PRAIRIE IRRIGATION SCHEDULING MANUAL

Agriculture and
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Prairie Irrigation Scheduling Manual

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Prairie Irrigation Scheduling Manual.

For more information, you can find us at www.agriculture.canada.ca or call us toll-free at 1-855-773-0241

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FOREWORD

Fresh water is a public resource with many competing users including agriculture. With competition for water increasing from other sectors and with the threat of future droughts and water shortfalls, it is important for producers to be good stewards and make the most of what has been allocated to them.

One of the first and most cost effective steps to improving water use efficiency is to develop a practical irrigation schedule. The key to a successful strategy is to identify the methods and utilize the tools available that work best for each individual's operation from a cost and comfort standpoint to ensure long-term application success.

This manual gives producers the tools for success to develop and implement irrigation scheduling practices into their daily operations. Topics such as soil-water-crop interactions, scheduling methods, available technologies and precision irrigation are covered, with the goal of providing the required knowledge and tools to apply irrigation scheduling practices from basic operations up to complex systems.

This manual builds upon past iterations of the Saskatchewan and Alberta Irrigation Manuals, adopting previously published information while providing important updates due to advances in scheduling technologies and the commercial availablity of precision irrigation.

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INTRODUCTION

After temperature, water is the most limiting factor affecting crop productivity on the Prairies. Furthermore, to maximize crop productivity, water needs to be available at the right time and in the right amount to match crop demands. Nature is rarely so accommodating, especially on the Prairies where up to half the precipitation falls in the winter. Some of that is available for spring growth, but during the growing season, precipitation may be sporadic, can be light enough to evaporate before it reaches the crop, so intense over a short period causing flooding, or so localized that fields only a few kilometres apart will have vastly different rainfall patterns. In addition, the climate in Western Canada historically cycles through extended periods of warm and cool growing seasons and through extended periods of high moisture and drought. When a warm summer coincides with lower than average precipitation, agriculture production is further challenged (Figures 1, 2).

Irrigation is:

The application of water to meet crop water demands that are not met through stored soil moisture and precipitation.

Irrigation water, when applied at the right time and at the right volume, can help to maximize crop yield and quality, protecting against seasonal water variability. Irrigation also opens up opportunities to grow higher value crops.

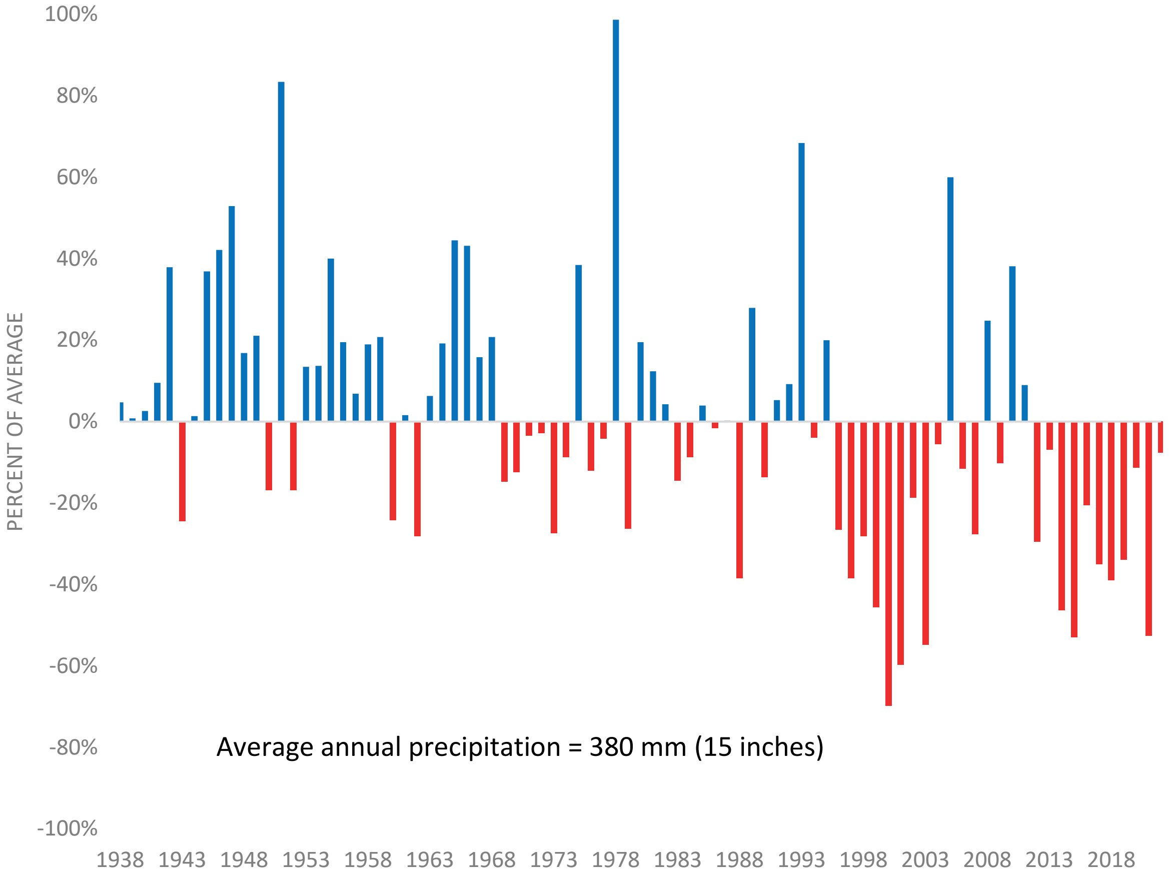


Figure 1. Deviation from average annual precipitation (380.0 mm = 15.0 inches), Lethbridge, Alberta (1938 – 2022) (bars above zero (blue) are years of above average precipitation; bars below zero (red) are years of below average precipitation)(ECCC).

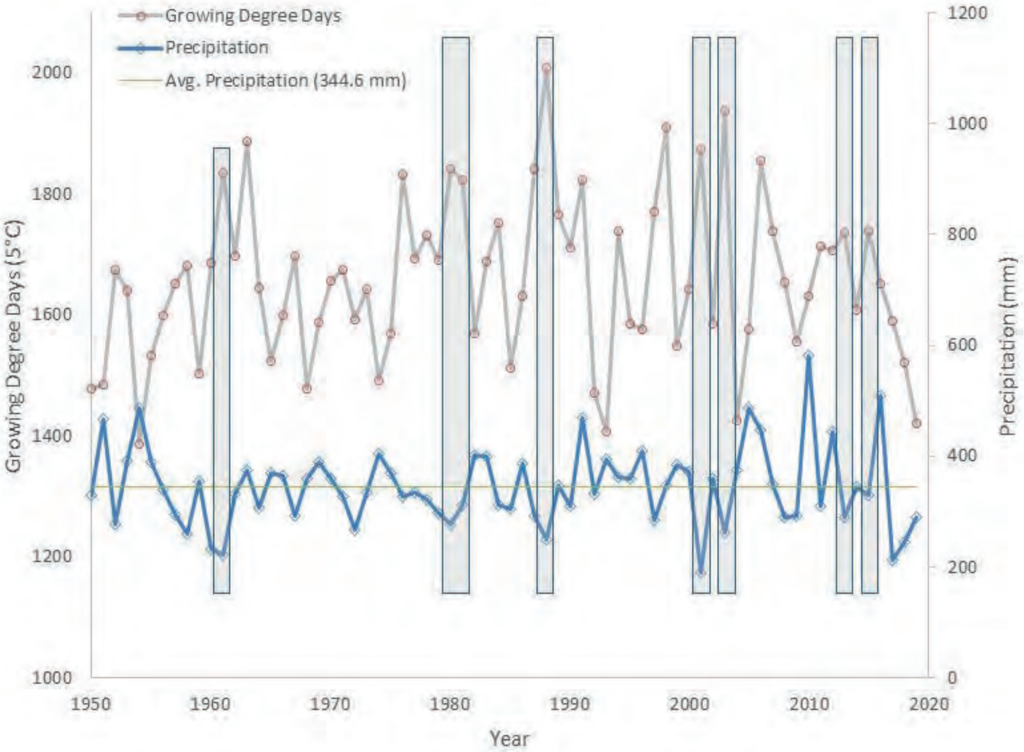


Figure 2. Annual growing degree days (base 5°C) and precipitation for Rosetown, Saskatchewan (1950–2019). Grey bars highlight years when relatively warm growing conditions coincided with below-average annual precipitation (NRCan, ECCC).

In Canada, irrigation on over 1 million hectares (2.5 million acres) of farmland accounts for 80% of national fresh water consumption. Little to none of the irrigation water is returned directly to the fresh water supply (lakes, reservoirs, rivers). And while fresh water is often seen as abundant (Canadian rivers account for 7% of the world's renewable freshwater flow), the critical constraint is geography – 60% of Canada's freshwater drains north away from where the majority of the population (85%), industry and agriculture are situated (i.e. within 300 km of the Canada-USA border). Therefore, use of Canadian fresh water resources must be carefully managed to ensure that a sustainable supply of good quality water, satisfying ecosystem needs (e.g. aquatic and terrestrial wildlife habitats) and fulfills transboundary (inter-provincial and international) water agreements.

SCHEDULING IRRIGATION: NEED TO KNOW

An irrigation system has substantial associated capital (piping, pumps, sprinkler system) and operational (power, maintenance, repair, labour, administration) costs. In order to get the most out of your investment, you will need to maximize efficiencies (i.e. reduce water and power consumption without sacrificing crop yield or quality). This can be accomplished by scheduling irrigation.

Proper irrigation scheduling prevents crop water stress. This means that water should be applied (1) before it is needed (**RIGHT TIME**), (2) only where it is needed (**RIGHT PLACE**), and (3) only as much as is required to top up soil moisture to field capacity (**RIGHT AMOUNT**). This approach can improve profitability:

- Higher crop yield, quality and uniformity
- Lower nutrient loss through reduced leaching
- Better water-use efficiency (less unnecessary water applied)
- Lower operating costs (less unnecessary pumping)

Irrigation scheduling can be complicated by a field's inherent variability in landscape and soil properties, as well as variation in soil fertility. These factors interact with weather conditions leading to differences in crop stage and water needs across a field.

Four key pieces of information are required to schedule irrigation effectively:

- Soil water holding capacity
- Soil moisture status
- Plant water stress indicator(s)
- Crop and growth stage-specific water usage

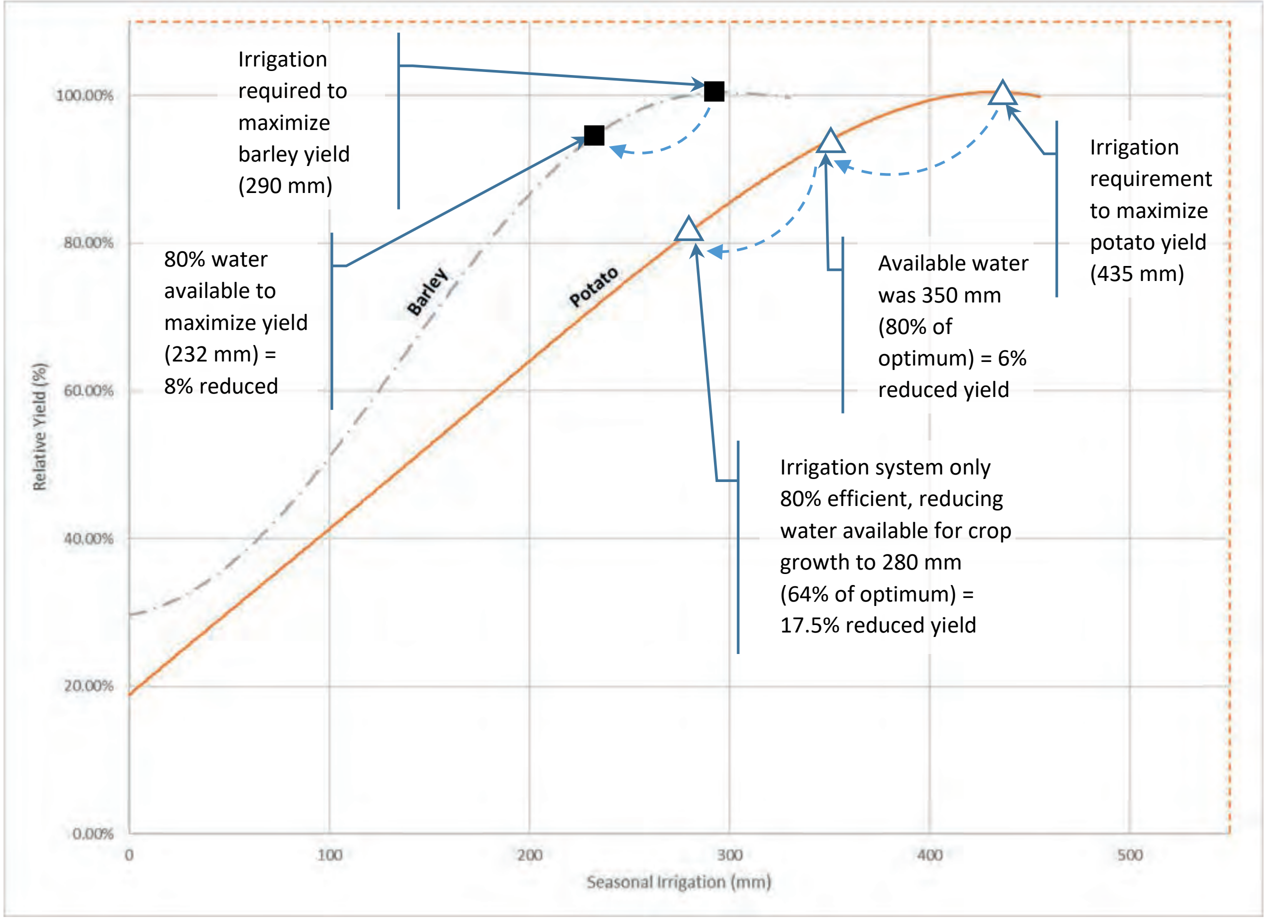
A fifth factor, rainfall, is usually accounted for by measuring soil moisture, or by using a local rain gauge or weather station, or regional data gathered via a government or private network. In scheduling systems that use complex models, rainfall is included to estimate soil moisture.

The simplest scheme to scheduling is to irrigate the entire field according to the area in the field with the greatest water need. This approach ensures that little to none of the crop is under underwatered; however, it may result in parts of the field being overwatered. Water need may be determined by visual cues (e.g. wilting, poor vigor) or by checking root zone moisture with a spade. At the other end of the spectrum, sophisticated systems may employ a fleet of soil moisture sensors, remote imagery (e.g. satellite, drones) and controllable irrigation zones (i.e. irrigate only the parts of the field where the crop needs water). This approach requires more management but, if done correctly, all plants receive the right amount of water leading to optimized crop yield, quality and uniformity as well as reduced energy (pumping) costs and lower water-use.

The relationship between water and yield

A primary reason to schedule irrigation according to crop needs is to optimize yield for the irrigation water you have available (i.e. you may not always have all the water you require to maximize yield). This is usually defined by terms such as *water use efficiency* or *water productivity*. In agriculture, these two terms are often used interchangeably. Historically, *water use efficiency* is used by engineers to describe the efficiency of the overall system (conveyance, irrigation, management, crop), whereas *water productivity* is used by agrologists to define the efficiency of the cropping system. Regardless, both refer to the amount of water required to produce each unit of crop. As an irrigator, you strive to maximize productivity and profitability.

When a crop is under stress (nutrient deficiency, pressure from pests, severe heat, drought), the ultimate impact is reduced yield (biomass, grain, fruit). In the case of water stress, plants can suffer from too much (flood) or too little (drought) water. Water-Yield curves show how crop yield is affected by seasonal water availability. These curves do not account for irrigation timing, but they show the impact that insufficient or excess water (total seasonal) has on crop yield (Figure 3; Appendix D: Examples 1, 2: page 77).



Irrigation required to maximize barley yield (290 mm)

80% water available to maximize yield (232 mm) = 8% reduced

Irrigation requirement to maximize potato yield (435 mm)

Available water was 350 mm (80% of optimum) = 6% reduced yield

Irrigation system only 80% efficient, reducing water available for crop growth to 280 mm (64% of optimum) = 17.5% reduced yield

Figure 3. Modelled Water-Yield curves for irrigated barley and potato (Model output based on 2018 weather data from Outlook, Saskatchewan. Analysis completed using FAO AquaCrop 6.1).

Water-Yield curves show the relationship for an ideal system, where reduced yield is due to insufficient water applied to meet crop demands (= crop stress). In the real world, not all water applied via irrigation reaches the crop because of water lost to inefficient design, components or management of the system (e.g. sprinkler evaporation, drift, runoff, deep drainage, crop stress). These inefficiencies along with poor scheduling can have a compounding effect on crop yield. To account for system inefficiencies, additional irrigation water is required to achieve the desired yield response (Figure 4).

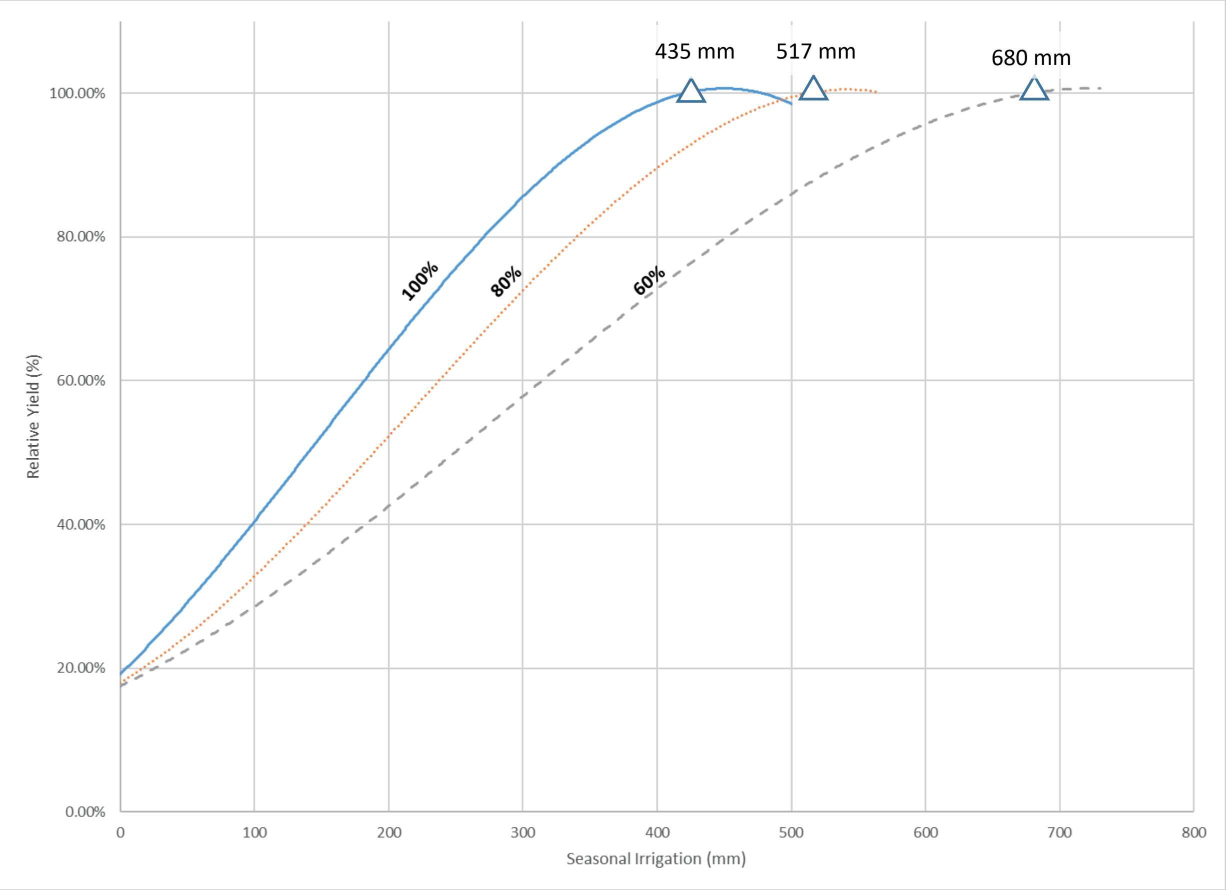


Figure 4. Modelled Water-Yield curves for irrigated potato under different system efficiencies (Model output based on 2018 weather data from Outlook, Saskatchewan. Analysis completed using FAO AquaCrop 6.1).

Soil-Crop-Water Interactions

To effectively schedule their irrigation, producers need to understand the physical characteristics of their soil. Soil physical characteristics determine the interaction between the soil and water and vary with inherent soil properties such as texture.

Soil is constructed of three different phases, solid, liquid, and gaseous. Mineral particles and organic materials create the solid phase and occupy 30-60% of the total soil volume. Air and water are located in the pore space between the solid soil particles and take up the remainder of the soil volume, which defines total porosity. The texture of the soil dictates the size, shape, and distribution of the soil pores. The movement and retention of water in the soil is dependent on this soil characteristic.

The amount of available water for crop growth in soils is found in the pore-space and depends on the soil texture (e.g. sand vs. clay), compaction and organic matter levels. Soil texture is defined by the percent of sand, silt and clay (Figure 5). In addition, soil characteristics can vary significantly across a field, further complicating matters.

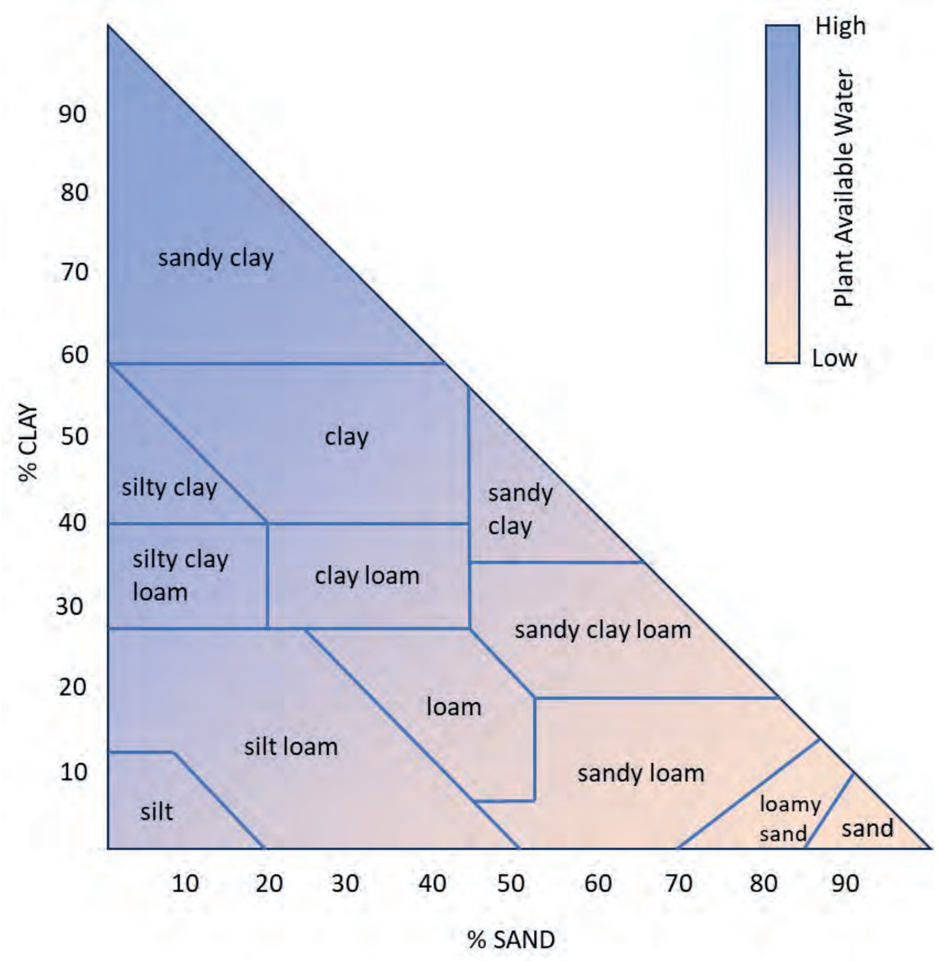


Figure 5. Soil textural triangle following Canadian system of soil classification. Adopted from: © Asim Biswas is licensed under a CC BY (Attribution) license

Take home message:
Soil texture is a key factor in irrigation scheduling as it affects how much water a soil can store and the fraction of that stored water that is available for crop growth.

Mapping out your soils

Irrigation certification documents or published soil survey maps can be used as an initial source of information about soil properties, such as texture, at a given location. During irrigation certification/licensing or initial development process, soil mapping may be required, by provincial regulators, to determine if the land is suitable for irrigation; these maps can be a valuable source of information for irrigation management. Most provinces provide soil survey maps by request or using online portals:

Alberta – https://soil.agric.gov.ab.ca/agrasidviewer/
Saskatchewan – https://sksis.ca/
Manitoba – https://www.gov.mb.ca/agriculture/soil/soil-survey/index.html

Soil survey is an inventory of the properties of the soil (such as texture, internal drainage, parent material, depth to groundwater, topography, degree of erosion, stoniness, pH, and salinity) and their spatial distribution over a landscape. Soil types are identified by unique names which have characteristics particular to them (e.g. Bradwell [abbreviated BR] is a very fine sandy loam in the dark brown soil zone). There are two major cautions regarding the limitations and suitability of soil survey maps: polygon delineation and scale.

The boundaries of soil map polygons imply that there are abrupt changes in soil type across the landscape; in reality, soil varies continuously, grading from one type to the next. The lines on a map are thus only approximations of where these transitions occur (Figure 6).

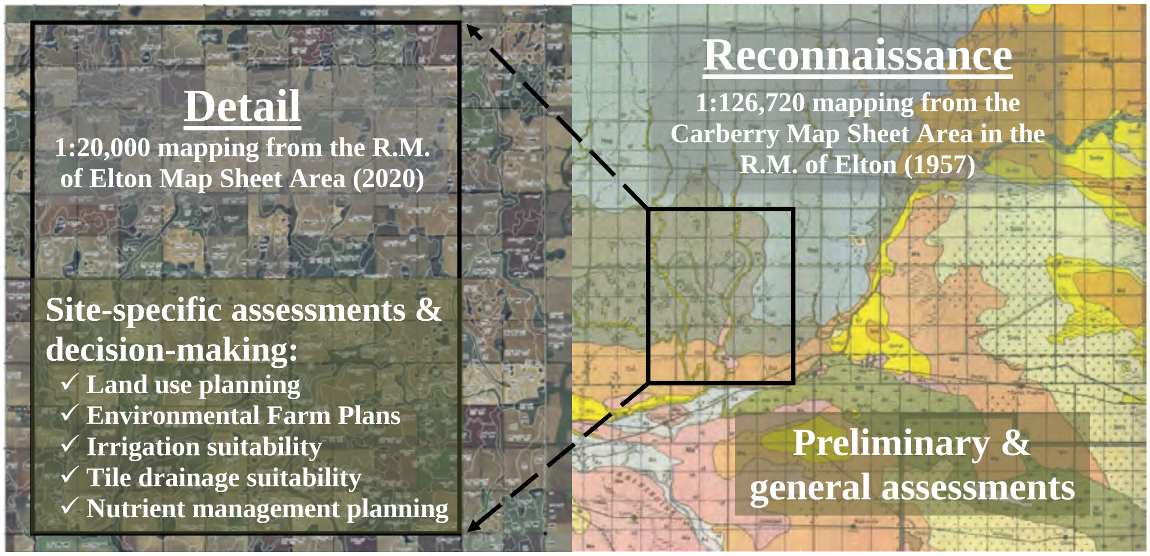


Figure 6. Difference in map scale for general assessment and irrigation suitability (Timmerman 2023)

Map scale determines the reliability of the information portrayed on a map and its suitability for a particular purpose. Small-scale or reconnaissance maps (ex. 1:125000) offer only a broad picture of the dominate types and distribution of soils that occur over a relatively large area. This inherent limitation stems from the small number of site inspections carried out on each section of land (approximately six samples per 260 Ha (640 acres)) in a reconnaissance survey. These maps are therefore best suited for obtaining only a preliminary indication of general type of soil could be found at a given location. By contrast, large-scale or detailed maps can have sufficient resolution for farm and field-level assessment and management due to the larger number of sample over each section of land. When detailed soil survey data is needed but unavailable, on-farm soil surveys can be conducted, either for a specific purpose, such as irrigation suitability, or for overall agronomy and land management.

