26/06/2012	1911.632
	7	27/06/2012	2233.392
	8	28/06/2012	2244.748
	9	29/06/2012	200.6267
2013	12	Missing Data	
2014	1	08/10/2014	1457.383
	2	09/10/2014	1635.297
	3	10/10/2014	1646.653
	4	14/10/2014	1741.289
	5	15/10/2014	1570.945
	6	16/10/2014	1654.224
	7	17/10/2014	1612.585
2014	8	20/10/2014	1203.76
	9	21/10/2014	1093.983
	10	22/10/2014	1101.554
2015	8	Missing Data	
2016	1	17/05/2016	1082.63
	2	18/05/2016	1075.06
	3	19/05/2016	1082.63
	4	20/05/2016	1086.41
	5	24/05/2016	1090.20
	6	25/05/2016	1086.41
	7	26/05/2016	1093.98
	8	27/05/2016	1082.63
	9	28/05/2016	1112.91
	10	29/05/2016	1090.20
2017	1	16/05/2017	1457.38
	2	17/05/2017	1639.08
	3	18/05/2017	1639.08
	4	19/05/2017	1393.03
	5	23/05/2017	1393.03
	6	24/05/2017	912.28
2018	1	06/06/2018	1623.94
	2	07/06/2018	1654.22
	3	08/06/2018	1616.37
	4	11/06/2018	1521.73
	5	12/06/2018	1635.30
	6	13/06/2018	1639.08
	7	14/06/2018	1075.06
	8	15/06/2018	1093.98
2019	1	14/05/2019	1642.11
	2	15/05/2019	3229.71
	3	16/05/2019	5441.91
	4	17/05/2019	6957.96
	5	21/05/2019	7874.03

Regulated Parameters

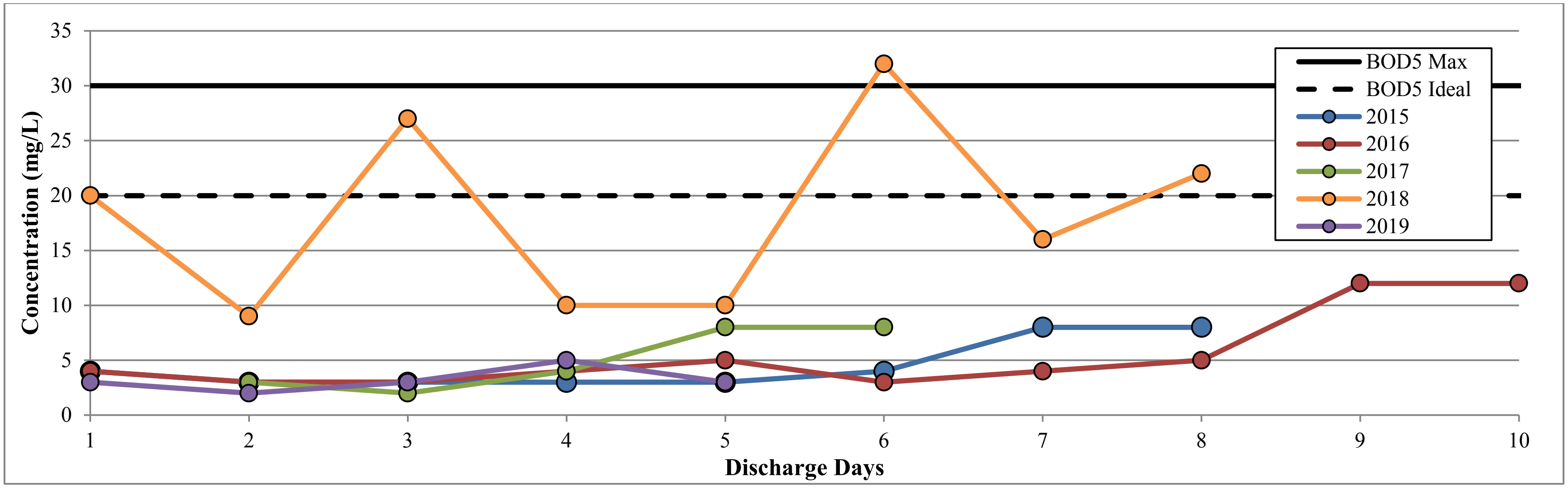


Figure R3 - Effluent BOD_5 concentrations by discharge days

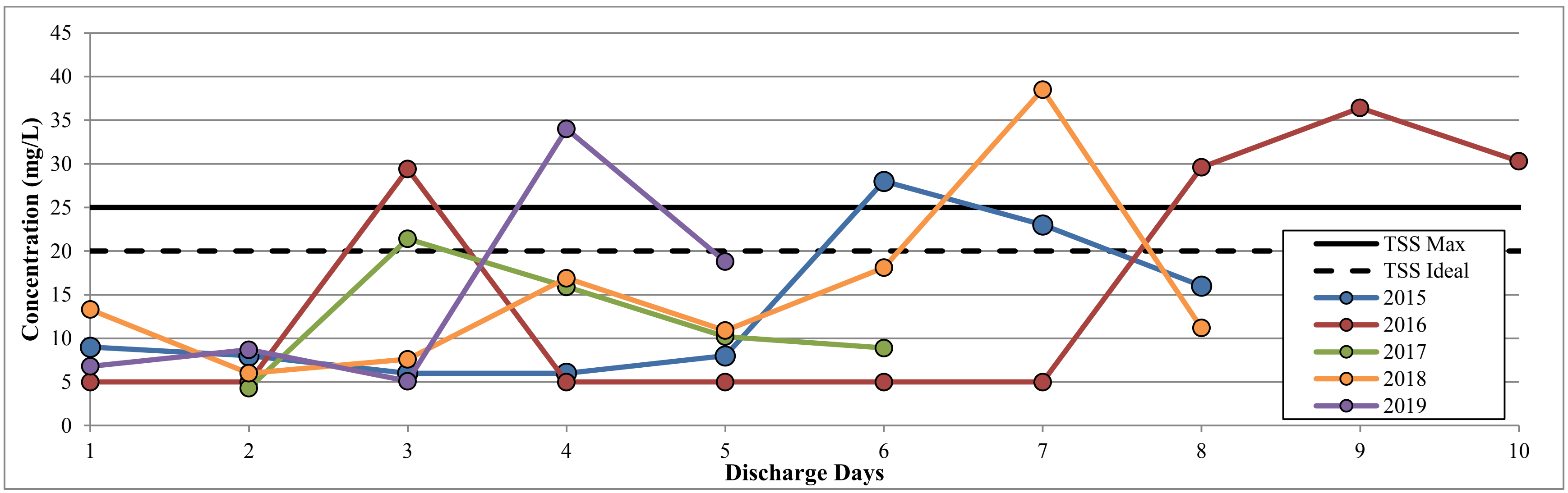


Figure R4 - Effluent TSS concentration by discharge days

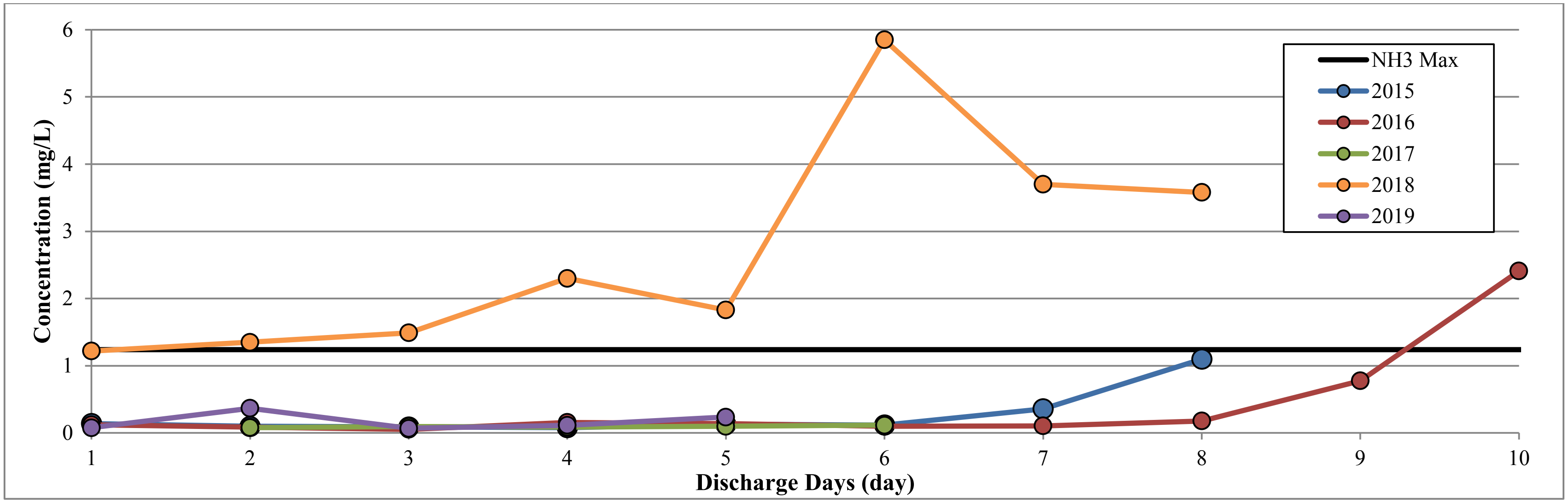


Figure R5 - Effluent un-ionized ammonia (NH_3) concentration by discharge days

Additional Parameters of Interest

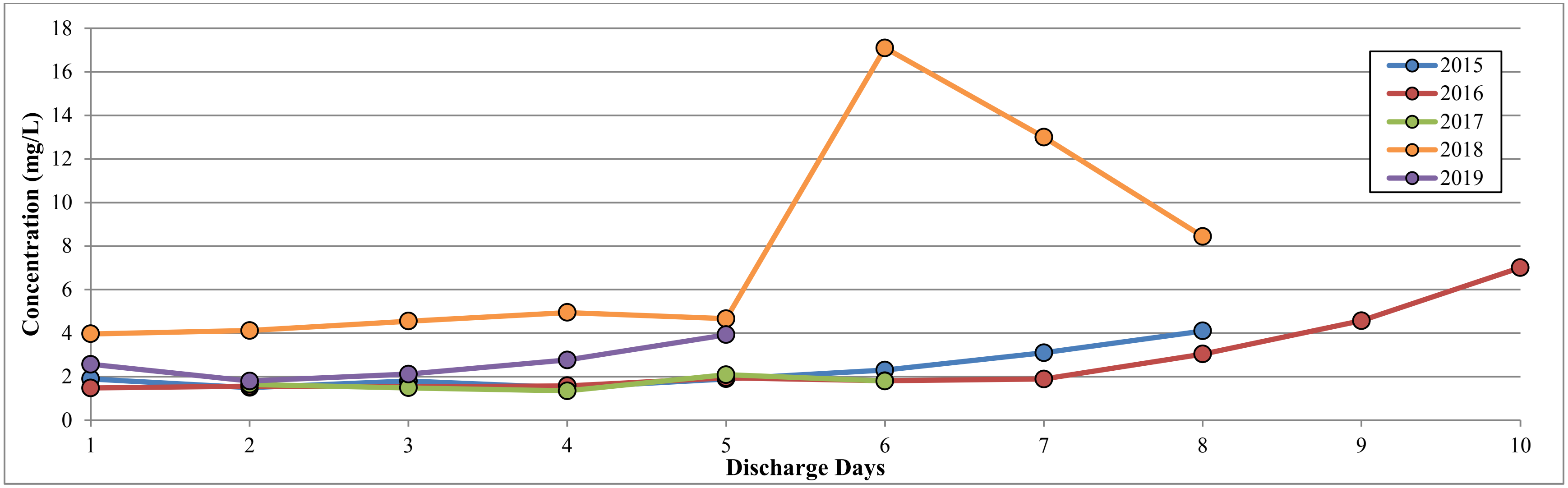


Figure R6 - Effluent nitrogen (N) concentration by discharge days

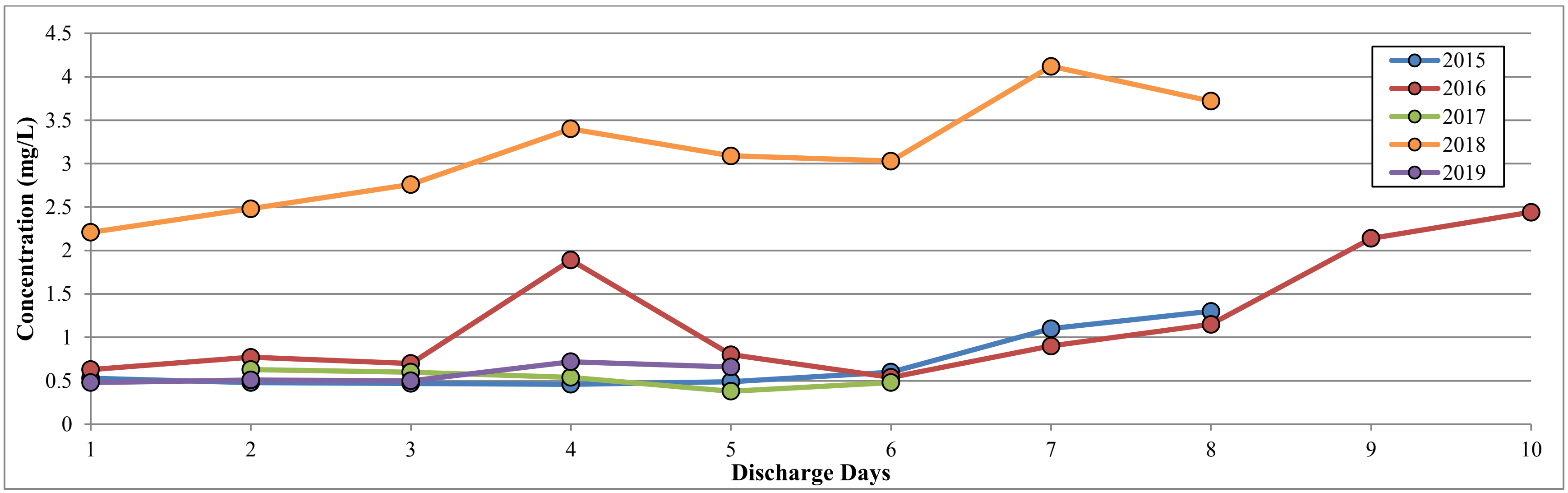


Figure R7 - Effluent phosphorus (P) concentration by discharge days

Table R2 - Daily effluent quality by treatment period

Date	CBOD5 (mg/L)	BOD5 (mg/L)	Thermotolerant Coli. (MPN/100mL)	TDS (mg/L)	TSS (mg/L)	Total Coli. (MPN/100mL)	E. Coli. (MPN/100mL)	pH (pH Units)	Conductivity (µS/cm)	Ammonia NH3 (mg/L)	Nitrogen (N) (mg/L)	Phosphorus (P) (mg/L)
19/05/2015	-	4	<1	3090	9	32	<1	9.16	5230	0.14	1.9	0.53
20/05/2015	-	3	2	3070	8	9	<1	9.09	5230	0.10	1.5	0.48
21/05/2015	-	3	2	3050	6	38	<1	9.06	5160	0.09	1.8	0.47
22/05/2015	-	3	1	3030	6	360	<1	9.08	5240	0.08	1.5	0.46
25/05/2015	-	3	<1	3150	8	730	<1	8.95	5390	0.13	1.9	0.49
26/05/2015	-	4	6	3240	28	2300	<1	8.90	5460	0.12	2.3	0.60
27/05/2015	-	8	11	3440	23	9600	2	8.28	5770	0.36	3.1	1.10
28/05/2015	-	8	22	3410	16	110000	8	7.93	5990	1.10	4.1	1.30
14-15 Average	-	5	6	3185	13	15383	1	8.81	5434	0.27	2.3	0.68
14-15 SD (σ)	-	2	8	162	8	38368	3	0.45	298	0.35	0.9	0.33
17/05/2016	-	4	<1	2490	<5	145	<1	9.31	5020	0.124	1.48	0.63
18/05/2016	-	3	1	2900	<5	118	<1	9.29	5120	0.087	1.56	0.77
19/05/2016	-	3	16	2880	29.4	>200.5	<1	9.29	5110	0.055	1.54	0.70
20/05/2016	-	4	2	2930	<5	>200.5	10	9.25	5150	0.157	1.58	1.89
24/05/2016	-	5	1410	2650	<5	>200.5	2	9.14	5200	0.141	1.95	0.80
25/05/2016	-	3	16	2960	<5	>200.5	5	9.11	5220	0.100	1.81	0.54
26/05/2016	-	4	140	2710	<5	>200.5	11	9.09	5330	0.106	1.89	0.90
27/05/2016	-	5	>2420	2980	29.6	>200.5	36	8.75	5330	0.180	3.04	1.15
30/05/2016	-	12	>2420	3310	36.4	>200.5	>200.5	8.42	5740	0.776	4.57	2.14
31/05/2016	-	12	>2420	3460	30.3	>2420	980	8.30	6040	2.410	7.01	2.44
15-16 Average	-	6	885	2927	15.6	409	124	8.995	5326	0.414	2.64	1.20
15-16 SD (σ)	-	4	1143	289	13.8	707	307	0.37346	320	0.732	1.81	0.69
16/05/2017	-	M	M	M	M	M	M	M	M	M	M	M
17/05/2017	-	3	62	2270	4.3	190	67	9.02	4340	0.081	1.65	0.63
18/05/2017	-	2	16	2460	21.4	48	12	8.96	4340	0.097	1.49	0.60
19/05/2017	-	4	7	2460	15.9	29	2	9.03	4350	0.086	1.35	0.54
23/05/2017	-	8	214	2360	10.2	345	31	9.38	4640	0.099	2.09	0.38
24/05/2017	-	8	51	2690	8.9	231	50	9.12	4890	0.117	1.80	0.48

