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# SUSTAINABLE WATER MANAGEMENT AT THE MCGILL MACDONALD CAMPUS FARM

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# SUSTAINABLE WATER MANAGEMENT FOR THE MCGILL MACDONALD CAMPUS FARM

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## ABSTRACT

*Without proper care, the quality of agricultural soil for monoculture degrades over time. However, good management can optimize yield and therefore profitability. This project aims to propose a better management plan for the Macdonald Campus Farm Field 86. After conducting a thorough analysis of the field data, with geospatial analysis tools and consulting different experts and farm staff members, we established that the field's main concern was related to water. Essentially, the field does not drain effectively and water accumulates reducing production. Establishing an effective water management plan is particularly challenging in this field, since it exhibits a very irregular topography and elevation differences of more than 9 meters. Additionally, emphasis was given toward choosing a solution that would mitigate contamination of waterways, often caused by conventional water management practices such as tile drainage. To solve the problem, we researched different water management possibilities and assessed their feasibility as well as respective environmental, social, and economical aspects. We concluded that the best possible solution was the creation of a recycling water system in addition to a surface and subsurface drainage plan. Thus, we designed two ditches and a pond using the weather data for our field as well as analysis tools, such as DRAINMOD, and water balances to attain this goal. The result is a well-defined drainage design which will most probably have beneficial social, environmental, and economic impacts on Field 86.*

**Keywords***:* drainage, irrigation, recycling drainage, Québec

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# REMARKS

Data analysis for this report was mainly achieved using programming language such as Python and R. The steps performed and the results obtained are described but the code is not presented. Access to the written codes as well as exact DRAINMOD input parameters can be requested to any of the corresponding authors.

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## *LIST OF ACRONYMS AND ABBREVIATIONS*

| | |
|---|---|
| American Society of Agricultural and Biological Engineering | ASABE |
| American Society of Agricultural Engineers | ASAE |
| Commission for Environmental Cooperation | CEC |
| Evapotranspiration | ET |
| Food and Agriculture Organization | FAO |
| Field 86 | F86 |
| Geographic Information System | GIS |
| Global Navigation Satellite System | GNSS |
| Global Position Systems | GPS |
| Institut de recherche et de développement en agroenvironnement | IRDA |
| Intensity Duration Frequency | IDF |
| Organic matter | OM |
| Plant Available Water | PAW |
| Power Take-Off | PTO |
| Real-Time Kinematic | RTK |
| Soil Moisture | SM |
| United State Department of Agriculture | USDA |
| United State Department of Agriculture Natural Resources Conservation Service | USDA-NRCS |

# 1. INTRODUCTION

Proper land and water management is crucial for sustainable agriculture with quality fields. Many issues can arise from poor administration such as loss of nutrients through runoff, soil compaction, noxious weeds, etc. For this project, we looked into the implemented water management systems at McGill's Macdonald Campus Farm (also referred to as the MAC Farm). Located on 205 hectares of land in Sainte-Anne-de-Bellevue MAC Farm is more than 100 years old and has been active ever since as a teaching and crop farming establishment. It is mainly producing forages and corn for the farm's animals but also cultivates soybeans as well as other fruits and vegetables at its Horticulture Research Centre. Even though it aims to be "an innovative leader at the cutting edge of agricultural technology" it desperately needs updates when it comes to its water management (McGill University, 2021). In effect, its installations for this purpose were poorly maintained and have not been upgraded in many years.

Therefore, we were quite interested in the opportunity to modernize the campus' farm, improve its fields overall quality and, ultimately, increase its crop yield. Designing a proper water management plan for all its fields would have been far out of the scope of this project, thus, we decided to focus on one particular field. After discussing our goals with the very helpful staff members of the MAC Farm, Mr. Paul Meldrum and Mr. Martin Chaumont, as well as our esteemed professors, Dr. Chandra A. Madramootoo and Dr. Viacheslav Adamchuk, we opted to study field 86 (F86). In view of the fact that this field presents water management problems and that a fair amount of data is readily available for us to use in our analysis.

Accordingly, our mission for this project is to improve yield and soil quality by analyzing different field properties to create a proper land and water management plan. We are guided by our vision to design innovative sustainable management solutions for overall field quality improvement. This report presents our journey in the accomplishment of our aims. First, a few key concepts are reviewed and described to facilitate the understanding of the later sections. Second, F86 issues are defined and explained in relation to the data we acquired. Third, potential impacts and solutions are thoroughly assessed and defended. Last, our final design is presented and its impacts assessed.

# 2. LITERATURE REVIEW

## *2.1. SOIL*

In order to optimize crop growth through improved water management strategies, it is first necessary to properly understand certain aspects of the field with which we are working and the basic requirements of a fertile soil. As such, this section of the literature review will provide an in-depth explanation regarding soil composition and its relationship with water, the main types of soil in our region of interest, the characteristics of an optimal soil for crop growth, and the price at which MAC Farm chosen crops can be sold. All this information will be orientated toward a better understanding of the main factors that must be accounted for during our design.

### *2.1.1. SOIL COMPOSITION AND WATER*

The soil composition and water relationship are crucial for proper agricultural water management since it is the determining factor in many decisions (chosen crop, period of sowing, etc.). In fact, soils are a combination of mineral solids, organic matter solids, water and air (Easton and Bock, 2016). Mineral solids are from geologic weathering, whereas the organic matter solids are from living organisms and plant and/or animal residues. Water and air fill the remaining empty space (pores) (Easton and Bock, 2016). The relative proportion of the three soil mineral solids (clay, silt, and sand) determines soil textural classes; this is depicted in Figure 1 (Smallholder Soil Health Assessment, 2020). Soils with a high sand content are classified as coarse-textured and soils with a relative proportion of 40% or higher of clay are classified as fine-textured; other combinations of the three soil constituents are considered medium-textured soil (Ritchey et al., 2015). Soil texture determination is crucial in agriculture since it affects soil drainage, water-holding and pH buffering capacities, soil tilth, aeration, susceptibility to erosion, and cation exchange capacity (Easton and Bock, 2016).

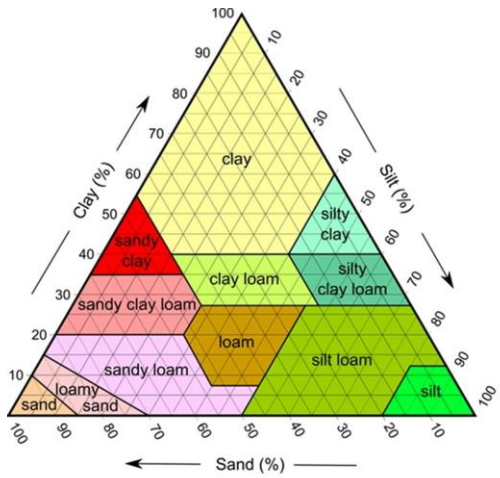
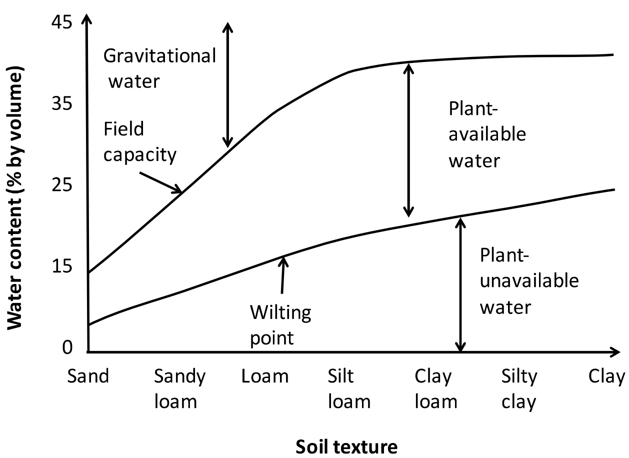



**Figure 1. USDA Soil Textural Triangle.** The United State Department of Agriculture Natural Resources Conservation Service (USDA-NRCS) created this figure to help determine soil textures using mineral solids proportion (Smallholder Soil Health Assessment, 2020).

Additionally, soil water content, or the amount of water held within its pores, highly depends on soil textures. Effectively, the water available to nurture plant growth, plant-available water, is computed by doing the difference between field capacity and the wilting point, which are properties affected by the soil texture (Easton and Bock, 2016). Field capacity is the water content present in a soil after it drains under gravity for approximately a day. Water content above field capacity is referred to as gravitational water and its availability for plant growth depends on environmental conditions (Easton and Bock, 2016). The wilting point is the minimum water content needed for crops to grow; below that point plants wilt or die (Kirkham, 2005; Easton and Bock, 2016). Figure 2 shows the relation between water content and the different soil textures. Therefore, soils with large plant-available water content and an amount of gravitational water that is similar to the amount of unavailable water are ideal for agricultural purposes; they drain efficiently, have enough water available for growth and are not readily at risk of droughts  (Easton and Bock, 2016). Consequently, loamy soils are highly desirable.

**Figure 2. Water Content vs. Soil Texture.** This graph shows the relationship between the water content, in % by volume, and the soil texture. Sand is the texture that holds the less water, silt loam has the most plant-available water and clay holds the most plant-unavailable water (Easton and Bock, 2016)



The adverse effects of excessive water retention include potentially anoxic conditions, drowning of the crops, and some difficulties accessing the field with machinery. Accordingly, the volume and content of soil air is a major factor for the optimal growth of crops and is directly linked to the drainage of the field (Kokulan, 2019). It should also be noted that, usually, soils where excessive tilling methods and heavy machineries are used tend to be more compacted. Soil organic matter (OM) gives water-holding capacity, permits slow release of nutrients for crop growth and generally improves soil structure. Explaining why it is regarded as beneficial for agricultural purposes. However, tilled fields tend to contain a lower proportion of OM (Easton and Bock, 2016).

At last, water absorption depends on soil compaction level and microstructure. Hence, irrigation and rainfall will be absorbed differently depending on the amount of water already in the soil and the rate of water application. For instance, small rainfall events on a dry soil will not penetrate the soil and irrigation will not be efficiently absorbed if a large quantity is applied at once (Huffman, 2013).

### *2.1.2. Soils in Quebec*

The main designated provincial soil in Quebec is “Sainte-Rosalie" soil. This soil has high clay content, which helps retain considerable amounts of water during dry periods. However, this high clay content can retain an undesirably large amount of water during the rainy season, which increases the need for proper drainage systems. . Nevertheless, it is known for being a very suitable soil for the growth of hay, corn, and soybeans (Government of Canada, 2020b). Additionally, there are multiple soil orders in Quebec, each with specific characteristics. The most dominant soil order in the province is Podzol, which covers approximately 39% of the territory. It is mainly composed of the Humo-Ferric great group and is concentrated in the northern part of the province. The second most dominant one is the Brunisol, covering about 17% of the land. This order is mainly composed of the Dystric great group, which mainly occurs in the Taiga and Boreal Shield Ecozones. Although, our project is meant to be implemented in southern Quebec, near Montreal, where the soil consists mainly of Humic gleysol (Moore, 2021). Gleysolic soils are resulting from prolonged water saturation and are mainly found in the Saint-Lawrence River lowlands. Again, this type of soil is characterized by a rich clay-content, leading to large amounts of water retained in the soil and potential drainage issues. Furthermore, the Humic subgroup is created by water erosion or tillage translocation (Canadian Society of Soil Science, 2020). Hence, the soil around Montreal is prone to drainage issues caused by the excessive retention of water.

Moreover, it is important to find efficient drainage solutions in Quebec since the area of fertile land is highly restricted. Out of the 1 million square kilometers of soil in Quebec, there are only about 600 square kilometers of class 1 soil, 10,000 square kilometers of class 2 soils, and 13,500 square kilometers of class 3 soils. Class 1 soils are the most auspicious for agricultural activities; they do not have significant limitations for crop growth. Class 2 soils have moderate limitations for crop growth and class 3 soils have severe limitations for crop growth. Overall, this means that approximately 88% of the fertile land in Quebec is dedicated to either cropland or pasture (Moore, 2021). Such information emphasizes the necessity for proper management of the available fertile land in Quebec.

#### *2.1.3. Corn and Soybeans Particularities*

One of the advantages of growing corn and soybeans on the same field is that they both require similar conditions to attain optimal growth rates. In fact, both corn and soybean require a loose, well-drained, and medium-textured soil. Also, it is reiterated that well-drained soils tend to be optimal for the growth of those crops; poor drainage leads to detrimental growth conditions. Furthermore, both crops require a soil with high organic matter content and sufficient water-holding capacity. Such characteristics are provided by the medium-textured soil. However, corn and soybeans requirements for optimal growth regarding temperature are slightly different. Corn requires a temperature of 75 to 86 degrees Fahrenheit, whereas soybeans can start germinating at temperatures as low as 55 to 60 degrees Fahrenheit. This being said, higher temperatures mixed with intermittent moderate rain, or irrigation, tend to further optimize the growth rate of such crops (Willis, 2019b; Willis, 2019a).

Furthermore, the price at which these crops are sold will be necessary to assess the profit pertaining to our project. Hence, it is primordial to have a sense of the price at which corn and soybeans are sold on the Chicago Board of Trade. However, the prices are constantly changing but we can approximate that a bushel of corn can be sold for 5 to 6 USD (Trading Economics, 2021a) and a bushel of soybeans can be sold for 12 to 13 USD (Trading Economics, 2021b).

### ***2.2. Climate Change Impacts on Agriculture and Water Management***

Agriculture depends largely on weather conditions and is therefore very sensitive to climate change. As explained previously, corn and soybeans need optimal water supply, sun exposure, and temperature to achieve maximum yield. Additionally, many calculations and estimations in agriculture and water management are based on climate data. Hence, it is essential to consider future changes in weather to create a durable and resilient design. Consequently, expected precipitation, temperature, and drought and their possible consequences on crops growth will now be reviewed.

Mean temperatures worldwide are increasing due to climate change; in Canada, a rise of about 1.7ºC was reported in 2020. This trend is not expected to stop, and more days over 30ºC are anticipated during summers (Government of Canada, 2020a). Yet, Almaraz et al. (2008) noted that temperatures over the average were generally less detrimental to corn growth than temperatures under the average. In fact, rising temperatures, mostly in the spring, could be beneficial to corn and soybean growth, as they would allow for earlier sowing and consequently a longer cultivation period. Likewise, corn and soybeans are grown in warmer climates, such as in the United States, with no major problem other than a need for irrigation (Huffman et al., 2013; Kelley, 2018). Overall, temperatures are rising in Quebec, but it should not prevent anyone from growing forage crops.

Even if precipitation patterns are changing at some locations, there is no clear trend in Quebec (Almaraz et al., 2008). Yet, the Government of Canada (2020a) seems concerned about an increase in early spring rain, as it could delay the beginning of growing seasons. Likewise, the study by Almaraz et al. (2008) correlated high May precipitation with lower yearly corn production. Hence, precipitation might be changing, but it is not clear exactly how.

Drought is becoming a major concern in agriculture as it can destroy harvests. In Almaraz et al. (2008) analysis, two of the lowest yield years in Monteregie were associated with major drought events. Quebec's agricultural lands around the Saint-Lawrence River historically have a generally very moist climate but can still be dry during the summer months. Furthermore, as most fields are drained, they are more vulnerable to drought (Mejia et al., 2000). If the Province's higher temperatures might not be that concerning for plants directly, they still will increase evapotranspiration. Since precipitations are not changing, this might positively affect soil water deficit. Yet, the Government of Canada (2020a) mentioned that the losses due to evapotranspiration could be balanced by more effective use of water resources due to higher CO2 levels. Furthermore, if an increase in drought is already happening in western Canada, the situation in Quebec is not evident. Moreover, a 2016 report of the forestry sector registered no noticeable change in drought in the province. Yet, it mentioned that it has expected to happen at one point (Lajoie et al., 2016). Additionally, the summers of 2020 and

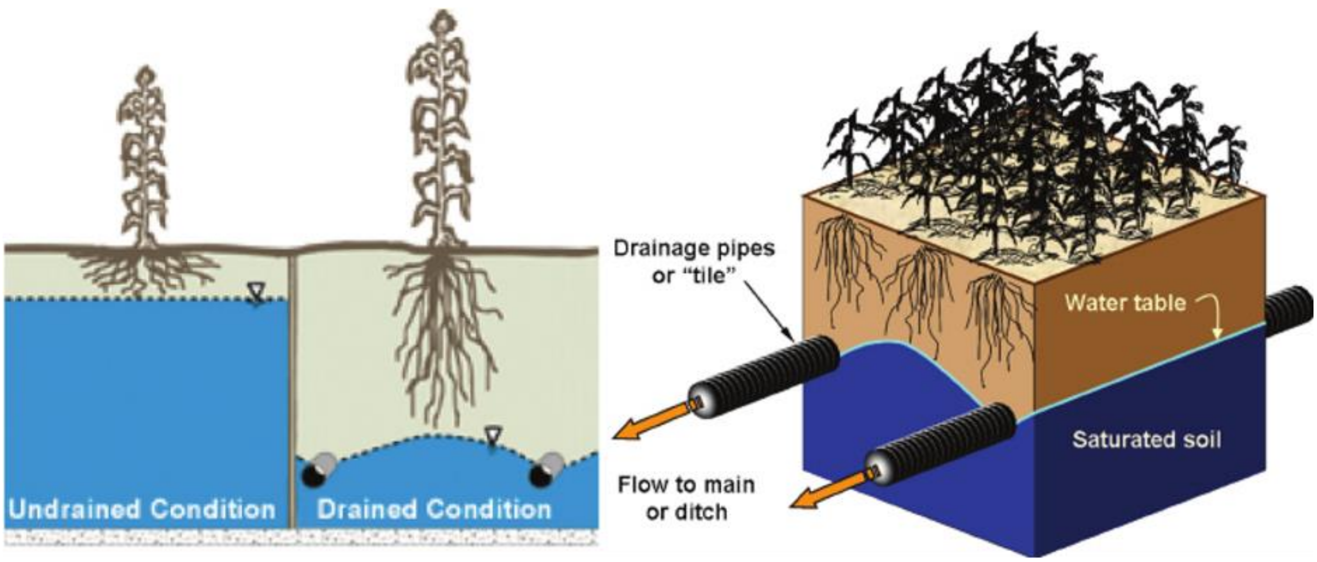
2021 both had undergone major heat waves and historical droughts (Ministère de l'Environnement et de la Lutte contre les changements climatiques, 2020, 2021). In brief, it is not obvious exactly how and if droughts will become a major issue in Quebec.

## *2.3. DRAINAGE*

Drainage is an agriculture practice used to remove excess water and prevent flooding's consequences on crops and soil quality. Due to its numerous benefits in agriculture, it is used extensively within Canadian and American Temperate climate zones (Kokulan, 2019). In Canada, 14% of croplands use subsurface drainage, most of which are in Ontario and Quebec, where F86 is located (Easton et al., 2016; Kokulan, 2019). To better understand this practice and verify what can be applied to our project, this section starts by exploring the difference between the two conventional types of drainage: surface and subsurface drainage. We will then overview the benefits of drainage and describe other solutions, such as best management practices, alternative forms of drainage and complementary methods.

### *2.3.1. CONVENTIONAL DRAINAGE PRACTICES*

The two most common drainage practices are surface drainage and subsurface drainage (Huffman, 2013). Surface drainage consists of shallow surface drains, ditches, and vegetated waterways to evacuate surface water whenever it accumulates, during the spring as the snow melts or during rainfall events (Huffman, 2013). Shallow surface drains can either be put at an equal parallel distance or laid out more randomly. The second option is mostly used to adapt to field irregularities such as potholes and depressions. Incorporating vegetation in ditch design is significant as it can help with erosion and water quality (Huffman, 2013). Subsurface drainage, commonly referred to as tile drainage, consists of putting porous pipes, usually made of corrugated plastic, under the ground to lower the water table, as illustrated in (Easton et al., 2016). Surface inlet, open tubes at the surface connected directly to underground drains, can be added at problematic locations such as depressions and potholes to optimize water removal. Surface drainage can be used by itself, but subsurface drainage always has to be enhanced by the primer (Huffman, 2013).




a) b)

**Figure 3. Subsurface Drainage.** This figure illustrates the difference in water table height with and without tile drainage. a) shows how plant roots go deeper under drained conditions than they would under undrained ones. b) illustrates a typical tile drainage system (Blann et al., 2009)**.**

### *2.3.2. Drainage in Quebec*

As this project takes place in southern Quebec, it is important to discuss the main water management practices employed in agriculture in the province. In the eastern Canadian provinces, the climate is moist and temperate. In the spring, it is not unusual to experience excess soil water that can delay tillage operation due to limited vehicle mobility in the field. Flatter areas with low hydraulic gradients to watercourses and compacted soil with rather low hydraulic conductivities are the most impacted. From the beginning of agriculture in Canada, surface drainage was used. In fact, open field ditches were placed parallel to the land to receive its excess water. This is still done today. However, this technique is not sufficient to handle all the accumulated water and creates logistic problem, such as difficult access to the field the machinery (Madramootoo et al., 2007). Thus, subsurface drainage is now generally used in combination with surface drainage, ditches (Gagnon et al., n.d.; Madramootoo et al., 2007). It was introduced in the 1940s, but it was only from 1960 to 1990 that the system was installed in most fields. This is mainly due to financing programs from the government to support farmers in installing subterranean drains. Subsurface drainage showed great results in Quebec such as increased yield, increased fertilizer uptake, reduced cost, etc. (Gagnon et al., n.d.). Nevertheless, the province is not immune to the typical drainage problems. Algae bloom, the presence of *E. coli* in drains and nutrients pollution are issues that also plague agricultural practices in Quebec (Madramootoo et al., 2007).

### 2.3.3. *Benefits of Drainage*

As mentioned earlier, drainage is very popular because it has many benefits that increase farmers' revenue. The most noticeable benefit is yield gains and, consequently, profit. In brief, it prevents damage related to prolonged exposure to water. Tile drainage effect water has the extra benefit allowing roots to grow deeper by lowering the water table and increasing access to well oxygenated soil (Huffman, 2013; Easton et al., 2016). Additionally, tile drainage extends the growing season by increasing the speed at which the snow melts and the resulting water absorption rate, thus allowing the field to dry earlier in the spring. Surface drainage is not as efficient but does accelerate water evacuation once the snow is melted. It is important to note that machinery cannot go on wet areas without risking getting stuck and that wet soil is more vulnerable to compaction (Easton et al., 2016). Drainage, therefore, allows farmers to access their fields and sow earlier, which typically increases yield and income. Moreover, it reduces year-to-year variability and can help reduce surface runoffs and, thus, diminishes erosion (Easton et al., 2016). Also, drainage increases nitrification by making nitrate more readily available to plants allowing once again yield amelioration (Kokulan, 2019). Finally, it can make conservation practices such as reduced tillage and residue cover even more efficient (Easton et al., 2016). Overall, subsurface drainage usually provides higher yield increases than surface drainage; yet, since it is more costly, the latter option should be considered first (Huffman, 2013).

### 2.3.4. *Best management Practices*

Pertaining to the many issues related to tile drainage, alternatives have been developed in recent years. Mainly, tile drainage increases fertilizer loss to waterways, which creates many problems such as algae bloom; a drainage issue that will be covered in further detail in a later section of this paper. Thus, because of the growing environmental concerns, Best Management Practices (BMPs) are becoming increasingly important. Applying BMPs is mostly to consider the impacts on soil and water quality in your decision process (OMAFRA, 2021). Two simple examples of BMPs are using the right amount of fertilizer, pesticide, and herbicide at the right time and reducing tillage (Easton et al., 2016; Kokulan, 2019). Another example of BMPs that can help with water management issues is winter forage or cover crops  (Frankenberger et al., 2004).

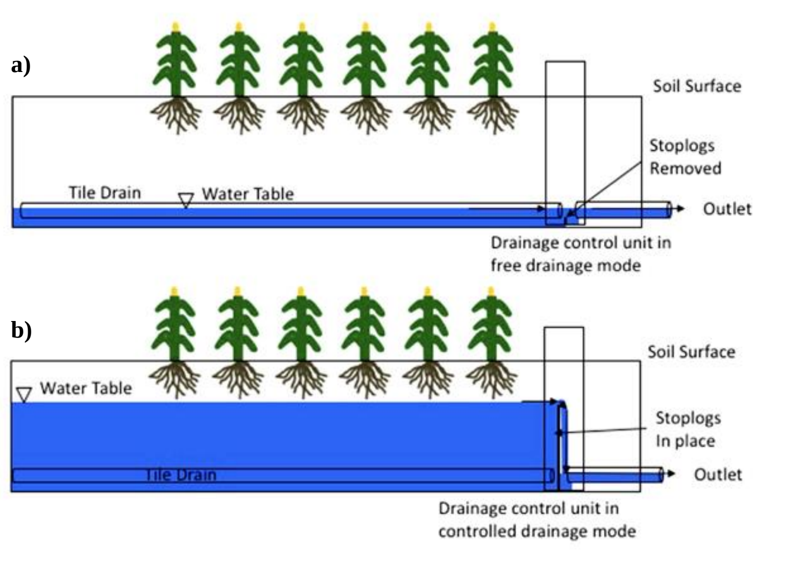
### 2.3.5. *Drainage Alternatives*

Additionally, both to improve the environment and to be more resilient to climate change, some drainage innovations have been developed. First, it is important to realize that drainage needs vary over the seasons, spring and fall usually being peak times as opposed to summer, when concerns are more toward water deficit than excess (Huffman, 2013). Those varying needs are expected to become more prevalent with the changing climate because of the predicted more frequent and intense precipitation events as well as longer droughts (Transforming Drainage, 2021). Consequently, Transforming Drainage is an USA based group concerned with the impacts of climate change on agricultural water management and of drainage on the environment. They are currently studying three drainage practices that could help: controlled drainage, recycling water and saturated buffers (Transforming Drainage, n.d.). In addition to these new techniques, water filters such as woodchip bioreactors can be used to treat the outflowing water and reduce fertilizer concentration (Kokulan, 2019).

