Project No. 21615
Date: March 31, 2016
Portage la Prairie, MB
Revised: June 1, 2016

Research Report

Final Report

Development of a Decision-Support Tool for Economic Considerations of On-Farm Surface Water

Subsurface Drainage as a Water Management Strategy: Adaptive, Economic, and Environmental Considerations

For:
Manitoba Agriculture, Manitoba

Innovative Solutions for Agriculture and Beyond

21615
March 31, 2016
Portage la Prairie, MB
Revised: June 1, 2016

Final Report

Research Report

Development of a Decision-Support Tool for Economic Considerations of On-Farm Surface Water

Subsurface Drainage as a Water Management Strategy: Adaptive, Economic, and Environmental Considerations

Avery Simundsson
Project Leader

Lorne Grieger, P.Eng.
Project Manager,
Agricultural R&D

Harvey Chorney, P.Eng.
Vice President,
Manitoba Operations

ACKNOWLEDGEMENT

This project was funded by the Canada and Manitoba governments through Growing Forward 2, a federal-provincial-territorial initiative.

The author of this report would like to thank Gary Sands and Thomas Scherer for their assistance and explanations of optimal subsurface drainage systems, as well as Precision Land Solutions, K & S Tiling, and Professor Sri Ranjan of the University of Manitoba, and several local producers for contributing their time to engage in interviews and discussions on tile drainage in Manitoba.

Growing Forward 2

A federal-provincial-territorial initiative

Canada Manitoba

Table of Contents

List of Tables

List of Figures

1. Executive Summary

The purpose of this report is to highlight growing challenges facing prairie agriculture due to increasingly frequent and widespread flood and drought events caused by climate change, and the possibility of using sustainable water management practices as a solution for risk mitigation. Subsurface drainage, in particular, is discussed due to its ability to protect agriculture crops from moisture-related issues, reduce negative environmental effects of agriculture, and reduce peak flows and downstream flooding. This report is not meant to be a guide for the design and economic evaluation of tile drainage systems; it is to act as a decision-support tool by providing information about the technology, design principles, and economic factors involved in implementing a drainage system. In this manner, its aim is to give producers the knowledge to evaluate the practice and ask the right questions when deciding what water management strategy will be beneficial for their specific operation.

Information was gathered from task force reports, published research, interviews with industry professionals, academics, and research technicians, workshops and seminars, extension publications, standing senate committee reports, thesis reports, and knowledge summaries, among others. The majority of information is from the Midwest United States, due to a significantly higher amount of long-term research, on-farm implementation, available extension services, and Best Management Practices (BMP's) recommendations, but information is focused on conditions specific to Manitoba and the prairies wherever possible.

Environmental benefits of subsurface drainage include a significant decrease in phosphorus, sediment, and nitrogen in downstream waters due to less overall outflow from the field. Subsurface drainage is also an effective method of controlling salinity in soils and improving soil structure for better permeability, aeration, and root development. It provides the ability to reduce the severity of flood events by improving the capacity of soil to retain water, (also reducing drought conditions) and slowing drainage flow from the field into drainage channels, especially if control structures are used.

The economics of installing tile are extremely variable and cost/acre, crop response, and payback period are site-specific. Installation costs, annual maintenance, crop response, weather conditions and commodity prices all contribute to the long-term economic value of the system. Subsurface drainage provides added value (timeliness of field operations, improvements to growing conditions) that may be difficult to quantify financially. Soil characteristics and conditions at the field outlet have the greatest effect on the capital cost of the system. Flat landscapes, characteristic of much of Manitoba, are particularly well-suited for design of tile drainage systems.

Tile drainage systems must be designed individually for each site and many different design configurations that provide equally effective drainage are possible. Multiple tools and resources including computer software, excel spreadsheets, mathematical formulas, extension services, and online calculators are available for design and financial analysis of subsurface drainage systems specific to an individual operation.

Tile drainage has been proven to increase yields and can dramatically reduce annual yield variability, showing the best results when used in combination with surface drainage. Crops planted early in the year, such as oats, will see the highest decrease in annual yield variability, due to the greater chance of excess moisture earlier in the growing season, and water-sensitive crops, such as corn and potatoes, will see the largest increase in yield compared to undrained or surface-drained land. Soils with low permeability (clay based) will likely enjoy more yield benefit from subsurface drainage but will also likely have a higher capital project cost.

2. Introduction

Climate change is now widely accepted with forecasts of increasing extremity and variability of weather events in the Prairie region. A knowledge summary provided by the Prairie Adaptation Research Collaborative (Prairie Adaptation Research Collaborative, 2008) explains that though there are potential benefits accompanying the changes, such as a warmer and longer growing season, negative impacts such as increased frequency and intensity of droughts, as well as growing extremity of precipitation events and flooding are likely to accompany them. Furthermore, the periods of increased precipitation and temperature are predicted during winter and spring, meaning a greater chance of spring flooding with decreased available moisture in the later summer months when the demand for water is generally the greatest (Prairie Adaptation Research Collaborative, 2008). Specifically this translates to greater and more frequent floods and droughts.

Agriculture is among the most vulnerable sectors to climate change due to its dependency on weather conditions (Manitoba Sustainable Development, 2012). Manitoba, currently the least-water deficient province, stands to gain the most from the proposed model of climate change; an earlier spring melt means more growing days, providing an opportunity to grow higher-value crops. However, the Interlake region of Manitoba has the lowest-ranking adaptive capacity of any census division on the Prairies (Darren Swanson, 2009). Saskatchewan and Southern Alberta face serious risks of desertification with further drought. The ongoing drainage of depressional storage and natural wetlands for production acres has continued to reduce the available water during critical times (Stacey Dumanski, 2015). Severe drought accompanied by periodic, intense rainfall events also has the potential to increase soil erosion, which will in turn affect stream sedimentation and increased eutrophication of bodies of water (Prairie Adaptation Research Collaborative, 2008). The combination of these factors creates a very real threat to the future of the Canadian agro-ecosystem.

The sustainability and wealth of the Prairie Provinces are intimately linked to the quality and quantity of available water (Prairie Adaptation Research Collaborative, 2008), and the effects of climate change are predicted to cause a crisis in water quality and quantity with widespread implications (Darren Swanson, 2009). Warming temperatures and a longer growing season has potential to create higher value in Canadian agriculture, but only if the accompanying negative impacts are pro-actively addressed. The threat to water resources due to climate change indicates that increased control over available water through drainage strategies combined with erosion control methods are crucial to the prosperity of agriculture in the Canadian Prairie Provinces. The regional variation and uncertainty attached to climate change indicates that increasing the adaptive and resilient capacity through proper management and effective policy, with an emphasis on regional management, are very important in ensuring long-term sustainability (Tarnoczi, 2009). Increasing land and commodity prices have led to a greater investment in currently owned land, rather than seeking to purchase new land. The cost of subsurface drainage, previously reserved for areas producing high-value crops, is becoming more justifiable for a wider variety of operations. The ability to have increased control over water table depth and to reduce water leaving the field as run-off presents a practical solution to both flood and drought conditions.

Initial costs for adaptability measures, such as subsurface drainage, can be prohibitive for some operations and a thorough understanding of all operating costs and potential cash-flow is imperative in making an economic decision. Regional research or professional consultation should be undertaken before any major systems are implemented and greater research, analysis, and communication specific to each region of the prairies is necessary to confidently make decisions on BMP’s unique to each area.

3. Project Objective

The objective of this project is to provide information in regards to subsurface drainage as a water management strategy in Manitoba. In discussing the technology, the design and implementation process, and environmental and economic considerations, the aim is to arm producers with the information necessary to make decisions on managing the transfer of water on their land.

4. Prairie Agriculture and Climate Change

Discussion of climate change is no longer a debate of whether or not it exists-it is now a question of how it will affect us. Changes in climate have previously been slow enough that humans were able to modify their practices without excessive stresses. However, there is strong evidence that the current climate change will occur at a pace beyond our historical ability to adapt (Standing Senate Committee on Agriculture and Forestry, 2003).

The Prairie region of Canada represents the northern geographic limit of arable land in North America and spans 550 000 km^2 across Alberta, Saskatchewan, and Manitoba (Tarnoczi, 2009). It makes up a significant portion of agricultural land in Canada- approximately 80%- which is an important part of the Canadian economy. The Millennium Ecosystem Assessment has identified the western Prairie Provinces as a hotspot for environmental degradation due to climate change effects and human activity (D.W.Schindler, 2006). Impending climate change is predicted to alter the physical landscape and agricultural map of the Canadian prairies, and the industry itself. The expected warmer temperatures have the potential to enable better yields, new crops, and a northwards extension of agricultural land. These benefits may be offset by reduced water availability and drought, limited available soil in the north, soil erosion, more frequent floods, increased insect outbreaks, and more vigorous weeds (Standing Senate Committee on Agriculture and Forestry, 2003).

It is becoming ever clearer that a shift is needed in our current agricultural practices. Increasing variability, frequent extreme weather events, and unpredictable shifts in weather patterns suggest that more adaptability and resilience are necessary to thrive under these conditions of uncertainty. Resilience is defined by the capacity to experience a disturbance and reorganize during changing conditions so as to maintain original processes, functions, identity, and feedbacks of the system (Tarnoczi, 2009). For social-ecological systems, resilience is related to the following items (Carl Folke, 2002):

1. The magnitude of shock that the system can absorb and remain within a given state
2. The degree to which that system is capable of self-organization
3. The degree to which the system can build capacity for learning and adaptation

There is a tight link between resilience, diversity, and sustainability. More resilient systems are able to absorb larger changes or shocks without upsetting or fundamentally changing. When large transformation is needed, resilient systems can adapt without sacrificing provision of services (Carl Folke, 2002). Adaptive management includes experimentation and learning as being integral to the process (Stephen Barg) and this should be embraced amidst uncertainty and change.

The biggest effect of climate change is likely to be on Canada's water resources (Standing Senate Committee on Agriculture and Forestry, 2003). Escalating variability in precipitation means growing extremes of wet or dry. Adaptation measures include engineering and infrastructure but also technology to improve efficiency. Water-use conflicts will increase and in some circumstances, the use of available water may have to be allocated. Water management is one practice that will clearly play a large role in sustainability and long-term planning. The ability to prevent excess moisture from damaging crops while simultaneously conserving moisture for periods of aridity will require a greater degree of control over drainage and consideration of outflow.

5. Importance of Drainage

There is no doubt the drainage is intrinsically linked to yield. Properly drained soils reduce water stress on crops, and promote root development necessary for maximizing yields and quality of production. Drainage allows for timelier operation of equipment, preserves soil structure by minimizing compaction, helps to control salinity, and decreases annual variability in production capacity (Gary R. Sands P.). It can also improve the opportunity for the land steward to employ other conservation practices, such as minimum tillage. Drier soils warm faster, providing an environment for earlier germination and growth in spring in comparison to wetter soils (Gary R. Sands C. H.). Without drainage, the amount of arable land suitable for crop production would be significantly decreased.

The effect of delayed spring planting on Manitoba crop yields is estimated by the Manitoba Agricultural Services Corporation (MASC) in **Table 1** (Manitoba Agriculture, 2015):

Table 1: Estimated yield reduction for Manitoba crops as planting date is delayed (Manitoba Agriculture, 2015).

Planting Date % Yield Reduction				
	Corn	**Canola**	**Flax**	**Peas**
1st Week of May	-	-	-	-
2nd Week of May	5	-	-	5
3rd Week of May	10	5	5	15
4th Week of May	20	10	15	20
1st Week of June	30	20	25	30

Increasing amounts of water during winter and spring without a proper drainage strategy (including regional strategies) will keep producers out of the field for longer, decreasing profit before the season has even started. Earlier field access increases the amount of time the crop is in the ground, effectively increasing the growing season and maximizing the available solar radiation. An extended growing season gives a prolonged period of productivity- meaning greater flexibility in the timing of operations and managing unexpected events. Prolonged productivity also increases plant uptake of nutrients, minimizing the amount remaining in the field that may be washed into waterways through run-off. Anxious producers may also enter the field before it is sufficiently dry, causing further drainage issues through compaction and damaging the soil structure. Water-logged fields during the season have a significant effect on crop yields and even two days of saturated soil can result in a substantial decrease in yield. Plants that visibly recover after periods of excess moisture likely have still undergone changes that will decrease yield, regardless of physical appearance.

One way to understand the financial effects of effective drainage is to convert a yield map into a profit map, as seen in **Figure 1**. A yield map is an excellent tool to show the results of weather, seeding, and inputs, but it lacks actual profit information. The end goal of crop production should be to maximize profit, not to maximize yield, and these two may not always overlap. Adding the cost of inputs used to produce yield in each area of the field reveals how much profit was earned per acre. Quantifying the difference in profit in wet/dry areas of the field can show the potential monetary impact of improved drainage.

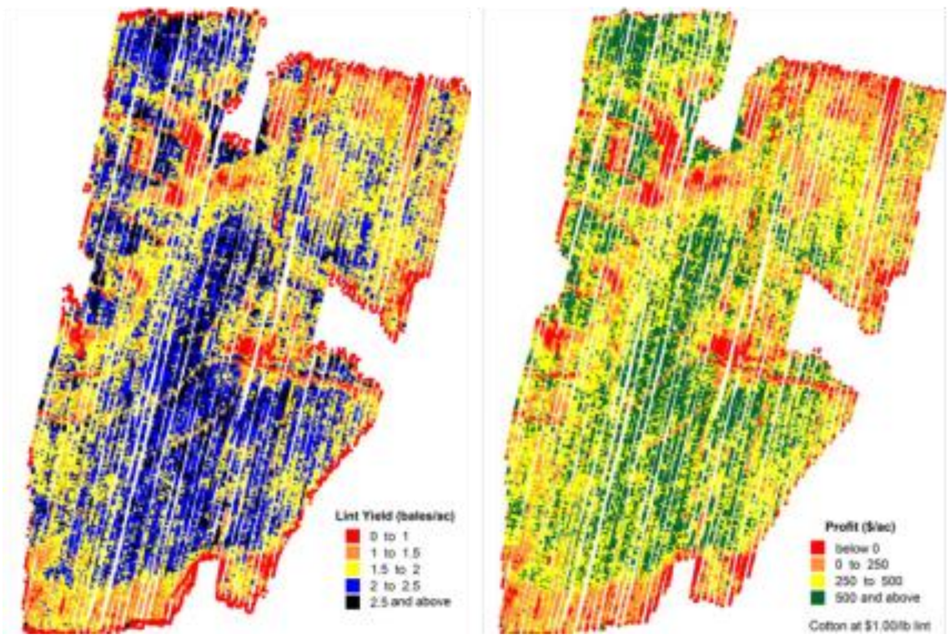

Figure 1: Using a yield map to create a profit map in order to assess the economic return on tile drainage (Vellidis Research Group, 2016).

An effective drainage management strategy should have the following targets:

- Maintaining an effective soil structure to promote permeability
- Reducing soil erosion and increasing nutrient retention
- Remaining within the capacity of the surrounding drainage systems
- Fulfilling legal requirements and adopting BMP's

Increasing unpredictability and extremity of climate and weather are creating a need for more flexible strategies in dealing with both flood and drought conditions. Controlling the peak flow of spring melt is of primary concern for flood prevention, while still addressing extreme precipitation events later in the season (Manitoba Sustainable Development, 2012). When choosing a water management or drainage strategy, any current issues in the system must be clearly identified in order to choose an appropriate strategy to address and solve these problems. Besides excess moisture due to weather, uneven soil moisture, moisture-sensitive crops, naturally high water tables, depressional land, impermeable soils, and seepage areas are conditions that should be addressed through drainage improvement.

5.1 Other Water Management Strategies

Drainage infrastructure is not the only solution to better water management. Other options can be successful in minimizing flood damage and retention of surface water or minimizing soil moisture depletion. It is important to consider if the land is worth more to you drained, or to someone else (or in a different operation) undrained. If drainage improvements are not calculated to add value to an operation, alternate cropping patterns, other uses for the land, or sale of the land for re-investment in more productive soils may be considered. On-site water retention pools, conservation of wetlands, multi-purpose crops, tillage strategies, and crop selection to reduce run-off should be considered and used in conjunction in a water management strategy to maximize benefits (Don Flaten, 2012).

6. Surface Drainage

Surface drainage is any system that is designed to remove water from the field over the surface of the land. The purpose of surface drainage is to prevent excess water from causing crop damage through avoiding ponding of water on the surface of fields, and controlling run-off in a manner that minimizes soil erosion and sediment loading (Larry C. Brown). Adequate drainage should remove excess water within 24-48 hours to avoid crop damage. Surface drainage is most suitable for less permeable soils, or soils with fragipans (dense, natural subsurface layer) and clay subsoils, or conditions which cause water to be slow, or unable, to infiltrate the soil (Department of Agricultural and Biological Engineering). Design of a surface drainage system requires a topographic survey to develop a contour map of the area and annual maintenance to ensure its full functionality and erosion control. Common methods of surface drainage include (to be used independently or in complement): shallow surface drains (open drains), land levelling/smoothing, and land forming.

6.1.1 Shallow Surface Drains

Shallow surface drains are primarily used to prevent pooling water in fields. For fields that drain well but have areas of difficulty, ditches are dug following the contours of the land to target more poorly drained zones. Land containing natural depressions can take advantage of a herringbone arrangement while parallel ditches are dug to provide uniform drainage across an area (Bryanna Thiel, 2015).

6.1.2 Field Levelling and Smoothing

Field levelling and smoothing moves soil across a field to create a more uniform, sloped topography to promote even draining. This can be done very accurately through the use of laser technology, GPS, and GIS data. In areas of shallow topsoil it may be necessary to remove the top soil before leveling to prevent exposure of subsoil and loss of topsoil in areas of the field (Bryanna Thiel, 2015).

6.1.3 Land Forming

Land forming creates deliberate contours in the land to direct drainage down a particular path. This is often used in conjunction with other drainage strategies to increase efficiency by directing the flow of water in the most advantageous direction (Bryanna Thiel, 2015).

6.1.4 Considerations

Under the right circumstances and with available technology, these methods can be designed to be very effective and are relatively inexpensive in relation to subsurface methods. However, they are not without cost and extensive earth moving, specialized equipment, and land grading can still result in a high initial price and annual maintenance costs must be considered (Larry C. Brown). In addition, land grading can expose less fertile subsoil and surface drainage systems must be carefully designed to minimize losses (sediment, phosphorus, etc.) as well as soil erosion (Gary R. Sands P.).

Surface drainage methods are currently the most common method of controlling moisture across the prairies. Though the practice gives significant benefit over no drainage, surface drainage methods alone may not increase the resilience or adaptability of a region in regards to the expected changes in climate. Particularly in heavy rainfall events, systems conveying water quickly from the field may overwhelm nearby ditches, exacerbating the effects. Increasing run-off is detrimental to both field productivity and surrounding waterways by facilitating greater loss of soil sediment and nutrients. Surface drains used in conjunction with subsurface drainage have been shown in many studies to provide a greater benefit than surface drainage alone.

7. Introduction to Subsurface Drainage

Subsurface (tile) drainage refers to an underground network of perforated, high-density polyethylene tubing. These tubes are arranged in different designs but generally involve a series of lateral drains leading to larger sub-main and main drains. Water percolates through the soil from the surface, seeps into the tubing and is carried to the larger main line, and then to one or multiple outlets draining into an open waterway (Bryanna Thiel, 2015). Depending on topography and design, a pump may be required to transfer the water from the outlet to the open waterway. In this manner, gravitational water that may displace air and hinder plant growth in soils near the surface is allowed to drain under circumstances where it might otherwise remain in the soil, and sufficient water is left available for plant uptake (Eidman, 1997).