Date	CBOD5 (mg/L)	BOD5 (mg/L)	Thermotolerant Coli. (MPN/100mL)	TDS (mg/L)	TSS (mg/L)	Total Coli. (MPN/100mL)	E. Coli. (MPN/100mL)	pH (pH Units)	Conductivity (µS/cm)	Ammonia NH3 (mg/L)	Nitrogen (N) (mg/L)	Phosphorus (P) (mg/L)
16-17 Average	-	5	70	2448	12.1	169	32	9.10	4512	0.096	1.68	0.53
16-17 SD (σ)	-	3	84	157	6.6	132	27	0.17	247	0.014	0.29	0.10
06/06/2018	-	20	365	2730	13.3	>2420	0	8.19	4890	1.22	3.97	2.21
07/06/2018	-	9	770	2790	6	>2420	5	8.17	4910	1.35	4.12	2.48
08/06/2018	-	27	>2420	2900	7.6	>2420	21	8.31	5030	1.49	4.55	2.76
11/06/2018	-	10	>2420	0	16.9	>2420	3	8.05	5040	2.30	4.95	3.4
12/06/2018	-	10	687	0	10.9	>2420	4	8.39	5140	1.83	4.66	3.09
13/06/2018	-	32	>2420	0	18.1	>2420	3	8.23	5190	5.85	17.10	3.03
14/06/2018	-	16	>2420	0	38.5	>2420	20	8.26	5430	3.70	13.00	4.12
15/06/2018	-	22	>2420	0	11.2	>2420	121	8.11	5590	3.58	8.44	3.72
2017-2018 Average	-	18	1740	1052	15.3	>2420	22	8.21	5152	2.67	7.60	3.10
2017-2018 SD (σ)	-	9	945	1453	10.2		41	0.11	247	1.61	4.93	0.63
14/05/2019	-	3	4	2370	6.8	18	1	9.62	4520	0.079	2.57	0.48
15/05/2019	-	2	3	2300	8.7	29	5	9.44	4580	0.368	1.8	0.51
16/05/2019	-	3	2	2710	5.1	10	0	9.45	4620	0.069	2.12	0.5
17/05/2019	-	5	1	2490	34	25	0	9.33	4710	0.114	2.77	0.72
21/05/2019	-	3	4	3020	18.8	>200.5	3	8.79	5510	0.238	3.93	0.66
2018-2019 Average	-	3.2	2.8	2578.0	14.7	56.5	1.8	9.3	4788.0	0.2	2.6	0.6
2018-2019 SD (σ)	-	1.1	1.3	292.0	12.0	80.8	2.2	0.3	409.5	0.1	0.8	0.1

Appendix S – System Wide Analysis

The following appendix presents various figures associated with the results of the analysis on system-wide parameters obtained from grab samples of all major components of 17 Wing Detachment Dundurn's wastewater treatment lagoon system. This appendix includes the plots and table listed below. The data was obtained from the sampling programme that was undertaken in the 2018-2019 treatment period (Aug 2018, Oct 2018, and Apr 2019) and data collected from the operators during the 2019 discharge programme.

- Figure S1 plots the conductivity of all major components;
- Figure S2 plots the pH of all major components;
- Figure S3 plots the dissolved oxygen concentration in all major components;
- Figure S4 plots the total suspended solids concentration in all major components;
- Figure S5 plots the total dissolved solids concentration in all major components;
- Figure S6 plots the Escherichia coli concentration in all major components;
- Figure S7 plots the total coliform concentration in all major components;
- Figure S8 plots the 5-day biochemical oxygen demand concentration in all major components; and,
- Figure S9 plots the 5-day carbonaceous biochemical oxygen demand concentration in all major components.

System Wide Parameters

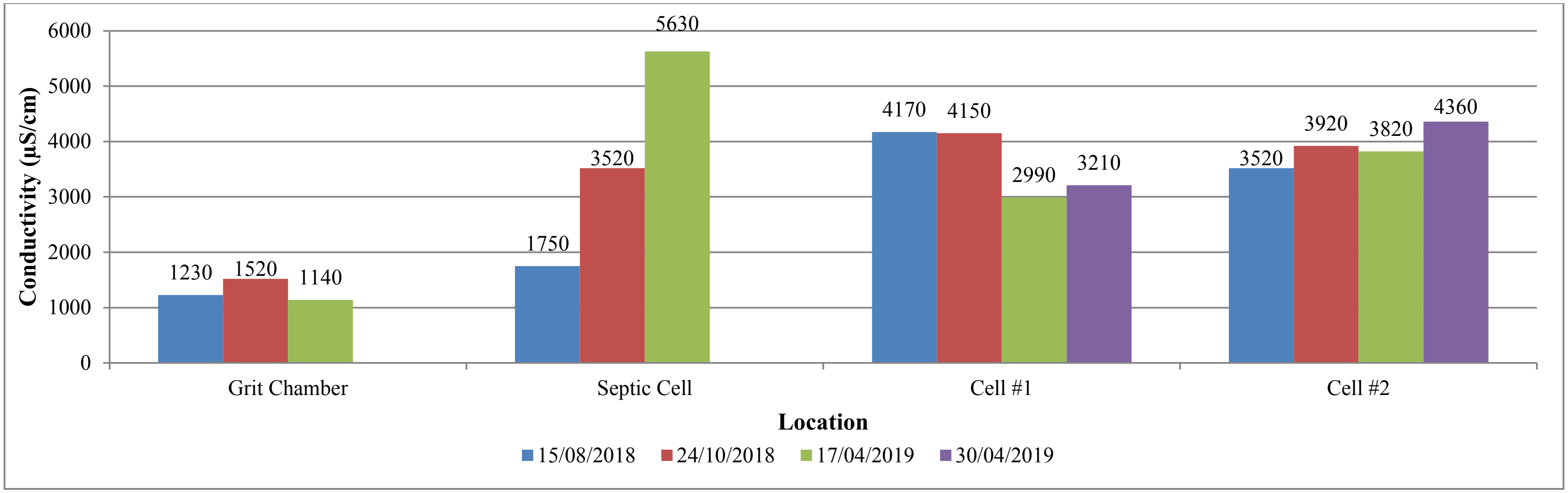


Figure S1 - Conductivity in all major components

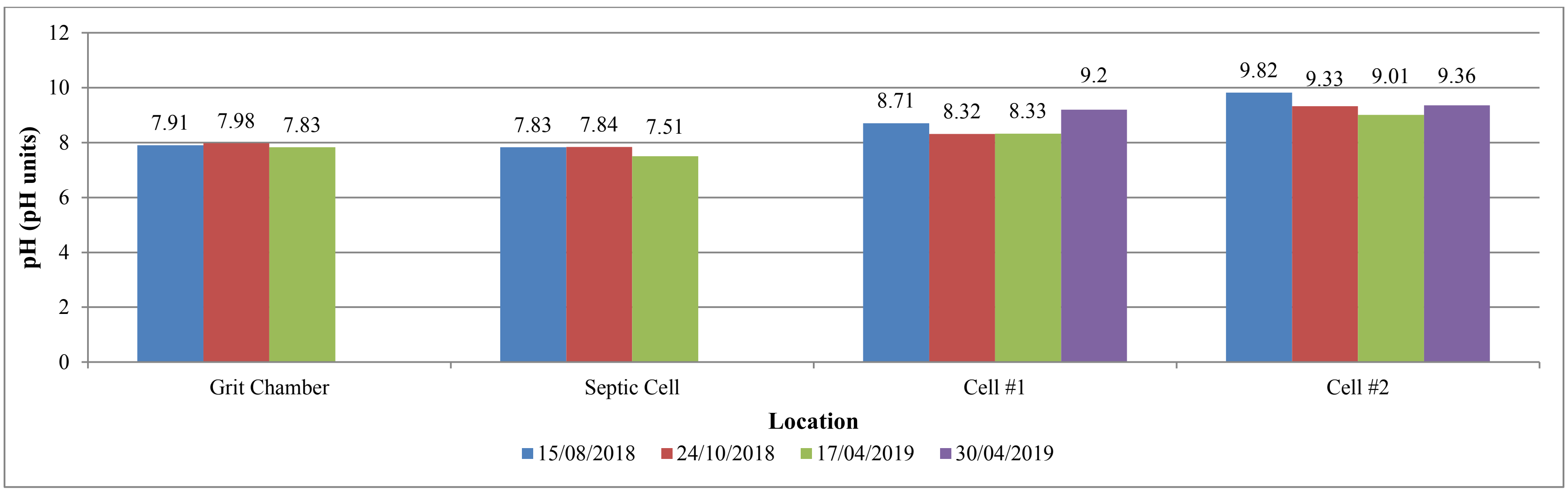


Figure S2 - pH values in all major components

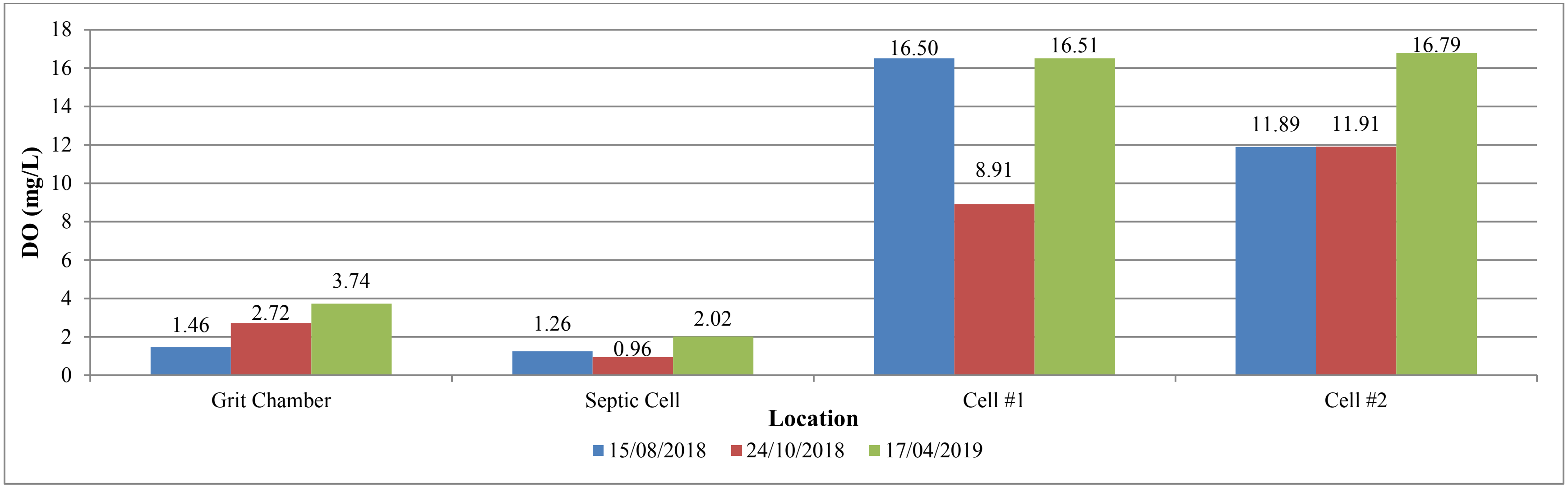


Figure S3 - Dissolved oxygen concentrations in all major components

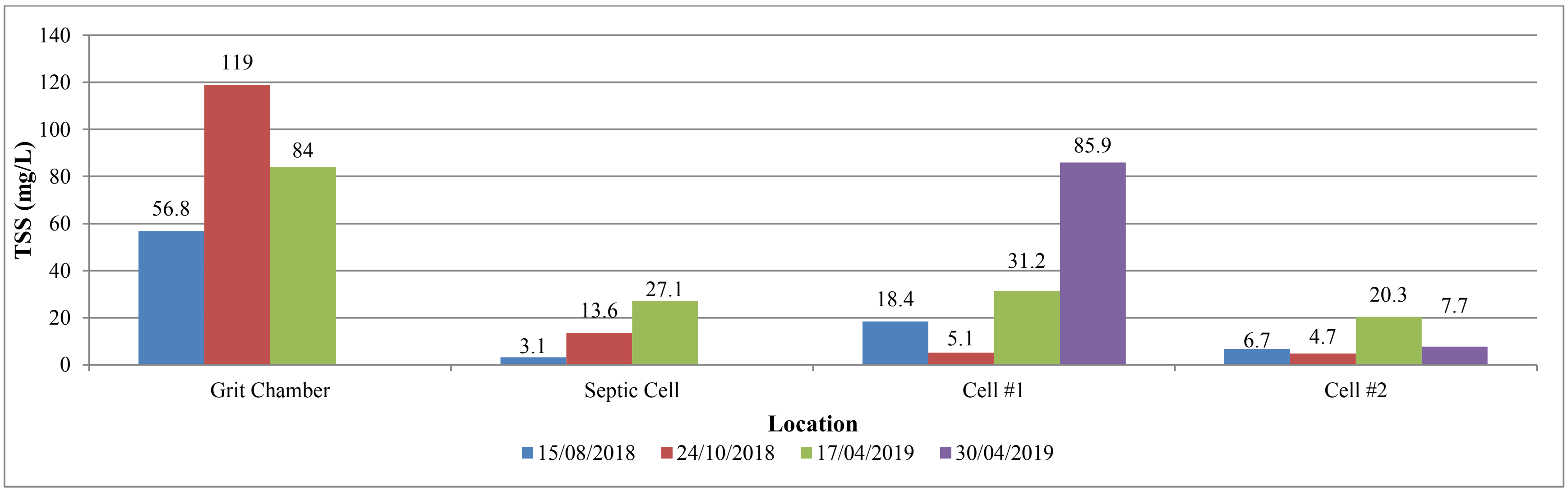


Figure S4 - Total suspended solids concentrations in all major components

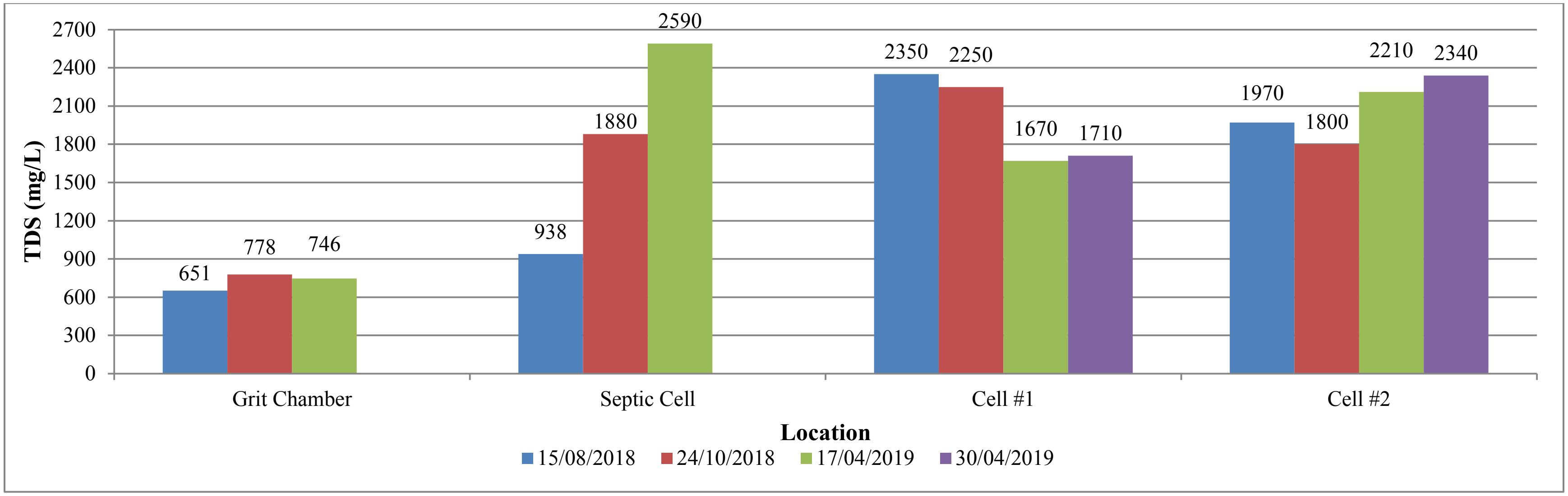


Figure S5 - Total dissolved solids concentrations in all major components

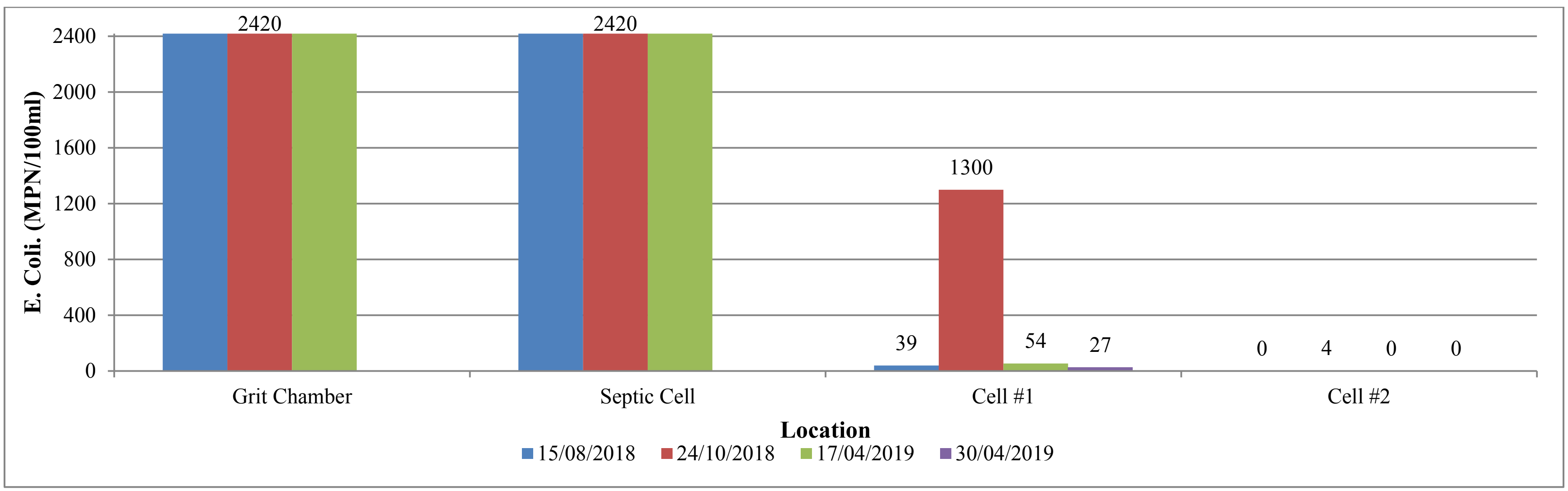


Figure S6 - Escherichia coli concentrations in all major components (Upper detection limit = 2420/100mL)