**Controlled drainage, as illustrated in**

Figure 4, is based on regulating the water table height depending on the plant needs. It uses a structure that allows the water to drain up to the desired height (Kokulan, 2019). This way, water is only released when necessary. Thus, it can reduce nitrogen loss to waterways by 15% to 75%, and, by keeping more water, diminish the need for irrigation if drought occurs (Frankenberger et al., 2004). The usual pattern is to lower the water table in the spring to allow the snow to melt and the field to dry. Then, raise it after sowing to adjust it to the crops' needs and, finally, raise it after harvesting before winter to limit nitrogen outflow (Frankenberger et al., 2004). However, this system works only on a relatively flat field, the water table should not vary more than one or two feet. Nevertheless, it can be separated in different controlled areas of ten to twenty acres (Frankenberger et al., 2004). It is unclear if it can increase yield more than free drainage; it depends significantly on the field's properties and climate conditions. However, in Ontario, increased gains were observed for soybeans and corn production (Kokulan, 2019).

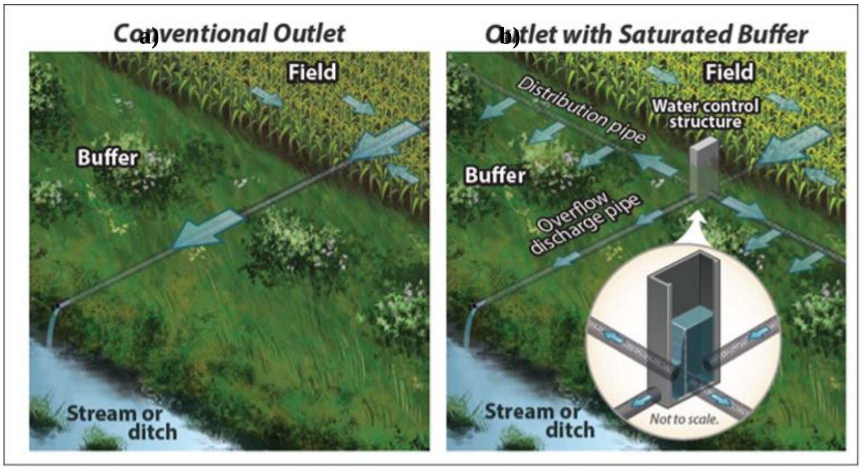
**Figure 4. Controlled Drainage.** This figure demonstrates a controlled drainage structure and how it can be adjusted to crop's needs. The top image illustrates a typical spring scenario in which the structure allows a maximum of water out of the field. The bottom image illustrates the opposite scenario in which the structure is raised to preserve water.




Recycling water is the idea of storing drainage water in a pond to use it when irrigation is needed; water is only released in nearby waterways when it exceeds the pond storage capacity (Frankenberger, 2017). Since it is a closed-loop system, it prevents fertilizers from leaching in the surrounding waterways. In addition, the vegetation and wildlife present in the pond naturally removes some fertilizers and pesticides. As an example, on the Transforming Drainage Ohio research site on recycling water, the nitrate concentration was reduced by 28% (Frankenberger, 2017). This particular site also contains a wetland added to the pond, which both filters water and compensates for the losses created by the drainage (Kokulan, 2019). Another benefit is that, since the water is stored locally, it can help reduce the amount of outflowing water in neighboring fields, a problem often encountered in drainage designs (Frankenberger, 2017). However, there is, as of now, not a lot of research done on recycling water and it is difficult to know the exact benefits and drawbacks of such systems. Careful analysis and a lot of work would be needed to create a recycling water system. In addition, there are concerns regarding e-coli proliferation in ponds (Kokulan, 2019).

A Saturated buffer is an installation that allows drainage water to reach the outlet (stream or ditch) more slowly and to be filtered by vegetation and microorganisms (Jaynes, 2018). As illustrated in Figure 5, it consists of a water control structure that can divert drainage water to a perforated distribution pipe located parallel to a stream or a ditch (Jaynes, 2018). When there is too much water, the structure lets the water reach the stream directly to prevent flooding in the field. The distribution pipes let water infiltrate the buffer so that it slowly reaches the stream. The buffer is a piece of land, with a minimum width of 30ft, in which typical vegetation grows. When water flows in, denitrification and plants intake reduce nitrate concentration (Jaynes, 2018). Additionally, since the water reaches the stream slowly, the buffer diminishes the speed in the waterway, thus reducing erosion (Huffman, 2013). The soil type of the buffer has to be either clay or loam, as sand and silt let the water go too fast. In addition, it needs to be situated lower than crops to effectively drain the productive part of the field (Jaynes, 2018).

**Figure 5. Saturated Buffer.** a) shows a conventional tile drainage outlet, b) shows a tile drainage system with a saturated buffer. A close-up illustration of the water control structure used in the system s also showns in b) (USDA, 2018).




### 2.3.6. *Complementary Method: Laser Land Levelling*

In addition to drainage methods, laser land levelling is commonly used practice for better water and land management. In fact, laser levelling decreases irrigation water requirement for surface drainage by evenly distributing water and increasing other farming practices efficiency (Manpreet-Singh et al., 2020). According to different studies, it also leads to greater field productivity, better crop growth and yield, saves time and water as well as enhanced general productivity of the farm (Larson et al., 2012; Aryal et al., 2015; Manpreet-Singh et al., 2020). However, in the presence of very uneven fields with notable hills and valleys, this procedure is not ideal; moving around large volumes of soils is very costly and damaging to the overall field quality in addition to sometimes being impossible (shallow bedrock). If performed, land-levelling plan should be done prior to any drainage design.

## 2.4. *IRRIGATION*

Crops need enough water to achieve maximum yield, which explains the widespread use of irrigation in agriculture. In very dry climates, it is indispensable for plant survival, but in Quebec's climate, corn and soybeans can thrive without it. Likewise, irrigation can be expensive and rarely worth it on low-value crops, such as the ones grown in field 86. However, irrigation will be considered due to the risks of drought and the possibility of using a recycling water system. Hence, the main irrigation methods used, and the variety of crops irrigated in Canada will be explored. Afterward, an overview of the potential of surface irrigation due to climate change will be done. Finally, this section will mention the benefits of sub-irrigation in Quebec.

The most commonly used irrigation technology in the United States and Canada is sprinklers (Ansieta & Marzook, 2021; Huffman et al., 2013). Sprinklers are quite versatile since water outflow and duration can be easily adjusted. Additionally, they can be used to apply fertilizer. Moreover, they are easy to install and can be moved either manually or mechanically. Major issues with sprinkler irrigation are initial cost and labour. Finally, other methods exist, such as drip or surface irrigation but are less common (Huffman et al., 2013).

Based on the 2014 Canadian Water Survey, Quebec is the Canadian Province that irrigates the less. Besides, irrigation seems to be only used for high-value crops such as fruits and vegetables: the survey did not report any data regarding irrigation of forage crops. Nevertheless, a simulation of irrigation requirements based on South-western Quebec's climate reported seasonal needs of about 146.6 mm for corn and 210.5 mm for soybeans (Gallichand et al., 1991). Hence, there seems to be a potential for higher yield in the province if irrigation is to be used. Yet, as explained by Mejia et al. (2000), Quebec farmers generally do not irrigate these crops simply because the amount of labour and cost is not worth the benefits.

Although the Province does not irrigate forage crops at the moment, climate changes might press farmers to begin doing so. In fact, it is done extensively in dryer, yet similar climates, such as in the American State of Michigan (Kelley, 2018). Though warmer, both regions are classified in the same ecoregions, meaning that this state could be a good proxy for Quebec's future conditions (CEC, n.d.). In Michigan, irrigation in July is indispensable to optimize corn yield. Likewise, the Quebec agriculture research firm IRDA recently began an experiment to test irrigation potential on forage crops in the province. This clearly shows a renewed interest in grain and hay crop irrigation. In a videoconference, the research director Carl Boivin stressed the need for further research in that field (Centre d'expertise en agriculture biologique et de proximité, 2021). In brief, there is interest in irrigation of lower value crops, but we will need to wait to get any good insight on its profitability.

Sub-irrigation has been proposed as a cheaper alternative to surface irrigation in Quebec (Mejia et al., 2000). As controlled drainage, sub-irrigation is considered a water table control management. However, it is not the exact same procedure, as it requires pumping water back into the rooting system through the subsurface drains. It is advantageous in Quebec as it uses the already installed underground drainage pipes and is quite low in labour. Likewise, it can reduce nitrate leaching as it does not create runoff and can increase yield, like other irrigation practices (Mejia et al., 2000). A flat field is needed to use this type of irrigation. Marmanilo et al. (2021) recently published an economic analysis in Quebec and in Ontario on grain-producing farms using sub-irrigation. The study concluded that although the economic gain was marginal, the possible benefit on water quality makes it worth the extra effort. Moreover, the government could encourage the practice by creating incentives for better management. In a few words, sub-irrigation seems to be one of the best solutions for the irrigation of low-value crops but needs more support to be adopted by farmers.

In conclusion, corn and soybeans are very rarely irrigated in Quebec. Yet, climate change possible impact on water availability is pressing researchers to assess the potential of forage crops irrigation. Likewise, the cheaper practice of sub-irrigation seems to be a good alternative but can only be done in flat fields.

## ***2.5. Tools for Water Management Design***

### *2.5.1. Geographic Information Systems (GIS)*

Many tools are available to help design water management strategies. For this project, sensor collection of data, global navigation satellite system (GNSS), geographic information systems (GIS) as well as programming languages are among the most useful. In fact, sensors are increasingly important in agricultural procedures; they permit the collection of reliable field physical and chemical data (Chapungo and Postolache, 2021). Often the data gathered are geolocalized due to the fact that global position systems (GPS) are simultaneously used at the moment of collection. This provides the users with localized precise data that can be put through different software, often GIS. These software were developed to collect, store, manipulate, analyze and display all forms of geographically referenced information. It is a computer-based system and different programs exist that make use of it (ArcGIS, QGIS, CAD, etc.) (Li et al., 2021). Finally, programming languages, such as Python, enable the processing of large amounts of data efficiently. Altogether, these tools help the creation of precise and effective agricultural management alternatives.

### *2.5.2. DRAINMOD*

The main software used for water management throughout this project was DRAINMOD. This simulation software was developed in 1980 and is mainly used to simulate the soil hydrology (NC State University, 2022). It allows the user to input precise day-to-day data for the precipitation, evapotranspiration, and temperature at the location of the field as well as the soil type and layout of the drainage system. The outputs that can be obtained from this software include, among other, surface runoff, drainage, infiltration, and water table depth (Singh et al., 1996). Due to the high precision of data that can be inputted in the software, it can provide tailored result almost anywhere in the world. For the past 30 years, DRAINMOD has been used effectively for a variety of reasons in eastern Canada as seen in Prasher et al. (1994), Helwig et al. (2002), Dayyani et al. (2010), Golmohammadi et al. (2016) and Jiang et al. (2018). Some of the sites used for these papers are at the Macdonald Campus Farm, since some of their authors are faculty members.

# 3. PROBLEM DEFINITION

As previously mentioned, the MAC Farm is also a research and teaching establishment, therefore, a lot of data exists on its fields and management. This was highly beneficial for us as it provided us with most of the data we needed. By having soil analysis results, topographic data, yield data and drainage maps, in addition to Government Canada's weather data, we had enough information to properly assess the state of F86 and its problems

## *3.1. FIELD DESCRIPTION*

Field 86 is situated north of the highway 40 and of the Ecomuseum Zoo as well as east of the Arboretum in Sainte-Anne-de-Bellevue. Its western and northern borders are shared with a wooded area, whereas only a few trees line its eastern border. The southern border follows the farm road; see Appendix 1 for the map. In all, F86 has a roughly rectangular area of 13.6 ha rotated approximately N27°W, as seen in Figure 6.

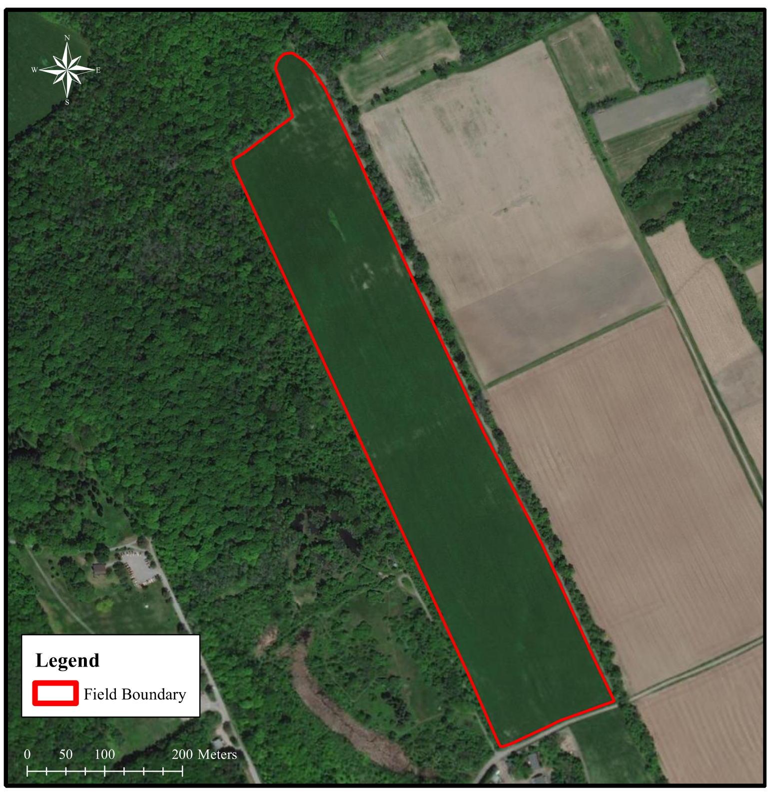



**Figure 6. Map of F86 Borders.** This figure shows F86 an its surroundings, in red are its borders. This map was created by our team using ArcGIS and the data provided by Dr. Adamchuk.

### *3.1.1. Soil Type*

The soil type information comes from a survey of the MAC Farm completed in 1971. For the purpose of this project, and since soil type does not drastically change over a period of 50 years, we assumed that the data provided are still representative of F86 (Veenstra, 2010). The data showed that the main soil textural class of F86 is loam (57%) while fine sandy loam (15%), clay (14%), clay loam (8%), loam sand (5%) and sandy loam (1%) covers the remaining areas, this is summarized in Table 1 and illustrated in Appendix 2. Clay loam, fine sandy loam, loam, and sandy loam are considered medium-textured soil, whereas clay soil is considered fine-textured and loamy sand soil is considered coarse-textured. Clay, loamy sand and sandy loam soils are present in lower parts of the field, whereas no clear correlation can be made for the other soil textures. This information is crucial for water management solutions as water travels differently through each soil class.

| Soil Type | Area ($m^2$) | Area (%) |
|---|---|---|
| Loam | 81476.3 | 57% |
| Fine sandy loam | 20901.25 | 15% |
| Clay | 20114.90 | 14% |
| Clay loam | 12225.08 | 8% |
| Loam sand | 7243.33 | 5% |
| Sandy loam | 2118.78 | 1% |
| **Total** | **144079.64** | **100%** |

**Table 1. F86 Soil Types.** This table summarizes the different soils present in F86 and the area they cover.

### *3.1.2. Elevation*

Field elevation data were collected with a Real-Time Kinematic (RTK) GPS in 2013. We are not aware of who did the survey or in what context it was demanded. Figure 7 shows the interpolated elevation map of F86, which was obtained by performing a Kriging Interpolation on the RTK-GPS point data, details of this operation can be found in Appendix 3. As a result of the computations, we know that our field has a difference in elevation of about 9 m, with the highest point being at 15.48 m and the lowest at 6.27 m. However, it is far from being uniformly distributed: it is not a steady slope starting from one to the other. In fact, as you can see from Figure 7, we noted three distinct elevated areas and a lower plane at the northern end of F86. This irregular elevation will cause water to accumulate in the little valley created and affect surface water displacement speed. Together creating additional challenges for water management and influence drainage design. F86 can be divided in three distinct watersheds, as seen in Figure 8.

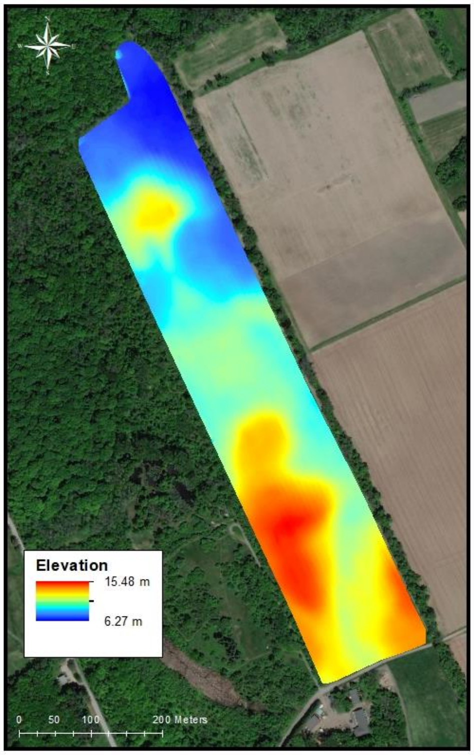



**Figure 7. F 86 Elevation Map.** This map shows the difference in elevation of Field 86. The warmer (red) the color, the higher the elevation and the colder (blue) the color, the lower the elevation is. The highest point of the field stands at 15.48 whereas the lowest point is at 6.27m. Our team created this map using ArcGIS and the elevation data provided by Dr. Adamchuk.


**Figure 8. F86 Watersheds.** This figure presents the three distinct watersheds of field 86. This was created using public data from the government of Quebec and using QGIS.

### *3.1.3. Soil Properties*

Soil analysis was performed last year, in 2020, as well as in 2015. We are assuming that both were done by the agricultural services company Logiag inc. In 2020, 15 soil samples were taken, whereas 52 samples were collected in 2015, all samples were geolocalized, which helps establish field zone characteristics. Effectively, different soil properties were reported such as organic matter content, pH, cation exchange capacity as well as the soil nutrient content (P, K, N, Ca, etc.). In 2015, bulk density and moisture content were additionally recorded; the results of both soil analyses can be found in Appendix 4 and Appendix 5. After studying the data, we could not foresee that soil properties would be the major yield-limiting factor. In fact, Dr. Adamchuk and Mr. Martin Chaumont, both confirmed that it would be very unlikely for the nutrients, and other soil properties, to be problematic since the farm always follows recommendations from certified agronomists.

### 3.1.4. *CURRENT DRAINAGE SYSTEM*

The state of the current drainage installations is quite uncertain, Figure 9 shows the current subsurface drains layout but its current state is quite uncertain. In effect, we are not aware of the exact condition or of the age of the drains. We know that work was performed in 1967, 1970, 1976 and 1997; Appendix 6 presents more information. However, some subsurface drains were inspected last summer and were confirmed clogged. When walking in and around F86, we did not notice any surface drainage, no ditch or surface drains. Mr. Chaumont again confirmed our observation.

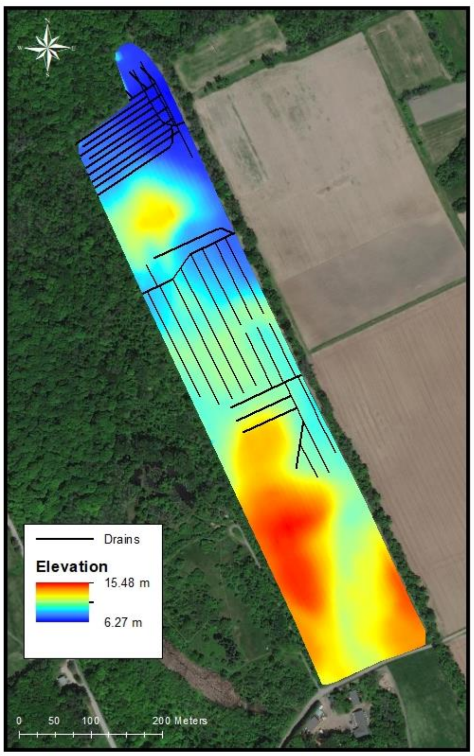



**Figure 9. F86 Elevation and Drainage.** This map shows Figure 7 with the current tile drains shown on it. Dr. Adamchuk provided the data used to create this map.

Given the uncertainty, Mr. Chaumont was our main reference for the current drainage problems of F86. In fact, he described how the water tends to accumulate at the surface in lower areas and pointed out that the entirety of the field drains very poorly. He mentioned clogged drains and problems with the existing water outlet. Effectively, the collectors' outlet is quite far from F86 as it is close to the neighbourhood east of the field. Furthermore, he explained that, in the springs, the field receives a lot of water from the melting snow of the Arboretum and, adding to the poor drainage, it sometimes prevents fieldwork, delaying soil preparations and sowing. A recent visit to the field confirmed the accumulation of surface water, even after the snow has been gone for weeks, see Figure 10.

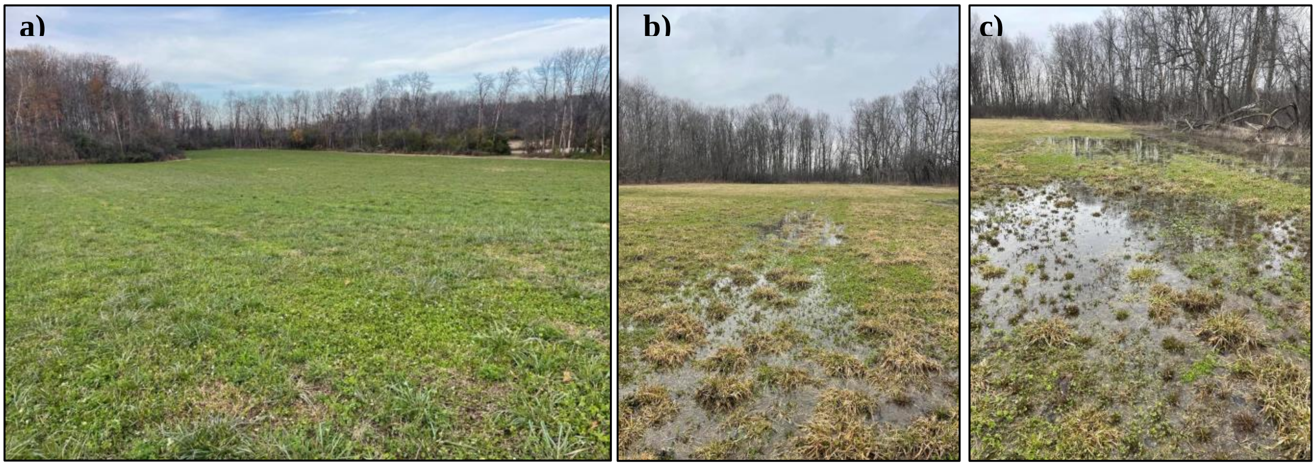


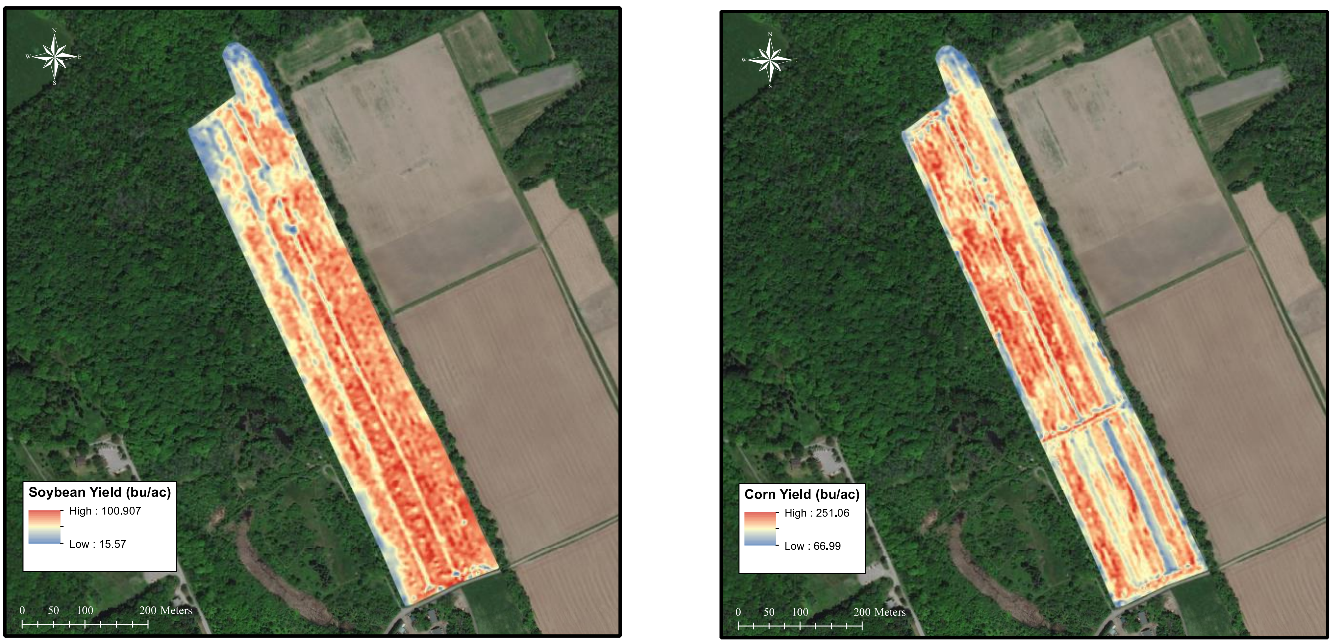

**Figure 10. Site Pictures.** Figure 10a shows the field the northeast corner of the field in late September. The soil surface was dry and no accumulation of water could be seen. The figure 10b and 10c show the same corner in early April. The soil surface was soft, sponge-like, and a lot of surface water was present. These were taken by us during field visits.