There is a misconception that tile drainage removes more water from the field than might otherwise be drained through surface methods alone. Tile drainage does not remove additional water from the field; rather, it moves water away from the root zone more quickly than surface drainage alone. This prevents prolonged periods of saturation in the root zone, which can be very detrimental to the crop in a very short period of time. Gravitational flow is very slow under saturated conditions and water may remain in the root zone for many days until it can slowly percolate down. Subsurface drainage allows the water in that zone to percolate down within 24 hours. Tile drainage will not lower the water level below the depth of the tile and it simply a way to ensure that the most critical top layer of the soil maintains both adequate moisture and aeration necessary for crop production during critical events (excessive rainfall, spring melt, etc.). Subsurface drainage is also a conservation practice, reducing surface run-off, which is more likely to carry sediment and phosphorus from the field. This is particularly true in the spring, which is historically the time of highest sediment and nutrient losses.

This system is particularly useful in addressing high water tables, sediment and nutrient loss, and salinity problems (Bryanna Thiel, 2015). Subsurface drainage removes excess water from the plant root zone by lowering the water table and maintaining it below a specific depth (Larry C. Brown). Not only does this promote root growth, it also prevents a high water table from allowing salts to be wicked to the surface in saline areas and can actually reduce salinity levels to noticeably improve production (Agvise Laboratories). Tiling reduces the total amount of water drained from the field, therefore reducing the amount of nutrients and sediment leaving the field. Similar to surface drainage, it is still subject to the availability and capacity of open waterways to transport water away from the outlets.

One of the largest factors inhibiting installation of tile is the initial cost. Depending on a number of factors including soil characteristics, physical topography, available outlet, crop response, ensuing seasonal weather, and installation choices, laying tile can cost anywhere from $600-$1200/acre. It can be difficult to accurately calculate the payback period of the system, as it is dependent on uncontrollable factors that are difficult to predict (weather, commodity prices, etc.). Historically, tile drainage was only an economical option for high-value, water-sensitive crops (potatoes, sugar beets, etc.). More recently, rising commodity prices and increasing land values, along with increasingly extreme weather, is creating more value in tile investment for more producers.

Particularly in regards to excess moisture, subsurface drainage allows for draining late into the fall, and sometimes even into the winter months. The tile generally stops flowing once the depth of frozen soil is one foot. This allows for a significant portion of drainage to occur during a non-peak time of year with less risk of overwhelming the exterior drainage system. This gives soils a greater capacity for water retention during the spring melt, which is historically the time for peak flows and nutrient loss. There is a strong correlation between saturation levels in the falls and flood conditions in the following year. Increasing the soil's capacity for water retention is crucial in lowering peak flows into watersheds, minimizing the risks of downstream flooding, and conserving nutrients in the field. Tiling also creates conditions for better soil structure, aeration, and root development.

Fields, crops, and agricultural operations have a vast degree of variability, and this extends to the drainage system that is most appropriate for them. The needs of the farm the crop must be carefully assessed alongside the capacity of the field and available watershed before making any drainage decisions.

7.1 Components of a Subsurface Drainage System

A subsurface drainage system consists of a series of lateral tubing (3"-5" in diameter) arranged in a parallel, herringbone, double main, or random arrangement as shown in **Figure 2**, on the following page.

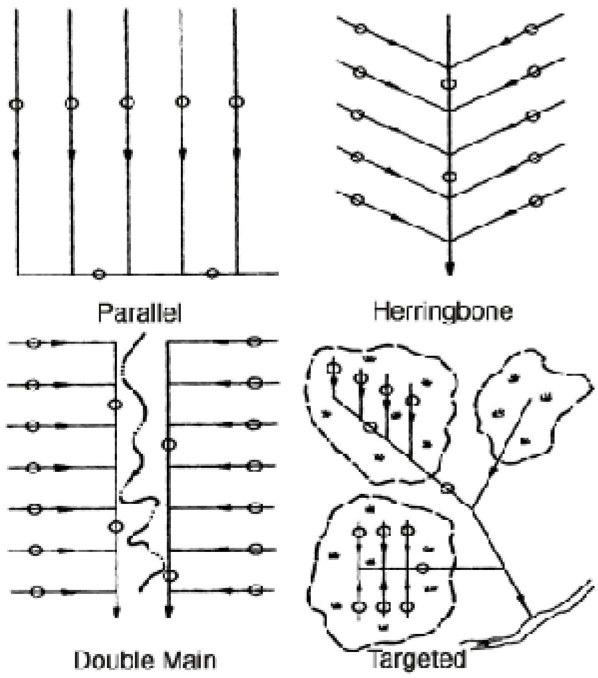

Figure 2: Various drainage system layout alternatives (Robert Evans W. S., 1996).

A parallel arrangement is used on a flat grade of land with uniform soil. A herringbone arrangement may be used for long, narrow stretches of land. The double main system is used where a depression (often a natural watercourse) divides the field. A random system is used where the topography is undulating or rolling, or to manage isolated wet areas (Hofstrand, 2010). The cost of a parallel arrangement is relatively easy to predict once the variables (tubing size, spacing, etc.) are decided, but a random arrangement can be more difficult to estimate.

The laterals make up the majority of the system and lead to the larger mains or submains, which are usually around 10% of the total pipe laid. **Table 2** gives some idea, though it will vary based on the aggressiveness of the system (drainage coefficient), as to what acreage can be drained based on size and grade of the main drain (Planning to Drain Your Land, 1998):

Table 2: Acreage drained by a main drain laid at a specified grade (Planning to Drain Your Land, 1998).

	Acres Drained by Main Drain				
	Main Drain Size (“)				
Grade (%)	**4**	**6**	**8**	**10**	**12**
0.05	2	6	12	20	35
0.1	3	8	16	30	45
0.2	4	13	24	40	70
0.3	5	17	30	50	80
0.5	6	20	35	70	125

Because of the larger size of the main drains, they may require the use of a backhoe for installation and are therefore more expensive to install. The spacing and depth of the laterals is dependent on soil type and characteristics, tile depth, tile size, arrangement, and drainage coefficient. The appropriate combination of these factors should be chosen to allow the system to lower the water table from the active root zone within 24 hours after a rainfall (Gary R. Sands C. H.). Several different layouts may work equally as well for one area of land and many options should be explored to find the most cost-efficient and effective method to meet the criteria of a particular system. Once the tile is installed, it is very difficult, expensive, and time-consuming to make changes if proper foresight was not used during the design and installation phase. A properly designed system will provide many years of function with minimal maintenance and the ability to make modifications when deemed necessary at minimal cost.

The laterals are connected to the main line at or above the centerline of the main to prevent any backflow. Designs requiring more connections and fittings may add extra cost to the system, as they require additional labour and excavation to install. Junction boxes, which can serve as sediment traps, should be placed where two or more drains join at different elevations or where a drain changes direction abruptly. In sections where pipe diameter changes or the grade changes from a steep to flat grade, pressure relief wells can be installed to prevent blow outs, or pipe bursts, from temporary overloads. Breathers and vents should be installed where the line is longer than ¼ mile or where the line changes from a flat to steep grade to allow air into the drain. Rodent traps should also be placed on any openings to prevent small animals from crawling in the lines and causing blockages. Filters (sock) or envelopes of sand, gravel, or synthetic materials should be used where sediment and silt may build up in the drain (Department of Agricultural and Biological Engineering).

7.2 Control Structures

A control structure is an option that can be used to regulate the outflow of water from the drainage system (Gary R. Sands C. H.). This increases the ability to manage the depth of the water table and conserve water in the root zone, reducing overall outflow and loss of nutrients. It can also be used to protect against over-drainage, storing some rainfall in the soil for drier periods of the growing season, or to lower the water table at critical times (i.e. before a flood event, before field work, etc.). A pump station may be used as a control structure, if already in place, or structures can be placed strategically in the field based on topography and elevation change (Gary R. Sands C. H.).

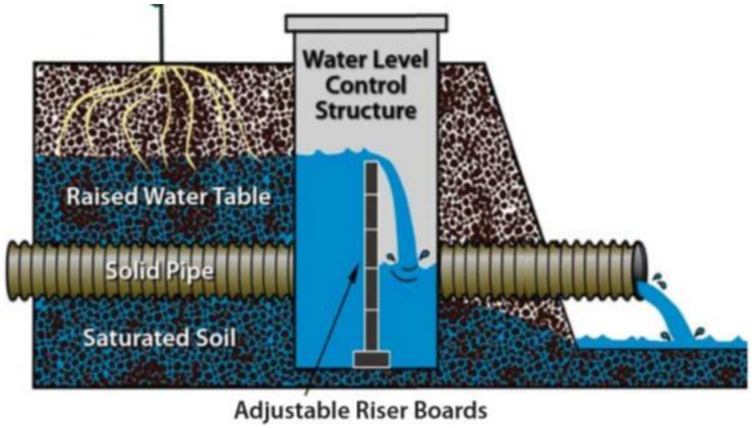

Figure 3: Typical Drainage Water Management Control Structure (United States Deparment of Agriculture Natural Resources Conservation Service (USDA NRCS)).

A standard control structure uses removable panels ('stop logs') to manage the depth of the water table below the surface, changing the level by adding or removing panels (**Figure 3**). The more panels that are present, the higher the water table will rise before it is able to drain. These structures can only control areas that are uniform in elevation. Using a single control structure over a large variation in elevation will result in large variation in the depth of the water table. A field can be divided into "drainage management zones", designated by desired feet of elevation change within the zone (**Figure 4**). For example, to maintain control of the water table to within one foot of the desired depth, a structure must be placed in a drainage management zone with a minimum of one foot of elevation change (Gary R. Sands C. H.). Control structures are more cost-effective on flat land, as single control structure will be able to control a larger number of acres.

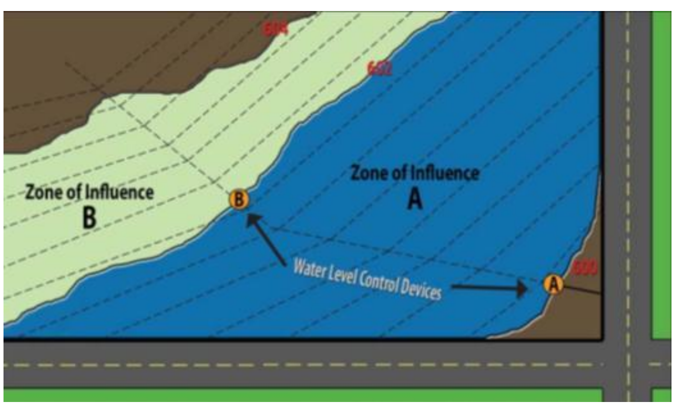

Figure 4: Elevation lines dictate drainage management zones, and therefore the necessary number of control structures (United States Deparment of Agriculture Natural Resources Conservation Service (USDA NRCS)).

This style of control structure requires manual removal and replacement of stop-logs, and more control structures required means a higher cost, and a greater degree of manual management. In response, fully-automatic, inline water gates controlled by downstream water pressure, or head, have been designed (**Figure 5**). These inline devices, which act as pressure valves, are installed underground and are float-activated.

The head pressure from a one-foot increase in water elevation between the downstream and upstream side of the device triggers the float and will allow water to flow through (Prinsco, 2016). In this manner, these devices a can control the water table in one foot increments.

Figure 5: Water gate float-activated control valve (Cooley, 2011).

Along with aiding in nutrient retention, proper management of the water table improves trafficability and reduces compaction. Excess moisture in fields is often a determining factor for completing necessary fieldwork and in a time-crunch, a producer may cause severe compaction issues if activities are resumed too soon after precipitation. Compaction damages soil structure and promotes the development of tillage pans, further reducing drainage ability (Robert Evans J. G., 1996). There has not been extensive study involving the interaction of water table depth, compaction, and tillage pans but general observation has shown that at water table depths of at least 3 feet, there appears to be no visible compaction issues (Robert Evans J. G., 1996). Therefore, it is recommended to lower the water control elevation to a depth of at least three feet, two or more days before tillage operations or other heavy equipment operation (Robert Evans J. G., 1996). It is also advised not to install subsurface drain pipe in saturated soil conditions, as this increases the likelihood of compaction around the drain, severely decreasing their effectiveness (OMFRA, 2011).

8. Subsurface Drainage as a Conservation Practice

Subsurface drainage has become an increasingly popular water management strategy for several reasons. Rising land and commodity prices have made it more cost-effective to invest in increasing productivity on land currently used for production rather than seeking to acquire higher value land. Subsurface drainage provides several advantages over surface drainage alone, namely nutrient retention, potential for water table control (which provides increased adaptability to climate change), and salinity management.

8.1 Nutrient Retention

High levels of phosphorus and nitrogen in waterways result in algae bloom and eutrophication, causing water quality issues for humans and the environment alike. One of the largest problems of eutrophication is the increased oxygen consumption of the algae. This leaves the water anoxic, which is stressful and even fatal to fish populations dependent on oxygen. Manitoba's Lake Winnipeg is an example of this issue; its algae blooms are considered the worst algae problem of any large freshwater lake in the world (Casey, 2006). Agricultural run-off is a contributor to increased levels of phosphorus and nitrogen in waterways, particularly in the spring when run-off levels are highest.

A subsurface drainage system enhances the soil's ability to absorb water through improved soil structure and decreased compaction. This means that during a rainfall event, it takes longer for the soil to hydrate to a saturated condition, and therefore more time before it reaches the drainage system. In some cases, this may mean an elimination of surface runoff if the rain is slow enough to completely infiltrate into the soils. Otherwise, it is delayed, giving more time for plant uptake and reducing peak flows. In very heavy rainstorms, subsurface drainage may have less or no impact as the rainfall is too fast to infiltrate the soil (OMFRA, 2011).

Reducing the nitrogen, phosphorus, and sediment leaving a field is beneficial for external waterways, but also protects the producer's financial investment. The management strategy of the drainage system has an effect on the amount of nutrients in the outlet flow. Water from surface drainage systems contains higher concentrations of organic nitrogen, phosphorus, and sediment than subsurface systems. Alternatively, subsurface run-off contains higher concentrations of nitrates. Neither system is particularly effective in reducing the nutrient *concentration* of the outflow (Robert Evans J. G., 1996). However, there is a difference in the overall *amount* of nutrients leaving the field. Subsurface drainage has been shown to be superior to surface drainage in terms of nutrient retention in the field, reducing sediment loses by 16%-65% and phosphorus losses by up to 45% (Lowell Busman). This is not due to a reduced concentration in the drained water, but rather a reduction in the total amount of water drained. **Figure 6** shows the difference in sedimentation in water samples from surface and tile drained fields.

Figure 6: Water samples taken from surface and tile drained fields (Kandel, 2016).

Reduction in nitrogen concentrations in drained water can fluctuate widely and is influenced by rainfall, soil type, drainage system, and management intensity (Robert Evans J. G., 1996). Regardless, nutrient transport is nearly proportional to drainage outflow and the most certain way to reduce the transport of phosphorus and nitrogen from the field is to reduce the overall water drained from the field (Robert Evans J. G., 1996) (Don Flaten, 2012). Efficient drainage also prevents loss of nitrogen as a gas through denitrification, which occurs in anaerobic, water-logged soils.

Because nitrate is soluble in water, it easily travels where water travels and is more prevalent in subsurface water. BMP's involving the application of nitrogen, and other inputs, notably reduce downstream nutrient loading and are most often for the benefit of the producer and the environment. Avoid applying inputs when the soil is saturated, when the tiles are discharging water (after a rain or if there is a forecast of rain within 24 hours), if there is snow on the ground, and around surface inlets. Always apply the correct rates of application according to soil tests and calibrate equipment to ensure uniform application (OMFRA, 2011) (Veen, 2015).

8.1.1 Control Structures and Nutrient Management

The depth at which the water table is maintained can also have an effect on the amount of water (and therefore nutrients) leaving the field. A higher water table generally reduces total surface runoff by retaining more water in the soil for plant uptake, therefore reducing losses (Robert Evans J. G., 1996). However, the depth must be sufficient to allow for proper root growth and development. Thus, it is necessary to reach a compromise of keeping the water table at the highest level possible to restrict nutrient loss while still allowing sufficient depth for root development and growth (Robert Evans J. G., 1996). Note that this is the optimum control method for nutrient retention, but may not be compatible with other priorities, such as salinity management.

Thorough drainage of the field during the fall and winter gives the soil a greater capacity to retain water in the spring. This is essential for preventing nutrient loss, as a significant portion of field nutrients lost in drainage water are removed during the spring melt. Minimizing the drainage during this time can have a considerable effect on reducing downstream water degradation due to agricultural sources, as well as mitigating the risk of flooding.

Control structures have been proven to decrease the volume of drained water (15-35%), slightly increase surface run-off (because the soil has less available capacity), and decrease nitrogen losses up to 50% compared to subsurface drainage alone (Lowell Busman). While *concentrations* of nitrogen and phosphorus in drained water have not been proven to be significantly different in controlled or uncontrolled drainage, the reduction in water flowing off the field in a controlled drainage system reduces the total nitrogen and phosphorus entering nearby waterways (Robert Evans J. G., 1996). In 14 field studies, controlled drainage was shown to reduce annual transport of nitrogen by 45% (9 lbs/acre) and total phosphorus by 35% (.11 lbs/acre) compared to uncontrolled systems by reducing outflows by up to 30% (Robert Evans J. G., 1996). This reduction is dependent on rainfall, soil type, drainage system, crop needs, and management intensity.

8.1.2 Pothole Drainage

Potholes (depressions) in a field can be directly drained through the use of surface inlets, or tile risers **Figure 7**. Tile risers are vertical, slotted pipes that rise out of the ground and provide a direct connection to the underground system for surface water. They can also double as breathers to allow air to enter the line. Using tile risers is no longer a recommended practice, as it provides a direct conduit for sediment and nutrients (phosphorus, nitrogen) to directly enter drainage water ways, as well as presenting an obstacle to be driven around in the field.

An alternative to a tile riser called ‘blind inlet’ has been shown to be effective in draining potholes while reducing nutrient concentration in drainage water (**Figure 7**). The purpose of a blind inlet is to accelerate the drainage of water by placing intensive drain pipe within coarse media, while still providing a layer of soil to allow for filtration of nutrients and sediment. Rather than creating a direct path to the subsurface drainage system, blind inlets are constructed by digging a square pit at the lowest point of the pothole and placing septic tile between two layers of limestone gravel. The gravel is covered by landscape fabric and coarse soil is used to backfill the remaining depression (Smith, Delaying Drainage From Prairie Potholes Protects Water Quality, 2013). The coarse soil and gravel promote infiltration while slowing the percolation of water to the drainage system. This allows for longer uptake of nutrients by plants, trapping of sediment, and lower amounts of overall water discharge while still moving excess water quickly past the root zone.

Figure 7: Tile riser in the field, left (Morrison, 2012), and construction of a blind inlet, right (Smith, Delaying Drainage from Prairie Potholes Protects Water Quality, 2013).

