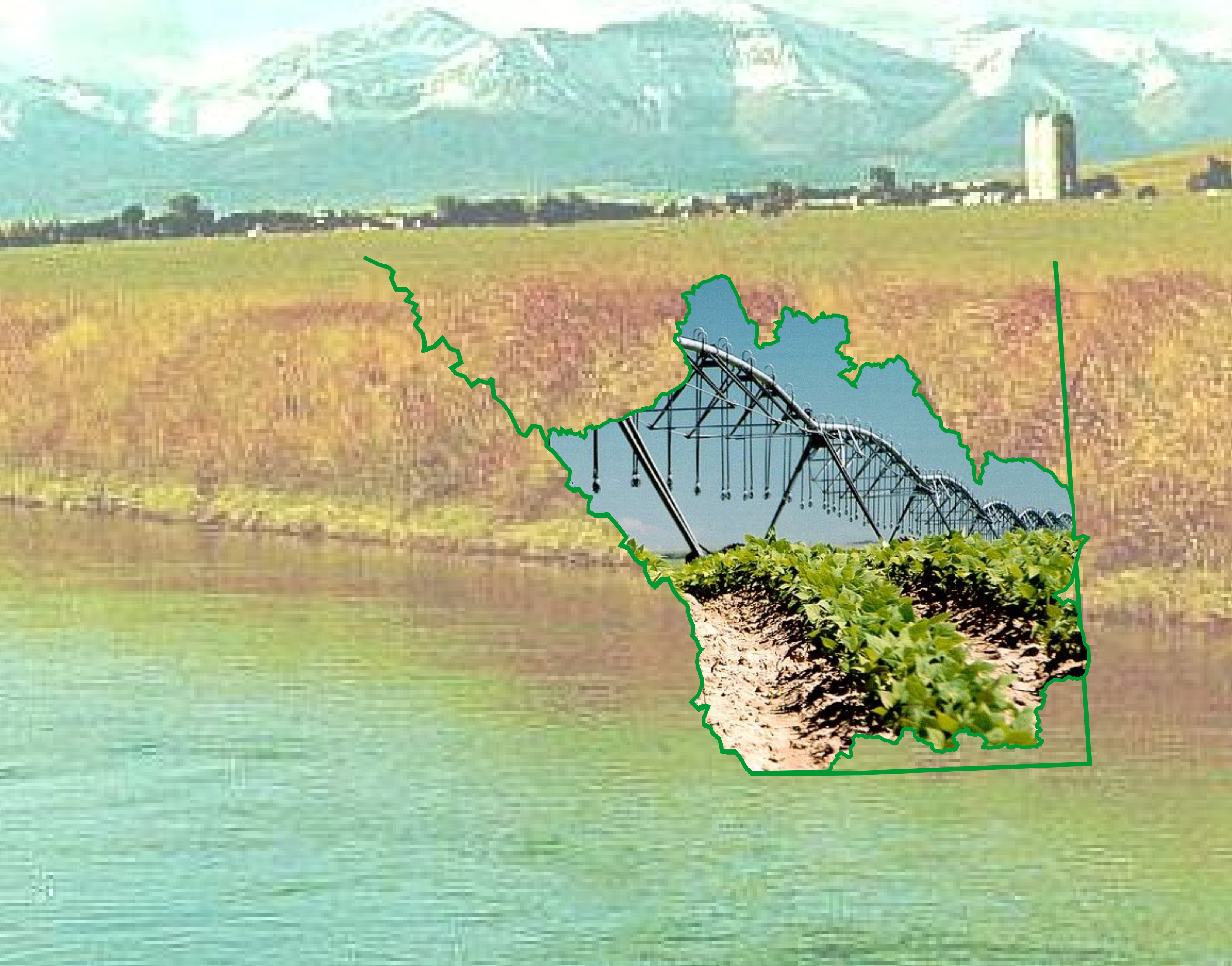
SOUTH SASKATCHEWAN RIVER BASIN

IRRIGATION

in the 21st Century

Volume 2:
On-Farm Irrigation Water Demand



SOUTH SASKATCHEWAN RIVER BASIN IRRIGATION IN THE 21ST CENTURY

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South Saskatchewan River Basin
Irrigation in the 21st Century

Volume 2:
On-Farm Irrigation Water Demand

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Volume 2 On-Farm Irrigation Water Demand