### *3.2.Yield Information*

Yield data are collected every year by the MAC Farm staff when harvesting. We were able to obtain precise yield data for 2015, when soybeans was cultivated and in 2016, when corn was planted. We do not have data for 2017 but we have the average yield data for the last four years (2018 to 2021), when the field was cultivated for hay or silage (Table 2 shows yields summary). However, for the purpose of this project, precise yield data are much more useful since tells us exactly where are the low yield areas of the field; it helps us pinpoint where problems. Again, we interpolated the geoferenced point yield data to create the yield maps shown in Figure 11. Low yields tend to be found in lower areas as well as close to the field borders, which is typical. Overall, no important problem can be seen with those maps. When looking at the field yield average for both 2015 and 2016, respectively 4,467 kg/ha and 10,808 kg/ha, we see that they are above the Quebec's yield average of 2,900 kg/ha and 10,000 kg/ha (Statistique Canada, 2021). Thus, F86 is overall quite suitable for both productions, based only of those two years of harvest; Mr. Chaumont, who agreed that those crops were never harshly impacted by the field's conditions, verified this assumption. However, he mentioned quite a few problems when it came to cultivating alfalfa. He stated that on lower, wetter, areas, alfalfa struggles to grow and often dies, creating bald patches in the field.

| Cut\Year | 2018 (kg) | 2019 (kg) | 2020 (kg) | 2021 (kg) |
|---|---|---|---|---|
| 1 | 42 550 | 23 230 | 164 210 | 139 910 |
| 2 | 199 490 | 72 460 | 22 650 | 82 820 |
| 3 | | 119 280 | 62 890 | 55 980 |
| 4 | | 21 230 | 70 350 | 35 280 |
| **Average (kg/ha)** | **8 399.52** | **4 098.43** | **5554.22** | **5448.20** |

**Table 2. Yields for 2018 to 2021.** This table summarize the total yield for each cuts of year 2018 to 2021, in kg. In red, they cultivated a mix of alfalfa and sundangrass and, in blue, it was a very wet spring. The last row shows an average per ha for the year.




a) b)

**Figure 11. Yields for 2015 and 2016.** a) shows the soybeans yield map of 2015 and b) shows the corn yield map of 2016.

### 3.2.1. *Soybeans and Corn Yield Correlation*

As previously discussed, it is unlikely that the soil content and properties impact the field enough to significantly negatively affect the yield. Nevertheless, using RStudio, we decided to statistically assess the data to verify that a correlation could not in fact be established. First, to identify which correlation method to employ, normality of the data was estimated using a quantile-quantile plot. Based on the results shown in Appendix 7, for all the field properties observed, normality was confirmed. Thus, it was possible to use the Pearson correlation. This method measures the strength of the linear relationship between two variables, in this case, the yield and a soil property. This computation was mainly to verify if we should further investigate the soil nutrient content. We are aware that the testing of linear relationships is a big approximation of the real relationship that exist between soil properties and yield. Nevertheless, we deemed it satisfactory for the purpose of this project and the correlation matrix that resulted from our analysis, show very little correlations, as shown in Figure 11.

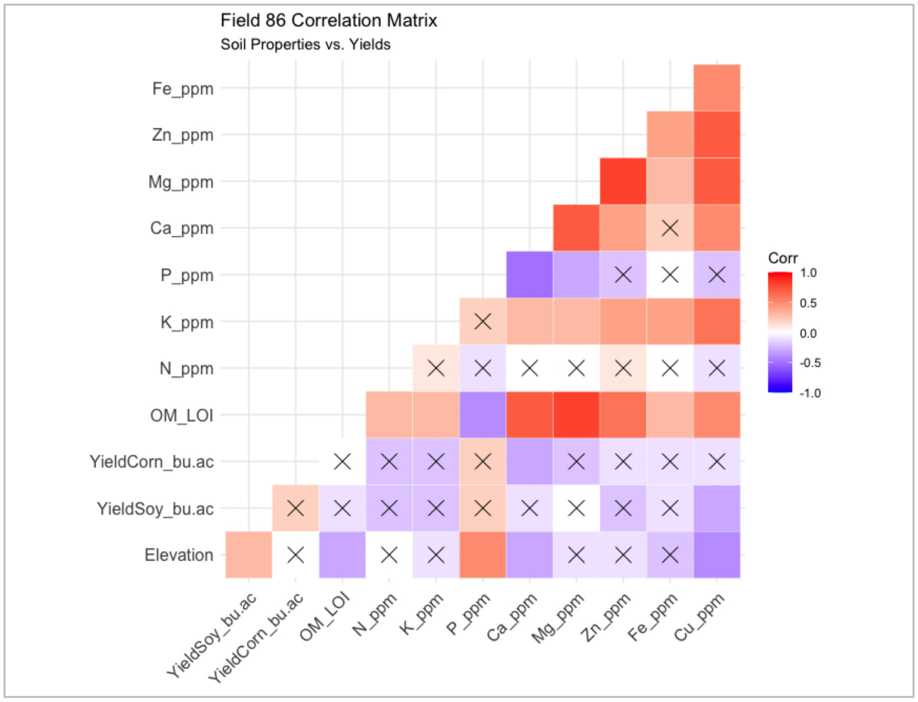



**Figure 12. Correlation Matrix.** This figure shows the results for the Pearson correlation analysis that we performed using RStudio.

### *3.3. WEATHER INFORMATION*

We decided to analyze the local climate conditions in Sainte-Anne de Bellevue since climate predictions were not particularly precise for our site. We focused on historical data and noticeable change, as well as on climate predictions to improve our design resilience. The goal was to determine if we needed to select water management features that mitigate climate change. We also wanted to verify if we could base our design on historical data or if we will need to adjust it to predictions. Finally, we wanted to see how the weather was related to yield variability. This section will first explain the method used to analyze the data. We will then look at our results regarding temperature and precipitation.

### 3.3.1. *Method*

We downloaded all the data from the Government of Canada historical climate data website. Most were recorded at the Sainte-Anne de Bellevue weather station, about 500m from our field. Since the maximum period we could download manually was a month, we created a Python code to download multiple CSV files simultaneously and join them. We based the code on a similar work by Siang Lim, a UBC Computer Science and Engineering graduate (Lim, 2017). We were able to get hourly and daily weather data from 1993 up to 2020. The set contains different attributes such as temperature, precipitation, and wind speed. Afterward, we cleaned and reorganized our data with Pandas and other Python libraries as well as Matplotlib for our graphs.

### 3.3.2. *Precipitations*

Total Precipitation will help us determine the size of many of our water management features such as a potential ditch or pond, by informing us of the volume of water we need to store. Our mentor suggested that we get a general idea of the weekly summer precipitation average, which we did, the results are displayed in Figure 12.

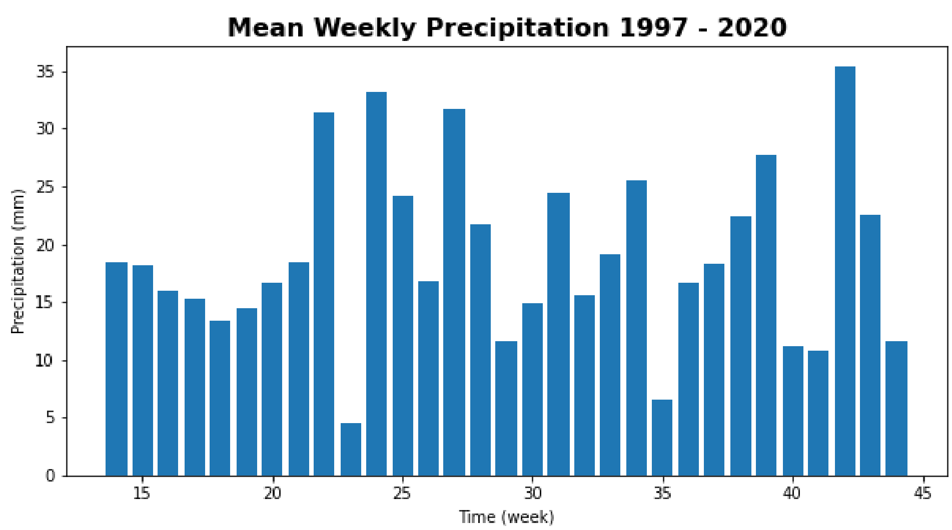



**Figure 13. Weekly Mean Precipitation in Sainte-Anne-de-Bellevue.** This graph shows weekly mean summer precipitation in Sainte-Anne de Bellevue based on data collected between 1997 and 2020. The time represents week number from the first week number 14 (first week of April) to the week number 44 (last week of October).

As explained, the goal of this section is to look at trends and see if the climate is changing. The purpose of Figure 13 was to assess the evolution of monthly weather over the years. Yet, nothing except the randomness of rain patterns can be identified from this graph.

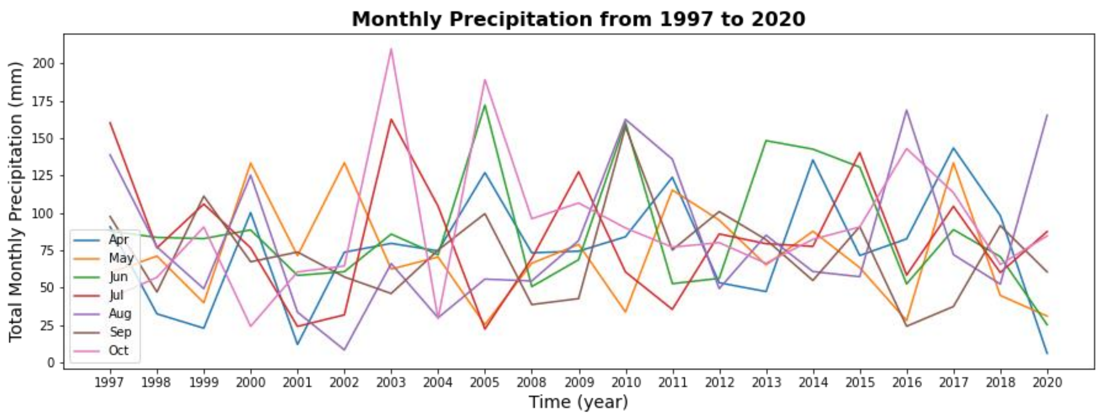



**Figure 14. Sainte-Anne-de-Bellevue Total Precipitation, 1997-2020.** This graph displays the total precipitation in Sainte-Anne de Bellevue between 1997 and 2020 for each month of the growing season (beginning of April to the End of October). We can see no clear trend nor change regarding precipitation patterns.

Rainfall intensity is as important as the amount of precipitation because it influences the ratio of infiltration and runoff. Runoff is the surface water that can be collected through surface drainage. Conversely, infiltrated water is used by plants and collected by tile drainage when in excess (Huffman, 2013). In brief, as explained earlier, soils absorb water differently depending on their microstructure, moisture and the rate at which water is applied. If rainfall intensity is too high, the soil cannot absorb all the water and there are runoffs (Huffman, 2013). For example, high intensity but short rainfall will cause more runoffs than a lower intensity longer rainfall even though both led to equal precipitation amounts. Thus, when designing a water management system, we need to take this into consideration (Huffman, 2013).

### *3.3.3. TEMPERATURES*

Looking at temperatures is critical because it affects the evapotranspiration of plants, and therefore, can either increase or decrease soil moisture content (Huffman, 2013). Figure 14 displays that the average temperature in Sainte-Anne has been increasing, mostly in the month of July. However, spring and fall temperatures have been quite stable. This graph seems to corroborate the generally accepted assertion that global mean temperature is getting warmer. We however do not have enough information to predict specifically how it will affect our field and, subsequently, our design. The second graph compares our two years of yield data with the average temperatures, we can see that in both cases fall was warmer than usual. Spring was exceptionally cold in 2016. Due to the small amount of yield data and similarity between the years, it is impossible to make any conclusions. Due to this same issue, we did not pursue any further analysis between yield and weather.

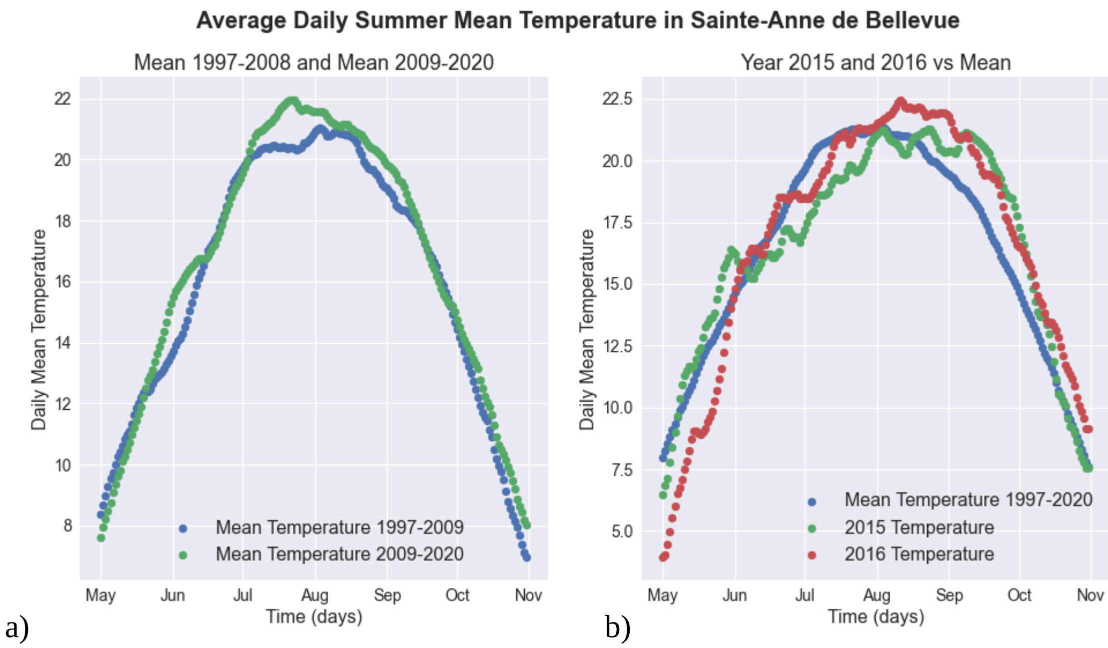



**Figure 15. Average in Sainte-Anne-de-Bellevue, 2009-2020.** Graphs of the average summer temperatures in Sainte-Anne de Bellevue using a rolling average with a window of 30. a) compares the mean temperature from 1997 to 2009 to the mean temperatures from 2009-2020 and display a light increase between periods. b) compares 2015 and 2016, the two years in which we had yield data, to the mean temperature based on data from 1997 to 2020.

### 3.3.4. *Final Notes on Weather Information*

We recognize that the goal of this analysis was way out of the scope of this project and required expertise, which is for the moment out of our reach. Although there is no doubt that climate is changing, we do not have the tools to make detailed assumptions as to how it will impact our field. However, it helped us understand the difficulty of meteorological predictions and will prevent us from making simplistic climate assumptions.

# 4. POTENTIAL WATER MANAGEMENT SOLUTIONS

Before proposing the following alternatives, a variety of standard and regulations were verified. Notably, standards from the American Society of Agricultural Engineers (ASAE) and its recent version the American Society of Agricultural and Biological Engineering (ASABE) were looked into as well as the various regulations from the government of Quebec and the Montreal municipality. More details can be found in Appendix 8.

## *4.1. DISCARDED ALTERNATIVES*

Before analyzing any specific solutions, we will explain why we discarded the ideas of using controlled drainage and land leveling. The main reason is that control drainage can only work on a relatively flat area, with a maximum elevation difference of 1 to 2 feet; F86 elevation difference is over 9 meters (29.5ft). Nevertheless, it is possible to divide the field into control sections of a minimum of ten acres. Thus, we tried dividing our field into sections of similar elevation but quickly concluded that it did not solve our problem and that the field was unsuitable to control drainage. The unevenness of the field also prevents any major leveling work, because it would require moving an enormous amount of soil. The impact on soil quality would most probably be more detrimental than possible gains.

## *4.2. ASSESSMENT OF ALTERNATIVES*

After visiting Field 86, analyzing its properties, and conducting the literature review, we identified possible water management solutions. For each alternative, we will explain why we believe it is relevant and give a preliminary idea of where and how it could be applied. Finally, we will assess our different options based on the following criteria, from the most important down to the least:

1. **Yield Increase:** The yield increase is the most important because it is the only way our project can create direct monetary gains. It is the main factor determining if the project is economically viable.
2. **Water Quality:** Drainage increases fertilizer and pesticides seepage through waterways. We decided to make this our second most important criterion because environmental degradation and waterway pollution are already widespread and very concerning.

3. **Long Term Field Quality:** Good drainage and water management can prevent field compaction and loss of organic soil due to erosion. It maintains the field productivity over time and therefore increases long-term gain. In addition, we believe that we ought to provide quality soil to future generations.
4. **Ease of maintenance:** The amount of work to maintain our system will influence the long-term cost. It is therefore important to try minimizing these requirements.
5. **Capital Expenditure:** Initial capital expenditure will significantly influence the desirability of our project. However, due to the MacDonald Campus Farm academic setting, we believe it should not be the primary concern. In addition, as part of the Environmental and Agricultural Faculty, we believe our client will prioritize sustainability and long-term gain.

With this in mind, we can now consider how the different drainage solutions can apply to Field 86 water issues. First, we will explore surface drainage, and then look at tile drainage, and finally at the possibility of adding a saturated buffer and a recycling water system. We will use Figure 15 in the next section anytime we refer to a specific drainage element.

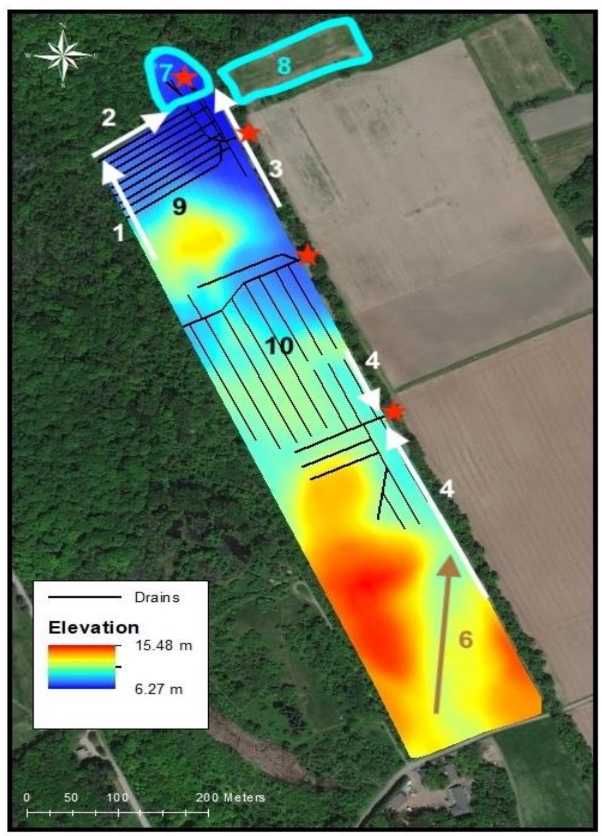



**Figure 16. Tentative Water Management Solutions.** This figure is further explained in the section that follows. Here is a summary of the presented elements:

- Red stars: field water outlets
- White arrows: surface drainage
- Blue lines: recycling water solutions
- Brown arrow: field drain

These features were added to Figure 9.

### *4.2.1. Surface Drainage*

Surface drainage is the first thing to consider when designing a water management plan, and it is what we will do. As explained earlier, all the water from the Arboretum melted snow is discharged into the field during spring. Drain number 1 and number 2 could redirect all this water directly towards an outlet without it having to pass through our field and cause potential erosion and flooding. However, because of the irregular topography, multiple ditches going towards different directions and outlets will probably be required. Ditches number 3, 4 and 5 give an idea of how this could look. Depression caused by this irregular topography will cause further challenges, as water will accumulate there. Using random field drains in locations such as number 6 could help improve the situation and redirect accumulated water towards ditches. Yet, due to the considerable depth it will probably not be enough. Likewise, surface drainage does not impact groundwater, therefore, it most likely won't evacuate enough water to dry the field in spring or deal with large precipitation events. In brief, we will almost certainly have to come with a surface drainage plan; we, however, doubt it could resolve all the field problems.

We will now analyze surface drainage based on our criteria. First, it should increase yield, but it might not tremendously. As explained in the drainage section, yield increases due to drainage because it prevents plant death due to extended flooding, and plants' roots can grow deeper when the water table is lower. Surface drainage only accomplishes the first. Furthermore, it will negatively impact water quality; however, the impact will be mild because nitrate is the major concern and is mostly evacuated through underground water. It will likely improve long-term field quality by reducing erosion. Finally, it is the cheapest drainage solution.

### *4.2.2. Tile Drainage*

Since our field's main problem is that water evacuates slowly, mainly in spring, tile drainage could improve the situation significantly. As explained previously, one of Mr. Chaumont's concerns was that they could not access the field early enough and had to delay fieldwork. Tile drainage could solve this problem because it allows fields to dry more quickly in spring by absorbing the snow as it melts. As a result, machinery can get on the field earlier, extending the production period. In addition, tile drainage combined with surface inlet could deal with water accumulation in field 86's potholes and valleys more efficiently than surface drainage. Figure 11 displays the actual tile drainage, and, as we can see, it covers the lowest, most problematic areas. Yet, as told earlier, it is pretty old and does not work for the moment. Therefore, the first step would be to inspect these drains and see if they can be unclogged and repaired. Then, we will fix, replace, or add new drains depending on our findings.

Tile drainage has upsides and downsides regarding its ability to achieve our goals. It will increase yield and long-term field quality for previously detailed reasons. Conversely, it has the most negative impacts on water quality because it drastically increases nitrate and other field pollutants seepages. On the other hand, it does not require that much maintenance except regular inspections and occasional unclogging to avoid recreating the actual problem. In terms of initial investment, it is higher than surface drainage, but historically, the cost-benefit is positive because of the yield increases. However, since our field only struggles with alfalfa, we might not achieve a positive return on investment.

#### *4.2.3. Saturated Buffer*

We will now explain why and where we would consider a saturated buffer in the field water management plan. As stated many times, if we are to add more drainage, we will negatively impact downstream water quality. Adding a saturated buffer would reduce the amount of fertilizer in the water released in the environment, particularly nitrate concentration. Nevertheless, a saturated buffer needs to be at least 30 meters wide. We do not have much spare space at the field periphery and will need to sacrifice some cropland. Consequently, we need to minimize the length of the buffer and put it in a location that will maximize its efficiency. Thus, place it where the highest amount of contaminated water will flow. Hence, the two proposed sites are alongside ditch number 2 and number 3 as most of the field water drains towards these lower points.

Adding a saturated buffer will help us achieve many of our designated criteria. First, it does not affect yield but is always combined with tile drainage; thus, a similar increase will occur. However, the gain might be slightly smaller than the previously discussed case due to the area lost to the buffer. In terms of water quality, it will have a reduced impact compared to conventional practices. Nevertheless, it does not altogether remove contaminants, and our water management plan will still be more detrimental to the environment than if nothing had been done. The impact on long-term soil quality will be identical to tile drainage, and it shouldn't require much more maintenance nor a significantly higher initial cost.

### *4.2.4. Recycling Water*

Creating a recycling water pond could be very beneficial to field 86. As explained previously, making a water recycling pond minimizes the impact on waterways by keeping field water within controlled boundaries. It would also allow for irrigation in drought, a possible risk due to rising temperatures. Furthermore, water from our field travels through the entire adjacent field before reaching the outlet, which can cause erosion and displace moisture issues. Thus, creating a pond would allow us to discard water directly next to the field and avoid the need for it to travel a long way.

We identify two low elevation potential locations to dig a pond. The first location, number 7 on the map, is the least productive part Figure 11**.** Additionally, a tile drainage outlet seems to go straight into that field. The second location, number 8 on the map, is an entire field known to be constantly flooded. Martin Chaumont informed us that they tried growing switchgrass in this field last summer, but the water never left the area, and they could never harvest. This location is farther away from our field and is larger and could therefore store more water. The required storage volume will mostly depend on precipitations. We were also informed that there is probably a well in that field. Overall, we believe both locations have a lot of potential, but further analysis is required.

The creation of a pond answers to many of our criteria. It does not directly drain the field, but since it is combined with a drainage system, it has similar yield advantages. Besides, the irrigation potential could bring even further increase. However, it might decrease gains by taking up productive land space. Recycling water is the most beneficial solution regarding water quality as it creates a close loop in which nutrient fertilizers and pesticides minimally escape into waterways. In fact, a study by Reinhart et al. (2019) on two sites in the United States Midwest, found that annual nitrate loads were reduced by 20% to 37% and phosphorus loads by 17% to 39%. The advantages related to field quality are equivalent to using tile drainage. The biggest downside of the recycling water system is that it might require more maintenance and will have a high initial cost.