In two studies performed by the ARS National Soil Erosion Research Laboratory in Indiana, water samples from the risers had consistently higher concentrations of phosphorus, sediment, and nitrogen in comparison with the blind inlet water samples (Smith, Delaying Drainage From Prairie Potholes Protects Water Quality, 2013). Concentrations of phosphorus and sediment in water samples from the blind inlets were 78% and 79% lower, respectively, than those of tile risers. In 2010, rainfall in Indiana was significantly above average. Water samples were collected from a 770 acre basin with blind inlets, and a 735 acre basin with tile risers. Compared with discharge in previous years, discharge from the basin drained with tile risers increased 417%, and total phosphorus loading increased 737%. In the basin drained with blind inlets, concentrations were significantly less dramatic- discharge increased 64%, and total phosphorus loading increased 92%. The slower water discharge from the blind inlet had no visible negative effects on the crop.

Another alternative to tile risers is an intensive drain, seen in **Figure 8**, sometimes called a spiral drain depending on the configuration. This option has been studied less by the academic community but is rather supported by anecdotal information. In this design, a high density of tile is placed in a problem area either as closely spaced parallel rows, or as a coil. This allows for faster drainage of problem areas while still allowing for filtration through the soil to prevent sediment and nutrient loss (Carlson, 2016).

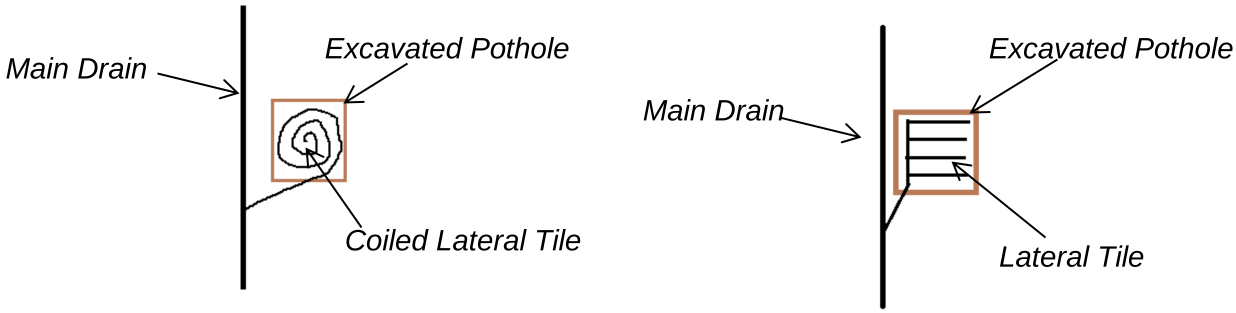

Figure 8: Two alternative configurations to blind inlets that provide intensive drainage

Including a gravel layer in the design of intensive drainage facilitates faster percolation in the presence of ponding. A 25-year study in Ohio by Schwab et al. backfilled some shallow drains with gravel to monitor changes in flow rate. Flow rates in pipes with the permeable backfill were increased by a factor of 2 or 3 in the presence of ponding, but remained the same when ponding was absent (G.O. Schwab, 1985).

8.2 Salinity Management

Soil salinity has a negative effect on crop yield by limiting the amount of water available to plants, regardless how much moisture is in the soil, and therefore causing drought-like symptoms in the plant (Manitoba Agriculture, 2008). Salinity develops as excess water from well-drained recharge areas moves and collects in poorly drained discharge zones. The level of salinity is highly influenced by moisture conditions and will change from season to season. In a wet year, there may be enough dissolving and leaching of salts that the effects are not present in plants. However, this excess water contributes to the salinity problem in dry years when the increased evaporation reduces moisture in the soil, leaving the salts behind, and draws previously washed-down salts up to the root zone through capillary action. Fine textured soils in areas with soluble salts and high water tables are the most susceptible to salinity issues.

Reclamation of saline soils requires flushing the salts down out of the root zone and preventing capillary rise (Manitoba Agriculture, 2008). This is accomplished by adopting water management practices which improve drainage, lower the water table, and promote the downward movement of salts (Manitoba Agriculture, 2008). Excessive rainfall and poor drainage have augmented salinity issues in certain areas of the prairie region and it will continue to worsen without active mitigation.

Tile drainage lowers the water table and effectively desalinizes the root zone through leaching. It prevents capillary rise by maintaining the water table a certain depth below the root zone and has been proven to significantly improve salinity issues over time. A study by Agvise monitored the salinity of a tile-drained field over the course of ten years (Agvise Laboratories). Ten locations across the field were selected and measured and samples were collected at depths of 0-6” and 6-24” after harvest. The results are shown below in **Figure 9**.

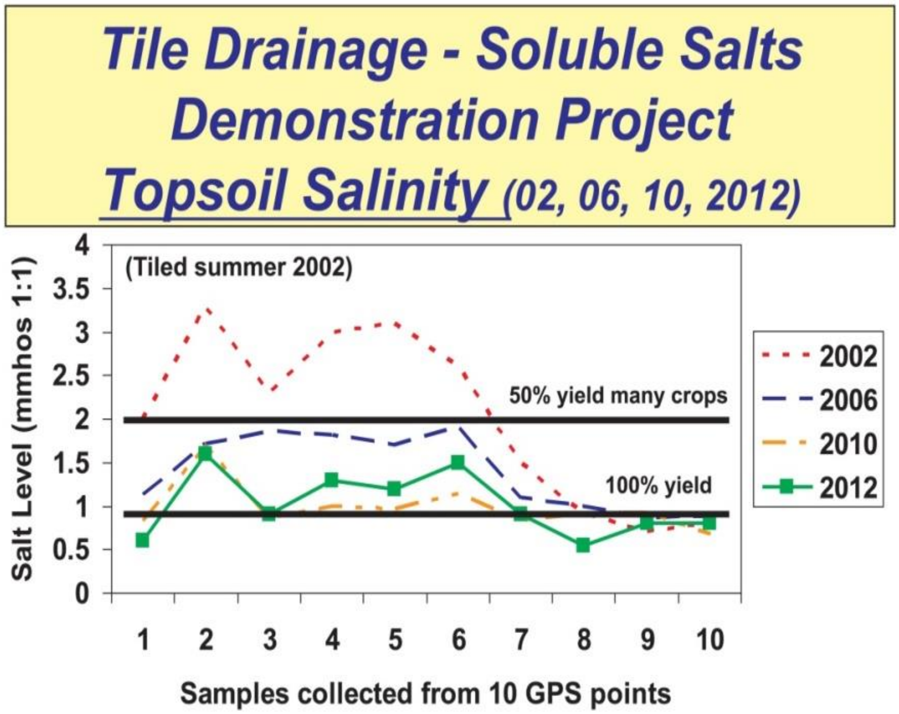

Figure 9: Results of a 10 year field study on the effects of tile drainage on salinity (Agvise Laboratories)

A significant reduction in salt levels can be seen in the first four years, which continues into the next four as well. The last two years of the study received little rainfall, and therefore there was no excess water drained to leach salts from the surface and salt levels rose slightly in some locations. However, it is very clear that seasons with sufficient rainfall allowed salts to be leached away from the surface and decreased salinity in the field. The two sites with the greatest salinity prior to tile installation saw a dramatic decrease in the level of salts over the 12 year period, shown in **Figure 10**.

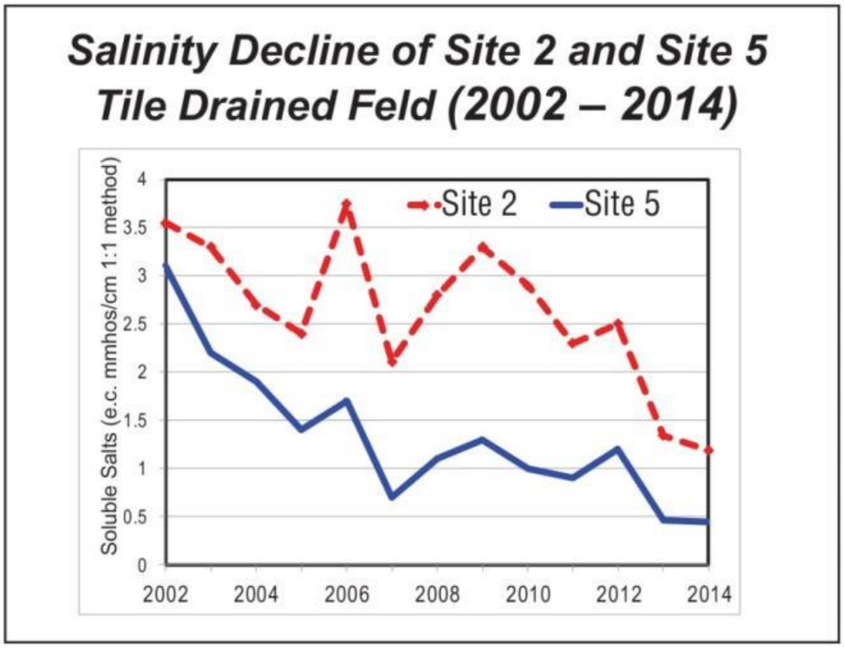

Figure 10: Two sites of the highest salinity samples saw a dramatic decrease in salinity after the installation of tile (Agvise Laboratories).

8.2.1 Sodic Soils

There are different salts that cause salinity in soils. Sodic soils are those where sodium is the dominant salt present. A relatively small amount of sodium salts can have a negative effect on soil structure and create sodic soil conditions, sometimes called "alkali", or "gumbo" (Cavers, 2002). Sodic or saline-sodic soils are not well-suited for tile drainage. Tile will function as it should for the first few years, but after several years, performance often decreases. This is due to changes in soil chemistry resulting from the removal (through leaching) of salts causing a breakdown of the natural structure, soil swelling and dispersion, and sealing around the drain lines (Larry Cihacek, 2012). Once this has happened, there is little that can be done to restore the effectiveness of the tile. Knowing and understanding a soil's profile, series, and properties are important in preventing installation of tile in these soils. Characteristics of sodic soils can be difficult to identify at the surface level and deep soil testing is necessary to fully evaluate a soil's potential to have successful subsurface drainage. Most drainage designers take the soil's physical properties into account, but may pass over chemical properties.

A pH greater of 8.5 often indicates high sodium saturation, indicating a need for further evaluation (Larry Cihacek, 2012). Of particular interested in the Sodium Adsorption Rate (SAR). SAR values over 10 indicated a limited drainage capacity due to sodic conditions. Areas identified for possible sodic conditions should be sampled to a minimum depth of 6 feet in 1 foot increments. A minimum of three samples within the area should be taken, which can then be composited into one sample for each depth increment. A minimum of one soil sample per five acres in the area of concern should analyzed (Larry Cihacek, 2012). Manitoba's soil surveys provide a guide for soil properties, but on-site reconnaissance is necessary to ensure accurate information for a particular parcel of land. **Table 3** gives a guide to the characteristics of saline and sodic soils.

Table 3: Chemical characteristics of saline, sodic, and saline-sodic soils (Larry Cihacek, 2012)

CHARACTERISTICS OF SALINE, SODIC, AND SALINE-SODIC SOILS					
Soil Type	**pH**	**Electrical Conductivity (EC), mmhos/cm**	**Exchangeable Sodium Percentage (ESP), %**	**Sodium Adsorption Rate (SAR)**	**Drainage Ability**
Saline	<8.5	>4	<15	<13	May be Limited
Sodic	>8.5	<4	>15	>13	Very Limited
Saline-Sodic	<8.5	>4	>15	>13	Very Limited

8.3 Soil Structure

By facilitating drainage, tile systems enhance the permeability of the soil through improving soil structure. Schwab et al. studied the soil properties on plots 16 years after the drains were installed. Results showed that the soil structure had improved such that it had better hydraulic conductivity, less unconfined compressive strength, and less surface crust resilience compared to the untiled plots. Soil bulk density was decreased and soil porosity was increased by tile, though to a lesser extent (G.O. Schwab, 1985).

8.4 A Large-Scale Water Management Strategy for Climate Change

Water in the soil profile falls into three categories: the hygroscopic fraction (water bound to soil particles), the plant-available fraction (water available for plant uptake), and the drainable fraction (water available to move through the soil profile in reaction to gravity) (Basin Technical and Scientific Advisory Committee, 2012). Depending on current conditions, water may exist in the profile in any combination or singularity of these categories. In a system without subsurface drainage, water in surface depressions and the drainable soil fraction is considered retention (long-term) storage as it has no pathway to downstream flow. When the drainable fraction is at capacity, the water in held surface depressions will remain there until it evaporates or is able to infiltrate into the ground. The potential for retention storage to alleviate flood events depends on the conditions preceding the flood and what portion of the retention storage is available (Basin Technical and Scientific Advisory Committee, 2012).

In the presence of subsurface drains, the drainable fraction is considered detention (short-term) storage, as it will be removed slowly through tile over a time period dependent on the management and physical properties of the system in place. As drainable water is removed, water stored in depressions is able to infiltrate through the soil profile, also becoming detention storage rather than retention. The ability to control this flow of water is beneficial in reducing peak flows by delaying run-off, and improving field access during planting and harvesting (Basin Technical and Scientific Advisory Committee, 2012). Water can be intentionally released before a flood event to give the soil maximum ability to absorb the incoming water, and can also delay discharge after a flood event to prevent overloading of downstream drainage systems.

Tile drainage can extend the growing season by allowing faster warming of the soil for germination and earlier field access. An increased window for crop growth allows for the opportunity for a greater uptake of water and nutrients from the field. This aids in preventing the loss of excess nutrients, and decreasing the water leaving the field.

8.4.1 Flood Management

In a rainfall event, water can do three things:

1. Infiltrate the soil to be stored in the root zone
2. Pass downwards to groundwater
3. Remain on the surface to pond, evaporate, or run-off

In a field equipped solely with surface drainage, all three of these options are available until a point where the soil is saturated. Once the soil is saturated, water can no longer pass through the soil profile and remains on the surface to pool or run-off. A high amount of surface run-off from an intense precipitation event can cause flooding downstream as these waterways reach and exceed their natural capacity. This flooding may prevent the effectiveness of downstream water management and can cause damage to other crops, property, or ecosystems.

Subsurface drainage, if implemented correctly, increases the ability of water to infiltrate into the soil, therefore decrease the amount of water that runs off the surface. Subsurface drainage can reduce surface runoff by 29%-45% and can reduce peak flow from watersheds by 15%-20%, particularly in fine textured soils (Lowell Busman). However, in the absence of control structures, subsurface drainage does have the potential to increase peak flows in more permeable soils. Locally based research is essential to understanding the overall effects of drainage on downstream hydrological effects (Lowell Busman). A 25-year study in Ohio concluded that, based on 15 major flow events, tile drainage reduced peak flows by an average of 32% compared with surface drainage alone. Using all flows in excess of 5.9 inches in a 24 hour period over 17 years, they found that the number of flood events were reduced 46% by tile drainage (G.O. Schwab, 1985). Subsurface drainage does not necessarily increase the capacity of the soil to hold water. It changes how a portion of the water on and below the surface is stored, as well as how it is released over time (Basin Technical and Scientific Advisory Committee, 2012).

Subsurface drainage also reduces peak flow volumes (Heather Fraser, 2001). By constantly removing water from the critical root zone, there is a greater storage capacity for precipitation, depending on conditions prior to the precipitation. If the soil is very wet prior to precipitation, peak flow is reduced by only 20%. When conditions were dry, a reduction of up to 87% was recorded. Tile drainage has the ability to remove water from the top of the soil profile very efficiently, therefore being more likely to have capacity to retain water from running off in successive rainfall events. This is especially true during the spring season. Tile allows the fields to slowly drain excess moisture in the fall much longer than surface drainage alone. In the spring when there is a significant amount of excess water due to snow melt, the soil has a significantly increased capacity to hold this water acting as a buffer by spreading the drainage over a longer period of time.

8.4.2 Drought Management

During dry growing seasons, a system that rapidly removes moisture from the field is detrimental without control mechanisms (Robert Evans J. G., 1996). With drought conditions expected to increase in frequency, continuing current management practices without specific emphasis on water conservation and retention may prove unsustainable. Water table management through control structures gives increased power to the landowner to retain water if deemed necessary (Robert Evans J. G., 1996). Improved soil structure due to proper drainage also allows plant roots to penetrate deeper to reach a depleted water table. In some cases, these systems can also be modified to provide sub-irrigation, if desired.

The control does not *increase* the *physical ability* of the soil to hold water (although some reports say the resulting improved soil structure *does* increase the ability to hold water (Heather Fraser, 2001)); it gives greater control over *when* and *how* it is drained. In North Carolina, controlled drainage has been designated a "Best Management Strategy" for improving agricultural drainage (Robert Evans J. G., 1996). It is important to note that the water level in outlet ditches may be considerably different from the water table level in the field, and the response time to a control may take several days to adjust to the desired level, making the ability to monitor the system essential (Robert Evans J. G., 1996).

9. Designing a Subsurface Drainage System

When implementing tile drainage, it is important to do it right the first time and with the capacity to expand or modify in later years. Once tile is installed, it is unlikely it will ever be uninstalled and if properly planned and installed, the system will be functional for many years to come. Tile installed over 50 years ago is still in use and being modified or expanded in many parts of the United States. If installed well the first time with proper planning and foresight, it will provide benefit for many years and remain adaptable as technology improves or the land needs change (i.e. a design with no control drainage included can still be built to accommodate control drainage in the future, if desired, at minimal cost to retrofit).

How a drainage system is designed can greatly affect the initial investment required for implementation, as well as costs of retrofitting or expanding later. A single project may have many equally functional designs depending on the goals and long-terms plans for the system. Profitability on the farm should be the driver behind installation and design decisions. This section will examine the calculable costs of installation due to design parameters and how field characteristics will affect the overall design. Many resources exist to aid in the general design of a subsurface drainage system including specialized software programs. Several free tools can be found online and links to them are included in the **Resources** section of this report. The parameters necessary for design of a drainage system will be discussed in this section.

Tile drainage is a long-term investment and once installed, it can provide many years of service and is unlikely to ever come out of the ground. Careful thought and planning can have a large impact on the continuing function of the system. The Best Management Practices Cropland Drainage Guide of Ontario recommends the following steps, shown in **Table 4**, when planning a subsurface drainage system (OMFRA, 2011):

Table 4: Recommended steps for planning a subsurface drainage system

Information Required to Plan a Subsurface Drainage Project	
Step	Information Needed
1. Reconnaissance	• Nature and extent of drainage problem • Location and condition of existing drainage system if one already exists • Feasibility of outlet on neighbour's property – if necessary • Whether activities or conditions on neighbouring property contribute to drainage problem • Location of any utilities or pipelines
2. Problem Analysis	• Watershed area • Suitability of outlet • Suitability of grades for mains • Drainage system design
3. Detailed Survey and Checking for Legal Outlet	• Survey information to size watershed, to size field to drain, and to verify the presence of a legal outlet • Estimate of surface runoff and water volume/rates of subsurface flow through drains
4. Design Options and Costs	• Consideration and cost of any regulatory or municipal bylaw requirements (e.g. proper outlet, protection of wetlands, habitat, utilities and pipelines) • This step embraces all technical, environmental management, regulatory and economic information to help you make the best business decision
5. Approvals and Funding	• Compliance with any regulatory or municipal bylaw requirements

The design objectives when considering subsurface drainage are to (Sands, Subsurface (Tile) Drainage Design),

- remove as much water as quickly and economically as possible
- have a system that functions with hydraulic efficiency and uniformity
- create a maintenance-free system
- provide for the agronomic needs of the crop
- minimize unwanted environmental effects
- design with the future in mind

The two parameters that can increase the cost of tile installation most significantly are the soil characteristics (namely permeability), and the outlet conditions. The soil permeability will determine the appropriate spacing and depth of the tile, and therefore the overall amount of tile needed. The conditions at the outlet will determine whether or not a lift station (pump) is needed, which can add substantial cost, as well as if a long length of main drain (which is significantly more expensive that lateral pipe) is required to reach an appropriate open waterway. These parameters, and others, are discussed at length below.