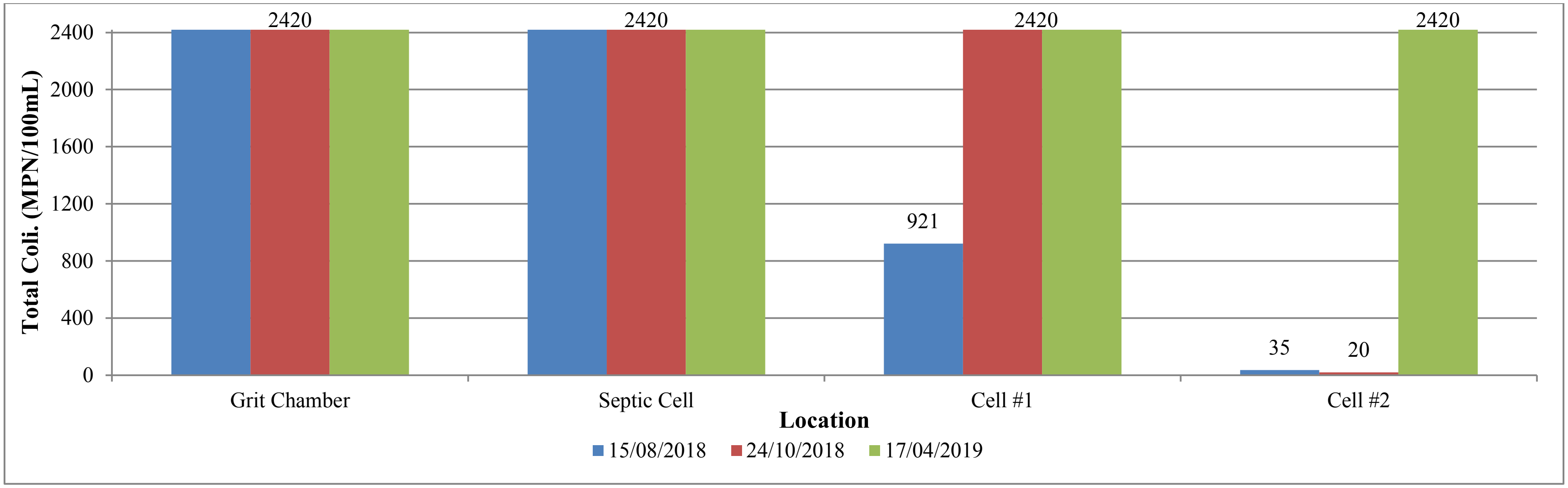


Figure S7 - Total coliform concentrations in all major components (Upper detection limit = 2420/100mL)

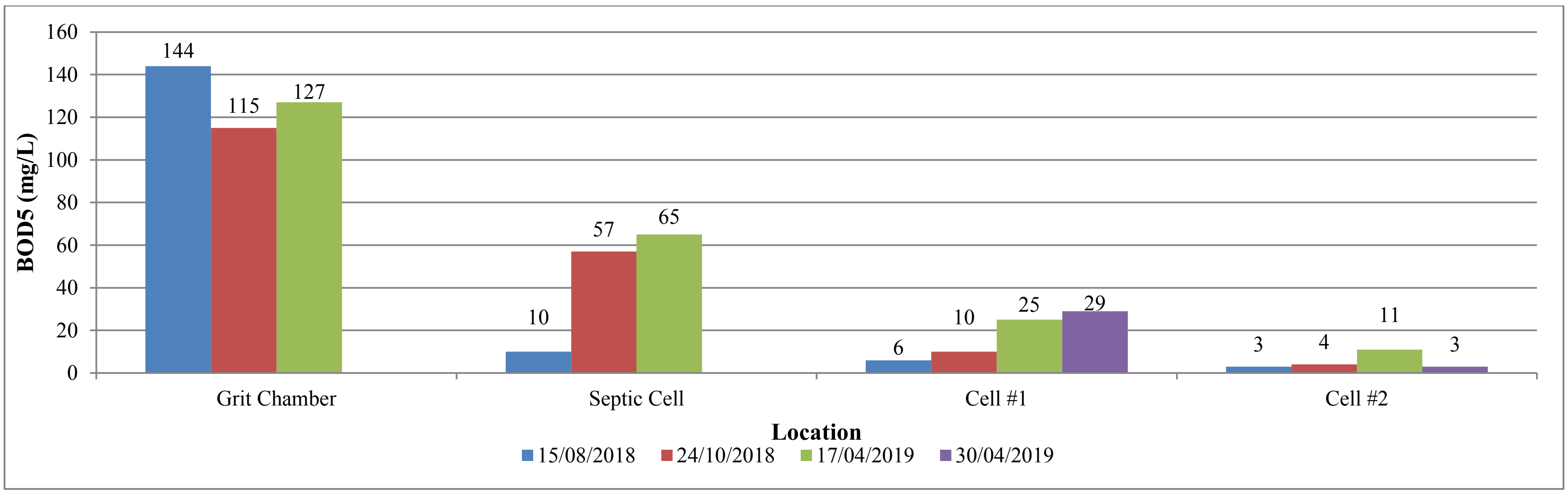


Figure S8 - 5-day biochemical oxygen demand concentrations in all major components

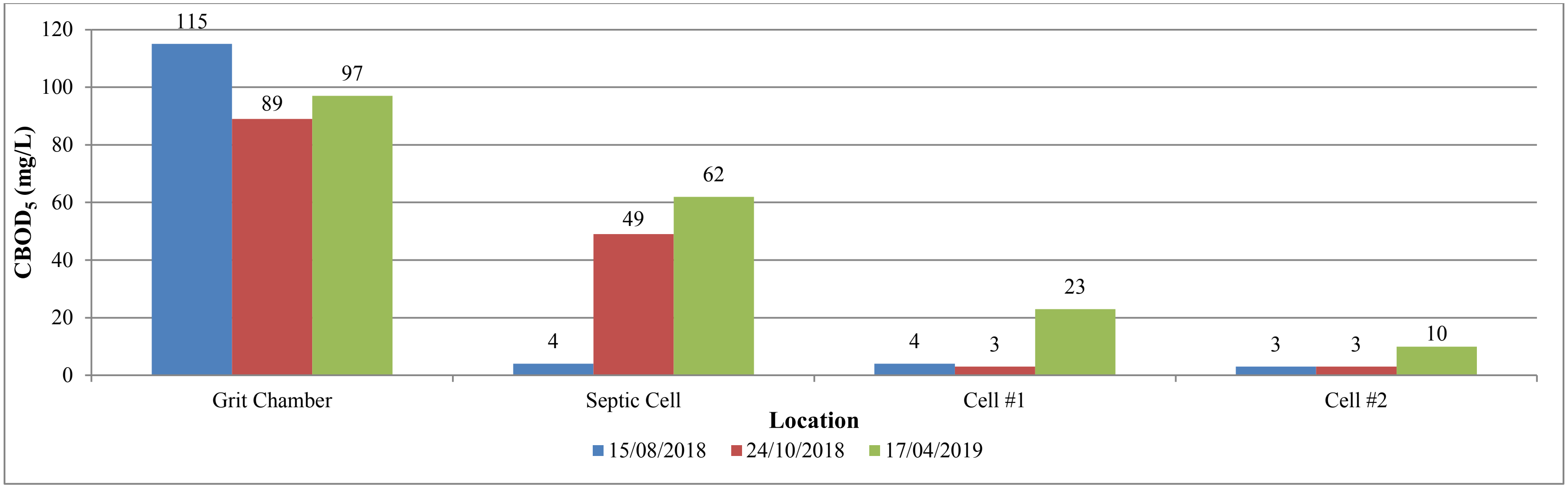


Figure S9 - 5-day carbonaceous biochemical oxygen demand concentrations in all major components

Table S1 - System-wide parameters by sampling rounds

Sampling Date	Location	Conductivity (µS/cm)	pH (pH units)	DO (mg/L)	TSS (mg/L)	TDS (mg/L)	E. Coli (MPN/100mL)	T. Coli. (mg/L)	BOD_5 (mg/L)	$CBOD_5$ (mg/L)
15/08/2018	Influent	1230	7.91	1.46	56.8	651	>2420	>2420	144	115
	Septic	1750	7.83	11.89	3.1	938	>2420	>2420	10	4
	Cell #1	4170	8.71	16.5	18.4	2350	39	921	6	4
	Cell #2	3520	9.82	11.89	6.7	1970	0	35	3	3
24/10/2018	Influent	1520	7.98	2.72	119	778	>2420	>2420	89	115
	Septic	3520	7.84	11.91	13.6	1880	>2420	>2420	57	49
	Cell #1	4150	8.32	8.91	5.1	2250	1300	>2420	10	3
	Cell #2	3920	9.33	11.91	4.7	1800	4	20	3	4
17/04/2019	Influent	1140	7.83	3.74	84	746	>2420	>2420	127	97
	Septic	5630	7.51	16.79	27.1	2590	>2420	>2420	65	62
	Cell #1	2990	8.33	16.51	31.2	1670	54	>2420	25	23
	Cell #2	3820	9.01	16.79	20.3	2210	0	>2420	11	10
30/04/2019	Cell #1	3210	9.20	-	85.9	1710	27	-	29	-
	Cell #2	4360	9.36	-	7.7	2340	0	-	3	-

Appendix T – Surface Water Analysis

The following appendix presents various figures associated with the results of the analysis of the various surface water bodies in the vicinity of 17 Wing Detachment Dundurn's wastewater treatment (WWT) lagoon system. This appendix includes the plots and table listed below. The data was obtained from the sampling the Brightwater/Beaver Creek at locations upstream and downstream near the WWT lagoon system and where the creek meets the boundary of the detachment's training area. The results from sampling of water bodies immediately north of the WWT lagoon system was also included.

- Figure T1 through Figure T5 plots the concentration of various selected parameters for the Brightwater/Beaver Creek at the boundaries of the detachment for the 2015 to 2019 discharge periods;

- Figure T6 through Figure T9 plots the changes in concentration of various selected parameters for the Brightwater/Beaver Creek at the boundaries of the detachment for the 2015, 2016, 2017, and 2019 discharge periods;

- Figure T10 and Table T1 detail the changes in concentrations of various selected parameters for the Brightwater/Beaver Creek at locations up and downstream from the WWT lagoon system during various days when no discharge is occurring. The dates correspond to sampling rounds conducted in Aug 2018, Oct 2018, and Apr 2019 augmented by pre-discharge data collected from the operators; and,

- Figure T11 and Figure T12 plot the concentration of various selected parameters for the stagnant water bodies located immediately north of the WWT lagoon system. The data was collected during the sampling rounds conducted in Aug 2018, Oct 2018, and Apr 2019.

