Alberta Irrigation Management Manual

2016

Alberta Agriculture and Forestry

Unit Conversion Factors

	SI Units		Imperial Units
Area:	1.0 hectare (ha)	=	2.471 acres
Length:	1.0 millimetre (mm)	=	0.0394 inches
	1.0 metre (m)	=	3.281 feet
Mass:	1.0 kilogram (kg)	=	2.205 pound (lb)
Volume per Unit Time:			
	1.0 litre per second (L s^{-1})	=	15.85 U.S. gallons per minute (gpm)

Abbreviations

AIMM	Alberta Irrigation Management Model
AD	Allowable depletion
E_a	Irrigation system application efficiency
ERZ	Effective root zone
ET or ET_c	Evapotranspiration or crop evapotranspiration
FC	Field capacity
IMCIN	Irrigation Management Climate Information Network
MAD	Management allowable depletion
PAW	Plant-available water
PWP	Permanent wilting point
SMD	Soil moisture deficit
TDR	Time domain reflectometer

ALBERTA IRRIGATION MANAGEMENT MANUAL

Irrigation Management Section
Irrigation and Farm Water Branch

2016

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INTRODUCTION

Irrigation management of crops is a complex and multifaceted process that ensures that the agronomic (e.g., soil fertility, pest control), technical (irrigation systems and associated technology), human (manager's skills, knowledge, and decision making), and water factors that control plant growth do not limit the achievement of optimal and profitable crop production. Proper irrigation management depends on accurate irrigation scheduling that minimizes problems related to the misapplication of water. According to Broner (2005), the purpose of irrigation scheduling is to determine the appropriate amount of water to apply to the crop and the proper timing of application. Irrigation management is a decision-making process that is influenced by available irrigation water supply, the soil water-holding capacity and infiltration rate, and crop water needs. As Howell (1996) indicated, on-farm implementation of irrigation scheduling information into an operational irrigation plan is far more complicated than a simple definition because outside factors (labor, harvesting, crop culture, system maintenance, etc.) must also be considered. Because of this complexity, irrigators must be well-trained and skilled in irrigation management.

Competent irrigation managers know when to irrigate, how much water to apply, and when to stop irrigation (i.e. the timing and amount of irrigation). The amount and timing of irrigation in turn are influenced by the goal of irrigation scheduling. Some of the goals of irrigation scheduling are to maximize yield (i.e. yield per unit of land, yield per unit of water, yield per unit of energy), to implement managed deficit irrigation and/or to optimize economic profits. In Alberta, irrigation management information and training are provided to help irrigators become competent water managers.

An effective irrigation scheduling program consists of four elements: knowledge of soils and crops, methods for measuring soil water status, estimates of irrigation system application efficiencies, and a method for estimating daily crop water use. With this knowledge, irrigators can develop profitable irrigation scheduling programs that are based on sound irrigation management principles. The success of any irrigation management program depends on the type of irrigation system used, which influences the development of a local irrigation management philosophy.

The irrigation management philosophy in Alberta is to ensure that water is available at germination and for early crop development by applying light, frequent

irrigations. This method is possible with centre pivot sprinkler irrigation systems because water can be applied in increments as little as 7 mm per day. Additional water can be applied to promote vigorous early growth and to increase available soil water reserves in the entire root zone during pre-flowering growth stages. The greatest portion of the current irrigated land in Alberta uses centre pivot sprinkler systems (Figure 1), which allow the flexibility of applying irrigation water in varying amounts depending on crop water need.

The objective of this manual is to provide current information on beneficial irrigation management practices for optimum production of major irrigated crops in Alberta.

BACKGROUND

Irrigation management is one of the most important factors affecting crop yield and quality (Stark, 2003). Water stress at any growth stage reduces yield. Therefore, to prevent water stress-induced losses, irrigation scheduling should match water applications to crop water requirements in a timely and efficient manner. In addition to accounting for crop water use, soil permeability, soil water storage capacity, and irrigation water availability, knowing irrigation equipment (system) capabilities and limitations is paramount in having an effective irrigation management program.

The management of the irrigation system, as well as the entire philosophy about irrigation sufficiency, changes with different irrigation methods. The application amount with surface irrigation is sufficient for water to travel from the top of the field to the bottom of the field using border dykes or contour ditches, or covers a confined area to a specific depth using basin irrigation methods. Application amounts are dependent on the length of the field and the width of the borders and contours or basin area. The approach to irrigation management using surface irrigation systems is to “fill-up” (to field capacity or above) the root zone each time irrigation water is applied, often in excess of what the soil can retain, and to rely on stored soil water to supply the crop for an extended interval between irrigation applications.

The approach to irrigation management does not change with conversion from surface to wheel-move irrigation. Wheel-move irrigation systems are designed and sprinklers sized to apply approximately 13 mm (0.5 inch) per hour. Typical operation of a wheel-move

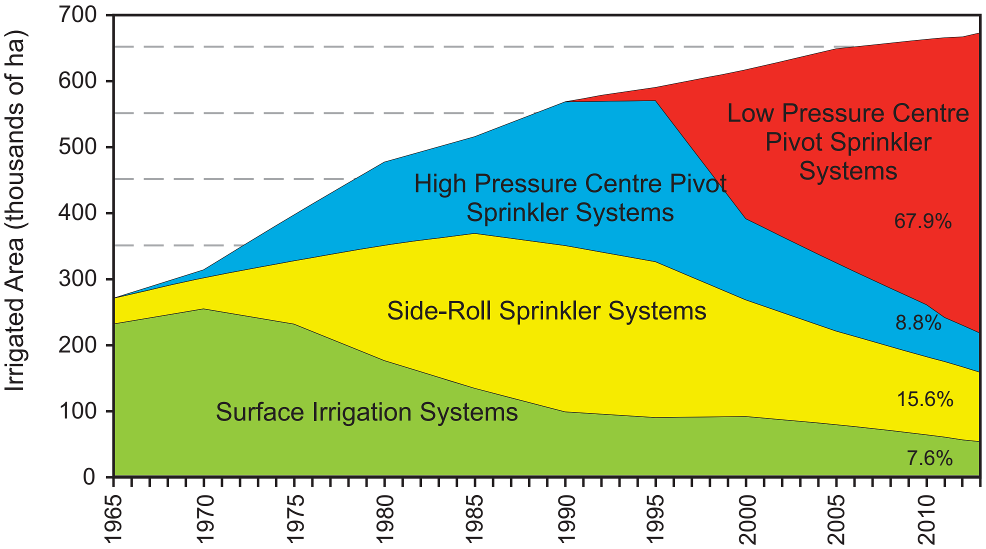


Figure 1. The change in the irrigated area and the associated irrigation system mix from 1965 to 2013 (ARD, 2014).

system is to leave it in one location for 8 or 12 hours to apply 100 or 150 mm of irrigation water, respectively. The approach towards irrigation management is similar to surface irrigation; that is to "fill-up" the soil root zone each time irrigation water is applied and to rely on retained soil water in the root zone to supply the crop for extended periods of time. Labour requirements and crop height limit the number of irrigations with wheel-move systems to two or three per year, making it difficult to meet crop water needs, especially later in the growing season.

With centre pivot irrigation, a soil profile at field capacity or "full" is seldom the irrigation application goal. Centre pivot systems are not designed to apply a large amount of irrigation water at one time; rather a 2-day circle with a 400 m centre pivot system with capacity of 60 L s^{-1} (¼ mile length, 950 US gpm capacity) typically applies 15 to 20 mm. Irrigation decisions are always based on how a crop uses soil water (transpiration) on a daily basis and management of the irrigation system is for a fairly shallow root zone depth.

Irrigation scheduling for centre pivot irrigation requires frequent applications that match the soil water extraction pattern of the crop grown. The best a properly designed centre pivot system is able to do is to "keep up" with crop water extraction (evapotranspiration) during times of peak demand. If the system is not adequate to meet peak water-use requirements, it may be necessary or desirable to "build-up" soil water reserves during "off-peak" times for plant roots to access stored soil water during peak evapotranspiration.

Proper irrigation management, when using a centre pivot irrigation system, focuses on replacing the soil water transpired by the crop within the upper 50 cm or 50 percent of the root zone depth. Realizing that at peak water use, the 15 to 20 mm applied by the irrigation system in 2 days could be transpired by the crop within 3 days, timely information about soil water status is essential to ensure the crop is not stressed during critical growth stages.

In Alberta, centre pivots represent almost all new systems being purchased and can typically irrigate from 40 to more than 200 ha, depending upon the lateral length. Where desired, a centre pivot system can be programmed to irrigate only a segment of a circular field. Rotation speed can also be slowed or increased to vary water application rates. Centre pivot technology serves as the foundation for many technological innovations. For instance, modern pumps, sprinklers, and centre pivot systems offer considerable water and energy-saving opportunities, as well as water management flexibility to achieve optimum crop production. Pumping systems can deliver water to irrigate land at higher elevations than the canal source – land that was previously inaccessible to irrigation. Drop-tube sprinklers reduce evaporation losses by reducing the distance between sprinklers and the crop. They also allow for low pressure operations that conserve energy. Pump and pivot systems can be programmed to apply varying amounts of water, including fertilizers and pesticides, to different areas of a field, or to meet site-specific crop needs and soil conditions. They can also be automated to decrease labor demand. Since centre pivot sprinkler systems are increasingly dominating the irrigation system mix in Alberta (Figure 1), irrigation management practices and philosophy have changed to reflect this new reality.

Centre pivots have a high level of irrigation application efficiency and uniformity but have a limited daily application rate compared to gravity irrigation systems. For centre pivot systems to apply water to meet crop water use and ensure water stress does not reduce potential yield and quality of most spring-seeded crops in Alberta, the effective root zone (ERZ) depth should be varied and management allowable depletion (MAD) should be kept small (i.e., 30 to 40 percent of available). These adjustments are meant to accommodate the practical use of sprinkler irrigation systems that, at best, meet peak crop water use.

For most crops, yield-reducing stress becomes pronounced if available soil water drops to less than 60 percent (Bauder and Carlson, 2005). Bauder and Carlson (2005) found that an allowable depletion of 40 percent of available (60 percent of available remaining in soil) to be suitable to avoid yield-reducing water stress for cereals, dry beans, peas, and sugar beets. This means irrigation should start just before available moisture reaches 60 percent to allow time for irrigation water to be applied before soil water is depleted to a

Table 1. Peak water use for major irrigated crops in southern Alberta (ARD, 2011a).

Current irrigated crops	Peak daily water use (mm)
Alfalfa hay†	10, 9, and 8
Barley	7
Canola	7
Dry bean	7
Pea	6
Potato	7
Silage corn	8
Spring wheat	7
Sugar beet	8
Timothy hay†	8 and 6

† Peak daily water use for multiple cuts during the years of production of perennial crops.

critical level. Many local crops transpire 6 to 8 mm per day during the peak water-use period (Table 1), so irrigation decisions necessary to ensure adequate soil water for transpiration with standard quarter-section centre pivot systems must be made on a 2- or 3-day basis. Decision-support tools designed to assist Alberta irrigators with irrigation management decisions must provide information quickly (on a daily basis). In addition to knowing how to schedule irrigations, irrigators in Alberta are encouraged to learn about soil-water-plant relationships.

SOIL – WATER – PLANT RELATIONSHIPS

Soil acts as a reservoir that holds water for plant use. Plants use water extracted from soil for growth and cooling purposes. The water content of a soil after being saturated by rainfall or irrigation and allowed to drain freely is called field capacity (FC). The point at which a crop can no longer extract water from the soil is called the permanent wilting point (PWP). The amount of water held by soil between FC and PWP is considered plant-available water (PAW) or simply, available water. Soils have diverse water retention characteristics and require different irrigation management techniques. For example, soil textural characteristics dictate the water-holding capacity, infiltration rate, and internal drainage rate (water percolation rate). Soils also differ in their adequate depth for active root development (adequate root zone): some have underlying layers (gravel or hard pan) that would restrict root growth. The PAW at FC in the root zone varies with soil texture (Table 2) and, to some extent, organic matter content.

Plant-available soil water depends on soil water-holding capacity and the effective root zone (ERZ) depth. Plant available water-holding capacity of soil can be obtained from charts that provide information based on soil texture (Table 2). To prevent plants from experiencing water stress during the growing season (goal of irrigation), the yield-reducing soil water limits must be known for different crops and soils.

Management allowable depletion (MAD) is the percentage of the PAW at FC that an irrigator allows plants to deplete before irrigating (Burt, 2010). The MAD varies with soil, crop type, and crop growth stages. The amount of soil water a crop can extract from the root zone before yield-reducing stress is experienced by the crop is known as allowable depletion (AD). Allowable depletion is typically expressed in units of depth (e.g., mm), whereas MAD is expressed as a percentage (e.g. percent of available water). Knowledge of the ERZ depth and MAD of crops is paramount to designing an effective and efficient on-farm irrigation scheduling program that satisfies crop water requirements.

Table 2. Estimated hydraulic properties of southern Alberta soils (AAFRD, 2004).

Textural class	Bulk density (Mg m^{-3})	Porosity (%)	Field capacity (% by weight)	Permanent wilting point (% by weight)	Available water-holding capacity[†]		
					(% by weight)	(% by volume)	(mm m^{-1})
Loamy Sand	1.60	40	10	4	6	10	100
Sandy Loam	1.55	42	14	5	9	14	140
Loam	1.50	43	20	8	12	18	180
Sandy Clay Loam	1.45	45	20	9	11	16	160
Silt Loam	1.45	45	21	7	14	20	200
Clay Loam	1.40	47	26	12	14	20	200
Silty Clay Loam	1.40	47	29	13	16	22	220
Sandy Clay	1.45	45	26	14	12	17	170
Silty Clay	1.40	47	33	18	15	21	210
Clay	1.35	49	31	17	14	19	190

[†] Available water-holding capacity by volume for each textural class was derived by multiplying bulk density by percent available water-holding capacity by weight.

EFFECTIVE ROOT ZONE DEPTH

The effective root zone (ERZ) is the depth within which most plant roots are concentrated. If soil is viewed as a reservoir that holds water for plant use, the capacity of this reservoir for a particular soil textural type is determined by multiplying available water-holding capacity or PAW of that soil (Table 3) by the ERZ depth. Plants extract most of their water from this zone (USDA, 1990). The ERZ depth is determined by crop type, growth stage, and restricting layers or conditions in the soil profile (Yonts and Klocke, 1997). Some of the soil factors that influence the root zone depth may be physical (compaction, unsuitable temperature, and high water table) and/or chemical (salinity, acidity, and sodicity). The ERZ depth reaches a maximum during the flowering stage of crops. Root development of any crop varies widely with the type of soil and plant variety.

For most plants, the concentration of roots is greatest in the upper part of the root zone (Figure 2). Plant extraction of PAW in soil is most rapid in the zone of greatest root concentration and where the most favorable conditions of aeration, biological activity, temperature, and nutrient availability occur. Water also evaporates from the upper few millimeters of the soil; therefore, water is diminished most rapidly from the upper part of the soil (USDA, 1997).

Provided there are no physical or chemical constraints and soil water is present, a crop will typically use about 40 percent of the PAW from the first quarter, 30 percent from the second quarter, 20 percent from the third quarter, and only 10 percent from the last quarter of the ERZ (Figure 2). This indicates the need for making soil water measurements at different depths within the ERZ in order to estimate soil water status. Since about 70 percent of the crop's water requirement is taken from the upper half of the dynamic ERZ, it is common practice in Alberta to ensure that soil water is maintained above the allowable depletion in the top half of the ERZ during the growing season (particularly in the early stages of growth before flowering).

Effective irrigation scheduling maintains a stress-free soil moisture environment in the ERZ at all stages of plant growth. The term “dynamic effective root zone” is used to show the impact of crop growth stages on its

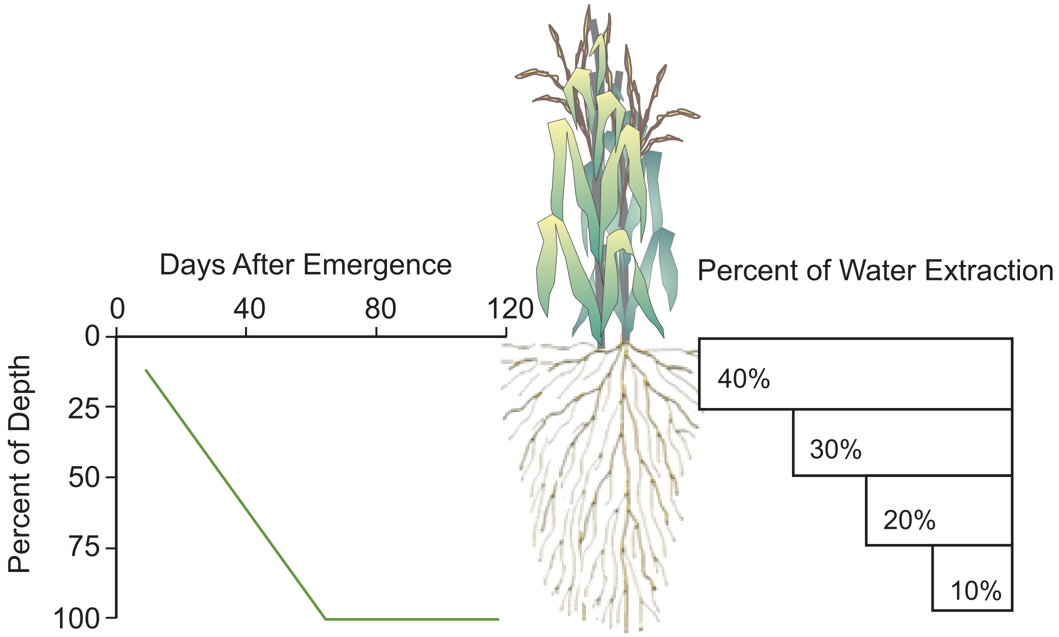


Figure 2. Effective root zone soil water extraction and plant root development patterns (adapted from Kranz et al., 2008).