### 4.2.5. *PUGH CHART*

We created the following Pugh Chart to summarize our assessment and help us decide which solution to prioritise based on our criteria (Table 3).

| | **Weight Factor** | **Baseline** | **A** | **B** | **C** | **D** | **E** | **F** |
|---|---|---|---|---|---|---|---|---|
| **Yield Increase** | 4 | 0 | 1 | 1 | 4 | 3.5 | 4 | 4 |
| **Water Quality** | 3 | 0 | -1 | -2 | -3 | -1 | 0 | 0 |
| **Long Term Field Quality** | 3 | 0 | 1 | 1 | 2 | 3 | 1 | 3 |
| **Ease of Maintenance** | 2 | 0 | -0.5 | -1 | -1.5 | -1.5 | -1.5 | -2 |
| **Capital Expenditure** | 2 | 0 | -0.5 | -0.5 | -1 | -1.5 | -1.5 | -2 |
| **Total** | | 0 | 0 | -1.5 | 0.5 | 2.5 | 2 | 3 |

**Table 3. Pugh Chart.** This table shows the summary of the assessed alternatives.

**Baseline**: Nothing is done in the field
**A:** We only do surface drainage.
**B:** We only unclog the existing drains.
**C:** We do surface drainage and tile drainage.
**D:** We do surface and tile drainage and add a saturated buffer.
**E:** We create a recycling water storage pound and do surface drainage only.
**F:** We create a recycling water storage pound in addition to surface and tile drainage.

Option F scored the most points.

# 5. FINAL SOLUTION

Based on the analysis of the situation and assessment of potential alternatives our final proposed solution is to implement systems of surface, subsurface and recycling drainage. The following sections details the design of each system as well as the calculations effectuated to create them. Figure 16 shows the final map of our design.

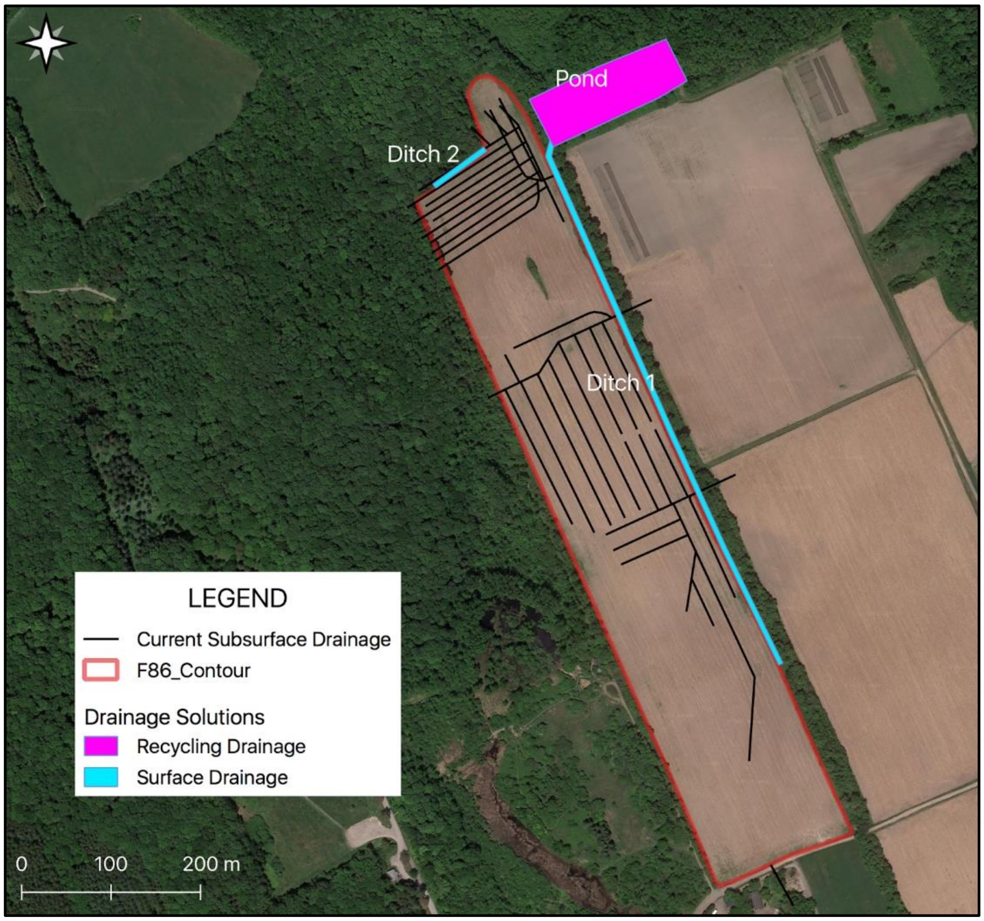



**Figure 17. Final Solutions.** This map presents the final design of our water management plan. The ditches are not to scale in order for us to see them easily, however they are correctly placed. This was created using QGIS.

## *5.1. SURFACE DRAINAGE*

The first part of our solution is the implementation of two ditches to increase the potential for surface drainage. The first ditch will be located along the eastern side of the field, while the second ditch will be located on the northern part of the field. The exact locations of the ditches can be seen in the Figure 16. The length of ditch 1 and ditch 2 is 880 meters and 100 meters, respectively. The area drained by each of those ditches has been calculated relatively to the area of the watersheds they board.

As previously discussed, the field was divided in three watersheds (see Figure 8). Watershed 1 (blue), 2 (pink) and 3 (green) are 35498.45 $m^2$, 8772.09 $m^2$, and 91545.37 $m^2$, respectively. It has been estimated that one third of the first watershed and the entirety of the third watershed are drained by the first ditch. As for the second ditch, it only drains the third of the first watershed. Thus, the total area drained for the first and second ditches are 103366.35 $m^2$ and 11832.818 $m^2$.

In addition, we also had to find the peak runoff rate to obtain the peak flow rate in the ditches, and thus determine the dimensions of the ditches. To obtain such information, the DRAINMOD software was used to simulate the surface runoff rate from January 2019 to December 2021. The historic precipitation and temperature data for Sainte-Anne-de-Bellevue during this period was found on the Government of Canada website and inputted as text files in the software (Government of Canada, 2022). Moreover, the soil data for this field was also inputted in the software. The data from Madramootoo (1990) was used. The volumetric water content at different pressure heads, depth to impermeable layer from soil surface, saturated hydraulic conductivity, saturated water content, wilting point water content, maximum rooting depth, earliest day for field work, earliest day to plant, field working days to plant, working hours during spring, infiltration parameters A and B as a function of water table depth, drainage volume as a function of water table depth, upward flux as a function of water table depth, and rooting depth patterns were retrieved from this paper. The soil data was inputted as a combination of direct inputs in the software and a text file. Also, the daily evaporation values were also inputted in the model as a text file. The calculations for such values have already been discussed previously in this paper. Finally, the old drainage map provided by Mr. Chaumont (see Appendix 6), giving us the depth, spacing, location, and length of the subsurface drains, was also used to manually set up the DRAINMOD model.

Once all the data was inputted manually or through text files in DRAINMOD, the surface runoff was obtained. Figure 17 represents the results obtained; the peak surface runoff is 5.397 centimeters. For matters of simplicity and to ensure that the ditches are designed for the worst-case scenario, it was assumed that the rainfall events last two hours, and thus that the peak surface runoff is attained in two hours.

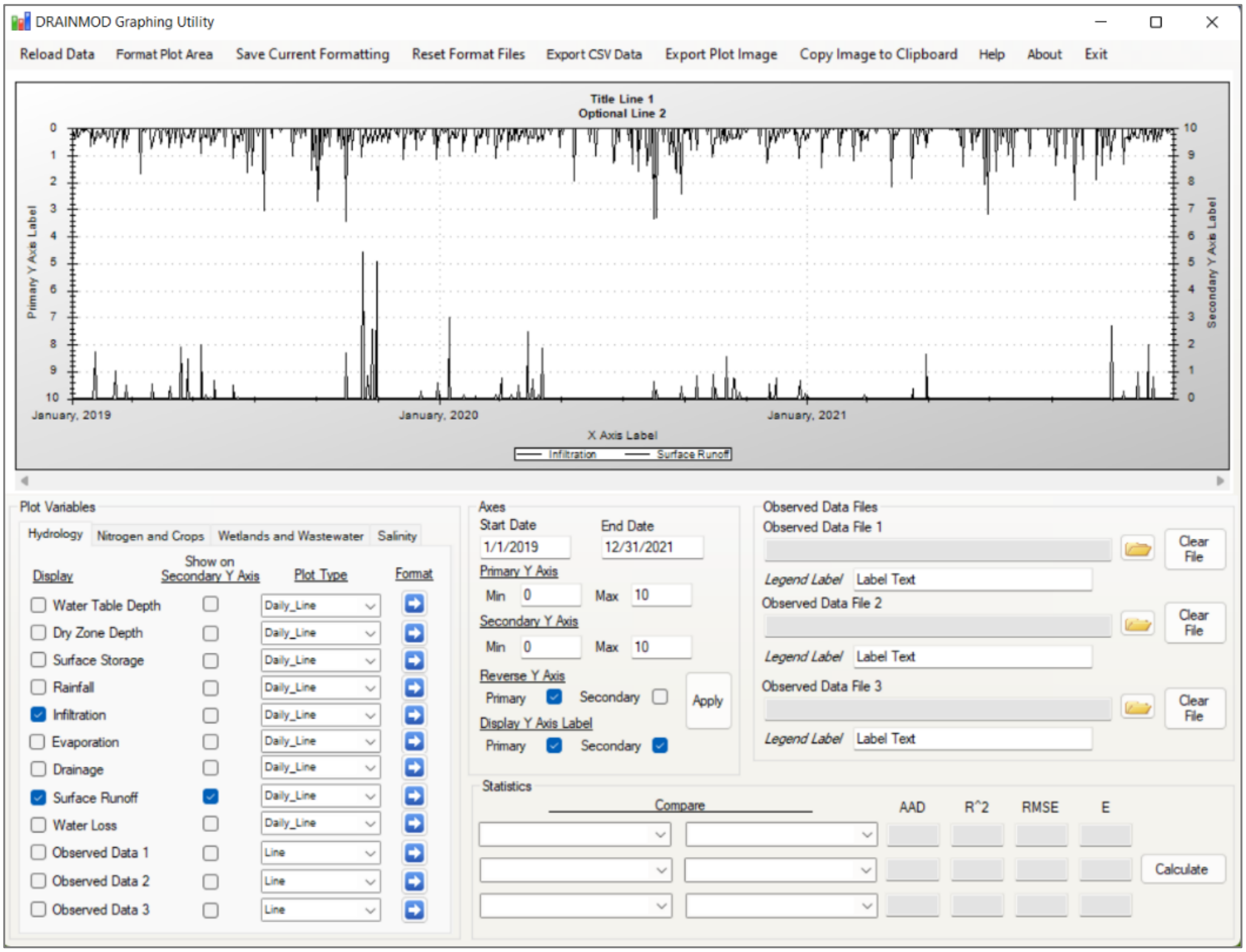



**Figure 18. Infiltration & Surface Runoff, January 2019 to December 2021.** This figure shows the resulting infiltration and surface runoff for field 86 from January 2019 to December 2021.

Now that the peak surface runoff for the field as well as the area drained by each ditch was found, the calculations for the peak flow rate in the two ditches could be done using the following equation:

$$Q = A * SR/T$$

Where:

Q : Flow rate ($m^3/s$)
A : Area of cross-section ($m^2$)
SR : Surface Runoff (m)
T : Time (s)

Hence, the peak flow rate in the first and second ditch is 0.775 $m^3/s$ and 0.089 $m^3/s$, respectively.

In order to accurately represent the most likely scenario in an uncontrolled ditch, a parabolic waterway was assumed. Thus, the following equations found in an oral presentation presented by Professor Qi (Qi, 2021) were used to determine the width and depth of the two ditches:

$$Q = \frac{C_u * A^{\frac{5}{3}} * S_f^{1/2}}{n * P^{2/3}}$$

Where:

Q : Flow rate ($m^3/s$)
Cu : Unit coefficient
A : Area of cross-section ($m^2$)
$S_f$ : Slope of the ditch (m/m)
n : Manning's roughness coefficient
P : Perimeter of cross-section (m)

---

$$A = \frac{2 * t * d}{3}$$

A : Area of cross-section (m2)
t : Width of ditch (m)
d : Depth of ditch (m)

$$P = \frac{A}{R}$$

P : Perimeter of cross-section (m)
A : Area of cross-section ($m^2$)
R : Hydraulic radius (m)

$$R = \frac{2 * d}{3}$$

R : Hydraulic radius (m)
d : Depth of ditch (m)

$$v = \frac{Q}{A}$$

v : Average flow velocity (m/s)
Q : Flow rate ($m^3/s$)
A : Area of cross-section ($m^2$)

$$n = \frac{1}{\left(2.1 + (2.3 * x) + (6 * \ln(10.8 * v * R))\right)}$$

n : Manning's roughness coefficient
x : Retardance class factor (x = 2 for B)
v : Average flow velocity (m/s)
R : Hydraulic radius (m)

---

In those equations, the unit coefficient ($C_u$) was equal to 1.0 because SI units were used. Additionally, the slope of the ditch ($S_f$) was found by dividing the length of the ditch by the difference in height from one end of the ditch to another. This information was found using the elevation map of our field; the first and second ditches had total elevations of 11 and 3 meters, respectively. Since the length of the first and second ditch is 880 and 100 meters, the slopes are 0.0125 and 0.03, respectively. It was also assumed that the bottom of the ditches would be composed of an unmowed native grass mixture with good stand. According to table 8.4 presented in the same presentation from Professor Qi (Qi, 2021), this represents a retardance class B. Thus, the appropriate equation for retardance class B was used to calculate the Manning's roughness coefficient (n). However, the Manning's roughness coefficient is required for the calculation of the average flow velocity (v), but the average flow velocity is required for the Manning's roughness coefficient calculation. Hence, a first value for the Manning's roughness coefficient was hypothesized and twenty iterations were conducted. The answers obtained could be considered valid as soon as an error of 1% or less was of observed. The tables presenting the iterations effectuated for both ditches can be found in Appendix 9. As can be seen in such tables, the error at the twentieth iteration was way lower than 1%, confirming the validity of the results. Thus, the minimum length and depth of the first ditch to sustain the peak flow rate are 1.5 and 0.7 meters, respectively. For the second ditch, the minimum length and depth to sustain the peak flow rate are 0.75 and 0.35 meters, respectively.

### *5.2. SUBSURFACE DRAINAGE*

Although a renewed subsurface drainage system is needed, this report will not present its design. This is explained by the lack of information regarding its current state but also by the limited knowledge we currently possess on the matter. Our analysis was sufficient to justify a more profound investigation, which is what the firm Logiag Inc. was employed for. Experts in this field are currently examining the F86 to upgrade its current subsurface drainage. Thus, we decided to focus our final design on the surface drainage and recycling system.

## 5.3. RECYCLING SYSTEM

In order to properly design the recycling system additional computations for the evapotranspiration and irrigation needs had to be effectuated.

### 5.3.1. EVAPOTRANSPIRATION

Reference evapotranspiration ($ET_{ref}$) was first obtained to calculate irrigation requirement for field 86, to determine the pond minimum size, and to add precision to DRAINMOD calculations. All computations were done using Python. Meteorological data were taken from Environment Canada's Pierre-Elliot Trudeau International Airport Weather Station, except for the radiation values. The initial idea was to use Sainte-Anne the Bellevue's Weather Station, but some entries were missing. Hence, since both stations are located about 15 km apart, it was assumed that using the airport's data would not significantly affect the outcome of our computations. Daily data were used except for mean wind speed, which was only available in hourly format. Thus, the later was downloaded hourly and averaged to get mean daily values. All equations in the following sections are from Huffman et al. (2013). The Penman and Monteith equation was chosen to calculate daily evapotranspiration as recommended by the FAO since we had access to all the necessary data.

$$ET_{ref} = \frac{0.408\Delta R_n + \gamma \frac{C_n}{T + 273} (e_s - e_a)u_2}{\Delta + \gamma(1 + C_d u_2)}$$

**Variables**

| | |
|---|---|
| $ET_{ref}$ | = reference ET for a well-watered crop (mm/day) |
| $\Delta$ | = slope of the saturation vapor pressure (kPa/ºC) |
| $R_n$ | = net radiation at the crop surface (MJm-2day-1) |
| T | = mean daily temperature at station (ºC) |
| $u_2$ | = mean daily wind speed at 2m above the soil surface (m/s) |
| $e_s$ | = mean saturation vapor pressure (kPa) |
| $e_a$ | = mean actual vapor pressure (kPa) |

**Constants**

| | |
|---|---|
| P | = mean atmospheric pressure = 101.8 (kPa) |
| $\gamma$ | = psychometric constant = 0.000665 * P = 0.067697 |
| $C_n$ | = 1600 |
| $C_d$ | = 0.38 |

| | |
|---|---|
| $$e_s = \frac{e_s(T_{max}) + e_s(T_{\min})}{2}$$ | $$e_s(T) = 0.6108 \exp\left(\frac{17.27T}{T + 237.3}\right)$$ * This was used with T equal to maximum and minimum daily temperatures ($T_{min}$ and $T_{max}$) |
| $$e_a = \frac{e_s(T_{\min})\frac{RH_{max}}{100} + e_s(T_{\max})\frac{RH_{min}}{100}}{2}$$ $RH_{max}$ = Maximum relative humidity of the day<br>$RH_{min}$ = Minimum relative humidity of the day | $$\Delta = \frac{2504 \exp\left(\frac{17.27t}{(T + 237.3)^2}\right)}{(T + 237.3)^2}$$ $$u_2 = \frac{u_z 3.44}{\ln(16.26 * 10 - 5.42)}$$ |
| **Net long-wave radiation** $$R_{nl} = \sigma\left[\frac{(T_{\max}+273)^4 + (T_{\min}+273)^4}{2}\right]\left[0.34 - 0.14(e_a)^{0.5}\right]\left(1.35\frac{R_s}{R_{so}} - 0.35\right)$$ | |
| $$R_n = (1{-}\propto)R_s - R_{nl} = (1 - 0.23)R_r = R_{nl}$$ | |

Reference evapotranspiration as calculated gives values for full grown alfalfa, hence, we needed to adjust it to corn at its different development stages. Accordingly, actual evapotranspiration ($Et_a$) was obtained by multiplying $ET_{ref}$ with the crop coefficient (Kc).

$$Et_a = Kc * ET_{ref}$$

The crop coefficient is used to adjust ETref to crops' specific transpiration patterns. It englobes the effects the ground cover, canopy characteristics and aerodynamics resistance of a specific crops (Huffman et al., 2013). Crop coefficients vary depending on the growing stage: adult plants transpire more since they have more leaf surface. Figure 19give a general idea of how Kc varies through the seasons. The specific coefficient values used are the following from Gallichand et al. (1991):

$Kc_{init} = 0.51$ $Kc_{mid} = 1.05$ $Kc_{end} = 0.55$

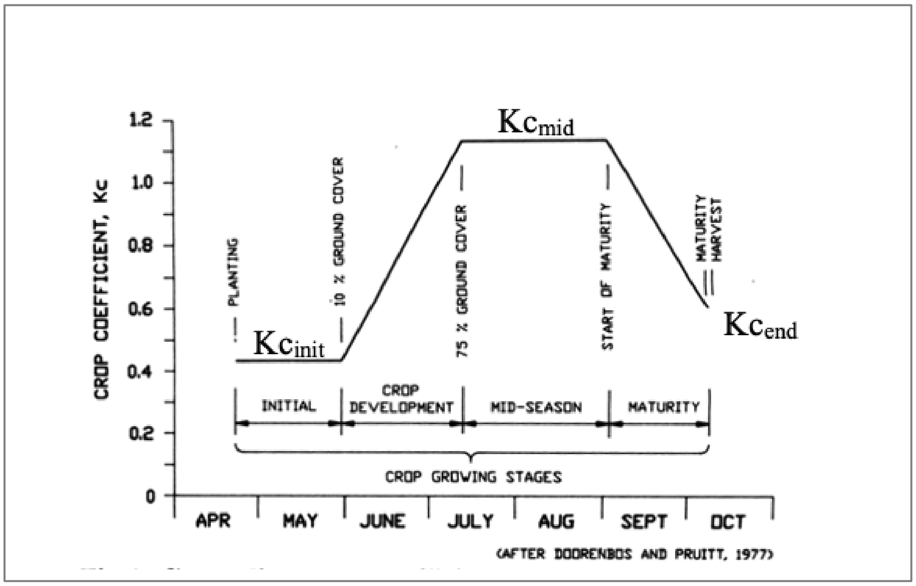



**Figure 19. Crop Coefficient.** This graph was directly taken from Gallichan et a. (1991) and shows crop coefficient variation throughout the season.

The crop development stage was determined to be from May 20th to June 19th. The mid-season was set from June 20th and August 31st and the maturity period from September 1st and September 15th. The model did not include an initial phase.

Figure 20 demonstrates that evapotranspiration is higher during the months of June and July. Conversely, it is lower at the beginning of the season when the plant is small, and at the end when it begins to wilt. The use of the crop coefficient to get actual ET, makes this pattern even clearer since corn physiology varies more than alfalfa throughout its growth stages.

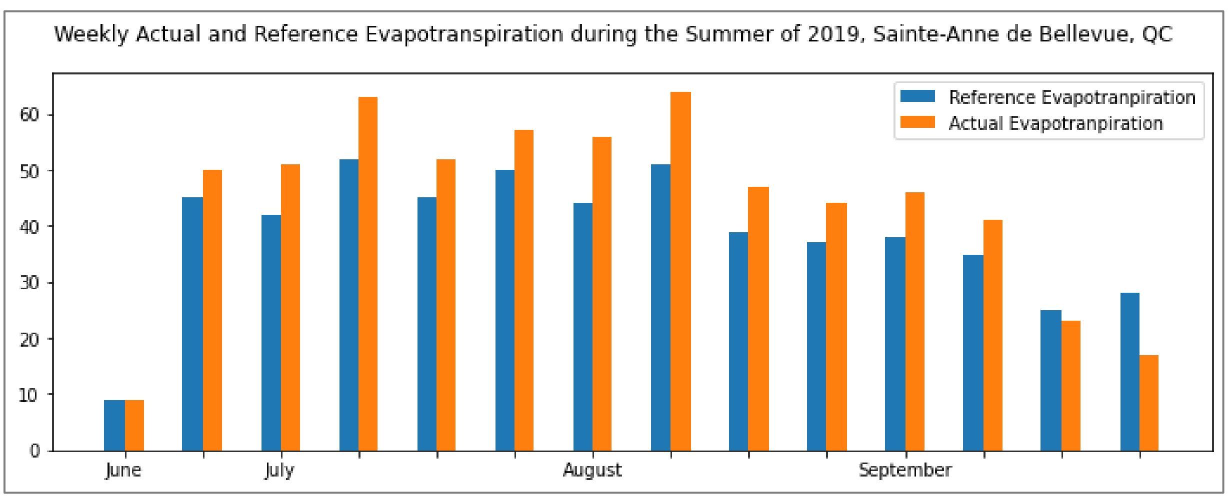



**Figure 20. Weekly Actual & Reference ET.** This figure presents the weekly Actual and Reference Evapotranspiration during Summer of 2019 in Saint-Anne-de-Bellevue.

Table 4 displays results very similar to the seasonal corrected pan results from Barnett et al. (1998) which were equal to 596.5 mm and 536.6 mm for the summers of 1995 and 1996 respectively. These results were adjusted to well-watered grass and thus our results based on corn should be a bit higher, but not significantly. Furthermore, the summers of 1995 and 1996 were most probably colder than the years modelled. All this said, all our values seem in a reasonable range to Barnett et al. (1998) experimental data.

| Year | Reference ET (mm) | Actual ET (mm) |
|---|---|---|
| 2015 | 501 | 565 |
| 2016 | 560 | 643 |
| 2019 | 540 | 620 |
| 2021 | 499 | 568 |

**Table 4. Total Seasonal Evapotranspiration.** This table shows the total seasonal evapotranspitation in mm for 118 days.

### *5.3.2. IRRIGATION*

Irrigation requirement is the first step to see if the pond we intend to design should be coupled with an irrigation system. Furthermore, irrigation needs will allow us to choose the size of a pond, as it will give us indication on corn's needs. Finally, this section will allow us to identify critical periods for irrigation and determine when water should be applied. Hence, the water balance method was used to calculate irrigation requirements.

The water balance method is based on the soil ability to retain a fixed amount of water (plant available water (PAW)). Accordingly, water can be added by irrigation and precipitation and removed by evapotranspiration, and deep percolation. Hence, soil moisture ($SM_t$), the percentage of the soil available water, was computed daily using the following equation:

$$SM_t = SM_{t-1} + Pe_t + Irr_t - Ks_t * ETa_t - DP_t$$

$SM_t$ = Soil Moisture (mm)
$SM_{t-1}$ = Soil Moisture on the previous day (mm)
$Pe_t$ = Effective Precipitation (mm)
$Ks_t$ = Soil Moisture Factor
$Irr_t$ = Irrigation (mm)
$ETa_t$ = Actual Evapotranpiration (mm)

Daily soil moisture was computed from June 15$^{th}$ to September 15$^{th}$, as irrigation is very unlikely to be required out of this period. On the first day, soil moisture was assumed to be equal to a hundred percent of the maximum plant available water. Two values were tested: 100 mm as proposed by this project supervisor Dr. Chandra A. Madramootoo, 202 mm from the following equation also proposed by our supervisor:

$$PAW = (\theta_{FC} - \theta_{PWP}) * RD = (439 - 186) * 0.8 = 202\ mm$$

$\theta_{FC}$ = Field capacity (mm/m)
$\theta_{PWP}$ = Permanent wilting point (mm/m)
RD = Rooting depth (m)

**Values for corn in clay loam were taken from Gallichand et al. (1991)

Since plant water availability determines the maximum of water the soil can hold, any value of soil moisture of that limit was considered lost as runoff. In brief, soil moisture was never allowed to go over that determined value.