Boundaries Comparison

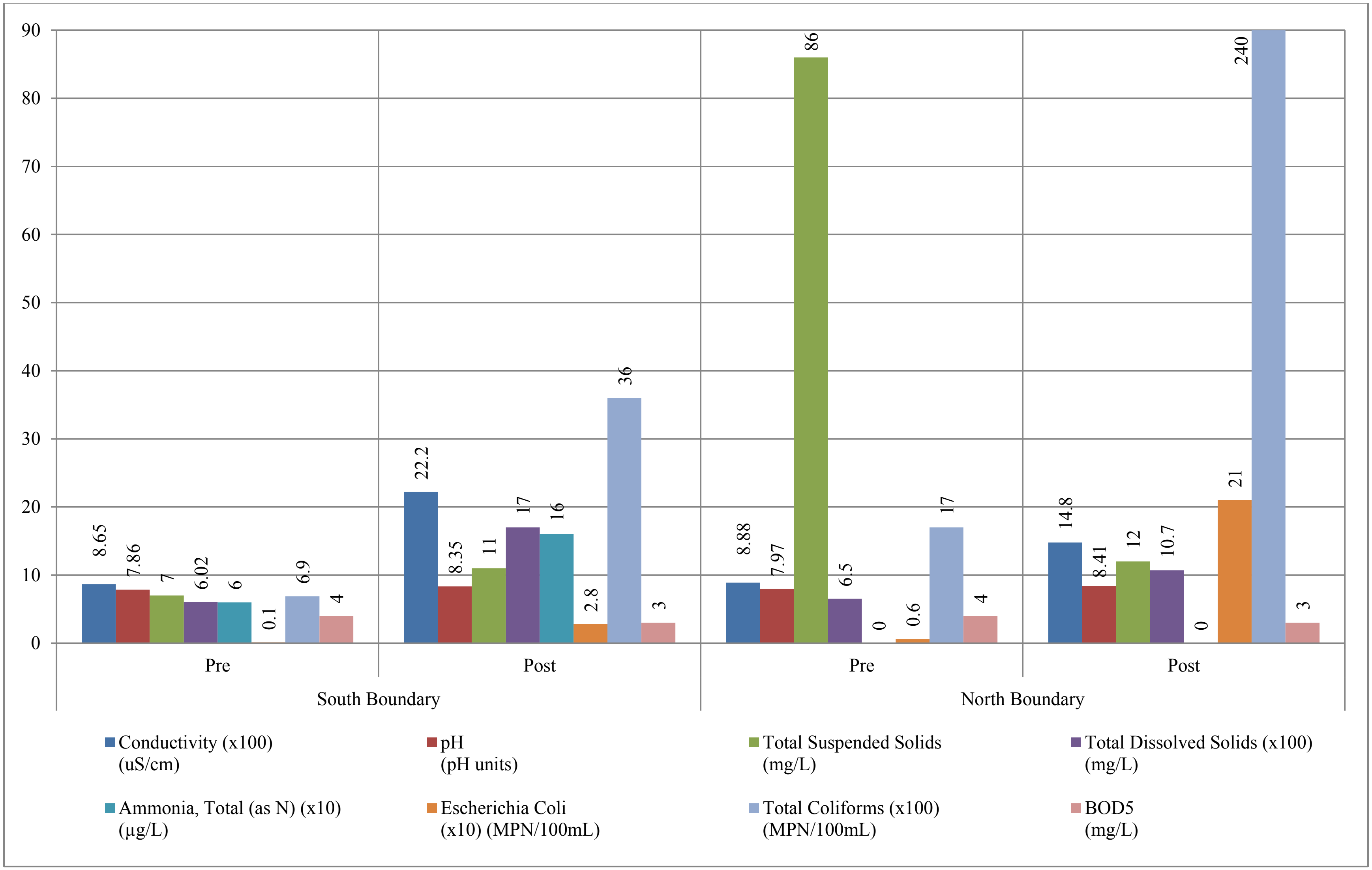


Figure T1 - Concentration at boundaries for the 2015 discharge period

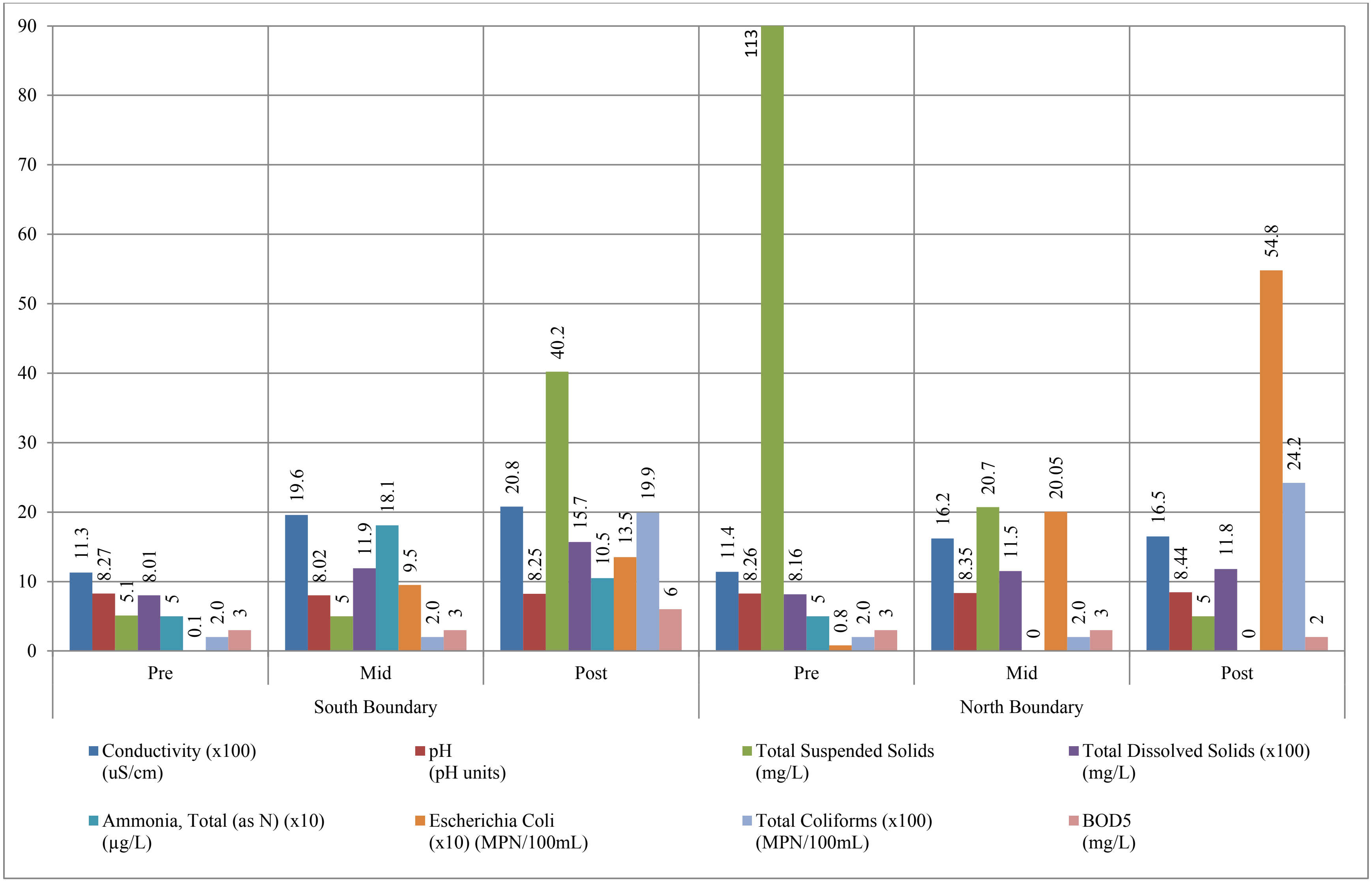


Figure T2 - Concentration at boundaries for the 2016 discharge period

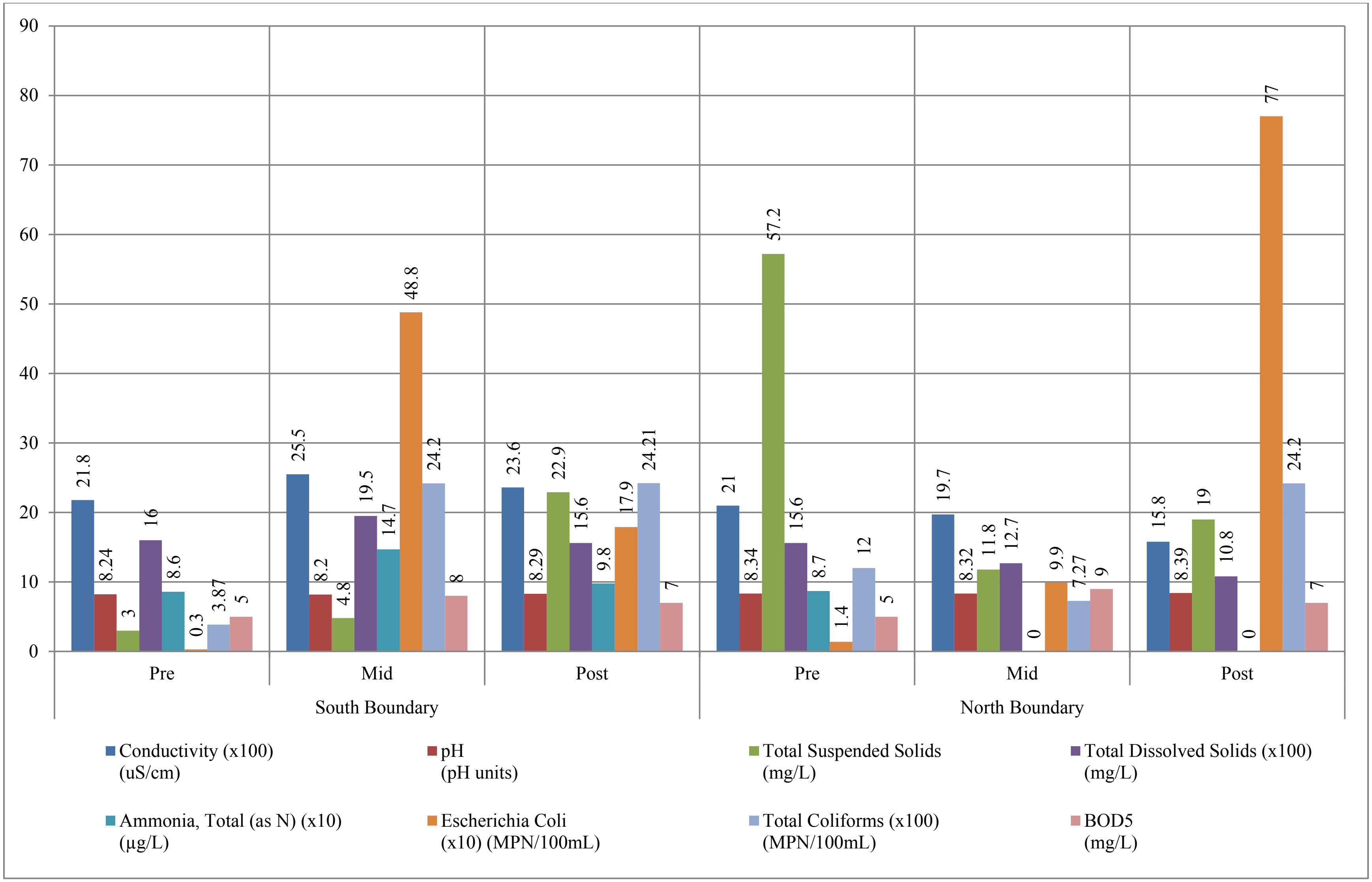


Figure T3 - Concentration at boundaries for the 2017 discharge period

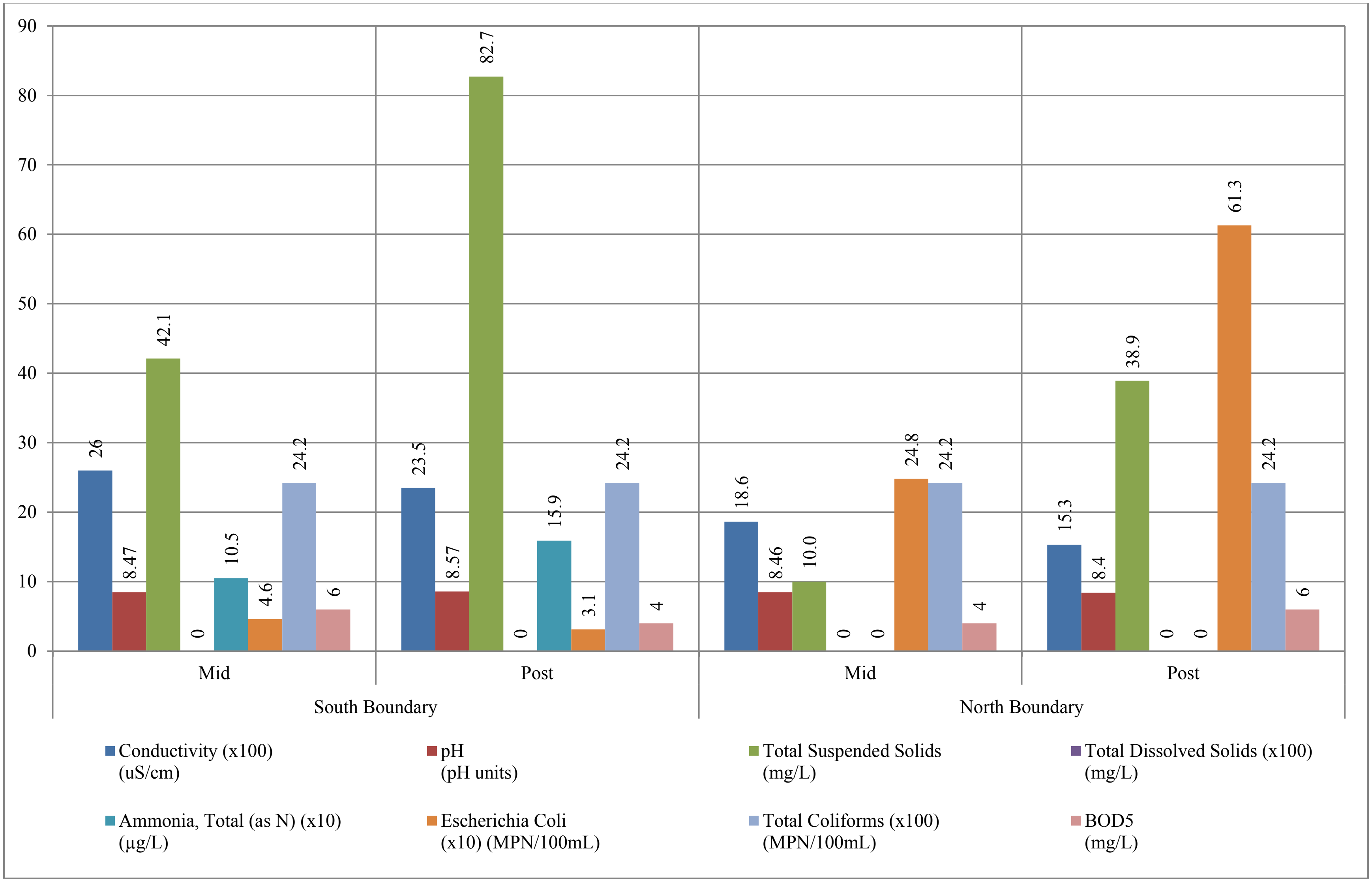


Figure T4 - Concentration at boundaries for the 2018 discharge period

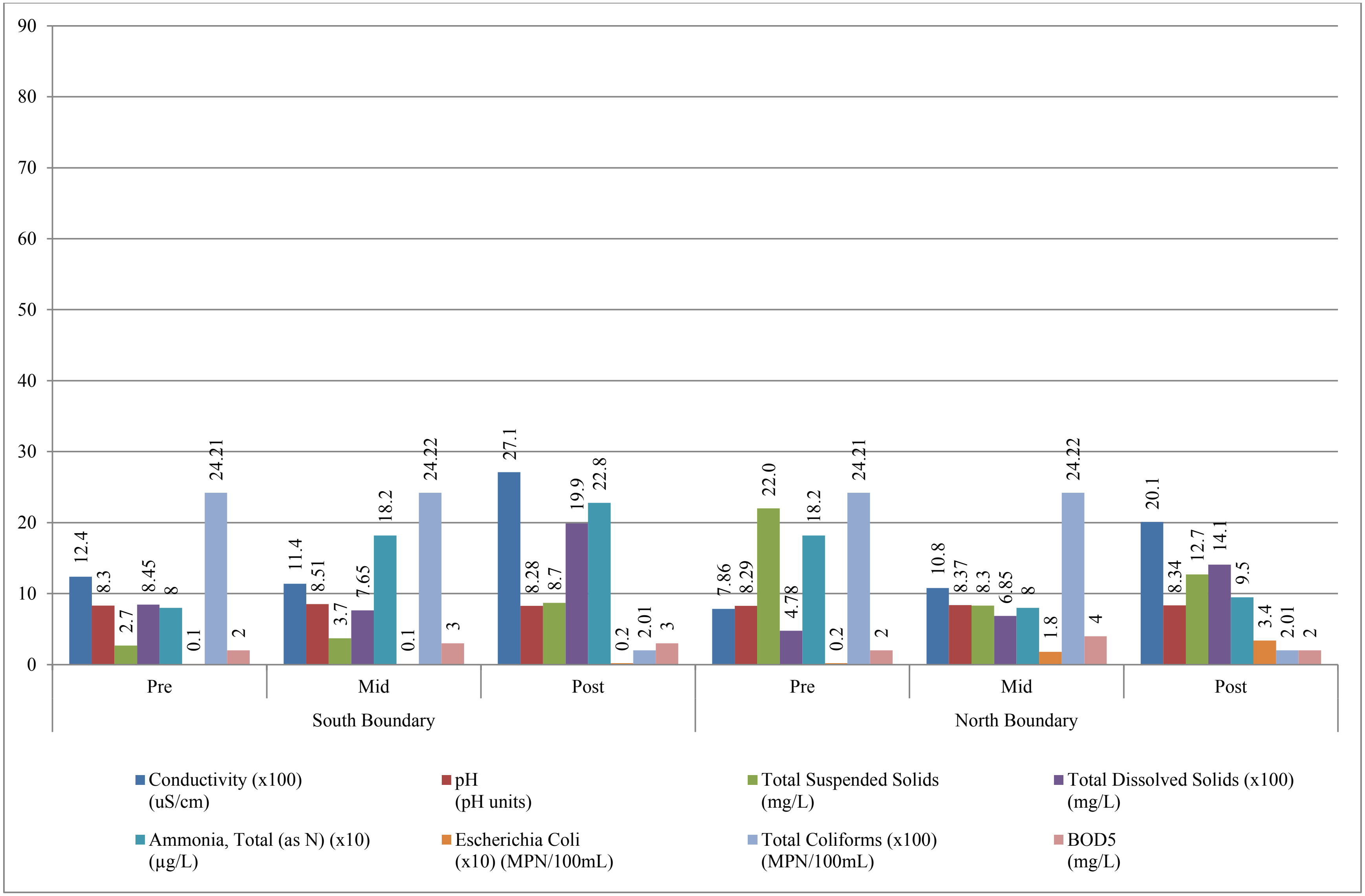


Figure T5 - Concentration at boundaries for the 2019 discharge period

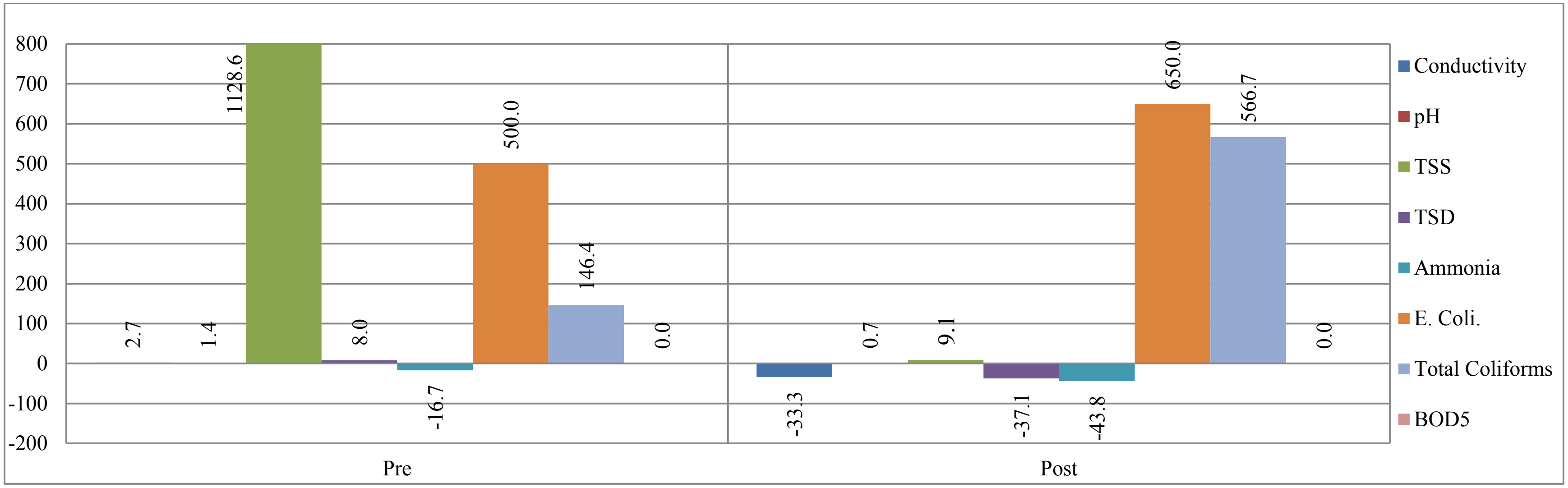


Figure T6 - Concentration change at boundaries for the 2015 discharge period (all values in %)