ERZ in unrestricted soil with adequate moisture. If unrestricted, rooting depth increases as the plant matures and a crop's water use increases until the peak water-use period (maximum crop water-use period) when roots have reached maximum growth.

The maximum daily crop water demand is reached at the beginning of the reproductive growth stage for most crops in Alberta. When the plant has reached physiological maturity, the ability of roots to extract soil water diminishes with time and crop water needs become minimal. Awareness of the root zone depth during all stages of crop development enhances an irrigation manager's ability to effectively manage nutrients and water in those layers containing active roots.

The ERZ depths for some crops grown in Alberta in an unrestricted soil profile are provided in Table 3. A range of numbers (e.g., 0.5 – 1.0 m) implies that the ERZ depth changes with growth stages of a crop. The first number is the root zone depth used in the early stages of crop development (e.g., vegetative), whereas the last number is the root zone depth used in later stages of growth (e.g., reproductive). A single number ERZ depth is only used for established perennial crops (i.e. alfalfa and timothy) and very shallow-rooted annual crops such as potatoes (Table 3).

The concept of varying root zone depth with growth stages is used in Alberta to ensure a crop is well-irrigated. To ensure that ample water is available to any crop during the early (vegetative) growth stages (i.e. tillering to late boot for cereals), the MAD should not be exceeded in the upper half of the ERZ. Irrigation applied during the vegetative growth stages should start before the MAD is reached to prevent adverse impacts of water stress.

This irrigation practice necessitates light and frequent irrigation applications during vegetative growth stages. The goal of this irrigation practice is to meet crop water requirements and build up soil water to near field capacity in the bottom half of the root zone for crop use later during the peak water-use period when flowering occurs (ARD, 2011a). This irrigation scheduling strategy results in varying both the irrigation amounts and intervals as controlled by varying the ERZ depth with a fixed MAD for most crops.

Table 3. Effective root zone depth for major crops in Alberta (ARD, 2011a).

Crops	Effective root zone depth (m)[†]
Alfalfa hay	1.2
Barley	0.5-1.0
Canola	0.5-1.0
Dry bean	0.3-0.6
Pea	0.4-0.7
Potato	0.6
Silage corn	0.5-1.0
Spring wheat	0.5-1.0
Sugar beet	0.5-1.0
Timothy hay	0.5
Winter wheat	0.5-1.0

[†] For annual crops in Alberta, the first number indicates the effective root zone depth during the vegetative growth stage and the second number is the root zone depth used from flowering (mid-season) to physiological maturity.

MANAGEMENT ALLOWABLE DEPLETION

Management allowable depletion (MAD) is the percentage of PAW that can be removed from the soil without seriously affecting crop growth and development (Burt, 2010). In simpler terms, the MAD of any crop is the allowable percentage of water that can be withdrawn from the soil between irrigation events without stressing the crop to the point where significant reductions in crop yield or quality are experienced. The MAD is generally defined for each crop and is a management decision based on yield and product quality objectives. In addition to local knowledge of the ERZ depth, knowledge of the MAD for crops of interest is crucial for developing an effective and efficient on-farm irrigation scheduling program. The MAD for a crop is usually expressed as a percentage of the PAW at FC in the root zone (Table 4).

Selection of the MAD is an irrigation management decision based on the water stress sensitivity and growth stage of the crop, the PAW in the root zone, rainfall patterns, the availability of pumped or delivered water (USDA, 1997), the irrigation system used, and the irrigation scheduling goal. The MAD should be evaluated according to crop needs and, if necessary, adjusted during the growing season.

Although the recommended MAD values (Table 4) are considered universal, in reality, they are site-specific and reflect climate, soil texture, and irrigation management goals at a particular location. Thus, irrigators are encouraged to adjust MAD values for their crops based on crop growing conditions and irrigation goals.

Table 4. Management allowable depletion for major crops grown in Alberta (ARD, 2011a).

Crops	Management allowable depletion (% of plant-available water)
Alfalfa hay	40
Barley	40
Canola	40
Dry bean	40
Pea	40
Potato[†]	30-35
Silage corn	40
Spring wheat	40
Sugar beet	40
Timothy hay	40
Winter wheat	50

[†] For potatoes, the MAD of 35 percent is used for most growth stages except tuber initiation, the growth stage at which 30 percent of plant-available water is used.

IRRIGATION SCHEDULING METHODS

The choice of irrigation scheduling method depends to a large degree on the objectives of the irrigation manager and the irrigation system availability and capability. In Alberta, the focus is to improve irrigator decision-making through education about different irrigation scheduling methods and technologies. Various irrigation scheduling methods are used in North America (USDA, 2004; 2008).

Based on two surveys performed by the USDA in 2003 and 2008, methods of irrigation scheduling that had the largest increase were 'feel of soil" and "personal calendar schedule". The use of reports on daily crop ET, soil water sensing devices, and commercial or government scheduling services had moderate increases (Table 5).

The preferred methods for deciding when to irrigate in both years in the United States were the "crop condition" and "feel of soil" (Table 5). All other methods had a relatively low level of use. Although, this kind of comprehensive survey has never been done in Alberta, the most commonly used method, based on observations made by an experienced irrigation advisor, is the "feel of soil" method (Hyland, personal communication). The "crop condition" irrigation scheduling method is discouraged in Alberta because by the time the signs of water stress are apparent in a plant, a large reduction in potential yield may have already occurred.

Of the methods listed in Table 5, the ones that have been gaining use are the ET-based method, which generates reports on daily crop ET, and use of consultants. Recently, use of ET-based irrigation methods in Alberta (i.e. a web-based calculator (IRRI-Cast) and the Alberta Irrigation Management Model (AIMM) (ARD, 2011b)) are becoming more common because of the potential labor, energy, time, and water savings.

Generally, irrigation scheduling methods can be categorized into three methods: plant-based, soil-based, and ET-based methods.

Table 5. Methods used in deciding when to irrigate in the United States (USDA, 2004; 2008).

Irrigation Scheduling Method†	2003 (% of farms)	2008 (% of farms)	% Change
Condition of crop	79.4	77.7	-2.1
Feel of soil	34.8	42.6	22.4
Personal calendar schedule	19.3	25.1	30.1
Scheduled by water delivery organization	12.5	11.8	-5.6
Reports on daily crop water evapotranspiration (ET)	7.2	9.1	26.4
Soil water sensing device	6.8	8.6	26.5
Commercial or government scheduling service	6.4	8.0	25.0
When neighbors begin to irrigate	6.7	6.9	3.0
Plant water sensing device	1.5	1.7	13.3
Computer simulation models	0.5	1.4	180.0
Other	8.9	8.7	-2.2
Number of irrigated farms	210,106	206,834	-1.6

† Respondents could choose more than one method.

Plant-based methods

The theory of using plant-based methods to schedule irrigation is that plant growth is directly related to plant water status and only indirectly related to soil moisture and atmospheric conditions. According to the USDA irrigation experts, this method is advantageous because the plant essentially integrates soil water with atmospheric environments and reflects the prevailing conditions in growth processes (USDA, 1991). Examples of plant-based irrigation management methods used in the US and other parts of the world include: stomatal conductance and thermal sensing (Jones, 2004), sap flow (Cohen et al., 1981), xylem cavitation or fracture (Tyree and Dixon, 1983) and leaf water potential and photosynthesis rate per unit leaf area (Allen et al., 1999).

In Alberta, soil-based irrigation scheduling methods are preferred and encouraged compared to plant-based methods because plant-based methods do not give information on 'how much' irrigation to apply at any time, only whether or not irrigation is needed. An additional disadvantage of the plant-based methods is that they are subject to homeostatic regulation (limited time of day to take accurate plant water activity measurements); therefore, they are not sensitive to plants that maintain high water status over a wide range of soil moisture content. A substantial portion of potential yield may have already been lost by the time water stress is apparent in a plant (Jones, 2004).

Soil-based methods

Measuring soil water is a crucial part of determining the amount of water needed to bring the soil water in the crop root zone to field capacity for an irrigation scheduling program. The amount of water required to bring soil water to field capacity is referred to as the net irrigation amount and can be determined by direct or indirect measurement of soil water.

Many direct soil-water measurement tools are available for assisting irrigation managers in ensuring soil water is always optimal for crop use. Soil measurement methods have been widely reviewed (Gardner, 1986; Stafford, 1988; Campbell and Mulla, 1990; and Phene et al., 1990). Tools that measure soil moisture are widely available in various configurations and methods of measurement. Most of these moisture sensors must be calibrated for the soil in which they are used.

Gravimetric soil sampling and the hand-feel methods remain the soil–moisture-measuring methods most widely used by growers and consultants (Howell, 1996). Manual soil samplers, either a “step-on” Oakfield soil sampler (Figure 3) (Oakfield Apparatus Inc., 2011) or a “crank-type” Dutch auger (Figure 4) (Deakin Equipment Ltd., 2011), are used by irrigators in Alberta. Water content of samples obtained can be estimated based on the “hand feel” of the soil (Table 6). The available water capacity is the portion of water in a soil that can be readily absorbed by plant roots of most

Figure 3. Oakfield Model L soil sampler (Oakfield Apparatus Inc., 2011).

Figure 4. Edelman Dutch auger (Deakin Equipment Ltd., 2011).

Table 6. Estimation of soil water using the hand-feel method (USDA-NRCS, 2004).

	Coarse Texture - Fine Sand and Loamy Fine Sand	Moderately Coarse Texture - Sandy Loam and Fine Sandy Loam	Medium Texture - Sandy Clay Loam, Loam, and Silt Loam	Fine Texture - Clay, Clay Loam, or Silty Clay Loam
Available Water Capacity, mm m^{-1}				
	50 - 100	108 - 142	125 - 175	133 - 200
Plant Available Water, %	Soil Moisture Deficit (SMD), mm m^{-1}			
0 - 25	Dry, loose, will hold together if not disturbed, loose sand grains on fingers with applied pressure. SMD 100 - 42	Dry, forms a very weak ball, aggregated soil grains break away easily from ball. SMD 142 - 83	Dry soil aggregations break away easily, no moisture staining on fingers, clods crumble with applied pressure. SMD 175 - 92	Dry, soil aggregations easily separate, clods are hard to crumble with applied pressure. SMD 200 - 100
25 - 50	Slightly moist, forms a very weak ball with well-defined finger marks, light coating of loose and aggregated sand grains remain on fingers. SMD 75 - 25	Slightly moist, forms a weak ball with defined finger marks, darkened color, no water staining on fingers, grains break away. SMD 108 - 58	Slightly moist, forms a weak ball with rough surfaces, no water staining on fingers, few aggregated soil grains break away. SMD 133 - 67	Slightly moist, forms a weak ball, very few soil aggregations break away, no water stains, clods flatten with applied pressure. SMD 150 - 67
50 - 75	Moist, forms a weak ball with loose and aggregated sand grains on fingers, darkened color, moderate water staining on fingers, will not ribbon. SMD 50 - 17	Moist, forms a ball with defined finger marks, very light soil/water staining on fingers darkened color, will not slick. SMD 75 - 25	Moist, forms a ball, very light water staining on fingers, darkened color, pliable, and forms a weak ribbon between thumb and forefinger. SMD 92 - 33	Moist, forms a smooth ball with defined finger marks, light soil/water staining on fingers, ribbons between thumb and forefinger. SMD 100 - 33
75 - 100	Wet, forms a weak ball, loose and aggregated sand grains remain on fingers, darkened color, heavy water staining on fingers, will not ribbon. SMD 25 - 0	Wet, forms a ball with wet outline left on hand, light to medium water staining on fingers, makes a weak ribbon between thumb and forefinger. SMD 33 - 0	Wet, forms a ball with well-defined finger marks, light to heavy soil/water coating on fingers, ribbons between, thumb and forefinger. SMD 42 - 0	Wet, forms a ball, uneven medium to heavy soil/water coating on fingers, ribbons easily between thumb and forefinger. SMD 50 - 0
Field Capacity 100	Wet, forms a weak ball, moderate to heavy soil/ water coating on fingers, wet outline of soft ball remains on hand. SMD 0	Wet, forms a soft ball, free water appears briefly on soil surface after squeezing or shaking, medium to heavy soil/water coating on fingers. SMD 0	Wet, forms a soft ball, free water appears briefly on soil surface after squeezing or shaking, medium to heavy soil/water coating on fingers. SMD 0	Wet, forms a soft ball, free water appears on soil surface after squeezing or shaking, thick soil/water coating on fingers, slick and sticky. SMD 0

crops (USDA-NRCS, 2004). Soil moisture deficit (SMD) is the amount of water required to raise the soil water content of the crop root zone to field capacity (USDA-NRCS, 2004).

In addition to the "hand-feel method", electrical resistance blocks, tensiometers, neutron gauges (neutron scatter), time-domain reflectometers (TDR), and capacitance probes are a few of the available soil moisture measuring tools used for irrigation scheduling.

Electrical resistance blocks use electrodes embedded in porous gypsum blocks to relate an electrical resistance measurement to soil moisture. Soil moisture tension in centibars is the measurement unit provided by the meter. Soil moisture tension is a measure of how hard a plant has to work to extract water from the soil. A major disadvantage of electrical resistance blocks is that they are affected by salts, fertilizers, and temperature; therefore, they are not recommended for irrigation scheduling of field crops (USDA, 1991). In Alberta, electrical resistance blocks might be considered for orchard or nursery applications where they are not disturbed or moved for many years (Harms, 2002).

Tensiometers use a porous ceramic cup attached to the bottom of a clear plastic tube, water reservoir, and calibrated vacuum gauge to measure soil moisture tension in centibars (University of Minnesota, 1991). Tensiometer contact with the soil may be affected by the longer drying-wetting cycle that occurs in irrigated field crops, making the instrument unsuitable for irrigation scheduling of field crops. Electrical resistance blocks and tensiometers are effectively used in a horticultural setting where the soil moisture is kept near field capacity.

The neutron scatter method is expensive and highly regulated (radiation license required). The technique is based on the measurement of fast-moving neutrons (generated from an Americium 241/Beryllium source) that are slowed in soil by an elastic collision with existing hydrogen particles in the soil (ICT International, 2009). The slowed neutrons are measured as counts, which are proportionate to soil moisture content. The Campbell Pacific Nuclear International Inc. model 503DR1.5 is an example of an instrument that uses the neutron scatter method to determine soil water content (Figure 5). If calibrated to each field, the neutron scatter method is very accurate. The neutron scattering method has remained mainly a research tool, but according to Howell (1996), it has found some use by consultants in the United States.

The TDR and capacitance methods are widely available and measure the dielectric constant (the ratio of the amount of electrical energy stored in an insulator when an electrical field is imposed across it relative to a vacuum) of the soil and relate it to soil water. These methods are also affected by soil electrical conductivity, acidity, and temperature (ICT International, 2009).

In search for a workable soil moisture sensor for Alberta, Harms (2002) evaluated several sensors and found them to be less accurate and reliable than the neutron probe method due to their small sphere of

Figure 5. Campbell Pacific Nuclear International Inc. neutron moisture meter.

influence within the soil matrix. Most of these methods also required the user to have a basic understanding of soil-water relationships. This understanding is necessary to interpret and relate the soil water content units to a decision on when to irrigate. Further, a more advanced understanding of soil-water relationships is required to calibrate the instruments for particular soil textures or to utilize the more advanced features included with some of the soil moisture probes. Harms (2002) concluded that, despite the neutron probe method being expensive and posing a radiation hazard, it was the most accurate soil moisture measuring device tested. The hand-feel method remains the most accessible method used for estimating soil water content in Alberta.

The appropriate use of soil water measuring tools by irrigators in their irrigation management programs prevents over- and under-irrigation and contributes to desired crop yield and quality.

Evapotranspiration (ET)-based methods

The ET-based irrigation management methods are sometimes referred to as weather-based methods. The general approach to these methods is to maintain a running balance of current soil moisture available to the plant by tracking the ET losses and the additions from irrigation and precipitation (Henggeler et al., 2011). This procedure is like maintaining the balance in a bank checking account; hence, it is commonly referred to as the “checkbook” method of irrigation scheduling.

Modeling ET with weather data has evolved with advancements in modeling procedures and data collection methods. Palmer (2005) observed advancements in weather station and data transfer by satellite, phone, radio, or wireless networking contribute to modeled ET-based irrigation scheduling. Computers now make the calculation of complex mathematical ET equations fast, while the internet makes the information almost instantly available to irrigation managers. The ET-based water balance irrigation scheduling methods are increasingly being used throughout the world because they are easy to apply (Jones, 2004). For instance, as a strategy to reduce groundwater withdrawals while maintaining crop productivity in Texas, Colaizzi et al. (2009) found that the most promising irrigation scheduling methods they evaluated were: (1) increasing weather-based irrigation scheduling using the Texas High Plains ET Network (TXHPET) and (2) converting gravity irrigation systems to sprinkler systems. Furthermore, to help improve irrigation efficiency, the Bureau of Reclamation and Bonneville Power Administration partnered to create a network of automated agricultural weather stations – called “AgriMet” – in the Pacific Northwest U.S. (Palmer 2011). These stations collect and telemeter the meteorological parameters required to model crop ET. The information is used by irrigation districts, farmers, resource conservation agencies, and agricultural consultants for irrigation scheduling and related purposes. Alberta has a similar weather station network referred to as the Irrigation Management Climate Information Network (IMCIN) that collects data used for ET-based irrigation management.