Irrigation was added whenever the soil moisture went under thirty percent. Based on our mentor insights, the quantity added was the amount required to bring back soil moisture to ninety percent of the total holding capacity minus the actual precipitations:

$$Irr = PAW * (0.9 - 0.3) - P_e$$

Effective precipitation was calculated from precipitation values to reflect the limited water quantity the soil can absorb from precipitations. In brief, due to soil physics discussed earlier, very small water events are all lost to runoffs and rain events are only absorbed partially. The equation used is a large simplification and can be better calculated by the DRAINMOD software. Yet, for the purpose of irrigation requirement the equation where P is the precipitation proposed by the Farwest website, a non-profit public portal in partnership with the BC Ministry of Agriculture was deemed suitable (Pacific Field Corn Association, 2022).

$$P_e = \begin{cases} 0 & if\ P < 5mm \\ 0.75 * P & if\ P \geq 5mm \end{cases}$$

Actual evapotranspiration, as previously calculated, assumes that plants have access to an unlimited amount of water. Yet, as mentioned previously, corn in Quebec is not irrigated and, thus, has a limited amount of water. Furthermore, due to the high cost of irrigation it was decided to allow water availability to go down to thirty percent of the total soil total capacity. This will be discussed in the next section with irrigation calculation. Nevertheless, evapotranspiration was adjusted to the limited amount of water in the soil with the use of a soil coefficient as proposed by Gallichand et al. (1991).

For clay loam, Gallichand et al. (1991) proposed to keep the coefficient equal to one between a hundred and seventy-five percent of the total soil capacity. Afterward, it is suggested to diminish evapotranspiration linearly as water availability goes down. Additionally, the soil coefficient, compared to the crop coefficient, depends on the daily water availability, and had to be calculated as part of the irrigation water balance, which will be explained later. In brief, it was calculated in function of the fraction of water in the soil calculated on the previous day. With this said, the following expression was used to calculate this coefficient:

$$Ks_t = \begin{cases} 1 & if\ F_{t-1} < 0.75 \\ 0.75 * F_{t-1} & if\ F_{t-1} > 0.75 \end{cases}$$

$Ks_t$ = Daily Soil Coefficient
$F_{t-1}$ = Fraction of the Soil Moisture Left in the Soil From the Previous Day

This estimate was not found in any other project and might be an oversimplification of the reality. Yet it was considered acceptable for the purpose of this project.

Therefore, as expected, irrigation is mostly required during the months of July and August. However, the values in September do not seem quite right, as it is very unlikely irrigation would be needed at this period of the year. Similarly, irrigation is required more often when the maximum water retention is lower. In fact, as shown in Figure 21a, water was only applied in the field twice, whereas in Figure 21b it was done almost every week. It is hard to determine which scenario is more likely. As explained earlier, although Quebec's farmers don't irrigate corn, there seems to be potential for higher yield although it isn't clear if that would be profitable in the current conditions.  Hence, we do not have precise data to validate whether irrigation should have been applied and thus it is difficult to establish which scenario is more likely.

a)

b)

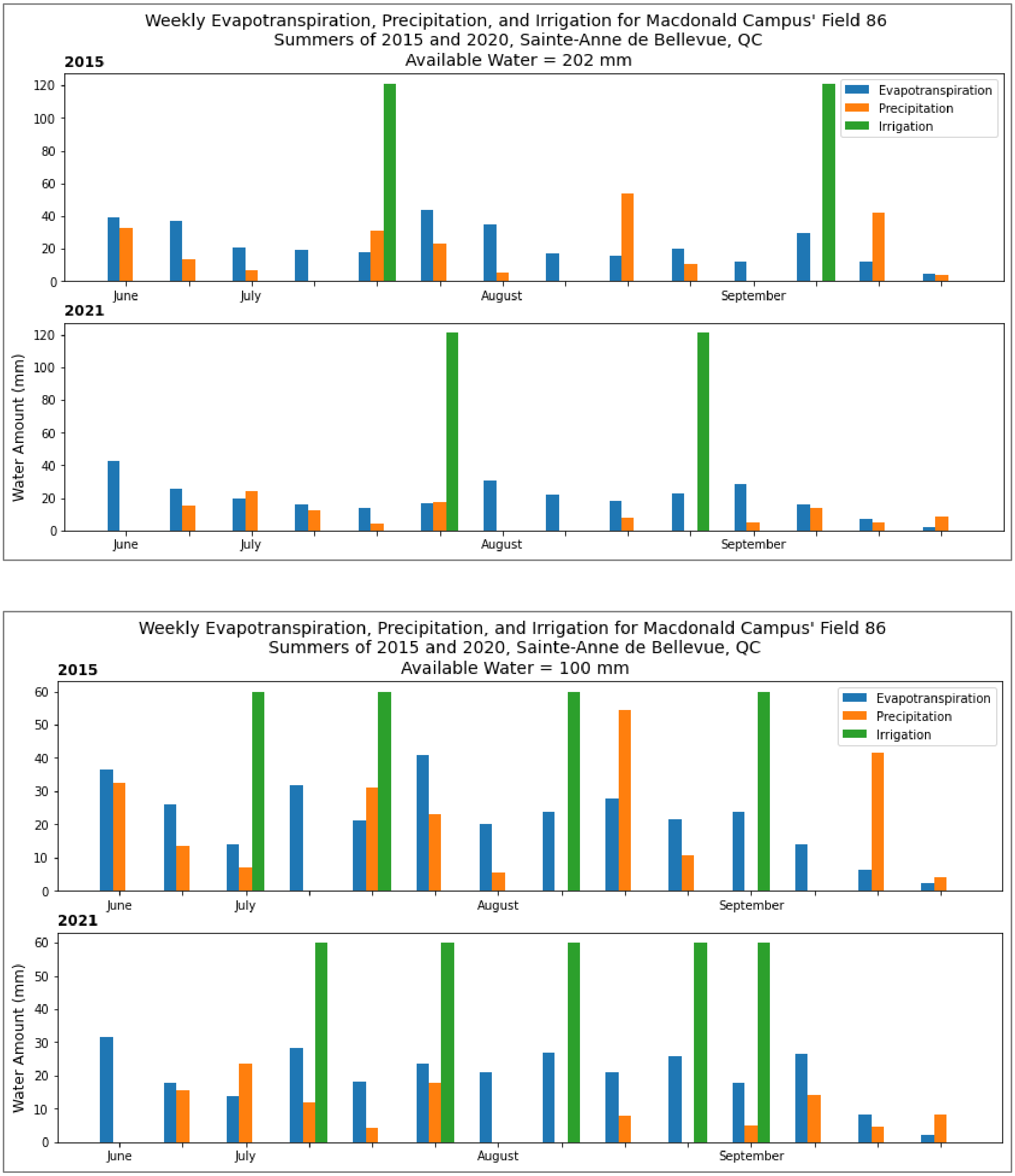



**Figure 21. Water Availability Scenarios.** These two figures show the weekly evapotranspiration, precipitation and irrigation for F86 in the summers of 2015 and 2020. Figure 20a shows the result when available water was set at 202 mm and Figure 20b when set at 100 mm. ET values were adjusted to water availability as well. Additional years can be found in **Appendix 10** and **Appendix 11** .

It is important to point out that the large quantity recommended for irrigation, particularly in the first scenario, should not be applied all at once. Simply put, if such a quantity of water was to be applied on a dry field, the soil would not be able to absorb everything, and an extensive quantity would be lost. Hence, the irrigation requirements represent the amount of water the soil needs to be refill with and not the exact amount that should be applied at once. Furthermore, not all water applied by irrigation even if done at an appropriately, will be absorbed by the soil, a factor the model did not consider. More calculations and research would be required to propose an exact irrigation schedule. However, the quantity is a good estimation of the water needed and should be precise enough to calculate the pond size, which is the main goal of the present calculations.

Seasonal results are twice those of Gallichand et al. (1991) when using maximum soil moisture of 100mm (300 mm vs. 146 mm). The results, shown in Table 4 with 202 mm are smaller, but still way bigger, hence, the model seem to overestimate the irrigation needs. Still, Temperatures are clearly higher than they were in 1991, meaning more water should be lost to evapotranspiration and could explain the higher requirements. Moreover, as just explained, the irrigation requirement observed in Figure 21 in early September, are most probably wrong, another factor that could contribute the high observed irrigation values. However, there is not enough evidence to modify these results and they will be kept as such. Furthermore, as previously mentioned, drained fields tend to dry more rapidly and hence require more irrigation. This detail was not considered in this paper's model or in Gallichand et al. (1991). Thus, the larger amount of water computed by this model might be more representative of a drained field. Yet, this no more than an assumption and would need more computation and research to be considered valuable.

To conclude, the model values, although different from the ones proposed by Gallichand et al. (1991), can be considered valuable for the purpose of calculating pond dimensions and choosing an irrigation system; as a rough estimate of the water flow is sufficient to determine the minimum size. Furthermore, it confirms the need for more research on the possible benefits of irrigating forage crop as it shows water deficit during the summer. It would be interesting to adjust the model at some point and to validate it with field experiments. Overall, although the model might need further adjustments, the smaller results from the 202 mm scenario will be used for the design of the pond.

| Maximum Soil Moisture = 202 mm | | | |
|---|---|---|---|
| Year | Evapotranspiration Adjusted to Water Availability (mm) | Effective Precipitation (mm) | Irrigation (mm) |
| 2015 | 323 | 223 | 242 |
| 2016 | 351 | 169 | 242 |
| 2019 | 267 | 134 | 242 |
| 2021 | 283 | 113 | 242 |
| **Maximum Soil Moisture = 100mm** | | | |
| Year | Evapotranspiration Adjusted to Water Availability (mm) | Effective Precipitation (mm) | Irrigation (mm) |
| 2015 | 309 | 223 | 240 |
| 2016 | 321 | 169 | 300 |
| 2019 | 302 | 134 | 300 |
| 2021 | 282 | 113 | 300 |

**Table 5. Seasonal Results.** This table presents the results for a maximum soil moisture of 202 mm and 100 mm for a season of 118 days.

### *5.3.3. Pond*

To design our pond, we needed to know the required size for irrigation and find a suitable location. Hence, we created a second water balance based on the paper by Reinhart et al. (2019). We used the output based on the Penman and Monteith Evapotranspiration values from DRAINMOD and from the irrigation requirement computations shown previously. First, the minimum area needed to establish our pond was determined to guide the choice of a location. Afterward, we picked a slightly larger area and calculated the daily volumes in the pond and the total volume of water lost to the environment. As illustrated by **Figure #,** the phenomena affecting the pond are different than those affecting the field. Except for this detail, the calculation method is identic; each daily volume is equal to the previous day's volume in addition to inflows and outflow as proposed by Reinhart et al. (2019):

$$V_t = V_{t-1} + P_t + D_t + SR_t - E_t - Irr_t - S_t$$

$V_t$ =Volume of water in the pond ($m^3$)
$V_{t-1}$ = Volume of water in the pond on the previous day ($m^3$)
$P_t$ = Precipitation in the pond ($m^3$)
$D_t$ = Drainage Outflow in the Pond ($m^3$)
$SR_t$ = Surface Runoff to the Pond ($m^3$)
$E_t$ = Open surface evaporation ($m^3$)
$Irr_t$ = Irrigation ($m^3$)
$S_t$ = Seepage ($m^3$)

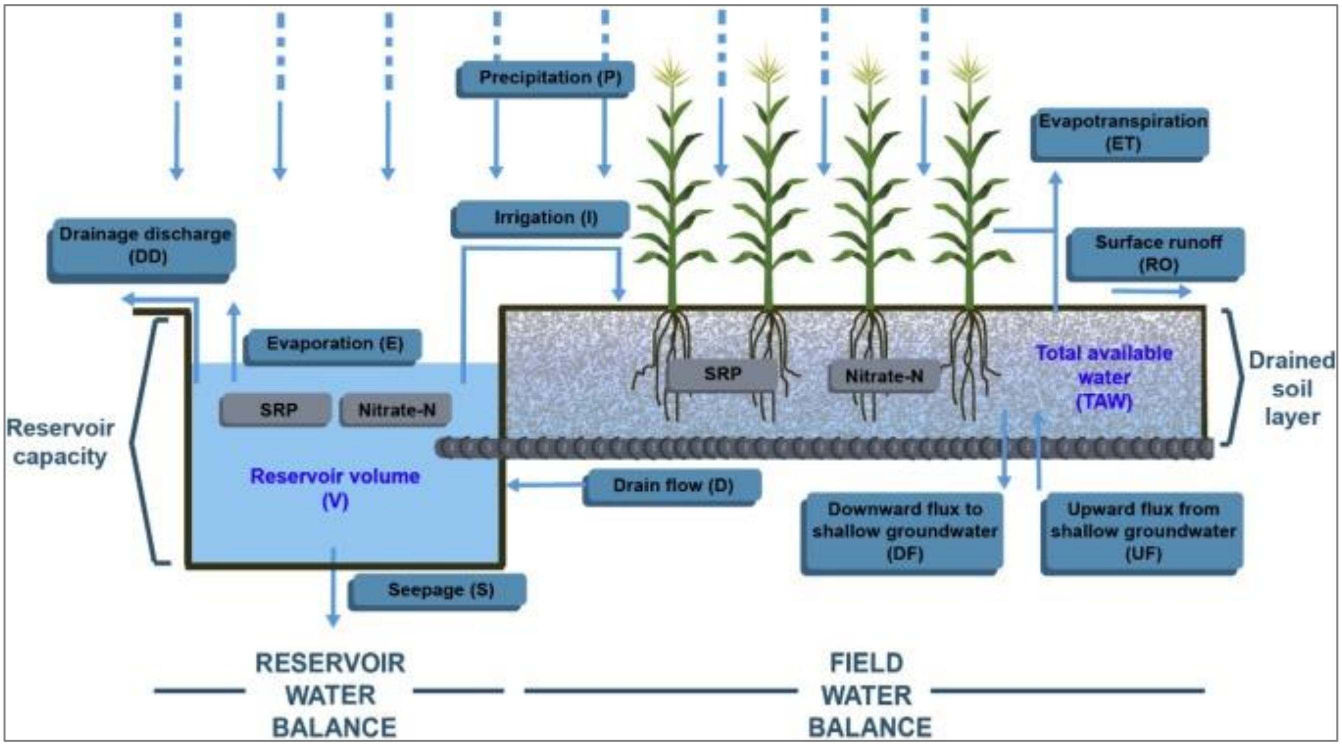



**Figure 22. Water Balance.** This figure shows the water balance for a field and a pond. This was taken from Reinhart et al. (2019).

The calculation was performed for the year of 2021 as it was the year with the less precipitation. The water balance was conducted between the first day of April and the last day of October. Drainage and surface runoff values were taken from DRAINMOD output, irrigation from the previous calculation and precipitation directly from Environment Canada. Likewise, seepage rate was fixed at 0.9 mm/day as estimated by Reinhart et al. Finally, open surface evaporation was calculated based on the Dalton's Law found in Huffman et al. (2013):

$$E = C(e_s - e_a)$$

E = rate of evaporation (mm/day)
C = a constant ($mm^{-1}kPa^{-1}$)
$e_s$ = saturation vapour pressure at the temperature of the water surface (kPa)
$e_a$ = actual vapour pressure of the air (kPa)

Saturation and actual evaporation vapour pressures were taken from the evapotranspiration calculation and thus not adjusted the water surface temperature. The C constant was evaluated for a shallow pond with Meyer's equation from Huffman et al. (2013), where $u_{76}$ is the average wind speed at 7.6 m above ground:

$$C = 112.5 + 25.1 * u_{7.6}$$

The wind speed was adjusted from 2 m above ground ($u_2$) as used in the evapotranspiration to the required 7.6 m/s ($u_{7.6}$). The following equation, where $z_0$ is the terrain description parameter for rough pastures and, thus, had a value of 0.01m:

$$u_{7.6} = u_2 * \frac{\ln\left(\frac{7.6}{z_0}\right)}{\ln\left(\frac{10}{z_0}\right)}$$

The pond volume was simplified by using a simple multiplication between the average depth of 2m and the areas that we wanted to test. To get the minimum size, we simply tested different areas until there was no water shortage. Shortages were calculated by summing any negative results from the water balance, which were than adjusted back to zero.

The minimum required sized for the pond to provide water without shortage was about 7000 m2, but it would mean the pond would go dry. Furthermore, the year chosen had very low precipitations, but more intense droughts could be expected due to climate change. Therefore, crops could require more irrigation and, thus, a larger pond. Similarly, our irrigation calculation assumed that all water was to be absorbed by the soil and did not account for the lost when transporting the water, due to evaporation when applied or simply the water lost through seepage or runoff if applied on dry soil or in too large quantity (Huffman et al., 2013). Finally, soybeans require a bit more water than corn (Gallichand et al., 1991). Hence, we aimed for a slightly larger pond.

Figure 23 shows the two possible locations for the recycling pond. Area A, as mentioned earlier, has already very low yield and is one of the most problematic locations of the field since, water tends to accumulate due to its low elevation. Area B, was used for switch grass in the past year but suffers from even more water accumulation problems then Area A. As mentioned by Mr. Chaumont, it is already pond-like and has not been used for years. Furthermore, Area B is positioned in a way that permits to easily receive the drained water from the field adjacent to F86 as well as also irrigate that field if needed. Finally, Area A is 3477 $m^2$ and Area B 9742 $m^2$, hence only Area B was suitable for the minimum required pond size of 7000 $m^2$ and was therefore selected.

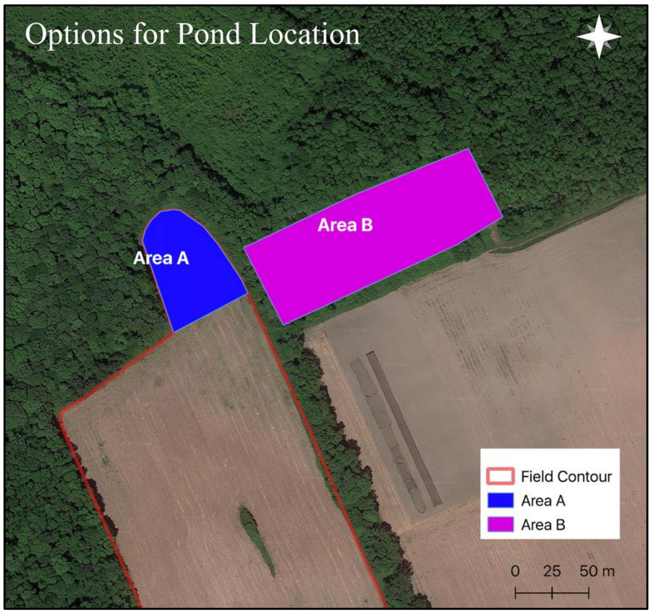



**Figure 23. Options for Pond Location.** This figure presents the two best locations for pond implementation near Field 86. This map was created using QGIS.

Reinhart et al. (2019) recycling pond water calculations resulted in an outcome very similar to. In brief, the pond gets filled up at the beginning of the year from snow melt and does not lose a significant amount of water to evapotranspiration due to low temperature and the fact that plants are not fully grown. As crops develop and temperature get warmer less water is dumped in the pond and at one point it is even pumped out for irrigation. Hence, from July to September, the pond volume diminishes.

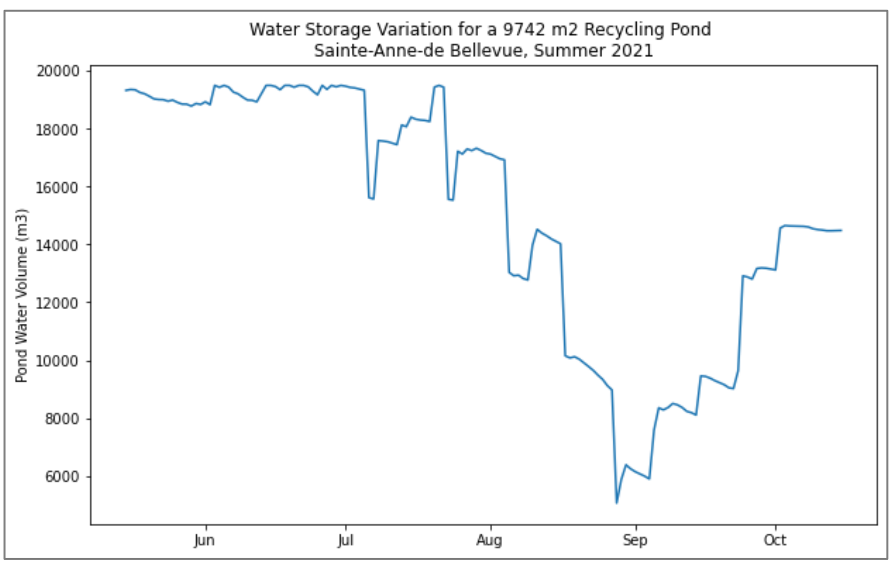



**Figure 24. Water Storage Variation.** This figure presents the change in water volume in a recycling ponf from May 15th to October 15th, in Sainte-Anne-de-Bellevue. This is the results of our computations and Python code.

In this paper's model, the minimum volume reached by the pound was 5067 $m^3$, meaning 0.52m was left at the bottom of the pond. This seems like an acceptable amount, mostly since irrigation values seem a bit overestimated. Likewise, 2021 was the driest year meaning and hence represents high irrigation needs. Therefore, we can confirm that the area chosen is suitable for the establishment of a 2m average depth pond. Furthermore, Reinhart et al. (2019) recommended using a pond area equal to about 6% percent of the total area, which is equal to about 7622 $m^2$, a value very close to our chosen area. Thus, the reservoir chosen should be able to furnish water for irrigation during most years.

#### 5.3.3.1. Pond Design Considerations

Designing a pond requires further planning than just digging a hole. Hence, this section will overview two elements that should be considered when designing a pond: the need for a spillway and the importance of vegetation. However, this list is not at all exhaustive, and more research will be required before beginning the project

A spillway is necessary so that the pond does not overflow and flood the fields we are trying to protect from water accumulation whenever there is a large rainfall event. The two main types of spillways used for farm ponds are drop inlet and excavated earth spillways (USDA, 1981). Drop inlets are vertical pipes open at the pond surface where water can fall when the level is too high (Huffman et al., 2013). In our case, it could be connected to the already existing drainage system and flow out at the same outlet. Usually, even if using a drop inlet, an earth spillway is required for major events. Basically, water needs to be naturally direct toward a single outlet toward a ditch or stream that can lead the water out. This spillway needs to be protected from erosion by vegetation or harder material like rocks (USDA, 1981).

Vegetation is essential for the pond to sustain its main purpose, removing agricultural contaminants such as nitrate and phosphorus. Furthermore, plants help retain the banks and can serve as a habitat for wildlife nurturing local biodiversity (USDA, 1981). Particular attention should be given to only establish native species. Finally, fishes could also be integrated, as they would also participate in the aforementioned benefits.

### 5.3.4. *PUMP*

The pond is located downstream from the field. Hence, a pump is required to take the water from the pond to the field. For our situation, a power take-off (PTO) pump is the best option. The advantage of PTO pumps is that they can be connected directly to the driveshaft of a tractor, are very powerful, require low maintenance, and are easy to use (Jim, 2012). Multiple options are available near the MAC farm to purchase a PTO pump. Companies like Harnois Irrigation (Harnois Irrigation, n.d.) and Dubois Agrinovation (Dubois Agrinovation, 2022) offer PTO pumps at prices ranging from 4600$ to 9500$. Depending on their size and quality, PTO pumps can operate sprinklers and water guns at a rate of 275 to 1200 gallon of water per minute (Dubois Agrinovation, 2022).

## ***5.4.COST***

An important factor in every project is to determine the cost of the project over its lifetime. Yet, due to a lot of uncertainty, it was not possible to establish clearly how much investment would be required for project. Yet, information was available for some elements of the project and will now be discussed.

The cost of a recycling pond was roughly estimated to be between 1000 and 3000 USD per acre feet by Frankenberger et al. (2017). This mean that the pond needed in the project would cost between 16 000 and 47 000 USD. Moreover, the pump was established between 4600$ to 9500$ and cost of ditches can be estimated between 12 000 and 36 000 USD (HomeAdvisor, 2022).

The yield gain as explain earlier are not clear in Quebec regarding forage where research is being done at to moment to determine the profitability. Yet, on a Missouri site that has been using recycling drainage, they have seen a 15% increase in corn yield and a 6% increase in soybeans yield (Frankenberger et al., 2017). Yet, due to the low price of forage, yield increase will most likely be worth the expenses required. However, as the MacDonald farm is part of an educational facility, we believe the innovative nature of this project and the potential for learning might justify this project. As previously mentioned, there is not that many site yet on recycling drainage and a lot of id yet to be learned. Furthermore, their seem to be a renewed interest in corn and soybean irrigation. Hence, McGill university could invest in this project to promote better management practices in Quebec.

## 5.5. *SOCIAL, ENVIRONMENTAL & ECONOMICS IMPACTS*

Before choosing potential solutions, it is first important to look at the general environmental, economical, and social impacts of water management. Understanding both the positive and negative impacts of our potential solutions is primordial. Hence, this part of the report will present the positive and negative consequences of surface and subsurface drainage.