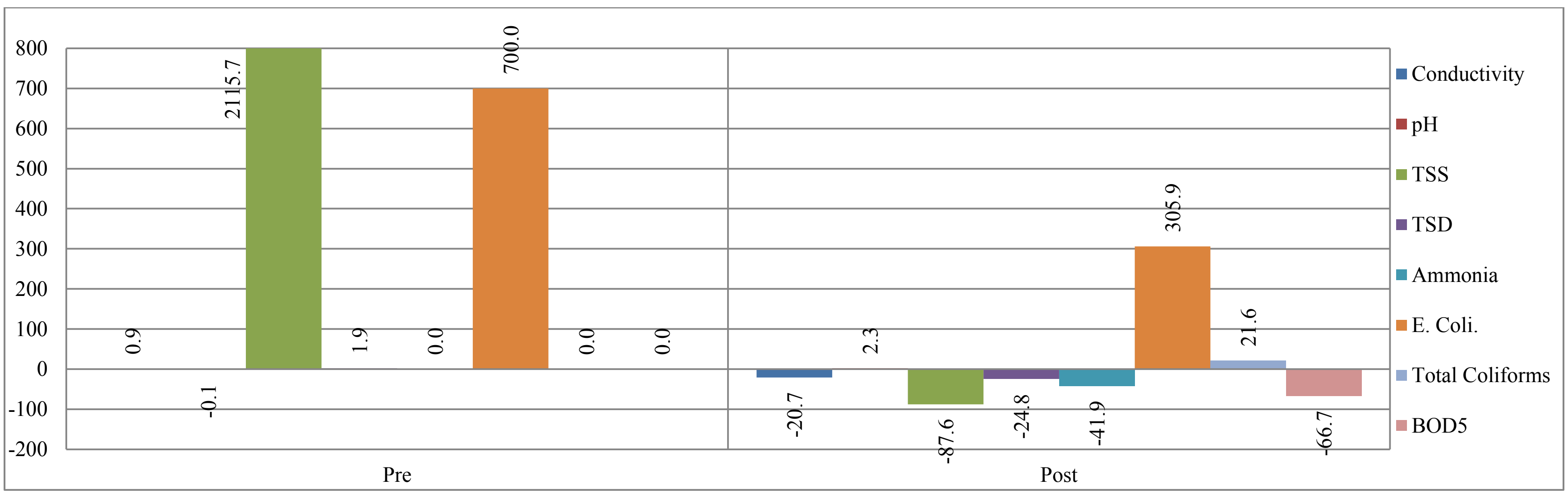


Figure T7 - Concentration change at boundaries for the 2016 discharge period (all values in %)

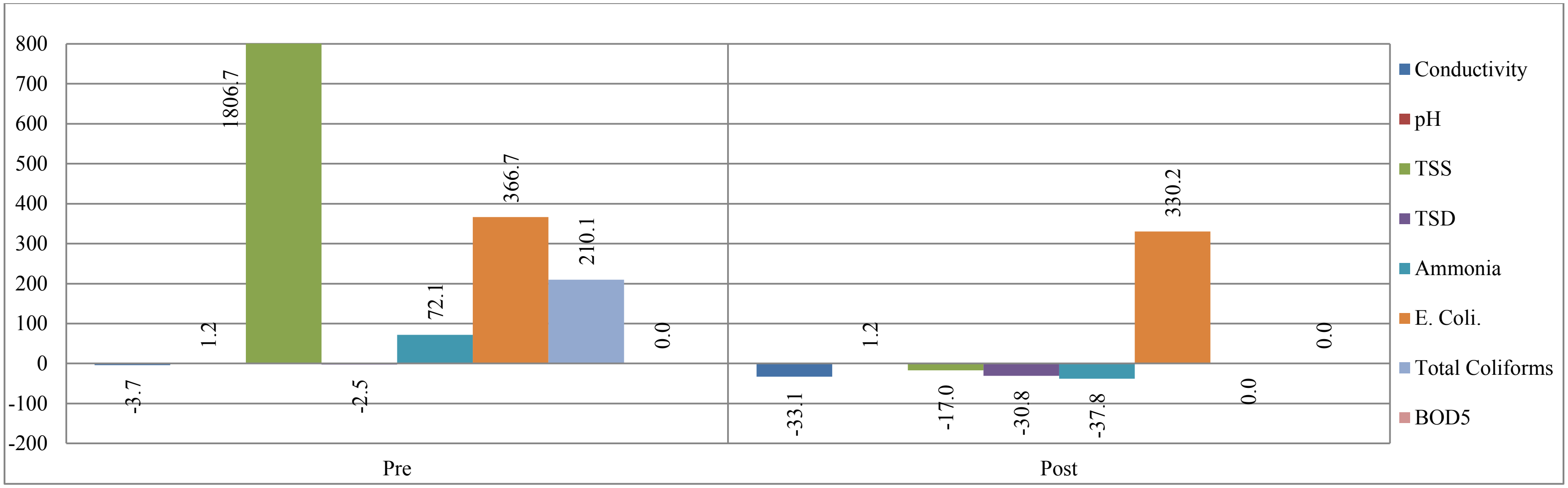


Figure T8 - Concentration change at boundaries for the 2017 discharge period (all values in %)

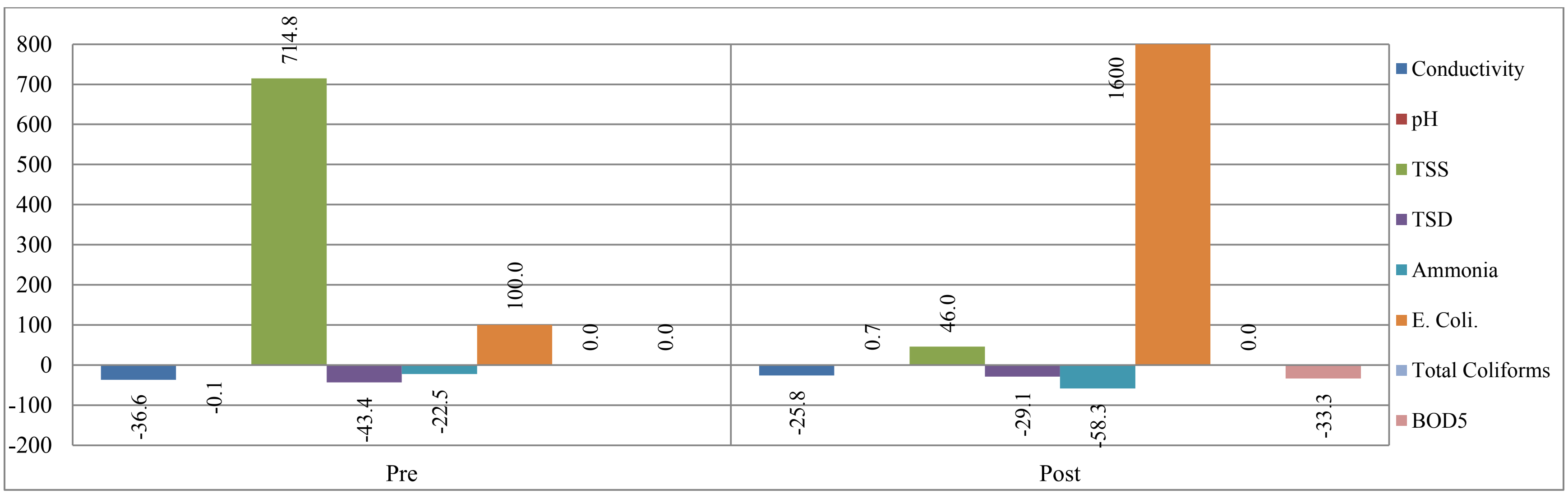


Figure T9 - Concentration change at boundaries for the 2019 discharge period (all values in %)

Non-Discharge Creek Quality

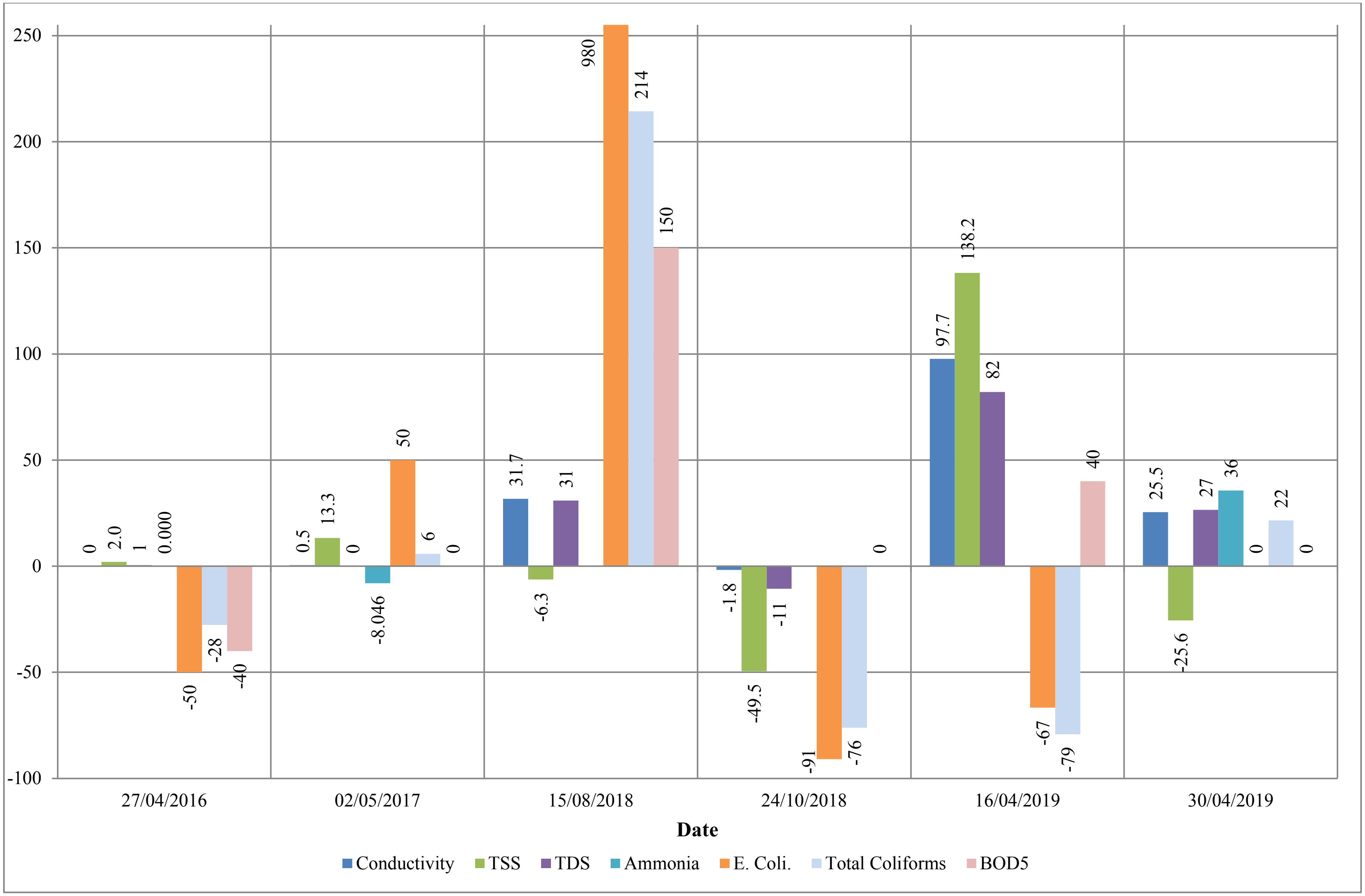


Figure T10 - Change in parameter concentrations up & down the stream from WWT Lagoon (all values in %)

Table T1 - Creek North and South of lagoon quality

Date	Location	Conductivity (µS/cm)	pH (pH units)	Total Suspended Solids (mg/L)	Total Dissolved Solids (mg/L)	Ammonia, Total (as N) (mg/L)	Escherichia Coli (MPN/100mL)	Total Coliforms (MPN/100mL)	BOD5 (mg/L)
27/04/2016	South	1140	8.27	5	787	0.05	4	200.5	5
27/04/2016	North	1140	8.27	5.1	791	0.05	2	145	3
02/05/2017	South	2170	8.27	3	1620	0.087	2	613	5
02/05/2017	North	2180	8.27	3.4	1620	0.08	3	649	5
15/08/2018	South	1420	8.57	11.1	978		5	770	4
15/08/2018	North	1870	8.63	10.4	1280		54	>2420	10
24/10/2018	South	1660	8.13	10.3	1110		11	>2420	2
24/10/2018	North	1630	8.13	5.2	992		1	579	2
16/04/2019	South	2180	8.27	3.4	1620		3	649	5
16/04/2019	North	4310	8.73	8.1	2950		1	135	7
30/04/2019	South	1100	8.29	4.3	760	0.070	0	165	2
30/04/2019	North	1380	8.2	3.2	962	0.095	1	200.5	2