I. Potential evapotranspiration in southern Alberta from historical weather data

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ABSTRACT

Irrigation planners in the South Saskatchewan River Basin (SSRB) of southern Alberta have traditionally used historical weather and potential evapotranspiration (PE) data to predict future water requirements. Demand for irrigation water has approached the available supply in portions of the SSRB, therefore, Alberta Environment established guidelines for irrigation expansion in 1991. This study was initiated to create a daily historical PE database for the SSRB. Several empirical equations for determination of PE were evaluated for use with the Gridded Prairie Climate Database (GRIPCD) historical weather data set recently compiled for southern Alberta by Environment Canada and Agriculture and Agri-Food Canada. The Priestley-Taylor and Hargreaves equations compared most favorably to modified Penman-Monteith and daily disc atmometer PE data. A modified Priestley-Taylor equation, with an α coefficient adjusted from 1.7 to 1.66, provided the most reasonable estimate for PE based on historical weather data. The modified Priestley-Taylor equation was used to create a database containing daily PE values for the SSRB from 1920 to 1995. Mean seasonal PE values ranged from about 460 mm at the headwaters of the Red Deer River Basin to about 820 mm in southeastern Alberta. All of the irrigation districts in southern Alberta had mean seasonal PE values greater than 700 mm during the 76-year period.

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INTRODUCTION

In southern Alberta, as in many other parts of the world, demand for water has approached the available supply. Irrigation has traditionally been the largest licensed user of water in the South Saskatchewan River Basin (SSRB). Alberta Environment established a water management regulation for the SSRB in 1991 that established guidelines for irrigation expansion (Alberta Environment 1991). The regulation indicated that the guidelines for limiting irrigation expansion would be reviewed in 10 years. Hence, irrigation districts in southern Alberta were given the opportunity to review and update requirements for water delivery and crop use within their areas, as input to the water allocation review.

Irrigation planners and modelers often use historical weather and potential evapotranspiration (PE) data to assess long term irrigation development scenarios. Potential evapotranspiration and crop water use for southern Alberta have been well documented (Sonmor 1963; Hobbs and Krogman 1966a, 1966b, 1968, 1976; Underwood McLellan Ltd. 1982). Irrigation scheduling and water use planning in southern Alberta have been based on the relationship between evapotranspiration from a well-watered crop and evaporation from free water surfaces in open pans and disc atmometers. Crop coefficients have been developed for most crops grown in southern Alberta based on disc atmometer (Krogman and Hobbs 1976) and meteorological data (Hobbs and Krogman 1983). Mean PE and crop use curves developed from meteorological data are similar to those derived from disc atmometers.

Significant advances have been made in modeling, understanding of physiological processes, and use of computers for data acquisition and processing. FAO (1990) recommended adoption of the modified Penman-Monteith equation as the standard to determine reference crop evapotranspiration. Jensen (1995) advocated use of the modified Penman-Monteith equation for its accuracy and robustness under all climatic conditions.

Assessment of current and future water demand requires as many years of historical weather data as possible. A 70-yr record of air temperature and precipitation data (1920 to 1989), the Gridded Prairie Climate Database (GRIPCD), was recently compiled by McGinn et al. (1994) for evaluation of the potential for climate change on the Canadian prairies (McGinn et al. 1999). The database contains daily air temperature, solar radiation, rainfall, snowfall, and snow depth data for each node within a 50 km grid.

The purpose of this study was to determine daily PE throughout the SSRB from 1920 to 1995 for use in estimation of potential irrigation water demand. An isopleth map of mean historical PE was also developed as a planning tool for irrigation districts, modelers, and regulators.

METHODS

Historical weather data

The number of weather stations in southern Alberta that historically recorded temperature (maximum and minimum), wind, precipitation, relative humidity, and solar radiation is limited. A large number of weather stations recorded only temperature and precipitation, but these data tended to be short-term and at times were not continuous. The GRIPCD developed by Environment Canada and Agriculture and Agri-Food Canada (AAFC) was selected for this study (McGinn et al. 1994). This data set was compiled and designed as a common weather database to validate agricultural models. The major grid points correspond to the Canadian Climate Centre Global Circulation Model grid locations, using a finer spatial resolution of approximately 50 km x 50 km (McGinn et al. 1994). Data for each node were estimated by interpolating data from up to five of the nearest weather stations using a nearest neighbor approach, weighting each neighbor by the inverse distance squared (McGinn et al. 1999). The original database consisted of 70 years of data (1920 to 1989). Grid weather data for 1990 to 1995, obtained from S.M. McGinn, AAFC, Lethbridge, AB, were subsequently added to the GRIPCD. A total of 57 grid locations in southern Alberta were used for this study (Fig. 1).