To increase the resolution of soils information for a field, collect additional soil samples throughout the field. The number of sample locations will depend on field variability, the required level of detail and your budget. As field variability increases so does the number of soil samples required, which in turn increases the time and cost.

Soil samples can be collected using a number of commercially available tools. Common tools include a Backsaver soil core sampler (Figure 7) and a Dutch auger. Other tools can range from a simple spade to a truck-mounted hydraulic soil punch (Figure 8).

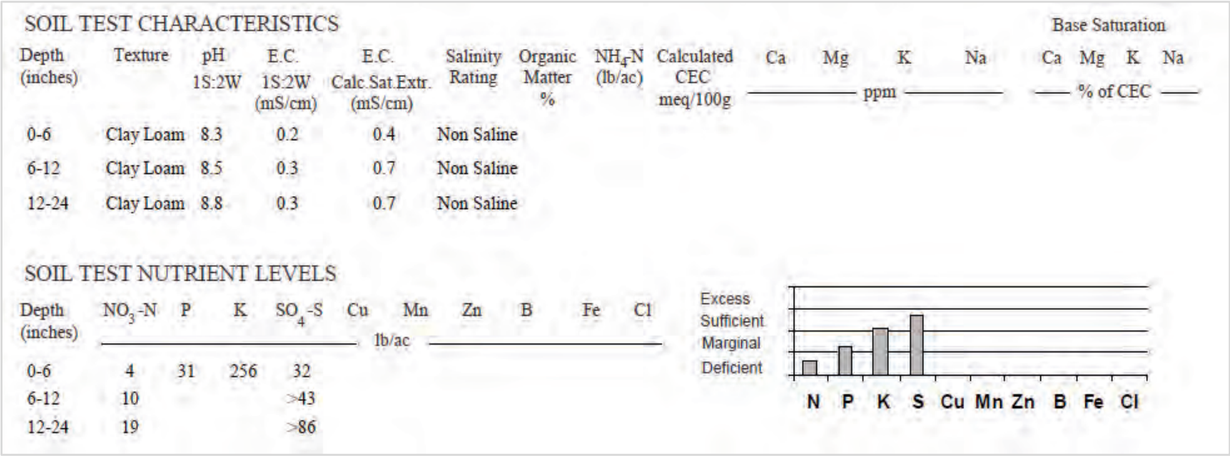
Figure 7. Soil sample collection using a JMC Backsaver soil core sampler.

Figure 8. Hydraulic soil sampler/coring machine mounted to tractor.

When sampling soils for textural analysis, it is important to:

i) Take a sample to a depth that covers the bulk of the crop rooting zone (0.5–1.0 metre / 1.5–3.0 feet).
ii) Sample throughout the field (gridded or targeted) based on field variability.
iii) Sample by depth (e.g. 0–15, 15–30, 30–60 centimetres / 0–6, 6–12, 12–24 inches) or horizon (change in materials) for testing and reference.
iv) Take a large enough sample, as required by a testing lab or to analyse using the hand feel method (Appendix A: Figure A1, page 65).

You can determine the soil texture yourself using the hand-feel method (Appendix A: Figure A1, page 65) or contract an agrologist to conduct the on-site analysis for you (Figure 9). In addition, soils information may be included as part of the Provincial irrigation development and approval processes. Contact your provincial agriculture department to inquire about published reports (see Irrigation Scheduling Assistance, page 64).



SOIL TEST CHARACTERISTICS

Depth (inches)	Texture	pH 1S:2W	E.C. 1S:2W (mS/cm)	E.C. Calc Sat Extr. (mS/cm)	Salinity Rating	Organic Matter %	NH_4-N (lb/ac)	Calculated CEC meq/100g	Ca	Mg	K	Na	Base Saturation Ca	Mg	K	Na
									ppm				% of CEC			
0-6	Clay Loam	8.3	0.2	0.4	Non Saline											
6-12	Clay Loam	8.5	0.3	0.7	Non Saline											
12-24	Clay Loam	8.8	0.3	0.7	Non Saline											

SOIL TEST NUTRIENT LEVELS

Depth (inches)	NO_3-N	P	K	SO_4-S	Cu	Mn	Zn	B	Fe	Cl
	lb/ac									
0-6	4	31	256	32						
6-12	10			>43						
12-24	19			>86						

Figure 9. Sample soil report showing inherent soil characteristics (e.g. texture) and dynamic variables (e.g nutrient levels).

Take home message:
Soil sampling is the only dependable method to determine the soil texture of your field and is the first step in developing a successful irrigation scheduling management plan.

Soil Classification for Irrigation

Provincial governments generally set a minimum standard for soil suitability to be approved for irrigation development. Soil suitability looks at physical and chemical characteristics that may result in further degradation under irrigation or are not considered compatible with irrigation.

During the irrigation development process, provincial regulators may conduct a soil survey, or refer to published surveys, to evaluate a number of characteristics, usually based on laboratory analysis:

i) Salinity – soil salinity is defined as the accumulation of soluble salts within the root zone. These salts increase the osmotic pressure on plants, making it more difficult to extract water from the soil and increase plant stress. Irrigation has the potential to increase salinity through poor irrigation management, raising the water table or introducing additional salts by irrigating with poor quality water. Salinity is evaluated by measuring the electrical conductivity (EC) of a saturated paste created from a soil sample. An EC value less than 4 dS/m is considered acceptable, values above this level are considered moderately to severely saline.

ii) Sodicity – sodic soils are associated with high concentrations of exchangeable sodium in the profile, which can hamper plant growth (sodium toxicity) and degrade soil structure. High sodium soils exhibit poor soil structure, at its most severe described as *columnar* or *prismatic*, with a density that impedes water infiltration and root. Sodicity is quantified by calculating the Sodium Adsorption Ratio (SAR) of a saturated paste. An SAR value below 9 is considered acceptable.

iii) Drainage – soils with poor drainage are usually not well suited for irrigation, as indicated by low infiltration rate and saturated hydraulic conductivity. This may result in high rates of ponding and/or runoff. Soils with low permeability layers are susceptible to becoming saturated under irrigation, resulting in insufficient aeration for healthy plant roots and poor crop productivity.

Other soil characteristics are taken into account when approving a parcel of land for irrigation. The scrutiny on soils is to ensure that water resources are used sustainably. Irrigators may receive conditional approval to irrigate if a remediation plan is implemented. This usually involves improving the drainage within the field (commonly sub-surface tile drainage) and the use of soil amendments or implementation of a leaching plan to reclaim the soil.

Irrigation Water Classification

The quality of water used for irrigation is an important factor; it can have an impact on both plant and soil health. It is essential to match the quality of the irrigation water with the soil it is to be applied, therefore avoiding crop failure and potentially long-term degradation to the soil.

Plant health concerns relating to irrigation water quality are mainly around toxicity effects from dissolved minerals or chemicals and biological contaminants. Soil health concerns from irrigation water focus on the breakdown of soil structure due to accumulation of sodium-based salts and salinization.

Recommended guidelines for major ions, heavy and trace metal ions, biological parameters and pesticides have been developed by the Canadian Council of Ministers of the Environment (Appendix A: Table A1, page 66). The water quality parameters of greatest concern for soil health are sodium adsorption ratio (SAR) and salinity, defined by electrical conductivity (EC) or total dissolved solids (TDS).

Sodium Adsorption Ratio

Excess sodium in irrigation water relative to calcium and magnesium or relative to the total salt content can adversely affect soil structure and reduce the rate at which water moves into and through the soil (permeability, infiltration) as well as reduce soil aeration. When calcium is the predominant cation, the soil tends to have a granular structure that is easily worked and permeable. Sodium can adversely affect the physical condition of soil, so that when the soil is wet it disperses clay particles or "runs together" and becomes very tight and limits water movement. When adsorbed sodium exceeds 10 to 15% of the total cations the clay particles are dispersed, resulting in a soil that becomes puddled when wet, lowering permeability and forming a hard impermeable crust when dry. The magnitude of the effect of excess sodium can be related to the relative proportions of sodium ions and calcium plus magnesium ions in the irrigation water, defined by SAR (Appendix C: Equation 1, page 74).

Salinity

Salinity of water is measured in either electrical conductivity (EC) or total dissolved solids (TDS). EC is reported in milliSiemens per centimeter (mS/cm), while TDS is reported in milligrams per litre (mg/l). Generally, 1 mS/cm of EC is equivalent to 640 mg/l of TDS, but can be as high as 1,000 mg/l. All irrigation water adds salt to the soil. Water with high ECs will salinize the soil and require irrigation beyond crop demand, also referred to as leaching requirement or leaching fraction.

Leaching fraction

The amount of water required to leach excess salts from the soil, known as leaching requirement, is dependent on the salt content of the irrigation water and the average soil salinity tolerated by the crops grown (Appendix A: Table A2, page 67). Knowing the quality of your irrigation water and the tolerance of the crops expected to be irrigated, you can calculate your leaching requirement and the amount of water to apply based on local evapotranspiration estimates (Appendix D: Example 3: page 77). The key to maintaining acceptable salt levels in the soil is to apply slightly more water than is being lost to the atmosphere through evaporation and transpiration, this will help leach salts downward below the root zone.

Highly utilized irrigation water supplies are frequently tested for irrigation suitability. Private irrigators with localized water sources (wells, ponds) should have their irrigation water supply tested periodically as quality can change over time.

Other factors associated with irrigation water quality can include pathogen content, specifically when irrigating horticultural plants, which may require a pre-treatment, and algae content, which can result in plugged pumps and sprinkler nozzles. This issue is usually addressed with a water intake screen or filtration system where the system is prone to plugging (micro-irrigation, drip irrigation).

Each province across the prairies will have their own specific requirements, monitoring and guidelines for the use of water for irrigation. To access this information please refer to the following websites for their most up to date information:

Alberta
https://www.alberta.ca/irrigation-strategy

Manitoba
https://www.gov.mb.ca/sd/water/water-rights/water-use/index.html

Saskatchewan
https://www.saskatchewan.ca/business/agriculture-natural-resources-and-industry/agribusiness-farmers-and-ranchers/crops-and-irrigation/irrigation

Soil-water characteristics

Understanding the following soil-water characteristics is key to developing and implementing an irrigation schedule:

- **Field capacity**: The maximum amount of water a soil can hold against gravity. Also known as water holding capacity.
- **Maximum allowed depletion**: Soil moisture level that triggers irrigation, a level set above the permanent wilting point.
- **Permanent wilting point**: The amount of water in soil below which will lead to permanent plant damage.
- **Plant-available water**: The amount of water between field capacity and permanent wilting point (= Field capacity − Permanent wilting point).
- **Saturation**: The maximum amount of water a soil can hold when all the pore spaces are filled.
- **Water holding capacity:** See Field Capacity.

(See Box: Soil-crop-water terms defined, page 14).

In general, the larger the soil particle (e.g. sand), the less plant-available water there is at field capacity. Conversely, fine textured soils have more plant-available water at field capacity (Appendix A: Figure A2, page 67). However, fine textured soils are also prone to waterlogging (due to poor drainage) and compaction, whereas coarse textured soils tend to be free from these issues.

Irrigation schedules are designed to maintain soil moisture levels in the 'safe zone.' Irrigation is typically triggered at a soil moisture level defined as the ***maximum allowed depletion*** within the crop's root zone (Appendix D: Example 4: page 78). The maximum allowed depletion is usually set at 50%, or greater, of plant available water (i.e. well above the permanent wilting point) to reduce the incidence of plant stress due to low moisture availability (Figure 10; Table A2).

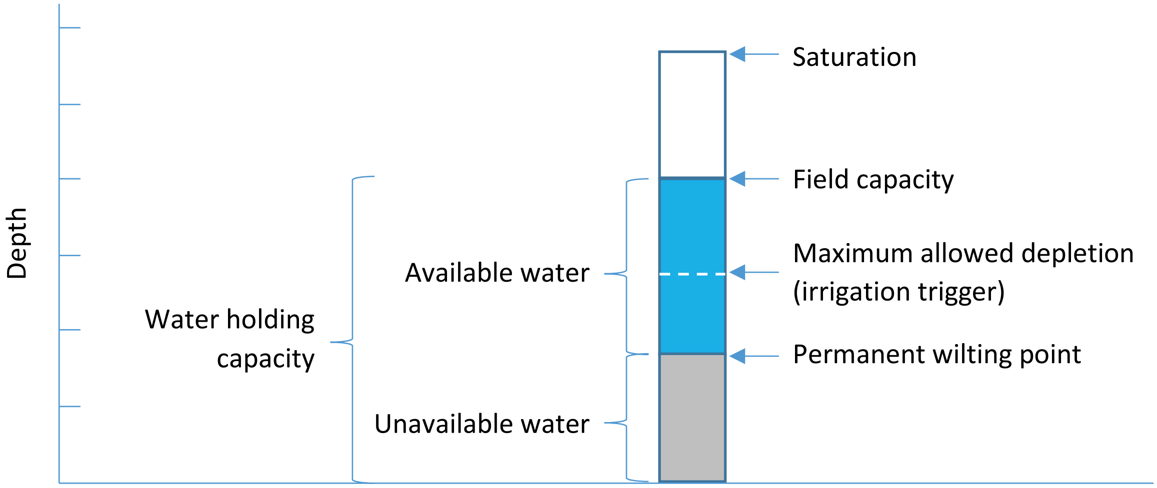


Figure 10. Illustration of water relations of a general soil in terms plant-available and unavailable water.

Take home message:
Once you have set the maximum allowed depletion and know how the crop's rooting depth changes throughout the growing season, you can calculate the amount of water that needs to be maintained in the soil. This information is the basis for developing an irrigation schedule.

Soil-crop-water terms defined

Capillary water: see **Plant-available water.**

Field capacity: soil moisture content when excess moisture has been drained from soil profile due to gravity, typically measured two days after irrigation. Also known as Water holding capacity.

Maximum allowed depletion: in irrigation scheduling, soil moisture should be managed/maintained at a level above permanent wilting point. Plants begin to experience stress as the water level approaches permanent wilting point. In practice, maximum allowed depletion is generally set at 50% of plant-available water for most crops (NRCS 2005).

Permanent wilting point: plants remove water from the soil via suction (a negative pressure). When the water level falls below a plant's ability to extract water via suction, the plant becomes stressed and, if not corrected immediately, permanent damage (permanent wilting, eventually death) occurs.

Plant-available water: volume of water between field capacity and permanent wilting point (also known as Capillary water).

Pore space: soil volume that is not occupied by solid material. The pore space is filled by a combination of air and water. The average pore size is related to the physical soil characteristics such as particle size (large particles = large pore spaces), organic matter composition and compaction [for the purpose of irrigation scheduling, assume no compaction].

Saturation: soil moisture content where all pore space is filled with water. No air is present in the soil and if water is not drained, crop damage will occur.

Unavailable water: volume of water that is tightly bound to soil particles (hygroscopic water) which requires more suction to remove than a plant is capable of producing.

Water holding capacity: see **Field capacity.**

Crop water requirements

A crop's daily and total seasonal irrigation requirement depends on crop type, selected variety, development stage, crop condition, nutrient management and weather.

On a daily basis, water use increases as the crop grows and matures. For annual crops, the daily crop water-use rate peaks during the critical periods of flowering and seed set (Figure 11). For perennial crops, the rate peaks after cutting/grazing. Seasonal crop water-use (also known as *seasonal evapotranspiration*) is the sum of daily amounts of water, over the growing season, that is consumed by the crop for growth and cooling.

Daily water use charts are produced regionally for major crops, calculated using local climatic conditions (assumes soil moisture is non-limiting). The water-use is shown as a curve as daily water-use changes over the growing season as the crop progresses through its development stages. Daily water-use is also heavily influenced by the weather (e.g. temperature, wind speed, humidity, cloud cover, light intensity) and can range widely over the short term (i.e. over days). The range is shown on crop water-use charts as high, average and low water-use curves (Figure 11).

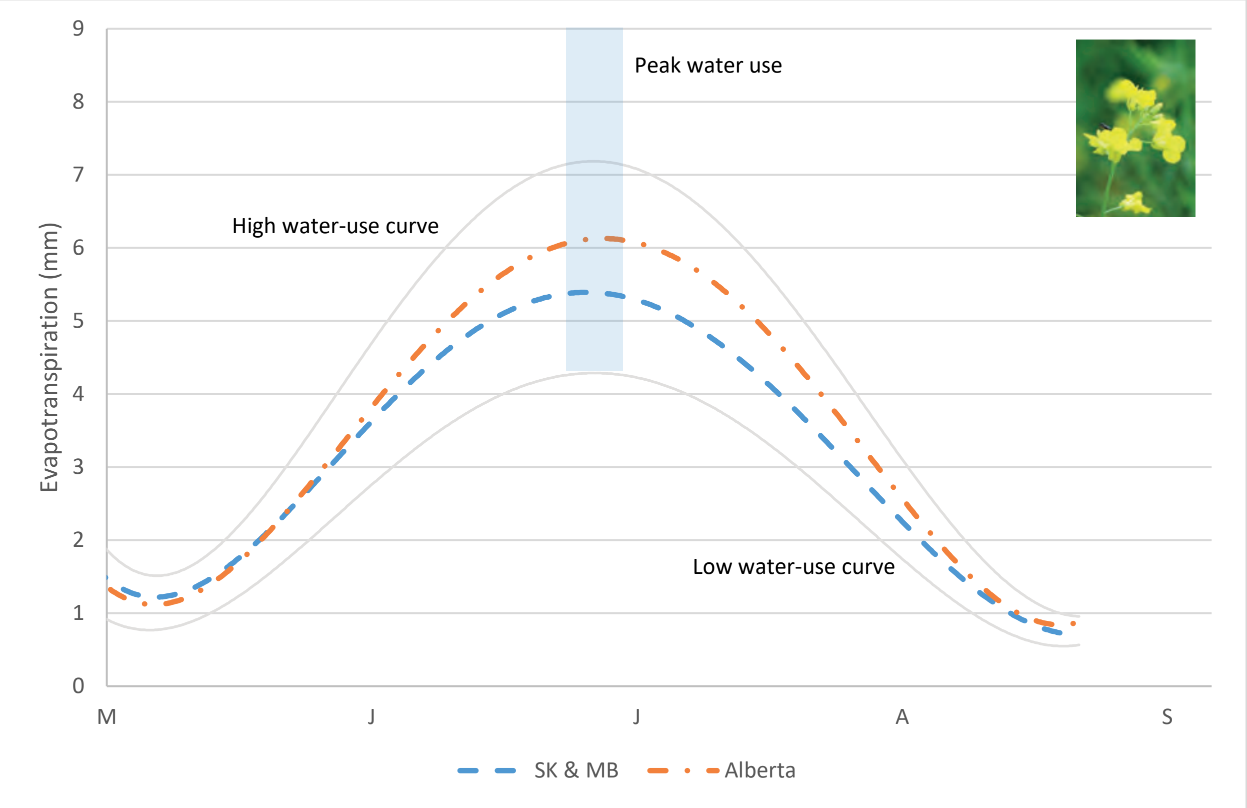


Figure 11. Daily water-use for CANOLA, based on climatic data from 2014–2023 (Outlook, SK., Carberry, MB., and Lethbridge AB) (Additional crop specific water-use curves are available in Appendix B.)

In addition to understanding how water use changes with crop stage, rooting depth is another important factor in determining how much water to apply. As the crop develops throughout the growing season, the active root depth increases (Figure 12; Appendix A: Table A4: page 68). This means that as the root zone increases, the plant has access to a greater volume of soil and potentially greater water resources. At the same time, it means that you need to increase the soil depth you are managing to ensure you are providing enough water to wet the entire root zone. Note that crops draw approximately 70% of their water from the top 50% of the active root zone. Therefore, do not allow this portion to dry out, even if there is adequate water deeper down (Figure 12).

A well-designed irrigation system should be able to keep up with the crop’s water demand, with a safety margin to account for some irrigation system downtime and inefficiency. The amount of water that can be applied during a single event, it should be noted, is limited by the system design. In addition, the time required to apply irrigation is often significant enough that it should be taken into account when irrigating (irrigation applications should be scheduled to account for the application time).

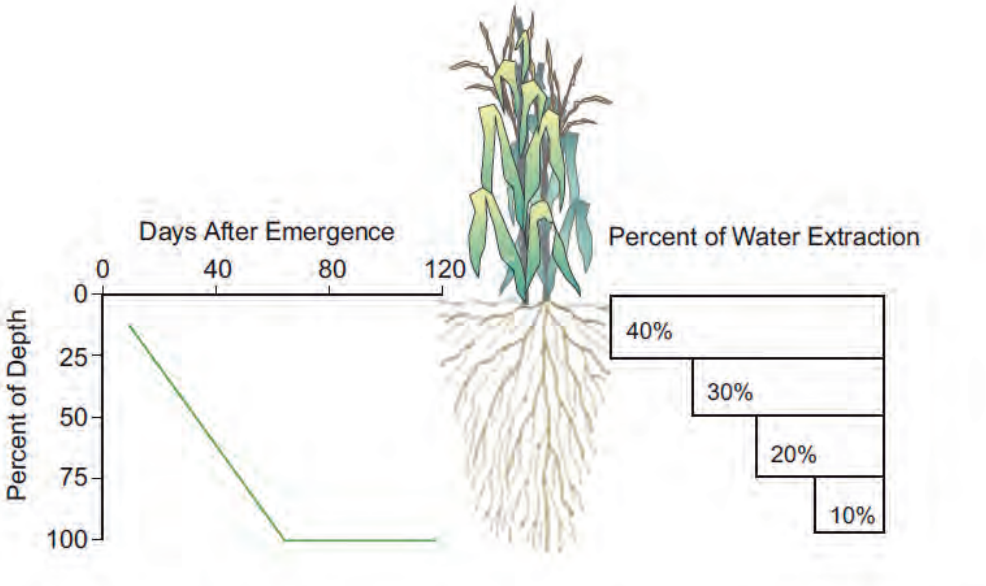


Figure 12. Effective root zone soil water extraction and plant root development (used with permission from University of Lincoln-Nebraska)

Application rate charts are available from the manufacturer and should be considered when determining the irrigation depth to apply as the crop will continue to use water during the time it takes for the pivot make its revolution. This factor is often missed in irrigation scheduling. Appendix A: Table A6 (page 69) is an example of the irrigation depth applied by a low-pressure centre irrigation pivot for various flow rates and circle times (Appendix D: Example 5: page 78).

In addition, system efficiency varies depending on the irrigation method. For example a high pressure centre pivot may only be 80% efficient whereas a trickle irrigation system is 90% efficient or higher. Converting to a higher efficient irrigation system means more water is applied to the soil over the same amount of time (Appendix D: Example 6: page 79).

Irrigation Systems and Impact on Schedules

Currently, irrigation system types and methods vary widely in Canada. They range from the antiquated method of flooding a field with a canal or pipe system, to the more advanced variable rate irrigation system and subsurface drip technology. It is important to develop an irrigation schedule that takes into account the irrigation system and method that will be implemented on your farm.

Irrigation system components (pump, pipeline, irrigator) are generally sized to supply enough water to meet peak demand of the crop types in your region. As a result, during peak growing periods and under hot and dry conditions, your irrigation system may need to run continuously in order to apply enough water to meet crop water demand. A proper early-season irrigation schedule will help you maintain soil moisture reserves to provide some flexibility during peak growing periods.

Irrigation system type affects irrigation scheduling in two important ways:

i) application time and,
ii) application efficiency.

Application time – Mechanical move systems (pivot, lateral, wheel move, etc.) require time to advance across a field as they apply water. Irrigation systems can only apply water at a rate for which they were designed based on the pumping capacity and travel speed, as the case with mechanical move. It is important to have your irrigation system apply water to match your soils infiltration rate, excessive application rates can lead to ponding/runoff and reduced application efficiency. Additionally, some irrigation systems (lateral move, wheel move) require downtime to move between irrigation locations or change pipeline connections, it is important that this downtime (not irrigating) be taken into account when determining the irrigation schedule. This may require additional water to be applied, as to not fall behind on irrigation requirements.

Application efficiency – An irrigation systems application efficiency is determined by the amount of water that will get to the soil and be available to the crop. Application efficiencies vary significantly depending on the type of irrigation system being utilized (Table A5). Water can be lost through run-off, deep drainage, evaporation and wind drift. As such, the irrigator must apply additional water to account for anticipated losses to the environment.

Take home message:

1. Apply only what your crop needs

Irrigation depth is determined by either measuring soil moisture content or by estimating a crop's water use since the last irrigation. Each irrigation application should raise the soil moisture content to field capacity.

2. Know how deep to go

The depth to which soil moisture should be managed (irrigate) fluctuates throughout the season as the crop develops and rooting depth increases. For example, early in the growing season the rooting depth of a crop may be 7.5–15 centimetres (3–6 inches), compared to the end of the growing season when the same crop may have a rooting depth of 90 centimetres (3 feet).

3. Design for your thirstiest crop

A multi-year crop rotation plan is the norm for Prairie crop production. The amount that an irrigation system is capable of delivering over a 24-hour period must satisfy the thirstiest crop in your rotation at peak water-use. During this critical period, continuous irrigation may be necessary to keep up with crop water demand (Figure 11).