Stagnant Water Bodies Quality

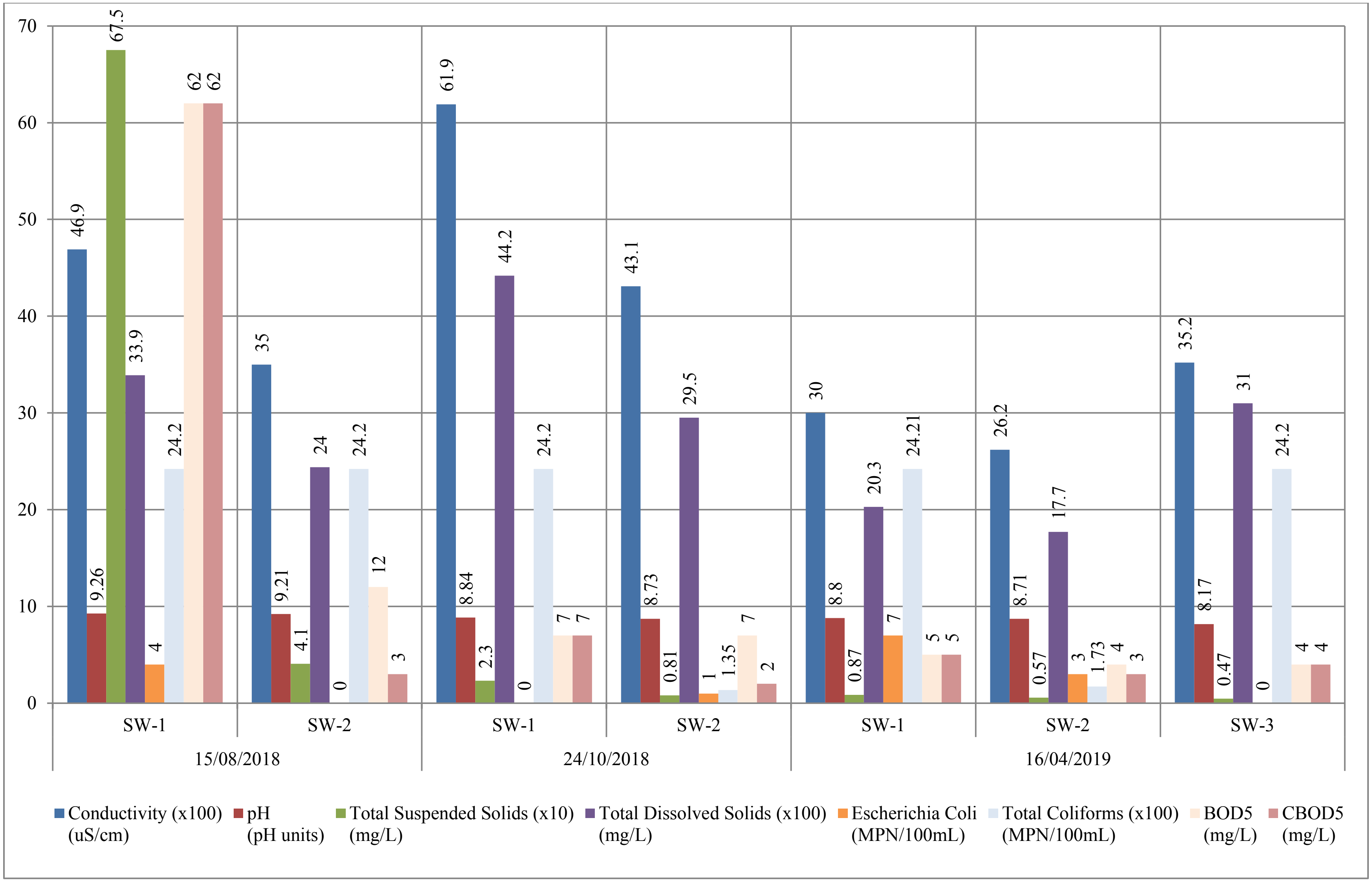


Figure T11 - Stagnant water bodies' quality by sampling date

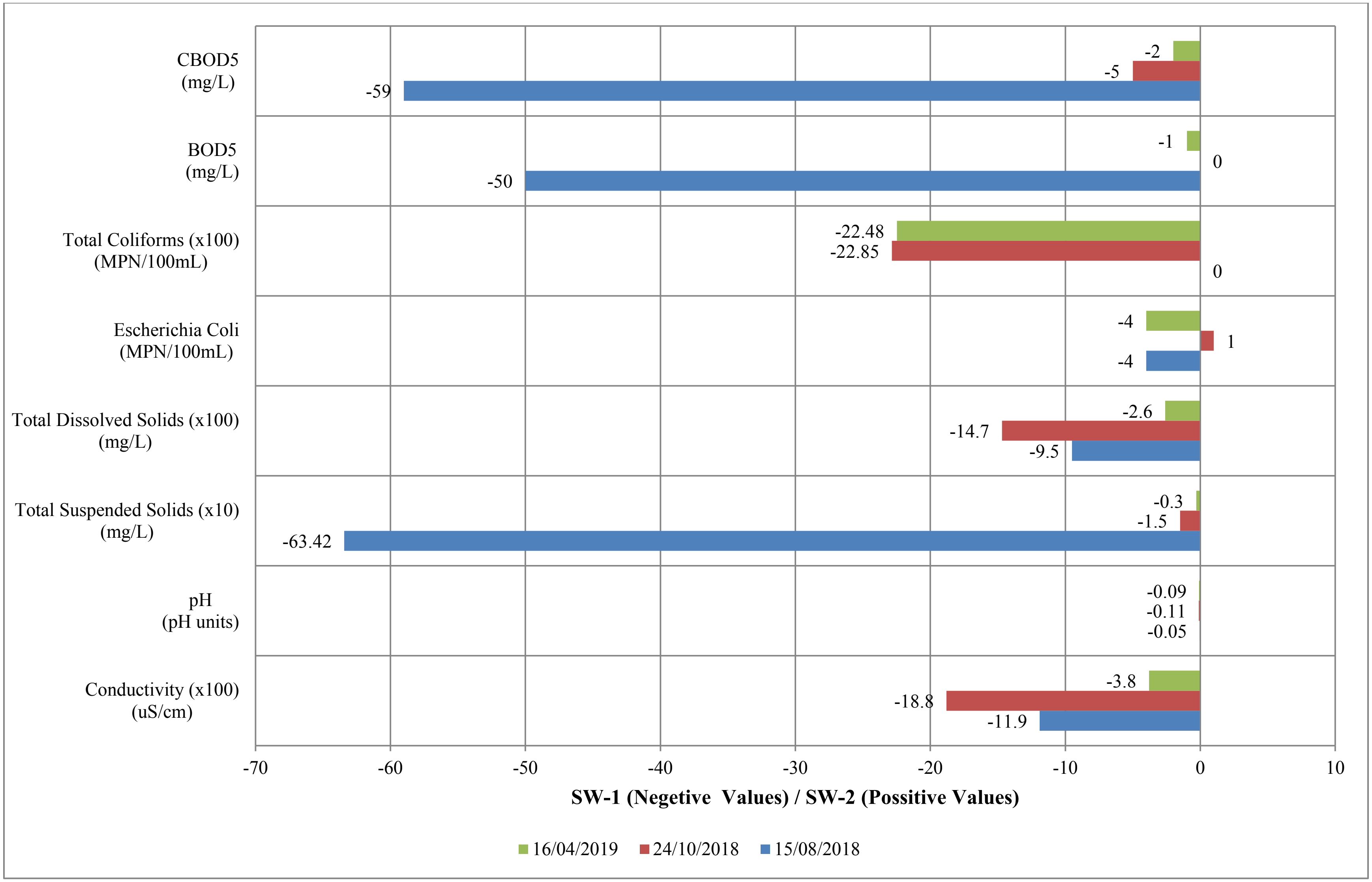


Figure T12 - Concentration difference between SW-1 and SW-2 by sampling date. Negative values indicate a higher concentration in SW-1

Appendix U – Groundwater Analysis

The following appendix presents various figures associated with the results of the analysis of the groundwater elevation and quality obtained in the series of nine (9) monitoring wells (MW) at the site of 17 Wing Detachment Dundurn's wastewater treatment (WWT) lagoon system. This appendix includes the plots and table listed below. The data was obtained from the 2003 to 2017 groundwater monitoring programme and the field study portion of this research project conducted during the 2018 to 2019 treatment period.

- Figure U1 plots the variation in groundwater elevation in all MWs at every sampling round from 2003 through 2019;

- Figure U2 plots the groundwater elevation variation in each MW over the recorded period of 2003 through 2019;

- Figure U3 plots the average monthly groundwater elevation by well over a one-year period;

- Table U1 presents the groundwater elevation data of all MW;

- Figure U4 through Figure U6 presents satellite imagery overlaid by the groundwater elevations of the MW during each of the sampling round (Aug 2018, Oct 2018, and Apr 2019);

- Figure U7 through Figure U9 plots the concentration of various parameters in the groundwater during each of the sampling round (Aug 2018, Oct 2018, and Apr 2019);

- Figure U10 through Figure U12 presents satellite imagery overlaid by the groundwater temperature of the MW during each of the sampling round (Aug 2018, Oct 2018, and Apr 2019);

- Figure U13 through Figure U15 presents satellite imagery overlaid by the groundwater conductivity of the MW during each of the sampling round (Aug 2018, Oct 2018, and Apr 2019);

- Figure U16 through Figure U18 presents satellite imagery overlaid by the groundwater pH of the MW during each of the sampling round (Aug 2018, Oct 2018, and Apr 2019); and,

- Figure U19 presents the history of total coliform hits in all monitoring well for the period of 2011 to 2019.