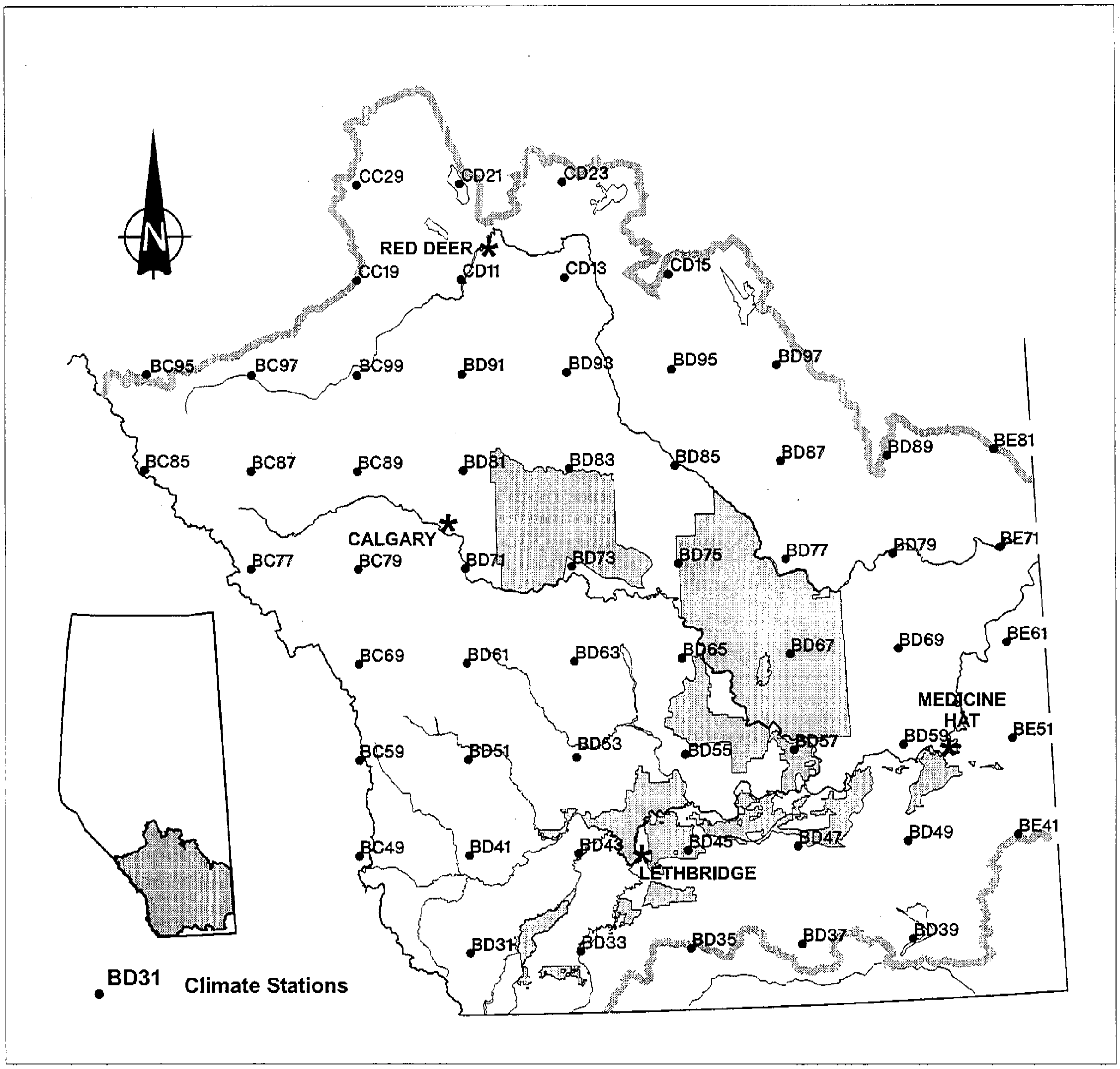

Fig. 1. Climate database stations (50 km x 50 km).