9.1 Soil Permeability, K_{sat}

The permeability of soil can be represented by the value K_{sat}, the coefficient of permeability measured in terms of the rate of water flowing through saturated soil in a given period of time (Soil Permeability). This characteristic is the most important in determining appropriate drain spacing of the laterals, but is also the most variable and difficult to accurately obtain (Hornberger, 1978). Permeability can change throughout a field and different layers of the soil. As the ability of the water to flow through the soil (hydraulic conductivity) increases the recommended drain spacing will increase as well. The graph taken from the Manitoba Soil Management Guide shown in **Figure 11** gives approximate values of K_{sat} for various soil types. Soil types are explained in the diagrams shown in **Figure 12** and **Figure 13**. Sources of available site-specific K_{sat} values across the prairies are also available in the **Resources** section of this report. To obtain the most accurate reading of the K_{sat} value for a soil, it can be calculated manually.

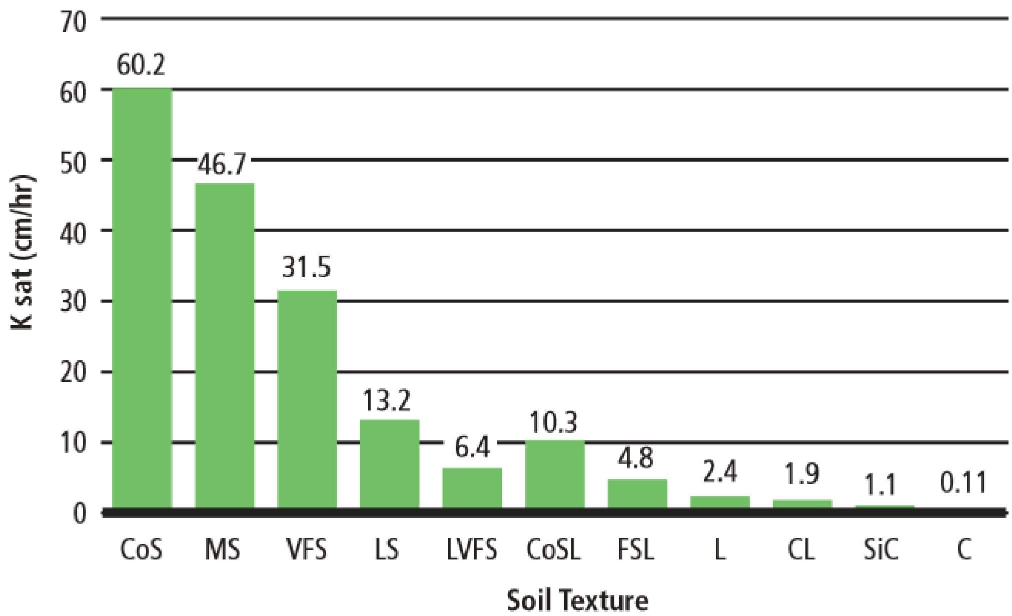

Figure 11: Approximate permeability of general soil types (Manitoba Agriculture, 2008).

Texture Group	Texture Class	Texture Class Symbol
Very Coarse	Very coarse sand	VCoS
	Coarse sand	CoS
	Medium sand	S
Coarse	Fine sand	FS
	Loamy coarse sand	LCoS
	Loamy sand	LS
	Loamy fine sand	LFS
Moderately Coarse	Very fine sand	VFS
	Loamy very fine sand	LVFS
	Coarse sandy loam	CoSL
	Sandy loam	SL
	Fine sandy loam	FSL
Medium	Very fine sandy loam	VFSL
	Loam	L
	Silt loam	SiL
	Silt	Si
Moderately Fine	Sandy clay loam	SCL
	Clay loam	CL
	Silty clay loam	SiCL
Fine	Sandy clay	SC
	Silty clay	SiC
	Clay	C
Very Fine	Heavy clay (>60 %)	HC

Figure 12: Legend of textural classes of soils (Manitoba Agriculture, 2008)

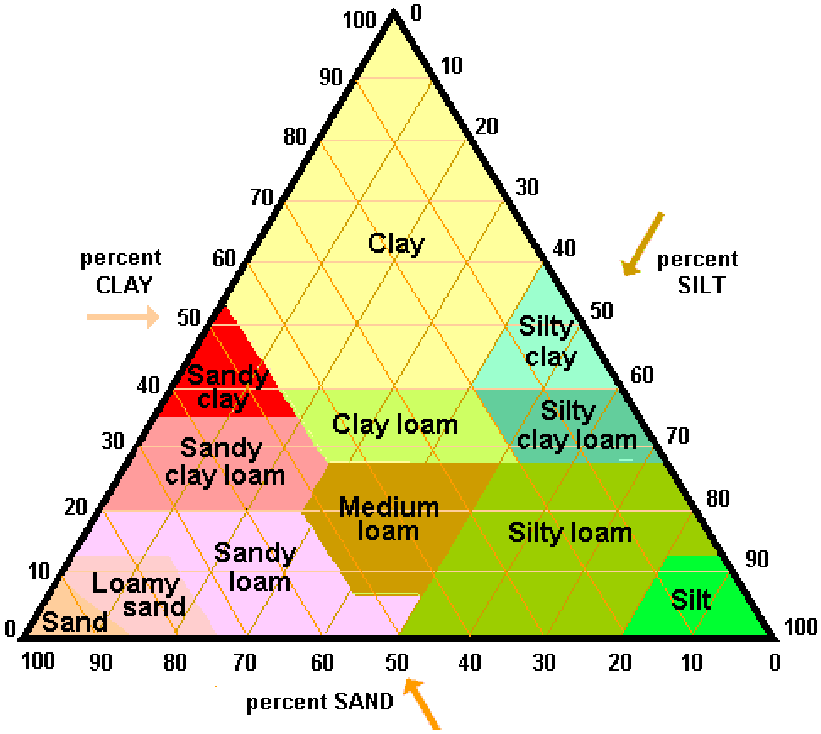

Figure 13: Soil texture triangle (OnePlan, 2016).

The following method will allow you to determine the K_{sat} value for your soil, as shown in **Figure 14** (Soil Permeability):

1. Using a bucket auger, drill a hole about 1 meter deep in the soil. Fill the hole to the top with water.
2. Every five minutes for at least 20 minutes, refill the hole to the top to be sure that the soil is fully saturated.
3. Fill the hole to the brim and use a centimeter-marked ruler and a stopwatch to measure the rate at which the water level drops. Keep track of the distance P between the water surface and the top of the hole. When the rate becomes nearly constant, you may stop measuring.
4. Measure as precisely as possible the total depth of the hole (H) and its diameter (D) in meters.
5. For each of the measurements taken of time/distance, calculate K_{sat} using the following formula:

$$K_{sat} = \left(\frac{D}{2}\right) \times \ln \frac{\left(\frac{h_1}{h_2}\right)}{2} \times 2(t_2 - t_1)$$

Where (D/2) is the radius of the hole (D=diameter), ln is the natural logarithm, h_1 and h_2 are two consecutive depths of water in meters (h_1 at the start and h_2 at the end of the time interval), and (t_1 - t_2) is the time elapsed between readings (in seconds).

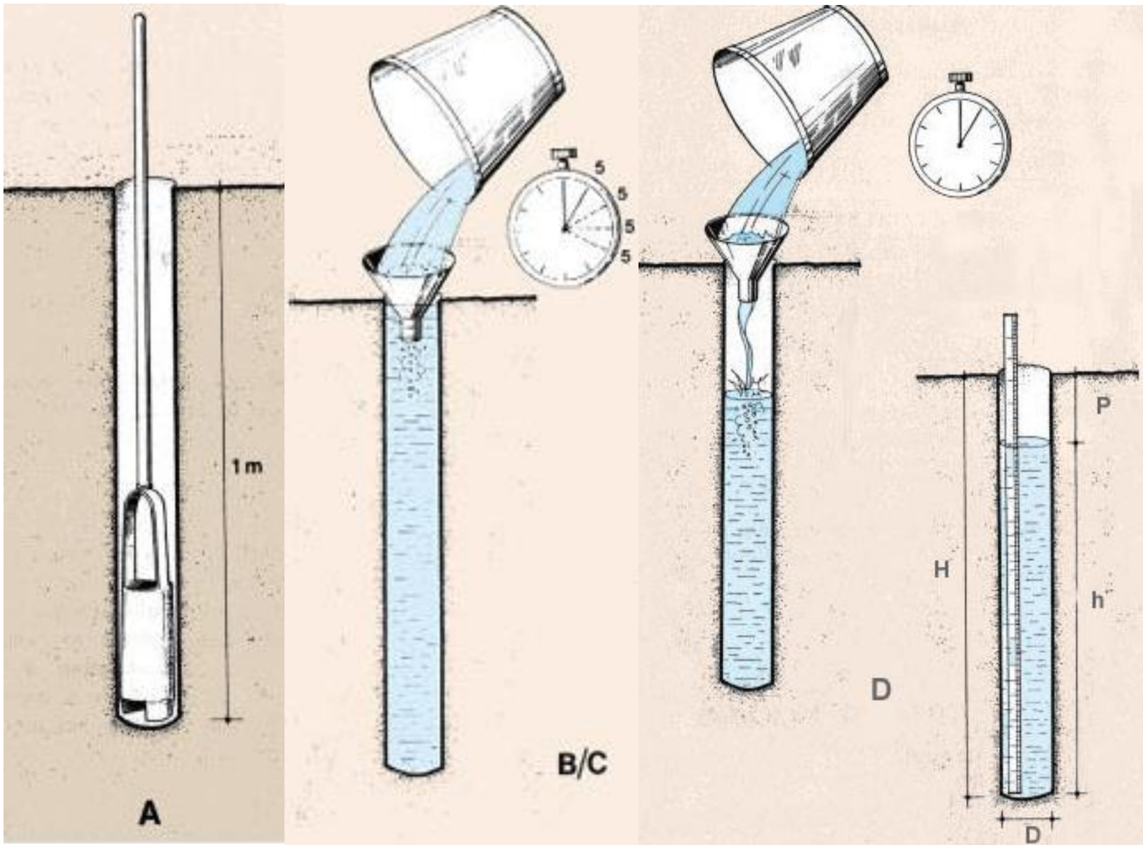

Figure 14: Steps 1, 2, 3, and 4 of measuring soil permeability (K) (Soil Permeability).

Keeping all measurement units in meters and seconds will give you a K_{sat} value in units of m/s. If you wish to convert this value to cm/day, simply multiply K by 8.64 x 10^6. **Table 5** shows an example of calculating K_{sat} values for readings taken at 0, 1, 2, 3, 5, 7, 10, and 15 minutes where D = 0.12m (r=0.06m) and H = 1.15 m.

Table 5: Example of calculating rates of permeability (K_{sat}) (Planning an agricultural subsurface drainage system, 2016).

Time (sec)	0	60	120	180	300	420	600	900
Distance (cm)	0	1	2	3.5	6.5	8.5	12	17.5
h_1	1.15	1.14	1.13	1.115	1.085	1.065	1.030	0.975
h_2	1.14	1.13	1.115	1.085	1.065	1.030	0.975	…
h_1/h_2	1.00877	1.00885	1.01345	1.02765	1.01878	1.03398	1.05641	…
ln (h_1/h_2)	0.00873	0.00881	0.01336	0.2727	0.01861	0.03342	0.05488	…
A=0.06xln(h_1/h_2)	0.00053	0.00053	0.0008	0.00164	0.00112	0.00201	0.00329	…
$t_2 - t_1$	60	60	60	120	120	180	300	…
B=2($t_2 - t_1$)	120	120	120	240	240	360	600	…
K=A/B	$4.4x10^6$	$4.4 x10^6$	$6.6x10^{-6}$	$6.8 x10^{-6}$	$4.6 x10^{-6}$	$5.5 x10^{-6}$	$5.4 x10^{-6}$	…

The average value of K_{sat} will give a good estimate of the permeability of your soil. This test can be done at several locations throughout the field for greater accuracy.

9.2 Drainage Coefficient

The drainage coefficient is defined as the physical capacity of water that can be removed from an area within a period of 24 hours, usually between 1/4" (6.4 mm) and 1" (25.4 mm). Based on soil characteristics, tile spacing, and tile depth are chosen to give the desired coefficient and dictate the capacity of the system to remove water from the root zone. A higher coefficient translates to a higher capacity (i.e. removing moisture from the active root zone more quickly to avoid water-related damage). It is measure of risk-tolerance, defining the aggressiveness of the system design, and is independent from soil properties (Planning an agricultural subsurface drainage system, 2016). This value typically ranges from $^{3}/_{8}$" to ½" (9.5 – 13 mm) per day for mineral soil, and ½" to ¾" (13 – 19 mm) for organic soil, but there is no "correct" value- the value is chosen based on the drainage goals of the system and takes into account both crop needs and soil type (Scherer T. , 2015). A higher drainage coefficient is more expensive (in the same soil), as it involves more pipe at a tighter spacing.

There are some instances when it is advisable to consider a higher value of drainage coefficient:

- Land growing high-value crops
- Coarse textured soil
- Low water-tolerance in crops
- Flat topography implying poor natural surface drainage
- Large amounts of crop residue left in the field
- Low crop evapotranspiration
- Frequent low-intensity rain is common
- Timing for planting and harvesting is critical

The aggressiveness of the drainage coefficient will be dependent on what level of protection is desired (average conditions, any conditions, etc.) and the risk-aversion of the producer. Long-term observation and experience in the local area are helpful in determining a reasonable value.

Calculations to find an appropriate drainage coefficient for a given depth and spacing can be calculated using a re-arrangement of a steady-state Hooghoudt equation- a well-known equation for specifying drain spacing when designing networks of parallel drains in drainage systems. The equation is based on estimating the maximum water table height between two drains. Though "steady-state" is rarely the condition in the field, the calculation provides suitable results for agricultural drainage design (Scherer T. , 2016) (A. Shokri, 2015). This equation is discussed in further detail in the "Tile Spacing" section.

Table 6 gives general recommendations for parallel drain lateral spacing and depth for different soils and drainage coefficients. Keep in mind that these are for *reference only* (Department of Agricultural and Biological Engineering).

Table 6: Suggested parallel drain lateral spacing and depths for different soils (Department of Agricultural and Biological Engineering).

Soil Type	**Subsoil Permeability**	**Drain Spacing (ft.) for Drainage Coefficients of:**			**Drain Depth (ft.)**
		Fair Drainage (1/4")	*Good Drainage (3/8")*	*Excellent Drainage (1/2")*	
Clay Loam	Very Low	70	50	35	3.0-3.5
Silty Clay Loam	Low	95	65	45	3.3-3.5
Silt Loam	Moderately Low	130	90	60	3.5-4.0
Loam	Moderate	200	140	95	3.8-4.3
Sandy Loam	Moderately High	300	210	150	4.0-4.5

There exists a relationship between depth and spacing such that a given spacing of tile at a certain depth will provide the same drainage if placed deeper with increased tile spacing. Closer and shallower drains are better suited for sub-irrigation while deeper, wider drains provide more flexibility for controlled drainage. A minimum depth of 2 feet (0.6 m) is recommended to prevent damage from any field equipment (OMFRA, 2011). **Figure 15** is a visual description of a deep, wide system and a shallow, close system providing equal drainage capacity.

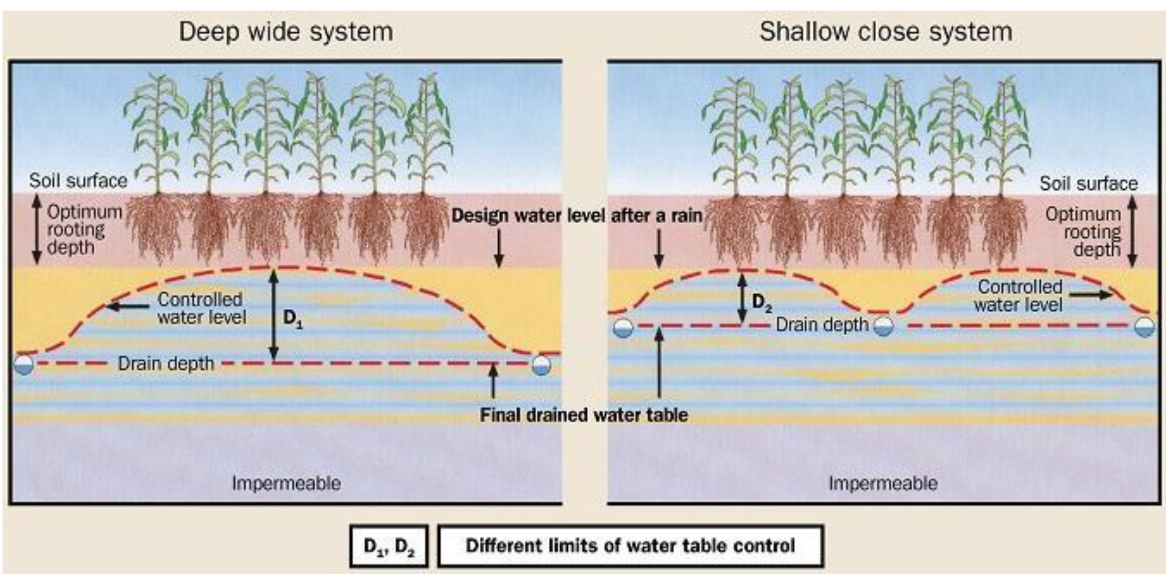

Figure 15: Depiction of deep, wide drains and close, shallow drains providing and equal drainage capacity (Brook, 2013).

9.3 Pipe Grade and Size

The rate of flow depends on a combination of the grade of drainage and the inner diameter and surface (corrugated, smoother) of the tile. A decrease in pipe diameter must be accompanied by an increase in grade to maintain the same flow rate. In very flat areas, larger pipe sizes may be required to account for a very small allowable grade. This flow capacity can be expressed as the number of potential acres that can be drained by a certain diameter of pipe.

Table 7 shows the potential acres drained for various sizes of pipe (CPE = corrugated) for a coefficient of ¼" (6 mm).

Table 7: Potential acres drained by drain size, type, and grade for a drainage coefficient of ¼" (6 mm) per day (Planning an agricultural subsurface drainage system, 2016)

		DRAIN DIAMETER (INCHES)							
% Grade (ft/100 ft)	**Drain type**	**4**	**5**	**6**	**6**	**10**	**12**	**15**	**18**
	CPE	5.0	9.0	14.6	32	50	82	126	206
0.1	*Smooth*	7.5	13.5	22	47	.86	140	253	411
	CPE	7.0	12.7	21	45	71	116	179	291
0.2	*Smooth*	10.5	19.1	31	67	121	197	358	582
	CPE	8.6	16	25	55	87	142	219	356
0.3	*Smooth*	12.9	23	38	82	149	242	438	712
	CPE	10	18	29	63	101	164	253	411
0.4	*Smooth*	14.9	27	44	95	172	279	506	823
	CPE	12	22	36	77	124	201	310	504
0.6	*Smooth*	18	33	54	116	210	342	620	1008
	CPE	14	25	41	89	143	232	358	582
0.8	*Smooth*	21	38	62	134	243	395	715	1163
	CPE	16	28	46	100	160	260	400	650
1	*Smooth*	24	43	69	150	271	441	800	1301
	CPE	19	35	57	122	195	318	490	797
1.5	*Smooth*	29	52	85	183	332	540	980	1593
	CPE	22	40	66	141	226	367	566	920
2	*Smooth*	33	60	98	212	384	624	1131	1840

Having sufficient flow to avoid stagnation or sedimentation is important. The slower the flow of water in the pipe, the more likely particulate will drop out of the flow and accumulate. It is recommended to select a grade and size of pipe that will provide a minimum flow of 0.5 ft/s (0.15 m/s) for drains not subjected to fine sand or silt and of 1.4 ft/s (0.42 m/s) for drains that may contain fine sand and silt in order to avoid sedimentation (Planning an agricultural subsurface drainage system, 2016). It is also important to select a grade that will not cause excessive speed of flow, and therefore potential pressure problems and blow-outs. **Table 8** gives a guide for minimum grades to maintain the lowest allowable velocity in various diameters of pipe.