Unlike the plant-based irrigation scheduling methods, ET-based methods indicate “how much” water and “when” to apply. Despite being easy to use, ET-based methods tend to be less accurate than direct soil water measurements, need accurate local estimates of precipitation and runoff, require good estimates of crop and soil coefficients, and require regularly maintained and calibrated weather monitoring instruments. These methods estimate ET and calculate crop water requirements for different crops and climatic regions.

In Alberta, crop water requirements (soil water deficit or irrigation requirements since the last irrigation) are increasingly being estimated by a web-based calculator found at the IMCIN website and by the Alberta Irrigation Management Model (AIMM) (ARD, 2011b). The Alberta IMCIN is an irrigation scheduling decision-support system that uses data from the nearest meteorological station to assist in on-farm irrigation scheduling operations. The IMCIN calculator, known as IRRI-Cast, and the AIMM use the modified Penman-Monteith equation (Eq. 1) to estimate ET (Jensen et al., 1990). This ET function assumes ideal crop and growing conditions. If ideal conditions do not exist, over- or under-estimation of crop water use may result.

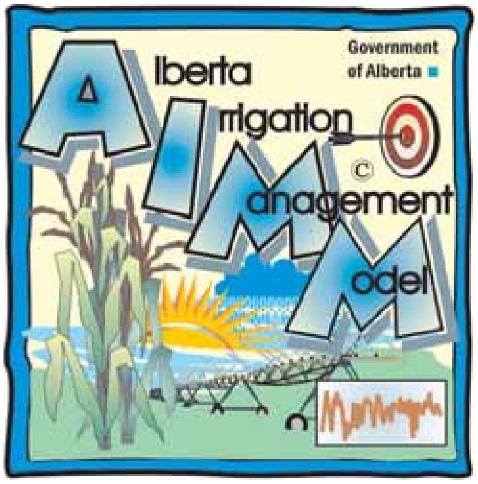
For this reason, irrigators in Alberta are encouraged to employ in-season corrections to the modeled ET estimates to reflect field conditions by directly measuring soil water content (ground-truthing).

$$ET_{ref} = \frac{0.408\Delta(Rn - G) + \gamma \dfrac{1700}{T + 273} \mu_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.40\mu_2)} \qquad (1)$$

Where:

ET_{ref} = evapotranspiration for alfalfa reference crop (mm d^{-1})
Δ = slope of vapor pressure curve (kPa $°C^{-1}$)
γ = psychometric constant (kPa $°C^{-1}$)
Rn = net radiation (MJ m^{-2} d^{-1})
G = soil heat flux density (MJ m^{-2} d^{-1})
T = mean daily air temperature (°C)
μ_2 = wind speed at 2 meter height (m s^{-1})
e_s = saturation vapor pressure (kPa)
e_a = actual vapor pressure (kPa)

Meteorological parameters that influence ET (temperature, solar radiation, relative humidity, and wind speed) are used in Eq. 1 to estimate ET for a well-watered reference crop (ET_{ref}). The most common reference crops are cool-season grass (short reference) and alfalfa (tall reference) fully covering the ground. In Alberta, alfalfa is used as the reference crop. Daily and cumulative ET for local crops (ET_{crop}) is estimated using Eq. 2, which is adjusted to the crop of interest using a specific crop coefficient (K_c). The meteorological parameters used in the AIMM model are downloaded from the IMCIN weather stations in the irrigated areas of Alberta (Figure 6).



$$ET_{crop} = K_c * ET_{ref} \qquad (2)$$

Where:

ET_{ref} = evapotranspiration for alfalfa reference crop (mm d^{-1})
ET_{crop} = crop evapotranspiration (mm d^{-1})
K_c = crop coefficient

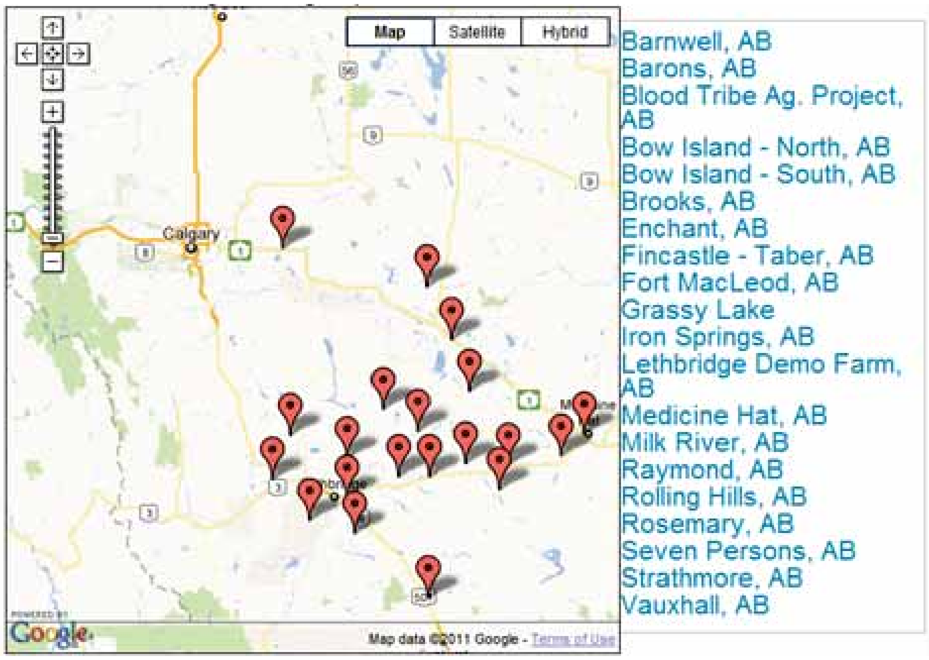


Figure 6. A network of meteorological stations for reference ET predictions (ARD, 2011b).

Information available from the web-based IMCIN calculator is very similar to many other web-sites designed to assist irrigators with irrigation scheduling. The water balance method is used to generate information on how a crop is extracting soil water so an irrigator can decide on when to irrigate and how much water to apply. Many irrigators apply irrigation amounts based on cumulative crop ET for a period of time (e.g., weekly) minus any rainfall received; data that are obtained from the IMCIN website.

The AIMM is adaptable and can be applied to various geographic locations (including locations in Saskatchewan, Manitoba, and Ontario), but it has features specific to the irrigation district structure found in southern Alberta (network blocks, water supervisor's name, email address, etc.). In Saskatchewan, which has similar climatic conditions as Alberta, the Alberta-developed irrigation management model (AIMM) is being used to simplify on-farm irrigation scheduling operations (Tollefson et al., 2002). The AIMM software is different from most other ET models in that it is capable of forecasting crop water requirements and tracking available soil water throughout the growing season in the major irrigated areas of southern Alberta.

The AIMM is a detailed software program that is specific to individual fields (ARD, 2011b; Figure 7). There are many similar irrigation management software programs available; however, most are provided through irrigation management consulting firms. Additionally, the weather data used in the AIMM are quality-controlled and acquired more frequently than irrigation scheduling models used in other parts of North America.

An additional unique feature of the AIMM is that it has been combined with centre pivot communication and control technologies to enable a single irrigator to effectively manage irrigation on a large number of fields to save time, energy, and labour. The AIMM also has the capability of keeping farm records on irrigation water applied, fertilizers, pump specifications and operations, weather data for crop insurance and planning purposes, pesticides, and soil analyses.

The AIMM and the overall irrigation management program have a strong technology transfer support program through education and training, a web-based help manual, and the availability of irrigation management expertise.

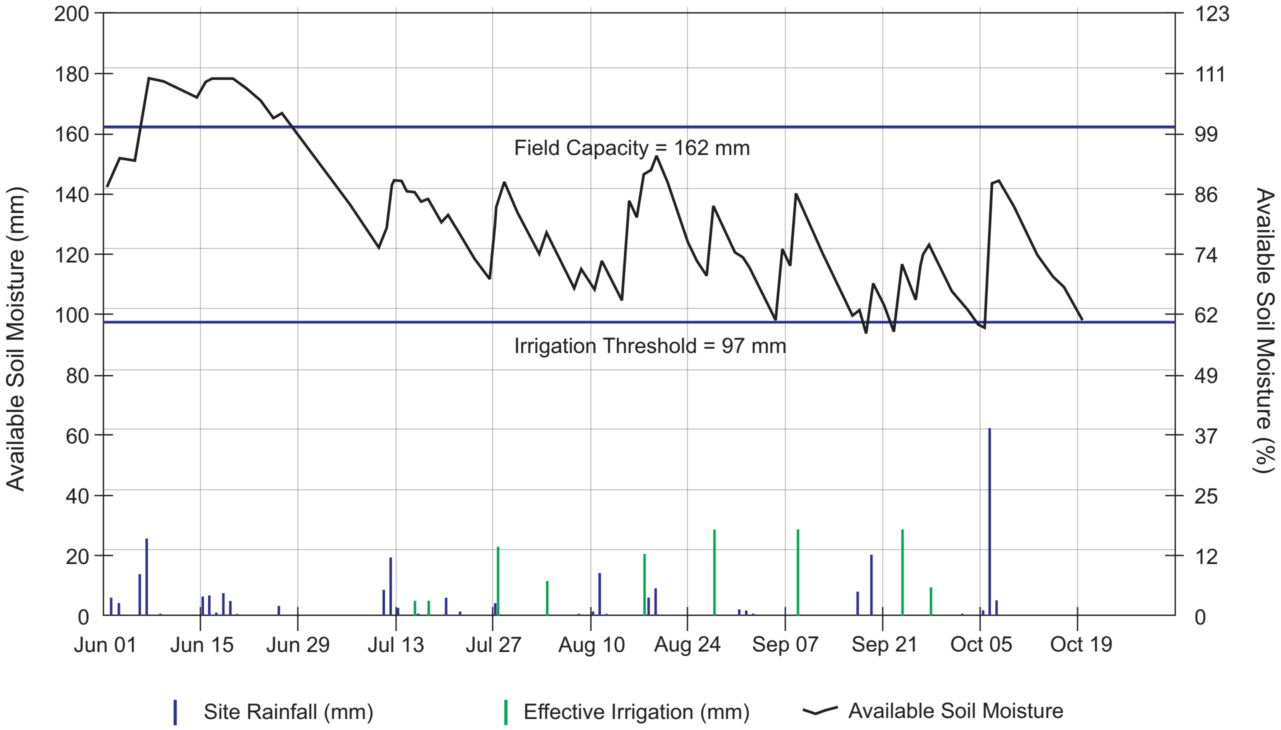


Figure 7. Graph from the Alberta Irrigation Management Model depicting soil water status, rainfall, and irrigation amounts.

IRRIGATION SYSTEM APPLICATION EFFICIENCIES

Different irrigation systems have different application efficiencies. Irrigation system application efficiencies have steadily improved since the introduction of sprinkler irrigation in southern Alberta. Application efficiencies have increased from less than 30 percent in 1965 to greater than 70 percent in 2007 (AECOM Canada Ltd., 2009). Understanding the application efficiencies of different irrigation systems can help producers make critical irrigation management decisions for optimum crop yield and quality.

Irrigation system application efficiency is defined as the amount of water stored in the root zone that is available to meet crop transpiration needs in relation to the amount of irrigation water applied to the field (Heermann and Solomon, 2007). The efficiency of different irrigation systems varies depending on many factors: type of irrigation system, age of the system, type of nozzles, height of the sprinklers above the crop canopy, upkeep of the system, design of the field (gravity irrigation), size of the stream (gravity irrigation), type of crop and growth stage, irrigation management, environmental factors, and numerous other soil, crop, weather, and agronomic variables. Irrigation system application efficiencies include any possible application losses: wind drift of water droplets away from the target area, evaporation of water droplets before infiltration into the soil, surface runoff from the field, and deep percolation of applied water below the crop rooting depth. Thus, most irrigation system application efficiencies are displayed as a range that reflects variation in the factors that can affect system application efficiencies. For design, comparative, forecasting, or irrigation analysis purposes, a single application efficiency value is usually selected for each irrigation method (Table 7).

Table 7. System application efficiencies by irrigation method in southern Alberta.

Irrigation Method	Range[†] (%)	Design (%)
Gravity – Undeveloped		30
Gravity – Developed	40 – 80	62
Sprinkler – Solid Set		72
Sprinkler – Hand-move	60 – 85	67
Sprinkler – Wheel-move – 2 Laterals	60 – 85	68
Sprinkler – Wheel-move – 4 Laterals	60 – 85	70
Sprinkler – Pivot – High pressure	75 – 90	73
Sprinkler – Linear – High pressure	75 – 90	73
Sprinkler – Pivot – Low pressure	75 – 95	84
Sprinkler – Linear – Low pressure	75 – 95	84
Sprinkler – Volume gun – Stationary	55 – 75	65
Sprinkler – Volume gun – Traveller	55 – 75	66
Micro – Spray – Sprinkler	70 – 95	82
Micro – Drip – Trickle	70 – 95	88

[†] Sources: Howell, 2003; Alberta Agriculture and Rural Development, 2011c.

These application efficiency values (E_a) are used in irrigation management to determine the gross irrigation application amount that needs to be applied to offset system losses (Henggeler et al., 2011). Equation 3 may be used to calculate the gross irrigation depth or amount (d_{gross}) (Henggeler et al., 2011):

$$d_{gross} = d_{net}/E_a \qquad (3)$$

Where:
d_{gross} = the gross amount to apply (mm)
d_{net} = the net application amount (mm)
E_a = irrigation system application efficiency (decimal)

For example, a net irrigation amount (d_{net}) of 15 mm with a low pressure centre pivot requires a gross irrigation amount of about 18 mm (15 mm/0.84 = 18 mm).

Irrigation Management and Equipment Effects on Irrigation System Application Efficiencies

Each time an irrigation system applies water, a fraction of the water applied is lost through spray evaporation, spray drift outside the target area, evaporation from the soil surface and crop canopy, and by surface runoff if the rate of application exceeds the intake rate of the soil. Some of these losses may be reduced with irrigation equipment that decreases evaporation losses or with management practices, such as reservoir tillage in row crops, which minimize surface runoff. Losses vary considerably in response to environmental factors, irrigation equipment characteristics, and irrigation management practices.

Operation of the irrigation system can have a significant influence on the overall irrigation system application efficiency. For example, a standard quarter section centre pivot operating at 57 L s^{-1} (900 U.S. gpm) would have losses of about 4 mm per application. The effect of speeding up or slowing down the centre pivot on overall irrigation system application efficiency is shown in the following table.

Time for one circle (days)	1	2	3
Gross Application (mm)	9.7	19.3	29.0
Assumed Losses (mm)	3.5	4.0	4.5
Net Application (mm)	6.2	15.3	24.5
Overall Efficiency (%)	64	79	84

If losses could be reduced to 2 mm per application through use of more efficient irrigation equipment, such as drop tubes and higher efficiency sprinkler nozzles, irrigation system application efficiencies could be further enhanced.

Time for one circle (days)	1	2	3
Gross Application (mm)	9.7	19.3	29.0
Assumed Losses (mm)	1.8	2.0	2.2
Net Application (mm)	7.9	17.3	26.8
Overall Efficiency (%)	81	90	92

Irrigators typically operate centre pivot systems to complete a circle in about two days, except during the early part of the growing season when more frequent irrigations are performed to promote germination and emergence of crops. Surface runoff and soil trafficability are key considerations in determining the most appropriate pivot speed for improved irrigation system application efficiency.

IRRIGATION MANAGEMENT OF MAJOR CROPS IN ALBERTA

The goal of irrigation management is to use available irrigation water effectively in managing and controlling the soil moisture environment of crops to do three things: promote the desired crop response, minimize soil degradation, and protect water quality.

Proper irrigation management requires a good understanding of a number of factors:

- soil fertility (crop nutritional requirements)
- soil-water-plant relationships
- crop type
- crop sensitivity to water stress
- crop growth stages
- availability of a water supply
- climatic factors that affect crop water use such as rainfall, temperature, humidity, wind, and net radiation
- irrigation system capabilities and limitations

Equipped with this knowledge, an irrigator can develop a workable and efficient irrigation scheduling program.

Strategies

A workable and efficient irrigation management strategy should be crop-specific. Crop-specific irrigation management strategies mean available water is used efficiently to meet specific crop water requirements for maximum water productivity.

Generally, the goal is to ensure that water is available at germination and in early development by applying light, frequent irrigations (if there is no rainfall). This method promotes vigorous growth and replenishes and increases available soil water content in the entire root zone during the pre-flowering growth stages. Such a strategy will ensure sufficient soil water is available to meet crop demand during the peak water-use period, which typically occurs during the flowering and fruit-formation growth stages.

Crop-specific irrigation management strategies are usually applied to adjust for the following differences among crops:

- effective root zones
- sensitivity to water stress
- types (cool versus warm-season)
- vulnerability to diseases at various crop growth stages
- response to soil fertility levels
- plant population/densities
- physiological maturity (timing of last irrigation)
- potential income

Setting up an effective on-farm irrigation management program

The following steps may be followed when setting up an effective irrigation management program.