Groundwater Elevation

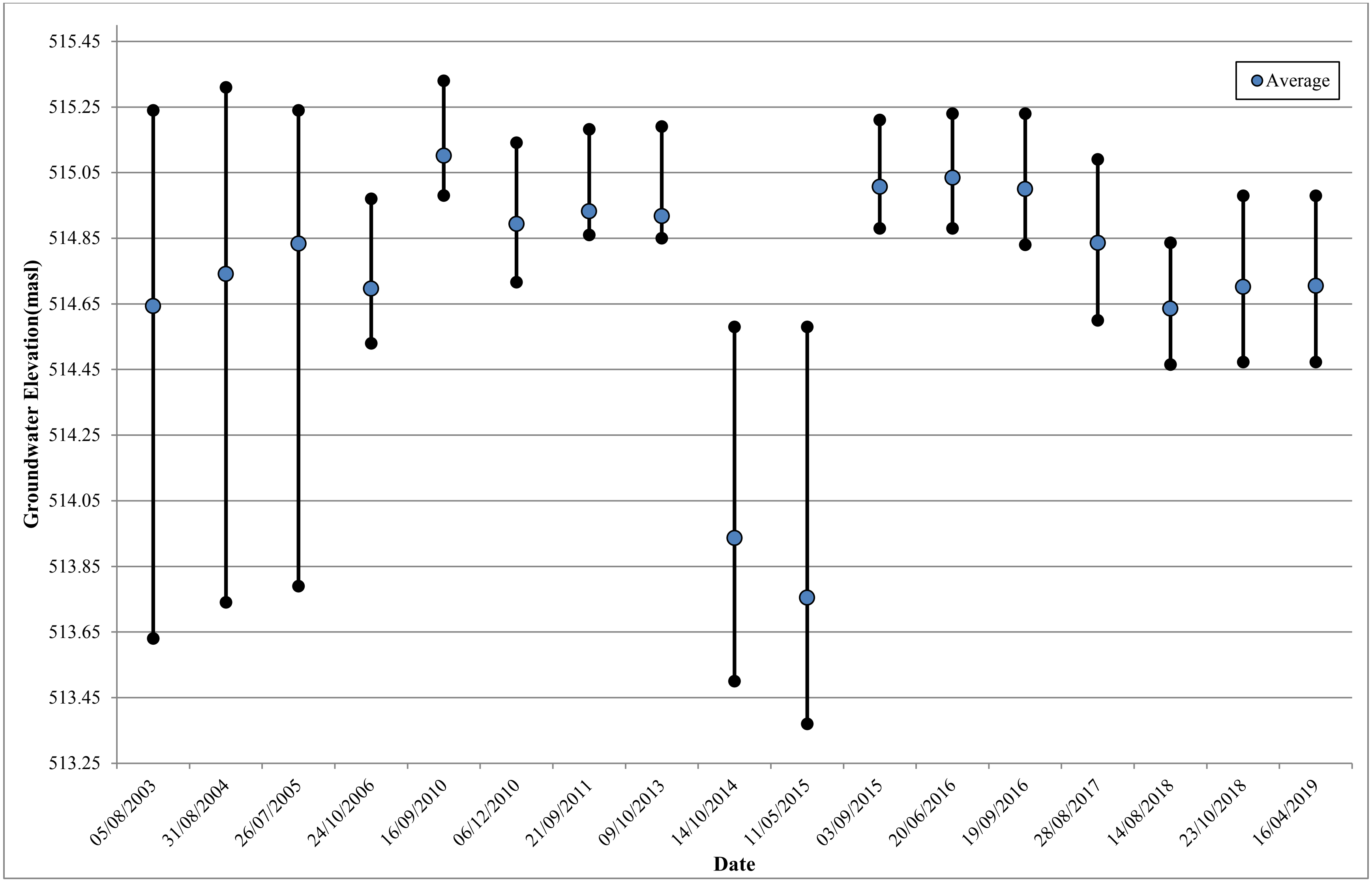


Figure U1 - Groundwater Elevation Ranges in all MWs between 2003 and 2019 data

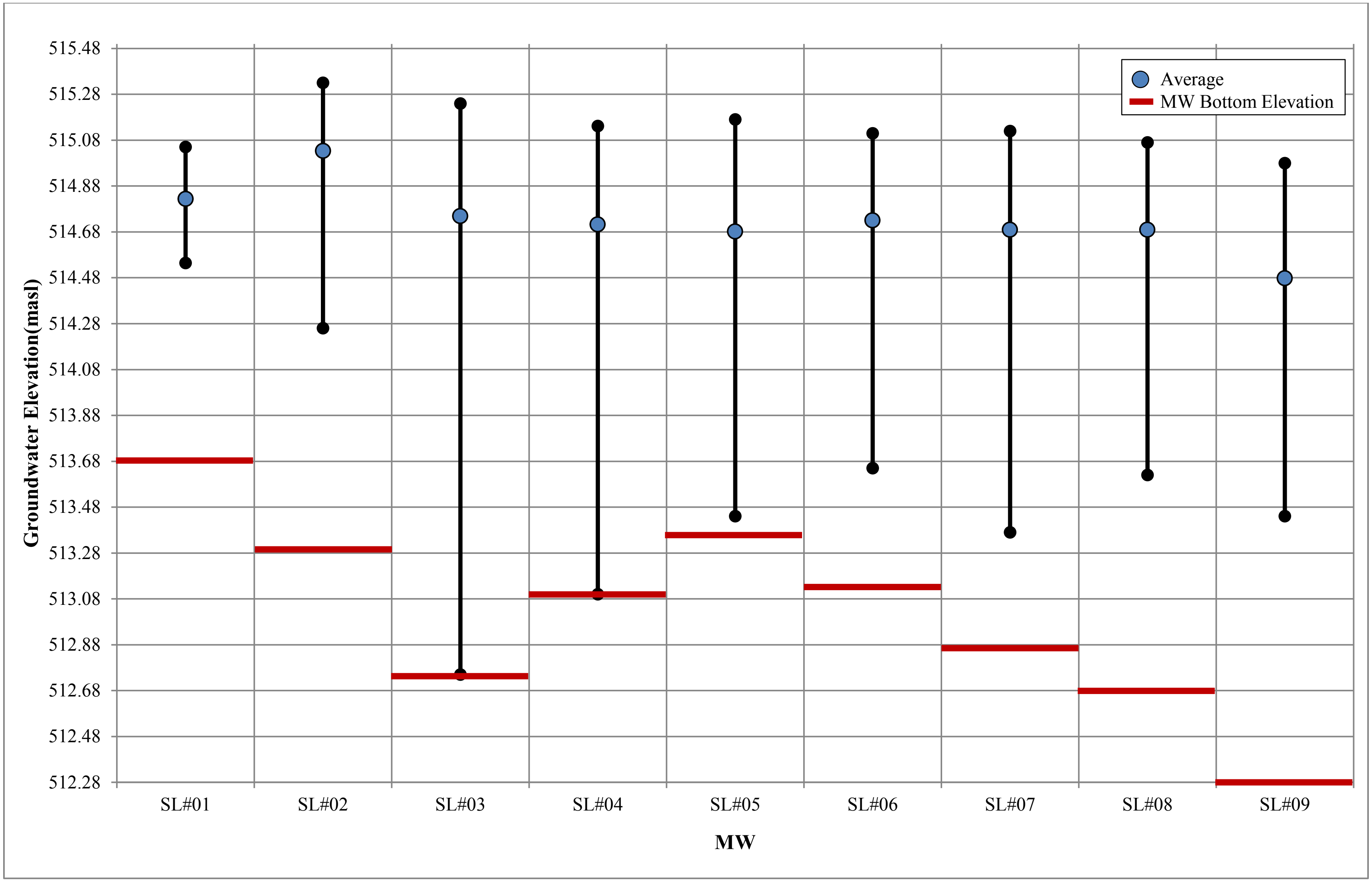


Figure U2 - Variation in Recorded Groundwater Elevations 2003–2019

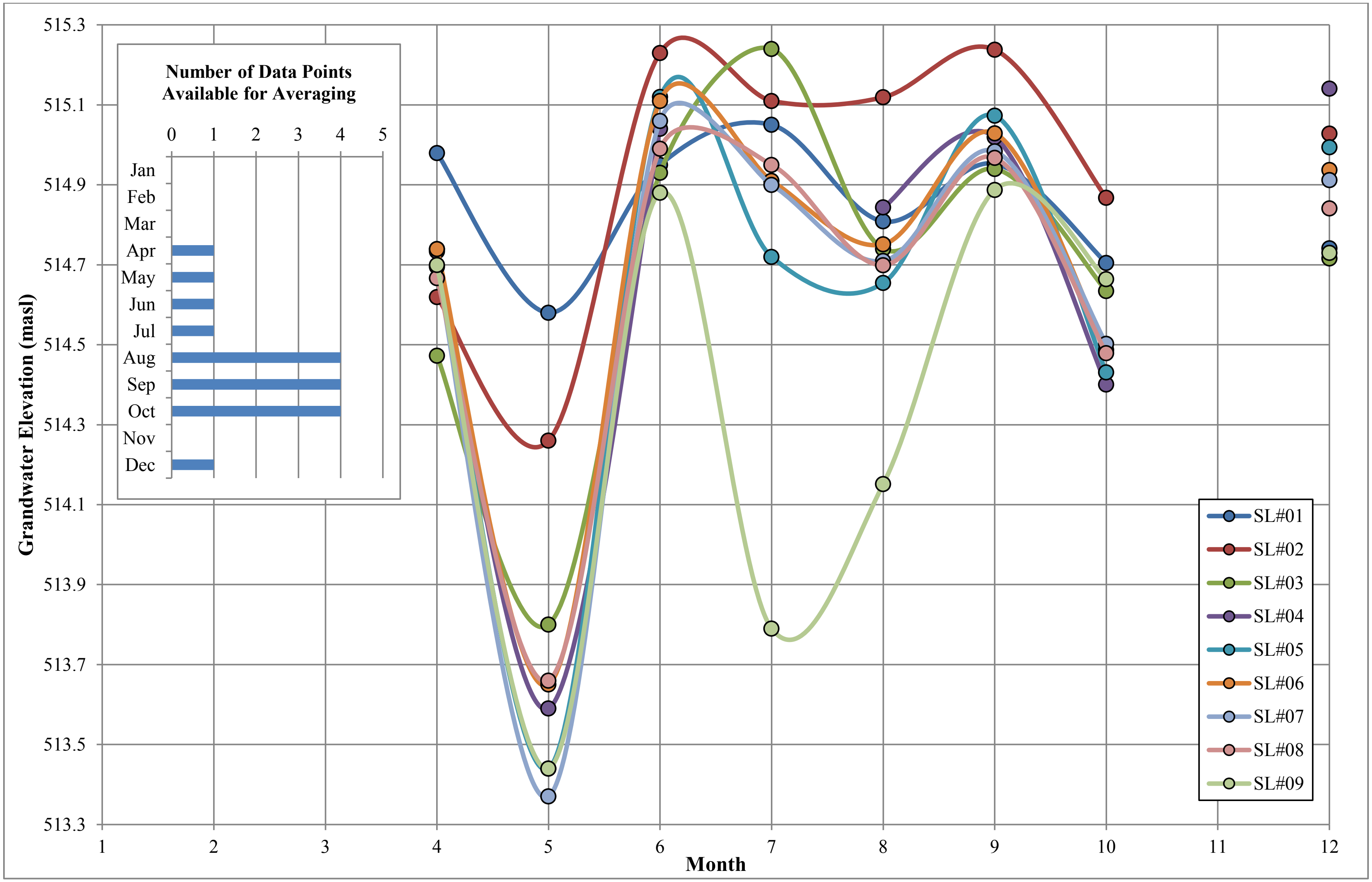


Figure U3 - Monthly average groundwater elevation

Table U1 - Groundwater elevation by well and sampling dates

Date	SL#01	SL#02	SL#03	SL#04	SL#05	SL#06	SL#07	SL#08	SL#09	Max	Min	Average
05/08/2003	514.91	515.24	514.82	514.80	514.44	514.62	514.59	514.74	513.63	515.24	513.63	514.64
31/08/2004	514.98	515.31	514.88	514.88	514.54	514.74	514.73	514.87	513.74	515.31	513.74	514.74
26/07/2005	515.05	515.11	515.24	D	514.72	514.91	514.90	514.95	513.79	515.24	513.79	514.83
24/10/2006	514.68	514.97	514.65	514.65	514.60	514.53	514.74	514.74	514.71	514.97	514.53	514.70
16/09/2010	515.03	515.33	514.99	515.11	515.17	515.11	515.12	515.07	514.98	515.33	514.98	515.10
06/12/2010	514.74	515.03	514.72	515.14	514.99	514.94	514.91	514.84	514.73	515.14	514.72	514.89
21/09/2011	514.89	515.18	D	514.90	514.96	514.93	514.88	514.86	514.86	515.18	514.86	514.93
09/10/2013	514.89	515.19	D	514.89	514.89	514.89	514.85	514.86	514.88	515.19	514.85	514.92
14/10/2014	514.58	514.33	D	513.59	513.50	513.79	513.68	513.62	514.40	514.58	513.50	513.94
11/05/2015	514.58	514.26	513.80	513.59	513.44	513.65	513.37	513.66	513.44	514.58	513.37	513.75
03/09/2015	514.93	515.21	514.89	515.04	515.10	515.07	514.97	514.97	514.88	515.21	514.88	515.01
20/06/2016	514.95	515.23	514.93	515.04	515.12	515.11	515.06	514.99	514.88	515.23	514.88	515.03
19/09/2016	514.96	515.23	514.94	515.03	515.06	515.01	514.97	514.97	514.83	515.23	514.83	515.00
28/08/2017	514.80	515.09	514.75	514.85	514.90	514.92	514.84	514.60	514.77	515.09	514.60	514.84
14/08/2018	514.54	514.84	514.51	D	514.74	514.73	514.68	514.59	514.46	514.84	514.46	514.64
23/10/2018	514.67	514.98	514.62	514.47	514.73	514.74	514.74	514.70	514.67	514.98	514.47	514.70
16/04/2019	514.98	514.62	514.47	514.73	514.74	514.74	514.70	514.67	514.70	514.98	514.47	514.71
Max	515.05	515.33	515.24	515.14	515.17	515.11	515.12	515.07	514.98			
Min	514.54	514.26	512.75*	513.10**	513.44	513.65	513.37	513.62	513.44			
Average	514.82	515.03	514.75	514.71	514.68	514.73	514.69	514.69	514.48			

*Adjusted to account for dry well recorded on 14/10/2014

** Adjusted to account for dry well recorded on 14/08/2018

Figure U4- Groundwater elevation map - 14/08/2018

Figure U6 - Groundwater elevation map - 24/10/2018

Figure U5 - Groundwater elevation map - 16/04/2019

Groundwater Quality

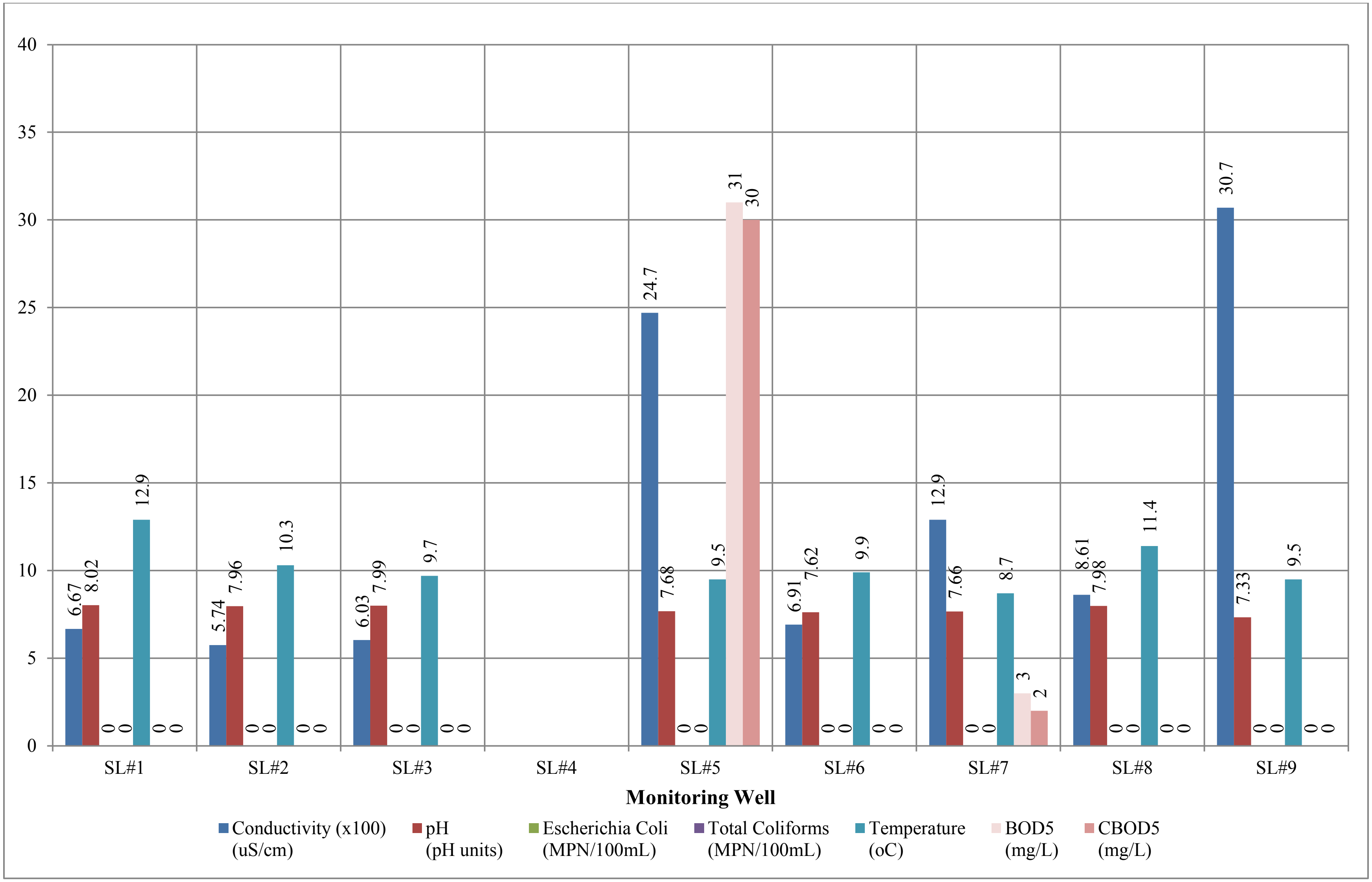


Figure U7 - Groundwater quality - 14/08/2018 (BOD_5 and $CBOD_5$ detection limit = 2)

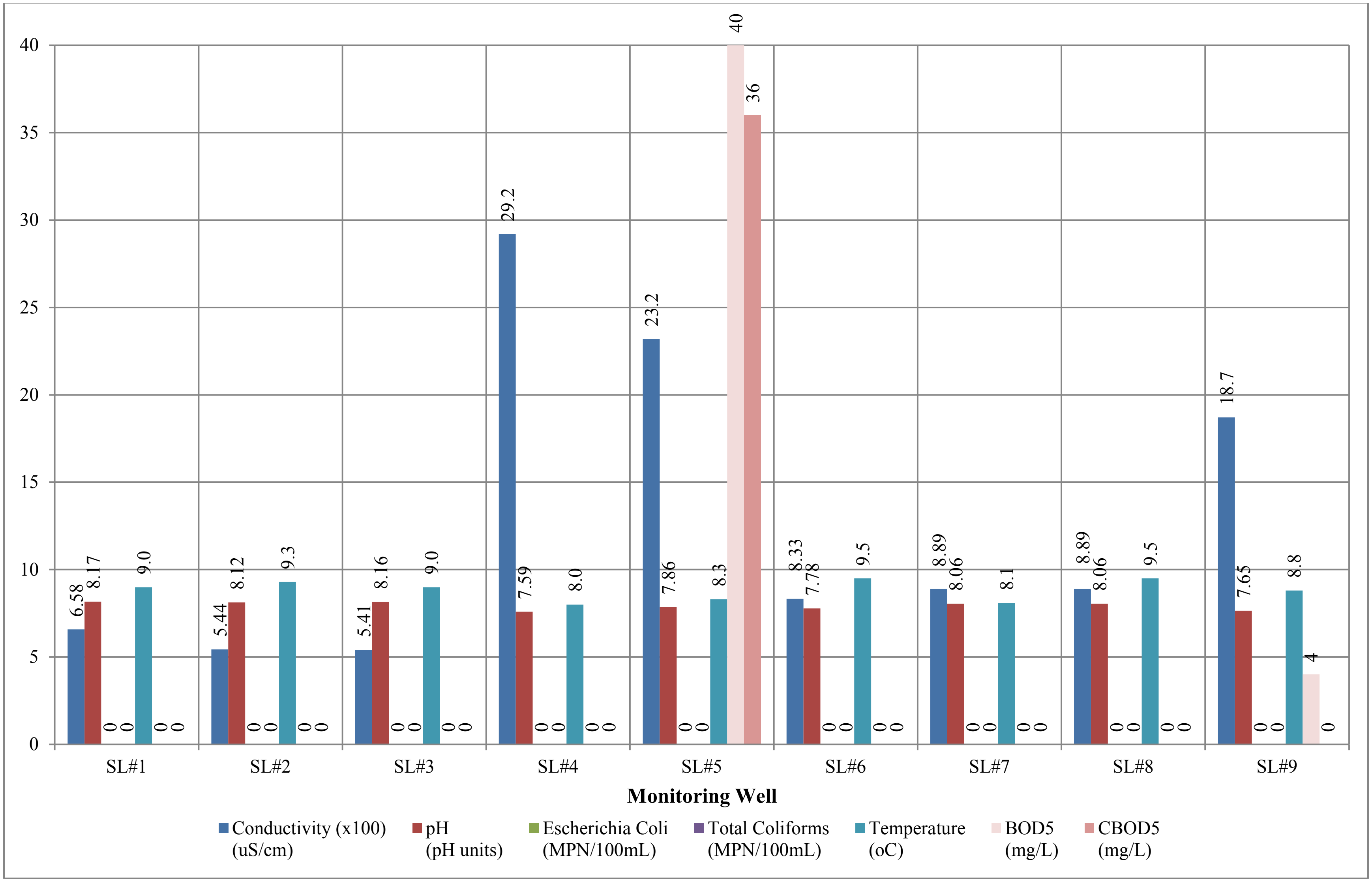


Figure U8 - Groundwater quality - 23/10/2018 (BOD_5 and $CBOD_5$ detection limit = 2)

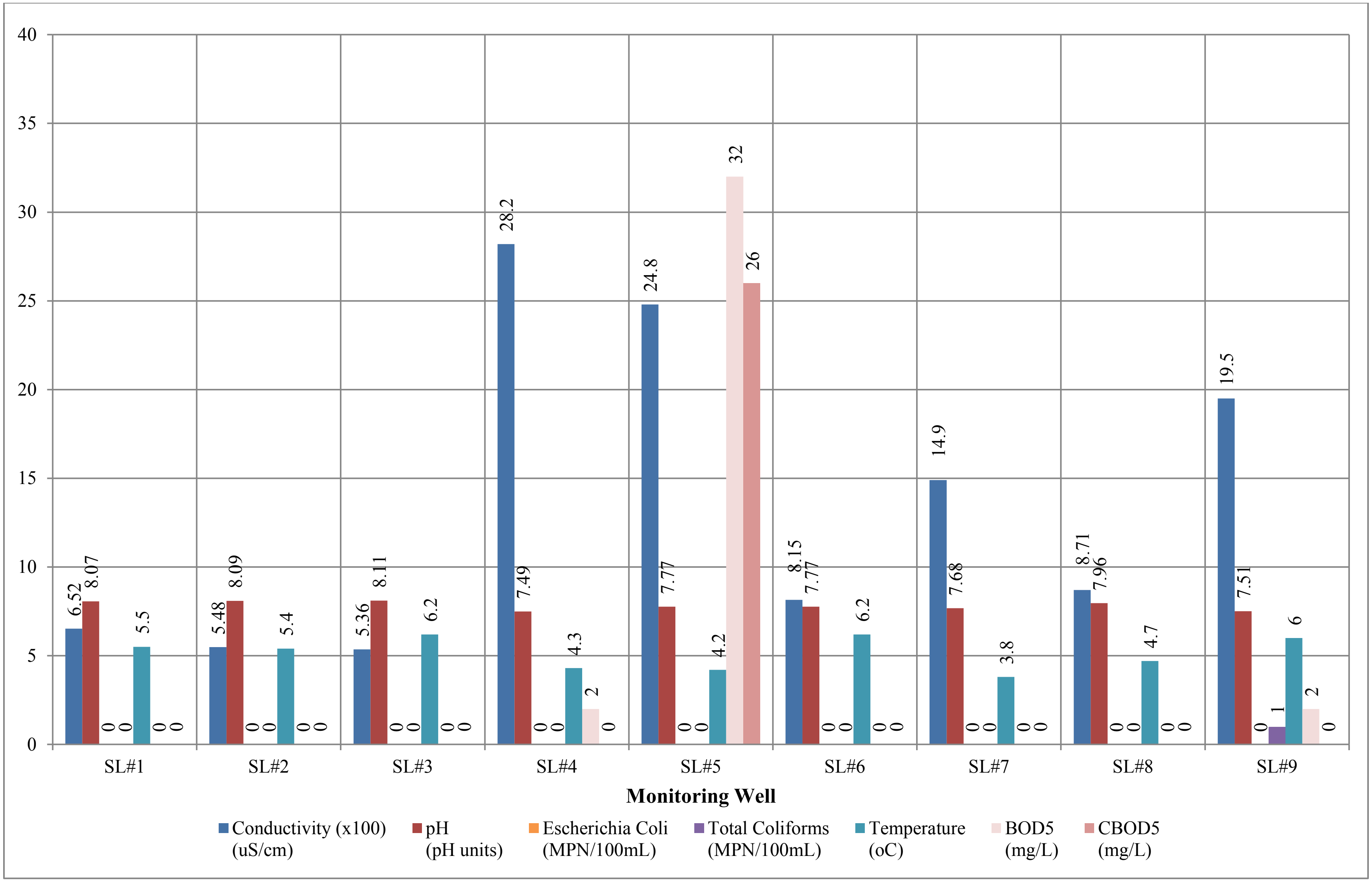


Figure U9 - Groundwater quality - 16/04/2019 (BOD_5 and $CBOD_5$ detection limit = 2)

Groundwater Temperature Maps

Figure U12 - Temperature map - 14/08/2018

Figure U11 - Temperature map - 24/10/2018

Figure U10 - Temperature map - 16/04/2019

Groundwater Conductivity Maps

Figure U14 - Conductivity map - 14/08/2018

Figure U13 - Conductivity map - 24/10/2018

Figure U15 - Conductivity map - 16/04/2019

Groundwater pH Maps

Figure U16 - pH map - 14/08/2018

Figure U17 - pH map - 24/10/2018

Figure U18 - pH map - 16/04/2019

Record of Total Coliforms Hits (2011–2019)