Table 8: Recommended minimum grades for various sizes of pipe (Sands, Subsurface (Tile) Drainage Design).

Drain Inner Diameter (in)	**MINIMUM GRADE**			
	Drains not subjected to fine sand or silt (min velocity 0.5 ft/sec)		*Drains with possibility of fine sand or silt entering (min velocity 1.4 ft/sec)*	
	Tile	Tubing	Tile	Tubing
3	0.08	0.10	0.60	0.81
4	0.05	0.07	0.41	0.55
5	0.04	0.05	0.30	0.41
6	0.03	0.04	0.24	0.32

To find the overall fall across the pipe due to grade, the following formula can be used:

$$fall = \frac{distance \times \%\, grade}{100\%}$$

The main pipe must be sized to accommodate water from all laterals leading into it. It is proactive to oversize the outlet pipe to sustain the possibility of future expansion of the system, avoiding the need to dig up and re-install a larger main pipe if the expansion occurs. An oversized pipe also allows more room for marginal error in design calculations. The size of the main pipe does not have to be uniform throughout, and the diameter can be increased to meet the necessary capacity as more laterals connect, as shown in **Figure 16**. This may save on overall cost of the system, depending on the cost of these added connections.

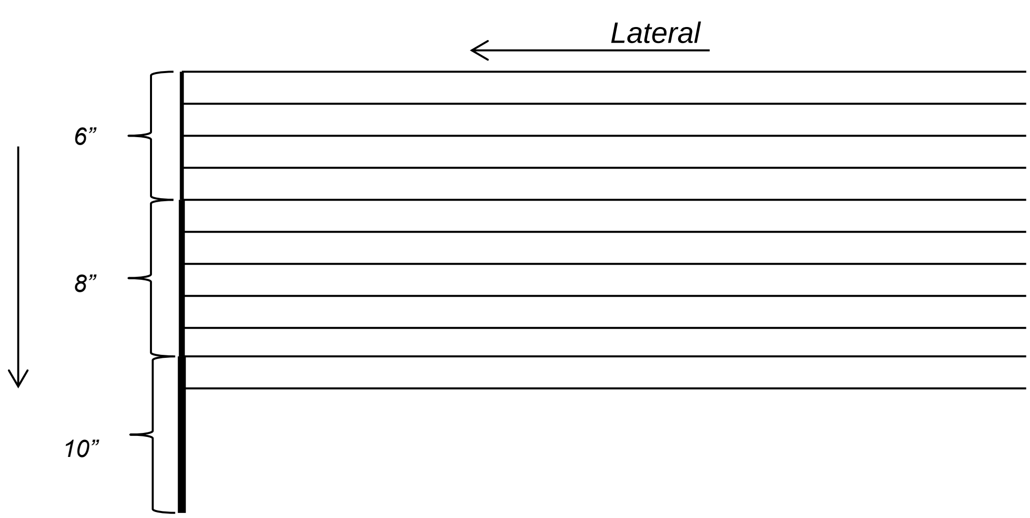

Figure 16: Different size of main drain may be used along the length to save on cost

9.3.1 Layout

Common orientations (parallel, herringbone, targeted, double main) were introduced previously. When choosing a system layout, the following points should be considered (OMFRA, 2011):

- Lateral drains should be parallel to field contours rather than follow them. This will produce more uniform results and may make control drainage more efficient
- Orientate lateral drains to be askew of tillage or planting patterns. This both reduces potential for damage from machinery and ensures that row planting/tillage will not alter the flow path of surface water
- Pipe connections require excavations and can increase time and costs. Minimize the number of short laterals where possible to reduce connections to the main header
- Minimize the number of outlets to reduce cost and maintenance
- Several layouts should be designed and considered for a balance of cost and function to ensure long-term satisfaction and function of the drainage system
- Consider future modifications, such as control structures etc., to the system and design to accommodate possible changes

Drainage is a long term investment and future benefits should be fully weighed out against initial costs.

9.3.2 Drain Envelope (Sock)

In soils where silt and sediment are a concern (fine sands or coarse silts), a drain envelope (or “sock”) may be implemented. A drain envelope is a material placed around the pipe which can either facilitate flow into the drain, or create a barrier to certain sized particles. Fine textured soils with a clay content of 25%-30% are generally stable enough to avoid the need for a sock due to their natural cohesiveness, but soils free of clay with a coarse texture necessitate a geotextile sock barrier. In soils composed of less than 25-30% clay, water movement is difficult to predict and the use of a sock should be decided by a professional contractor (Planning an agricultural subsurface drainage system, 2016).

A sock is not designed to be a filter. A filter is clogged and changed at the end of its life cycle- the sock does not get clogged over time. Drain envelopes can be constructed of gravel and organic fibre or thin geotextile. Synthetic drain envelope can endure a long life of service if kept out of UV light (Planning an agricultural subsurface drainage system, 2016).

Ochre is an iron oxide that occurs in acidic sands or poorly drained sands due to chemical and microbiological processes. It is naturally occurring in sandy land with a high organic content and often in newly cleared and drained land. It can be recognized at drain outlets as a bright red deposit and will seal drain openings if not addressed immediately (OMFRA, 2011). If iron ochre is suspected, there is no current long-term solution. The design can be abandoned or altered to include entry ports for high-pressure rinsing. Shallow and closely spaced pipes may also be less prone to ochre, especially when “blinded” with an envelope of oak and pine sawdust. Reducing aeration and oxygen in the system by keeping the pipes flooded through a control structure may slow ochre formation (Ford, 1993).

9.4 Outlet

The outlet of the system is very important and can be the determining factor in the feasibility of a tile drainage system (Department of Agricultural and Biological Engineering). The outlet channel must have the capacity to carry the water from the drainage system in addition to the area already serviced by the channel.
In the event that the outlet ditch is too shallow and permission to make the ditch deeper cannot be granted, or the ditch is not deep enough for a gravity outlet, a pump (or a “lift station”) must be installed. A pump gives greater control over the water leaving the field, and also allows for a steeper grade on laterals if necessary (i.e. for very flat fields). Ideally, the lift station location will be both close to both the ditch outlet and a power source. Being far from either can increase costs significantly. If there is no suitable location that fits these criteria, it is generally more economical to place the station closer to the power source and run a longer pipe to the outlet rather than to bring in power from the grid. Alternatively, off-the grid power can be used. The location should be easily accessible, especially during a flood event, for repairs, maintenance, and monitoring. Erosion control at the outlet is essential and banks where main drains connect to the natural waterway must be stabilized. The receiving water way should be riprapped and if there is a chance the outlet pipe will be below the surface of the water in the drainage channels, breather valves should be installed to prevent a syphoning effect. Rodent grates are important to prevent blockages due to animal entry and all outlets should be monitored regularly, especially after large rainfall events.

If a lift station is a part of the design, the choice of pump is an important consideration. The pumps used for this application are similar to the sump pump in a basement. The sump in the field is a hole lined by a corrosion-preventative coating where the pump resides. Plastic sump casings have caused ditch fires in rural areas and therefore metal caps are recommended over plastic. The sump is generally around 10’-15’ (3.0-4.6 m) deep with the bottom 3’ (0.9 m) accommodating the pump. The size is dependent on the amount of water storage necessary for an appropriate pump cycle. Crushed rock can be added to the bottom of the sump in the absence of clay soil to add stability for the pump (Scherer T. , 2015).

Low-head pumps with axial or mixed-flow impellers are commonly used in drainage lift stations, either submersible or shaft-driven. Approximately 3’ (0.9 m) of water are required above the inflow of water for a submersible pump to provide anti-vortex protection (preventing cavitation) and to cool the motor (Scherer T. , 2015). Pumps which can handle debris are advisable to avoid damage from any debris in the pipes. Set-ups for shaft-driven and submersible pumps can be seen in **Figure 17**:

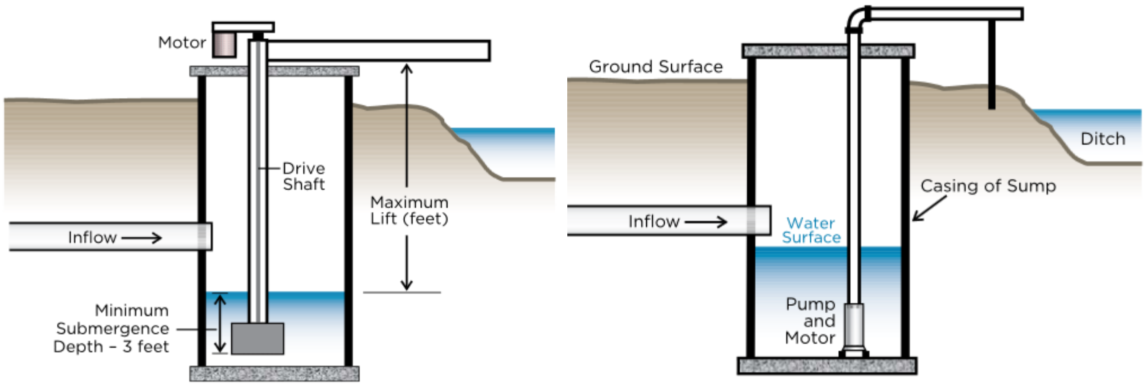

Figure 17: Set-up for submersible and shaft driven lift stations (Scherer T. , 2015)

The size of pump necessary is dependent on the maximum flow rate (determined by the system's drainage coefficient) into the sump and the total "head" to outlet the water into the ditch. The maximum pump flow rate in gallons/min (Q) can be determined by the following modified fluid flow equation:

$$Q(gpm) = 18.9 \times Dc \times A$$

Where D_c is the chosen drainage coefficient, A is the area draining into the pump (acres), and 18.9 is a constant. The metric equivalent, with the flow rate in m^3/h, is

$$Q(m^3/h) = 4.1 \times Dc_{cm/d} \times A_{ha}$$

where the drainage coefficient is measured in cm/day and the area drained is measure in hectares. The majority of the time, the pump will likely be operating significantly under capacity. Some systems choose to use two smaller pumps instead with one being the primary operator and the second to provide additional power when needed. This system is more energy efficient and also allows the second pump to act as a back-up if the primary pump should fail.

Table 9 shows the maximum flow rate on a per acre basis that will flow into the sump for selected drainage coefficient values (Scherer T. , 2015).

Table 9: The 24 hour volume and flow rate produced per acre for a design drainage coefficient (Scherer T. , 2015).

Drainage coefficient (acre/in/day)	Gallons of water from one acre of land	Average gallons per minute of flow per acre in 24 hours (1440 minutes)
¼	6,800	4.7
$^3/_8$	10,210	7.1
½	13,610	9.5
¾	20,420	14.2

The pump head must also be determined. Head refers to the total vertical distance that must be overcome to outlet the water. This includes the distance from the surface of the water in the sump to the outlet combined with the equivalent measures of friction losses through the pipes. Pump sizes required for peak flow rates (gpm) and head values are shown in **Table 10**.

Table 10: Pump motor size in horsepower required based on head and peak flow rate, assuming an efficiency of 30% (Scherer T. , 2015).

Total Head (feet)	Pump Motor Size (HP)				
	Peak Flow Rates				
	500 gpm	**750 gpm**	**1000 gpm**	**1250gpm**	**1500 gpm**
8	3	5	7.5	10	10
10	5	7.5	10	10	15
12	5	7.5	10	15	15
14	7.5	10	15	15	20
16	7.5	10	15	20	20

It is generally not advised to use single-phase motors for sizes greater than 10 HP. In cases where more power is needed, two smaller pumps can be used instead. One can be used as the main pump with the second as a back-up when necessary.

Floats are one way to control the pump cycle. Most pump manufactures recommend a maximum of 10 cycles per hour. To increase the pumping time and decrease the number of pumping cycles for a constant flow rate and a selected pump, a larger storage volume is necessary. This storage can be in the form of vertical (at the lift station sump) or horizontal storage (in an oversized main drain). For example, a system draining 160 acres with a drainage coefficient of $^3/_8$ and a float-controlled pump with 3’ of vertical difference between ‘on’ and ‘off’ run on 10 cycles per minute requires a 10’ diameter sump. If a 4’ diameter sump is used instead, horizontal storage in the form of a 63’ length of 2’ diameter main pipe can replace the lost vertical storage volume.
An appropriate volume of storage can be calculated as such:

$$\textit{Storage Volume (ft}^3\textit{/acre)} = \frac{2 \times max\ flow\ rate\ of\ pump\ (gpm)}{Number\ of\ Cycles/hour}$$

Table 11 gives storage requirements for various drainage coefficients and cycles per hour.

Table 11: Cubic feet of storage for each drained acre based on drainage coefficients and maximum pump cycles (Scherer T. , 2015).

Drainage Coefficient	**Storage in Cubic Feet Per Acre**			
	Cycles per Hour			
	6	***8***	***10***	***12***
¼	1.6	1.2	0.9	0.6
3/8	2.4	1.8	1.4	1.0
½	3.2	2.4	1.9	1.3
¾	4.7	3.6	2.8	1.9

An increasingly common pump for this application is a variable frequency motor drive (VFD) pump which converts single or three-phase power to variable frequency three-phase output power (Scherer T. , 2015). A three-phase motor is generally smaller and less expensive and also puts less strain on the motor during start-up by reducing the in-rush of current. Variable frequency also allows for the pump to adjust its rpm based on the water level in the sump, matching the rpm to the flow rate of water entering the sump. This significantly reduces the required storage volume.

System maintenance and consideration of pressure in the system is important. Any long discharge pipelines require check valves to prevent pressure surges (water hammer) and outlets designed to be submerged in the drainage ditch should be equipped with a relief valve to prevent siphoning (Scherer T. , 2015). If operating in cold conditions, it is important to check often for ice formation, which can cause damage including pulling wires from connections or dislodging floats. A more hands-off option to manage cold conditions is to put a stock tank water heater in the sump. Operation of the pump should be checked after a heavy rain. Digital systems connected to smart phones are simple methods of being able to constantly monitor water levels in the sump and in the field. Thomas Scherer, an extension agricultural engineer at the University of North Dakota, has been working with lift stations for 15 years. He gives the following cold weather advice regarding lift pumps (Scherer T. , 2016):

- Pumps have worked into January in very wet falls with no problems so long as the pump is operating in a fairly continuous manner. Pumps will generally stop after frost has penetrated about 1 foot into the soil.

- It is not uncommon for 6 inches to 1 foot of ice to form on the sump in the spring, but this generally melts once the frost is out of the ground and the water starts flowing into the sump.
- VFD pumps generally have no problems in the winter, but are often turned off before the temperature goes significantly below freezing. Regardless, it is not advisable to try and start the pump at air temperatures below 1 ^{o}F (-17 ^{o}C).
- Float-controlled pumps have the most difficultly in cold weather, as the significant weight of the ice forming on the floats and wires can cause considerable damage. However, this problem is solved through a livestock water tank heater in the sump.
- One issue with lift stations seen in the winter is animals searching for a warm place in the sump and perishing. This problem can be solved by installing a heavy gauge rubber mat to seal the opening where the pipe goes into the sump top.
- New lift stations may be more susceptible to winter freezing in their first year due to the deeper frost penetration in the loose soil.

9.5 Control Structures

There is a discrepancy between water supply and water usage in prairie agriculture. The majority of seasonal water is available in the spring, but the greatest crop need for water arises later in the summer. This creates an excess of available water early in the season and a deficiency later on, both with the ability to cause crop damage (**Figure 18**).

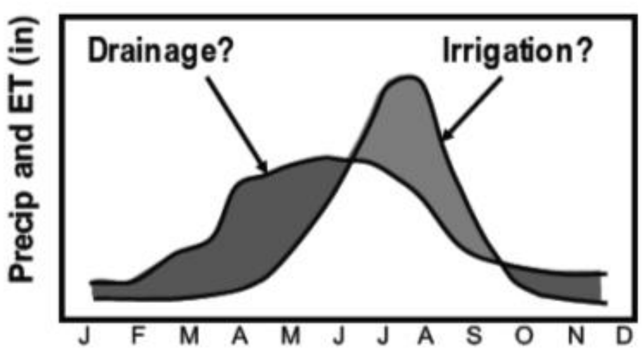

Figure 18: Excess and deficiency of available water due to supply and crop demand (Sands, 2016 Extension Subsurface Drainage Design & Water Management Workshop, 2016).

Control structures can help to overlap the supply and demand by retaining water in the field for later use. Even if control structures are not part of the initial design, it is wise to design the system based on management zones so that the system can be retrofitted with control structures later if desired.

Drainage channels are typically constructed to follow the slope of a field, encouraging outflow. If lateral tile is installed following this pattern, the number of control structures required for the system can increase exponentially, as seen in **Figure 19** (Sands, 2016 Extension Subsurface Drainage Design & Water Management Workshop, 2016).

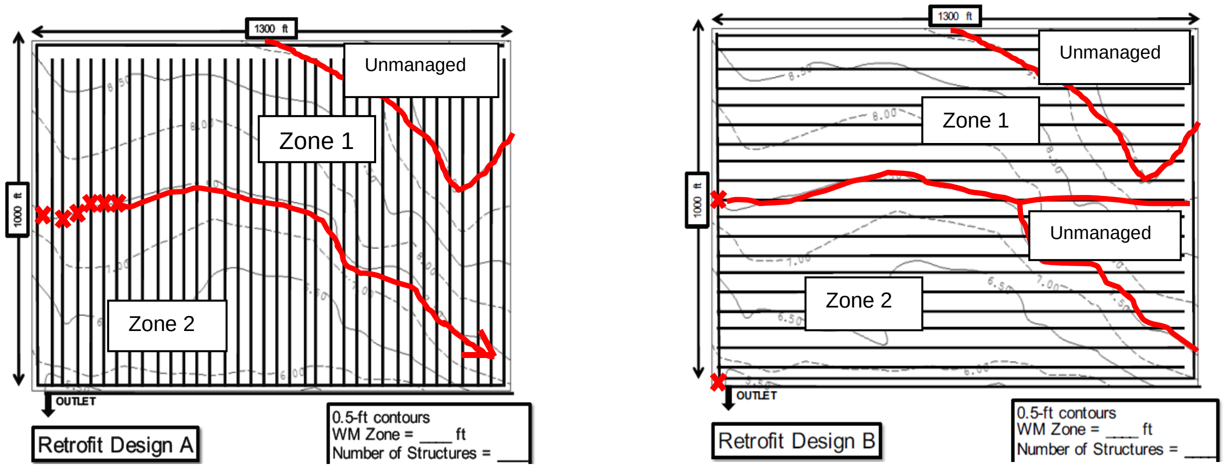

Figure 19: A comparison of two different layouts to be retrofit with control drainage (Sands, 2016 Extension Subsurface Drainage Design & Water Management Workshop, 2016)

To retrofit Design A where the laterals follow the slope of the land, a control structure is required on every lateral along the contour line that separates the two management zones. If the main drain follows the slope as in Design B, two control structures can be used to manage the same zones, with a slightly larger unmanaged zone. This is more cost-effective, easier to implement, leaves obstacles at the edge of the field rather than in the middle, and is much less intensive to manage. The two tile designs presented here are very simplistic and many more arrangements are possible.