1. Determine the effective root zone (ERZ) depth of the crop and the corresponding available water-holding capacity of the soil.
2. Select the predominant soil type that should be used for irrigation management (available water capacity varies with soil texture).
3. Define the allowable soil water depletion (AD) limits for the selected soil type and crop to be grown.
4. Establish a soil moisture monitoring system and regularly keep track of the soil water deficit.
5. Initiate irrigation when the soil water deficit is expected to approach the allowable depletion limit.
6. Know your irrigation system application rate and efficiency (E_a) and compare with crop water use patterns. Be aware that many irrigation systems can barely “keep up” to crop water demand during peak water-use periods, so start early to apply the necessary amount.

Effective irrigation management for different crops uses soil water levels in the ERZ as a measure for starting and stopping irrigations in order to maintain adequate soil water content.

Irrigation scheduling for alfalfa hay

Water requirement. Alfalfa is a high water use perennial forage crop because it has a deep root system, produces a substantial amount of above-ground biomass, and has a longer growing season compared to other irrigated crops in southern Alberta.

In addition to requiring adequate soil water, alfalfa is more productive when it is grown under optimal conditions: well inoculated with appropriate nitrogen-fixing bacteria (*Rhizobium meliloti*), well fertilized, pest-free, seeded in a soil with adequate internal drainage, seeded using a proper seeding rate for optimum and uniform canopy, and adequate day length and temperature.

The water requirement for alfalfa hay depends on cultivar selection, growth stage, canopy density, harvest date, climatic conditions, and irrigation and crop management. Alfalfa grown under optimal conditions requires 540 to 680 mm of water per growing season in southern Alberta. It is estimated that irrigated alfalfa uses about 100 to 125 mm of water for every ton (907.2 kg or 2,000 lb) of hay produced.

Alfalfa is relatively drought tolerant, but its growth depends on the availability of water to the roots. Water is needed for germination and early seedling growth. If PAW is kept between 60 and 100 percent, alfalfa will germinate and grow rapidly into a full stand in the year of establishment.

Adequate water and fertilizer are essential for alfalfa to emerge quickly from dormancy in the spring and reach the first-cut peak daily water use of nearly 9 mm in late June, the second-cut daily peak water use of nearly 8 mm in early August, and the third-cut peak water use of nearly 7 mm in late September (Figure 8). Because alfalfa is a cool-season crop, the greatest percentage of the seasonal yield (nearly 40 percent) comes from the first cut, which also has the highest water-use efficiency of the three cuts.

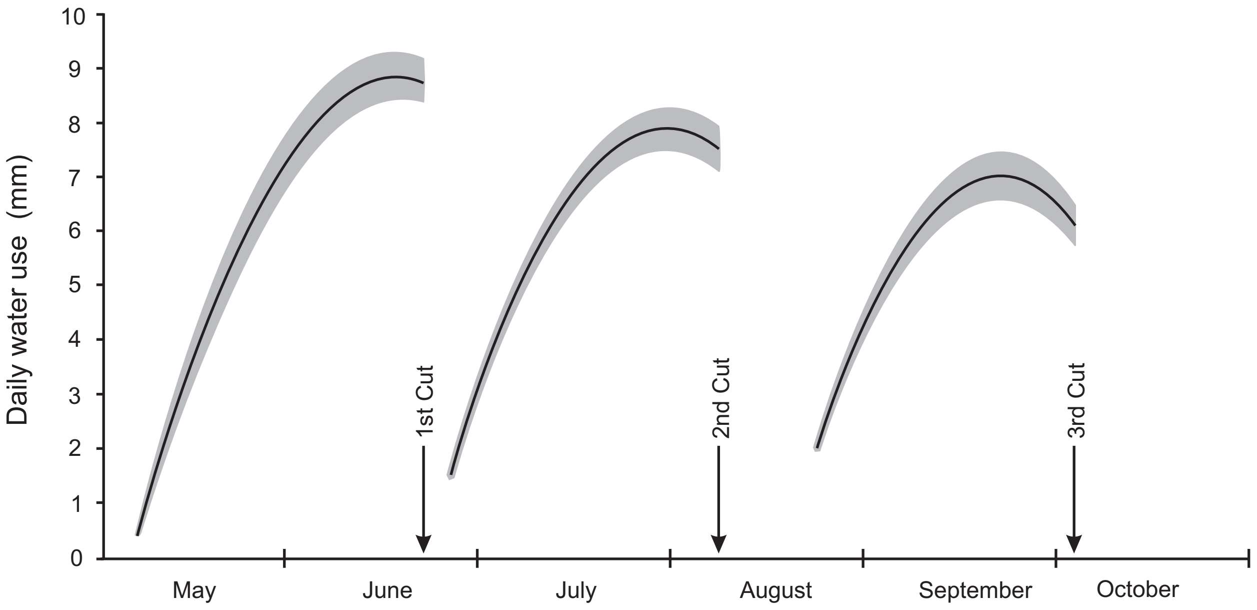


Figure 8. Daily water use for the first, second, and third cuts during different growth stages of irrigated alfalfa hay in southern Alberta. The shaded area indicates variation in alfalfa water use depending on cultivar, plant density, age, and climatic conditions. Differences among cuts reflect differences in climatic conditions such as photoperiod and temperature (ambient and soil).

Typically, the roots of a well-irrigated alfalfa plant grow to an ERZ depth of 120 cm in a well-developed soil profile. Root distribution is concentrated near the surface; hence, alfalfa obtains nearly 40 percent of its seasonal water from the upper 30 cm, 70 percent from the upper 60 cm, and 90 percent from the upper 90 cm of the 120-cm root zone in the production years.

Since only 10 percent of seasonal water use for alfalfa is extracted from the 90 to 120-cm depth, it is essential for irrigators to pay more attention to the water status in the upper 90 cm of the ERZ. The ERZ depth changes from a few millimeters at emergence to a maximum depth of 120 cm at the end of the establishment year.

The roots of non-irrigated alfalfa (particularly tap-rooted varieties) penetrate deeper than 120 cm (adaptation to stress from water deficits) and reach maximum depths in the third year of the stand.

Irrigation scheduling. The availability of adequate soil water for emergence, stand establishment, and achievement of maximum, high-quality yields is crucial for producing a profitable alfalfa hay crop.

Establishment year. Establishment of a high-yielding alfalfa stand requires careful attention to fertilizer, weed control, and effective irrigation water management. Irrigation can be used most effectively in promoting germination and emergence by wetting the soil profile to field capacity before seedbed preparation and the seeding operation. Avoid irrigation just after seeding because it may cause seed washing and crusting of some soils and reduce the plant population and stand uniformity.

After emergence, the alfalfa seedling roots require ample water for rapid growth. To ensure that ample water is available to the young roots during the early seedling and vegetative growth stages (unifoliolate, cotyledonary, and trifoliolate leaf bud formation), and contractile (crown development) growth stages (i.e. the first 10 weeks), light and frequent irrigations (15 mm per irrigation event) should be applied to maintain soil water in the 0 to 30-cm depth at greater than 60 percent of available in the establishment year.

Irrigation water applied during the early growth stages should meet crop water requirements and build up soil water to near field capacity in the 30 to 120-cm depth for later crop use after the contractile growth stage. To prevent runoff, irrigation water application rates should not exceed soil intake (infiltration) rates.

The practice of withholding irrigation following emergence for the purpose of increasing root penetration is counterproductive because early water stress (PAW less than 60 percent) will suppress seedling root growth more than shoot growth for alfalfa. Water stress decreases stem number and diameter, internode numbers and length, and leaf size; hence, stand vigour and health.

If alfalfa is seeded in the spring and stand establishment is adequate and healthy, the initial cut may occur in the first or second week of August (16 weeks from seeding) after contractile growth is complete, followed by a full irrigation to fill up the 120-cm root zone. Availability of water to the roots enables the crop to recover quickly from defoliation stress and rapidly grow to a full stand prior to winter.

As the ambient and soil temperatures cool down, the day length shortens, and soil water is depleted by the growing alfalfa crop in the fall, the taproots start to enlarge and extend into deeper soil horizons. These roots store carbohydrates produced by photosynthesis. Stored carbohydrates provide energy for re-growth after cutting, winter survival, and initial spring growth. Soil water should be monitored so that the crop goes into winter when the PAW is about 70 percent. Available soil water greater than 70 percent (near field capacity) contributes to increased alfalfa winterkill or winter injury.

Production years. Effective first-cut, second-cut, and third-cut alfalfa irrigation scheduling uses a 120-cm ERZ depth during production years. Adequate soil water, coupled with a balanced and adequate fertility program, is critical for alfalfa growth for high yield and quality.

A well-fertilized and pest-free alfalfa stand will reach maximum yield and quality if ample water is available in the ERZ during production years. To ensure that ample water is available to alfalfa roots, PAW should not be depleted to less than 60 percent in the 120-cm root zone.

Irrigations should be scheduled to fill the entire root zone to 100 percent of PAW, especially during dry and hot periods in July. The last irrigation before cutting should be far enough in advance that the PAW is nearly 70 percent during harvesting and should be timed with the proper application amount within a week after cutting.

Full irrigations should always be applied immediately after the first and second cuts to maintain high alfalfa water productivity. Irrigation management for the third-cut alfalfa hay crop should be designed to encourage the accumulation of carbohydrates in the roots to provide energy for re-growth after cutting, winter survival, and spring growth.

Soil water should be monitored so that the PAW in the ERZ is about 70 percent when the third cut is completed, typically after a killing frost in early October (Figure 8).

Irrigation scheduling for barley (grain)

Water requirement. The water requirement for barley depends on variety, growth stage, canopy density, climatic conditions, and irrigation and crop management. Barley grown under optimal conditions (well-fertilized, well-irrigated, seeded in standing stubble, pest-free, and uniform and optimum canopy) requires 380 to 430 mm of water per growing season in southern Alberta. When seeded into soil with available water between 60 and 100 percent, barley will germinate, grow rapidly, and reach a peak water use of nearly 7 mm per day during the flowering and fruit-formation growth stages (Figure 9).

Typically, the roots of barley grow to an ERZ depth of 100 cm in a well-developed soil. Root distribution is concentrated near the surface; hence, barley obtains more than 70 percent of its seasonal water from the upper 50 cm of the ERZ. The ERZ depth changes from a few millimeters at emergence to a maximum depth of 100 cm at the flowering growth stage.

Irrigation scheduling. Adequate soil water is critical for barley during the emergence, vegetative (pre-flowering), flowering, and fruit-formation growth stages. Ideally, PAW in the 0 to 50-cm depth should be greater than 60 percent at planting.

Barley needs to have sufficient water for germination and root development during the early stages of growth. If seeded in a dry seedbed (less than 60 percent of available in the 0 to 50-cm depth) in late April before irrigation water is available, the first and subsequent irrigations (15 mm per irrigation event) should be applied as soon as irrigation water is available in early May. These irrigations should be light and frequent to maintain a moist soil surface, to prevent crusting, and to encourage rapid emergence and early root development. Ideally, irrigation to increase seedbed soil water should be applied before seeding.

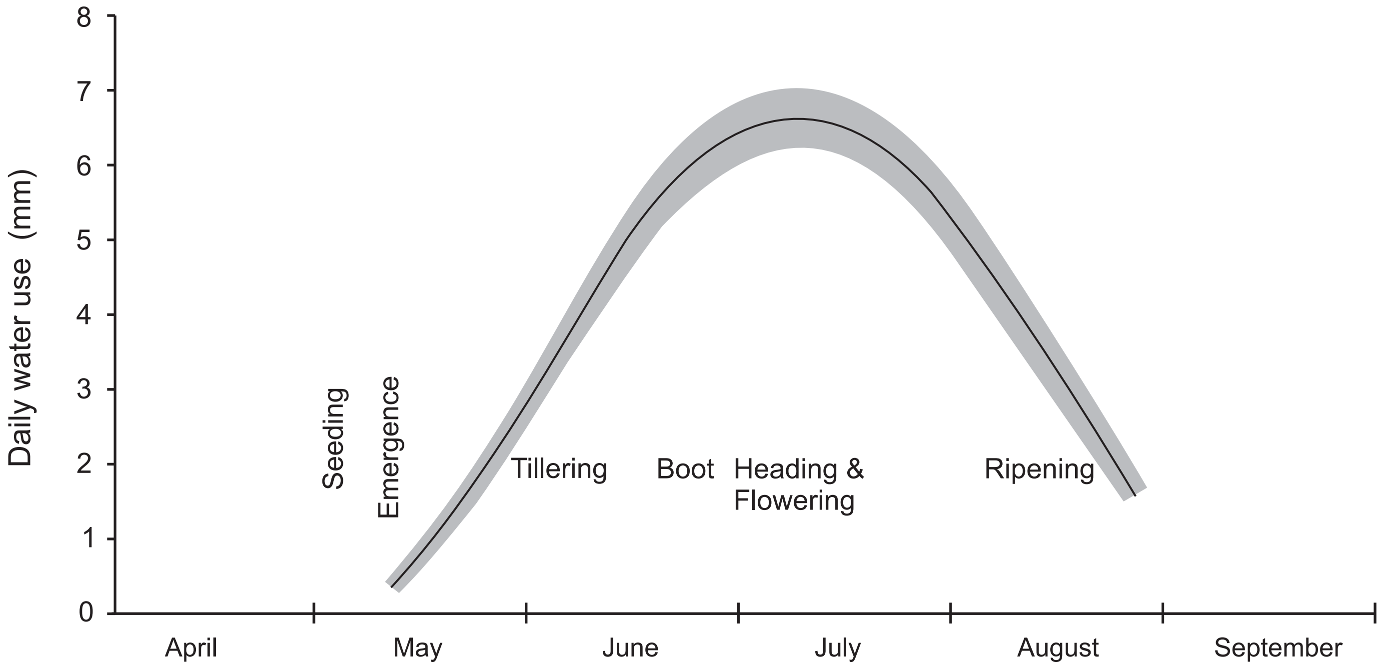


Figure 9. Daily water use during different growth stages of irrigated barley in southern Alberta. The shaded area indicates variation in barley water use depending on plant type, cultivar, and climatic conditions.

If well-fertilized, a pest-free barley stand will reach maximum grain yield and quality if ample water is available in the root zone during the tillering and flowering growth stages. To ensure that ample water is available to barley during the vegetative growth stages (i.e. tillering to late boot), PAW should not be depleted to less than 60 percent in the upper 50 cm of the 100-cm root zone.

Any irrigation applied during the vegetative growth stages should start when the available soil water is near 65 percent of available to prevent the PAW from being depleted to less than 60 percent.

Maintaining PAW above 60 percent in the upper 50-cm depth during the vegetative growth stages necessitates light and frequent irrigation applications. Irrigation water applied during the vegetative growth stages should meet crop water requirements and build up soil water to near field capacity in the 50 to 100-cm zone for use during the peak water-use period when flowering is occurring.

In general, barley is most sensitive to inadequate soil water during the flowering growth stage. Inadequate soil water during this stage results in flower abortion.

Barley roots reach maximum extension at the flowering growth stage. To ensure that soil water is adequate throughout the root zone during flowering, the monitoring depth of the root zone should be increased from 50 to 100 cm at the early heading growth stage, and PAW should not be depleted to less than 60 percent (i.e. MAD should not be greater than 40 percent).

Irrigations should be scheduled to fill the entire root zone (100 cm) to field capacity at the late boot growth stage to avoid applying irrigations during the flowering growth stage when the crop is most vulnerable to Fusarium Head Blight (FHB).

Increasing the irrigation management root zone from 50 to 100 cm at the late boot growth stage requires less frequent and larger irrigation volumes and results in increased water availability to the mature barley roots. This increased time between irrigations keeps the canopy dry, discouraging the incidence of FHB.

The timing of the last irrigation to refill the root zone for barley depends largely on the soil texture. The final irrigation may be applied at the soft dough growth stage when barley is grown in most soils except for loamy sand soils, which are limited by the lower water-holding capacity. The last irrigation to refill the root zone may be needed between the soft dough and hard dough stages on loamy sand soils. About 80 mm of water is required to carry barley from soft dough to physiological maturity in southern Alberta. No irrigation water is needed once the heads have completely turned colour from green to brown since the crop is mature at this point and yields have been established.

Irrigation scheduling for canola

Water requirement. The water requirement for canola depends on variety, plant architecture, growth stage, canola type (Polish or Argentine), canopy density, climatic conditions, and irrigation and crop management. Canola grown under optimal conditions (well-fertilized, well-irrigated, well-drained soils, pest-free stand, and uniform and optimum canopy) requires from 400 to 480 mm of water per growing season in southern Alberta. Average canola water use ranges from 0.1 mm per day soon after emergence to nearly 7 mm per day during flowering and early pod development stages (Figure 10).

Canola roots grow to an ERZ depth of 100 cm in a well-developed soil. Root distribution is concentrated near the surface; hence, canola obtains about 70 percent of its seasonal water from the upper 50 cm of the active root zone of 100 cm. The ERZ depth changes from a few millimeters at emergence to a maximum depth of 100 cm at the flowering growth stage.

Irrigation scheduling. Adequate soil water is critical for canola during the emergence, vegetative (pre-flowering: rosette, elongation, and bud), flowering, and pod-set (silique-set) growth stages. Ideally, soil water content in the 0 to 50-cm depth should be greater than 60 percent of available at planting.