4. It takes time to irrigate

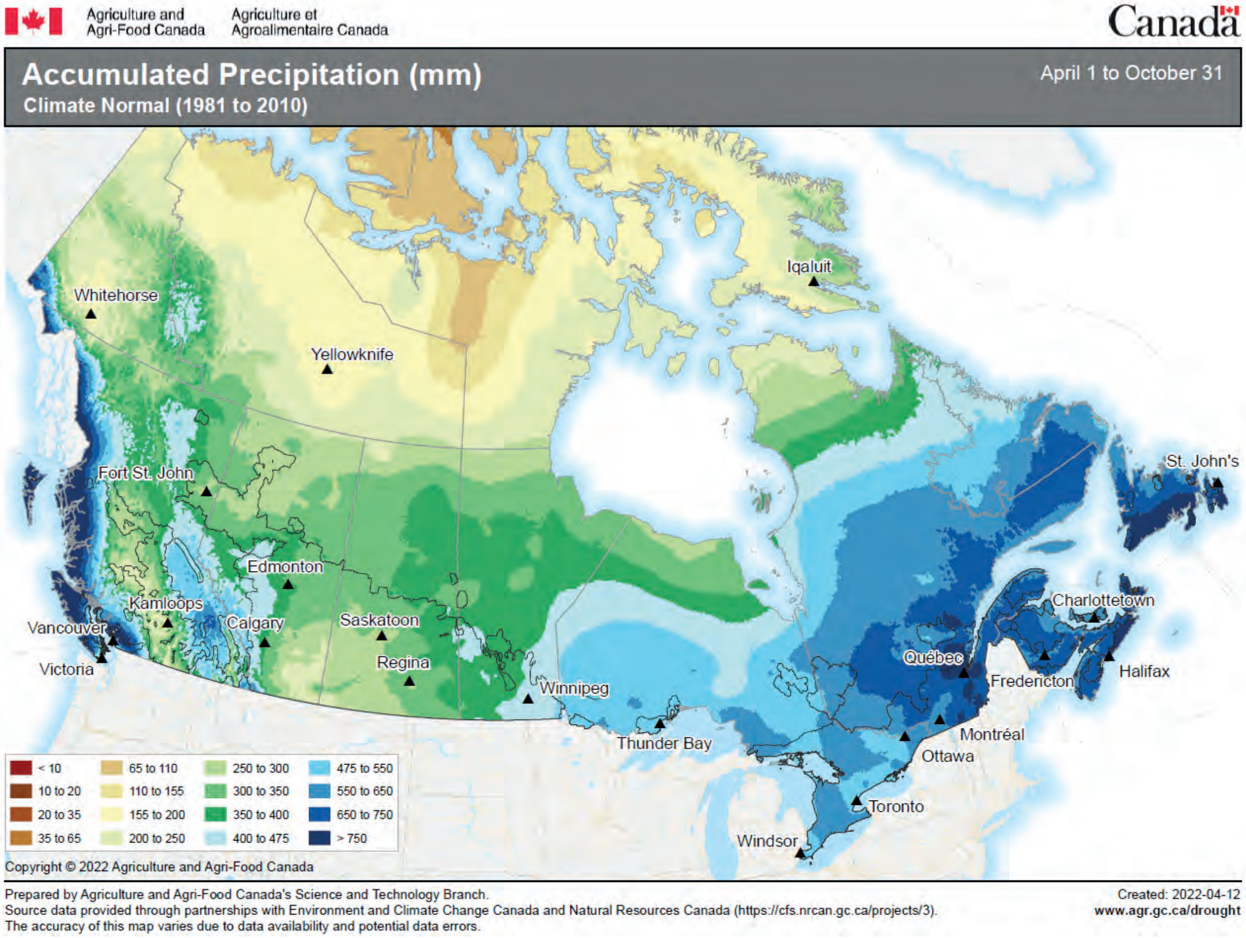
Take into account how long it takes for the irrigation system to deliver the required amount of water and downtime associated with travel and possible maintenance/repair.

5. System efficiencies impacts how much water reaches the soil

Regional Differences

Precipitation and evaporation patterns can vary significantly across the Prairie Provinces, sculpting the region's unique hydrological landscape. The majority of irrigation in Canada occurs over the region referred to as the Palliser Triangle. The Palliser Triangle is a semi-arid region of approximately 1 million acres, covering a vast majority of southern Alberta and Saskatchewan and a portion of south west Manitoba. This region is characterized by lower overall precipitation, with a considerable portion falling as snow during the colder months. Evaporation rates are influenced by factors like temperature, wind, humidity, and water body coverage. In general, the cold winters and relatively short growing seasons of the Prairie Provinces contribute to varying evaporation rates throughout the region. These intricate interactions between geography, climate, and local weather patterns result in a tapestry of precipitation and evaporation regimes that define the water availability and ecosystems of the Prairie Provinces.

The climate and subsequent weather patterns vary significantly across the region; growing season precipitation (Figure 13) is generally insufficient to meet crop water demands across most of the prairies, resulting in reliance on recharge from snowmelt or irrigation. Irrigation requirements vary significantly, with southern Alberta being more heavily reliant on irrigation for overall crop production compared to southern Manitoba where irrigation enables crop diversification (e.g. horticulture) and provides productivity assurances for higher-value crops. Climate change is expected to increase the variability of seasonal precipitation (flooding and droughts), demanding irrigation schedules become more adaptive on a year over year basis.


Accumulated Precipitation (mm)
Climate Normal (1981 to 2010)
April 1 to October 31

Copyright © 2022 Agriculture and Agri-Food Canada

Prepared by Agriculture and Agri-Food Canada's Science and Technology Branch.
Source data provided through partnerships with Environment and Climate Change Canada and Natural Resources Canada (https://cfs.nrcan.gc.ca/projects/3).
The accuracy of this map varies due to data availability and potential data errors.
Created: 2022-04-12
www.agr.gc.ca/drought

Figure 13. Historical Growing Season Accumulated Precipitation for Canada, 1981 to 2010 (Government of Canada, 2022)

Compounding the differences in regional climates and precipitation is the variation in soils where agriculture takes place across the Prairie Provinces (Figure 14). There are a variety of soils across the prairie region, but within the agricultural extents, the dominate soils consist of the Brown, Dark Brown and Black Chernozemic soils; these colours vary with organic matter content as a result of moisture conditions since the last glaciation. Traditionally, irrigation has taken place in the courser textured, Brown soils zone, but with increased variability in precipitation patterns and increased production of higher-value crops (e.g. horticulture), irrigation has expanded across most of the agricultural extents. Irrigation schedules developed across the region will vary and should be based on local climates, soils and cropping practices.

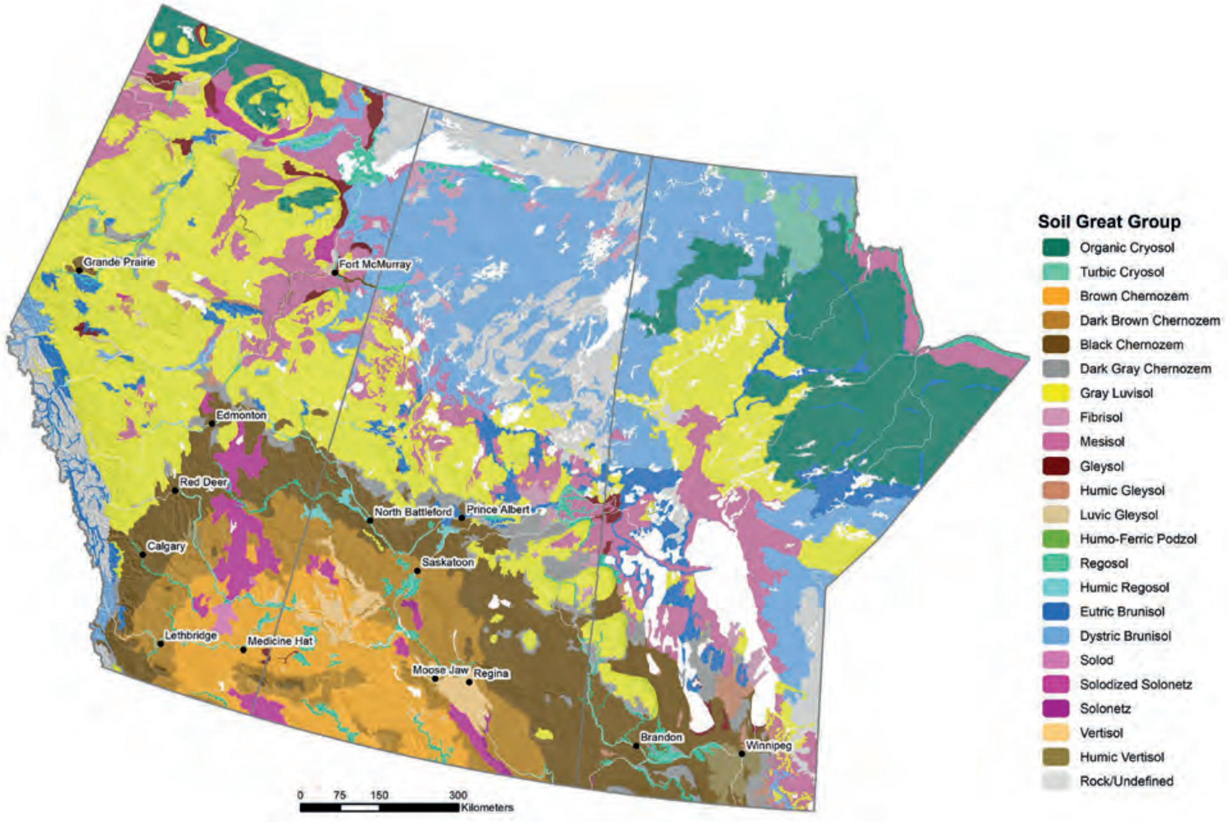


Figure 14. Map of soil great groups for the Prairie Provinces (D. Cerkowniak, Agriculture and Agri-Food Canada).

PUTTING IT TOGETHER: IRRIGATION SCHEDULES

In general, irrigation scheduling manages both the TIMING and DEPTH of irrigation events throughout the growing season. To simplify management, schedules are generally based on fixing one of the two variables (TIMING or DEPTH) and measuring or calculating the other variable.

i) **TIMING**: With a fixed time between irrigation events, the amount of water applied will vary as a result of daily demand. Fixed time schedules are useful in canal-based systems where water is ordered in advanced.
ii) **DEPTH** (or depletion): When applying a fixed water depth with each irrigation event, the time between events varies as a result of crop use or demand. Fixed depth schedules simplify system operation (i.e. fixed pivot settings = same amount of water is applied at each irrigation event).

Regardless of whether your irrigation scheduling system is based on a fixed time or fixed depth, irrigation water requirements need to be either monitored or estimated. In general, there are three approaches to determine irrigation water requirements.

i) **Soil-based**: soil moisture is measured or estimated.
ii) **Weather-based**: estimates water-use of the crop based on weather data (temperature, humidity, wind, solar radiation, etc.).
iii) **Plant-based**: uses plant response data and weather models to estimate crop water use.

Deficit Irrigation

Water scarcity has become a pressing concern affecting regions across the globe, including the Canadian Prairies. In general, irrigation schedules are designed to minimize crop water stress with the assumption that water supplies are not a limiting factor. Deficit irrigation acknowledges the variability of water availability and emphasizes the importance of optimizing water usage to ensure sustainable agricultural practices in the long term.

Benefits of Deficit Irrigation:

1. Water Conservation: Deficit irrigation promotes the responsible use of water resources by reducing unnecessary water consumption. By supplying crops with only a fraction of their total water requirements, growers can prioritize water availability for other higher value crops or service the same land base with reduced water supplies.

2. Stress-Induced Benefits to Plants: Subjecting crops to controlled water stress through deficit irrigation can trigger a series of physiological responses in plants. These responses include improved root development, increased root-to-shoot ratio, resulting in enhanced water-use efficiency.

3. Resource Allocation and Crop Quality: Deficit irrigation compels plants to allocate resources differently, focusing less on vegetative growth and more on the reproductive processes of flowering and fruit development. This shift can result in improved crop quality, and lower incidence of pest and disease damage.

Deficit irrigation requires a strategic approach through understanding crop-specific water requirements, prioritizing water applications during critical growth stages and reducing applications outside of these periods. Key components of a deficit irrigation strategy include:

1. Crop Type: Know the seasonal (i.e. total) water requirements for specific crops (Table A9, page 70) and the critical growth stage of each crop.
2. Growth Stages: Take into account water requirements by growth stages of a crop. This information is available from provincial extension services or can be estimated from crop water use curves (Appendix B).
3. Deficit Threshold: Determine the level of water deficit you are willing to accept. Common deficit levels range from 50% to 80%. Apply deficit levels of water during the growing season, except during critical growth stages. This will help preserve water while minimizing impact on yield and quality.
4. Record Keeping and Analysis: Keep detailed records of your irrigation schedules, weather conditions, and crop responses. Over time, analyze these data to fine-tune your deficit irrigation strategy for optimal results.
5. Consultation with Experts: If you are new to deficit irrigation or growing specific crops, consider seeking advice from agricultural experts or provincial agricultural extension services. They can provide valuable insights tailored to your specific circumstances.

Remember that successful deficit irrigation requires careful monitoring, adaptation, and an understanding of both your crops and local environmental conditions. It can be an effective tool for conserving water while maintaining acceptable yields, but it requires a proactive and informed approach.   By strategically applying less water than the maximum requirements of crops, farmers can conserve water, enhance water use efficiency, and cultivate crops that are more adaptable to changing climatic conditions.

Using sensors to measure/estimate crop water needs in irrigation scheduling

[Note: This section provides an introductory overview of sensor types.]

In order to schedule irrigation to meet crop water needs, you need take into account actual soil moisture status or estimate the crop water use since the previous irrigation event. This requires time-consuming site visits and data collection. Technological advances in computing and communication has increased the practicality and applicability of using sensors to aid in irrigation scheduling. Sensors can monitor, record and in some cases transmit soil moisture levels automatically. Sensor placement depends on the technology used to measure soil moisture.

Sensor types

In-place and hand-held

The largest selection of sensor types is in-place and hand-held types. However, while cost-effective, the user must take multiple readings and/or install several sensors throughout the field to get a good estimate of water requirements.

<u>Site selection</u>: Choose an average or representative location(s) in terms of soil properties, topography and productivity. If you select typically wet locations (low spot/fine texture), readings will tend to underestimate irrigation requirements elsewhere in the field. Conversely, if you select typically dry locations (knoll/coarse texture), readings will tend to overestimate irrigation requirements. If possible,

select a site easily accessible (via access road or pivot track) to limit crop damage. Be sure to mark sensor location(s) (e.g. attach flags) or record their GPS coordinates.

The general recommendation for locating soil moisture sensors in the soil profile is the middle of the top 50% of the maximum root zone depth (e.g. if the maximum water extraction depth for canola is 100 cm / 39 in, place the sensor at 25 cm / 10 in from the soil surface). This is where 70 – 80% of the crop's water consumption occurs. However, at the beginning of the season, when the root system is much less developed and shallower, soil moisture should be monitored nearer to the soil surface (e.g. 15 cm / 6 in below the surface). If resources allow, this means installing two sensors or a multi-depth sensor at each monitoring location.

Remote Sensors

Measuring soil moisture (or an indicator of soil moisture, e.g. plant productivity) from a distance means that nothing needs to be installed in the soil.

Irrigation system-mounted: Multiple measurements are taken as the irrigation equipment moves across a field.

Satellite-mounted: This type of remotely acquired data is available for free through government operated satellite systems or can be purchased from privately operated satellite companies. Depending on the satellite, sensors measure different reflected wavelengths from the ground (microwaves, RGB images, thermal, etc.) with varying resolution (5 to 100–metre pixels). The disadvantage of satellite obtained data is the time between visits. Depending on the satellite, return frequency can range from daily up to weekly. In addition, cloud cover can significantly limit data quality and availability.

Unmanned aerial vehicle (UAV or drone)-mounted: Sensors installed onto UAVs can generate, on demand, data at excellent resolution (< 1 metre pixel). However, this approach has limitations: the physical carrying capacity of a UAV, data processing requirements (data translation and storage) and software or a service provider that can translate the data into a useable form (e.g. soil moisture or irrigation demand maps) and adherence to Transport Canada rules (mandatory training, licence acquisition and insurance coverage).

Telemetry

As in other industries, sensors used in agricultural settings have continued to undergo a shift towards wireless communication, accompanied by data access via an internet connection. Irrigation sensors are no exception, with many suppliers offering radio and cellular options for remote access. One major limitation to be acknowledged is the reliability of cellular service/coverage. Because much of the equipment available commercially is from foreign sources, it is important to find out what service agreements exist between local telecoms and the sensor suppliers; these agreements may dictate the coverage area where these sensors can operate.

Soil-based irrigation scheduling

Each having advantages and disadvantages, soil-based schedules can use direct or indirect approaches to measure or estimate soil moisture content. As with any attempt to characterize a large area, collect data from multiple locations throughout a field to get a reasonable estimate for the whole field.

Gravimetric method to measure soil moisture

The gravimetric method is reliable as it is a direct measurement of the water within the soil. This process is intensive and requires soil samples to be oven-dried. It is therefore used primarily as a periodic check of other scheduling methods and calibration of soil sensors.

PROS: inexpensive; accurate

CONS – requires experience, multiple site visits, time

Method: Gravimetric

1. **Identify a representative location(s) in your field.**
2. **Use a soil probe (Figure 7) to take soil cores at 15- to 30-centimetre (6- to 12-inch) increments throughout the entire root zone.**
3. **Store samples in separate labelled plastic airtight bags to minimize evaporation prior to weighing.**
4. **Weigh wet soil sample using scale and record value.**
5. **Dry soil sample in oven at 110^{o}C (230^{o}F) for 12-16 hours.**
6. **Allow sample to cool before reweighing.**
7. **Calculate gravimetric water content and volumetric conversion (Appendix D: Example 7A, 7B: page 79).**
8. **Is percentage below maximum allowed depletion?**
    a. **IF Yes, go to Step 9.**
    b. **IF No, resample in a few days.**
9. **Determine irrigation depth (Appendix D: Example 7C: page 80).**
10. **Take into account system efficiency (Appendix D: Example 7D: page 80)**
11. **Irrigate as necessary.**

Hand-Feel method to measure soil moisture

The hand-feel method is exactly what the words imply – manipulate a soil sample by hand to determine approximate soil moisture content. This method requires experience for reliable estimates of soil moisture content. For the technique to be honed, it should be repeated over a range of water contents, as a given soil behaves differently at various moisture contents.

PROS: inexpensive, readily learned

CONS: requires experience to be accurate; requires multiple site visits

Table 1. Plant-available soil moisture of general soil textures based on hand feel.

% Plant-available Moisture*, **	**Sandy Loam**	**Loam**	**Clay Loam**	**Decision**
0–25	Dry, loose, flows through fingers	Powdery or easily broken down into powdery soil	Hard, cracked, difficult to break into powdery soil	Irrigate
25–50	Appears dry, will not form ball with pressure	Crumbly but will hold together from pressure	Somewhat pliable, will ball under pressure	
50–75	Balls under pressure, seldom holds together when bounced in hand	Forms ball, somewhat plastic, smears slightly with pressure	Forms ball, will ribbon between thumb and forefinger, slick feeling	Soil moisture sufficient
75–100	Forms weak ball, breaks easily when bounced in hand	Forms ball, very pliable, smears readily	Easily ribbons, has a slick feeling	
Field Capacity	Upon squeezing: no free water, wet outline of ball remains in hand, soil will stick to thumb when rolled			

* This is a rough estimate of moisture based on soil texture: use the soil classification that is closest in texture to your sample.

** Judgement should be used to determine where the soil moisture is within each range.

From: *Estimating Soil Moisture by Feel and* Appearance, United States Department of Agriculture-Natural Resources Conservation Service, 1998.

Method: Hand feel

1. **Identify a representative location(s) in your field.**
2. **Use soil probe/shovel (Figure 7) to take soil cores at 15- to 30-centimetre (6- to 12-inches) increments throughout the entire rooting zone.**
3. **Work soil sample in hand to estimate soil moisture content (Table 1, Figure 15).**
4. **Is the soil moisture range below maximum allowed depletion?**
    a. **IF Yes, go to Step 5.**
    b. **IF No, resample in a few days.**
5. **Based on estimated soil moisture content, determine the irrigation depth (Appendix D: Example 8, page 81).**
6. **Irrigate.**

Loamy Sand and Sandy Loam Soils

25–50% available moisture 50–75% available moisture 75–100% available moisture

Sandy Clay Loam, Loam and Silt Soils

25–50% available moisture 50–75% available moisture 75–100% available moisture

Clay, Clay Loam, Loam and Silty Loam Soils

25–50% available moisture 50–75% available moisture 75–100% available moisture

Figure 15. Available soil moisture ranges for various soil textures using hand feel method (NRCS).

Tensiometer

This device relies on the principle of matric potential, or tension, which varies in the soil with changes in soil moisture content. At field capacity, soil water is readily accessible to a plant root with little effort on the part of the plant (suction) being necessary. As the soil moisture level declines, the soil particles 'hold' on to the moisture with greater force. As a result, plants need to exert more force (suction) to remove the water from the soil, stressing the plant. Tensiometers measure this suction and translate it into an equivalent soil moisture content.

The tensiometer body is a solid tube, sealed at the top and with a ceramic tip at the base (Figure 16). After installation of the tensiometer in the soil, the tube is filled with water, primed and resealed. The ceramic tip allows water to pass from the sealed tube into the soil, creating a partial vacuum. The vacuum gauge at the top of the tensiometer indicates the change in suction pressure. When soil is wetted through rainfall or irrigation, moisture is drawn back into the tensiometer reducing the suction pressure in the tube.

Tensiometers are limited in practicallity at certain water contents and with certain soil textures. At high moisture content (Field Capacity) or in course soils (sands), large changes in water content occur over a relatively narrow range of measured tension (Figure 17), meaning that the devices are not sensitive enough to accurately characterize soil wetness under these circumstances.

PROS: inexpensive; mimics stress exerted on plant roots

CONS: indirect measure; unreliable over full range of pressures

Method: Tensiometer

1. **Soak tensiometer tip for 24 hours prior to installation.**
2. **Keep tip wet until installed in field; transport to field in water-filled bucket.**
3. **Identify a representative location(s) in your field.**
4. **Use a soil probe to create a small access hole, just wider than the tensiometer, to the desired depth.**
5. **Fill access hole with a soil-water slurry.**
6. **Place tensiometer into the slurry-filled hole – this ensures there will be good contact between ceramic tip and soil.**
7. **Replace soil around the tensiometer.**
8. **Fill tensiometer with water and use a vacuum pump to prime the gauge to 0.80 - 0.85 bars.**
9. **Check water level in the tensiometer periodically; refill when necessary and repeat Step 8.**
10. **Determine plant-available water by converting soil water potential readings (Figure 17).**
11. **Is the soil moisture below maximum allowed depletion?**
    a. **IF Yes, go to Step 12.**
    b. **IF No, return in a few days to re-read gauge.**
12. **Based on tensiometer reading, calculate irrigation depth (Appendix D: Example 9, page 81).**
13. **Irrigate as necessary.**

Figure 16. Tensiometers measure soil tension which can be translated into soil moisture content.

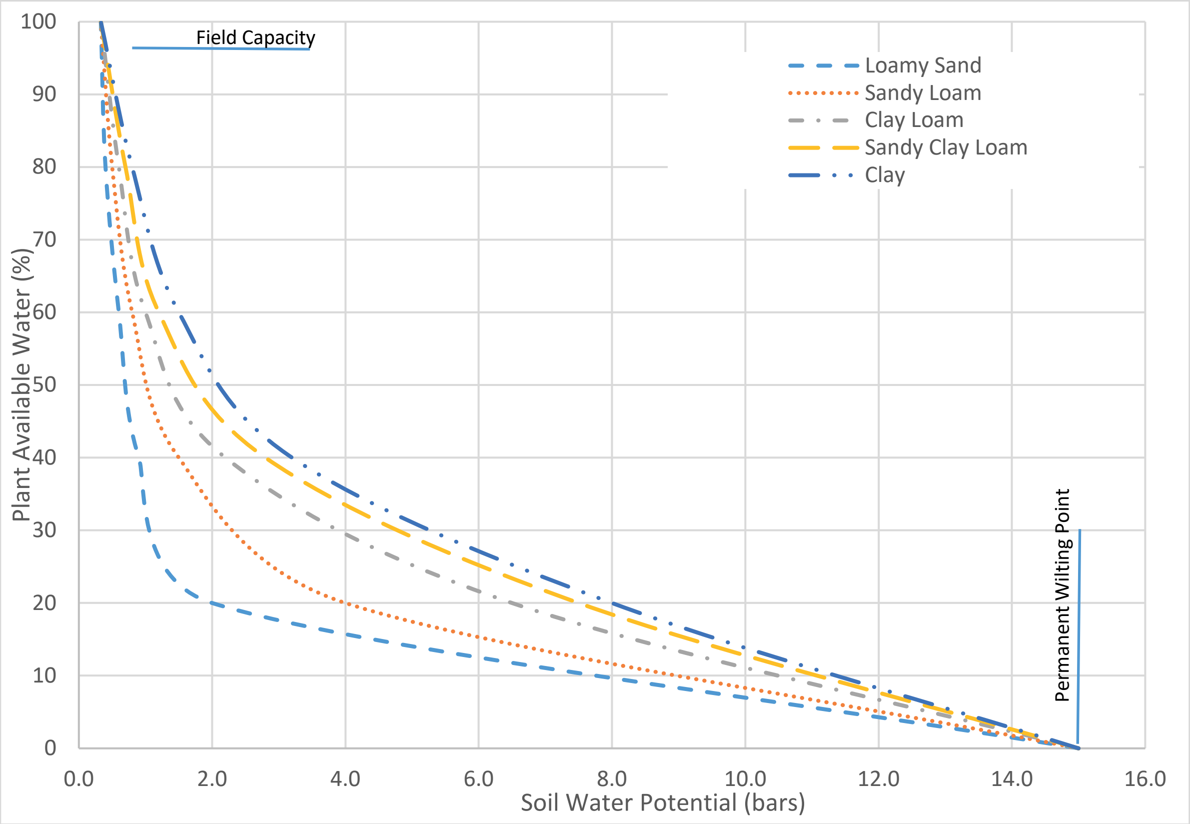


Figure 17. Plant-available water (%) as it relates to the amount of suction (soil water potential, bars) required to access water for common soil textures.

Electrical resistance blocks: gypsum blocks and granular matrix blocks

Electrical resistance blocks consist of electrodes embedded within a porous block (e.g. gypsum or ceramic) or granular matrix (Figure 18). The block is soaked in water before inserting into the soil. After a short period, the amount of water in the block and the soil equalizes. An electric current can then be applied to the lead wires to measure resistance. The observed resistance is inversely related to soil moisture. In simple terms, as water content goes down resistance goes up (high resistance = dry soil) and as water content goes up resistance goes down (low resistance = wet soil). Sensor manufactures offer readers that convert resistance data and display soil moisture tension or equivalent soil moisture content.

PROS: inexpensive; mimics root environment; easily installed

CONS: requires conditioning before installation; gypsum degrades in soil

Method: Electrical resistance block

1. **Electrical resistance blocks require a preconditioning period prior to installation:**
    a. **Soak blocks in water for 30 minutes, then air dry for 24 hours.**
    b. **Repeat several times (minimum 3 cycles).**
2. **Saturate blocks immediately prior to installation: transport to field in a water-filled bucket.**
3. **Identify a representative location(s) in your field.**
4. **Use a soil probe/shovel to make create a small pit or access hole at the desired measurement depth(s) (15–30 centimetre / 6–12 inch increments).**
5. **Fill access hole with a soil-water slurry.**
6. **Place electrical resistance block into the slurry-filled hole — this ensures there will be good contact between the block and soil.**
7. **If installing blocks at multiple depths in one hole, replace soil in layers, compacting each layer to match field conditions.**
8. **Connect wires to transmitter (automated readings). If using a portable meter instead (manual readings), protect wires.**
9. **Flag location for visibility and to prevent damage from equipment.**
10. **Determine plant-available water by converting from soil water potential reading readings (Figure 17).**
    a. **NOTE: some readers will automatically convert reading into volumetric moisture content or available water.**
11. **Is the soil moisture below maximum allowed depletion?**
    a. **IF Yes, go to Step 12.**
    b. **IF No, resample in a few days.**
12. **Based on reading, calculate irrigation depth (Appendix D: Example 9, page 81).**
13. **Irrigate as necessary.**

Figure 18. Example of a granular matrix block (left) attached to a PVC access tube (right).

Time domain reflectometry

Accurate and reliable, time domain reflectometry (TDR) probes can also be used to measure the electrical conductivity of the soil (useful in monitoring soil salinity levels).