It has been observed that drainage can be beneficial for crop production and overall soil health since it improves soil aeration by removing excess water, it increases field trafficability by drying the soil, it enables the crop to establish deeper roots to access deeper nutrients by reducing the compaction of the soil, it increases the plants' nitrate uptake by increasing nitrification in the soil, it makes earlier planting possible by increasing the heating rate of the soil, and it reduces surface erosion if subsurface drainage is implemented (Easton et al., 2016). However, drainage may also lead to negative consequences such as contamination of downstream water bodies, alteration of the natural hydrology of the field, loss of wetland, and increased surface erosion if surface drainage is implemented (Easton et al., 2016). Drainage decreases the time available for plants to assimilate nutrients in the soil, hence increasing the runoff of nutrients, such as nitrates and phosphates, in downstream water bodies. This leads to algal growth and eutrophication, which have detrimental impacts on the water bodies' ecosystems and surrounding environment. Furthermore, the soil hydrology in agricultural lands is very fragile and can be disrupted by drainage since it tends to create greater peak flow and lower base flow. This leads to further erosion and harmful conditions for aquatic organisms (Easton et al., 2016). However, the eutrophication of water body can potentially be considered negligible since a pond will be used to contain the runoff water. Hence, through proper management of the pond, avoiding severe eutrophication of downstream water bodies is possible.

In a similar manner, the positive economical impacts include the increase of overall soil health and crop growth rate as well as the reduction of the quantity of fertilizer required. Such outcomes are desirable since they increase the overall short-term and long-term profit by increasing the crop growth rate and ensuring that the field will keep optimal quantities of nutrients in the long-term. However, implementing a new drainage on the field also implies negative economic impacts. An initial investment will be required for the implementation of the new surface drainage system (digging the ditches) and the pump required for the recycling water technology. Fortunately, those two operations should not be overcomplicated and relatively cheap, thus reducing the economical cost of our project. Also, the subsurface drainage part of our design does not require the implementation of new subsurface drains. This reduces the initial investment required but may be problematic if drains are too clogged to be unclogged and need to be replaced in a few years. Then, some additional economical resources will be required for the maintenance of the system, such as the cleaning of the ditches and pond, and the energy required for the pump (Evans et al., 1996).

Finally, the positive social impacts of a new drainage system include a local food source for people of Sainte-Anne-de-Bellevue and a better use and conservation of the environment for future generations. A better conservation of the field is highly desirable since, as was mentioned above, agricultural lands in Canada are very rare and must be managed to ensure a sustainable food source for future generations. Although, some potential flaws in the design or extreme weather events may lead to negative social impacts, such as flooding or eutrophication of water bodies (Easton et al., 2016). This can lead to very harsh impacts on the fragile ecosystem and, ultimately, may prevent people from swimming or fishing in lakes and rivers due to toxicity.

# 6. CONCLUSION

This semester, we focused on the design of our final solution based on the information we gathered in the Fall. Accordingly, we redesigned the surface drainage on the field and implemented a pond to allow for the recuperation of runoff water and the implementation of a recycling water system. The main new features for the surface drainage are the pond and the two ditches. To evaluate their size, we computed both the surface drainage and the water balance on the field. Weather data was gathered and inputted in DRAINMOD to obtain the surface drainage and design the ditches. A water analysis allowed for the calculation of the optimal size of the pond and the feasibility of implementing the recycling water technology. Since we did not know the condition of subsurface drains in the field, we decided to keep the same drains and unclog them, if necessary, instead of inputting new drains.

Overall, we strongly believe that this solution results in the most beneficial social, environmental, and economic impacts. As was previously assessed, an increase in overall soil health, crop production, and sustainable farming practices can be foreseen. However, a high initial investment is required to implement the new surface drainage components as well as the pump for the recycling water. Since the economic aspect of the design was not the leading constraint, we truly believe the design we propose is feasible. Thus, we can assert that we have attained our goal of providing an improved water management system on Field 86 at the MacDonald Campus Farm, thus increasing its overall sustainability and viability.

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Limit=yearRange&Month=4&Day=13&StartYear=1840&EndYear=2022&Year=2022&selRowPerPage=25&Line=38&txtRadius=25&optProxType=city&selCity=45%7C31%7C73%7C39%7CMontr%C3%A9al&selPark=&txtCentralLatDeg=&txtCentralLatMin=0&txtCentralLatSec=0&txtCentralLongDeg=&txtCentralLongMin=0&txtCentralLongSec=0&txtLatDecDeg=&txtLongDecDeg=&timeframe=2

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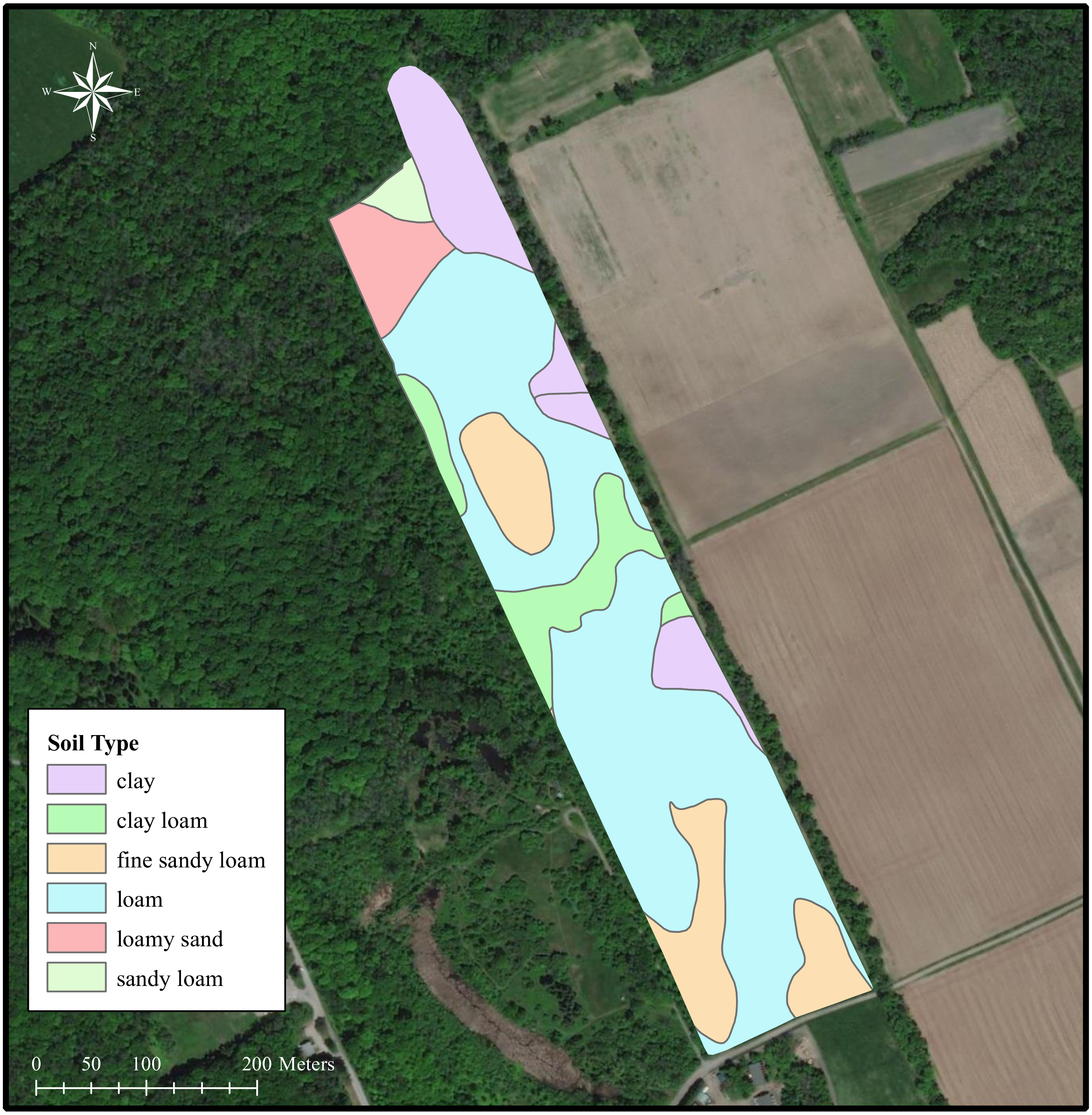
# 8. APPENDICES

## *APPENDIX 1. OVERVIEW OF FIELD 86*

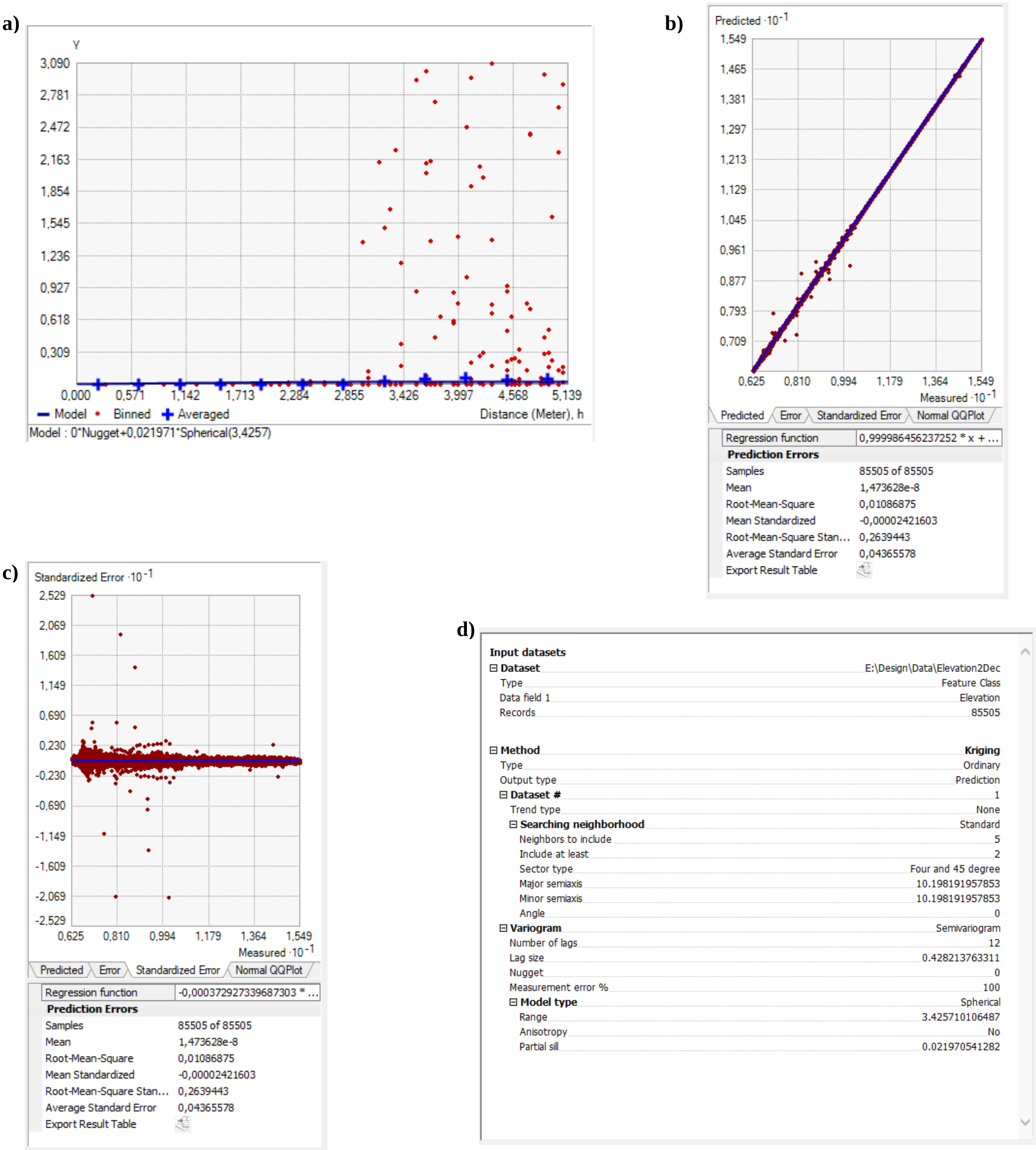

**Appendix 1. Overview of Field 86.** This is an overview of F86 (in red), it presents where it is in Saint-Anne-de-Bellevue. The yellow star is located on the McGill Macdonald Campus Library. This map was created by our team using the data provided by Dr. Adamchuk.

## *Appendix 2. Soil Types of Field 86*




**Appendix 2. Soil Types of Field 86.** This map shows all areas where the different soil types are present. Loam is the main type, whereas only a small area is sandy loam. This map was created by our team using the data provided by Dr. Adamchuk.

## *Appendix 3. Kriging Inperpolation for Elevation Map*




**Appendix 3. Kriging Interpolation for Elevation Map.** These figures shows some of the steps effectuated to obtain F86 elevation map. a) shows the semivariogram, b) the predicted errors, c) the standardized error and d) the method reports.

## *APPENDIX 4. 2020 FIELD 86 SOIL ANALYSIS RESULTS*

| Long. | Lat. | Field_no | Sample ID | Lab ID | pH | Buffer_pH | Lime | OM | P kg/ha | K kg/ha | Ca kg/ha | Mg kg/ha | Mn ppm | Na kg/ha | Zn ppm | Al ppm | CEC meq1 | Sat K | Sat Ca | Sat Mg | SatKMg Ca | B ppm | Cu ppm | Fe ppm | Elev. m |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| -73.936263 | 45.429456 | 86 | 086-1 | 720532 | 6.1 | 6.6 | 66 | 4.6 | 199 | 365 | 5313 | 438 | 57.5 | 25 | 6 | 882 | 21.8 | 1.9 | 54 | 7.46 | 63.7 | 0.5 | 2.54 | 217.84 | 11.3706999 |
| -73.936982 | 45.4302 | 86 | 086-2 | 720495 | 6.4 | 7 | 70 | 3.6 | 97 | 132 | 4682 | 593 | 34.5 | 28 | 3 | 790 | 17.4 | 0.9 | 60 | 12.68 | 73.6 | 0.5 | 1.79 | 155.24 | 14.8851995 |
| -73.935997 | 45.430412 | 86 | 086-3 | 719986 | 6.4 | 6.9 | 69 | 5 | 77 | 168 | 5834 | 615 | 72.6 | 30 | 3.8 | 806 | 20.8 | 0.9 | 63 | 10.99 | 74.5 | 0.7 | 2.09 | 181.08 | 11.4252005 |
| -73.937701 | 45.430944 | 86 | 086-4 | 720491 | 6.5 | 6.9 | 69 | 4.7 | 119 | 207 | 5689 | 773 | 69 | 29 | 4.5 | 788 | 21.1 | 1.1 | 60 | 13.62 | 74.9 | 0.8 | 1.97 | 176.86 | 14.5039997 |
| -73.936755 | 45.431488 | 86 | 086-5 | 719929 | 6.4 | 6.9 | 69 | 6.7 | 91 | 447 | 7733 | 959 | 39.4 | 31 | 5 | 731 | 27.1 | 1.9 | 64 | 13.17 | 78.7 | 1.1 | 3.09 | 153.72 | 10.2730999 |
| -73.938242 | 45.431679 | 86 | 086-6 | 719985 | 6.6 | 7 | 70 | 3.5 | 63 | 221 | 5436 | 824 | 32.8 | 28 | 2.6 | 844 | 20.2 | 1.3 | 60 | 15.16 | 76.4 | 0.4 | 2.06 | 155.21 | 12.2287998 |
| -73.937364 | 45.432194 | 86 | 086-7 | 720534 | 6.4 | 6.7 | 67 | 5.2 | 89 | 238 | 7280 | 636 | 34.3 | 38 | 4.4 | 784 | 25.8 | 1.1 | 63 | 9.17 | 73.2 | 0.6 | 1.95 | 179.56 | 10.842 |
| -73.939013 | 45.432602 | 86 | 086-8 | 719932 | 5.7 | 6.7 | 67 | 3.9 | 163 | 220 | 4421 | 332 | 19.6 | 29 | 3.3 | 861 | 18.4 | 1.4 | 54 | 6.71 | 61.8 | 0.4 | 1.7 | 225.96 | 10.1267004 |
| -73.938083 | 45.432938 | 86 | 086-9 | 720621 | 5.9 | 6.7 | 67 | 3.7 | 91 | 149 | 4626 | 503 | 24.7 | 34 | 1.8 | 943 | 19.2 | 0.9 | 54 | 9.75 | 64.4 | 0.4 | 1.52 | 178.11 | 10.5337 |
| -73.938803 | 45.433682 | 86 | 086-10 | 720607 | 5.7 | 6.4 | 64 | 3.4 | 109 | 175 | 3251 | 268 | 15.6 | 22 | 2 | 940 | 18.6 | 1.1 | 39 | 5.35 | 45.4 | 0.3 | 1.25 | 179.56 | 9.3144398 |
| -73.939522 | 45.434426 | 86 | 086-11 | 720612 | 6.3 | 6.8 | 68 | 3 | 53 | 122 | 3600 | 220 | 22.3 | 21 | 1.3 | 997 | 15.7 | 0.9 | 51 | 5.23 | 57.5 | 0.4 | 1.19 | 156.16 | 11.9312 |
| -73.938824 | 45.434954 | 86 | 086-12 | 720616 | 6.6 | 7 | 70 | 5.9 | 38 | 201 | 7986 | 947 | 51.3 | 37 | 3.5 | 858 | 26 | 0.9 | 69 | 13.55 | 83 | 0.9 | 2.29 | 182.43 | 8.5693398 |
| -73.940241 | 45.43517 | 86 | 086-13 | 720614 | 5.8 | 6.4 | 64 | 4 | 42 | 138 | 4035 | 279 | 28.2 | 32 | 2.2 | 899 | 20.3 | 0.8 | 44 | 5.12 | 50.3 | 0.4 | 1.59 | 178.34 | 8.1241398 |
| -73.93946 | 45.435783 | 86 | 086-14 | 720522 | 6.6 | 7 | 70 | 5.5 | 32 | 434 | 7837 | 1360 | 16.9 | 51 | 4.2 | 830 | 27.7 | 1.8 | 63 | 18.3 | 83.3 | 1 | 3.81 | 150.16 | 6.54703 |
| -73.939904 | 45.436421 | 86 | 086-15 | 719927 | 6.1 | 6.7 | 67 | 6 | 33 | 350 | 8627 | 878 | 14.4 | 48 | 2.8 | 895 | 29.9 | 1.3 | 65 | 10.94 | 76.8 | 0.7 | 2.85 | 163.07 | 6.7592402 |

**Appendix 4. 2020 Field 86 Soil Analysis Results.** This table shows the results of the soil analysis done in 2020. We believe Logiag inc. were the ones to collect the samples.

# *APPENDIX 5. 2015 FIELD 86 SOIL ANALYSIS RESULTS*

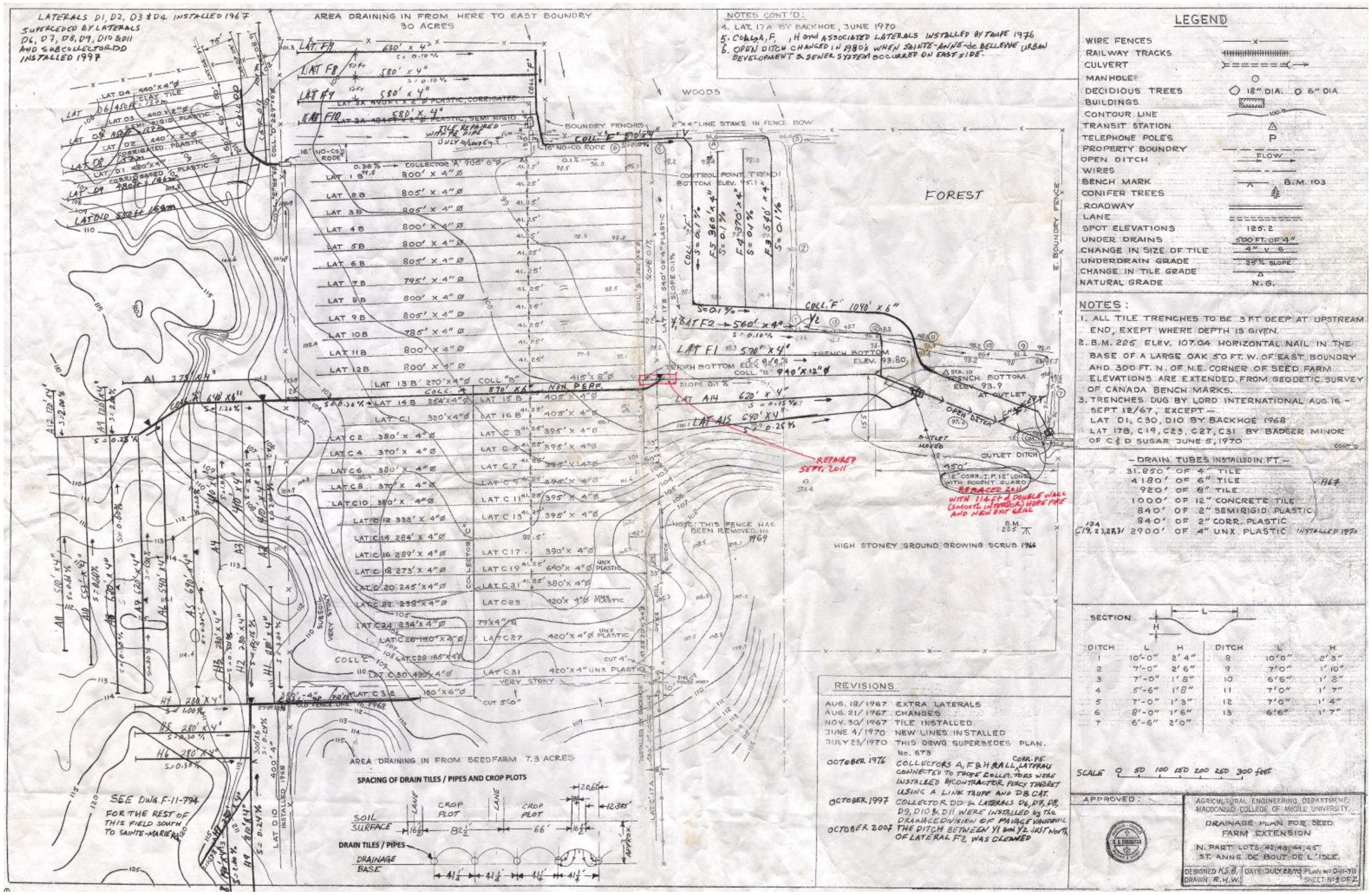
**Appendix 5. 2015 Field 86 Soil Analysis Results.** This table shows the results of the soil analysis done in 2015. We believe Logiag inc. were the ones to collect the samples.