Canola needs to have sufficient water for germination and root and leaf development during the early stages of growth. If seeded in a dry seedbed (less than 60 percent of available in the 0 to 50-cm depth) in late April before irrigation water is available, the first and subsequent irrigations (15 mm per irrigation event) should be applied as soon as irrigation water is available in early May.

These irrigations should be light and frequent to maintain soil water in the 0 to 50-cm depth at greater than 60 percent of available, to prevent crusting, and to encourage rapid emergence and early root and leaf development. Crusting should be avoided because it may lead to problems with crop emergence; hence, reduced plant populations and seed yield.

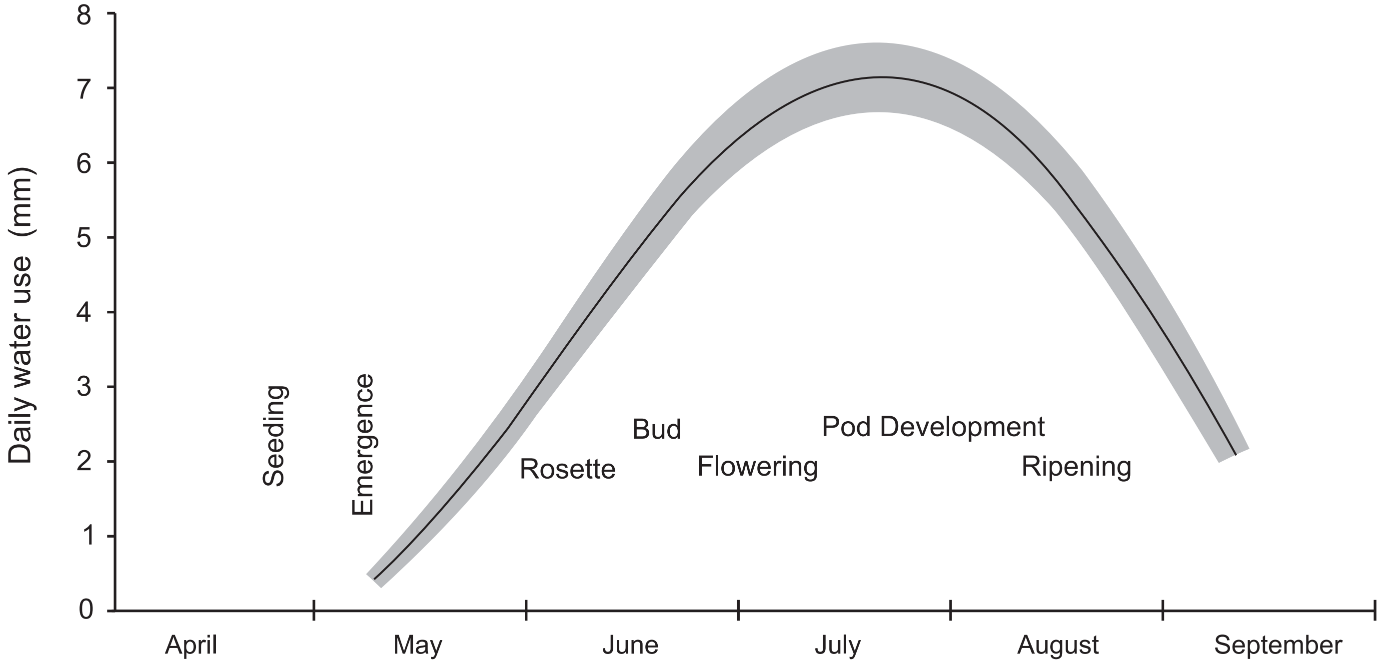


Figure 10. Daily water use during different growth stages of irrigated canola in southern Alberta. The shaded area indicates variation in canola water use depending on plant type, cultivar, and climatic conditions.

Water is essential for canola growth during most of its growth stages, but more critical during the flowering period (about 30 days). To ensure that ample water is available to canola during the vegetative (seedling, rosette, and elongation) growth stages, PAW should not be depleted to less than 60 percent in the upper 50 cm of the 100-cm root zone.

Irrigation water applied during the vegetative growth stages should meet crop water requirements and build up soil water to near field capacity in the 50 to 100-cm zone for use during the peak water-use period when flowering and pod-setting and development are occurring.

Inadequate soil water (less than 60 percent of available) during the canola growing season results in reduced root growth, leaf area, plant leaf retention, number of branches per plant, number of flowers forming per plant (due to reduced flowering period), number of seeds per pod, seed weight, and seed yield and oil content. More importantly, water stress during the flowering and pod set and development growth stages results in large yield losses.

Canola roots reach maximum extension during the flowering growth stage. To ensure that soil water is adequate throughout the root zone, the monitoring depth of the root zone should be increased from 50 to 100 cm, and PAW should not be depleted to less than 60 percent (i.e. MAD should not be greater than 40 percent).

Increasing the irrigation management root zone from 50 to 100 cm at the flowering growth stage requires less frequent and larger irrigation volumes and results in increased water availability to the mature canola roots. This practice also increases the time between irrigations, keeping the canola canopy dry and discouraging the growth of fungal diseases such as sclerotinia stem rot.

For effective control of sclerotinia, this irrigation strategy should be coupled with the appropriate application of registered fungicides, starting at 20 to 30 percent bloom. Terminate irrigation activities if sclerotinia growth is severe.

Under a disease-free environment, the last irrigation to replenish the canola root zone water content to field capacity should occur when the earliest pods begin to ripen in August.

Irrigation scheduling for dry bean

Water requirement. The water requirement for dry bean depends on variety, plant architecture (Type I, II, III, and IV), growth stage, bean class, canopy density, climatic conditions, and irrigation and crop management. Dry bean grown under optimal conditions (well-fertilized, well-irrigated, well-drained soils, pest-free stand, and uniform and optimum canopy) requires from 300 to 375 mm of water per growing season in southern Alberta. Average dry bean water use ranges from 0.1 mm per day soon after emergence to nearly 7 mm per day during flowering and early pod development stages (Figure 11).

Dry bean is shallow-rooted. Typically, the roots grow to an ERZ depth of 60 cm in a well-developed soil. Root distribution is concentrated near the surface; hence, dry bean obtains 85 percent of its seasonal water from the upper 40 cm of the ERZ of 60 cm. The ERZ depth changes from a few millimeters at emergence to a maximum depth of 60 cm at the flowering growth stage.

Dry bean grows well and has high yield and quality potential when the soil water in the active root zone is kept between 60 and 100 percent of the available water-holding capacity of the soil.

Irrigation scheduling. Adequate soil water is critical for dry bean during emergence, vegetative (pre-flowering), flowering, and pod-set growth stages. Therefore, it is best to have a soil profile (0 to 60-cm depth) that is near field capacity at planting.

Dry bean needs to have water for germination and root development during the early stages of growth. If the seedbed (surface 10 cm) is dry (less than 60 percent of available), a light irrigation of 15 mm should be applied prior to seeding. Inadequate soil water in these early growth stages results in reduced plant populations and biomass yield, which, in turn, reduces final yield.

Avoid irrigation just after seeding dry bean because it may lead to soil crusting, which results in problems with crop emergence; hence, reduced plant populations and reduced seed yield.

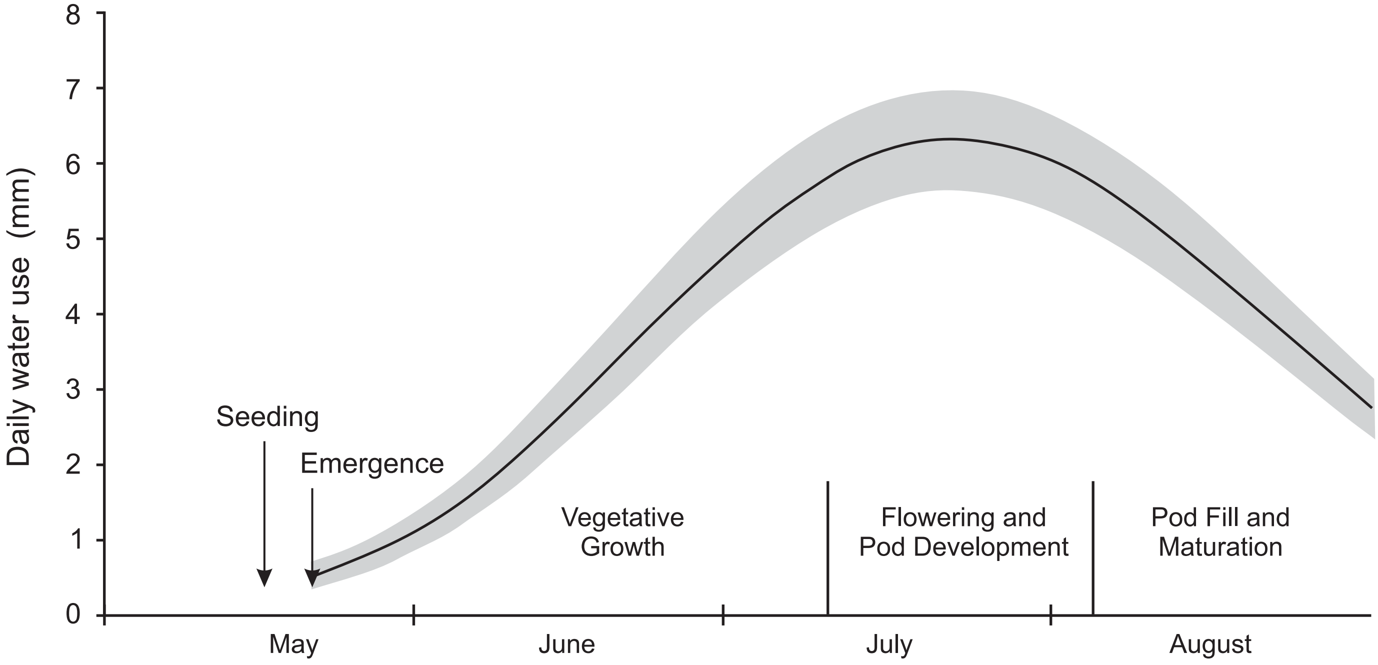


Figure 11. Daily water use during different growth stages of irrigated dry bean in southern Alberta. The shaded area indicates the variation in dry bean water use depending on plant type, cultivar, and climatic conditions.

Dry bean will reach canopy closure early, mature early, and yield more if ample water is available in the root zone during the vegetative (pre-flowering) growth stages. To ensure ample water is available to dry bean during the vegetative growth stages, PAW should not be depleted to less than 60 percent in the 30-cm root zone.

Managing soil water in a 30-cm root zone necessitates light and frequent irrigation applications during the pre-flowering growth stages. Irrigation water applied during vegetative growth stages should meet crop water requirements and build up soil water to near field capacity in the 30 to 60-cm zone for use during the peak water-use period when flowering and pod-setting is occurring.

In general, dry bean is most sensitive to inadequate soil water during the flowering and pod-set growth stages. Inadequate soil water during these stages results in flower and pod abortions.

Dry bean roots reach maximum extension at the flowering growth stage. To ensure that soil water is adequate throughout the root zone, the monitoring depth of the root zone should be increased from 30 to 60 cm, and PAW should not be depleted to less than 60 percent (i.e. MAD should not be greater than 40 percent).

Increasing the irrigation management root zone from 30 to 60 cm at the flowering growth stage requires less frequent and larger irrigation volumes and results in increased water availability to the mature dry bean roots. This increased time between irrigations keeps the soil surface dry, discouraging the growth of white mould.

Irrigation should be scheduled to fill the entire 60-cm root zone to field capacity at the beginning of the pod-fill growth stage to avoid frequent irrigation during the pod-fill and maturation growth stages when the crop is most vulnerable to white mould. This irrigation strategy may help reduce the severity of white mould infection.

Soil water may be depleted to near 50 percent of available during the pod-fill growth stage (without significant yield loss) if conditions for white mould exist (cloudy and humid weather conditions) before the next irrigation.

Irrigation scheduling for pea

Water requirement. Pea is an annual cool-season legume crop that is well-adapted to southern Alberta's semi-arid climate. Optimal pea yields can be obtained if the crop is seeded early in the spring in order to flower before the hot, summer weather conditions. The water requirement for pea depends on variety, plant architecture, growth habit, growth stage, canopy density, climatic conditions, and irrigation and crop management. Pea grown under optimal conditions (well-fertilized, adequately inoculated, well-irrigated, well-drained soils, pest-free stand, and uniform and optimum canopy) requires from 300 to 370 mm of water per growing season in southern Alberta.

Average pea water use ranges from 0.1 mm per day soon after emergence to nearly 6 mm per day during the flowering and early pod development stages (Figure 12).

Typically, pea roots grow to an ERZ depth of 70 cm in a well-developed soil. Root distribution is concentrated near the surface; hence, pea obtains 70 percent of its seasonal water from the upper 35 cm of the ERZ depth of 70 cm. The ERZ depth changes from a few millimeters at emergence to a maximum depth of 70 cm at the flowering growth stage.

Irrigation scheduling. Adequate soil water is critical for pea during the emergence, vegetative, flowering, and pod development growth stages. Ideally, soil water content in the 0 to 40-cm depth should be greater than 60 percent of available at planting.

Pea needs to have water for germination and root development during the early stages of growth. Inadequate soil water in these early growth stages results in reduced plant populations and biomass yield, which, in turn, reduce final seed yield.

A vigorous pea stand can result if available soil water is not depleted to less than 60 percent in the 40-cm root zone during the vegetative growth stages. Managing soil water in a 40-cm root zone necessitates light and frequent irrigation applications during the vegetative growth stages.

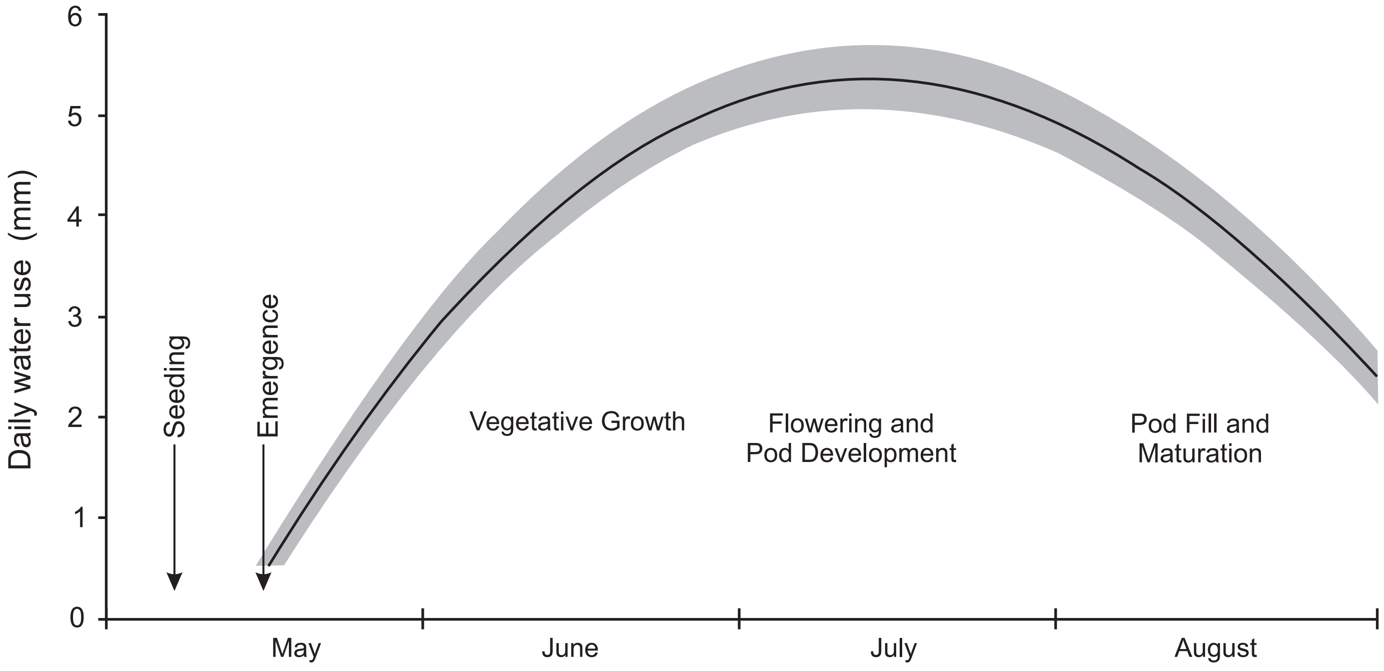


Figure 12. Daily water use during different growth stages of irrigated pea in southern Alberta. The shaded area indicates variation in pea water use depending on plant type, cultivar, and climatic conditions.

Irrigation water applied during vegetative growth should meet crop water requirements and build up soil water to near field capacity in the 40 to 70-cm zone for use during the peak water-use period when flowering (including pod set) and yield formation (pod development and pod filling) are occurring.

In general, pea is most sensitive to inadequate soil water during the flowering and yield formation growth stages. Inadequate soil water during these stages can drastically reduce pod and seed set, resulting from flower and pod abortions.

Pea roots reach maximum extension at the flowering growth stage. To ensure that soil water is adequate throughout the root zone, the monitoring depth of the root zone should be increased from 40 to 70 cm at first flower appearance, and PAW should not be depleted to less than 60 percent.