9.6 Legality

Tile drainage in Manitoba is regulated under the auspice of the Water Rights Act, available in updated form online. Like other forms of drainage, tile drainage requires a Water Rights license to construct, operate, or maintain the system. The following information is taken from the Drainage and Water Control Licensing Tile Drainage Requirements Fact Sheet obtained from Manitoba Sustainable Development (Manitoba Sustainable Development):

To obtain a Water Rights License, an application form (available online or through a regional office) must be submitted to Manitoba Sustainable Development accompanied by an application fee (currently $25). The following technical information must be included:

- Legal land location (section, township, range) of proposed project
- Number of acres to be tiled
- Lateral pipe location, size, flow direction, average depth (should not exceed 3 feet unless need is demonstrated), gradient, and connection details to header pipe
- Header pipe location, size, depth, outlet, flow direction
- Proposed run-off rates
- Sump pit location and size, pump out location, pump size, and proposed pump rate (if pump station is necessary)
- Annual proposed pump shut-off date

- Proposed water level (relative to prairie elevation) of float for pump operation
- Location and type of operational flow control structure (if deemed necessary) and operating plan
- A Receiving Drainage Network Report that clearly details, with drawings, the route from the proposed point of entry into the existing drainage system to the point where the discharge would enter an established drain/creek/river/lake/etc. for a minimum of 2 miles downstream of the proposed project.
- A Project Impact Statement from an Engineer/Hydrologist may be requested for proposed projects in sensitive areas.

Manitoba Sustainable Development also places the following design criteria upon tile drainage projects (at the time of writing- check for updates):

- A run-off coefficient not exceeding 3/8” in a 24 hour period
- Header pipe designed so that an operational control structure may be installed if necessary
- Average perforated header pipe depth not to exceed 5 feet
- Any pipe exceeding 5 feet of depth should be non-perforated unless a need for perforated can be demonstrated
- Outlet must be rip rapped and marked according to municipality, Manitoba Sustainable Development, or other provincial agencies
- Pump out electrical panel must be equipped with acceptable recording device (i.e. HOBO Data Logger) which annotates pump operations including length and frequency of pump operations
- All tile work must have a minimum 50 meter setback from any permanent or semi-permanent wetland

The following sign-offs must be obtained:

- From the municipality the system is installed in, as well as the landowner if the landowner is not the proponent
- For systems that outlet into municipal drains within one mile of the tile outlet and stay within the municipal drainage system, written approval of the affected municipality is required
- If the municipal drainage system outlets into/becomes a natural waterway within 2 miles of the proposed outlet, additional landowner signoff may be required
- For systems that outlet into natural drains that cross private property, written landowner approval is required for any affected landowner within 2 miles downstream of any outlet
- For systems that outlet into the Provincial Drain or Highways network, written authorization from the affected government agency is required

It should be noted that some municipalities or government agencies may have additional requirements with respect to tile drainage and project proponents are advised to contact their municipality directly. As a final condition of approval, as-built drawings of the final installed tile drainage are required.

10. Sub-Surface Irrigation

Sub-surface irrigation uses the infrastructure from tile drainage for the dual purpose removing and adding water to the field. It provides increased control over water entering and exiting the field and mitigation of both drought and flood conditions within the same system. Subsurface irrigation operates on the principle of capillary action. When water is pumped through the underground perforated pipe network, it rises through the soil particles and becomes available in the root zone for plant uptake. The water level in the field is maintained by a control structure. A water-use licence may be required for irrigation purposes.

There are certain site requirements to be met in order to be eligible for a successful subsurface irrigation system (Robert Evans W. S., Agricultural Water Management for Coastal Plain Soils, 1996):

- An adequate source of water near the field
- An overall slope of the field less than 1%
- Improved drainage (or at least very good natural drainage)
- Fairly permeable soils (Ksat > ¾"/hour)
- A high natural water table or a shallow and level impermeable layer (within 10-25' of the surface)
- A good drainage outlet at least 3' lower than the average land surface

In addition, several design changes are necessary to the subsurface drainage system for the dual purpose of irrigation as well. Tile should be installed as shallow as possible to aid in capillary uptake and generally requires approximately 30% closer spacing to work effectively (Robert Evans W. S., Operating Controlled Drainage and Subirrigation Systems, 1996). If a pump was not necessary for the drainage system without subsurface irrigation, it will be necessary if subsurface irrigation is to be included in the system. Management of the water table is crucial. The level of water table should be kept about one foot above the tile. Once it falls below the level of the tile, it can be very difficult to raise through sub-irrigation alone.

The cost of subsurface irrigation is almost entirely dependent on the cost of providing water (Robert Evans W. S., 1996). Excavated ponds are expensive and must be quite large to supply enough water throughout the season. If recharging the pond is possible, a smaller pond may be adequate and more affordable. Streams or rivers are the most economical source of water if available, but are also the most limited and unreliable, as they may also dry up under drought conditions. A deep well is the most dependable, but also the most expensive means of providing water.

Subsurface irrigation is best employed on very flat fields. Grading may be necessary to create an even field (Robert Evans W. S., 1996). An uneven surface makes it difficult to regulate the depth of the water table below the surface. A water table level that is adequately in the root zone in one area may be much too deep in other areas, causing symptoms of drought. Uneven topography may also be overcome through the use of control structures. The number of control structures necessary will depend on the fluctuation in topography, and it is recommended for the land surface to vary no more than one foot in the area served by one control structure, depending on the crop.

Subsurface irrigation may or may not be economically feasible depending on the expected increase in crop yield compared to subsurface drainage alone and the cost of modifying the drainage system to be used for irrigation. Research examining the effects of subirrigation on yield is limited in Canada and sometimes contradictory (Ranjan & Cordeiro, 2012). A study modelled over a ten-year period in North Carolina using DRAINMOD, a computer-based water management model developed to compare alternative drainage systems, shows fluctuations in annual net returns for conventional subsurface drainage, controlled subsurface drainage, and subsurface irrigation, shown in **Figure 20** (Robert Evans W. S., 1996). Points of interest in this diagram are that subsurface drainage experienced some of the highest annual profits in this time span, but also suffered the highest overall profit losses. Controlled drainage trials gave similar results with less variation in annual profit. Trials using subsurface irrigation did not experience dramatic profits as compared to the other two options, but garnered a net profit every year with the most consistent profitability.

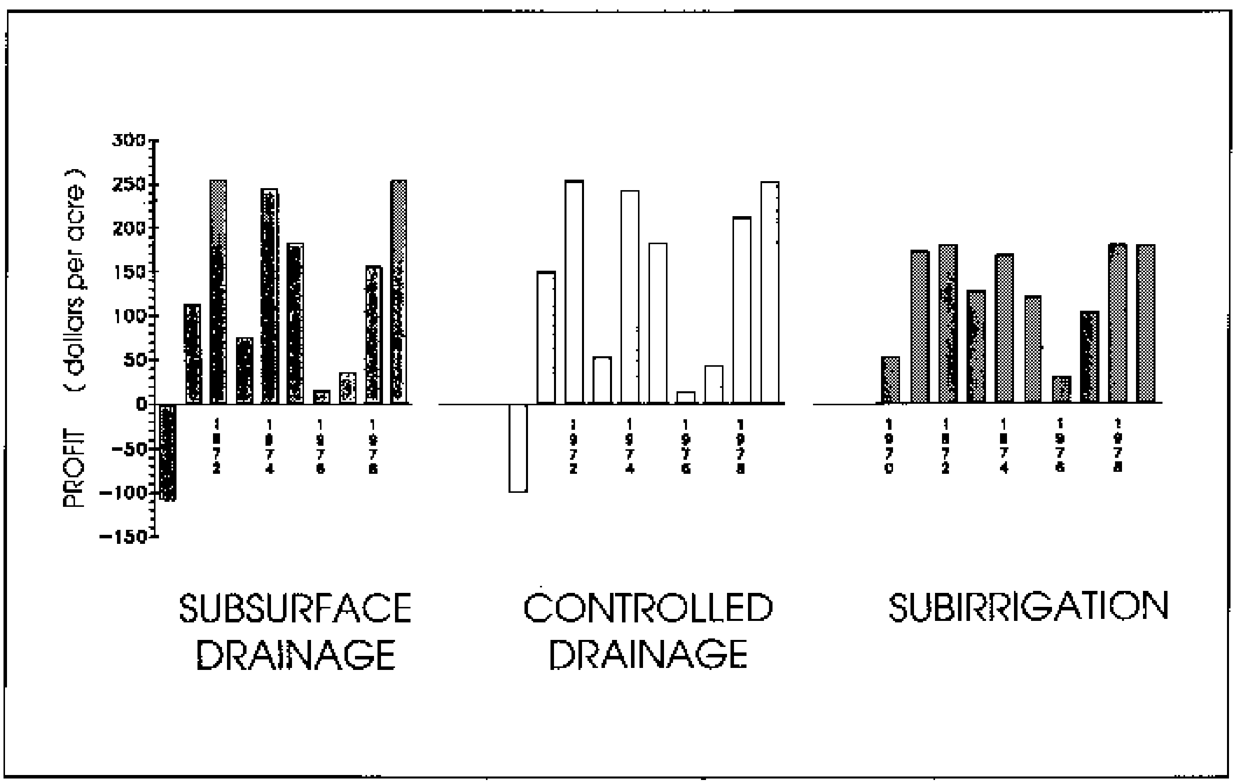

Figure 20: Fluctuations in annual net return for conventional subsurface drainage, controlled subsurface drainage, and subsurface irrigation (Robert Evans W. S., 1996).

11. Economics of Tile Drainage

An economic evaluation of tile drainage requires a great deal of information on a large amount of variables. However, reasonable estimations of cost can be made based on information most producers have access to for their own land. This section will identify how different features and options in the design affect the initial cost of the system, discuss the estimation of crop response and other economic benefits, and suggest methods of financial evaluation.

11.1 Factors Affecting Cost

The cost of installing tile varies significantly in different areas and is very site specific. Costs of installation with a contractor in Western Canada can vary from $600-$1200/acre, generally 2/3 material costs and 1/3 labour costs (Loewen, 2016) (Fraser, 2016). Moving the equipment to the site is a large part of the contractor cost and installing a larger amount of tile at one time, on a single farm or collectively in an area, can reduce the cost per acre. Tiling during a non-peak time for contractors may also provide room for negotiation on price. A report from Ontario in 2005 gives information from 2001 to 2004 (gathered by the Ontario Ministry of Agriculture and Food) on tile drainage activity. Ten agricultural tile sales organizations responded saying that over the three-year period, 32, 650 acres were tiled at an average cost of $524.61/acre (Richards, 2005).

Items that influence the overall cost of a tile drainage system include:

- tile spacing and depth,
- aggressiveness/risk-tolerance of the system,
- conditions at the outlet,
- self-installation vs. contractor installation, and
- additional features (sub-irrigation, control structures, etc.).

Other items to consider in evaluating economic feasibility are:

- crop rotation, expected yield increase, and expected rate of return vs investment,
- increase in land value,
- annual maintenance costs,
- legal considerations and easements, if necessary, and
- tax considerations.

In most cases, the factors that have the greatest influence on initial cost are the soil characteristics (which determine tile spacing), and the conditions at the outlet.

11.1.1 Tile Spacing

The soil characteristics dictate the ability of water to percolate through the soil, and therefore the required spacing to facilitate even drainage. The less permeable the soil, the closer together the tiles must be in order to provide consistent drainage throughout the field. In Manitoba, a common spacing is approximately 15 m (50') (M.R.C. Cordeiro, 2014). This is appropriate for many cases but it is dependent on the soil type and should not be chosen based on prevalence. A study by Dr. Sri Ranjan at the University of Manitoba modelled for corn over a period of 20 years in Manitoba found that for sandy loam soils, spacing as wide as 40 m (131') is reasonable without any significant yield loss during wet years (M.R.C. Cordeiro, 2014). Yield was particularly sensitive to excess moisture in the beginning of the growing season, indicating that the ability of the system to remove spring melt moisture from the fields is critical. This is especially true of crops that are planted earlier in the season.

Tile spacing is related to risk aversion. Tile in Manitoba can often be placed much farther apart than 15 m (requiring less total tile and, therefore, a lower initial investment) providing sufficient drainage for cropping needs. However, in a very wet year, there is a possibility of some crop damage due to excess moisture, see in **Figure 21**. There is also the risk that initial spacing estimates were not conservative enough and additional tile may need to be laid between existing rows at a later time. From a strictly a capital cost standpoint, it is most cost effective to install tile as deep as possible in order to space it as wide as possible for that particular soil type. In order to find the most economical solution over the life of the tile, the calculable risk must be taken into account- namely the risk of occasional crop damage or risk of miscalculation. **Figure 22** gives an idea of the relationships between financial benefits, nitrate losses, capital cost, and annualized net return.

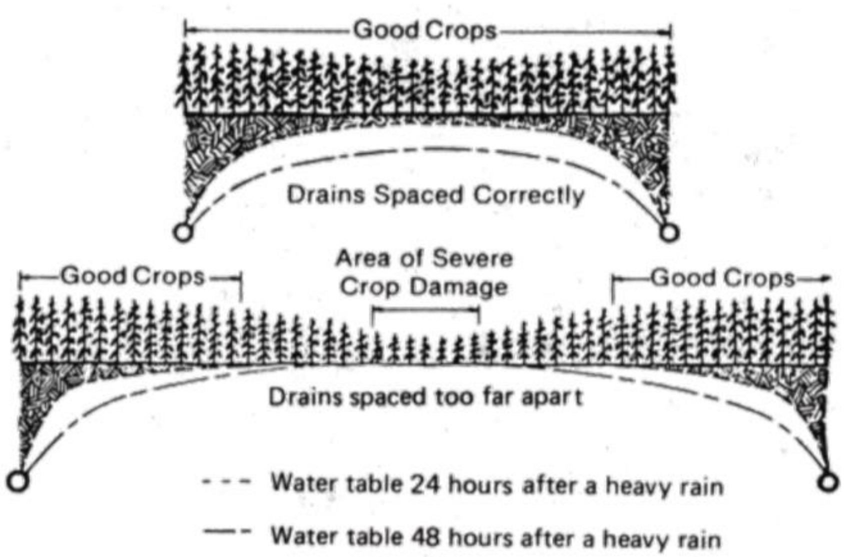

Figure 21: Effect of drains placed too far apart during a wet period (Sands, Subsurface (Tile) Drainage Design).

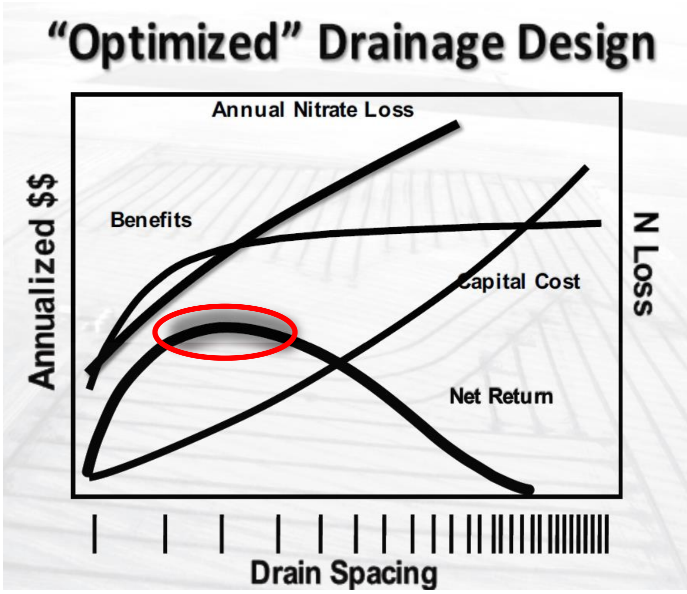

Figure 22: Chart detailing the optimization of tile drainage spacing for various costs and benefits (Sands, Extension Drainage Design & Water Management Workshop, 2016)

The cost of installing tile with closer spacing is also not a linear relationship (installing tile at 15 m spacing is not double the cost of installing tile at 30 m spacing), as the cost of transporting the machinery to the site is a sizable part of the installation price. Many producers will choose to be "rather safe than sorry" and space tile conservatively (closer) rather than too far apart. Tile spaced close together will simply provide a higher drainage coefficient, and therefore a more aggressive system. A control structure can mitigate the risk of over-draining, offsetting the risk of installing tile too close together. Also, if the tile is going to be used for the dual purpose of subirrigation, it should be as close to the surface as possible without crowding the root zone (Ranjan, 2016).

Table 12 gives general guidelines on the length of lateral drain pipe required to drain one acre for different spacing. Keep in mind that this can change significantly based on soil type, as well as pipe diameter and depth of installation (Planning to Drain Your Land, 1998).

Table 12: Length of lateral drainage pipe needed to drain one acre at a given drain spacing (Planning to Drain Your Land, 1998)

LATERAL DRAIN SPACING & DRAINAGE PIPE REQUIRED			
Spacing (feet)	*Feet per Acre*	*Spacing (meters)*	*Meters per Hectare*
20	2180	6	1640
30	1450	9	1090
40	1090	12	820
50	870	15	655
60	725	18	545

Knowing your soil type and K_{sat}, it is possible to approximate the required spacing for an area of land, and therefore create a preliminary estimate for cost based on prices given by local contractors.

11.1.1.1 Depth of Tile Installation

The depth of the tile will also have an effect on the required spacing. Tile should be deep enough to prevent damage from equipment and allow appropriate space for root development, but also shallow enough to be above any impermeable soil layer and to provide a water table depth within the reach of the root system. The most common depth in Manitoba designs is 0.9 m (3'), though this is not necessarily optimal for all cases, depending on the goals of the system (M.R.C. Cordeiro, 2014).

A relationship between tile spacing and tile depth exists, and several layouts may work for the same desired drainage. For example: recommendations for the clay-loam soils of southern Minnesota are 60' (18.3 m) spaced pipes placed 3' (0.9 m) deep, OR 80' (24.4 m) spaced pipes at 4' (1.2 m) deep. Both will remove water at the same rate and provide the same crop yields (Lowell Busman).

Deeper tile will allow for wider spacing and therefore likely lower costs. Greater depth will also allow for more control over the day-to-day water table depths and the potential to conserve water through providing a flexible drainage coefficient. Deeper tile is better suited for salinity management. However, a shallower tile design will minimize nitrate losses and drought risks by conserving more moisture in a dry year (Manitoba Agriculture, 2008) (Hay, Drain Spacing Calculations, 2012). Shallow drains can reduce sediment loss by up to 50% compared to deep tile (G.O. Schwab, 1985) but are less likely to control salinity issues. Appropriate depth should be decided based on optimal plant health, drainage strategy, and environmental considerations rather than cost of installation to maximize function of the system.

11.1.2 Drainage Outlet and Pipe Size

The location of the outlet must be considered during the design. The most economical and ideal outlet is a gravity outlet into the ditch adjacent to the field. Cost will increase as the main drain length increases to reach a suitable location for expulsion. Other factors that must be considered are the outlet ditch capacity, minimization of erosion due to the outlet, and any rules or regulations involving field drainage in the area (Sands, Subsurface (Tile) Drainage Design).