| Lab ID | Long. | Lat. | Water pH | WDRF BpH | Salts mmho | OM LOI | N | N1 | K | Zn ppm | Iron ppm | Mn | Cu ppm | Ca ppm | Mg | Na ppm | CECme 100 | FH Sat | FK Sat | FCa Sat | FMg Sat | FNa Sat | Mehlich P | NR | Moisture g | Moisture v | BD | Elev. m |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 74761 | -73.939738 | 45.433325 | 7 | 7.2 | 0.34 | 7 | 15.4 | 28 | 182 | 3.58 | 141.8 | 28.5 | 3.75 | 3580 | 397 | 11 | 21.7 | 0 | 2 | 82 | 15 | 0 | 74 | 0 | 0.2561 | 0.2589 | 1.01 | -9999 |
| 74762 | -73.940907 | 45.435292 | 7.1 | 7.2 | 0.32 | 6.2 | 21.1 | 38 | 120 | 3.25 | 61.3 | 13 | 1.74 | 2858 | 328 | 8 | 17.4 | 0 | 2 | 82 | 16 | 0 | 27 | 5 | 0.3412 | 0.3738 | 1.1 | -9999 |
| 74764 | -73.939998 | 45.434691 | 6.7 | 7.2 | 0.27 | 6.2 | 26.3 | 47 | 111 | 2.66 | 79.7 | 13.8 | 1.39 | 2074 | 219 | 7 | 12.5 | 0 | 2 | 83 | 15 | 0 | 31 | 5 | 0.304 | 0.3447 | 1.13 | 11.4890003 |
| 74765 | -73.938912 | 45.434212 | 6.7 | 7.2 | 0.23 | 6.1 | 17.2 | 31 | 195 | 2.75 | 165.6 | 9.5 | 2.31 | 2516 | 256 | 14 | 15.3 | 0 | 3 | 82 | 14 | 0 | 97 | 0 | 0.2272 | 0.2628 | 1.16 | 8.2410402 |
| 74766 | -73.93871 | 45.433137 | 6.5 | 6.7 | 0.2 | 4.2 | 22.4 | 40 | 85 | 1.13 | 59.2 | 3.7 | 1.05 | 1708 | 149 | 8 | 13.1 | 24 | 2 | 65 | 9 | 0 | 73 | 0 | 0.2319 | 0.265 | 1.14 | 10.2452002 |
| 74767 | -73.936703 | 45.431878 | 6.9 | 7.2 | 0.28 | 5 | 33.2 | 60 | 102 | 1.54 | 64.4 | 12 | 0.9 | 1969 | 90 | 7 | 10.9 | 0 | 2 | 90 | 7 | 0 | 34 | 5 | 0.2742 | 0.2852 | 1.04 | 9.6639996 |
| 74768 | -73.937597 | 45.430702 | 7.1 | 7.2 | 0.26 | 6.4 | 25.1 | 45 | 89 | 3.78 | 80.6 | 13.6 | 1.45 | 2695 | 442 | 11 | 17.4 | 0 | 1 | 77 | 21 | 0 | 96 | 0 | 0.2262 | 0.2402 | 1.06 | 15.1731005 |
| 74769 | -73.935463 | 45.42942 | 7.3 | 7.2 | 0.23 | 5.2 | 22.4 | 40 | 96 | 1.36 | 56.9 | 7.6 | 1.06 | 2399 | 162 | 9 | 13.6 | 0 | 2 | 88 | 10 | 0 | 69 | 0 | 0.2175 | 0.2491 | 1.15 | 13.5792999 |
| 74771 | -73.936875 | 45.429466 | 7 | 7.2 | 0.24 | 4.9 | 27.9 | 50 | 151 | 1.85 | 56 | 5.6 | 1.14 | 1924 | 107 | 9 | 10.9 | 0 | 4 | 88 | 8 | 0 | 166 | 0 | 0.2177 | 0.2663 | 1.22 | 13.4667997 |
| 74773 | -73.93668 | 45.42896 | 6.7 | 7.2 | 0.27 | 4.7 | 25.2 | 45 | 163 | 1.81 | 91.1 | 12.8 | 1.24 | 1753 | 120 | 8 | 10.2 | 0 | 4 | 86 | 10 | 0 | 99 | 0 | 0.2265 | 0.2891 | 1.28 | 12.8255997 |
| 74775 | -73.935208 | 45.429275 | 7.5 | 7.2 | 0.26 | 3.3 | 17.9 | 32 | 85 | 1.13 | 78.8 | 7.8 | 1.06 | 3367 | 85 | 9 | 17.8 | 0 | 1 | 95 | 4 | 0 | 88 | 0 | 0.1737 | 0.2087 | 1.2 | 13.7986002 |
| 74776 | -73.936732 | 45.429423 | 6.5 | 6.7 | 0.24 | 4.5 | 29.7 | 53 | 124 | 2.18 | 137.3 | 16.6 | 1.45 | 1759 | 118 | 8 | 13.5 | 25 | 2 | 65 | 7 | 0 | 131 | 0 | 0.2391 | 0.3034 | 1.27 | 12.9998999 |
| 74777 | -73.936068 | 45.429625 | 6.9 | 7.2 | 0.29 | 5.9 | 35.1 | 63 | 155 | 2.62 | 63.2 | 6.1 | 1.32 | 2214 | 182 | 7 | 13 | 0 | 3 | 85 | 12 | 0 | 85 | 0 | 0.295 | 0.315 | 1.07 | 11.9442997 |
| 74778 | -73.93551 | 45.429909 | 6.6 | 7.2 | 0.24 | 3.9 | 26.2 | 47 | 195 | 1.92 | 89.5 | 21.3 | 1.17 | 1384 | 106 | 7 | 8.3 | 0 | 6 | 83 | 11 | 0 | 157 | 0 | 0.2484 | 0.2964 | 1.19 | 13.6634998 |
| 74779 | -73.937158 | 45.429889 | 7.2 | 7.2 | 0.26 | 5.4 | 23.4 | 42 | 149 | 2.71 | 52.8 | 5.2 | 1.03 | 2243 | 211 | 6 | 13.4 | 0 | 3 | 84 | 13 | 0 | 95 | 0 | 0.2079 | 0.237 | 1.14 | 15.1286001 |
| 74780 | -73.936552 | 45.430219 | 6.7 | 7.2 | 0.22 | 3.7 | 24.4 | 44 | 100 | 1.56 | 54.2 | 4.7 | 1.05 | 1515 | 104 | 8 | 8.7 | 0 | 3 | 87 | 10 | 0 | 151 | 0 | 0.207 | 0.2554 | 1.23 | 12.5274 |
| 74781 | -73.935822 | 45.430494 | 7.1 | 7.2 | 0.25 | 4.9 | 22.8 | 41 | 60 | 1.38 | 62.2 | 6.4 | 1.11 | 2150 | 143 | 13 | 12.1 | 0 | 1 | 88 | 10 | 0 | 44 | 0 | 0.3021 | 0.3417 | 1.13 | 11.9045 |
| 74782 | -73.93771 | 45.43065 | 7.1 | 7.2 | 0.25 | 4.7 | 19.1 | 34 | 125 | 2.27 | 59.1 | 5.5 | 1.08 | 2317 | 185 | 10 | 13.5 | 0 | 2 | 86 | 11 | 0 | 64 | 0 | 0.2155 | 0.2558 | 1.19 | 14.9983997 |
| 74783 | -73.9371 | 45.430716 | 7.2 | 7.2 | 0.27 | 5.5 | 22.5 | 41 | 91 | 3.22 | 58.9 | 8.7 | 1.3 | 2711 | 346 | 10 | 16.7 | 0 | 1 | 81 | 17 | 0 | 80 | 0 | 0.2026 | 0.2301 | 1.14 | 15.2755003 |

| | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 06 | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 74784 | -73.936191 | 45.431136 | 7 | 7.2 | 0.24 | 6.9 | 19.2 | 35 | 120 | 3.36 | 84.1 | 16.2 | 1.74 | 3047 | 305 | 12 | 18.1 | 0 | 2 | 84 | 14 | 0 | 70 | 0 | 0.3072 | 0.3293 | 1.07 | 10.658 |
| 74785 | -73.937915 | 45.431071 | 7.3 | 7.2 | 0.31 | 5.9 | 30.5 | 55 | 182 | 3.39 | 164.4 | 20.9 | 1.24 | 2826 | 258 | 7 | 16.8 | 0 | 3 | 84 | 13 | 0 | 115 | 0 | 0.2474 | 0.2682 | 1.08 | 13.8339996 |
| 74786 | -73.937146 | 45.431365 | 7 | 7.2 | 0.31 | 6 | 32 | 58 | 141 | 2.85 | 96.1 | 12.9 | 1.41 | 2349 | 255 | 7 | 14.3 | 0 | 3 | 82 | 15 | 0 | 105 | 0 | 0.2744 | 0.317 | 1.16 | 11.7018003 |
| 74789 | -73.937867 | 45.431984 | 7.2 | 7.2 | 0.22 | 5.1 | 24.9 | 45 | 129 | 1.68 | 56.7 | 9.4 | 1.15 | 2199 | 272 | 8 | 13.6 | 0 | 2 | 81 | 17 | 0 | 47 | 0 | 0.2045 | 0.2447 | 1.2 | 12.8168001 |
| 74790 | -73.936817 | 45.431972 | 7 | 7.2 | 0.31 | 6.1 | 22.9 | 41 | 270 | 3.8 | 76.1 | 7.9 | 2.41 | 3101 | 381 | 12 | 19.4 | 0 | 4 | 80 | 16 | 0 | 90 | 0 | 0.2656 | 0.2604 | 0.98 | 9.6035204 |
| 74791 | -73.938567 | 45.432169 | 7.1 | 7.2 | 0.2 | 4.3 | 9.6 | 17 | 111 | 2.04 | 88.1 | 4.4 | 1.31 | 2271 | 204 | 12 | 13.4 | 0 | 2 | 85 | 13 | 0 | 66 | 0 | 0.1805 | 0.2218 | 1.23 | 10.0408001 |
| 74792 | -73.938209 | 45.432454 | 6.4 | 6.6 | 0.22 | 4.9 | 18.2 | 33 | 206 | 2.29 | 111.6 | 14.8 | 1.66 | 1853 | 152 | 7 | 15.3 | 27 | 3 | 61 | 8 | 0 | 127 | 0 | 0.222 | 0.2729 | 1.23 | 10.3948002 |
| 74793 | -73.937331 | 45.432781 | 7 | 7.2 | 0.22 | 5 | 14.6 | 26 | 120 | 2.12 | 77.4 | 8.9 | 1.4 | 2866 | 209 | 9 | 16.4 | 0 | 2 | 87 | 11 | 0 | 59 | 0 | 0.1916 | 0.2383 | 1.24 | 9.7435999 |
| 74794 | -73.939267 | 45.432939 | 6.9 | 7.2 | 0.27 | 4.7 | 27.4 | 49 | 115 | 1.34 | 64.6 | 8.7 | 1.17 | 2160 | 129 | 7 | 12.2 | 0 | 2 | 88 | 9 | 0 | 103 | 0 | 0.2095 | 0.2535 | 1.21 | 10.4102001 |
| 74795 | -73.9384 | 45.433161 | 6.7 | 7.2 | 0.17 | 4.6 | 19.3 | 35 | 68 | 1.17 | 63.5 | 6.5 | 0.99 | 1650 | 115 | 6 | 9.4 | 0 | 2 | 88 | 10 | 0 | 120 | 0 | 0.2391 | 0.288 | 1.2 | 10.4764004 |
| 74796 | -73.937643 | 45.433167 | 7 | 7.2 | 0.24 | 5.4 | 24.6 | 44 | 132 | 1.15 | 71.7 | 11.2 | 1.12 | 2230 | 113 | 9 | 12.5 | 0 | 3 | 89 | 8 | 0 | 112 | 0 | 0.2464 | 0.269 | 1.09 | 9.7260904 |
| 74797 | -73.939494 | 45.433482 | 6.9 | 7.2 | 0.22 | 6.5 | 17.2 | 31 | 133 | 2.34 | 106.8 | 23.1 | 1.6 | 3109 | 266 | 11 | 18.2 | 0 | 2 | 86 | 12 | 0 | 65 | 0 | 0.2378 | 0.2871 | 1.21 | 9.0978899 |
| 74798 | -73.938587 | 45.433807 | 6.6 | 7.2 | 0.26 | 5.3 | 30 | 54 | 139 | 2.91 | 117.6 | 27.4 | 1.46 | 2388 | 209 | 14 | 14.1 | 0 | 3 | 85 | 12 | 0 | 42 | 0 | 0.2508 | 0.2765 | 1.1 | 8.7016001 |
| 74799 | -73.938037 | 45.433786 | 7.3 | 7.2 | 0.27 | 6.2 | 19.7 | 35 | 148 | 2.28 | 62 | 13.2 | 1.44 | 3126 | 227 | 10 | 17.9 | 0 | 2 | 87 | 11 | 0 | 52 | 0 | 0.257 | 0.2751 | 1.07 | 8.4224901 |
| 74800 | -73.939878 | 45.433985 | 7 | 7.2 | 0.22 | 4.4 | 22.2 | 40 | 132 | 1.07 | 64.8 | 8.9 | 1.05 | 2360 | 164 | 12 | 13.6 | 0 | 2 | 87 | 10 | 0 | 59 | 0 | 0.2217 | 0.2738 | 1.24 | 9.8845901 |
| 74801 | -73.939061 | 45.43408 | 6.6 | 7.2 | 0.3 | 5.7 | 25.8 | 46 | 165 | 2.69 | 173.8 | 40.2 | 2.34 | 2761 | 281 | 18 | 16.6 | 0 | 3 | 83 | 14 | 0 | 74 | 0 | 0.2833 | 0.3034 | 1.07 | 8.4398603 |
| 74802 | -73.938708 | 45.434654 | 7 | 7.2 | 0.27 | 6.9 | 23.7 | 43 | 131 | 2.87 | 151.6 | 44.6 | 1.88 | 3484 | 394 | 12 | 21.1 | 0 | 2 | 82 | 16 | 0 | 24 | 10 | 0.315 | 0.3129 | 0.99 | 8.6611996 |
| 74803 | -73.940244 | 45.434751 | 7.1 | 7.2 | 0.29 | 6.2 | 30.8 | 55 | 97 | 2.4 | 81.2 | 10.4 | 1.03 | 2578 | 216 | 8 | 15 | 0 | 2 | 86 | 12 | 0 | 26 | 10 | 0.2912 | 0.3057 | 1.05 | 10.1969995 |
| 74804 | -73.939596 | 45.434883 | 6.8 | 7.2 | 0.25 | 5.1 | 24.6 | 44 | 107 | 2.69 | 126.7 | 30.7 | 1.46 | 2263 | 246 | 8 | 13.7 | 0 | 2 | 83 | 15 | 0 | 19 | 10 | 0.2405 | 0.2599 | 1.08 | 11.8753004 |
| 74805 | -73.938893 | 45.434905 | 7.2 | 7.2 | 0.34 | 9.8 | 34.6 | 62 | 171 | 2.34 | 95.9 | 19.6 | 1.66 | 4920 | 479 | 14 | 29.1 | 0 | 2 | 84 | 14 | 0 | 32 | 5 | 0.3998 | 0.3153 | 0.79 | 8.9635897 |
| 74806 | -73.940623 | 45.435229 | 6.7 | 7.2 | 0.23 | 6.3 | 21.2 | 38 | 123 | 4.41 | 79.7 | 15.2 | 2.38 | 2780 | 272 | 7 | 16.5 | 0 | 2 | 84 | 14 | 0 | 41 | 5 | 0.2732 | 0.3144 | 1.15 | 7.8762102 |
| 74807 | -73.939839 | 45.435519 | 6.7 | 7.2 | 0.25 | 6.7 | 32.6 | 59 | 147 | 2.19 | 83.3 | 6.2 | 1.53 | 2781 | 188 | 10 | 15.9 | 0 | 2 | 88 | 10 | 0 | 30 | 5 | 0.364 | 0.364 | 1 | 7.1485701 |

| | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 74809 | -73.94083 | 45.435591 | 7.1 | 7.2 | 0.38 | 6.5 | 31.7 | 57 | 182 | 4.02 | 72.1 | 21.6 | 2.44 | 3638 | 310 | 7 | 21.3 | 0 | 2 | 86 | 12 | 0 | 43 | 0 | 0.2979 | 0.3419 | 1.15 | 7.5938902 |
| 74813 | -73.93825 | 45.433744 | 7.4 | 7.2 | 0.26 | 4.3 | 24.1 | 43 | 81 | 1.86 | 46.2 | 3.7 | 1.22 | 2560 | 130 | 6 | 14.1 | 0 | 1 | 91 | 8 | 0 | 62 | 0 | 0.2137 | 0.2507 | 1.17 | 8.8240299 |
| 74814 | -73.937382 | 45.431214 | 7.2 | 7.2 | 0.28 | 5.7 | 20.8 | 37 | 147 | 3 | 78.2 | 14.7 | 1.57 | 2692 | 367 | 11 | 16.9 | 0 | 2 | 79 | 18 | 0 | 92 | 0 | 0.2024 | 0.2131 | 1.05 | 13.6307001 |
| 74817 | -73.940111 | 45.434552 | 7.1 | 7.2 | 0.3 | 6.6 | 24.1 | 43 | 190 | 3.83 | 105.9 | 13.8 | 2.82 | 3690 | 439 | 15 | 22.7 | 0 | 2 | 81 | 16 | 0 | 81 | 0 | 0.3026 | 0.3232 | 1.07 | 11.2649002 |
| 74819 | -73.936378 | 45.428864 | 7.6 | 7.2 | 0.29 | 5.1 | 22.8 | 41 | 214 | 2.16 | 74.6 | 14.9 | 1.3 | 3152 | 185 | 9 | 17.9 | 0 | 3 | 88 | 9 | 0 | 86 | 0 | 0.2265 | 0.2908 | 1.28 | 12.5861998 |
| 74820 | -73.937487 | 45.432457 | 7.2 | 7.2 | 0.3 | 5.3 | 22.4 | 40 | 117 | 1.83 | 64.5 | 5 | 1.4 | 2882 | 161 | 10 | 16.1 | 0 | 2 | 90 | 8 | 0 | 91 | 0 | 0.2251 | 0.2454 | 1.09 | 10.3507996 |
| 74821 | -73.937742 | 45.433303 | 7.4 | 7.2 | 0.28 | 4.5 | 19.7 | 35 | 114 | 0.97 | 54.8 | 10.1 | 1 | 2498 | 101 | 6 | 13.7 | 0 | 2 | 92 | 6 | 0 | 86 | 0 | 0.2262 | 0.2585 | 1.14 | 10.2334995 |
| 74822 | -73.938279 | 45.43291 | 6.4 | 6.6 | 0.24 | 5.2 | 29.5 | 53 | 117 | 2.32 | 115.7 | 6.3 | 1.34 | 1867 | 159 | 6 | 15.4 | 29 | 2 | 60 | 9 | 0 | 140 | 0 | 0.2616 | 0.3202 | 1.22 | 10.5857 |
| 74823 | -73.936994 | 45.430076 | 6.9 | 7.2 | 0.25 | 5.2 | 23.2 | 42 | 125 | 2.37 | 70.3 | 5.3 | 1.38 | 2057 | 197 | 7 | 12.3 | 0 | 3 | 84 | 13 | 0 | 156 | 0 | 0.2584 | 0.32 | 1.24 | 15.0720997 |
| 74824 | -73.935623 | 45.429577 | 7.2 | 7.2 | 0.31 | 4.6 | 32.8 | 59 | 131 | 1.57 | 43.2 | 4.1 | 1 | 2289 | 139 | 6 | 13 | 0 | 3 | 88 | 9 | 0 | 75 | 0 | 0.2288 | 0.273 | 1.19 | 12.8389997 |

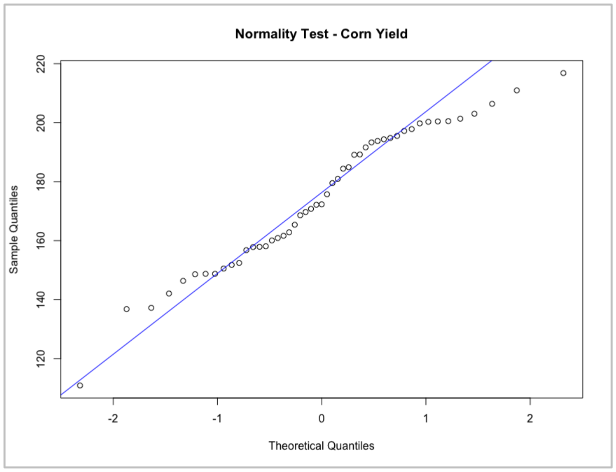
## *APPENDIX 6. FIELD 86 OLD DRAINAGE MAP*

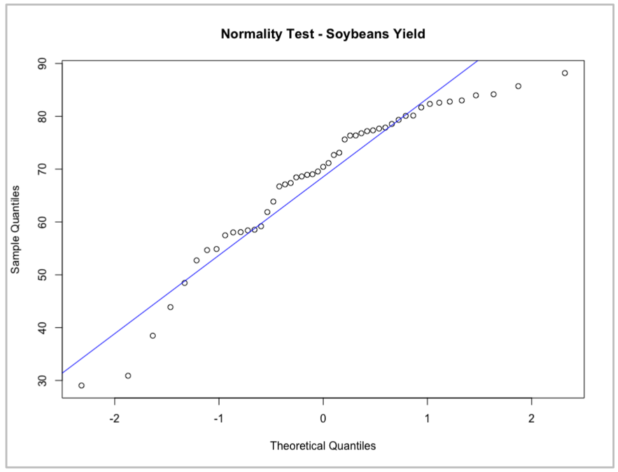


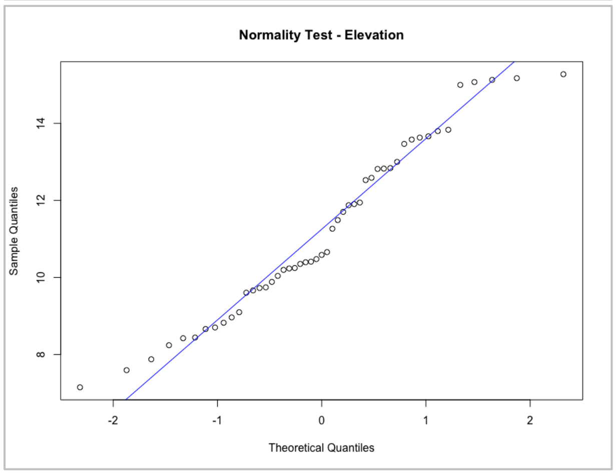

**Appendix 6. Field 86 Old Drainage Map.** This figure shows the previous work done in F86. Mr. Chaumont sent us this map and the engineers responsible for this design are difficult to identify due to the quality of the image.

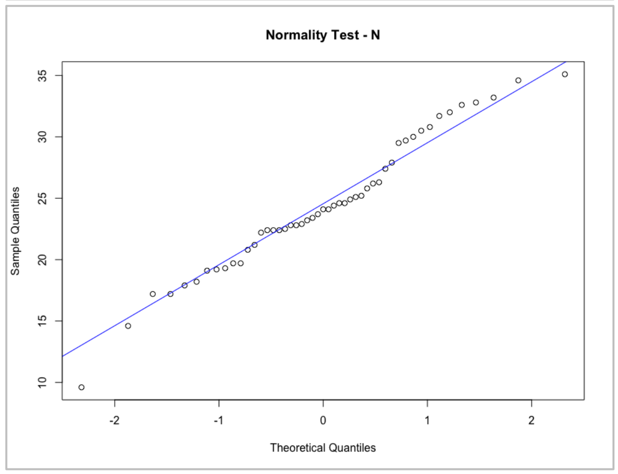
# *APPENDIX 7. NORMALITY TESTS*

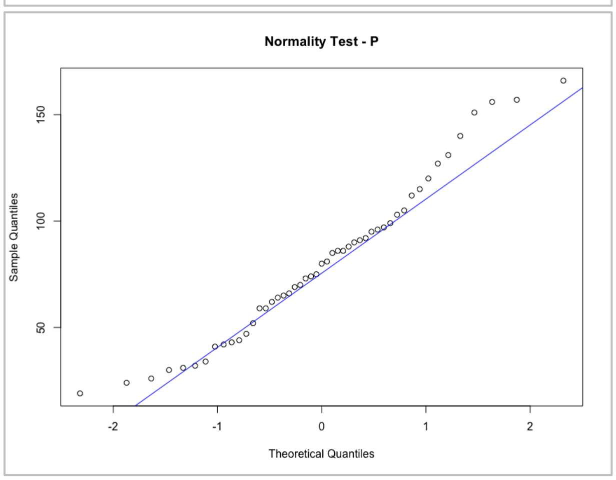
**Appendix 7. Normality Test of Soil Properties.** These graphs show the results of the normality test effectuated on each soil property that was tested for correlation.