The availability of sufficient, good quality water to pea plants during the flowering growth stage increases the number of pods (or marketable pods for fresh markets) and seeds per pod, whereas water availability during the pod development growth stage increases the pod and seed weights.

Increasing the irrigation management root zone from 40 to 70 cm at the flowering growth stage requires less frequent and larger irrigation volumes and results in increased water availability to the mature pea roots. This increased time between irrigations keeps the soil surface dry, discouraging the growth of fungal diseases. Irrigation may be stopped when the pods start to ripen.

Irrigation scheduling for potato

Water requirement. The water requirement for potato depends on variety, growth stage, canopy density, climatic conditions, and irrigation and crop management. Potato grown under optimal conditions (well-fertilized, well-irrigated, well-drained soils, pest-free stand, and uniform and optimum canopy) requires about 400 to 550 mm of water per growing season in southern Alberta.

Potato roots grow to an effective water extraction depth of 60 cm and obtain 70 percent of the seasonal water from the upper 30-cm depth.

Water use rates for potato begin at about 0.4 mm per day when the crop sprouts (emerges) and increase to as high as 7 mm per day (Figure 13) when the potato canopy completely shades the ground and tubers are bulking. Potato water demand decreases as the crop achieves full tuber bulking and maturation.

Irrigation scheduling. Potato is more sensitive to soil water deficits than cereals and forages; therefore, an allowable depletion of 35 percent of available (i.e. available moisture maintained between 65 and 100 percent) is typically used to trigger irrigations.

This narrow range of soil water content, coupled with the practice that potato is grown on soils with low to medium water-holding capacities, requires potato growers to closely monitor soil water and have reliable sprinkler irrigation systems that are capable of applying light, frequent, and uniform irrigations during the growing season.

The practice of reservoir tillage, or dammer-dyking, is also recommended to impede runoff and increase the uniformity of soil water content across a potato field.

Potato needs to have adequate and consistent soil water during most of its growth stages: sprouting, vegetative, tuber initiation (tuber set), tuber bulking, and

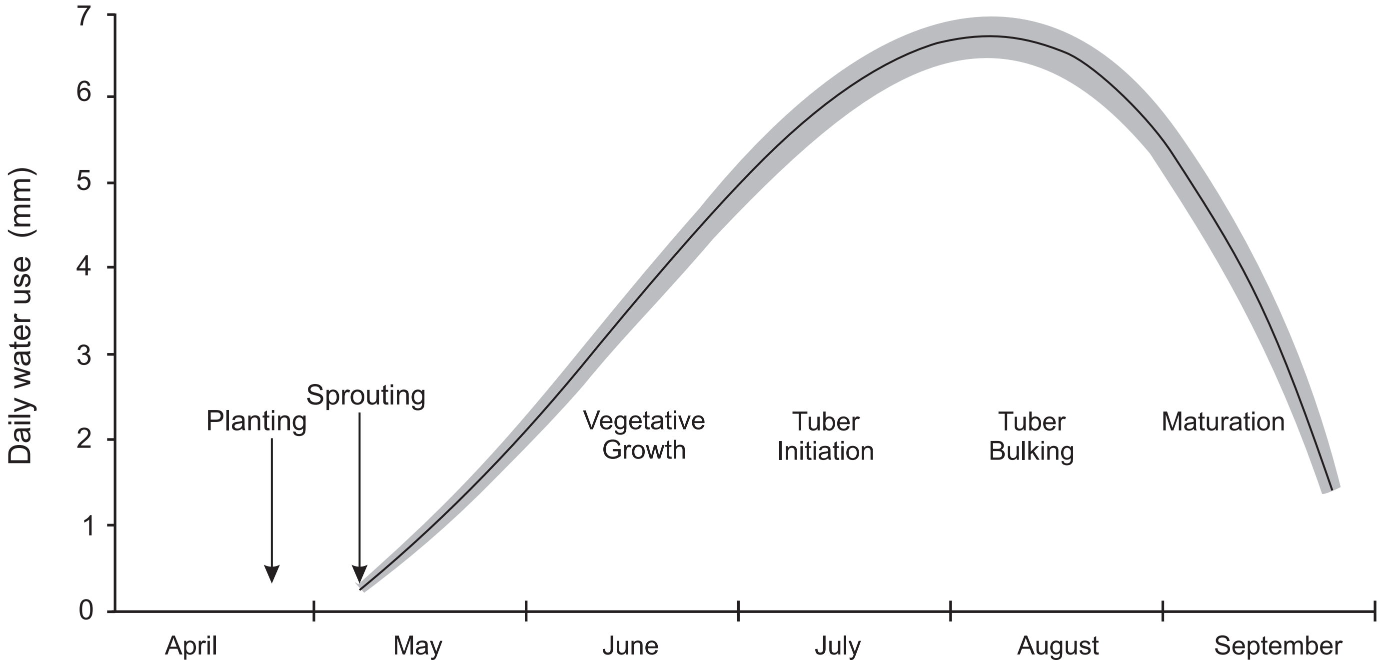


Figure 13. Daily water use during different growth stages of irrigated potato in southern Alberta. The shaded area indicates variation in potato water use depending on cultivar and climatic conditions.

maturation growth stages. To discourage damage to potato seed-pieces caused by various soil-borne diseases, it is recommended that producers avoid applying irrigation between planting and emergence.

Potato is most sensitive to water stress during the tuber initiation growth stage; therefore, special care should be taken to start irrigating when soil water in the top half of the root zone (0 to 60-cm depth) is near 70 percent of available. This practice increases the number of tubers per plant.

Irrigations applied during early growth stages should meet the crop water requirement and recharge the root zone for use during the peak water-use period when tubers are bulking (Figure 13).

The PAW should also be maintained between 65 to 100 percent during the tuber bulking growth stage. Soil water levels outside this desirable range at this growth stage will reduce marketable tuber yield and contribute to growth deformities (such as hollow heart, knobbiness, and cracks) and disease development.

Peak water use for potato approaches 7 mm per day during the full flower and tuber bulking growth stage. Demand begins to decrease from late tuber bulking to maturation.

The PAW in the root zone should be kept near 65 percent during maturation for ease of digging during harvesting. Harvesting when PAW is less than 65 percent may increase tuber damage.

The timing of the final irrigation will depend on the potato end use and potato variety. Tuber sizes for some table varieties can be regulated by controlling soil water levels during bulking. Thus, irrigation should be stopped based on the desired tuber size determined by the marketplace.

Irrigation scheduling for silage corn

Water requirement. Silage corn (maize) is a C4 (warm-season) crop, which means it requires both warm soil and high air temperature to grow steadily and achieve greater yield. Cool temperatures slow down the progress to corn maturity, whereas warm temperatures hasten maturity. Corn growth increases at increasing rates with maximum daily temperatures from 10 to 30°C, then at decreasing rates to 50°C (Ma et al., 2004). The water requirement for silage corn depends on variety, growth stage, canopy density, climatic conditions, and irrigation and crop management.

Typically, silage corn requires 500 to 550 mm of water per growing season when grown under optimum conditions (i.e. well-fertilized, well-irrigated, seeded in suitable row spacing, pest-free, and uniform and optimum canopy with 74,000 to 81,500 plants ha^{-1} (30,000 to 33,000 plants ac^{-1}).

When silage corn is seeded into warm soils (greater than 10°C) with available water between 60 and 100 percent in early May in southern Alberta, silage corn will germinate, grow rapidly, and reach a peak water use of approximately 7 mm per day around mid-July when the crop is nearing the end of the vegetative growth stage (Figure 14). The timing of crop growth stages will depend on crop variety/hybrid, seeding date, climate, and other environmental factors. During the reproductive stages (tasseling/silking, blister, and milk), the crop will require 4 to 7 mm per day. Crop water use declines to 2 to 3 mm per day during ripening.

Typically, the roots of silage corn grow to an ERZ depth of 100 cm in a well-developed soil. Root distribution is concentrated near the surface; hence, silage corn obtains more than 70 percent of its water from the upper 50 cm of the 100-cm ERZ. The ERZ depth changes from a few millimeters at emergence to a maximum depth of 100 cm at the tasseling and silking growth stages.

Irrigation scheduling. Adequate soil water is critical for silage corn during the emergence, vegetative (pre-tasseling), silking, and fruit-formation (i.e. blister, milk, and dough) growth stages. Ideally, PAW in the 0 to 50-cm depth should be greater than 60 percent at planting.

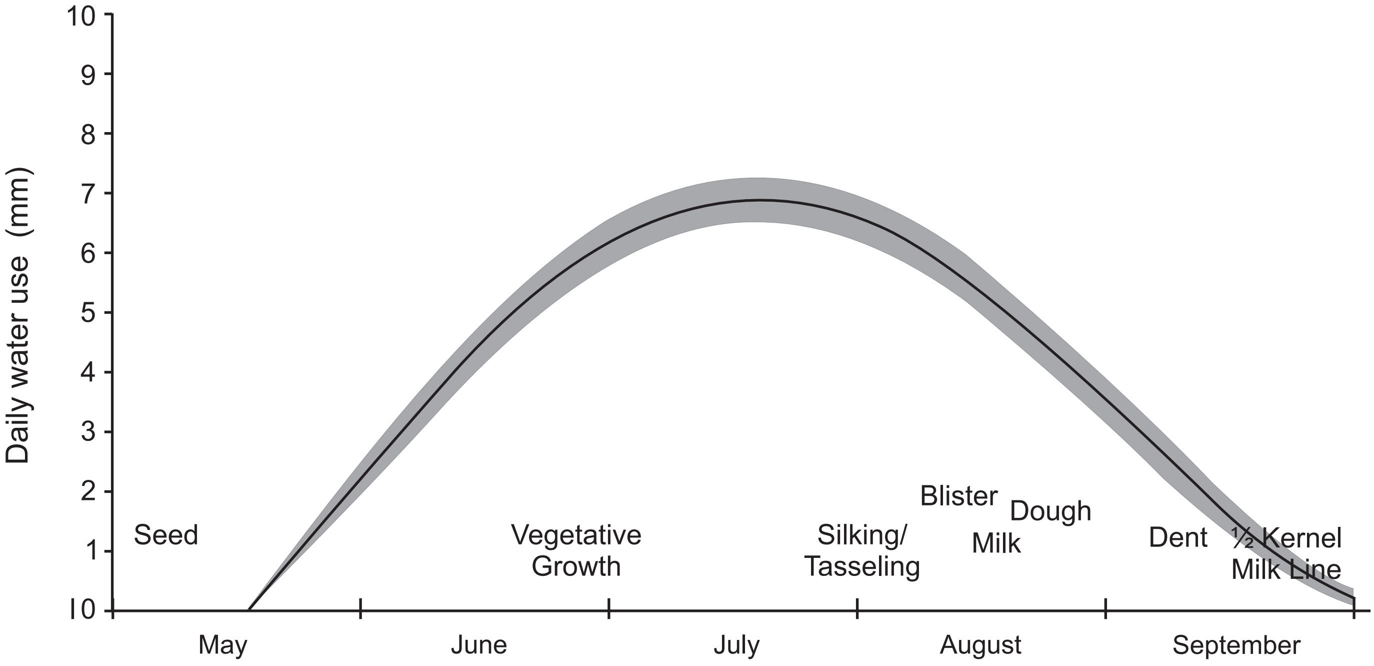


Figure 14. Daily water use during different growth stages of irrigated silage corn in southern Alberta. The shaded area indicates variation in silage corn water use depending on plant type, cultivar, and climatic conditions.

Silage corn needs to have water for germination and root development during the early stages of growth. If seeded in a dry seedbed (less than 60 percent of available in the 0 to 50-cm depth) in early May before irrigation water is available, the first and subsequent irrigations (15 mm per irrigation event) should be applied as soon as irrigation water is available. These irrigations should be light and frequent to maintain a moist soil surface, to prevent crusting, and to encourage rapid emergence and early root development. Ideally, irrigation should be applied before seeding if dry soil conditions prevail.

If well-fertilized, a pest-free silage corn stand will reach maximum silage dry matter yield and quality if ample water is available in the root zone during the emergence, leaf production (vegetative), tasseling, and silking growth stages. To ensure that ample water is available to silage corn during the vegetative through silking growth stages, PAW should not be depleted to less than 60 percent in the upper 50 cm of the 100-cm root zone.

Any irrigation applied during the vegetative through silking growth stages should start when the available soil water is near 65 percent of available to prevent PAW from being depleted to less than 60 percent in the 0 to 50-cm depth.

Maintaining PAW above 60 percent in the upper 50 cm depth during the vegetative through silking growth stages necessitates light and frequent irrigation applications. Irrigation water applied during early growth stages should meet crop water requirements and build up soil water to near field capacity in the 50 to 100-cm zone to ensure that ample water is available for use during the peak water use period (from late June until mid-August).

Silage corn is most sensitive to inadequate soil water during the tasseling and silking growth stages. Inadequate soil water during these stages results in water stress that may dessicate silks and pollen grains, cause poor pollination, seed set, and barren ear tips, thus resulting in poor silage yield and quality.

Silage corn roots reach maximum extension at the tasseling to silking growth stages. To ensure that soil water is adequate throughout the ERZ during these stages, the monitoring depth of the root zone should be maintained at 50 cm and then increased from 50 to 100 cm at the blister kernel growth stage, and PAW should not be depleted to less than 60 percent.

The timing of the last irrigation to refill the root zone for silage corn depends largely on the soil texture, prevailing weather conditions, and availability of irrigation water. The final irrigation to refill the root zone may be applied between the dough and dent growth stages, a week to 10 days before harvest.

A decision on the timing of corn silage harvest should be based on the actual whole plant (5-10 plants) silage water content. The whole plant water content at harvest should be between 62 and 70 percent (ideally at 65 percent water content or 35 percent dry matter content). This target silage water content at harvest results in better animal performance and lower feed costs.

Irrigation scheduling for spring wheat

Water requirement. The water requirement for spring wheat depends on variety, growth stage, canopy density, climatic conditions, and irrigation and crop management. Spring wheat grown under optimal conditions (well-fertilized, well-irrigated, seeded in standing stubble, pest-free, and uniform and optimum canopy) requires 420 to 480 mm of water per growing season in southern Alberta. When seeded into soil with available water between 60 and 100 percent, spring wheat will germinate, grow rapidly, and reach a peak water use of nearly 7 mm per day during the flowering and fruit-formation growth stages (Figure 15).

Typically, the roots of spring wheat grow to an ERZ depth of 100 cm in a well-developed soil. Root distribution is concentrated near the surface; hence, spring wheat obtains more than 70 percent of its seasonal water from the upper 50 cm of the ERZ. The ERZ depth changes from a few millimeters at emergence to a maximum depth of 100 cm at the flowering growth stage.

Irrigation scheduling. Adequate soil water is critical for spring wheat during the emergence, vegetative (pre-flowering), flowering, and fruit-formation growth stages. Ideally, PAW in the 0 to 50-cm depth should be greater than 60 percent at planting.

Spring wheat needs to have water for germination and root development during the early stages of growth. If seeded in a dry seedbed (less than 60 percent of available in the 0 to 50-cm depth) in late April before irrigation water is available, the first and subsequent irrigations (15 mm per irrigation event) should be applied as soon as irrigation water is available in early May. These irrigations should be light and frequent to maintain a moist soil surface, to prevent crusting, and to encourage rapid emergence and early root development.

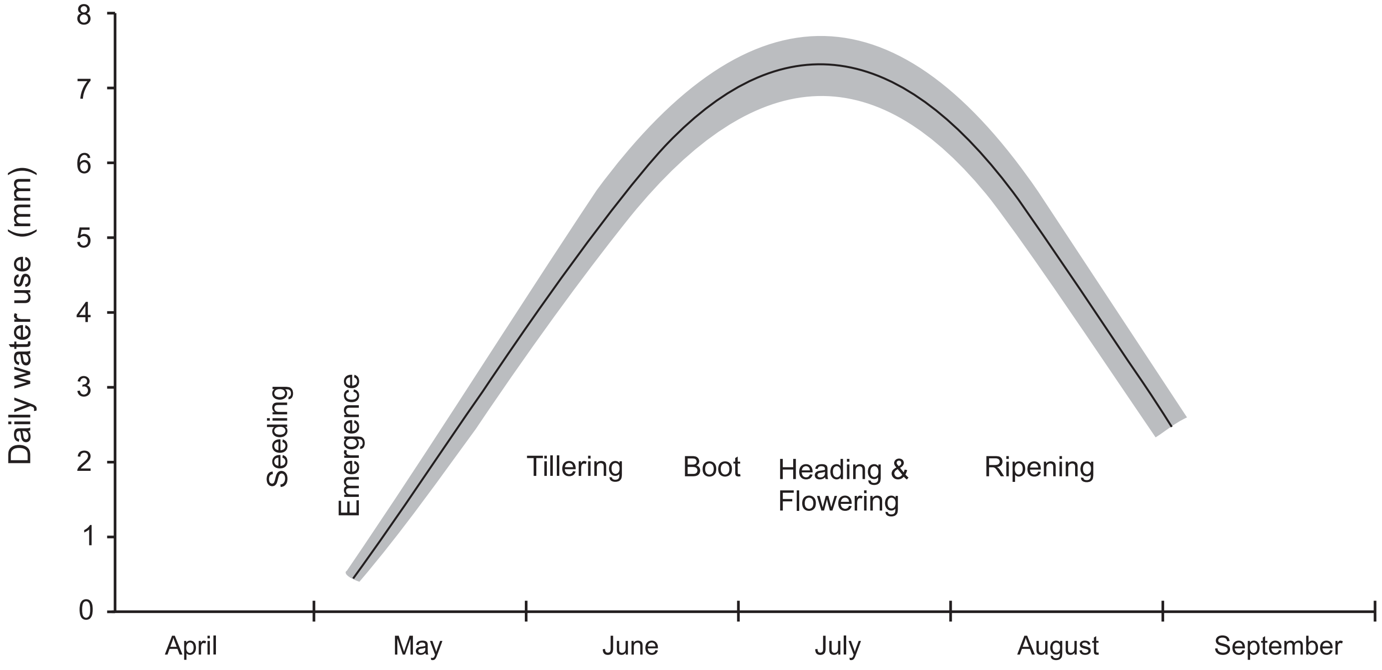


Figure 15. Daily water use during different growth stages of irrigated spring wheat in southern Alberta. The shaded area indicates variation in spring wheat water use depending on plant type, cultivar, and climatic conditions.