If the topography of the field and required grade do not allow for a gravity outlet, a pumped outlet, or “lift station”, must be installed (Gary R. Sands C. H.). This can have a fairly significant impact on the initial investment on the drainage system, as well as increasing annual maintenance and operation costs. According to one tile drainage installer in Manitoba, a lift station can add as much as $15 000-$20 000 to the initial price tag (Tom Scherer, 2015).

The ideal pump location is a compromise between being close to the drain outlet and being close to an electrical source. If both are relatively close, this allows for a smaller size of pump, and lowers the cost of extending the electric lines. If neither is close, the more economical option should be chosen (a larger pump/pipe vs. extension of electrical line). Soil stability in the area, accessibility, and impact on surrounding land and waterways must also be considered (Thomas F Scherer, 2011).
In choosing the appropriate pump, the following items must be determined, as discussed in the Outlet section (Thomas F Scherer, 2011):

- Flow rate
- Total head (maximum lift + friction losses)
- Appropriate pump type (submersible, above ground)
- Pump controls (float-on/off, variable frequency drive)

Knowing these will help to estimate the initial cost of the pump and construction of the accompanying components. Annual costs will vary depending on precipitation and electricity costs in the region. As an example, a northwestern producer in Minnesota recorded 35" of rain over his 5000 acres of tiled land during a very wet 2010 season. The average cost for pumping (25 stations) per acre was $6, with individual fields ranging from $3-$15/acre (Scherer T. , 2015). In Minnesota, the average retail price of electricity in 2010 was 8.41 cents/kWh (U.S. Energy Information Administration, 2012) .

11.1.3 Additional Costs

If control structures are part of the design, their added cost will depend on the number of structures necessary (depending on the elevation change in the field) as well as what type are used (Robert Evans W. S., 1996). The greater the unevenness of the land, the more control structures that will be necessary. Simple homemade structures (constructed recycled materials, concrete, treated wood, etc.) may be fabricated and installed for as little as $300, but a larger, pre-fabricated structure of aluminum or steel may cost more than $3000.

Licensing and permit fees may also be required, depending on the regulations of the area. Other costs may include topographical surveys, land grading, improvement of surface drains, blind inlets or intensive drains, breathers, or outlet/field border stabilization if required.

11.2 Self-Installation

The choice to self-install tile is generally made when producers do not have access to local contractors, or there are not enough contractors in an area to meet the demand.

Self-installation may also be appropriate for small-scale projects that an installer may not be interested in or where a producer has already invested in some of the equipment necessary. Self-installation is sometimes thought to be a way to save costs but this may not be the case.

Benefits of self-installation include timeliness of operation, the ability to tile little by little when operations allow, total control over quality, increased knowledge about soils and farmland, and better utilization of existing farm assets and equipment. Disadvantages include a large investment of time into learning and understanding the design and installation process, risks associated with novice mistakes, and time taken away from other necessary operations.

If self-installation is chosen for the purpose of saving costs, a thorough cost-estimate should be done and the following costs should be considered (Lovell, 2014):

- Purchasing a tile plow (for the laterals) knowing it will have a life of about 10,000 hours and can install 2000-3000 km of tile in its lifetime
- Renting a tile plow or trencher, if required
- Preliminary survey and planning (including investment of time in learning and designing)
- Wages of several trained individuals for the installation (4-6 people)
- Buying/renting a backhoe (for the main drains), or subcontracting this part of the installation
- Buying/renting a tile trailer, and RTK-GPS equipment or design and installation software
- Materials per acre (~$400-$600/acre) including tile, fittings, filter material, catch basins, etc.
- Time costs of learning a new technology when others are already experts
- Total operational costs/day including lost opportunity costs for other necessary operations
- Project time from start to finish comparison for self-installation and contracted work
- Machinery maintenance, breakdowns, etc.
- Time cost of mistakes and future lost profit due to low quality (uneven grade, suboptimal design, etc.)
- Locating utilities
- Clean-up
- Permits

This cost breakdown should be compared to several contractors to ensure that any cost savings (or lack thereof) from self-installation are fully realized. Manitoba has a number of drainage experts in ditching and tiling as well as several drain manufacturers. For those considering it, free modelling software such as DRAINMOD is available and has been used extensively worldwide to simulate the hydrology of poorly drained, high water table soils for long periods of time (DRAINMOD, 2013). Several sophisticated software programs also exist for design and analysis that can be transferred directly to precision farming technology to automate installation in the field.

Gaining practical experience with a crew before self-installation is beneficial to better understand the process and how variables interact. All aspects of design (hand-drawn maps, field notes, aerial photos, GPS geo-referenced maps, ground photos, etc.) should be recorded for future maintenance and improvement (Duncanson, 2016).
The following tips are given from Pat Duncanson at the 2016 Tile Drainage Extension Subsurface Drainage Design & Water Management Workshop in Marshall, MN (Duncanson, 2016):

- Oversizing lateral and header pipes allows for an increased margin of error
- Smooth operation of the plow is necessary for even grade. Slow tractor speeds are essential and a struggling tractor may require an extra pull tractor or pre-ripping
- Weight is more important than horsepower in a tractor
- Deeper installation and poor traction conditions may make it difficult to maintain grade
- Wind, fog, and precipitation affect laser operations
- Use a walker to visually inspect tubing going into the ground for damage to the tile or plow issues
- Survey all lines so to take the guesswork out of grade
- Check grade after installation
- Record and back-up all data related to installation

11.3 Economic Response

The economic response of the system is very site-specific and impossible to generalize for an easy analysis. Capital costs, crop rotation, prior production, tax and depreciation, subsequent commodity prices, appreciation of land value, and weather patterns can affect the return on investment and expected payback period. A number of best guesses and estimations based on expectations and historical data are needed to analyze an investment in drainage. To be viable, the land and its planned operation in the future must be more valuable as a drained system than other options, such as alternate uses, cropping patterns, and water management strategies, or selling to re-invest the money back in the farm.

Schwab et al. found that over a 13-year period, yields increased in the order of undrained, surface drained, shallow tile, deep tile, and a combination of surface and tile (deep or shallow) drainage (G.O. Schwab, 1985). Stands increased in a similar fashion. Variation in corn yield on an annual basis averaged 46% for undrained land, 33% for surface drained plots and 19% for three other tile drained systems. This shows tile drained systems in corn production not only see increased yields, but also a more consistent yield compared to undrained land or surface drainage alone. Response to the drainage system (in terms of yield variability) is, in decreasing order, oats, corn, and soybeans. This is partially due to the planting dates- oats are planted earliest when wetness is most likely to occur, and soybeans have the latest planting dates when the soil is likely to be warmer and drier. Benefit-cost ratios can be used to measure the overall value of an investment, expressing the ratio of monetary benefits to monetary costs. A higher the benefit-cost ratio indicates a better investment. In the 13-year study, ratios were found to be 2.2 for surface drainage and 2.0 for tile in corn production, and 2.1 for surface drainage and 1.2 for tile drainage in soybean production. Higher ratios for surface drainage are due to the comparatively lower initial cost.

Some factors resulting from improved drainage (improved soil structure, microbial activity, safeguarding soil productivity, reduced plant stress, environmental benefits, etc.) can also be difficult to measure definitively. Other factors to include are changes in operating expenses due to reduced fuel consumption, increased/decreased inputs, increased land value, increasing commodity prices, and timelier field operations (Tom Scherer, 2015) (Hofstrand, 2010). Increases in land value due to installation, financing, depreciation of the asset, and inflation should also be considered in a more in-depth analysis.

Expected yield increase will depend on the expected weather patterns and estimates should be made to reflect the weather cycle. Improved drainage may have less of an impact on dry years, meaning that yield increases in wet years must be greater than average. Estimates can be made by examining historical yields in wet/dry years. Yield mapping technology is also an accurate way to measure field level improvements, such as drainage (S. M. Swinton). Converting a yield map into a profit map is also an excellent way to both predict and track the increased profitability due to improved drainage.

More specific and also more intensive is the use of computer simulation tools, such as DRAINMOD designed by Dr. Wayne Skaggs of North Carolina State University (DRAINMOD, 2013). Once an average increased yield percentage is estimated for the required crop and rotation, this can be used with expected commodity prices for an economic analysis. The estimated increase in yield should also account for improved timeliness in planting. This will affect yield in terms of an increased growing season as well as drying costs. A longer growing season may allow for removing crop at slightly less moisture, reducing drying costs, but there may also be more grain to dry, increasing drying costs.

Advanced Drainage Systems (ADS) in Columbus, OH, a manufacturer of drainpipe, has developed software to determine annual and cumulative cash flow, return on investment, payback period, and break-even production per acre for tile installation (Olson, 1999). ADS estimates that the average payback period is 7 to 10 years with a return on investment generally being above 12% per year (1999). In critical years of wetness, this percentage can be much higher.

Many tools exist for financial analyses and a growing number are being tailored specifically to the agricultural industry. The Net Present Value Approach is the preferred tool for agricultural investment analysis, as recommended by the University of Alberta, Faculty of Extension, as it allows for incorporation of inflation, risk, and tax issues (Leonard Bauer, 2005). The Prinsco Analysis tool provides a much more basic analysis specifically for drainage investment. The University of Iowa has also designed an Excel spreadsheet to analyze the costs and returns in terms of Net Cash Returns and Payback (before and after tax) as well as Income Tax Depreciation. All can be found in the Resources section of this report. Other computerized investment calculators are constantly being developed in industry and extension programs. Professional consultation is always available for a detailed economic analysis if required.

12. Summary and Conclusions

Climate change is expected to cause increasing variability and extremity in weather patterns in the coming decades, particularly in the form of more frequent and widespread flood and drought events. Prairie producers are already feeling the effects of these changes and the industry must move towards more sustainable, adaptable, and resilient methods of farming. Water is expected to be severely affected in terms of both quantity and quality due to climate change and cooperative management of water, in particular, will be of extreme importance. The vast majority of crop insurance claims in Manitoba are moisture-related (both flood and drought) and are increasing in number. Water management strategies that provide greater protection from flood and drought events are necessary to keep prairie agriculture sustainable in the future.

Interest in tile drainage is growing across Manitoba and the prairies as it becomes a more financially justifiable option for water management. Costs of installation are site-specific and largely depend on soil characteristics, and outlet location, and are influenced to a lesser extent by desired aggressiveness of the system, acres being drained, and local contractor prices. Contractor costs in Manitoba vary $600-1200/acre. Systems in more permeable soils generally have lower capital costs, as drains can be installed with wider spacing. Heavier, clay based soils that require closer spacing for consistent drainage generally require a higher initial investment, but may still be economically viable. Factors that affect the economic analysis of tile installation include crop rotation, effects of earlier field access, improved soil structure, and subsequent commodity prices and weather patterns. Most institutions predict a return on investment between 7-10 years on average. Many tools exist to aid in economic evaluation, available in this report and through industry and extension services.

Tile drainage is not a new technology and has been researched for years in the United States, being considered a BMP in some states for sustainable water management in agriculture due to its protection from water-related damage. Tile drainage has been proven to increase yields and can dramatically reduce annual variability in yield, showing the best results for both when used in combination with surface drainage. Crops planted early in the year, such as oats, will see the highest decrease in annual yield variability, due to the greater chance of excess moisture earlier in the growing season, and water-sensitive crops, such as corn and potatoes, will see the largest increase in yield compared to undrained or surface-drained land.

Tile drainage systems with control structures can dramatically reduce peak flows, mitigating downstream flooding, and reduces overall outflow from the field, having significant effects on phosphorus and sediment leaving the field, as well as noticeably reducing nitrate losses. Control structures also give greater influence over the water table, leaving producers better equipped to deal with flood and drought conditions and increase the natural ability of the soil to drain over time through improved soil structure. Properly managed, this benefits producers and the entire surrounding area by creating a greater capacity for water retention in the soil. Tile drainage can also significantly control salinity in soils through leaching of the salts from the surface, leaving more water available for plant use.

Tiling designs are not a one-size-fits-all and must be customized for each site. Relationships exist between tile size, depth, spacing, and grade to produce numerous drainage plans that may be equally effective for a single site and should be evaluated for drainage goals, environmental aspects, cost of design, and ability to expand in the future. The most important aspects of the design are choosing a drainage coefficient, which will have an influence on most other design aspects, and designing for future additions. Infrastructure in subsurface drainage can also be used for subsurface irrigation, if the system is designed appropriately. Many tools and software programs at various costs are available to aid in both design and installation. A growing number of contractors are also available for consultation, surveys, design, and installation.

14. References

A. Shokri, W. E. (2015). Enhancement of the Hooghoudt Drain-Spacing Equation. *Journal of Irrigation and Drainage Engineering, 141*(6). Retrieved from http://ascelibrary.org/doi/abs/10.1061/%28ASCE%29IR.1943-4774.0000835

Agvise Laboratories. (n.d.). *Salinty Problems?- Tile Drainage Works!* (Agvise Laboratories) Retrieved January 20, 2016, from http://www.agvise.com/educational-articles/salinity-problems-tile-drainage-works/

Basin Technical and Scientific Advisory Committee. (2012). *Water Management Ooptions for Subsurface Drainage: Briefing Paper #2.* Red River Retention Authority. Red River Retention Authority. Retrieved from http://www.rrbdin.org/wp-content/uploads/2012/04/FINAL-Briefing-Paper-2-4-9-2012.pdf

Bill Uruski, F. K. (2015). *Agriculture Risk Management in Manitoba.* Province of Manitoba. Retrieved March 1, 2016

Brook, T. (2013, May). *Considerations When Planning to Drain Land*. (OMFRA) Retrieved March 17, 2016, from http://www.omafra.gov.on.ca/english/engineer/facts/13-033.htm

Bryanna Thiel, G. O. (2015). *Climate Change Adaptation and On-Farm Drainage Management in Delta, British Columbia: Current Knowledge and Practices.* Delta Farmers' Institute. Retrieved from http://www.bcagclimateaction.ca/wp/wp-content/media/UBC-Drainage-and-Subirrigation-Study-Final-Report_Approved.compressed.pdf

Carl Folke, S. C. (2002). Resilience and Sustainable Development: Building Adaptive Capacity in a World of Transformations. *Royal Swedish Academy of Sciences, 31*(5), 437-440. Retrieved from http://www.era-mx.org/biblio/Resilience.pdf

Carlson, B. (2016). Drainage Design Workshop. *An Overview of Conservation Drainage Techniques.* Marshall, MN.

Casey, A. (2006, November/December). Forgotten Lake. *Canadian Geographic*.

Cavers, C. (2002). *Please Don't Pass the Salt- Preventing and Managing Soil Salinity.* Retrieved March 17, 2016, from http://www.umanitoba.ca/faculties/afs/MAC_proceedings/2002/pdf/cavers.pdf

Cooley, E. (2011, October 25). *New technologies in drainage water management may open opportunities in Wisconsin's tile drained landscapes*. (University of Wisconsin-Extension) Retrieved February 29, 2016, from http://fyi.uwex.edu/discoveryfarms/2011/10/new-technologies-in-drainage-water-management-may-open-opportunities-in-wisconsin%E2%80%99s-tile-drained-landscapes/

D.W.Schindler, W. (2006). An impending water crises in Canaas western prairie provinces. *Proceedings of the National Academy of Sciences, 103*(19), 7210-7216. Retrieved from http://www.pnas.org/content/103/19/7210.full.pdf

Darren Swanson, J. H. (2009). *Prairie Climate Resiliance Project.* International Institute for Sustainable Development . Winnipeg: International Institute for Sustainable Development. Retrieved from http://www.iisd.org/sites/default/files/pdf/2009/pcr_adaptive_cap_ag.pdf

Department of Agricultural and Biological Engineering. (n.d.). *Illinois Drainage Guide (Online)*. (University of Illinois) Retrieved January 21, 2016, from http://wq.illinois.edu/dg/

Don Flaten, D. L. (2012, March 5). Retrieved from http://buller.prov.ca/BullerCentre/projects/biomass/Innovative%20water%20&%20crop%20mgmt%20proposal%202012%2003%2005.pdf

DRAINMOD. (2013). (Soil & Water Management Group NCSU BAE Deparment) Retrieved February 9, 2016, from http://www.bae.ncsu.edu/soil_water/drainmod/

Duncanson, P. (2016). 2016 Extension Subsurface Drainage Design & Water Management Workshop. *Should I do my own drainage, or call the contractor?* Marshall, MN.

Eidman, V. (1997, Spring). Minnesota Farmland Drainage: Profitability and Concerns. *Minnesota Agricultural Economist*, pp. 1-7.

Ford, H. W. (1993). *Iron Ochre and Related Sludge Deposits in Subsurface Drain Lines.* University of Florida, IFAS Extension. Universit of Florida Extension. Retrieved March 4, 2016, from http://ufdcimages.uflib.ufl.edu/IR/00/00/14/95/00001/AE02600.pdf

Fraser, J. (2016, January 14). Precision Land Solutions.

G.O. Schwab, N. F. (1985). *Tile and Surface Drainage of Clay Soils.* U.S. Department of Agriculture, Agricultural Research Service. Wooster: The Ohio State University Ohio Agricultural Research and Development Center.

Gary R. Sands, C. H. (n.d.). *Frequently Asked Questions about Subsurface (Tile) Drainage in the Red River Valley.* Retrieved from University of Minnesota Extension: http://www.extension.umn.edu/agriculture/water/publications/pdfs/faqs_of_tile_drainageprint_61313.pdf

Gary R. Sands, P. (n.d.). *Fact Sheet.* Retrieved from Science of Drainage: http://www.extension.umn.edu/agriculture/water/publications/pdfs/u_of_m_drainage_fact_sheet_m1292_sands_2010.pdf

Hay, C. (2012, July 5). *Drain Spacing Calculations*. (SDSU iGrow) Retrieved January 21, 2016, from http://igrow.org/agronomy/corn/drain-spacing-calculations/

Hay, C. (2016, January 21). Drainage Calculators.

Heather Fraser, R. F. (2001). *Environmental Benefits of Tile Drainage - Literature Review.* Guelph: Land Improvment Contractors of Ontario.

Hofstrand, D. (2010, July). *Understanding the Economics of Tile Drainage.* Retrieved from https://www.extension.iastate.edu/agdm/wholefarm/html/c2-90.html

Hornberger, C. &. (1978). *Drain Spacing*. (South Dakota State University) Retrieved January 19, 2016, from http://climate.sdstate.edu/water/drainspacingcalculatordocumentation.html

Kandel, H. (2016, February 18). Managing Salinity with Tile. Fargo, North Dakota, United States.

Larry C. Brown, A. D. (n.d.). *Ohio State University Extension.* Retrieved from Understanding Agricultural Drainage: http://ohioline.osu.edu/aex-fact/0320.html

Larry Cihacek, D. F. (2012, August). *Evaluation of Soils for Suitability for Tile Drainage Performance.* Retrieved March 17, 2016, from https://www.ag.ndsu.edu/pubs/plantsci/soilfert/sf1617tiledrain.pdf

Leonard Bauer, D. B. (2005, August 26). *Agricultural Investment Analysis.* Retrieved January

25, 2016, from Alberta Department of Agriculture and Forestry: https://drainage.farm/field-elevation-surveys-and-farm-tile-and-surface-drainage-system-design/

Loewen, K. (2016, January 18). K&S Tiling Ltd. (A. Simundsson, Interviewer)

Lovell, A. (2014, April 29). Do-it-yourself tile drainage. *Grainews*. Retrieved from http://www.grainews.ca/2014/04/29/do-it-yourself-tile-drainage/

Lowell Busman, G. S. (n.d.). *Agricultural Drainage: Issues and Answers.* Retrieved from University of Minnesota Extension: http://www.extension.umn.edu/agriculture/water/publications/pdfs/issues__answers.pdf

M.R.C. Cordeiro, R. S. (2014). *DRAINMOD Simulation of Corn Yield under Different Tile Drain Spacing in the Canadian Prairies.* Winnipeg: American Society of Agricultural and Biological Engineers.