TDR probes typically consist of two or three metal rods connected to a signal generator (Figure 19). The time required for an electrical signal to travel to the end of the rods and return (reflect) is relative to soil moisture content – the longer the signal's trip takes, the drier the soil, and vice versa. TDR probes report soil moisture as percent volumetric water content. To interpret readings, irrigators must know the soil texture to determine field capacity and permanent wilting point. TDR probe are available in different lengths in order to measure soil moisture at various depths. In addition, some TDR probes have built-in wireless capability to transmit data to allow irrigators to view soil moisture data from their mobile or desktop devices 24/7 and observe trends over time.

PROS: accurate; easily upgraded for remote monitoring

CONS: soil disturbance during installation can affect accuracy; expensive

Method: Time Domain Reflectometry

1. **Identify a representative location(s) in your field.**
2. **Dig a narrow pit (horizontal installation) or pilot hole (vertical installation) in the soil to a depth just below the desired deepest sensing depth.**
3. **Insert probes into profile at desired depths (use a rubber mallet if necessary); ensure tines are straight and parallel.**
4. **Replace soil in layers, compacting each layer to match field conditions.**
5. **Flag location for visibility and to prevent damage from equipment.**
6. **Monitor readings to determine available water (Figure 20).**
7. **Is the soil moisture below maximum allowed depletion?**
    a. **IF Yes, go to Step 8.**
    b. **IF No, continue to monitor.**
8. **Based on reading, calculate irrigation depth (Appendix D: Example 10, page 82).**
9. **Irrigate as necessary.**

Figure 19. Example of TDR probes with built-in data transmission capacity (left) installed in irrigation field (right).

Capacitance probe

Also known as a Frequency Domain Reflectometry (FDR) probe, this device generates an electric field with a power source and oscillator. It measures changes in soil moisture, as reflected by fluctuations in soil dielectric properties, directly adjacent to the sensor. Capacitance-based soil moisture sensors generally come in two forms: wafer type or tube type (Figure 21). The tube-type probe can consist of multiple sensors spaced at pre-set distances (e.g. 15, 30, 45 centimetres / 6, 12, 18 inches) inside a plastic watertight housing to measure soil moisture at multiple depths with a single unit. As with TDR probes, soil moisture is reported on percent volumetric basis.

Capacitance probes require good contact with the soil. Poor soil contact may introduce air gaps or allow water to flow alongside the probe. Both conditions reduce the probe's accuracy in measuring soil moisture.

PROS: fully integrated (probe and communication); limited disturbance; multi-depth

CONS: installation requires good contact with soil; complex circuitry (prone to failure)

Method: Capacitance probe - tube type (for wafer type, follow TDR method)

1. **Identify a representative location(s) in your field.**
2. **Dig a pilot hole using a soil probe or auger which is equal to or slightly smaller than the diameter of the probe.**
3. **Install the capacitance probe to the manufacturer's specified depth.**
4. **Fill gaps/space between around the probe at the soil surface, using hand to compress soil.**
5. **Activate the capacitance probe (if required) or connect probe to logging device.**
6. **Flag the location to prevent damage from equipment.**
7. **Monitor readings to determine available water (Figure 20).**
8. **Is the soil moisture below allowable depletion?**
    a. **IF Yes, go to Step 9.**
    b. **IF No, continue to monitor.**
9. **Based on reading, calculate irrigation depth (Appendix D: Example 10, page 82).**
10. **Irrigate.**

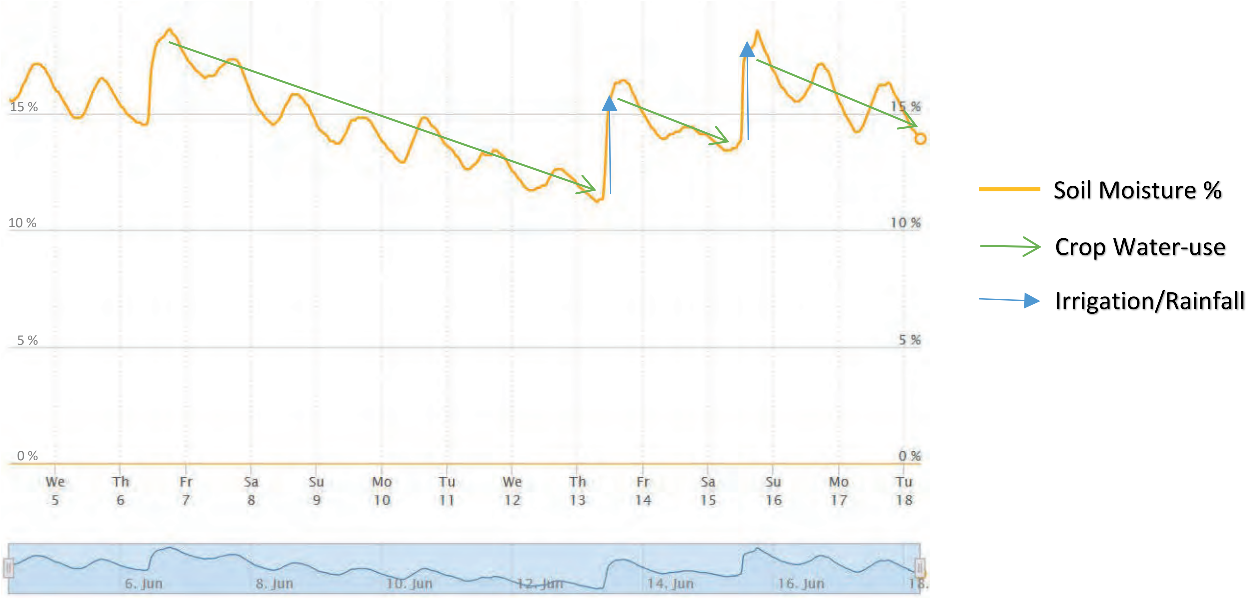


Figure 20. Typical soil moisture readings using TDR/Capacitance based irrigation sensor.

Figure 21. Example of a tube style capacitance probe (left) being installed in irrigation field (right).

Microwave radiometer

This device (Figure 22a) measures natural microwave emissions from the soil profile at a specific frequency. Soil moisture can be estimated by combining microwave readings with additional information such as soil texture and crop stage.

The data processing involved is complex and sensors usually require a service subscription to process the data. A service provider uses processed data to generate soil moisture maps (Figure 22b) which reveal the specific parts of the field requiring water. Depending on the map units or sensor output, determining irrigation depth is similar to soil-based techniques. Because this method of determining soil moisture is model-driven and relies on relatively new technology, installing a soil moisture probe or periodically taking soil samples for water content analysis, to verify readings, is prudent.

PROS: spatial information; non-contact; can measure at all crop stages

CONS: new technology for irrigation scheduling, service provider needed to perform complex calculations; results unreliable for hilled crops (e.g. potatoes)

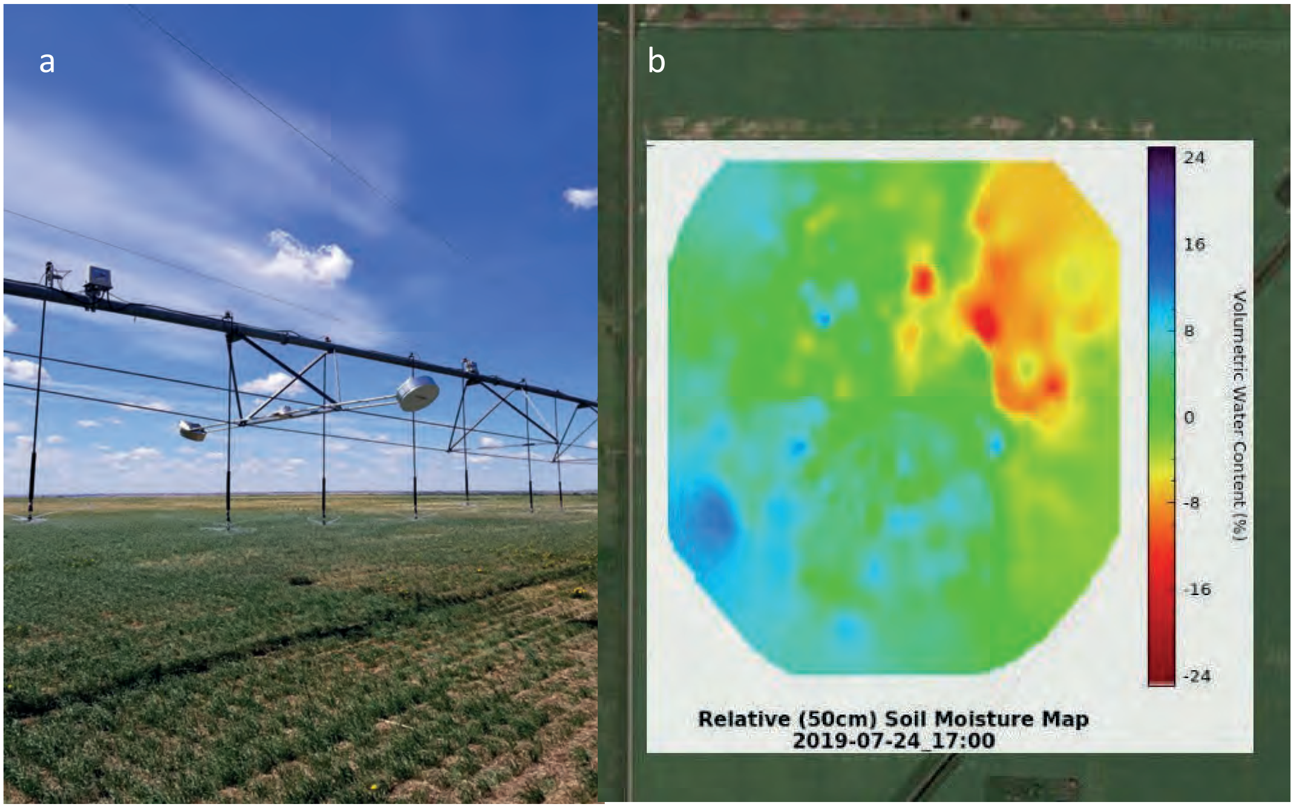


Figure 22. (a) Pivot mounted microwave radiometer and (b) example soil moisture map.

Neutron Probe

A neutron probe (Figure 23) is a sophisticated instrument used for measuring soil moisture content in a non-destructive manner. It operates based on the principle that hydrogen atoms, primarily found in soil water, can influence the behavior of neutrons. The probe consists of a radioactive source which emits fast neutrons into the soil. As these neutrons collide with hydrogen nuclei in the soil, they lose energy. By measuring the number of slow-moving neutrons that return to the probe, the instrument can indirectly assess the amount of hydrogen present, which correlates with soil moisture content. The probe's detector captures these returning neutrons, and the data is then processed to calculate the volumetric water content of the soil. This method offers an accurate and efficient way to monitor soil moisture levels across various depths, aiding agricultural and environmental studies, irrigation management, and water resource planning.

Method: Neutron Probe

1. **Identify a representative location(s) in your field.**
2. **Core a small hole for installation of an access tube, usually made of a thin-walled aluminum pipe, and 5 cm (2 in) in diameter, just large enough for the probe to fit snugly.**
3. **Install the access tube to the anticipated maximum depth of the seeded crops root zone, leaving 15 – 30 cm (6 in – 12 in) above the ground.**
4. **Fill any gaps around the tube at the soil surface, using hand to compress soil.**
5. **Place the neutron reader on the access tube, lower neutron source into the access tube to the desired depth.**
6. **Follow manufacturer's instructions for taking readings and record volumetric moisture content.**
7. **Cover the access tube, such as with a cap, when not in use to prevent water and debris from entering.**
8. **Flag the location to prevent damage from farming equipment.**
9. **Periodically take readings within the rooting depth, following manufacturer's recommendations.**
10. **Is the soil moisture below allowable depletion?**
    a. **IF Yes, go to Step 11.**
    b. **IF No, continue to monitor.**
11. **Based on reading, calculate irrigation depth.**
12. **Irrigate.**

PROS: non-destructive, accurate readings of volumetric moisture content

CONS: radioactive source (training and licensing required), field visits required for readings.

Figure 23. Neutron Probe Soil Moisture Sensor (L. Hingley, Government of Alberta)

Weather-based irrigation scheduling

Weather-based irrigation scheduling calculates changes to soil moisture by taking into account local weather data and estimated evapotranspiration. Runoff and drainage are additional factors, but in a well-managed system, these factors should be negligible and the calculation is simplified by assuming they contribute little to changes in soil moisture (Appendix C: Equation 3, page 74).

Cheque-book

The cheque-book method is an example of a water accounting method that relies on the principal of the water balance (water in and water out). Similar to using a cheque-book to keep track of home finances, this method tracks water deposits (irrigation and precipitation = credits) and withdrawal (evaporation and crop use = debits).

The cheque-book method is a simple system for estimating available soil moisture. The largest source of error is the evapotranspiration variable. Evapotranspiration estimates tend to be poor since they are based on crop stage and reported on a monthly basis (instead of taking into account day-to-day weather variability) (Appendix A: Table A7, page 69). A recommended best practice is to take periodic soil samples or use soil moisture sensors to correct for poor evapotranspiration estimates (Appendix D: Example 11, page 83).

Evapotranspiration

Evapotranspiration is dependent on the crop, variety, development stage, crop condition, management and weather conditions. The average daily evapotranspiration rate increases as the crop matures and reaches a maximum daily rate during critical periods like flowering and initial fruit/pod/grain development (Appendix A: Table A7, page 69).

Evapotranspiration is difficult to measure directly. However, it can be accurately estimated using models such as the FAO Penman-Monteith equation (Appendix C: Equation 4, page 75). Evapotranspiration is initially calculated for a reference crop (e.g. grass/alfalfa) using local weather data (Figure 24). Since water-use varies between crops, the reference evapotranspiration rate is adjusted with a crop-specific coefficient (Appendix C: Equation 5, page 75). In addition, crop water-use is affected by crop stage (Figure 25). To account for these factors, the reference evapotranspiration is adjusted more finely with crop- and crop stage-specific coefficients (Appendix A: Table A8, page 69).

Figure 24. Weather station.

Calculating evapotranspiration rate is complex and requires access to detailed environmental data that may not be available for your area. To overcome this limitation, select provincial governments have developed irrigation scheduling software or online applications that can complete these calculations with minimal input from the irrigator. Commonly used irrigation scheduling calculators available in the Western Canada are the Alberta Irrigation Management Model (AIMM) (Figure 26) and the BC Agricultural Irrigation Scheduling Calculator (BCAISC).

AIMM uses Environment and Climate Change Canada weather data from stations located throughout irrigation districts in Alberta as well as Outlook, Saskatchewan, while the BCAISC relies on data from a weather station network, supported by www.farmwest.com, spanning most of the agricultural extent of Canada. Users can start by selecting the weather station closest to their operations, then enter soil and cropping practice information to receive predicted soil moisture content and irrigation timing and rate recommendations. The free software, documentation and training material for AIMM are available online at https://agriculture.alberta.ca/acis/imcin/aimm.jsp, while the BCAISC is available on line at https://ag-calc.irrigationbc.com/. For additional information or support in using either of these services, contact irrigation extension staff in your province (see Irrigation Scheduling Assistance, page 64).

PROS: inexpensive; visual; alerts available

CONS: requires training; requires periodic corrections

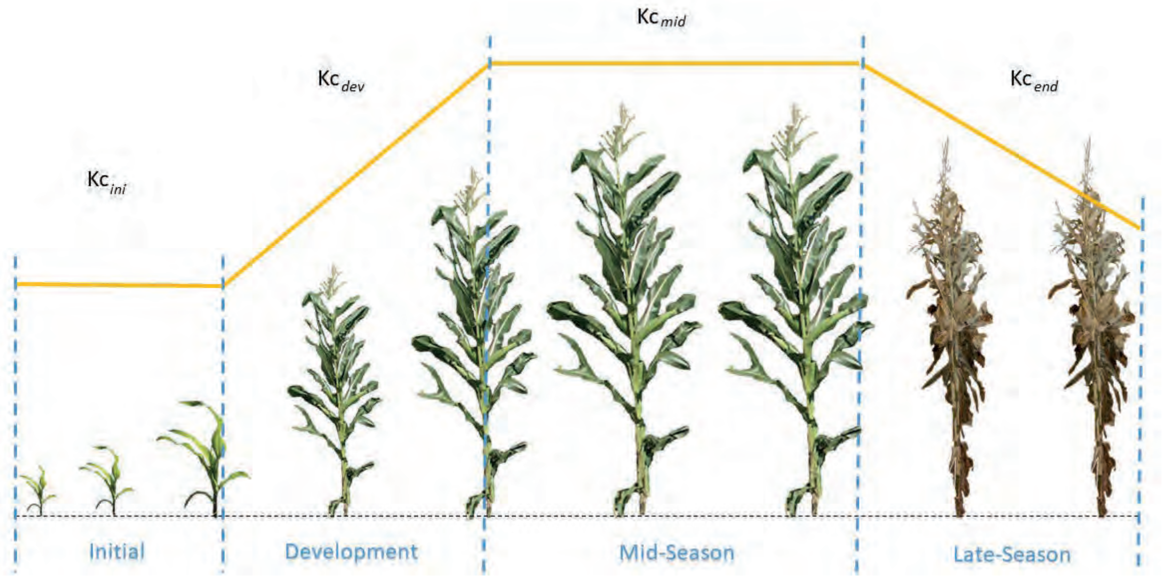


Figure 25. Crop water-use coefficient representation for different growth stages.

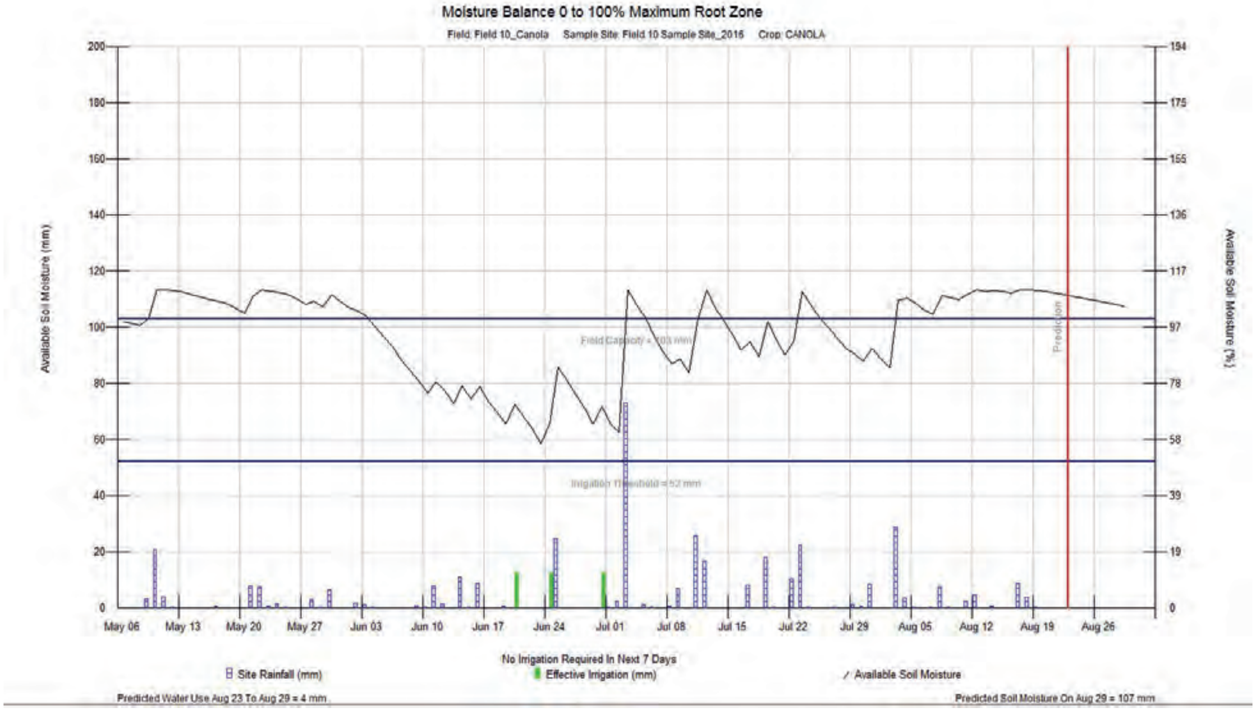


Figure 26. Alberta Irrigation Management Model (AIMM) sample graph output.

Plant-based irrigation scheduling

Plant-based irrigation scheduling methods measure crop condition (e.g. plant stress) to determine when to trigger/schedule irrigation applications. However, without additional information, plant-based methods may only indicate when and where your crop needs water but not how much. One plant-based irrigation scheduling scheme, a fixed depth schedule, consists simply of applying a fixed amount (e.g. 0.5 inches) whenever the crop shows signs of stress. A more complex scheme combines plant stress measurements with weather models to estimate irrigation requirements.

Two common plant indicators used in irrigation scheduling are the Normalized Difference Vegetation Index (NDVI) and crop canopy temperature.

Normalized Difference Vegetation Index (NDVI)

Sunlight is composed of several wavelengths. When sunlight hits a leaf, some of the visible light wavelengths are absorbed and used in photosynthesis (chiefly red, blue and, to a lesser extent, green), while other light wavelengths are reflected (e.g. non-visible near infrared). This means that the denser the canopy and the healthier the crop, the more visible light is absorbed and the more near-infrared light is reflected (Figure 27). Satellites or unmanned aerial vehicles (drones) can be used to measure these light characteristics at field scale.

The remotely captured data is used to calculate the Normalized Difference Vegetation Index (NDVI) — a value that relates plant growth to the ratio of reflected (near infrared) vs. absorbed light (red) (Appendix C: Equation 6). The Index can range between −1 and 1, but in practice falls between 0 (bare soil) and 1 (healthy, dense canopy). From this simple relationship, irrigators can quickly get a sense of crop health and canopy density using remote imagery.

Employing NDVI is a reactive, rather than proactive or predictive, approach to irrigation scheduling — water demand is estimated from NDVI of the stand as of the time of measurement. While matching irrigation to crop needs improves water-use efficiency, once water stress can be seen in NDVI imagery, yield potential may already been impacted and difficult to reverse (Bauer 2019). To counter this limitation, producers can use historical NDVI images to identify areas susceptible to water stress, adjusting irrigation schedules to not only address water deficiencies but also potentially improve yields.

Another limitation is that of relying reliance on satellites to capture reflectance data. Satellites are not always in position (directly overhead a given location) and return frequencies range from daily to weekly depending on source. Additionally, cloud cover can significantly affect reading accuracy. Drones or other land-based technologies can be used to collect the light reflectance data to supplement or address gaps in satellite coverage.

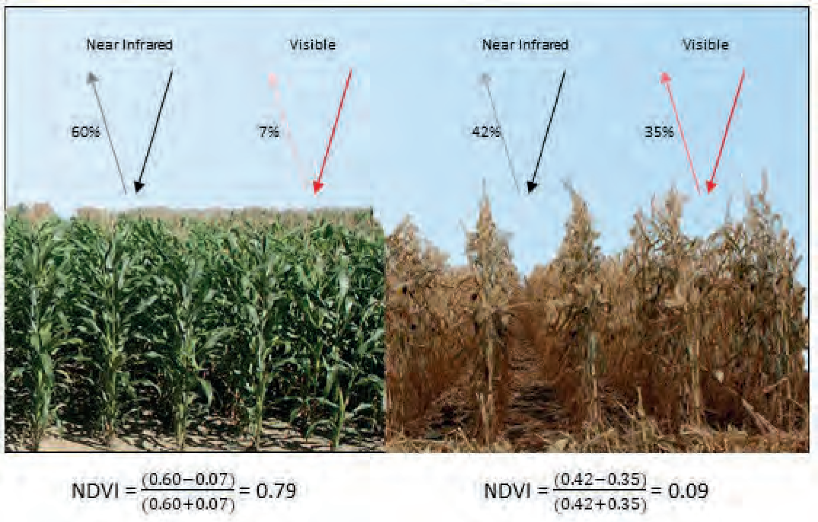


Figure 27. Interaction between visible (red) and near infrared light with a crop canopy.

PROS: spatial; minimal inputs; remote monitoring

CONS: images collection hampered by cloud cover; requires ground checks; requires training

IrriCAN: *an NDVI based online irrigation scheduling tool*

Combining remote imagery data with traditional weather-based models, IrriCAN (www.irrican.com), a spatial irrigation scheduling product adapted for Canadian irrigators from an Australian tool, IrriSAT (https://irrisat-cloud.appspot.com/). IrriCAN automatically imports data from Google Earth (satellite images, NDVI data, maps) and local weather feeds. The application takes into account the linear relationship between NDVI and crop water-use: a field with a dense, healthy crop (higher NDVI value) uses more water than a less dense, less healthy crop (lower NDVI value) (Appendix C: Equation 7, page 75). This relationship holds true regardless of the crop and is the basis for calculating evapotranspiration to estimate crop water use. Combining NDVI with weather-based estimates of crop water use more thoroughly and characterizes the variation in water requirements throughout the field (Figure 28), better informing irrigation scheduling. For assistance using IrriCAN, please contact your provincial irrigation extension service (see Irrigation Scheduling Assistance, page 64).

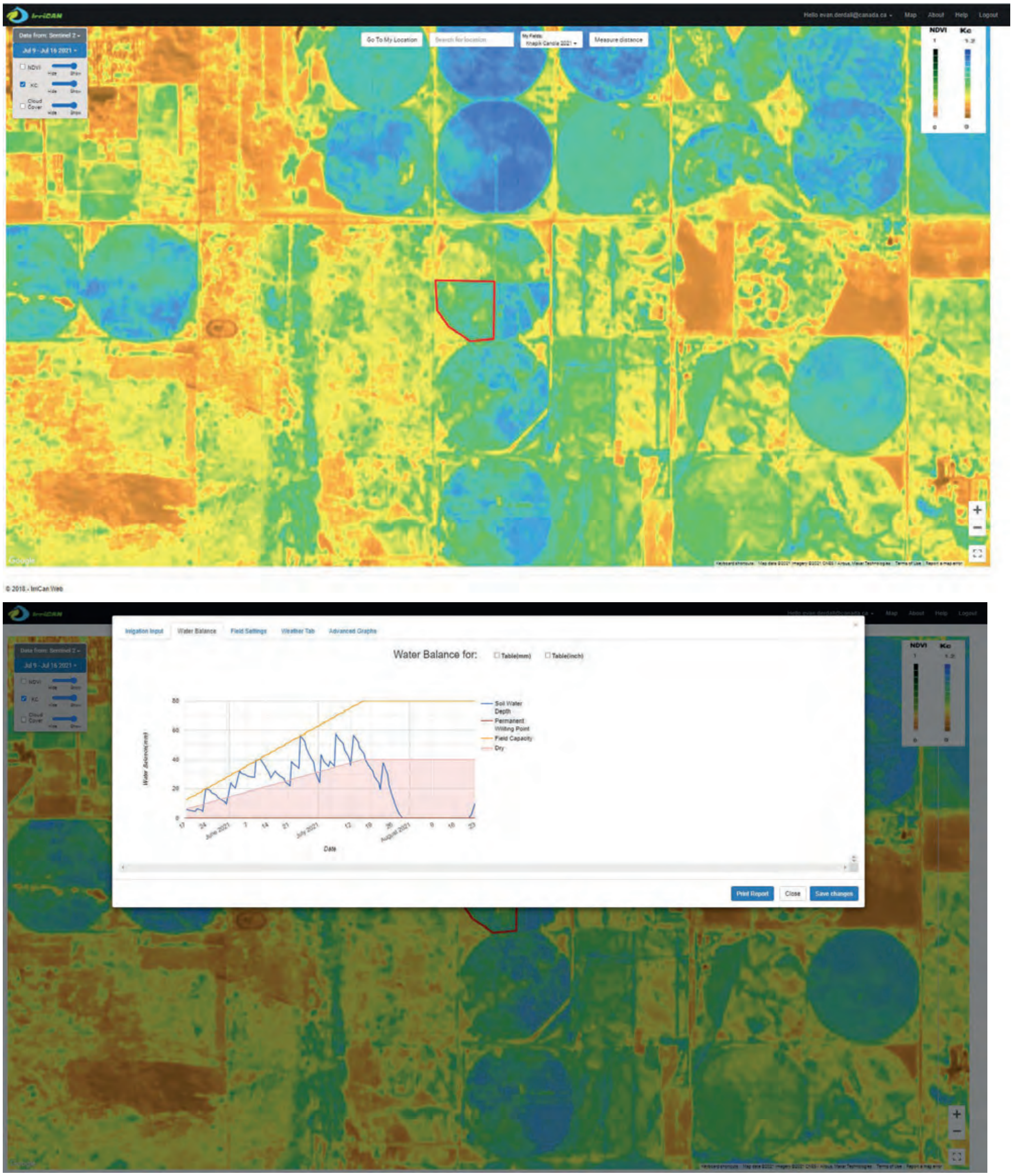


Figure 28. Top: IrriCAN map page showing weekly NDVI imagery. Bottom: Water balance generated for irrigated field.