If well-fertilized, a pest-free spring wheat stand will reach maximum grain yield and quality if ample water is available in the root zone during the tillering and flowering growth stages. To ensure that ample water is available to spring wheat during the vegetative growth stages (i.e. tillering to late boot), PAW should not be depleted to less than 60 percent in the upper 50 cm of the 100-cm root zone.

Any irrigation applied during the vegetative growth stages should start when PAW is near 65 percent to prevent PAW from being depleted to less than 60 percent.

Maintaining PAW above 60 percent in the upper 50 cm depth during the vegetative growth stages necessitates light and frequent irrigation applications. Irrigation water applied during the vegetative growth stages should meet crop water requirements and build up soil water to near field capacity in the 50 to 100-cm zone for use during the peak water-use period when flowering is occurring.

In general, spring wheat is most sensitive to inadequate soil water during the flowering growth stage. Inadequate soil water during this stage results in flower abortion.

Spring wheat roots reach maximum extension at the flowering growth stage. To ensure that soil water is adequate throughout the ERZ during flowering, the monitoring depth of the root zone should be increased from 50 to 100 cm at the early heading growth stage, and PAW should not be depleted to less than 60 percent (i.e. MAD should not be greater than 40 percent).

Irrigations should be scheduled to fill the entire root zone (100 cm) to field capacity at the late boot-early heading growth stages to avoid applying irrigations during the flowering growth stage when the crop is most vulnerable to Fusarium Head Blight (FHB).

Increasing the irrigation management root zone from 50 to 100 cm at the late boot to early heading growth stages requires less frequent and larger irrigation volumes and results in increased water availability to the mature spring wheat roots. This increased time between irrigations keeps the canopy dry, discouraging the incidence of FHB.

The timing of the last irrigation to refill the root zone for spring wheat depends largely on the soil texture. The final irrigation may be applied at the soft dough growth stage when spring wheat is grown in most soils except for loamy sand soils, which are limited by the lower water-holding capacity. The last irrigation to refill the root zone may be needed between the soft dough and hard dough stages on loamy sand soils.

About 80 mm of water is required to carry spring wheat from soft dough to physiological maturity in southern Alberta. No irrigation water is needed once the heads have completely turned colour from green to brown since the crop is mature at this point and yields have been established.

Irrigation scheduling for sugar beet

Water requirement. The water requirement for sugar beet depends on variety, growth stage, canopy density, climatic conditions, and irrigation and crop management. Sugar beet grown under optimal conditions (well-fertilized, well-irrigated, well-drained soils, pest-free stand, and uniform and optimum canopy) requires about 500 mm of water per growing season in southern Alberta.

Typically, sugar beet roots grow to an ERZ depth of 100 cm. Root distribution is concentrated near the soil surface; hence, a beet plant obtains 70 percent of its seasonal water from the upper 50 cm of the ERZ. The ERZ depth changes from a few millimeters at emergence to a maximum depth of 100 cm at full canopy closure and root enlargement growth stages.

Average sugar beet water use ranges from about 0.1 mm per day when the crop emerges to nearly 8 mm per day when the crop canopy completely shades the ground and the tap root is enlarging (Figure 16). Sugar beet water demand decreases as the old leaves start to die and temperatures start to cool down in the fall.

Irrigation scheduling. Adequate soil water is critical for sugar beet during emergence and early growth stages. Therefore, it is best to have a seedbed (0 to 50-cm depth) that is near 80 percent of available soil water at planting.

Sugar beet has small seeds that need to be planted at a shallow depth (2.5 cm), which can leave seedlings susceptible to inadequate surface soil moisture. The crop requires water for germination and root development during the early stages of growth.

If sugar beet is seeded in a dry seedbed (less than 60 percent of available in the 0 to 50-cm depth) in late April before irrigation water is available, the first and

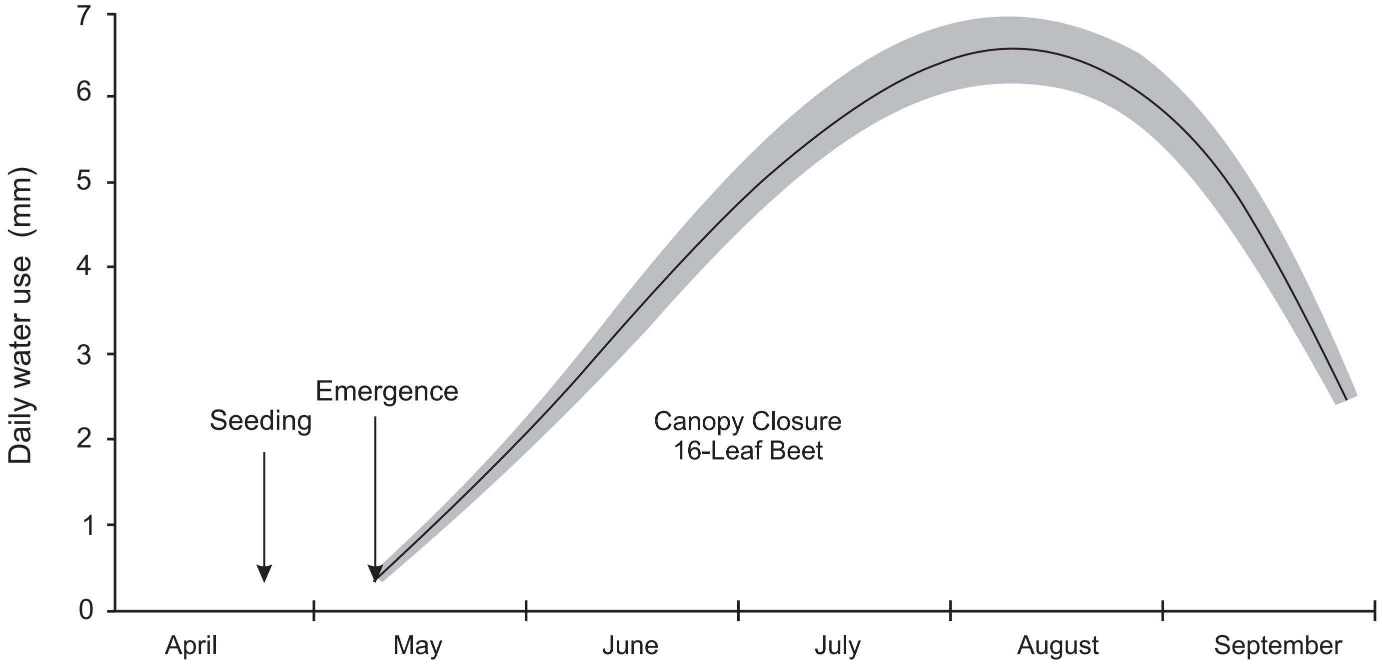


Figure 16. Daily water use during different growth stages of irrigated sugar beet in southern Alberta. The shaded area indicates variation in sugar beet water use depending on cultivar and climatic conditions.

subsequent irrigations (15 mm per irrigation event) should be applied as soon as irrigation water is available in early May. These irrigations should be light and frequent to maintain a moist soil surface, to prevent crusting, and to encourage rapid emergence and early root development.

Sugar beet will reach canopy closure early if PAW in the 0 to 50-cm depth is maintained at greater than 60 percent. Irrigation water applied before complete canopy closure (16-leaf growth stage) should meet crop water requirements and build up soil water to near field capacity in the 50 to 100-cm depth for use during the peak water-use period. Sugar beet peak water use occurs during a 30-day period in July (Figure 16).

Sugar beet reaches maximum extension at the full canopy closure growth stage. To ensure that soil water is adequate throughout the ERZ, the monitoring depth for irrigation scheduling purposes should be increased from 50 to 100 cm, and PAW should not be depleted to less than 60 percent (i.e. MAD should not be greater than 40 percent).

Increasing the irrigation management root zone from 50 to 100 cm at full canopy closure requires less frequent and larger irrigation volumes and results in increased water availability to the mature and enlarging sugar beet roots.

In general, any irrigation applied during the growing season should start when PAW is near 65 percent to prevent PAW from being depleted to less than 60 percent. Every irrigation application should also supply sufficient water to replace the water used by the crop as well as to accommodate losses within the irrigation system.

Some irrigation water may be applied just prior to harvesting to maintain soil moisture slightly above 60 percent of available for ease of digging.

Irrigation scheduling for timothy

Water requirement. Timothy is a cool-season grass that is most productive during spring and early summer under cool, long daylight conditions with abundant moisture. Timothy is more productive under a 21/16°C day/night combination than under warmer (27/21°C day/night) summer conditions. The optimum timothy growing condition is when daily high temperatures range from 15 to 21°C. As temperatures rise above 21°C, timothy tends to become dormant.

Re-growth after defoliation is variable and usually slower than the first-cut crop due to high summer temperatures greater than 28°C. Because of the temperature differences between spring and summer, the first cut timothy hay crop uses water more efficiently and generally yields 50 percent more than the second cut hay crop.

The water requirement for timothy hay depends on cultivar selection, growth stage, canopy density, harvest date, climatic conditions (especially temperature and photoperiod), and irrigation and crop management.

Timothy grown under optimal conditions (well-fertilized, well-irrigated, well-drained soils, pest-free stand, and uniform and optimum canopy) requires 500 to 550 mm of water per growing season in southern Alberta. The first cut hay crop consumes 60 percent (300 to 330 mm) of the seasonal water use and the second cut hay crop consumes the remaining 40 percent (200 to 220 mm).

Timothy needs to have water for germination and early growth. If available soil water is kept between 60 and 100 percent, timothy will germinate and grow rapidly into a full stand in the year of establishment.

If available soil water is near field capacity and adequate and balanced fertilizer is applied the following

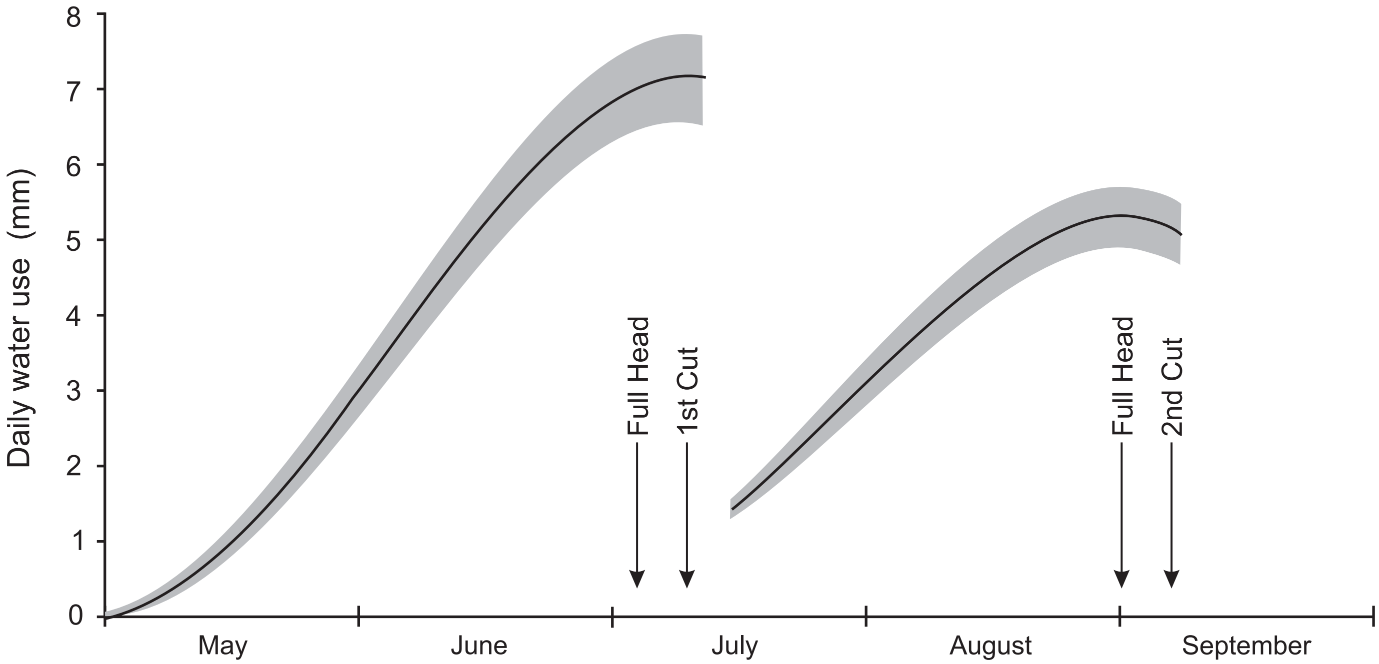


Figure 17. Daily water use for the first and second cuts during different growth stages of irrigated timothy hay in southern Alberta. The shaded area indicates the variation in timothy water use depending on cultivar, plant density, and climatic conditions.

spring, timothy will emerge from dormancy faster, and reach a peak water use of nearly 8 mm per day in late June for the first cut.

If adequately fertilized and fully irrigated immediately after the first cut, timothy will re-grow slowly in July. As the nights become cool in August, timothy will grow faster than in July and reach peak water use of 6 mm per day in late August for the second cut. The timothy peak water-use periods occur during the full head and the flowering growth stages in the production years (Figure 17).

Typically, the roots of timothy grow to an ERZ depth of 50 cm in a well-developed soil. Root distribution is concentrated near the surface; hence, timothy obtains nearly 70 percent of its seasonal water from the upper 25 to 30 cm of the ERZ. The ERZ depth changes from a few millimeters at emergence to a maximum depth of 50 cm at the end of the establishment year.

Irrigation scheduling. The availability of adequate soil water for emergence, stand establishment, and achievement of maximum, high-quality yields is crucial for producing a profitable timothy hay crop.

Establishment year. The establishment of a high-yielding, pure timothy stand requires careful attention to fertilizer and irrigation water management. Adequate soil water is critical for timothy during emergence and stand establishment in the year of establishment. Irrigations applied before emergence should maintain a moist soil surface to prevent crusting and encourage rapid emergence and early root development.

Ideally, PAW in the 0 to 30-cm depth should be maintained at greater than 60 percent during the emergence, early vegetative, tiller, and boot growth stages in the establishment year. This irrigation strategy results in light, frequent irrigations (12 mm per irrigation event) designed to recharge the 30-cm root zone. To prevent runoff, irrigation water application rates should not exceed soil intake (infiltration) rates.

Once timothy roots grow to the water extraction depth at the full head growth stage, the depth of root zone for irrigation should be increased from 30 to 50 cm. Irrigations should be scheduled to maintain PAW at greater than 60 percent and to fill the 0 to 50-cm depth to field capacity at the early heading growth stage and during the remainder of the growing season.

If timothy is seeded without a companion crop, weed control using a combination of chemical and cultural methods should be used to increase soil water availability to the young timothy stand during the early stages of growth. Mowing just above the timothy plants to prevent annual weeds from smothering the timothy seedlings is one of the best weed management practices for efficient timothy water use (Canadian Hay Association, 1999). The final mowing should be done in the fall to a height of 10 cm to prevent damage to the corms (bulbs).

Full irrigations should always be applied immediately after weed removal by mowing or early silage harvesting of a companion crop and in the fall prior to overwintering.

Production years. Effective first cut and second cut timothy irrigation scheduling uses a 50-cm root zone depth during production years. Adequate soil water, coupled with a balanced and adequate plant fertility program, is critical for timothy growth for high yield and quality.

If well-fertilized, a pest-free timothy stand will reach maximum yield and quality if ample water is available in the root zone during the spring and summer growing periods during production years. To ensure that ample water is available to timothy for spring and summer growth, PAW should not be depleted to less than 60 percent in the 50-cm root zone. Any irrigation applied should start when the PAW is near 65 percent to prevent PAW from being depleted to less than 60 percent.

Irrigations should be scheduled to fill the entire root zone to 100 percent of PAW. A full irrigation coupled with split nitrogen fertilizer application (about 60 percent of the spring application) is also required just after the first cut harvesting is completed in early July. Irrigation scheduling for the second-cut crop should also maintain PAW at greater than 60 percent in the 50-cm root zone. The final irrigation should be applied just after the second cut harvest to fill the root zone to 100 percent of PAW in early September.