Manitoba Agriculture. (2015, October 1). *Soil Management Guide*. (Manitoba Agriculture) Retrieved January 13, 2016, from https://www.gov.mb.ca/agriculture/environment/soil-management/soil-management-guide/drainage-management.html

Manitoba Agriculture. (2008). *Soil Management Guide.* Retrieved from http://www.gov.mb.ca/ana/major-initiatives/pubs/soil-management-guide.pdf

Manitoba Sustainable Development. (2012). *Excessive Moisture in the Manitoba Interlake Region.* Winnipeg: Government of Manitoba.

Manitoba Sustainable Development. (n.d.). Drainage and Water Control Licensing Tile Drainage Requirements Fact Sheet. Stonewall: Manitoba Sustainable Development.

Morrison, L. (2012, December 20). *Drainage Solutions: Surface Tile Intakes*. Retrieved March 20, 2016, from Corn and Soybean Digest: http://cornandsoybeandigest.com/conservation/drainage-solutions-surface-tile-intakes#slide-0-field_images-73551

Olson, J. (1999, March 1). Subsurface drainage pays big dividends. *Farm Industry News*.

OMFRA. (2011). *Best Management Practices: Cropland Drainage.* FSC.

OnePlan. (2016). *Estimating Soil Moisture*. (University of Idaho) Retrieved March 2, 2016, from http://www.oneplan.org/Water/soil-triangle.asp

Planning an agricultural subsurface drainage system. (2016). (University of Minnesota Extension) Retrieved January 19, 2016, from http://www.extension.umn.edu/agriculture/water/planning-a-subsurface-drainage-system/

Planning to Drain Your Land. (1998). (Land Improvement Contractors of Ontario) Retrieved January 21, 2016, from http://www.drainage.org/planning.htm

Prairie Adaptation Research Collaborative. (2008). *Climate Change Impacts on Canada's Prairie Provinces: A Summary of our State of Knowledge.* Prairie Adaptation Research Collaborative. Retrieved from http://www.parc.ca/pdf/research_publications/summary_docs/SD2008-01.pdf

Prinsco. (2016). *Water Gate*. (Prinsco) Retrieved February 29, 2016, from http://www.prinsco.com/prinsco-markets/fittings-accessories/water-gate-agriculture/

Ranjan, D. S. (2016, January 21). Subsurface Drainage and Irrigation Research. (A. Simundsson, Interviewer)

Ranjan, S., & Cordeiro, M. (2012, September). Corn Yield Response to Drainage and Subirrigation in the Canadian Prairies. *American Society of Agricultural and Biological Engineers*.

Richards, J. S. (2005). *The economic importance of agricultural drainage with emphasis on the enclosure of open drains in Ontario.* Ontario: Cordner Science. Retrieved from www.trca.on.ca/dotAsset/81627.pdf

Robert Evans, J. G. (1996). *Controlled Drainage Management Guidelines for Improving Drainage Water Quality.* North Carolina Cooperative Extension Service. Retrieved from http://www.bae.ncsu.edu/programs/extension/evans/ag443.html

Robert Evans, W. S. (1996, June). *Agricultural Water Management for Coastal Plain Soils*. (North Caroline Cooperative Extension Service) Retrieved from http://www.bae.ncsu.edu/programs/extension/evans/ag355.html

Robert Evans, W. S. (1996). *Economics of Controlled Drainage and Subirrigation Systems.* Biological and Agricultural Engineering. North Carolina Cooperative Extension Service. Retrieved from http://www.bae.ncsu.edu/programs/extension/evans/ag397.html

Robert Evans, W. S. (1996, June). *Operating Controlled Drainage and Subirrigation Systems*. (North Caroline Cooperative Extension Service) Retrieved January 28, 2016, from https://www.bae.ncsu.edu/programs/extension/evans/ag356.html

Robert Mcleman, B. S. (2006). Vulnerability to climate change hazards and risks: crop and flood insurance. *Canadian Geographer, 50*(2), 217-226. doi:10.1111/j.0008-3658.2006.00136.x

S. M. Swinton, J. L.-D. (n.d.). *Site-Specific Management Guidelines.* Retrieved February 9, 2016, from http://www.ipni.net/publication/ssmg.nsf/0/5C911A7DFA82C6B5852579E500763DE4/$FILE/SSMG-03.pdf

Sands, G. (2016). 2016 Extension Subsurface Drainage Design & Water Management Workshop. *Design of Managed Drainage Systems.* Marshall, MN.

Sands, G. (n.d.). Subsurface (Tile) Drainage Design. University of Minnesota Extension.

Sasaki, H. (2012). *Farmer Behaviour, Agricultural Management and Climate Change.* OECD Publishing. Retrieved January 26, 2016, from http://www10.iadb.org/intal/intalcdi/PE/2012/09774.pdf

Scherer, T. (2015). *Tile Drainage Pump Stations.* North Dakota State University, Agricultural Engineering. Fargo: North Dakota State University. Retrieved January 21, 2016, from https://www.ag.ndsu.edu/tiledrainage/documents/tile-drainage-pump-stations

Scherer, T. (2016, January 21). Agricultural Lift Stations for Drainage. (A. Simundsson, Interviewer)

Simundsson, A. (2016, March 9). Portage la Prairie, Canada.

Smith, D. (2013, October). *Delaying Drainage from Prairie Potholes Protects Water Quality*. Retrieved from United States Deparment of Agriculture AgReserach Magazine: http://agresearchmag.ars.usda.gov/2013/oct/water

Smith, D. (2013, October). Delaying Drainage From Prairie Potholes Protects Water Quality. *AgResearch Magazine*, pp. 18-19. Retrieved from

http://agresearchmag.ars.usda.gov/AR/archive/2013/Oct/water1013.pdf
Soil Permeability. (n.d.). (Food and Agricltural Organization of the United Nations) Retrieved January 19, 2016, from ftp://ftp.fao.org/fi/CDrom/FAO_training/FAO_training/General/x6706e/x6706e09.htm
Stacey Dumanski, J. W. (2015). *Hydrological regime changes in a Canadian Prairie basin.* University of Saskatchewan, Center for Hydrology. Saskatoon: Wiley Online Library. Retrieved from http://www.usask.ca/hydrology/papers/Dumanski_et_al_2015.pdf
Standing Senate Committee on Agriculture and Forestry. (2003). *Climage Change: We Are At Risk.* Parliment of Canada. Ottawa: Journals of the Senate. Retrieved January 26, 2016, from http://www.parl.gc.ca/Content/SEN/Committee/372/agri/rep/repfinnov03-e.htm
Stephen Barg, P. B. (n.d.). *Adaptive Policies Project: Chapter 1.* International Institute for Sustainable Development. Retrieved from http://www.iisd.org/pdf/2006/climate_designing_policies_chap1.pdf
Tarnoczi, T. (2009). *Climate Change in the Prairie Agro-ecosystem: Information Exchange and Producer-level Learning.* University of Manitoba, Natural Resources Institute. Winnipeg: University of Manitoba. Retrieved from https://umanitoba.ca/institutes/natural_resources/pdf/theses/Masters%20Thesis%20Tarnoczi%202009.pdf
Thomas F Scherer, T. S. (2011, November 22). *University of Minnesota Extension.* Retrieved January 21, 2016, from http://www.extension.umn.edu/agriculture/water/components/Forum-2011_T_Scherer.pdf
Tom Scherer, G. S. (2015, March). *Questions About Subsurface (Tile) Drainage.* Retrieved from https://www.ag.ndsu.edu/pubs/ageng/irrigate/ae1690.pdf
U.S. Energy Information Administration. (2012). *State Electricity Profiles 2010.* Washington, DC: U.S. Department of Energy. Retrieved from http://www.eia.gov/electricity/state/archive/sep2010.pdf
United States Deparment of Agriculture Natural Resources Conservation Service (USDA NRCS). (n.d.). *Drainage Water Management Plan.* Retrieved January 25, 2016, from http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs141p2_035556.pdf
Veen, S. V. (2015, October). *Operating and Maintaining a Tile Drainage System Factsheet*. (P. o. Ontario, Producer) Retrieved from Ontario Ministry of Agriculture, Food and Rural Affairs: http://www.omafra.gov.on.ca/english/engineer/facts/10-091.htm
Vellidis Research Group. (2016). *Precision Agriculture*. Retrieved March 2016, from Vellidis Research Group at The University of Georgia: http://vellidis.org/research-projects/precision-agriculture/

Appendix A

Additional Resources

Many resources exist to help with evaluation of drainage options for specific operations.

1. GIS4AG (http://soils.gis4ag.com/) offers excellent soil survey maps of western Canada complete with soil composition and K_{sat} for specific areas.

2. The Province of Manitoba has conducted soil surveys for years and has a number of detailed soil maps that can provide useful information necessary for drainage management and planning. (https://www.gov.mb.ca/agriculture/land/soil-survey/importance-of-soil-survey-mb.html#detailed)

3. The University of Minnesota Extension also offers a very brief guide in planning an agricultural subsurface drainage system and gives examples of acres drained per day based on drain size and drainage coefficient. (http://www.extension.umn.edu/agriculture/water/planning-a-subsurface-drainage-system/)

4. The Prinsco Profitabilty Analysis Tool (http://www.prinsco.com/resources/profitability-analysis-calculator/) was developed to assist in determining the estimated financial benefits from drainage improvement. It provides an estimate for the before tax rate of return, payback period, and breakeven yield improvement for select crops.

5. iGrow (http://igrow.org/drainage-calculators/), a service of South Dakota State University Extension, offers a number of online calculators to aid in selecting various parameters. The theoretical background behind the calculators is explained here (Hay, Drainage Calculators, 2016):

    - Pipe Sizing Related Calculators *(pipe diameter, area drained, minimum grade, maximum lateral length, lateral sizing, maximum laterals on a main)*:
      These calculators all use some form of Manning's equation, which is a very common equation governing uniform flow in open channels and is a function of channel velocity, flow area, and channel slope. The calculators assume the pipe is at capacity when the outlet (or end of the lateral) is flowing full. Coefficients necessary for the equation are taken from the American Society of Agricultural and Biological Engineers Standard (ASABE) EP260.5.

    - Drain Spacing Calculator/Drainage Coefficient Calculator:
      iGrow uses the Hooghoudt equation for calculations relating to drainage coefficient, pipe spacing, and pipe depth. The Hooghoudt drain-spacing equation, created by a drainage researcher from the Netherlands, is commonly used for developing drain spacing recommendations for a variety of applications. When a drainage coefficient is chosen as the primary driver, the calculator can be used to determine appropriate spacing and depth of the pipes for a lateral spacing arrangement. If depth and spacing are chosen externally from the equation, the equation can determine the optimal drainage coefficient. The equation creates a relationship between the desired amount of drainage per day with the hydraulic conductivity of the soil, the depth of the drains and impermeable layer below the drains, to give the optimal system parameters, based on that soil conductivity. The equation assumes homogenous soils, but an average hydraulic conductivity calculator is available on the site to compute an effective hydraulic conductivity to accommodate heterogeneous soils. Effective radii for different sizes of pipes used to calculate the equivalent depth are derived from the American Society of Agricultural and Biological Engineers Standard (ASABE) EP260.5.

Figure 1 below gives a visual representation of the Hooghoudt equation.

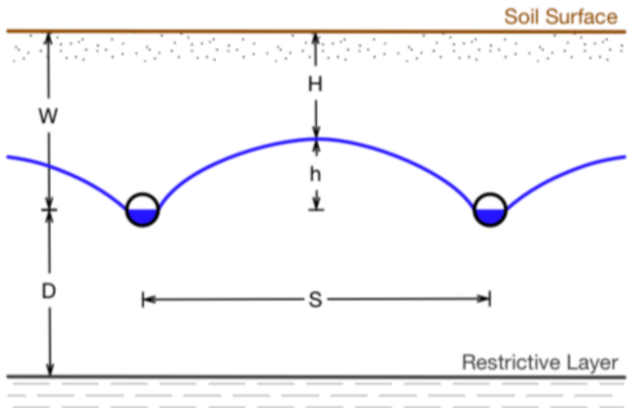

Figure 1: Visual diagram of Hooghoudt equation parameters (Hay, Drain Spacing Calculations, 2012)

- Subirrigation Spacing Calculator:
  This calculator is based on the steady-state Ernst equation, which is a modification of the Hooghoudt equation that provides the necessary drain spacing to meet the evaporative demand of the crop, rather than the necessary drainage flow.

- The Pump Equations:
  The Pump Sizing calculator is based on a tailored pump flow equation, shown here as Equation 1:

  $$Q(gpm) = 18.9 * Dc * A \qquad [1]$$

  Where Q is the maximum pump flow rate (gpm), D_c is the chosen drainage coefficient, and A is the area draining into the pump (acres). The required sump storage calculator for a fixed speed pump is based on the same theory of pump flow, shown in Equation 2:

  $$Volume\ (f^3) = \frac{2*Q(gpm)}{N} \qquad [2]$$

  Where f^3 is cubic feet and N is the number of cycles per hour.

6. Iowa State University Extension and Outreach has created a thorough financial calculator for both renters and landowners to analyze the return on investment for installation of tile drainage. (http://www.extension.iastate.edu/agdm/wholefarm/html/c2-90.html). It is available as an Excel document (File C-90).

7. The Illinois Drainage Guide (http://wq.illinois.edu/dg/) provides tile drainage information as well as several economic and yield calculators for profitability analysis. It also has numerous calculation programs for all aspects of the drainage design, including outlet ditch capacity, and pump capacity, grades, sizing, and much more. The "General Recommendations" program has a wide variety of options for spacing, pipe size, and drainage coefficients (as well as general guidelines) to optimize design.

8. Professional consultants are also an excellent source of information and expertise. They can help with the design of drainage systems for a specific acreage and can provide land surveys, system designs, and installation of tile.

9. The University of Alberta Faculty of Extension has published a thorough report (http://www1.agric.gov.ab.ca/$Department/deptdocs.nsf/all/bmi10157) detailing agricultural investment analysis completed by Dr. Len Bauer. It is a useful tool to aid in understanding how to evaluate the economics of an agricultural investment and can be readily used for drainage projects as well.

10. The Prairie Climate Resilience Project, completed through the International Institute for Sustainable Development, (https://www.iisd.org/pdf/2007/climate_adaptive_cap.pdf) contains a wide variety of information on the adaptive capacity and vulnerability of various regions of the prairies and the driving factors that dictate it.

11. Advanced Drainage Systems provides a free amortization worksheet, available for download, specifically for tile drainage (http://www.ads-pipe.com/en/documentlisting.asp?documenttypeID=668%A7ionstate=closed&headerstate=off), as well as several design calculators for tile drainage.

12. The Water Rights Act for Manitoba can be accessed online (https://web2.gov.mb.ca/laws/statutes/ccsm/_pdf.php?cap=w80). Additional information can be requested from specific municipalities, as well as from Manitoba Sustainable Development.

Appendix B

Glossary of Terms

Best Management Practice (BMP): Any structure, or non-structure, and/or managerial technique recognized to be the most effective and practical means of accomplishing a task while still allowing the productive use of resources

Blind Inlet/French Drain: A surface water inlet to a subsurface drainpipe in which water enters by percolation through placed granular material and intensive drain pipe, rather than through open-flow conduits. Does not obstruct tillage

Blow-out: High pressure in the piped due to overcapacity causing a portion of the pipe to burst, sometimes blowing a hole to the surface of the ground

Capillary Rise: Height that water will rise by surface tension above a free water surface in the soil, expressed as a length unit of water

Collector Main/Main Drain: A main drain that collects the water from lateral drains throughout the field on one or both sides of the drain pipe

Controlled Drainage: Conserving water in a subsurface drainage system by means of control dams, check drains, or a combination of both to make water available to crop at a favourable depth

Drain: Any closed conduit (perforated pipe or tile) or open channel used for removal of excess ground or surface water

Drainage Coefficient: The physical capacity of water that can be removed from an area within a period of 24 hours. This defines the aggressiveness of the drainage system and is selected based on soil type, crop, and risk-aversion of the producer.

Drain Envelope/Drain Sock: A synthetic material placed around subsurface drainage pipe to restrain the entry of soil particles with drainage water

Evapotranspiration: The combination of water transpired from vegetation and evaporated from the soil and plant surfaces

Field Capacity: Amount of water remaining in the soil when downward water flow caused by gravity is extremely low or non-existent

Fragipan: A dense, natural subsurface layer of hard soil with relatively slow permeability to water, mostly because of its extreme density or compactness rather than its high clay content or cementation

Grade: Slope of a channel or natural ground, often expressed in percent

Gravitational Water: Soil water that moves into, through, or out of the soil under the influence of gravity

Header Main: A main usually parallel to a drainage channel (and often along the field boundary) to capture water from a series of laterals and reduce the number of exit points at the drainage channel

Heavy Soil: Soils with a high clay content; soils requiring higher draught power requirements to plow

Hydraulic Conductivity: The rate at which water moves down through the soil

Hygroscopic Water: Soil water that is held so tightly by soil particles that it is unavailable to plants

Impermeable Layer: A layer of soil that significantly restricts the flow of water. If the permeability of a layer in the soil profile is about 1/10 of that in the soil above it, it can be considered impermeable

Infiltration: The process by which water on the ground surface enters the soil

Ksat: The coefficient of permeability, measured in terms of the rate of water flowing through saturated soil in a given period of time. This is based largely on the physical characteristics of the soil.

Lateral Drain: Secondary subsurface drainpipe that collects excess water from a field and conveys water to a header main/main drain for conveyance to the proper outlet

Outlet: A pipe (usually steel or rigid plastic) that connects a subsurface drainage system to a surface water system without causing erosion

Percolation: Downward movement of water through the soil profile

Permeability: The ease with which gases, liquids, or plant roots penetrate or pass through a layer of soil or porous media

Soil Structure: The arrangement of primary soil particles into secondary particles, units, or peds that make up the soil mass. Soil structure has a major influence on water and air movement, biological activity, root growth, and seedling emergence

Submain: Collects water from lateral pipes and delivers it to the main drain

Appendix C

Conversions

Due to the technology associated with subsurface drainage being built almost entirely around Imperial units, most of the information presented in this report appears in Imperial units. However, a conversion table can be used if metric units are desired.

Table 1: Unit conversions for metric to imperial

To Convert From	To	Multiply By
Centimeters	Inches	2.54
Litres	Cubic Feet	0.035
Hectares	Acres	2.47
Meters	Feet	0.305
Litre per minute	Gallons per minute	0.26
Cubic Meter per Hour	Cubic Feet per hour	35.31
Acre inch/day	Hectare meter/day	0.010

For further information with regards to this report, please contact:
Avery Simundsson at asimundsson@pami.ca

Saskatchewan Operations
Box 1150
2215 – 8th Avenue
Humboldt, SK S0K 2A0
1-800-567-7264

Manitoba Operations
Box 1060
390 River Road
Portage la Prairie, MB R1N 3C5
1-800-561-8378

Corporate Services
Box 1150
2215 – 8th Avenue
Humboldt, SK S0K 2A0
1-800-567-7264