Canopy temperature / crop water stress index (CWSI)

In daylight, the cooling effect of transpired water evaporating from a leaf's surface maintains internal leaf temperature near air temperature. When there is insufficient soil moisture (deficit), leaves reduce or shut down transpirational water loss by partially or fully closing their stomata to reduce drought stress. Unfortunately, this leads to a rapid temperature rise in the leaves, compounding drought stress with heat stress (soil moisture deficit → drought response → canopy warming). Crop canopy temperature can be measured with an infrared thermometer (Figure 29) to determine where and when canopy temperature is higher than air temperature, known as differential temperature (dT).

Note: the presence of insect pests and disease can also cause canopy temperature increases. If the pattern of temperature differences looks suspicious, such as prevalence in low, normally wet areas or persists after an irrigation event, you should inspect your crop. All plant-based scheduling methods are subject to these anomalies, warranting crop scouting to diagnose the cause of observed crop stress.

One way to describe the relationship between soil moisture stress and canopy temperature is to calculate the Crop Water Stress Index (Appendix C: Equation 8, page 76): an index value of 0 means that the crop is under no moisture stress; the closer the index is to 1.0, the greater the moisture stress.

Using canopy temperature is a more responsive approach to detecting crop stress due to lack of water than using Normalized Difference Vegetation Index; water stress is detected earlier and triggers irrigation at the first signs of water stress, limiting potential yield reduction. However, similar to the NDVI irrigation scheduling method, the Crop Water Stress Index can only advise when and where to irrigate, not how much. Additional information (climate scheduling models, soil measurements, etc.) is still required to determine how much water to apply.

PROS: reliable, early indication of plant stress; spatial applications

CONS: no guidance for irrigation depth (additional measurements required); requires crop canopy temperature (additional tools/technology)

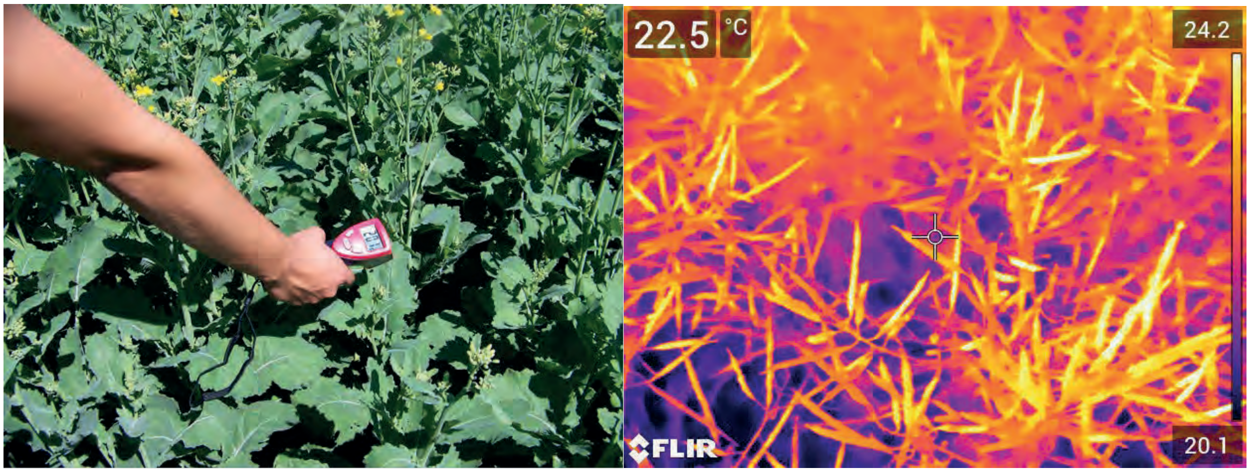


Figure 29. Handheld infrared thermometer (left) and thermal image of canola (right).

NDVI-dT Curves

Another plant-based method combines differential canopy temperature with NDVI values to guide irrigation timing. Researchers have developed NDVI-dT Curves, such as Figure 30 for a location in Saskatchewan. Using both an infrared thermometer and NDVI sensor (e.g. GreenSeeker), irrigators can take periodic measurements and utilizing available curves, determine if irrigation is required.

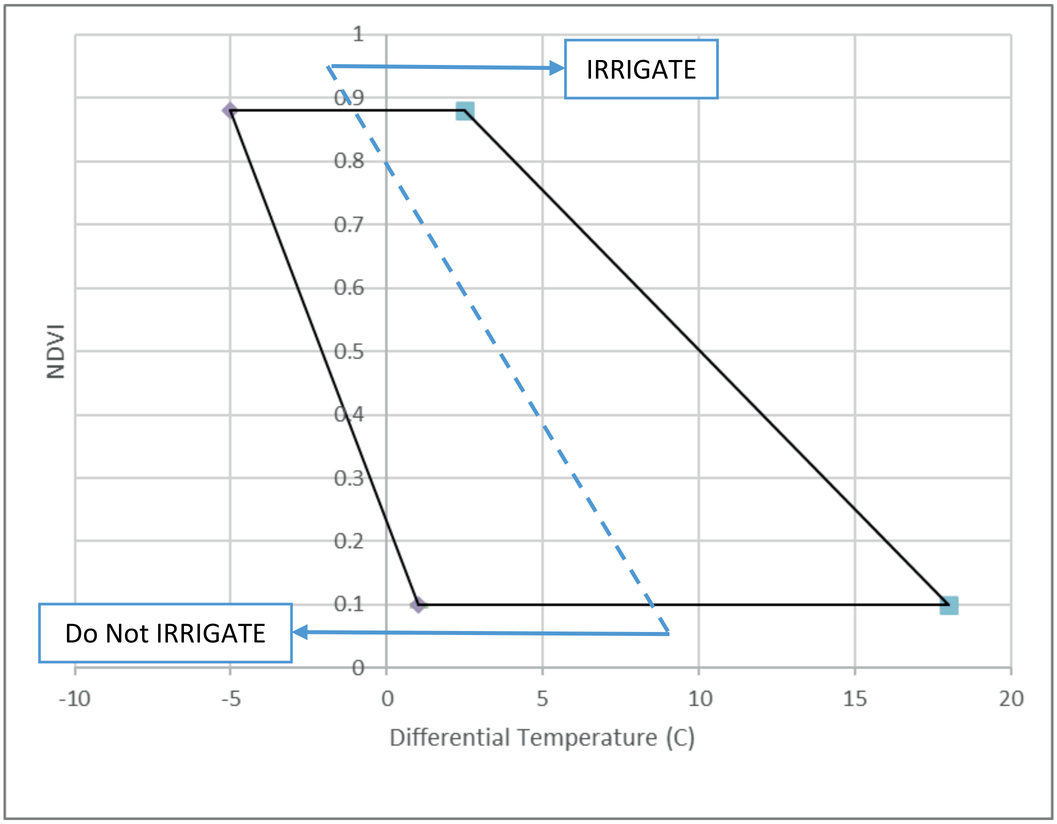


Figure 30. NDVI-dT Curve for Irrigated Wheat, Outlook, Sk (Derdall 2023)

Method: NDVI-dT (Readings should be taken around solar noon (12pm to 2pm)

1. **Identify a representative location(s) in your field.**
2. **Obtain NDVI value for the crop canopy**
3. **Take a temperature reading of the crop canopy**
4. **Calculate the differential temperature (Canopy Temperature – Air Temperature)**
5. **Refer to NDVI-dT (e.g. Figure 30)**
6. **Is the measurement point on the right side of the trapezoid?**
    a. **IF Yes, go to Step 7.**
    b. **IF No, continue to monitor.**
7. **Apply standard irrigation application, such as 12.5 – 25 mm (0.5 – 1.0 in).**

Specific Crop Considerations

Irrigation scheduling of crops should be tailored to their unique characteristics and needs. Irrigation schedules will need to adapt to the crop (growth stages, root depths, water demand), irrigation system (pivot, drip) and environmental factors (soil, weather). In Western Canada, a few crops require special consideration due to the impact irrigation management has on the quality and marketability of crops compared to traditional irrigated field crops.

Alfalfa

Alfalfa is a perennial forage crop grown extensively in the irrigated region of the Canadian prairies as a feed source for cattle production. Alfalfa is unique due to its perennial production cycle, deep rooting structure and multiple harvest dates during the growing season.

Alfalfa is relatively drought tolerant due to its deep rooting system, but will produce significant above ground biomass if it has adequate nutrients and available soil moisture is maintained above 60%. Alfalfa requires significant amounts of moisture, with seasonal average between 540 and 680 mm (Alberta Agriculture and Forestry 2011).

In the establishment year, alfalfa requires frequent irrigation applications until the root zone becomes developed enough to hold substantial water reserves. Alfalfa establishment requires significant water applications to meet its evapotranspiration requirements until cutting, which is usually mid-August during the first season. As the crop moves into the wintering period, soil moisture should be drawn down to 70% available soil water (ASM), anything above that can increase the risk of winterkill.

In production years, alfalfa water demand begins once the soil warms and the frost has completely left the rooting zone, which can be approximately 120cm at this point. Once alfalfa begins to grow in the spring, water demand rises quickly and irrigation schedules should be developed to maintain soil moisture above 60% ASM within the top 90 cm of the root zone. Irrigation schedules for alfalfa are dependent on cutting and baling schedules (Figure 31). Prior to cutting alfalfa, soil moisture should be above 70% ASM, this will provide sufficient reservoirs to allow for the alfalfa to be cut, dried and bailed prior to next irrigation event. This buffer will help prevent soil moisture falling below 60% ASM during the cutting period.

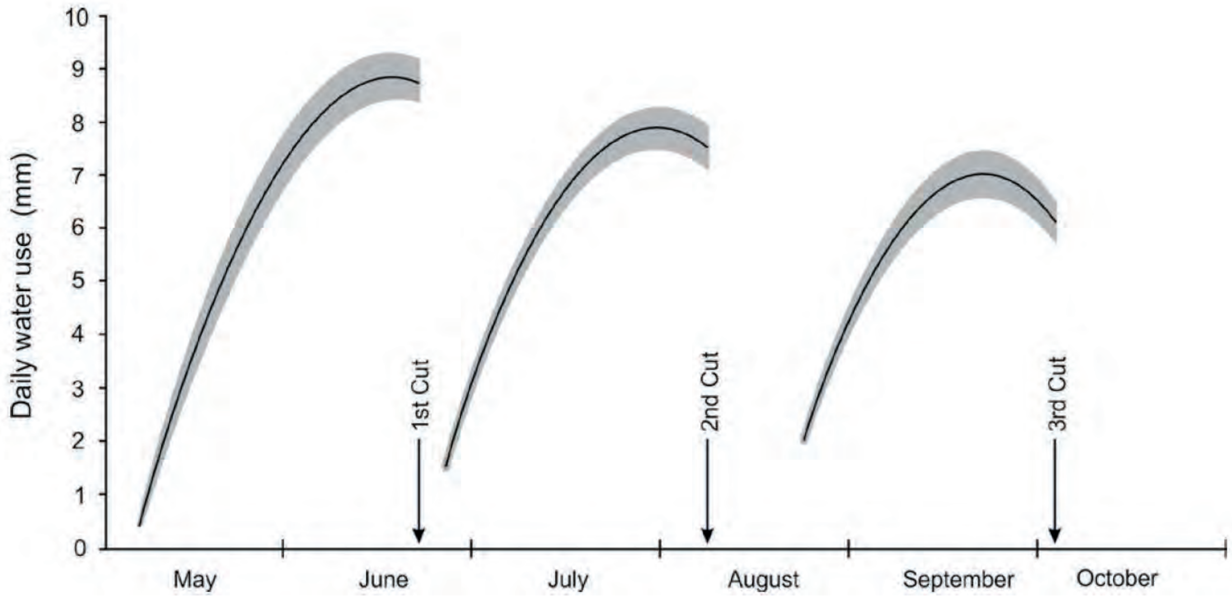


Figure 31. Daily water use for first, second, and third cuts of Alfalfa (Alberta Agriculture 2011)

Potato

Photo Credit: M.D. Timmerman, Manitoba Agriculture 2022

Irrigation management of potato crops is unique compared to most field crops due to; shallow rooting depth, impact of irrigation on tuber quality, and high crop value and associated production costs. Potatoes require consistent moisture throughout their growth stages, but the amount of water needed varies at different times. Understanding the growth stages is key to determining the right irrigation schedule (Adapted from University of Nebraska-Lincoln factsheet 2023 – Potato Growth and Irrigation Scheduling):

1. Planting to Pre-emergence – soil moisture during this vegetative period should be maintained above 60% of available soil moisture (ASM). Irrigation should be moderated during this period as it is important for proper soil aeration. If soil moisture is excessive (near field capacity), environments exist that promotes pathogens which cause soft rot, black leg, and stem and stolon canker.

2. Emergence to Tuber Initiation – This stage is the beginning of rapid growth of the vine of the plant. Soil moisture during this stage should be maintained between 70% and 80% ASM. Soil moisture below 60% ASM is considered in deficit and can inhibit canopy and root growth. Excess moisture during this stage can hinder root branching and lead to leaching of nitrogen. As the crop moves into tuber initiation, stress can result in tuber chaining and heat runners (Figure 32), reducing tubers and losing significant yield.

Figure 32. Heat Runners (left) and Tuber Chaining (Right) resulting from moisture stress (S. Graham, Simplot 2022)

3. Tuber Initiation to Full Bloom – tuber initiation is the start of the most intensive watering period during potato production. Optimal soil moisture is 70 – 80% ASM. Water deficit during this stage drastically increases tuber malformation and sugar-ends (Figure 33) resulting in quality deductions. Water stress also weakens plants resulting in yield decreases and causing plants to

be more susceptible to early blight and common scab. Excess/standing water can promote the development of brown centre and hollow heart of larger tubers.

Figure 33. French fry discoloration due to sugar end content (left – 0%, right 20%), resulting in price deduction (S. Graham, Simplot 2022)

Credit: S. Graham, Simplot 2022

4. Tuber Bulking – tubers begin to grow rapidly and require significant amounts of water to maintain growth. Soil moisture should continue to be maintained at 70 – 80 % ASM, with the bulking stage being most sensitive to water deficit. Insufficient moisture can make the plant susceptible to tuber malformation, early dying, early blight, brown spot and common scab. Whereas excess moisture can increase hollow heart, swollen lenticels, black leg, late blight, and susceptibility to rot.
5. Maturity – this is the period characterized by dying of the vine and leaves. As the vine dies, tuber skin sets, hardens and adheres to the core/flesh. Irrigation should be reduced during this period to allow for the potatoes to mature, with soil moisture being maintained between 60-65% ASM. If field drops below 50 – 55% ASM, a late season irrigation to bring moisture up to 60% ASM will help rehydrate tubers and mellow the soil for ease of harvest. Potato production requires close monitoring of soil moisture to prevent impacts on yield and tuber quality associated with deficit and excess moisture. As potato production is associated with high input costs, it is important to develop a proper irrigation schedule to protect your investment.

DRIP AND MICRO-IRRIGATION SCHEDULING

Drip and micro-irrigation refer to irrigation systems that slowly dispense water at, in, or near the plant root zone (Figure 34). This method usually involves the installation of polyethylene tubes above or below the soil surface near the crop roots to maximize the efficiency of the water delivery system.

a. Micro-Sprinklers. Low-flow spray emitters or micro-sprinklers are mounted above the soil surface. Surface is wetted during each irrigation event

b. Surface drip. Lines and passive emitters are placed at the soil surface or cove-red with a layer of soil < 5 cm thick. Surface is wetted during each irrigation event.

c. Subsurface drip. Lines and passive emitters are placed below the soil surface (20 to 40 cm deep). Surface is only wetted after large irrigation events.

Figure 34. Terminology in drip and micro irrigation (Source: USDA (a/b), Southern Irrigation (c))

Drip and micro irrigation have historically been used in high value and horticultural or perennial row crops due to the cost associated with this type of system. However, because of its high water use efficiency and reduced pumping requirements, sub-surface drip irrigation is becoming of interest to more traditional field crop applications. Drip irrigation systems offer benefits in water conservation and increased crop yields under conditions of water restrictions. Drip systems are characterized by low flow rates.

Drip Irrigation System Components

The main components of a drip irrigation system are similar to those of a centre pivot (Figure 35). The major difference is that the water delivery system itself is laid out permanently over the entire area of a field. The components are:

1. Pump – mechanical system that supplies water to system.
2. Filters - prevent debris and sediment from clogging the emitters, ensuring a consistent flow of water.
3. Valves and pressure regulators - maintain a consistent pressure within the system, ensuring even water distribution.
4. Control panel - set up programs to run regular, returning irrigation and/or fertigation applications as well as download past system information. Most often with a remote communication device such that programs can be designed on a computer or phone.
5. Tubing and Laterals - These transport water from the water source to the emitters. Mainlines deliver water to the field, and sub-mainlines or laterals distribute water within the field.
6. Emitters - These are devices that release water drop by drop directly to the plant root zone.
7. Zones - sets of laterals that are irrigated simultaneously. The pump requirement of a drip irrigation system can be maintained low by not irrigating the entire field at once.

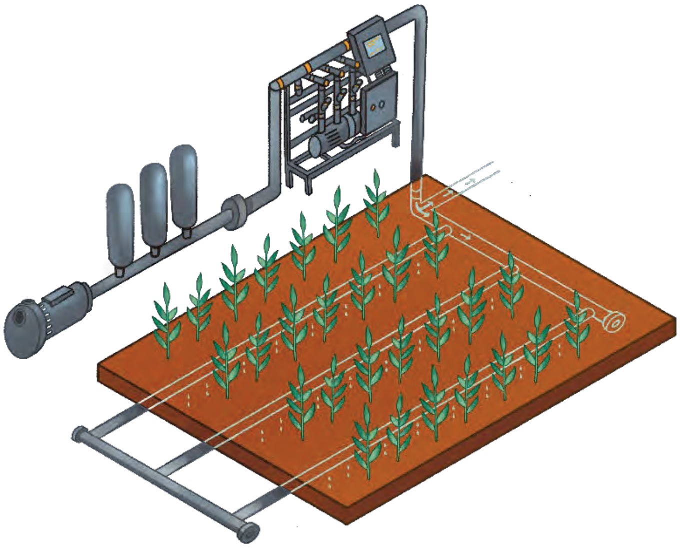


Figure 35. Components of a subsurface drip irrigation. Image credit Dana Woodward.

Where horticultural row crops are considered, line and emitter spacing is chosen to be in accordance with plant spacing. In field agriculture, one dripline serves multiple plant rows. The non-uniform wetting pattern generated by (subsurface) drip irrigation requires consideration of the maximum lateral spread of water that can be achieved in a field’s soil. In sandy soils, lines will need to be placed more closely together than in loamy soils. In high-clay soils, the low hydraulic conductivity and cracks may also prevent a regular shape of the wetting pattern.

Practically, a line spacing of 0.85 m (loamy sand) to 1.0 m (clay loam/silt loam/sandy clay loam) balances water distribution and economics in prairie fields. While the lines and emitters are distributed evenly throughout a field, irrigation is provided to parts of a field at a time in order to keep the pumping requirements low and allow for flexibility in irrigation applications in space. The group of zones in a system that needs to be watered simultaneously should be chosen such that the entire field can be irrigated to the maximum crop water need in 24 hours.

Irrigation Scheduling for Drip systems

The main factors guiding drip irrigation scheduling are the same as those guiding centre pivot irrigation scheduling: crop type, growth stage, weather, soil type, soil water levels. However, due to the large difference in flow rate between drip emitters and overhead sprinklers, decisions on the timing, frequency, and size of the application need to be considered differently.

Step-by-Step Guide to Scheduling

1. Determine Soil Moisture: Use a soil moisture sensor or method previously described to assess the water content at different depths. This helps avoid over- or under-irrigation by providing real-time data on soil moisture levels. Due to the uneven wetting around emitters, the placement of the sensor or sampling compared to the driplines and emitters needs to be considered. Ideally, one sensor location is chosen between two driplines and a second location closer to a dripline at 10 to 15 cm distance from an emitter. The first sensor location will provide information to assess early-season moisture conditions (i.e. when root systems are not fully developed), while the second location will provide information on mid- and late-season moisture conditions and potential for leaching of water from the rootzone.
2. Calculate Water Requirements: Consider the crop's water needs based on its growth stage and the local climate conditions.
3. Calculate run time for drip irrigation systems. Note that calculation needs to account for both the runtime of a zone and all the zones in the field (Equation 9, Appendix C, page 76; Example 12, Appendix D, page 83) shows the irrigation run time per zone.
4. Frequency Adjustment: Because drip systems deliver water slowly, amounts of water delivered during single applications are typically small. Therefore, systems need to be run more frequently than traditional centre pivot systems.
5. “building the bank”: it is more difficult to resolve soil moisture deficiencies with drip systems, particularly with subsurface drip systems. Larger applications can be applied in periods of low crop water demand. However, the concentrated water injection may lead to saturated conditions and rapid leaching because the water is injected deeper in the rootzone. These events may be difficult to notice, because it is all underground. SDI is therefore more suited to keep up regularly with crop water demand.
6. Monitor and Adapt: Regularly monitor soil moisture levels and plant health. Adjust the schedule as needed to accommodate changes in weather, plant growth, and other factors.

Special circumstances – scheduling around crop emergence

When irrigating a field crop at a plant row spacing smaller than the SDI drip line spacing, extra attention needs to be paid to soil moisture conditions around emergence. Frequent (small) applications are needed to create a moisture profile that allows for emergence along and between drip lines. This can, in effect, lead to some overirrigation in the beginning of the growing season, if there is not enough rainfall to help the crop germinate. This overirrigation can be compensated later in the growing season by keeping track of the water balance.

VARIABLE RATE IRRIGATION – PRECISION AGRICULTURE APPLIED TO IRRIGATION

Variable-Rate Irrigation (VRI) is a precision agriculture management practice applied to irrigation – only as much water as the crop needs (RIGHT AMOUNT) is applied where (RIGHT PLACE) and when (RIGHT TIME) the crop needs it.

Conventional irrigation systems are designed to apply water uniformly throughout the field with each application. However, fields are not uniform and can vary significantly in terms of elevation, soil texture, crop type and growth stage. This results in differences in crop water use/needs across a field. With irrigation technology advancements, irrigators can vary irrigation by small-area zones to better match the variability in crop requirements. Better control over in-field soil moisture reduces over- and under irrigation application and can significantly affect crop yield, quality and maturity synchronization (Figure 36).

Figure 36. Left: Soil moisture variability resulting in standing water. Right: variability in crop development .

VRI, as it relates to centre pivot irrigation, falls into two categories:

i) **Speed Control Variable Rate Irrigation (1-D control)**: The speed of the centre pivot is varied as it travels. Reduced speed results in increased irrigation depth, where increased speed results in decreased irrigation depth. This practice is limited to controlling the application depth in pie-shaped segments around the field (Figure 37a).

ii) **Site Specific Variable Rate Irrigation (2-D control)**: Both the speed of the pivot and sprinkler operation (on/off control valves) is varied. This allows irrigators to alter the application rate in small zones along the length of the irrigation system (Figure 37b).

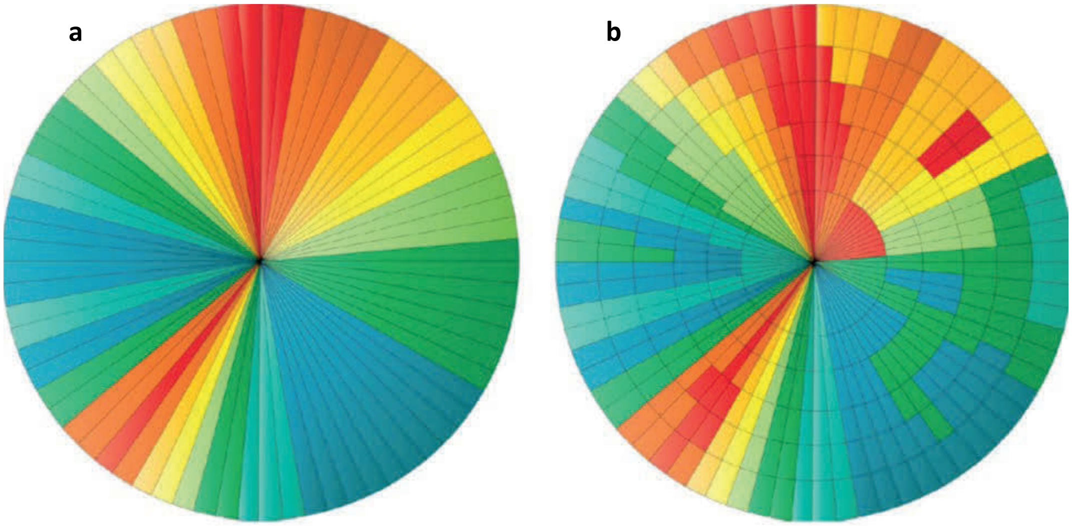


Figure 37. Schematic of a VRI plan: a) speed control and b) speed+sprinkler valve control.

Site Specific VRI Implications
Each SS-VRI systems is unique in how the zones are setup (number of sprinklers) and controlled (electric, hydraulic, pneumatic), and each system can be tailored to your unique field needs. It is important to understand the hydraulic processes that are occurring within your irrigation system and how they will change when it is converted from a traditional to SS-VRI system.

SS-VRI systems function by pulsing sprinklers on/off along the length of the irrigation system as it travels through the field. This pulsing or cycling of the sprinklers helps to regulate the water application as prescribed by the user. Sprinklers are cycled with use of a control valve mounted between the pivot span pipe and the sprinkler nozzle.

Traditional pivot systems operate at a fairly constant flow rate and pressure, applying a uniform rate of water across the field, with the application depth varying depending on the systems travel time. With SS-VRI, the flow rate is in constant flux, depending on the number of sprinklers cycling at any given time. Irrigation pumps are designed to generate consistent pressure at a fixed flow rate. As the flow rate fluctuates, as during SS-VRI operation, pressure can spike (when flow is restricted) or drop (when flow increases). These pressure waves can result in changes in sprinkler performance and more seriously, stress on irrigation piping, which can lead to premature failure.

To help extend the life of your irrigation components and ensure that sprinklers are operating as designed the following components should be considered in an SS-VRI system:

- Sprinkler pressure regulators - are spring filled devices mounted on each sprinkler. These simple devices maintain sprinkler pressure ensuring that discharge rates are as per specifications.
- Control valves – Irrigation pressure control valves are usually diaphragm based systems that are installed in a pipeline. These systems are designed to open/close (constrict) to regulate the pressure on the downstream side of the valve.