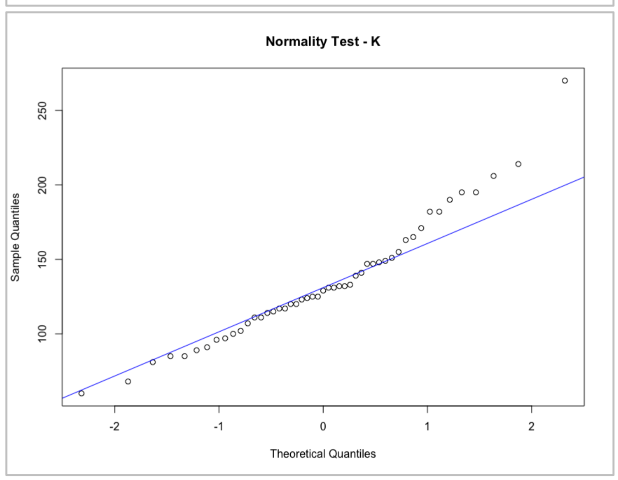


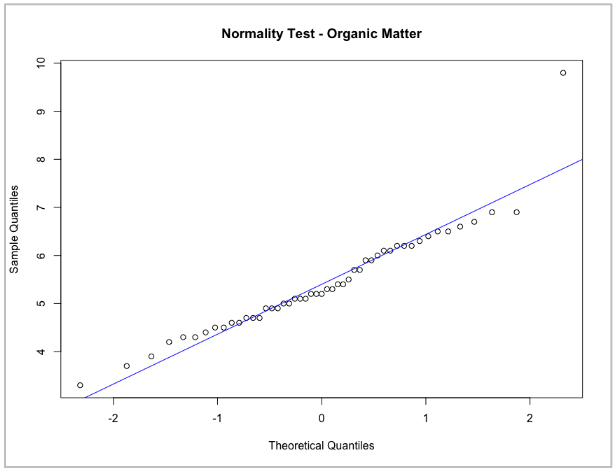



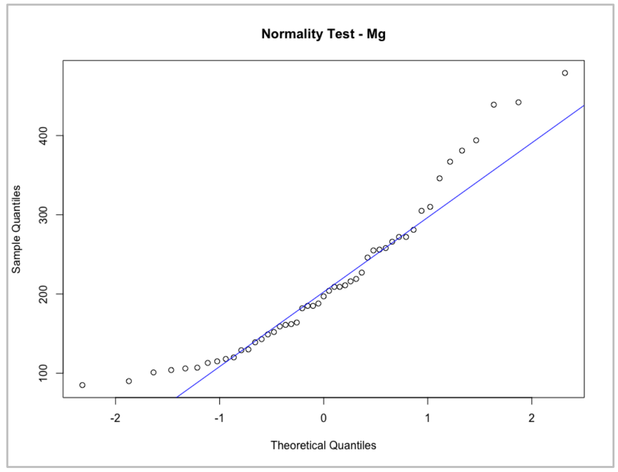



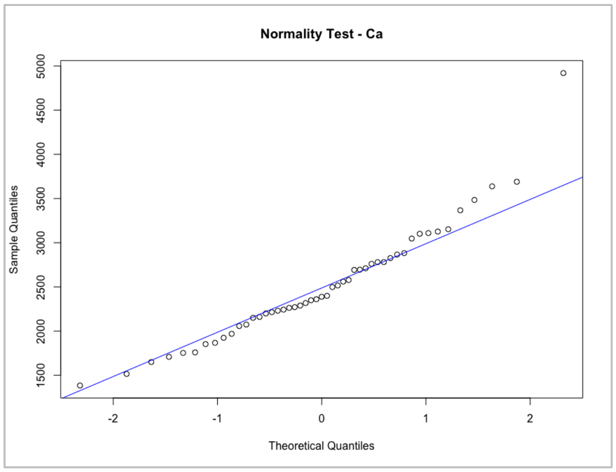



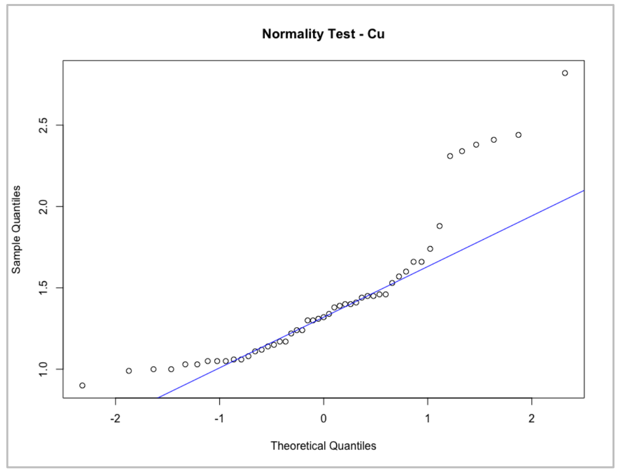



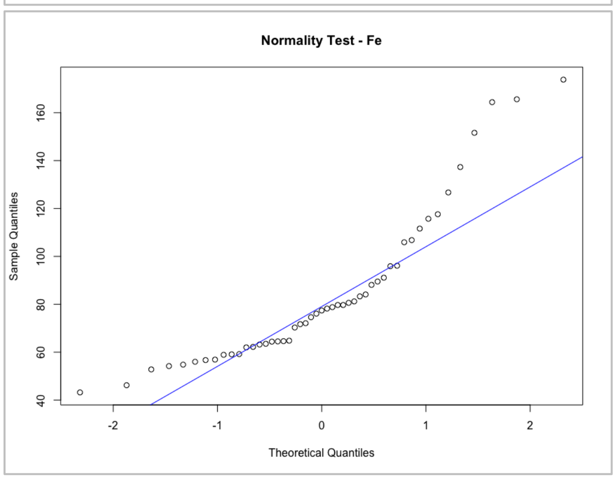



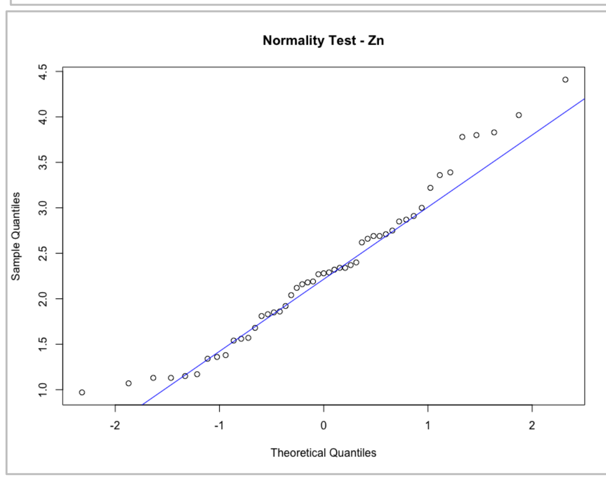

Normality Test - Organic Matter
Sample Quantiles
4
5
6
7
8
9
10
-2
-1
0
1
2
Theoretical Quantiles


Normality Test - Mg
Sample Quantiles
100
200
300
400
-2
-1
0
1
2
Theoretical Quantiles


Normality Test - Ca
Sample Quantiles
1500
2000
2500
3000
3500
4000
4500
5000
-2
-1
0
1
2
Theoretical Quantiles


Normality Test - Cu
Sample Quantiles
1.0
1.5
2.0
2.5
-2
-1
0
1
2
Theoretical Quantiles


Normality Test - Fe
Sample Quantiles
40
60
80
100
120
140
160
-2
-1
0
1
2
Theoretical Quantiles


Normality Test - Zn
Sample Quantiles
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
-2
-1
0
1
2
Theoretical Quantiles

## *APPENDIX 8. CONSIDERATION OF THE ENGINEERING & TECHNICAL REQUIREMENTS*

The use of approved standards is undoubtedly one of the most important engineering requirements of a design project. As such, we will be referring to multiple American Society of Agricultural and Biological Engineering (ASABE) standards pertaining to drainage, which have all been retrieved from the ASABE Technical Library (ASABE, n.d.). Even if we have yet to decide what our exact final solution will be, we know that we will have both surface and subsurface drainage, and that we will be designing for an agricultural field in a humid area. This part of the report will be dedicated to displaying the main standards that we will be using and explaining to what part of our design they will be useful.

For the subsurface drainage part, we will mainly be referring to the American Society of Agricultural Engineers (ASAE) standard, ASAE EP260.5, titled “Design and Construction of Subsurface Drainage Systems on Agricultural Lands in Humid Areas”. This standard offers in-depth explanations regarding multiple matters of interest to our project such as the type of materials that should be used, the proper way to prepare a construction plan and layout, the assessment of the grade of the drain, the equipment and on-site materials that could be used and the potential design modifications. Most importantly, the fifth and eleventh sections of this standard explain the design and the installation of the drain, respectively. In the fifth section, the main key features of a drain design are displayed and the proper way to assess them and do the related calculations are explained. This includes the field investigation, the adequate outlet to use depending on the drainage system, the spacing between each drain depending on the drainage requirements, the minimum depth of the drain depending on the type of soil, the grade that the drain should have, the calculation of the drainage coefficient and the drainage area, the capacity of the drain, the minimum drain diameter, the different types of loading that the drain may have to sustain, and the proper outlet protection. As for the eleventh section of the standard, it displays solutions regarding some issues that may occur during the installation of the drainage system. This includes wet soil working conditions, deep trenches, complicated bedding situations, alignment of the drains, already existing pipe drains, and much more.

Additionally, the ASAE EP260.5 standard lists some other standards that we may need for our final drainage design. For example, the ASAE EP369 standard titled “Design of Agricultural Drainage

Pumping Plants” may be required if there is a pump in our design, the ASAE EP407 standard titled “Agricultural Drainage Outlets – Open Channels” may be required if the outlet of our drainage system is an open channel, the ASAE EP479 standard titled “Design, Installation and Operation of Water Table Management Systems for Subirrigation/Controlled Drainage in Humid Regions” may be necessary if our final design implies the management of a water table and many other standards depending on the type of material used for the pipes. Hence, all these standards are providing us an in-depth look at what a subsurface drainage solution would need and will allow us to make a thoughtful decision.

For the surface drainage part, we will mainly be referring to ASAE EP302.4 standard titled “Design and Construction of Subsurface Drainage Systems on Agricultural Lands in Humid Areas”. The fifth section of this standard is the most important to our design project. It provides equations to calculate the design discharge coming out of our field as a function of the drainage area, proper field assessment methods and design modifications in the eventuality that land surface modification is required, and multiple design components for ditches. The design components provided for ditches include row drain and field drain dimensions, field lateral side slopes and berm width for unshaped spoil. The sixth section of this standard provides best-design practice regarding the construction of the surface drainage system such as land smoothing, land grading, bedding, crowning, water leveling, building of the laterals, and more. The eighth section of this standard displays the adverse effects of erosion and the proper methods for assessing, controlling and avoiding negative impacts coming from erosion. Finally, the ninth section of this standard gives insight on the maintenance that may be needed for a surface drainage system. Furthermore, the ASAE EP302.4 standard also suggests that we refer to the ASAE S268.4 standard titled “Design, Layout, Construction and Management of Terrace Systems” if there is a terrace system in the surface drainage part of our final design solution.

In addition to the engineering requirements of our design project, there are also some legal concerns, which must be assessed. There are multiple laws at the municipal and provincial levels which must be respected. This part of the report will be aimed at displaying some of the main regulations that may apply to our final design solution for a drainage system in Sainte-Anne-de-Bellevue. All the municipal regulations have been retrieved from the Montreal city website for “Réglements Municipaux” (Montréal, 2021), and all the provincial regulations have been retrieved from the Quebec government website “LégisQuébec” (Gouvernment du Québec, 2021). It is also important to note that we won’t be requiring any permits since our design is to be implemented on a private property and only involves agricultural drainage.

Municipal laws mainly focus on land surveying and property delimitation. Such regulations are not relevant to our design since it won’t be implemented near another private property. However, the sixth modification of regulation 387 and the third modification of regulation 87 may apply to some of our design solutions. Regulation 387-6 sets a limit regarding the amount of water that can be discharged in the municipal sewage system; this may be of concern if the outlet of our final design solution could lead to runoff in municipal sewage (Montréal, 2021). Furthermore, regulation 87-3 gives a formal definition of what can not be discharged into a municipal sewer system (Montréal, 2021). This includes substances with a toxic pH or containing certain concentrations of contaminants such as phosphorus or mercury.

Furthermore, the main provincial laws that we may have to account for during our design project are the section 979 of the “Civil Code of Québec” and the sections 159.7, 159.9 and 159.12 of the first chapter of the “Act Respecting the Communauté Métropolitaine de Montréal”. The section 979 of the “Civil Code of Québec” regulates the rights and duty of lower land-owner and higher land-owner regarding drainage or preventing natural flow (Gouvernment du Québec, 2021). This may be of concern for our final design solution, it will surely affect where and how we design our drainage system outlet. As for the “Act Respecting the Communauté Métropolitaine de Montréal”, the section 159.7 regulates the discharge of wastewater in a watercourse, section 159.9 dictates the liabilities and consequences that may apply if wastewater is discharged in a watercourse, and section 159.12 sets the required prevention measures that must be applied to avoid contamination of a nearby watercourse (Gouvernment du Québec, 2021). Such regulations will be of the utmost importance when designing our final drainage solution since our field is close to the Saint-Lawrence River. In addition to the engineering requirements of our design project, there are also some legal concerns, which must be assessed. There are multiple laws at the municipal and provincial levels, which must be respected. This part of the report will be aimed at displaying some of the main regulations that may apply to our final design solution for a drainage system in Sainte-Anne-de-Bellevue. All the municipal regulations have been retrieved from the Montreal city website for “Règlements Municipaux” (Montréal, 2021), and all the provincial regulations have been retrieved from the Quebec government website “LégisQuébec”

(Gouvernment du Québec, 2021). It is also important to note that we won't be requiring any permits since our design is to be implemented on a private property and only involves agricultural drainage.

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## *APPENDIX 9. DITCHES ITERATIONS.*

**a)**

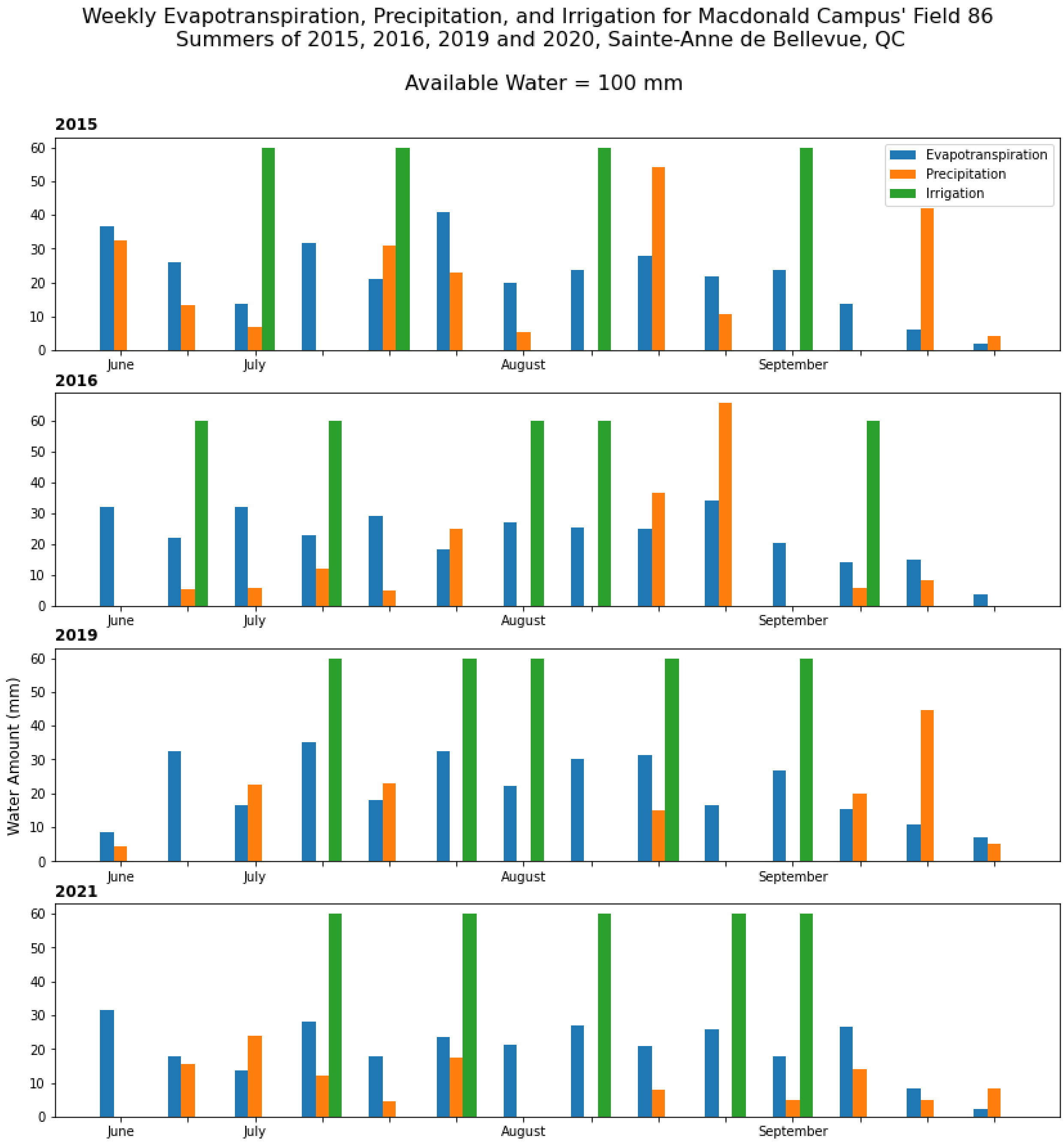
| iteration | t (m) | d (m) | R (m) | A (m2) | P (m) | Q (m3/s) | v (m/s) | n | Error |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 1.5 | 0.7 | 0.46666667 | 0.7 | 1.5 | 0.85610732 | 1.22301046 | 0.05677841 | -0.0323347 |
| 2 | 1.5 | 0.7 | 0.46666667 | 0.7 | 1.5 | 0.82929241 | 1.18470344 | 0.0574007 | -0.0109599 |
| 3 | 1.5 | 0.7 | 0.46666667 | 0.7 | 1.5 | 0.82030194 | 1.17185991 | 0.057617 | -0.0037683 |
| 4 | 1.5 | 0.7 | 0.46666667 | 0.7 | 1.5 | 0.81722243 | 1.16746061 | 0.05769201 | -0.0013019 |
| 5 | 1.5 | 0.7 | 0.46666667 | 0.7 | 1.5 | 0.81615984 | 1.16594262 | 0.05771801 | -0.0004506 |
| 6 | 1.5 | 0.7 | 0.46666667 | 0.7 | 1.5 | 0.81579226 | 1.16541751 | 0.05772701 | -0.000156 |
| 7 | 1.5 | 0.7 | 0.46666667 | 0.7 | 1.5 | 0.81566499 | 1.1652357 | 0.05773013 | -5.404E-05 |
| 8 | 1.5 | 0.7 | 0.46666667 | 0.7 | 1.5 | 0.81562091 | 1.16517273 | 0.05773121 | -1.872E-05 |
| 9 | 1.5 | 0.7 | 0.46666667 | 0.7 | 1.5 | 0.81560565 | 1.16515092 | 0.05773159 | -6.484E-06 |
| 10 | 1.5 | 0.7 | 0.46666667 | 0.7 | 1.5 | 0.81560036 | 1.16514337 | 0.05773172 | -2.246E-06 |
| 11 | 1.5 | 0.7 | 0.46666667 | 0.7 | 1.5 | 0.81559853 | 1.16514075 | 0.05773176 | -7.78E-07 |
| 12 | 1.5 | 0.7 | 0.46666667 | 0.7 | 1.5 | 0.81559789 | 1.16513985 | 0.05773178 | -2.695E-07 |
| 13 | 1.5 | 0.7 | 0.46666667 | 0.7 | 1.5 | 0.81559767 | 1.16513953 | 0.05773178 | -9.335E-08 |
| 14 | 1.5 | 0.7 | 0.46666667 | 0.7 | 1.5 | 0.8155976 | 1.16513942 | 0.05773178 | -3.233E-08 |
| 15 | 1.5 | 0.7 | 0.46666667 | 0.7 | 1.5 | 0.81559757 | 1.16513939 | 0.05773178 | -1.12E-08 |
| 16 | 1.5 | 0.7 | 0.46666667 | 0.7 | 1.5 | 0.81559756 | 1.16513937 | 0.05773178 | -3.88E-09 |
| 17 | 1.5 | 0.7 | 0.46666667 | 0.7 | 1.5 | 0.81559756 | 1.16513937 | 0.05773178 | -1.344E-09 |
| 18 | 1.5 | 0.7 | 0.46666667 | 0.7 | 1.5 | 0.81559756 | 1.16513937 | 0.05773178 | -4.655E-10 |
| 19 | 1.5 | 0.7 | 0.46666667 | 0.7 | 1.5 | 0.81559756 | 1.16513937 | 0.05773178 | -1.612E-10 |
| 20 | 1.5 | 0.7 | 0.46666667 | 0.7 | 1.5 | 0.81559756 | 1.16513937 | 0.05773178 | -5.585E-11 |

**b)**

| iteration | t (m) | d (m) | R (m) | A (m2) | P (m) | Q (m3/s) | v (m/s) | n | Error |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.75 | 0.35 | 0.23333333 | 0.175 | 0.75 | 0.1436018 | 0.82058171 | 0.09042325 | 0.11527179 |
| 2 | 0.75 | 0.35 | 0.23333333 | 0.175 | 0.75 | 0.12704856 | 0.72599179 | 0.0968593 | 0.06644741 |
| 3 | 0.75 | 0.35 | 0.23333333 | 0.175 | 0.75 | 0.11860651 | 0.67775151 | 0.1008908 | 0.0399591 |
| 4 | 0.75 | 0.35 | 0.23333333 | 0.175 | 0.75 | 0.11386711 | 0.65066917 | 0.10344439 | 0.02468559 |
| 5 | 0.75 | 0.35 | 0.23333333 | 0.175 | 0.75 | 0.11105623 | 0.63460702 | 0.1050745 | 0.0155138 |
| 6 | 0.75 | 0.35 | 0.23333333 | 0.175 | 0.75 | 0.10933332 | 0.62476185 | 0.10612056 | 0.00985729 |
| 7 | 0.75 | 0.35 | 0.23333333 | 0.175 | 0.75 | 0.10825559 | 0.6186034 | 0.10679416 | 0.0063075 |
| 8 | 0.75 | 0.35 | 0.23333333 | 0.175 | 0.75 | 0.10757277 | 0.61470155 | 0.10722891 | 0.00405443 |
| 9 | 0.75 | 0.35 | 0.23333333 | 0.175 | 0.75 | 0.10713663 | 0.61220929 | 0.10750992 | 0.00261381 |
| 10 | 0.75 | 0.35 | 0.23333333 | 0.175 | 0.75 | 0.10685659 | 0.61060909 | 0.10769174 | 0.00168827 |
| 11 | 0.75 | 0.35 | 0.23333333 | 0.175 | 0.75 | 0.10667619 | 0.60957821 | 0.10780944 | 0.0010918 |
| 12 | 0.75 | 0.35 | 0.23333333 | 0.175 | 0.75 | 0.10655972 | 0.60891268 | 0.10788568 | 0.00070662 |
| 13 | 0.75 | 0.35 | 0.23333333 | 0.175 | 0.75 | 0.10648442 | 0.6084824 | 0.10793507 | 0.00045757 |
| 14 | 0.75 | 0.35 | 0.23333333 | 0.175 | 0.75 | 0.1064357 | 0.60820398 | 0.10796707 | 0.00029639 |
| 15 | 0.75 | 0.35 | 0.23333333 | 0.175 | 0.75 | 0.10640415 | 0.60802371 | 0.1079878 | 0.00019203 |
| 16 | 0.75 | 0.35 | 0.23333333 | 0.175 | 0.75 | 0.10638372 | 0.60790695 | 0.10800124 | 0.00012444 |
| 17 | 0.75 | 0.35 | 0.23333333 | 0.175 | 0.75 | 0.10637048 | 0.60783131 | 0.10800995 | 8.064E-05 |
| 18 | 0.75 | 0.35 | 0.23333333 | 0.175 | 0.75 | 0.1063619 | 0.60778229 | 0.1080156 | 5.2262E-05 |
| 19 | 0.75 | 0.35 | 0.23333333 | 0.175 | 0.75 | 0.10635634 | 0.60775053 | 0.10801926 | 3.3871E-05 |
| 20 | 0.75 | 0.35 | 0.23333333 | 0.175 | 0.75 | 0.10635274 | 0.60772994 | 0.10802163 | 2.1953E-05 |

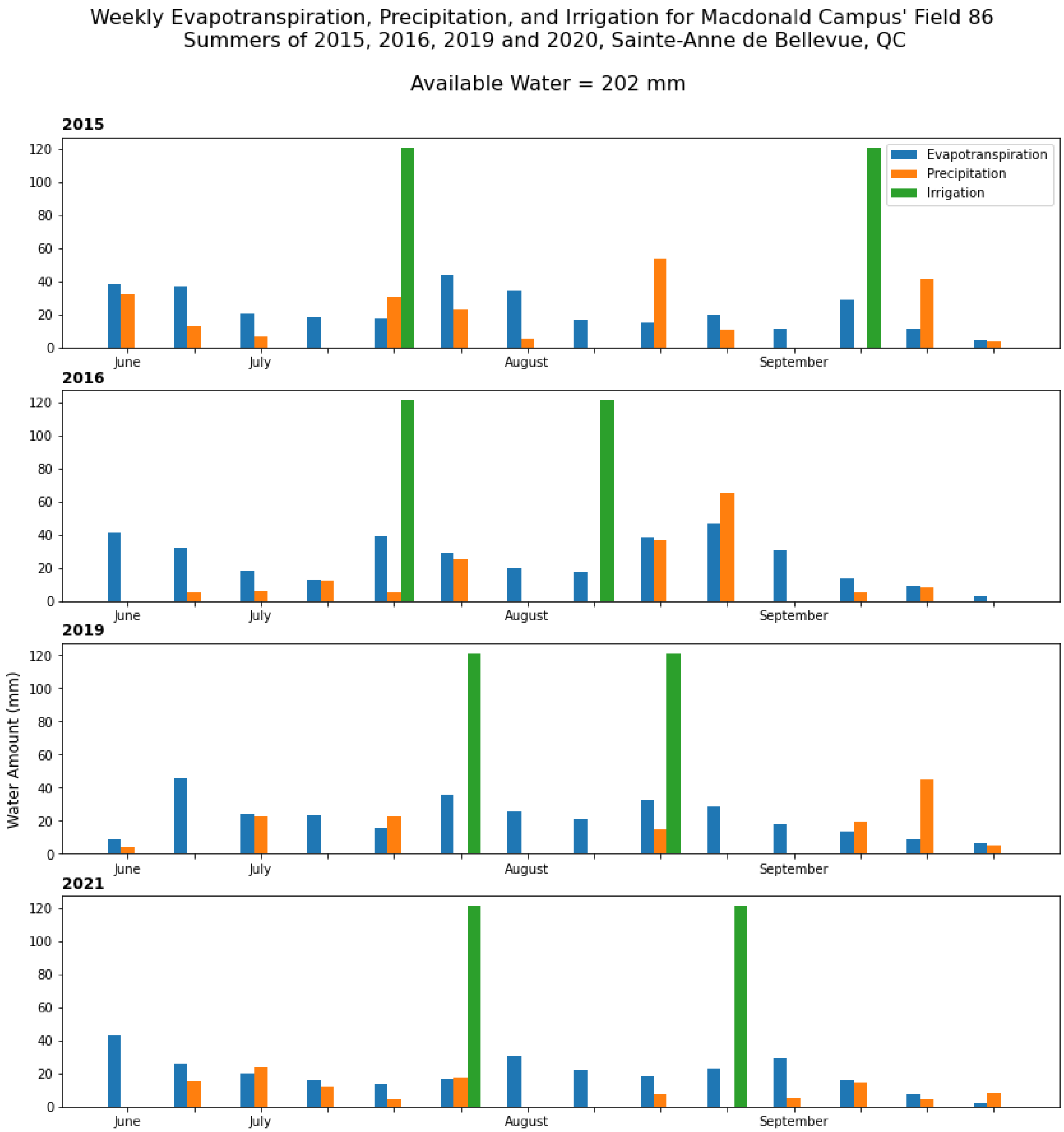
**Appendix 9. Ditches Iterations.** Appendix 9a presents the iterations effectuated for the measurements of ditch 1 and Appendix 9b shows the ones done for ditch 2.

## *Appendix 10. Additional Water Availability Scenarios (100 mm)*




**Appendix 10. Additional Water Availability Scenarios.** This figure shows the weekly evapotranspiration, precipitation and irrigation for F86 in the summers of 2015, 2016, 2019 and 2020, when water available = 100 mm.

## *Appendix 11. Additional Water Availability Scenarios (202 mm)*




**Appendix 11. Additional Water Availability Scenarios.** This figure shows the weekly evapotranspiration, precipitation and irrigation for F86 in the summers of 2015, 2016, 2019 and 2020, when water available = 202 mm.