Irrigation scheduling for winter wheat

Water requirement. The water requirement or evapotranspiration (ET) for winter wheat depends on variety, growth stage, canopy density, climatic conditions, and irrigation and crop management. Winter wheat grown under optimal conditions (well-fertilized, well-irrigated, seeded in standing stubble, pest-free, and uniform and optimum canopy) requires 400 to 430 mm of water per growing season in southern Alberta. When seeded into soil with available water between 60 and 100 percent in mid-September, winter wheat will germinate, grow rapidly, and reach a peak water use of between 1.5 to 2 mm per day in October prior to freeze-up or the dormancy growth stage. Winter wheat usually comes out of dormancy at the tillering growth stage in April of the following spring. Average winter wheat water use ranges from 0.1 mm per day soon after coming out of dormancy to nearly 7 mm per day during the flowering and fruit-formation growth stages (Figure 18).

Typically, the roots of winter wheat grow to an ERZ depth of 100 cm in a well-developed soil. Root distribution is concentrated near the surface; hence, winter wheat obtains more than 70 percent of its seasonal water from the upper 50 cm of the ERZ. The ERZ depth changes from a few millimeters at emergence to a maximum depth of 100 cm at the flowering growth stage.

Irrigation scheduling. The PAW in the seedbed soil profile (0 to 30-cm depth) needs to be near 80 percent at planting. Winter wheat needs to have water for germination and root development during the early stages of growth. If the seedbed is dry (less than 60 percent of available), a light irrigation of 15 mm should be applied prior to seeding. Inadequate soil water in these early growth stages results in reduced plant populations, which, in turn, reduce final grain yield. To ensure soil water is adequate for germination, irrigation should be applied prior to seeding to minimize emergence problems associated with soil crusting.

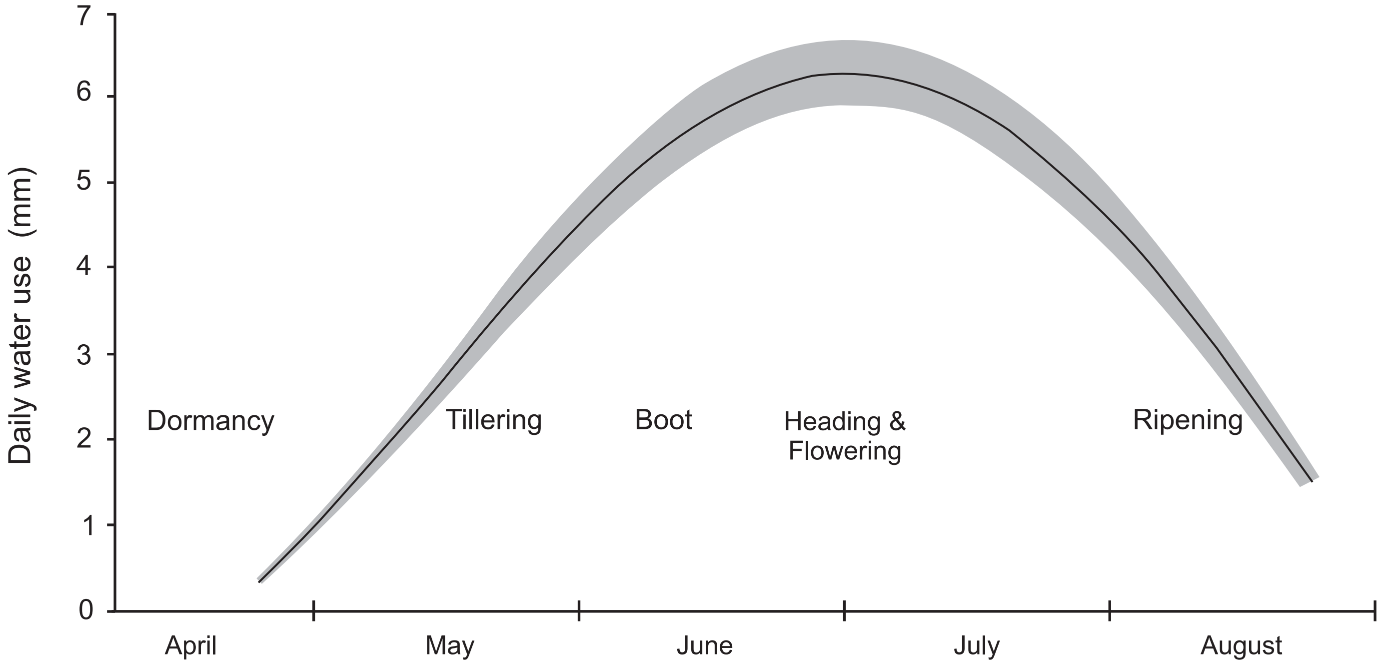


Figure 18. Daily water use during different growth stages of irrigated winter wheat in southern Alberta. The shaded area indicates variation in winter wheat water use depending on plant type, cultivar, and climatic conditions.

In southern Alberta, winter wheat is usually seeded in the middle of September, reaches full emergence at the end of September, and reaches the three-leaf or early tiller stages in October prior to freeze-up. The crop comes from dormancy in April when it is tillering, reaches canopy closure in May, heads out in June, flowers from late June to early July, and reaches physiological maturity in August.

If well-fertilized, a pest-free winter wheat stand will reach maximum grain yield and quality if ample water is available in the root zone during the tillering and flowering growth stages. To ensure that ample water is available to winter wheat during the vegetative growth stages (i.e. tillering to late boot), PAW should not be depleted to less than 50 percent in the upper 50 cm of the 100-cm root zone. Any irrigation applied during the vegetative growth stages should start when the PAW is near 60 percent to prevent the PAW from being depleted to less than 50 percent.

from being depleted to less than 50 percent.

Maintaining PAW above 50 percent in the upper 50-cm depth during the vegetative growth stages necessitates light and frequent irrigation applications. Irrigation water applied during the vegetative growth stages should meet crop water requirements and build up soil water to near field capacity in the 50 to 100-cm zone for use during the peak water-use period when flowering is occurring.

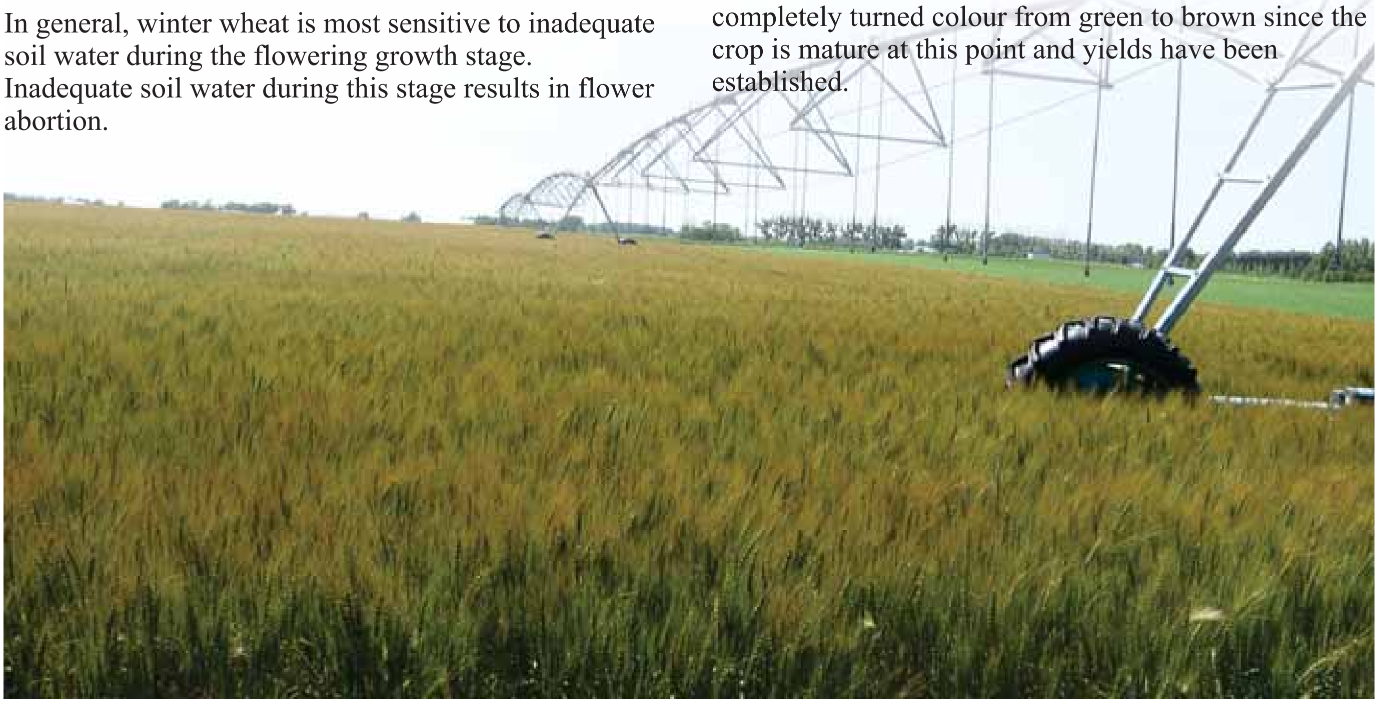
In general, winter wheat is most sensitive to inadequate soil water during the flowering growth stage. Inadequate soil water during this stage results in flower abortion.

Winter wheat roots reach maximum extension at the flowering growth stage. To ensure that soil water is adequate throughout the ERZ during flowering, the monitoring depth of the ERZ should be increased from 50 to 100 cm at the early heading growth stage, and PAW should not be depleted to less than 60 percent.

Irrigations should be scheduled to fill the entire root zone (100 cm) to field capacity at the beginning of the late boot-early heading growth stages to avoid applying irrigations during the flowering growth stage when the crop is most vulnerable to Fusarium Head Blight (FHB).

Increasing the irrigation management root zone from 50 to 100 cm at the late boot growth stage requires less frequent and larger irrigation volumes and results in increased water availability to the mature winter wheat roots. This increased time between irrigations keeps the canopy dry, discouraging the incidence of FHB.

The timing of the last irrigation to refill the root zone for winter wheat depends largely on the soil texture. The final irrigation may be applied at the soft dough growth stage when winter wheat is grown in most soils except for loamy sand soils, which are limited by lower water-holding capacity. The last irrigation to refill the root zone may be needed between the soft dough and hard dough stages on loamy sand soils. About 80 mm of water are required to carry winter wheat from soft dough to physiological maturity in southern Alberta. No irrigation water is needed once the heads have completely turned colour from green to brown since the crop is mature at this point and yields have been established.



OPPORTUNITIES FOR IMPROVED IRRIGATION MANAGEMENT

On-farm irrigation management may be improved: (1) through proper selection, operation, and maintenance of irrigation pumps and power units; (2) through upgrades of existing gravity or wheel-move irrigation systems to more efficient low pressure centre pivot sprinkler systems; and (3) by adoption of technologies and practices that optimize crop water use.

Irrigation Pumps and Power Units

Matching an irrigation pump and power unit to an irrigation system is the most important component of system design (Ring, 2011). Proper selection, operation, and maintenance of irrigation pumps and power units are essential for improved irrigation management. Ring (2011) provides detailed information on irrigation pumps and power units.

Irrigation System Upgrades

The irrigation sector in Alberta recently established an on-farm water-use efficiency target of 76.4 percent by 2015, an increase of 4.4 percent from 72 percent in 2005 (AIPA, 2010). This target is to be achieved through conversion of less efficient gravity, wheel-move, and high pressure centre pivot irrigation systems to more efficient low pressure, drop-tube centre pivot sprinkler systems. At least 70 percent of the irrigated area would have to be upgraded to low pressure, drop-tube centre pivot systems to attain this application efficiency target (AECOM Canada Ltd., 2009).

Upgrades of irrigation systems to low pressure, drop-tube centre pivot systems have been implemented steadily in the last 15 years (Figure 1). About 63.9 percent of the irrigated area within the 13 irrigation districts was irrigated with low pressure, drop-tube centre pivot systems in 2011 (ARD, 2012). About 183,000 ha of land within the 13 irrigation districts were irrigated with less efficient irrigation systems in 2011 (ARD, 2012), so potential energy and water savings with additional irrigation system upgrades are significant. Not all parcels of irrigated land are suitable for low pressure, drop-tube centre pivot systems and some producers cannot presently afford this technology; nevertheless, upgrades to more efficient irrigation systems are likely to continue as producers strive to reduce energy costs, to enhance crop yield and quality, and to conserve water.

New sprinkler nozzles developed by sprinkler manufacturers for low pressure, drop-tube centre pivot systems have the potential to increase application efficiencies even further. Development of variable-rate irrigation technology for pivot irrigation systems provides another option for enhanced water-use efficiency, reduced energy costs, and increased water conservation. Equipment manufacturers have also developed small linear pivot and articulating pivot systems for sprinkler irrigation of small, irregularly-shaped fields , which might also enhance upgrades to more efficient sprinkler systems.

Irrigation Management Practices

Hohm et al. (2002) examined irrigation management practices in southern Alberta from 1996 to 2000 for major irrigated crops irrigated with gravity, wheel-move, and centre pivot irrigation systems and determined that producers met an average of 84 percent of optimum crop water use. Opportunities for improved irrigation management were greatest for alfalfa, wheat, and canola. Nitschelm et al. (2011) studied irrigation management practices within six irrigation districts in southern Alberta from 2007 to 2009 and found that producers with pipeline deliveries and low pressure centre pivots met an average of 91 percent of optimum crop water use. However, about 17 percent of the fields examined met less than 80 percent of optimum crop water use, with alfalfa and cereal grains having the greatest opportunities for improved irrigation management.

Irrigation management information and tools described in this manual can help producers increase income through enhanced crop yield and quality, and can save money through adoption of more efficient irrigation systems and technologies. Methods and tools for irrigation scheduling may be used by producers for economic benefits as well as for optimization of energy and water use in irrigated agriculture.

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SAMPLE CALCULATIONS

Question 1: What are the total available water-holding capacity and the current available soil water content of a 1 m soil profile with loam texture in the upper 0.5 m and clay loam texture from 0.5 to 1 m. Soil water content in the field is estimated to be 80 percent in the upper 0.25 m interval, 70 percent in the second 0.25 m interval, 70 percent in the third 0.25 m interval, and 65 percent in the fourth 0.25 m depth interval.

Calculations:

a. Use Table 2 to determine the available water-holding capacity of each 0.25 m interval as follows:

Soil Depth (m)	Soil Texture	Available Water-Holding Capacity (mm m^{-1})	Available Water-Holding Capacity (mm)
0 – 0.25	Loam	180	45
0.25 – 0.50	Loam	180	45
0.50 – 0.75	Clay Loam	200	50
0.75 – 1.00	Clay Loam	200	50
Total			190

b. Calculate the current available soil water content for each depth interval in the 1 m soil using field estimates of soil water content as follows:

Soil Depth (m)	Available Water- Holding Capacity (mm)	Available Soil Water (%)	Available Soil Water (mm)
0 – 0.25	45	0.80	36.0
0.25 0.50	45	0.70	31.5
0.50 – 0.75	50	0.70	35.0
0.75 – 1.00	50	0.65	32.5
Total	190		135.0

The total available water-holding capacity of the 1 m soil is 190 mm and the current available soil water content is 135 mm.

Question 2: Given the current available soil water content of the soil described above, when will the next irrigation need to be applied for spring wheat?

Calculations:

a. Use Table 4 to determine the management allowable depletion (MAD) for spring wheat (40 percent of available soil water).

b. Calculate the allowable depletion (mm) and the minimum available soil water content (mm) prior to irrigation.

Available water-holding capacity, mm x MAD, percent = Allowable depletion, mm

190 mm x 0.40 = 76 mm

Available water-holding capacity, mm – Allowable depletion, mm = Minimum available soil water content, mm

190 mm – 76 mm = 114 mm

c. Calculate the current available soil water content that may be depleted prior to irrigation.

Current available soil water content, mm – Minimum available soil water content, mm = Balance of available soil water content that may be depleted, mm

135 mm – 114 mm = 21 mm

d. Use Figure 15 to determine the daily water use for spring wheat on July 1 (7 mm per day) and calculate the number of days until the next irrigation will need to be applied.

Balance of available soil water content that may be depleted, mm / Daily water use for spring wheat, mm per day = Number of days before irrigation is needed

21 mm / 7 mm per day = 3 days

The spring wheat will need irrigation in three days if precipitation is not received.

Question 3: Given that a low pressure centre pivot is operated to provide a gross application amount of 18 mm during a two-day circle, what is the net application amount available for crop use and when will the next irrigation need to be applied if no precipitation is received in the next week?

Calculations:

a. Use Table 7 to determine the system application efficiency for a low pressure centre pivot (84 percent).

b. Calculate the net irrigation amount using Equation 3.

Gross irrigation amount, mm x System application efficiency, percent =
Net irrigation amount, mm

18 mm x 0.84 = 15.1 mm

c. Calculate the number of days until the next irrigation is required.

Net irrigation amount, mm / Daily crop water use, mm per day =
Number of days before the next irrigation

15.1 mm / 7 mm per day = 2.2 days

This irrigation system can just keep up to peak crop water demand during a period of warm, dry weather in early July. Irrigation system application efficiencies would be reduced with strong winds. The irrigation system might not be able to keep up to the water requirement of crops with greater peak water demand. Soil water reserves must be increased earlier in the year or the irrigation system must be operated to provide a greater gross application amount, if the soil intake rate allows, for optimum crop yield and quality. A gross application of 27 mm applied in a three-day circle would result in a net application of about 23 mm. The irrigation system could just keep up to peak water demand of spring wheat if the system is operated continuously in the absence of precipitation.