- Variable Frequency Drives – Regulators and control valves are designed to maintain downstream pipeline pressure, but produce significant pressure spikes impacting upstream systems including the pump. Variable Frequency Drives (VFD), are electronic systems that have the ability of speeding up or slowing down a pump by varying the frequency of the power supply. Through regulating pump speed to meet downstream flow and pressure requirements, undue pressure spikes are limited, extending the life of irrigation components.

VRI Watering Prescriptions

VRI systems introduce a spatial component to traditional irrigation scheduling. Some irrigation scheduling methods are more easily adapted than others (e.g. remotely sensed vs. in-place monitoring), but all methods can be adapted.

To start, VRI requires a spatial irrigation application map referred to as a VRI-prescription. VRI-prescriptions have two components: zones (spatial) and rates (depths). Zones are areas of similar management with the number of zones and the irrigation rate that is applied to each zone depending on the variability of the field and capability of the irrigation system.

VRI zones are mapped out to follow one of two management methods (Figure 38):

- **Static**: Irrigation zones are created at the beginning of the growing season and remain constant (static) for the season. The application depth in each zone can change over the year but zone boundaries remain the same.
- **Dynamic**: Irrigation zones are created at the beginning of the growing season and their boundaries are continually updated throughout the growing season as spatial data becomes available.

Each method has benefits (simple vs. complex) and drawbacks (limited vs. adaptable). The management method will need to be adapted to suit the management system.

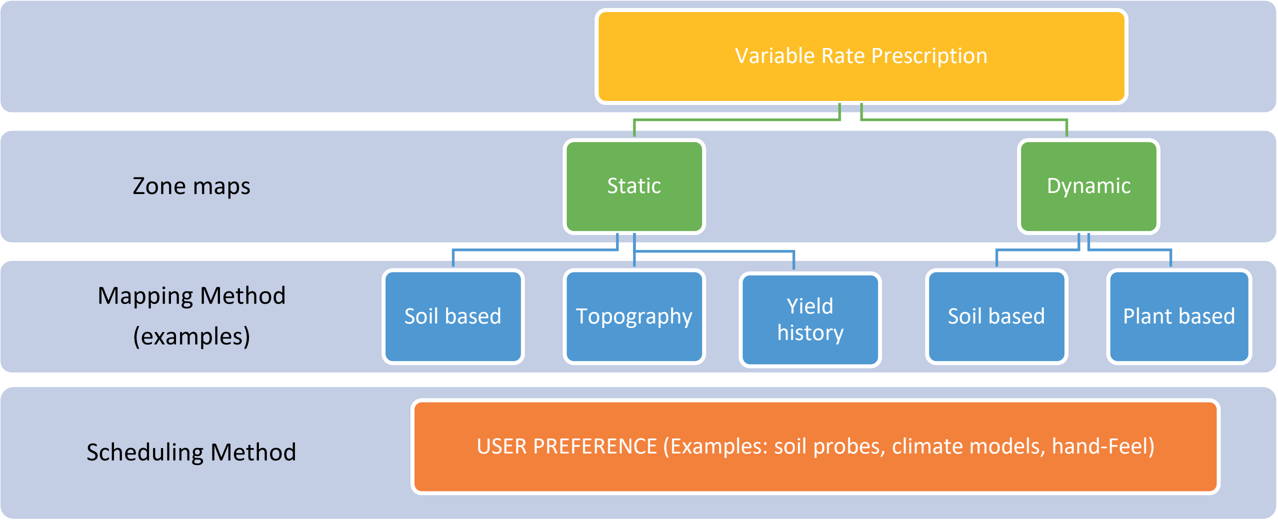
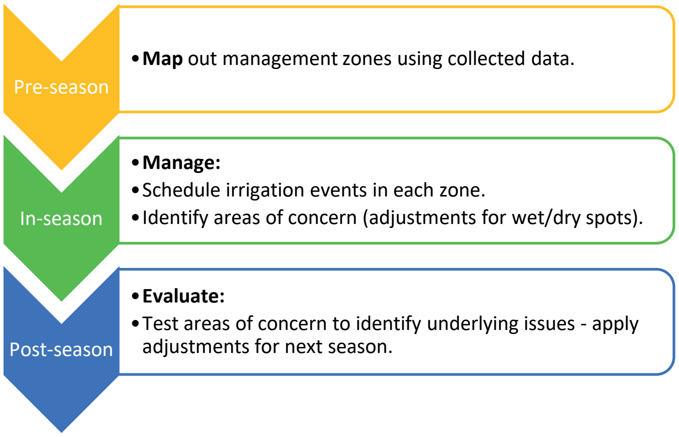


Figure 38. Variable Rate Irrigation prescription development method options.

Static VRI zones

Static zone management is broken down into three major components: zone mapping, manage and evaluate.

Static VRI zone management



- **Map** out management zones using collected data.

- **Manage:**
- Schedule irrigation events in each zone.
- Identify areas of concern (adjustments for wet/dry spots).

- **Evaluate:**
- Test areas of concern to identify underlying issues - apply adjustments for next season.

Mapping out the zones

Static management zones are based on field survey data collected outside the growing season and will not change during the growing season. Common survey types include soil texture, topography, fertility and yield.

Soil Texture

Since soil texture strongly impacts water holding capacity which in turns affects water availability for crop growth, it is a key factor in irrigation scheduling. It is therefore a critical component in developing VRI zones. Historical soil survey maps can be a first step to mapping out soil texture (Figure 39; Appendix D: Example 13, page 84). However, these maps are low resolution (typically 1:100,000 or lower) and should be supplemented with soil sampling (see: Mapping out your soils, pp. 7-9).

Electromagnetic and Electrical Conductance

Electromagnetic (EM) instruments (Figure 39) determine the electrical conductance (EC) of soil across a field (measured in milliSiemens/metre). Major factors influencing EC values are soil texture (particle size), moisture and salinity (and to a lesser extent, compaction and temperature). A high EC value could indicate high salinity, high clay content, high moisture (low area, seep) or some combination of these factors. A low EC value could be an eroded knoll, a relatively high area or sandy/gravelly soil or a combination of factors. To sort these issues out, sample soil from anomalous areas as well from a few average or representative sites. This data is then used to produce a spatial soil texture and salinity map by grouping areas of similar EC values adjusted with soil analysis and field history (e.g. poor crop, high kochia population).

Figure 39. Electromagnetic (EM) sensor on field sled for conducting EM and topographical surveys.

The number of irrigation management zones based on the EC-derived soil texture and salinity map should be selected to fit the irrigator’s comfort level in managing zones (Figure 40b; Appendix D: Example 14, page 85).

Topography

Although not absolute, the relationship between soil moisture content to topography follows some well-established trends (Yari et al 2017):

- High areas (hills, knolls) tend to be more eroded, prone to evaporation and internal drainage to lower elevations.
- Lower areas tend to collect water.

Zones can be grouped by areas of high elevation, mid-slopes, low elevation, and local depressions. Topography by itself may not be enough to develop a good VRI map, but it can add value to existing soil texture maps for identifying features or responses that are not captured in a soil texture map (Figure 40c; Appendix D: Example 15, page 85).

Yield Maps

A yield map is a good indicator of productivity under normal management practices. Areas or zones of similar productivity are assumed to have similar water demand throughout the growing season. VRI-prescriptions would be developed similar to other static methods (EC, topography) by grouping areas of similar yield ranges (e.g. top third, mid third and lower third).

Putting it Together

Static-based zone mapping methods are based on surveys or field data collected outside of the growing season. Each survey method results in a unique map but with many points of similarity (Figure 37). Using soil texture as a starting point, the other data can be used to adjust irrigation management zones.

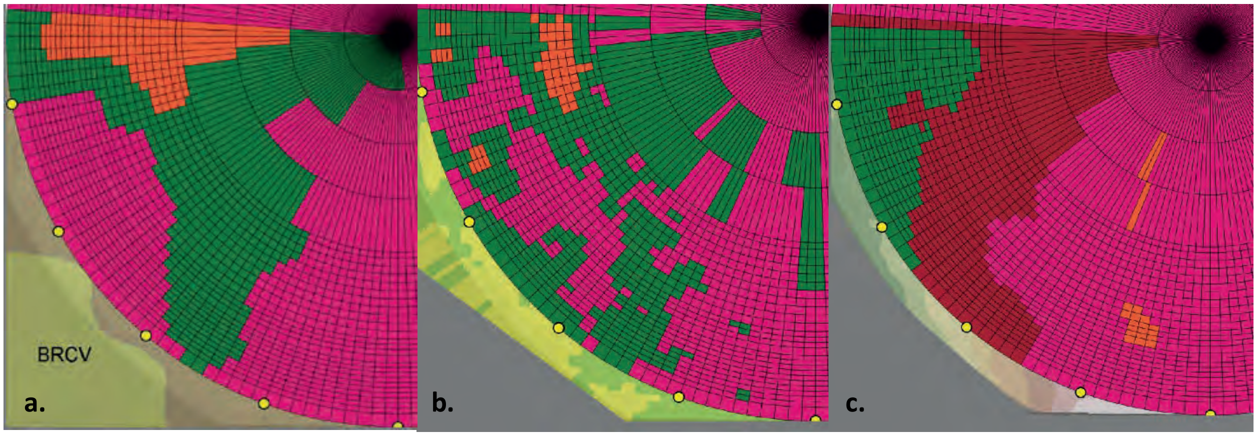


Figure 40. Example static zone maps based on (a) soil texture, (b) electrical conductivity, (c) topography for the same field.

Manage

Once the management zones have been created, the irrigator should schedule irrigation within each zone using the preferred irrigation scheduling method. This can be soil-based (eg. tensiometers, hand feel), weather based (eg. cheque-book) or plant-based (eg. IrriCAN). It is important to map out the zones and apply the method that works best with your production system, taking into account cost, location, labour, etc.

Evaluate

Evaluate the performance of your zone maps at the end of the irrigation season to determine if your management method is producing the desired results. Evaluation can consist of simple observations throughout the growing season, noting areas of concern (wet/dry). More intensive analysis may include review of yield or NDVI maps to identify areas of concern or adjust zone boundaries. It is important to continue to evaluate the irrigation zones to ensure you are getting the desired results from the investment in a VRI system.

Dynamic VRI zones

Dynamic management zones are developed at the beginning of the growing season and the boundaries are adjusted throughout the growing season as data is collected, following a process of mapping, manage (including ongoing data collection and adjustment) and evaluate.

Dynamic VRI zone management

Pre-season

- **Map** out management zones using previously collected data.

In-season

- **Manage:**
- Schedule irrigation events.
- Collect soil or plant response data.
- Adjust zones based on collected data.
- Repeat.

Post-season

- **Evaluate:**
- Technology and data collection timing.

Mapping out the zones

The benefit of dynamic response maps is that irrigation decisions are based on monitoring soil moisture conditions and/or plant response to environmental conditions. This is a better representation of what the plant experiences throughout the growing season.

Creating VRI dynamic management zones is more complex than for static management zones, requiring additional data collection and ongoing adjustments to the VRI-prescription throughout the growing season. Data collection is limited to remote sensing, as continual in-field sampling would end up damaging the crop. Advancements in remote sensing options and automated computer mapping systems has reduced much of the labour and time requirements of intensive dynamic mapping.

Soil-based

There are limited technologies available for remote soil moisture monitoring. One emerging technology is using microwave radiometers to estimate soil moisture. A relatively new sensing technology in agriculture, microwave radiometry has been used by NASA to estimate large-scale soil moisture status. Microwave radiometers measure specific microwave wavelength emissions from the soil. Like TDR and capacitance sensors (pages 30-33), soil moisture affects microwave emissions. Depending on the microwave wavelength (i.e. frequency), the sensing depth ranges from 5–30 centimetres (2–12 inches).

The data processing is complex and available sensors are partnered with a service subscription to generate soil moisture maps (e.g. SMARTDROP, Figure 41). Because microwave radiometer maps report in volumetric water content, these maps can be used for both irrigation zone mapping AND irrigation scheduling.

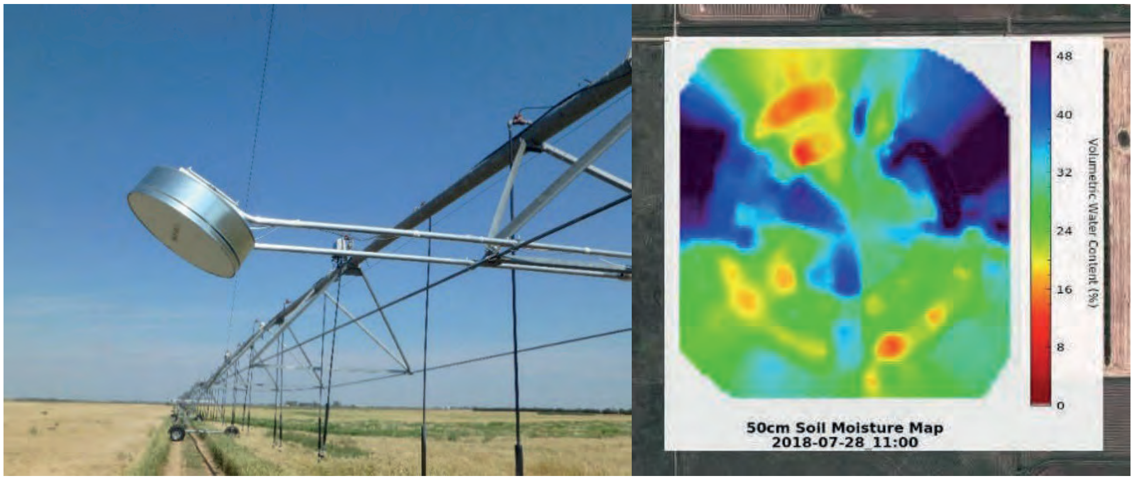


Figure 41. Left: SmartDROP microwave radiometer. Right: measured soil moisture map.

Figure 42 is an example of how radiometer imagery displays soil moisture status in a field and how it can change over as little as a week. In the August 8 image, some areas of the field have become wetter (area marked (1)) while others have become drier (area marked (2)). This difference could be due to irrigation on the left side only and/or due to topography with water draining from high (right) to low (left) elevation after a rainfall or irrigation event

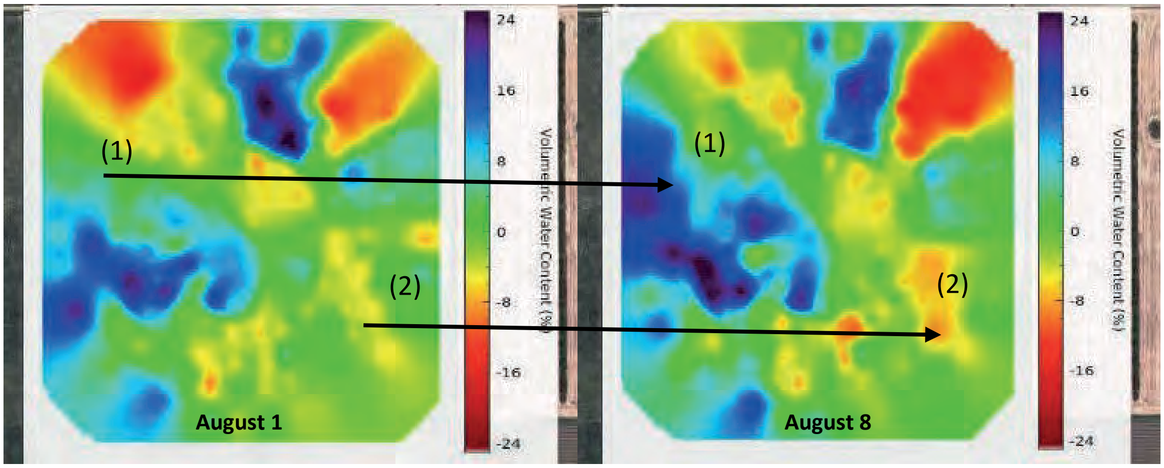


Figure 42. Microwave radiometer images for the same canola field taken one week apart. Values represent difference from average soil moisture content in percent volumetric water content for the day that the image was captured. Arrows highlight areas that have changed in their moisture status (i.e. become wetter (1) or drier (2)) relative to the average.

Plant-based

Plant-based zone mapping uses remotely sensed data on plant response to moisture stress (excess/deficit) to create zones. Options available for remotely sensing plant stress include i) Normalized Difference Vegetation Index (page 39) and ii) Crop canopy temperature or Crop Water Stress Index (page 43).

<u>Normalized Difference Vegetation Index</u>: Normalized difference vegetation index values can be broadly categorized into high, medium and low and fields can be mapped out along these categories. With each new image, the zones can be re-mapped according to the three categories (Appendix D: Example 16, page 86).

Historical images/data can be used to map out fields when current imagery is not available (e.g. due to cloud cover) or for those times in the season when remote imagery does not accurate accurately reflect estimates of soil moisture, crop productivity or plant stress (e.g. early season, before canopy closure). Historic photos can also help determine where and when crops are most likely to become stressed as well as to gain a better understanding how water is distributed in the field after irrigation/rainfall events (e.g. where does the water drain from and where does it drain to?) (Figure 43).

<u>Crop Canopy Temperature/Crop Water Stress Index</u>: Internal leaf temperature is maintained at or near air temperature through the cooling effect of the transpired water evaporating off the leaf's surface. Canopy temperature variability throughout the field can therefore be used to estimate soil water holding capacity. Areas with low soil water holding capacity will show increased canopy temperatures

more quickly than soil with higher soil water holding capacity (Bauer 2019). Temperature differential (canopy vs. air) can be grouped into broad ranges to map out zone boundaries.

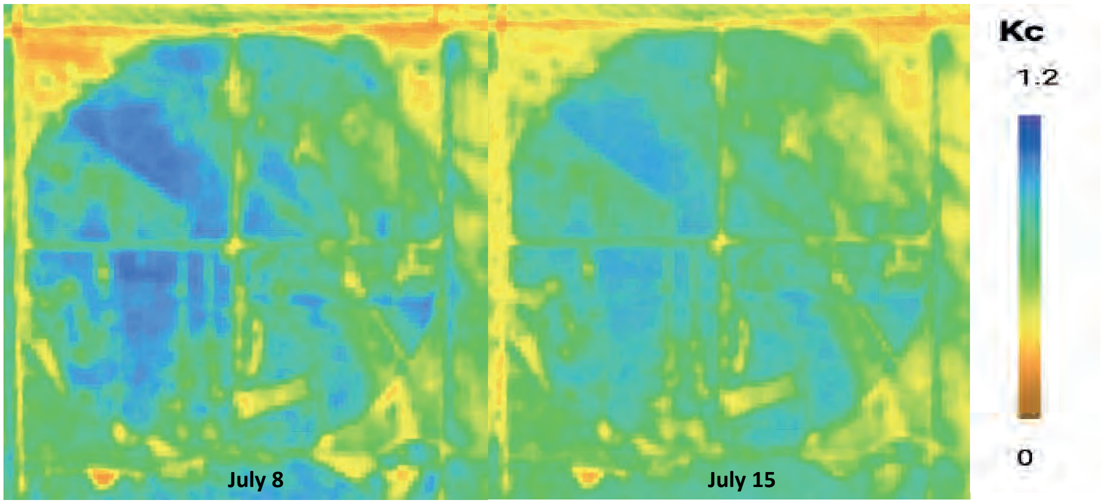


Figure 43. NDVI images from July 8th (left) and July 15th (right). In general, the overall crop health decreased over this period, indicating possibility of insufficient moisture to maintain crop health.

Manage

Soil-based

Remotely sensed soil moisture status can be used in conjunction with estimates of crop water demand (e.g. using crop- and growth stage-specific coefficients) to schedule irrigation for each identified zone. For example, the SmartDROP system (microwave radiometry) reports percent volumetric soil moisture content (Figures 41, 42). Soil texture can be used to determine plant available water in each zone (Appendix A: Table A3, page 68). Using these two pieces of information, it is relatively straight-forward to determine how much water to apply at the next scheduled irrigation event to bring the soil up to field capacity in each zone.

With further analysis of the soil moisture maps over time, water distribution patterns emerge (i.e. can see where water accumulates after irrigation/rainfall). This information can be used to fine-tune irrigation scheduling with the goal to even out soil moisture across the field. For example, areas with soil moisture near/just above maximum allowed depletion would be irrigated to meet crop water demand until the next scheduled irrigation event (MAINTAIN). Areas that are wet (e.g. near field capacity) would only need to be irrigated to keep soil moisture above maximum allowed depletion (no irrigation may be necessary, DRAW DOWN). The drier areas would need to be irrigated enough to bring the soil moisture level up to alleviate potential crop stress (e.g. up to maximum allowed depletion) **plus** enough to satisfy crop water demand (CATCH UP). Irrigation amounts would be recalculated for each scheduled irrigation event by evaluating how soil moisture status changed following the last irrigation event.

Plant-based

<u>Normalized difference vegetation index</u>: Normalized difference vegetation index values are closely correlated to crop water demand: high index values indicate a crop with a thick, lush canopy (high water demand); low index values indicate a weak, sparse canopy (lower water demand). This relationship can be used to convert index values into crop water-use coefficients and then plugged into crop water use equations/models to estimate irrigation needs for each zone. One advantage is that this data is then

crop- and growth stage-independent, reducing the need to rely on published crop water-use coefficients which (a) have been calculated on historical data (may no longer be accurate) and (b) may not be available for your area.

Crop canopy temperature/Crop water stress index: Crop canopy temperature, as it relates to the surrounding air temperature, can indicate soil water availability. This method only shows the relative crop water stress (e.g. Crop water stress index) and does not indicate actual moisture status or irrigation requirements. Therefore, it should be used in conjunction with an existing irrigation scheduling method. Alternative indices (e.g. Time-Temperature Threshold) are being evaluated that look at providing a better indication of when to irrigated based on canopy temperature.

Evaluate

The core principle of dynamic zone irrigation scheduling is continual adjustment of the irrigation prescription throughout the irrigation season. Irrigation zones and irrigation depths are adjusted with each new data set/image. The in-season evaluation can be supplemented by checking field and crop conditions to ensure the irrigation scheduling system is working as expected.

At harvest, yield maps can add to the performance analysis. Question to ask include:
- Did average yield go up?
- Did yield variation across the field decrease?
- How did typically low-yielding areas respond?
- How did typically high-yielding areas respond?
- How well does the yield variation map correspond to the mapped out irrigation zones?

Automation

With advances in sensor technology, computer processing and artificial intelligence, automated variable rate prescription systems are coming to market (Figure 44). These systems use proprietary sensors mounted on the irrigation system to continually monitor variables which are indicative of plant water stress. With the support of artificial intelligence, the computer system 'learns' to adjust sprinkler application rates throughout the year to minimize plant water availability.

Although these automated systems help develop VRI prescriptions for the user, it is still important to implement an irrigation schedule, through one of the previously recommended approaches (Soil based, Weather based, Plant based) to know when it is time to irrigate.

Figure 44. Automated Site Specific Variable Rate Irrigation (SS-VRI) sensors and valves mounted on a centre pivot irrigation system (InteliRain 2023)

WHEN TO STOP IRRIGATING

The last irrigation should be scheduled to provide sufficient soil moisture to carry the crop to maturity. However, unnecessary late season irrigation, depending on the crop and crop stage, can have little to no effect on final yield and adds additional input costs (pumping, water) and unnecessary equipment wear and tear. In addition, wet soil due to unnecessary irrigation can delay harvest (can affect maturity/seed moisture content, field access) and lead to soil compaction from heavy harvest equipment. Avoiding late season irrigation has the added benefit of allowing the soil to dry down so that it can hold more snow melt and spring precipitation leading to less run-off (Appendix A: Table A9, page 70; Appendix D: Example 17, page 87).

IRRIGATION SCHEDULING ASSISTANCE

As irrigation water is a public resource and availability can fluctuate between years, it is important to make sure that irrigation water is being used efficiently. Applying the wrong amount of water (too much/too little) at the wrong time can result in crop stress or increase the risk of disease development. These issues can result in lower yields and increased costs.

Irrigation Agrologists with the Provincial Ministry Employees can provide technical assistance related to irrigation scheduling and can demonstrate on-farm practices to irrigators.

Provincial Irrigation Agrologists can work with new or existing irrigators throughout the growing season to help ensure they understand the fundamental principles of effective irrigation scheduling. At the end of the growing season, the irrigator will have the technical knowledge and practical skills to continue scheduling in the future.

Contact your Provincial or Federal Irrigation Staff for Assistance:

Alberta:
Alberta Ministry of Agriculture and Irrigation
Toll free: 310-FARM (3276) (in Alberta)
Phone: 403-742-7901 (outside Alberta)
Email: 310farm@gov.ab.ca

Saskatchewan:
Saskatchewan Ministry of Agriculture – Irrigation Office
Phone: 306-867-5500
Email: irrigation@gov.sk.ca

Manitoba:
Phone: 844-769-6224 (General Enquiries)
Email: agriculture@gov.mb.ca

Government of Canada:
Canada-Saskatchewan Irrigation Diversification Centre
Phone: 306-867-5400
E-mail: aafc.csidc-crdi.aac@agr.gc.ca

APPENDIX A: REFERENCE FIGURES AND TABLES

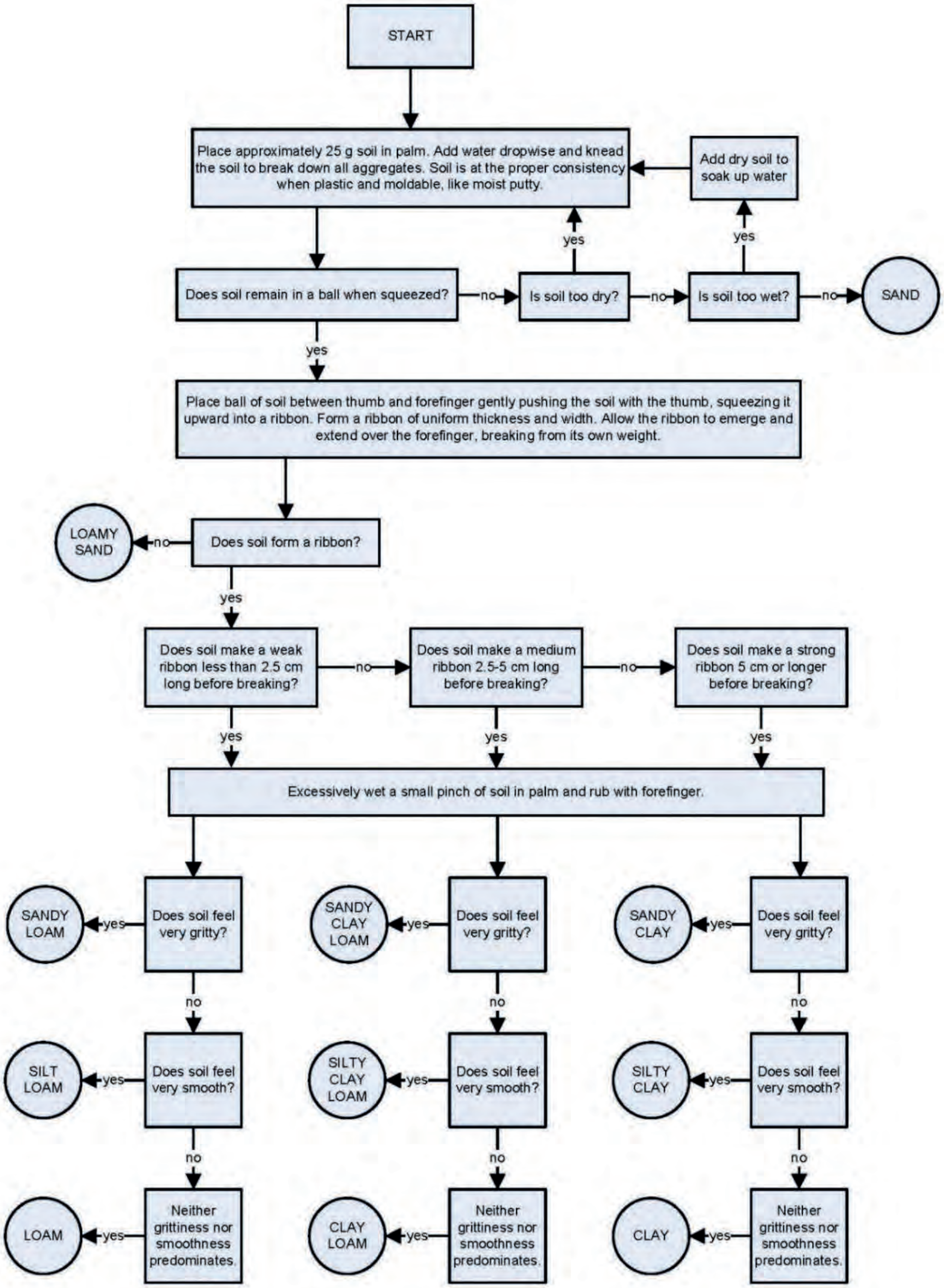


Figure A1. Hand feel texturing method. Determining soil texture by the “feel method”. Redrawn from “A Flow Diagram for Teaching Texture-by-Feel Analysis”, by Steve J. Thien, Journal of Agronomic Education, Vol.8, 1979, pp.54–55.