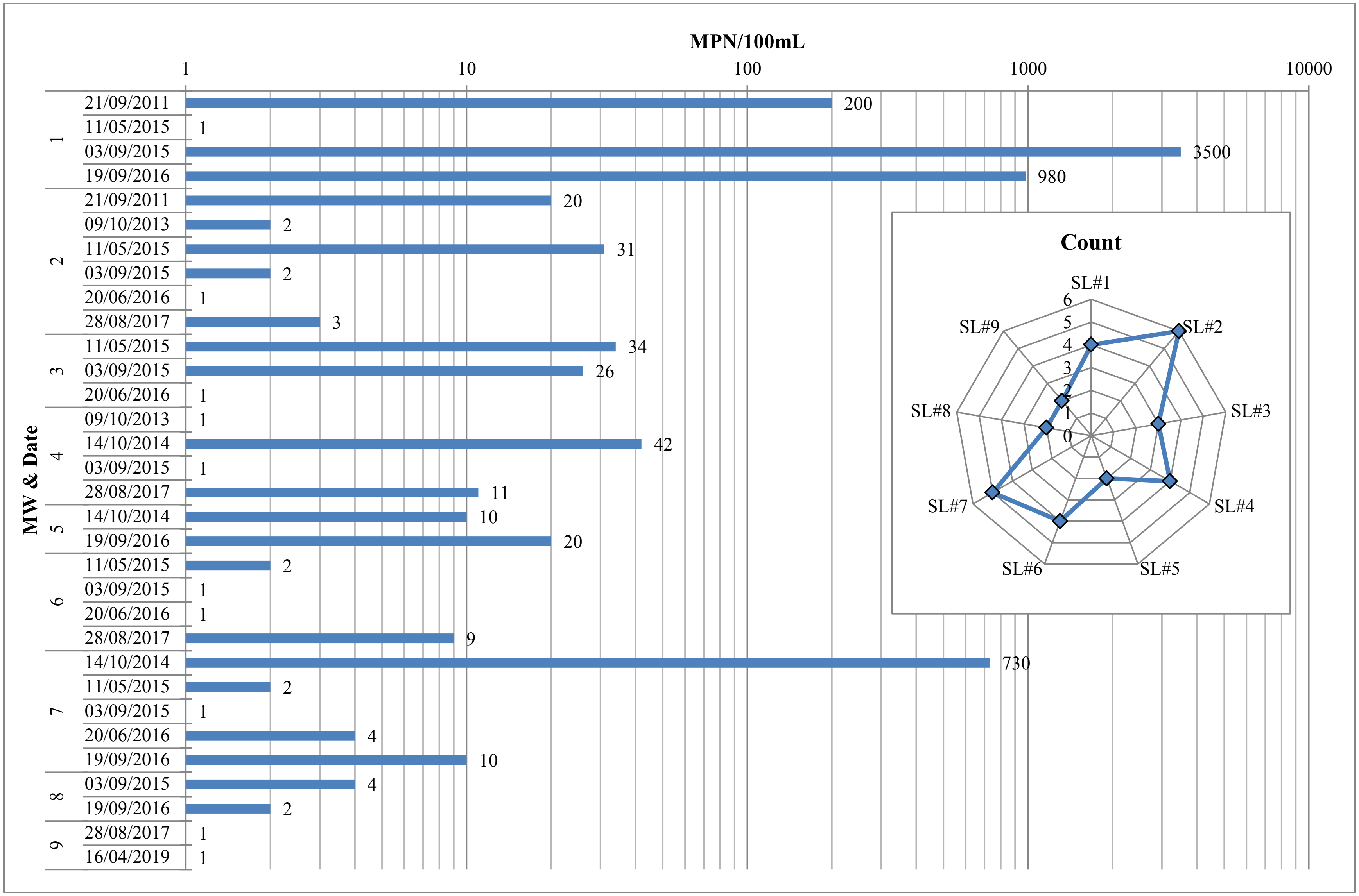


Figure U19 - Record of total coliforms hits (2011–2019)

Appendix V – RMC vs ALS Testing Results

The following appendix presents various figures associated with the comparison of RMC and the contracted laboratory (ALS Environmental) test results. In addition RMC duplicate tests are also compared. This appendix includes the plots and table listed below. The data was obtained from the Aug 2018, Oct 2018, and Apr 2019 sampling rounds conducted as part of this research project.

- Figure V1 and Figure V2 plot the fit between RMC and ALS results for conductivity and pH test; and,

- Figure V3 through Figure V5 plot the residual error between original RMC results for pH, conductivity, and turbidity over the original test results,

RMC vs ALS Testing Results

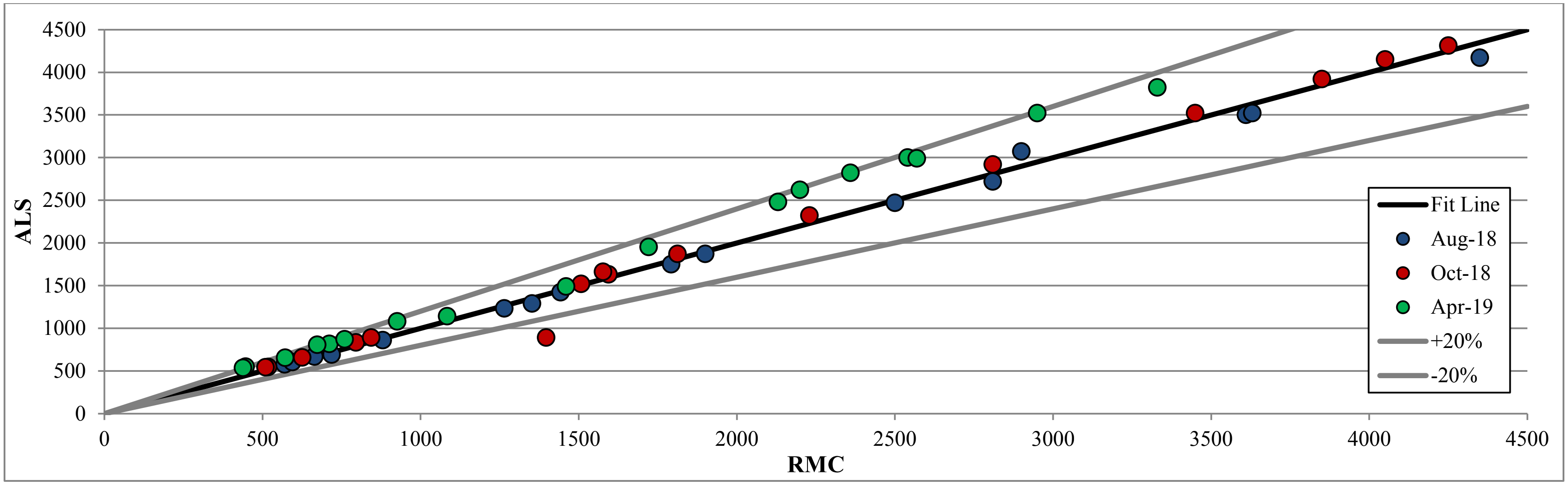


Figure V1 - Comparison of RMC and ALS pH results for Aug 2018, Oct 2018, and Apr 2019 sampling round. (All values in pH units)

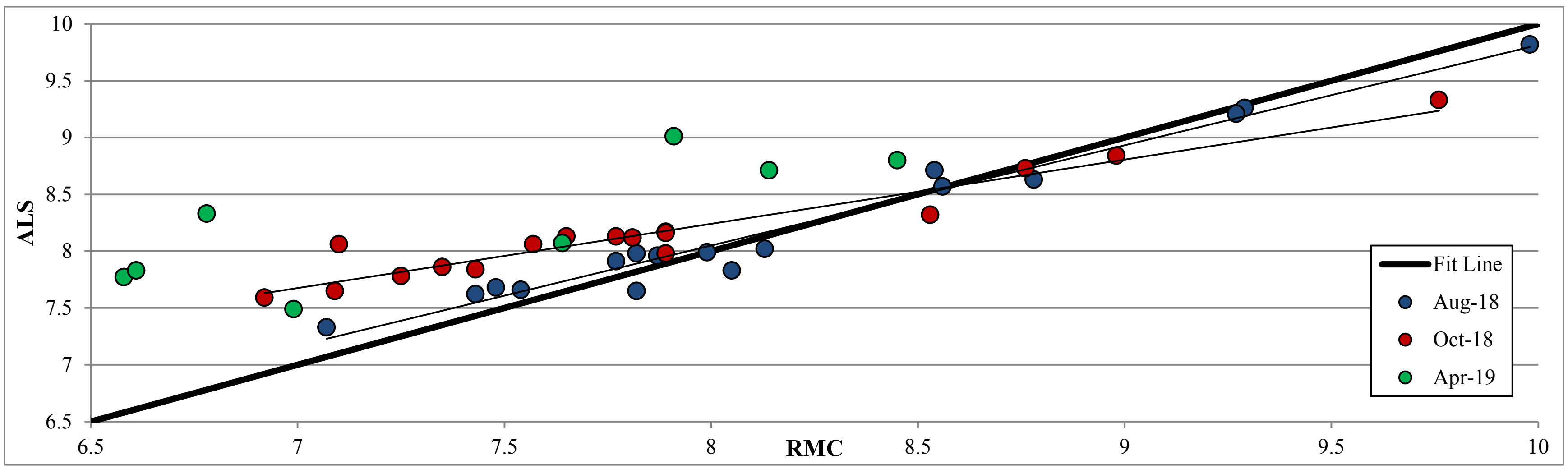


Figure V2 - Comparison of RMC and ALS conductivity results for Aug 2018, Oct 2018, and Apr 2019 sampling round. (All values in µS/cm)

Duplicates Comparison

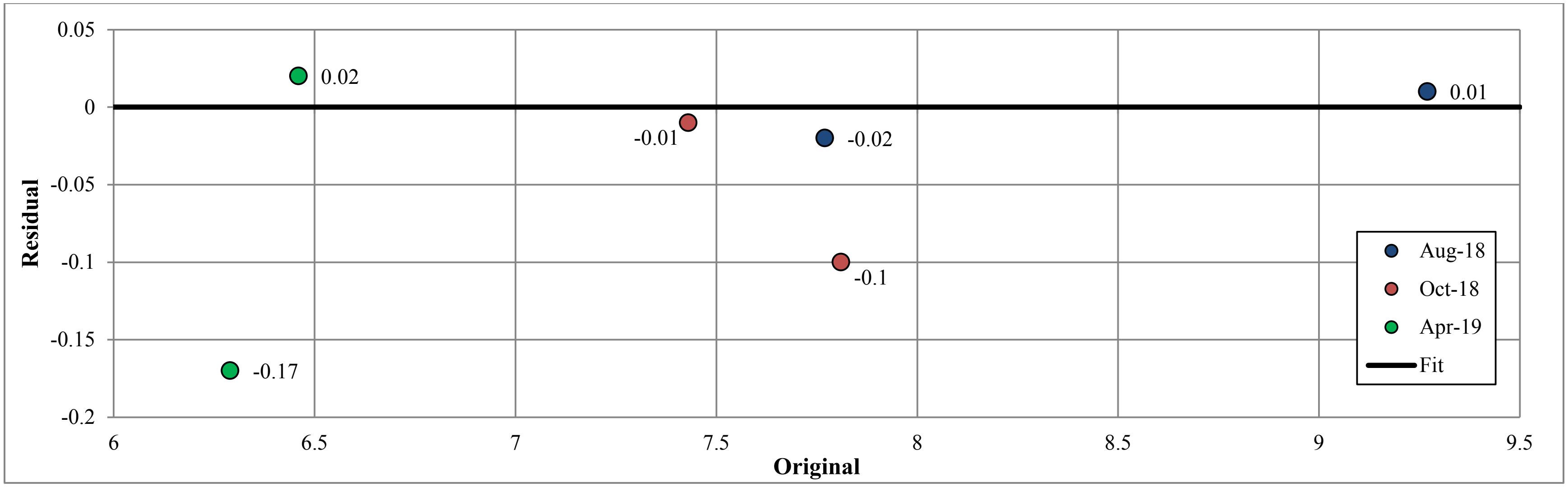


Figure V3 – Duplicate residual of pH testing conducted during the Aug 2018, Oct 2018, and Apr 2019 sampling round. (All values in pH units)

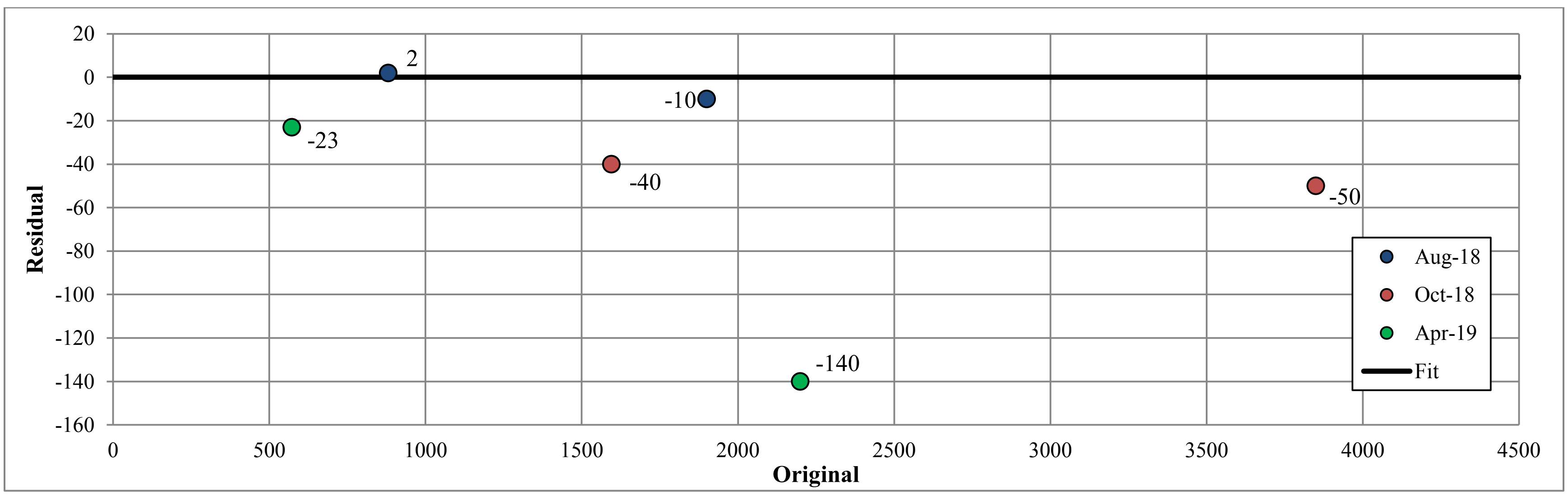


Figure V4 - Duplicate residual of conductivity testing conducted during the Aug 2018, Oct 2018, and Apr 2019 sampling round. (All values in µS/cm)

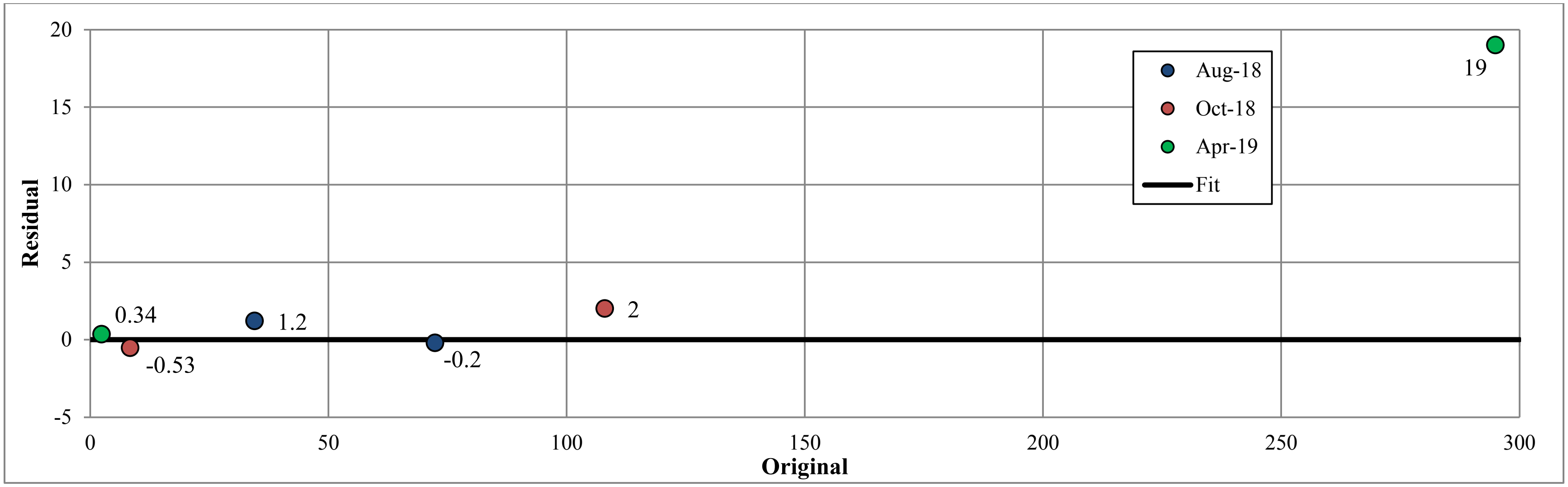


Figure V5 - Duplicate residual of turbidity testing conducted during the Aug 2018, Oct 2018, and Apr 2019 sampling round. (All values in NTU)