Table A1. Water Quality Guidelines for the Protection of Agriculture (Irrigation)

Parameter	Concentration (µg/L)
Aluminum	5,000
Arsenic	100
Beryllium	100
Boron	Variable*
Cadmium	5.1
Chloride	Variable*
Chromium, hexavalent (Cr(VI))	8
Chromium, trivalent (Cr(III))	4.9
Cobalt	50
Copper	Variable*
Fluoride	1000
Iron	5000
Lead	200
Linuron	0.071
Lithium	2500
Manganese	200
Molybdenum	10 for continuous use on all soils 50 for short-term use on acidic soils
Nickel	200
Selenium	Variable*
Uranium	10
Vanadium	100
Zinc	1000 when soil pH < 6.5 5000 when soil pH > 6.5
Aldicarb	54.9
Atrazine	10
Bromacil	0.2
Bromoxynil	0.33
Chlorothalonil	5.8 (other crops)
Cyanazine	0.5
Dicamba	0.006
Diclofop-methyl	0.18
Diisopropanolamine	2,000
Dinoseb	16
Metolachlor	28
Metribuzin	0.5
Simazine	0.5
Sulfolane	500
Tebuthiuron	0.27 (cereals, tame hays, and pastures)
Coliforms, fecal (Escherichia coli)	100 per 100 mL
Coliforms, total	1,000 per 100 mL

* Crop specific guidelines for these parameters can be found at https://ccme.ca/en/current-activities/canadian-environmental-quality-guidelines

Table A2. Crop Tolerance and Yield Potential of crops influenced by water salinity (EC_w) or Soil Salinity (EC_e). (Ayers and Westcot, FAO 1994)

Crop	**Yield Potential**							
	100%		90%		75%		50%	
	EC_e	EC_w	EC_e	EC_w	EC_e	EC_w	EC_e	EC_w
Barley	8.0	5.3	10	6.7	13	8.7	18	12
Wheat	6.0	4.0	7.4	4.9	9.5	6.3	13	8.7
Soybean	5.0	3.3	5.5	3.7	6.3	4.2	7.5	5.0
Corn	1.7	1.1	2.5	1.7	3.8	2.5	5.9	3.9
Bean	1.0	0.7	1.5	1.0	2.3	1.5	3.6	2.4
Broccoli	2.8	1.9	3.9	2.6	5.5	3.7	8.2	5.5
Potato	1.7	1.1	2.5	1.7	3.8	2.5	5.9	3.9
Carrot	1.0	0.7	1.7	1.1	2.8	1.9	4.6	3.0
Wheatgrass	7.5	5.0	9.9	6.6	13	9.0	19	13
Alfalfa	2.0	1.3	3.4	2.2	5.4	3.6	8.8	5.9

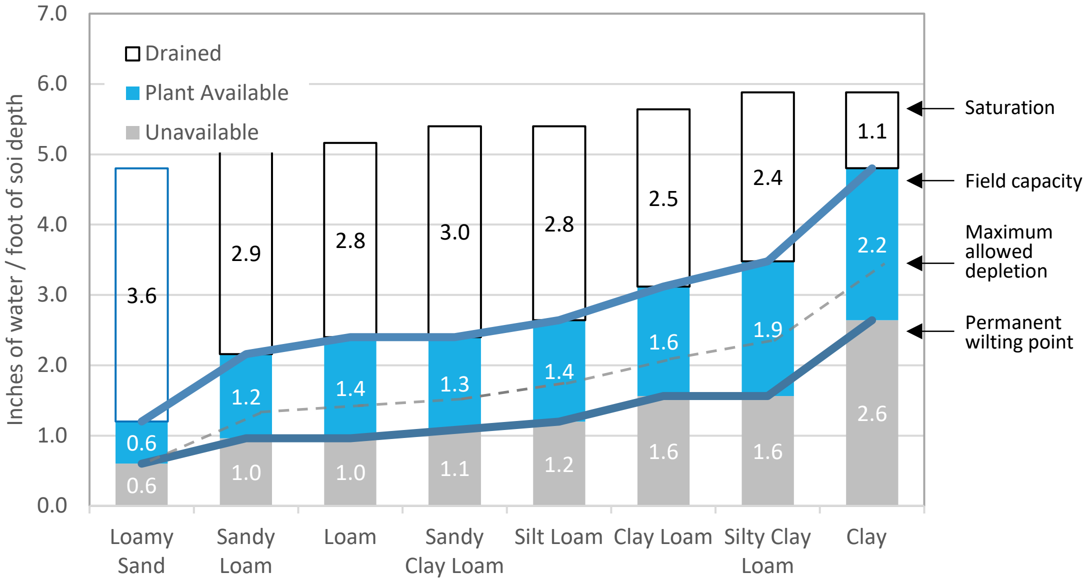


Figure A2. Relationship between saturation, field capacity and permanent wilting point for common soil textures.

Table A3. Average physical soil characteristics.

Texture	Field Capacity* %	Wilting Point* %	Available Moisture Holding Capacity* %	Available Moisture at Field Capacity Inches/foot	Infiltration Rate**	
					mm/hr	in/hr
Loamy Sand (LS)	10	5	5	0.84	25	1.00
Sandy Loam (SL)	18	8	10	1.68	18	0.70
Fine Sandy Loam (FSL)	20	9	11	1.85	15	0.60
Very Fine Sandy Loam (VL)	22	10	12	2.02	13	0.50
Silt Loam (SiL)	22	10	12	2.02	9	0.35
Loam (L)	24	12	12	2.01	8	0.30
Clay Loam (CL)	26	13	13	2.23	6	0.25
Clay (C)	40	22	18	3.02	4	0.15

*% moisture by weight-Form studies done randomly throughout Dark Brown Soil Zone

**Field experience and testing done by O.P. Bristol. % expressed by weight

Table A4. Maximum active root zone depth for various crops.

Crop	Active Root Zone centimetres (feet)	Crop	Active Root Zone centimetres (feet)
Alfalfa	120 (4.0)	Flax	100 (3.0)
Barley	100 (3.0)	Grass	80 (2.5)
Beans, dry	60 (2.0)	Lentil	60 (2.0)
Beans, faba	80 (2.5)	Pea	80 (2.5)
Canola	100 (3.0)	Potato	80 (2.5)
Corn, silage	100 (3.0)	Wheat	100 (3.0)

Saskatchewan Ministry of Agriculture and Food

Table A5. Approximate application efficiencies of irrigation equipment.

Irrigation Method	**Irrigation Efficiency**
Low Pressure Centre Pivot	90% +
Micro/Drip/Trickle	90% +
High Pressure Centre Pivot	80% +
Sprinkler Wheel Move	70% +
Volume Gun	60% +
Gravity	60% or less

Table A6. Centre pivot application depth (inches) based on a 133 acre pivot (100% efficiency).

Circle	System Flow Rate (usgpm)							
Time (hrs)	600	700	800	900	1000	1100	1200	1300
24	0.24	0.28	0.32	0.36	0.40	0.44	0.48	0.52
48	0.48	0.56	0.64	0.72	0.80	0.88	0.96	1.04
72	0.72	0.84	0.96	1.08	1.20	1.32	1.44	1.56
96	0.96	1.12	1.28	1.44	1.59	1.75	1.91	2.07

Table A7. Average daily evapotranspiration and critical water-use periods (inches/day).

Crop	May	June	July	Aug.	Sept.	Critical Period
Wheat	0.04	0.10	0.22	0.08	n/a	Tillering and flowering
Barley	0.04	0.12	0.22	0.04	n/a	Tillering and flowering
Canola	0.06	0.16	0.20	0.08	n/a	Flowering and pod development
Silage Corn	0.02	0.06	0.14	0.18	0.06	Tasseling and Grain filling
Dry Bean	0.02	0.08	0.16	0.12	0.02	Late bud through pod formation
Potato	0.02	0.06	0.14	0.16	0.10	Tuber initiation and bulking
Faba Bean	0.02	0.08	0.22	0.16	0.02	Early flowering
Flax	0.04	0.10	0.22	0.10	n/a	Flowering
Field Pea	0.04	0.08	0.20	0.08	n/a	Early flowering

Values are an estimate based on daily water-use data from 2004–2015 in Outlook, Saskatchewan; actual values may vary by ± 20%.

Table A8. Crop water-use coefficient (Kc) for common irrigated crops (Source – FAO).

Crop	Kc_{ini}	Kc_{mid}	Kc_{end}	Max. crop height (m)
Canola	0.35	1.15	0.35	0.6
Cereals	0.3	1.15	0.4	1.0
Corn	0.3	1.2	0.6	2.0
Dry Bean	0.4	1.15	0.35	0.4
Potato	0.5	1.15	0.75	0.6
Soybean	0.5	1.15	0.5	0.5 – 1.0

Table A9. Critical water requirements and timing (Source - Government of Saskatchewan, Irrigated Crop Diversification Centre 2023).

Crop	Seasonal Water Requirement	Critical Water Period	Irrigation Termination
Alfalfa	400 - 500 mm	After Cutting	Prior to killing frost
Wheat	300 - 400 mm	Tillering and Flowering	Soft dough
Barley	250 - 350 mm	Tillering through Flowering	Soft dough
Canola	350 - 450 mm	Late vegetation through Flowering and Pod development	Initial seed ripening
Flax	350 - 450 mm	Flowering	Prior to seed ripening
Corn	300 - 400 mm	Tasseling and Grain Filling	Dent stage
Peas	250 - 350 mm	Beginning of Flowering	Pod filling
Potatoes	300 - 400 mm	Tuber Initiation and Tuber Bulking	Beginning of vine ripening
Dry Beans	250 - 350 mm	Late Bud through Pod Formation	Mid-August
Faba Beans	250 - 350 mm	Beginning of Flowering	Half pod fill
*** Water requirements based on 10yr averages, vary depending on local weather conditions and potential evapotranspiration**			

APPENDIX B: DAILY CROP WATER-USE CURVES

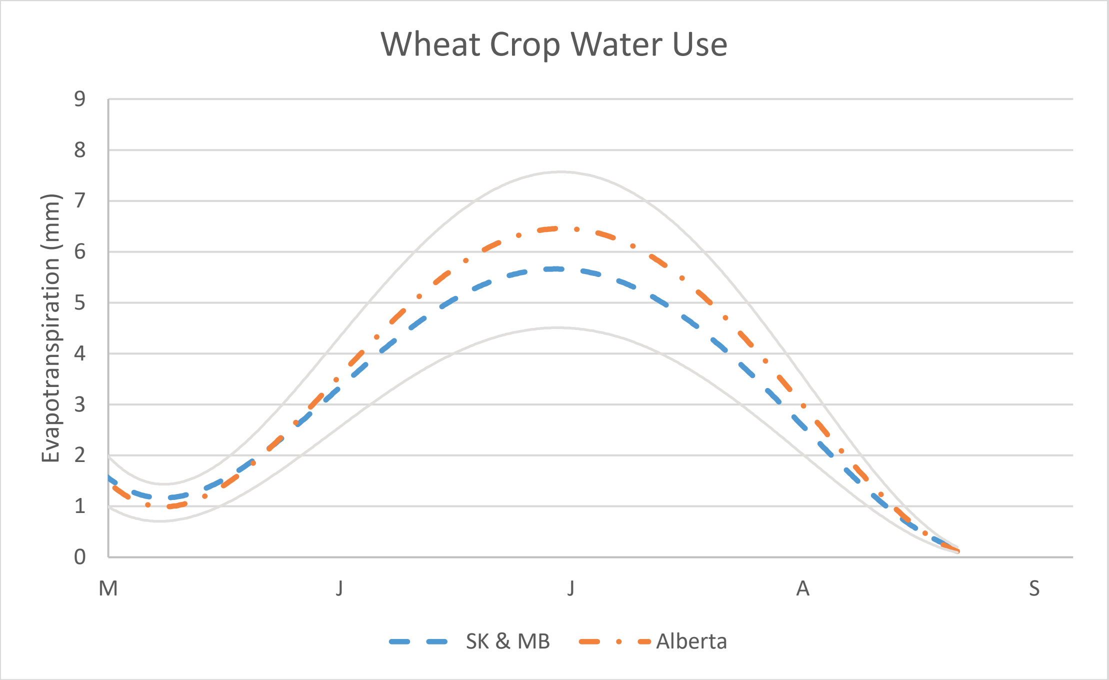


Figure B1. Daily water-use trends for WHEAT based on weather data and crop coefficients, 2014-2023 (Outlook, SK., Carberry, MB., Lethbridge, AB)

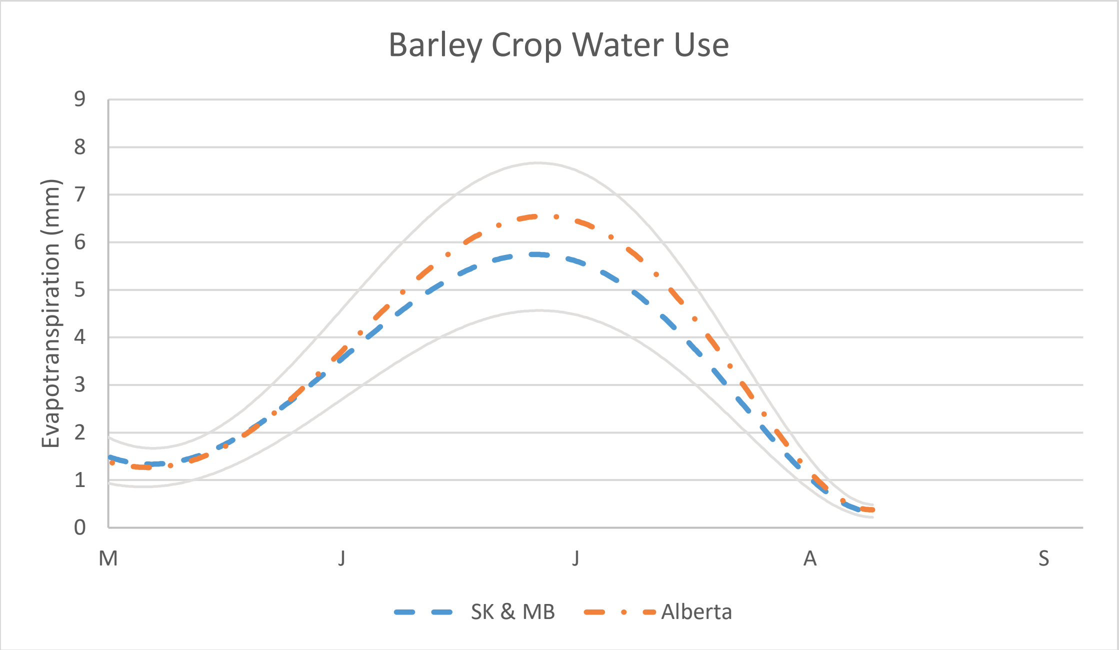


Figure B2. Daily water-use trends for BARLEY based on weather data and crop coefficients, 2014-2023 (Outlook, SK., Carberry, MB., Lethbridge, AB)

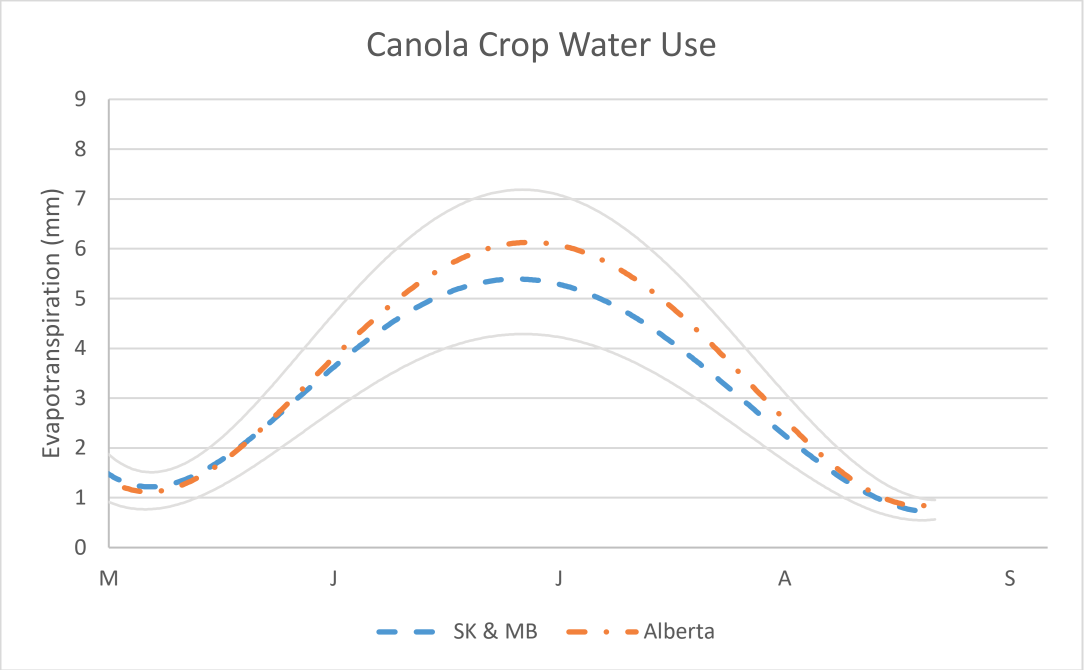


Figure B3. Daily water-use trends for CANOLA based on weather data and crop coefficients, 2014-2023 (Outlook, SK., Carberry, MB., Lethbridge, AB)

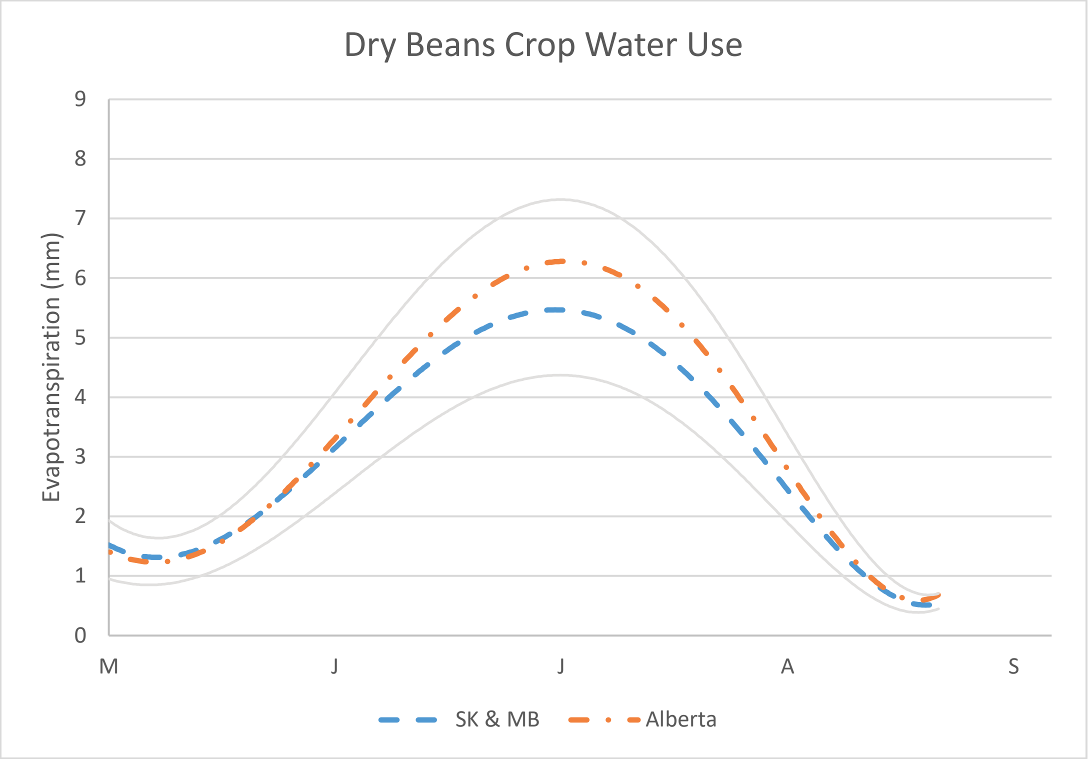


Figure B4. Daily water-use trends for DRY BEANS based on weather data and crop coefficients, 2014-2023 (Outlook, SK., Carberry, MB., Lethbridge, AB).

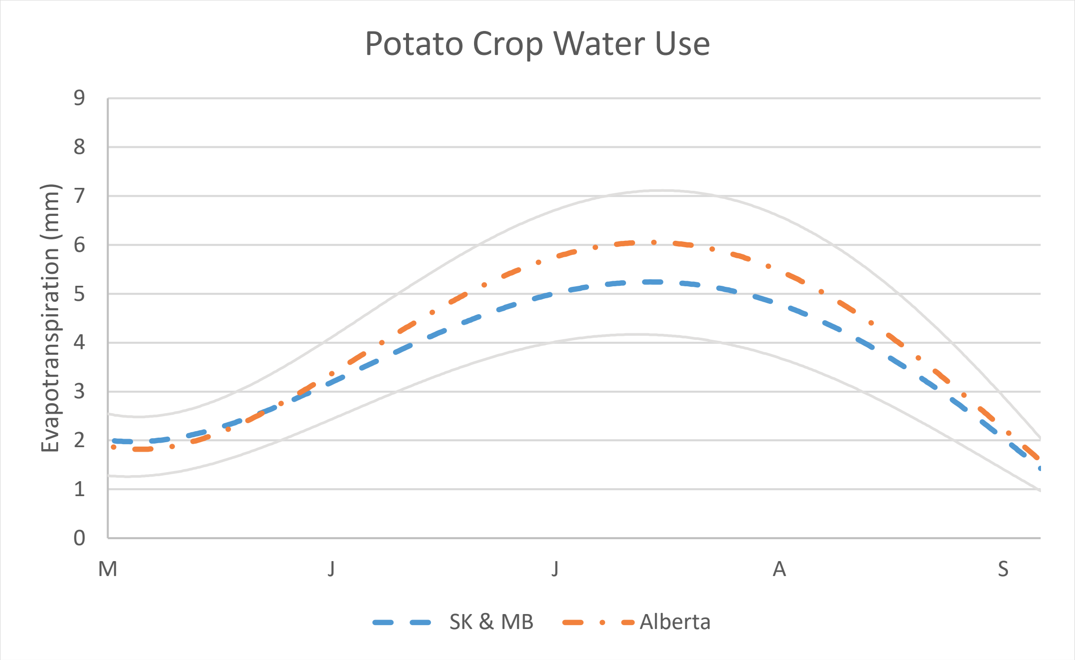


Figure B5. Daily water-use trends for POTATO based on weather data and crop coefficients, 2014-2023 (Outlook, SK., Carberry, MB., Lethbridge, AB)

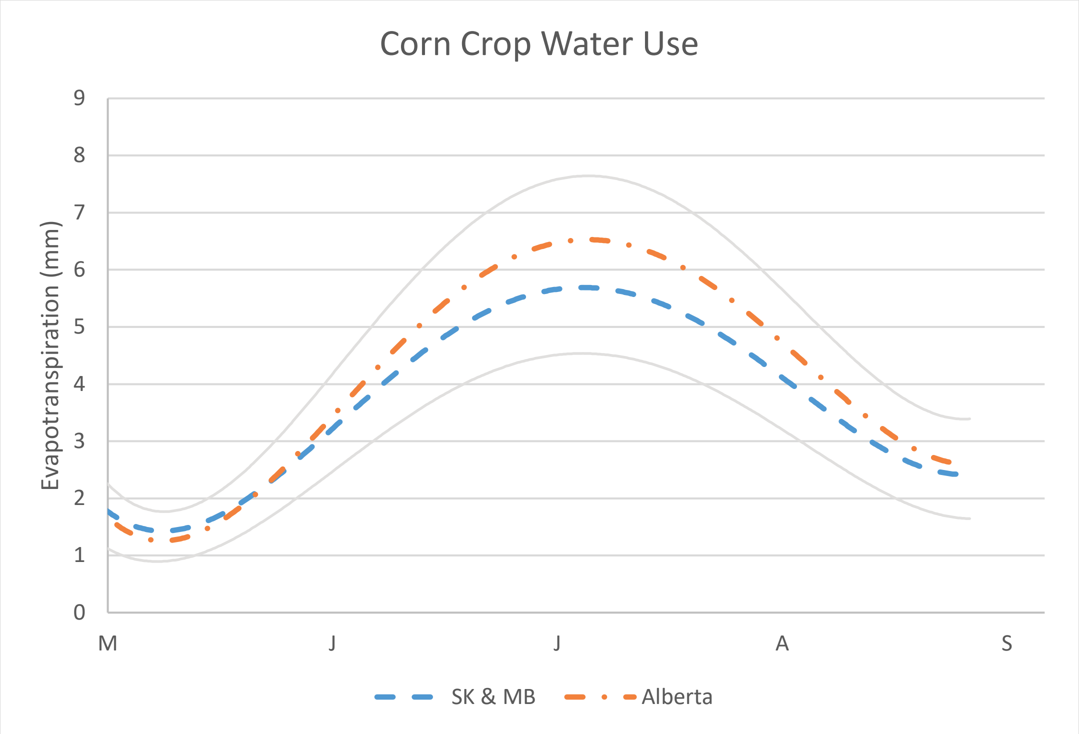


Figure B6. Daily water-use trends for CORN based on weather data and crop coefficients, 2014-2023 (Outlook, SK., Carberry, MB., Lethbridge, AB)

APPENDIX C: EQUATIONS

Equation 1: Sodium Adsorption Ratio (Irrigation Water)

$$SAR = \frac{0.275\,(Na)}{\sqrt{(Ca) + 1.64(Mg)}}$$

Where concentrations of Sodium (Na), Calcium (Ca) and Magnesium (Mg) are expressed as mg/L

Equation 2: Leaching Requirement and Applied Water

$$LR = \frac{EC_w}{5(EC_e) - EC_w}$$

where:

LR – leaching requirement to control salts within tolerance of the crop EC_e
EC_w – electrical conductivity of the irrigation water applied (dS/M)
EC_e – crop specific water use coefficient

$$AW = \frac{ET}{1 - LR}$$

where:

AW – seasonal applied water to meet leaching requirement (mm)
ET – seasonal evapotranspiration of the field/crop (mm)
LR – leaching requirement to control salts (calculated above)

Equation 3:

Calculating changes in soil moisture = Irrigation + Precipitation – Evapotranspiration

Where:

Irrigation: amount applied by the irrigation system, accounting for irrigation system efficiency (Appendix A: Table A5, page 68).
Precipitation: measured from regional weather station or local rain gauge.
Evapotranspiration: water removed from the system through evaporation (soil surface) and transpired through the crop, estimated from crop water-use charts/tables or calculated from local weather data.

Equation 4: Calculating evaporation

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$$

where:

ET_o – reference evapotranspiration (mm/day)
R_n – net radiation at the crop surface (MJ/m^2/day)
G – soil heat flux density (MJ/m^2/day^1)
T – mean daily air temperature at 2 metre height (^{o}C)
u_2 – wind speed at 2 metre height (m/s^1)
e_s – saturation vapour pressure (kPa)
e_a – actual vapour pressure (kPa)
Δ - slope vapour pressure curve (kPa/^{o}C^1)
γ – psychrometric constant (kPa/^{o}C^1)

Equation 5: Adjusting reference evapotranspiration for specific crops

$$ET_c = ET_o * K_c$$

where:

ET_c – crop specific evapotranspiration (mm/day)
ET_o – reference evapotranspiration (mm/day)
K_c – crop specific water use coefficient

Equation 6: Calculating Normalized Difference Vegetation Index

$$NDVI = \frac{NIR - R}{NIR + R}$$

where:

$NDVI$ – Normalized Difference Vegetation Index
NIR – Near infrared reflectance value
R – Red (visible) reflectance value

Equation 7: Calculating crop water use from Normalized Difference Vegetation Index

$$K_c = (1.37 * NDVI) - 0.086$$

where:

K_c – Crop water use coefficient
$NDVI$ – Normalized Difference Vegetation Index
NIR – Near infrared reflectance value

Equation 8: Crop Water Stress Index

$$CWSI = \frac{(T_c - T_a)_M - (T_c - T_a)_{LL}}{(T_c - T_a)_{UL} - (T_c - T_a)_{LL}}$$

Where:

T_c – Temperature of the crop canopy (°C)
T_a – Air temperature at the field location (°C)
$(T_c - T_a)_M$ – Temperature differential of the measured location (°C)
$(T_c - T_a)_{LL}$ – Temperature differential at lower limit (no stress) (°C); can substitute wet bulb temperature T_{wb}
$(T_c - T_a)_{UL}$ – Temperature differential at upper limit (full stress) (°C); can substitute maximum daily air temperature + 5°C (O'Shaugnessy et al. 2011)

Equation 9: Drip Irrigation Run Time

$$T_Z = \frac{S_e \times S_l \times D}{F \times E}$$

Where:

T_Z – irrigation run time per zone (hrs)
S_e – emitter spacing along the laterals (m)
S_l – lateral spacing (m)
D – depth of water applied (mm)
F – flow rate of each emitter (L/hr)
E – application efficiency

Equation X shows the irrigation run time per field:

$$T_f = \frac{T_Z \times n}{z}$$

Where:

T_f – irrigation run time per field (hrs)
T_Z – irrigation run time per zone for the desired irrigation depth (hrs)
N – total number of zones in the field
Z – number of zones that are irrigated concurrently

APPENDIX D: EXAMPLE IRRIGATION SCHEDULING CALCULATIONS

Example 1: Yield loss when irrigation water is insufficient to meet peak yield

A 20% reduction in irrigation water required for peak barley yield could result in approximately an 8% potential yield loss (Figure 3, page 4).

Example 2: Yield loss, taking into account irrigation deficit and irrigation system efficiency

To maximize potato yields, 435 mm of water is required. An irrigator was able to apply 350 mm to his potato crop in 2018, or 80% of optimal irrigation needs. In addition, his system and management practices were only 80% efficient, resulting in only 280 mm effectively reaching the crop representing 64% of crop needs to achieve maximum yield. If system was 100% efficient, yield would only have been reduced by 6% of optimum. However, the system inefficiencies cost more than an additional 10% of yield for a total reduced yield of 17.5% (Figure 3, page 4).

Example 3: Leaching Requirement

A corn crop is being irrigated under a centre pivot irrigation system with water from a local creek that has an EC value of 1.2 dS/m. Over the length of growing season the corn crop is expected to have a seasonal water requirement of 450mm, and the rainfall during the growing season was 108mm. It can be assumed that the centre pivot irrigation system has an application efficiency of 85%, how much water must be applied to meet seasonal water requirements for leaching? (Equation 2, Appendix C, page 74).

Seasonal water applied = Water Required ÷ System Efficiency

= 342 mm ÷ 0.85

= 402 mm

Leaching Requirement $= \frac{EC_w}{5(EC_e) - EC_w}$ EC_e of corn is 1.7 dS/m for 100% yield potential (Table A2)

$= \frac{1.2}{5(1.7) - 1.2}$

= 0.16

Applied Water $= \frac{ET}{1 - LR}$

$= \frac{402mm}{1 - 0.16}$

= 478 mm

Taking into account the salt content of the water and the application efficiency of the irrigation system, you will need to apply close to 478 mm of water to ensure proper salt leaching.

Example 4: Maximum allowed depletion (MAD)

A Silt Loam field seeded to potato with a rooting depth of 45 centimetres (1.5 feet).
Using Maximum Allowable Depletion (MAD) as an irrigation trigger, how much water should be applied to bring the root zone up to Field Capacity?

Root Zone depth: 45 centimetres (1.5 feet)

Plant Available Water = Field Capacity – Permanent Wilting Point (Appendix A: Figure A2, page XX)
= 2.6 inches water/foot – 1.2 inches/foot = 1.4 inches/foot

Maximum allowed depletion ~ 50% of Plant Available Water
= 1.4 inches/foot x 50% = 0.7 inches/foot

Maximum allowed depletion
= 0.7 inches/foot x 1.5-foot root zone = 1.1 inches (28 mm)of water

1.1 inches (28 millimetres) of water needs to be applied to bring the root zone up to field capacity

Example 5: Net water depth for of water applied to a field over a 48-hour period

During mid-June, canola uses approximately 0.16 inches (4 millimetres) of water per day (Appendix A: Table A7). Using a 900 US gallon/minute high pressure irrigation pivot (Appendix A: Table A5), what is the net depth of water applied to the field over a 48 hour period (Appendix A: Table A6)?

Depth applied in 48 hours = 0.72 inches (18.3 millimetres) x 0.8 (eff.) = 0.58 inches (14.7 millimetres)

Crop use during 24 hours = 0.16 inches (4 millimetres)

Crop use during 48 hours = 0.32 inches (8 millimetres)

Net water retained in field = 0.58 inches – 0.32 inches = 0.26 inches (6.6 millimetres)

Example 6: Water saving potential when converting to a higher efficient irrigation system

If a centre pivot irrigation system was converted from a high pressure pivot to a low pressure center pivot, how much water will be saved on a 48hr circle (Appendix A: Table A5) if the system flowrate is 900 usgpm?

Depth applied in 48hrs (Appendix A: Table A6) = 0.72 inches (18.2 mm) (100% efficiency)

Depth applied – high pressure centre pivot (Appendix A: Table A5) = 0.72 inches x 80%/100% = 0.58 inches (14.7 mm)

Depth applied – low pressure centre pivot (Appendix A: Table A5) = 0.72 x 90%/100% = 0.65 inches (16.5 mm)

Example 7: Irrigation depth required to bring root zone to field capacity

Soil samples were taken from a field with Sandy Loam soil. Rooting depth was 15 cm. The irrigation system is a high pressure centre pivot.

A. Calculate gravimetric moisture content (% water by WEIGHT)

% water by weight = $\frac{wet\ sample\ weight - dry\ sample\ weight}{dry\ sample\ weight}\ x\ 100\%$

Container weight = 50 grams (account for container when weighing)

Wet soil sample weight = 153.4 grams – 50 grams = 113.4 grams

Dry soil sample weight = 151.1 grams – 50 grams = 101.1 grams

% water by weight = $\frac{113.4\ grams - 101.1\ grams}{101.1\ grams}\ x\ 100\% = \mathbf{12.2}\%$

B. Convert gravimetric to volumetric moisture content (% water by VOLUME)

% water by volume = $\%\ water\ by\ weight * \frac{bulk\ density\ of\ soil}{bulk\ density\ of\ water}$* 100%

Bulk density of water = ~ 1.0 gram/centimetre^3

Bulk density of soil $= \frac{dry\ sample\ weight}{soil\ sample\ volume}$

Soil sample volume $= \pi * radius^2 * \text{length}$

Soil core radius = soil core diameter/2 = 2.54 centimetres/2 = 1.27 centimetres

Soil core length = 15 centimetres

Bulk density of soil = $\frac{101.1\ grams}{\pi * (1.27\ \text{centimetre})^2 * 15\ \text{centimetres}} = 1.33\ grams/centimetre^3$

(= silt loam)

% water by volume = $12.2\ \% * \frac{1.33\ grams/centimeter^3}{1.0\ \text{grams}/centimeter^3} * 100\ \% = \mathbf{16.2}\ \%$

Example 7: Cont'd

C. Calculate required irrigation depth to bring soil to Field Capacity

Irrigation depth = (Field capacity – Soil moisture content) x root depth

Field capacity of silt loam (Appendix A: Table A3, page 68) = Available water + Unavailable water

= 1.2 + 1.4 inches water / foot soil depth = 2.6 inches water / foot soil depth

Soil moisture content = 16.2 % x 12 inches water/foot soil depth = 1.9 inches of water/foot soil depth ≤ Maximum allowed depletion* → **irrigation required**

*Maximum allowed depletion = Available water at Field capacity/2 + Permanent wilting point [Appendix A: Figure A2 (silt loam), page 67]

= (1.4/2 + 1.2) inches of water/foot soil depth = 1.9 inches water/foot soil depth

Irrigation depth = (2.6 – 1.9) inches water/foot soil depth * 1-foot root zone **= 0.7 inches water**

D. Calculate required irrigation depth, taking into account system efficiency

The system efficiency of a high pressure centre pivot is 80% (Appendix A: Table A5)

Irrigation Depth = ((Field Capacity – Soil Moisture Content) x Root Depth) / Irrigation Efficiency

$$= \frac{(2.6-1.9)\ \text{inches of water/foot of soil} * 1\ \text{foot root depth}}{{}^{80}/_{100}} = 0.875\ \text{inches of water}$$

An irrigation depth of 0.875 inches of water is needed to bring root zone to field capacity.

Example 8: Irrigation depth required based on hand feel method

Samples were taken from a field with Sandy Loam soil. Samples were taken to a depth of 2 feet. Samples were broken into two sub-samples: 0–1 foot and 1–2 feet. Based on the texture and referring to Table 1, plant available moisture was estimated to be:

0–1 foot: 25–50% plant available moisture (estimate 40%) *(below maximum allowed depletion →* ***Irrigate****)*

1–2 feet: 50–75% plant available moisture (estimate 60%)

Sandy Loam Soil has 1.2 inches plant available water/foot of soil at field capacity (Appendix A: Figure A2, page 67). To bring the root zone back to field capacity we must irrigate:

0–1 foot: (100 – 40%) * 1.2 inches water/foot of soil = 0.72 inches of water

1–2 feet: (100 – 60%) * 1.2 inches water/foot of soil = 0.48 inches of water

Total irrigation water required to bring field up to field capacity = 0.72 + 0.48 inches of water

= 1.2 inches of water

Example 9: Irrigation depth required based on resistance block or tensiometer method

Electrical resistance blocks, placed at two depths (6” and 12”) in a Sandy Loam soil, sense soil water potentials of 6 and 2 bars respectively. Based on Figure 17 (page 28), plant available water is

0–6 inch depth: 6 bars = 15 % plant available water

6–12 inch depth: 1 bar = 50 % plant available water

Sandy Loam soil has maximum plant available water level of 1.2 inches water / foot soil depth (Appendix A: Figure A2, page XX) at field capacity. To bring the root zone back to field capacity we must irrigate:

0–0.5 feet: (100–15%)/100% * 1.2 inches water/foot of soil depth* 0.5 feet = 0.5 inches of water

0.5–1.0 feet: (100–50%)/100% * 1.2 inches of water/foot of soil depth * 0.5 feet = 0.3 inches of water

Total irrigation water required = 0.5 inches + 0.3 inches = **0.8 inches of water**

Example 10: Irrigation depth required based on TDR or Capacitance probe(s)

A capacitance probe is placed in a Sandy Loam soil with a single sensor at 15 centimetres (6 inches). At the current crop development, the root zone is approximately 20 centimetres (8 inches) deep. Sandy Loam soil has a field capacity of 18.3% (2.2 inches of water / 12 inches of soil depth) and a permanent wilting point of 8.3% (1.0 inches of water / 12 inches of soil depth) (Appendix A: Figure A2, page 67).

The current soil moisture is 12%. a) Should you irrigate? B) If yes, how much?

a) Irrigation trigger is at 50% of plant available water (i.e. maximum allowed depletion)
= [(Field capacity – Permanent wilting point)/2 + permanent wilting point]
= [(18.3% - 8.3%)/2 + 8.3%] = 13.3%

Current soil moisture (12%) is less than 50% plant available water (13.3%)
➔ **Irrigate**

b) To bring the root zone back to field capacity

Irrigation Depth = [(field capacity – current soil moisture)/100%] x root depth

= (18.3% - 12%)/100% x 8 inches

= 0.5 inches of water

Example 11: Cheque-book example of irrigation scheduling for canola grown on loam soil

Field capacity = 2.4 inches of water/foot of soil depth (Appendix A: Figure A2, page 67)

Permanent wilting point = 1.0 inch of water/foot of soil depth

Maximum allowed depletion (50% available water = irrigation trigger)

= (2.4 − 1.0)/2 + 1.0 = 1.7 inches water/foot of soil depth

Date	Initial soil water content*	Crop water-use*,† (ET)	Irrigation/ precipitation*	Final soil water content*
July 28	2.0	0.2	0	1.8
July 29	1.8	0.2	0	1.6
July 30	1.6	0.2	0.5	1.9
July 31	1.9	0.2	0	1.7
August 1	1.7	0.1	1.0	2.6
August 2	2.4 ‡	0.1	0	2.3
August 3	2.3	0.1	0	2.2

*All values in inches

†Estimated daily crop water-use (Appendix A: Table A7, page 69)

‡Field capacity is 2.4 inches of water/foot of soil; the excess 0.2 inches applied the day before has drained away by gravity

Example 12: Drip Zone Runtime

A wheat crop in early July needs 5.5 mm of water per day to keep up with evapotranspiration needs. In a field with 21 zones, that are irrigated 7 zones at a time, how long will the system have to run every day to deliver this application? The system has an emitter spacing of 0.6 m and the laterals are placed at 1.0 m, each emitter is sized to deliver 1.0 L/hr. Assume efficiency of 95% (Table A5)

$$T_Z = (0.6\text{m} \times 1.0\text{ m} \times 5.5\text{mm}) / (1.0\text{L/hr} \times 0.95)$$

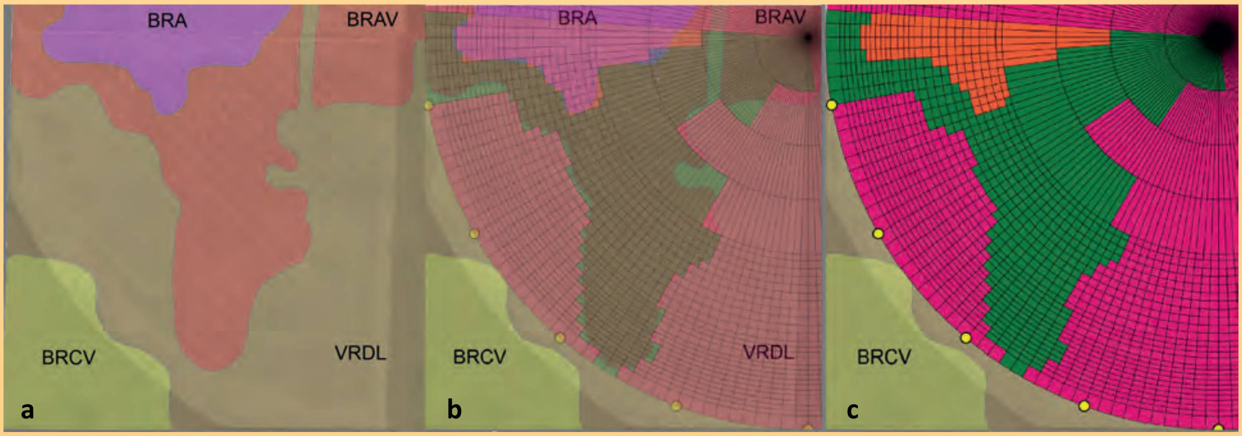
$$= (3.3\text{ L}) / (0.95\text{ L/hr})$$

$$= 3.47\text{ hrs}$$

T_f = 3.47 hrs x 21 zones / 7 zones run concurrently = 10.4 hrs

Note: 1 litre = 0.001 m^3

Example 13: VRI zone mapping using historical soil survey map



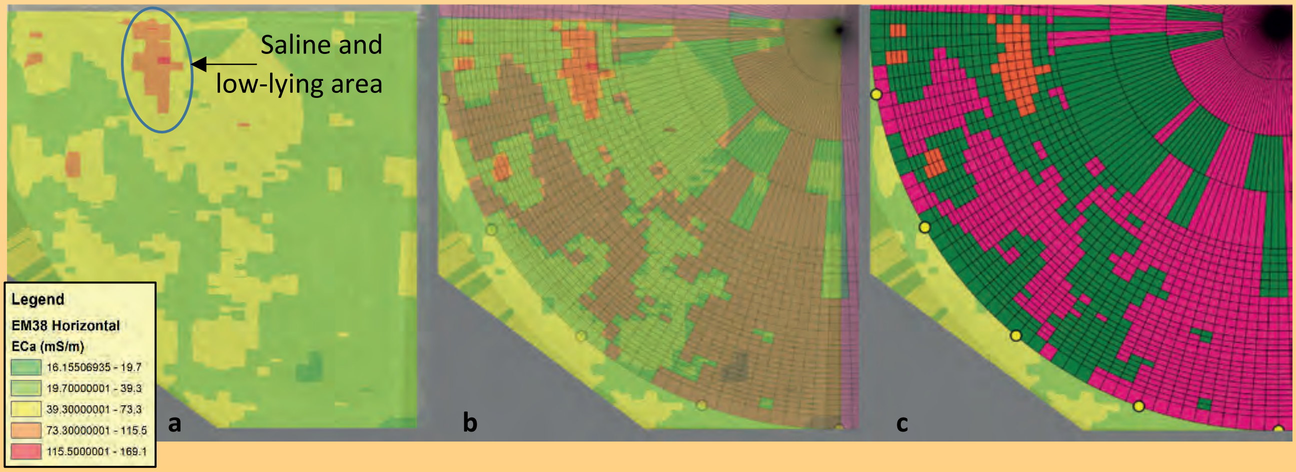
Historical soil survey maps (a) map out areas for each uniquely named soil association (usually abbreviated). Each soil association has unique soil characteristics including soil texture. A limited number of soils samples were taken to define a soil class and to identify its boundary. As a result, the resolution is coarse and not usually at a field scale.

In this example, the portion of the field investigated has three unique soil associations under the pivot (b):

- BRA (GREEN) – Bradwell Orthic Dark Brown – loam soil
- BRAV (ORANGE) – Bradwell/Vera – loam soil with sand, low dunes
- VRDL (PINK) – Vera Orthic Regosol – sand, low dunes, with till substrate

Based on this information, the field was initially mapped into 3 zones (c). The soil water holding capacity will increase from the sand (VRDL) to the loam soil (BRA). This will result in different schedules (timing and depth) for each zone.

Example 14: VRI zone mapping using apparent electro-conductivity map

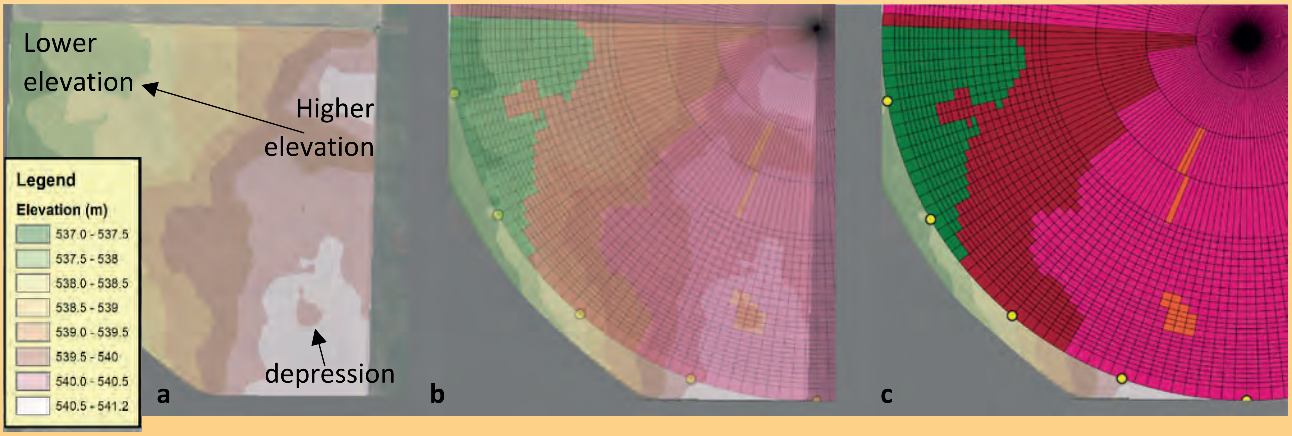


A field was surveyed with a Geonics EM38 (a, b). Electrical conductivity ranged between 16–170 milliSiemens/metre (mS/m). Based on the survey data, the field was divided into 3 zones (c):

Zone 1 (GREEN): 16–39 mS/m   Zone 2 (PINK): 39–73 mS/m   Zone 3 (ORANGE): 73+ mS/m

The land owner indicated that Zone 3 matched up to a saline area and a few low-lying areas that collect water. A combination of drainage and precision irrigation could bring this area into higher productivity (i.e. lower EC value).

Example 15: VRI zone mapping using topographic map



A topographic survey showed an elevation range of 538–541m (a, b). Based on this, the field was mapped into 4 zones (c):

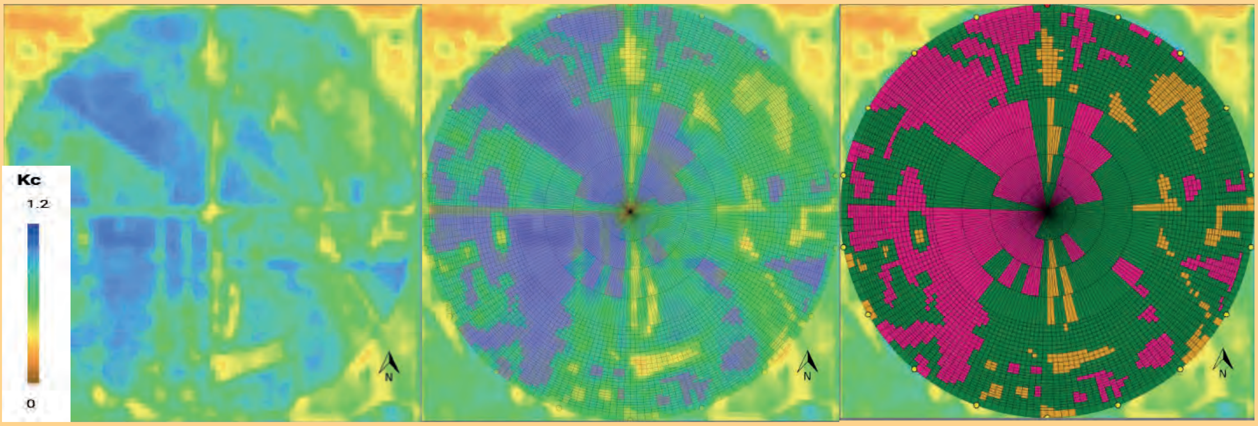
Zone 1: 537–538 metres (low elevation GREEN)

Zone 2: 538–539.5 metres (mid-slope RED)

Zone 3: 539.5–541 metres (high elevation PINK)

Zone 4: depressions (potholes ORANGE) – limit irrigation in these areas

Example 16: VRI zone mapping and scheduling using normalized difference vegetation index imagery



Using normalized difference vegetation index imagery, develop a dynamic irrigation prescription to schedule the next irrigation event.

Step 1: Convert normalized difference vegetation index values to crop water-use coefficients (Kc) [automatic in some systems, e.g. Irrican] – Appendix C: Equation 7, page 75

Step 2: Map field into distinct zones based on crop water-use ranges
Zone 1: high water use (blue), Kc>1 (average = 1.1)
Zone 2: moderate water use (green), 1 > Kc > 0.5 (average = 0.75)
Zone 3: low water use (yellow), Kc<0.5 (average = 0.4)

Step 3: Calculate required irrigation amount to satisfy crop demand
Estimated evapotranspiration (ET_o) since the last irrigation/rainfall event for the area for reference crop (grass/alfalfa) = 0.75 inches of water (e.g. published by Saskatchewan Ministry of Agriculture, AIMM)
Use Equation 3 (ET_o x K_c = water use) to calculate crop water demand for each zone
Zone 1: 0.75 inches of water x 1.1 = 0.825” → **0.8 inches of water**
Zone 2: 0.75 inches of water x 0.75 = 0.56" → **0.6 inches of water**
Zone 3: 0.75 inches of water x 0.4 = 0.3” → **0.3 inches of water**

Example 17: Scheduling the last irrigation

What is the minimum required irrigation to take a wheat crop to full maturity?

Crop: Wheat
Crop stage: Late milk (Appendix A: Table A9, page 70)
Daily crop water use (Appendix A: Table A7, page 69 for August): 0.08 inches water/day
Root depth (Appendix A: Table A4, page 68): 3 feet
Maturity date (expected): in 12 days
Soil: sandy loam
Plant available water (sandy loam) at field capacity (Appendix A: Figure A2, page 67): 1.2 inches water/foot of soil depth
Current soil moisture status: 14% (volumetric)

Current soil water content: volumetric content x 12 inches water/foot soil depth
= 14% x 12 inches of water/foot soil depth = (0.14 x 12) inches water/foot soil depth
= 1.68 inches of water/foot soil depth

Maximum allowed depletion (Appendix A: Figure A2, page XX): Total unavailable water + (total available water/2)
= (1.00 + 1.20/2) inches water/foot of soil depth = 1.60 inches water/foot of soil depth

Available water above Maximum allowed depletion: Current soil water content - Maximum allowed depletion
= (1.68 – 1.60) inches water/foot of soil depth = 0.08 inches water/foot of soil depth

Total available soil water (root depth) above Maximum allowed depletion: soil water content x root depth
= 0.08 inches of water/foot of soil depth x 3 feet = 0.24 inches of water

Crop water needs until maturity: Daily crop water use x days
0.08 inches water/day x 12 days = 0.96 inches of water

Irrigation required: Crop needs until maturity – available soil water
(0.96 – 0.24) inches of water = 0.72 inches of water ≈ 0.75 inches of water

→ **0.75 inches of water** is required to carry the crop to maturity

PRAIRIE IRRIGATION SCHEDULING MANUAL