The GRIPCD does not contain wind data due to the limited number of recording stations in southern Alberta and the extreme variability of wind speed and direction. Some solar radiation data were available, but not for the entire period from 1920 to 1995, and consequently were not used. Solar radiation was derived from top of atmosphere or extraterrestrial radiation (R_a), calculated from latitude (FAO 1990). Incoming solar radiation (R_s) was estimated from temperature data in the GRIPCD according to the method of Hargreaves and Samani (1982). Net radiation was subsequently determined using a modification of the Linacre (1992) method to calculate daytime radiation only (S.M. McGinn, Agrometeorologist, AAFC, Lethbridge, AB, pers. comm.). Missing temperature data (maximum or minimum) were generated using a median value for the missing day from the remaining years.

PE equations

The modified Penman-Monteith equation could not be used to develop the historical daily PE database due to the absence of historical wind and relative humidity data.

Temperature-based PE equations. Three temperature-based PE equations were selected from the literature based on the type of weather data available in the GRIPCD. The PE equations evaluated were:

1. Baier-Robertson 1 (Baier and Robertson 1965):

$$PE = 0.08636[-87.03+(0.928Tmax)+(0.933(Tmax-Tmin))+(0.0486Qo)] \qquad (1)$$

Where:

PE = potential evapotranspiration (mm/day),
Tmax = maximum daily temperature (°F),
Tmin = minimum daily temperature (°F), and
Qo = solar radiation at the top of the atmosphere (cal/cm^2).

2. Blaney-Criddle, SCS TR-21 (Jensen et al. 1990):

$$U = \Sigma KF = \Sigma kf \qquad (2)$$

Where:

U = estimated seasonal consumptive use (mm),
K = empirical consumptive use coefficient (dimensionless),
F = seasonal consumptive use factor (sum of monthly consumptive use factors for the months covering the growing season),
k = monthly consumptive use coefficient (dimensionless),

$$f = t\frac{p}{100} \qquad (2.1)$$

t = mean monthly air temperature (°F), and
p = mean monthly percentage of annual daytime hours (h).

Even though this equation is monthly-based, a daily time step methodology was developed. Percent daytime hours (Jensen et al. 1990) were used to estimate "p" as the daily percentage of monthly daytime hours (assuming an average of 30.5 days per month).

3. Hargreaves (Jensen et al. 1990):

$$\lambda E_{to}=0.0023R_A TD^{1/2}(T+17.8) \tag{3}$$

Where:

$\lambda = 2.501 - (0.002361T)$ (MJ/kg), (3.1)
E_{to} = potential evapotranspiration (MJ/m^2/day),
R_A= extraterrestrial solar radiation received on a horizontal surface (MJ/m^2/day),
TD = monthly mean maximum temperature - monthly mean minimum temperature (°C), and

$$T = \frac{Tmax + Tmin}{2} \quad (^\circ C). \tag{3.2}$$

The Hargreaves equation uses grass as a reference crop.

Solar radiation-based PE equations. Two solar radiation-based PE equations were also selected:

1. Priestley-Taylor (Jensen et al. 1990):

$$\lambda E_p = \alpha \frac{\Delta}{\Delta + \gamma} (Rn-G) \tag{4}$$

Where:

$\lambda = 2.501 - (0.002361T)$ (MJ/kg), (4.1)
E_p = potential evapotranspiration (MJ/m^2/day),
$\alpha = 1.7$ (constant),
$\Delta = (0.200(((0.00738T) + 0.8072)^7)) - 0.000116$ (kPa/°C), (4.2)

$$\gamma = \frac{c_p P}{0.622\lambda} \quad (kPa/^\circ C), \tag{4.3}$$

Rn = net radiation (MJ/m^2),

$$Rn = \left[\frac{0.63Rs1000000}{43200}\right] - 40 \quad (W/m^2), \tag{4.4}$$

$$Rn = \frac{Rn_{(W/m^2)}43200}{1000000} \quad (\mathrm{MJ/m^2}), \tag{4.5}$$

$G = 0$ (MJ/m^2/day),
$c_p = 0.001013$ (MJ/kg/°C), (4.6)

$$P = 101.3\left[\frac{(T+273.16) - (0.0065H)}{T+273.16}\right]^{5.256} \quad (\mathrm{kPa}), \tag{4.7}$$

R_s = total incoming solar radiation (MJ/m^2),

$$T = \frac{Tmax + Tmin}{2} \quad (°\mathrm{C}), \text{ and} \tag{4.8}$$

H = elevation (m).

Due to the semi-arid climatic conditions of southern Alberta, an α value of 1.7 was used (Jensen et al. 1990).

2. Jensen-Haise (Jensen et al. 1990) :

$$\lambda E_{tr} = C_t(T - T_x)R_s \tag{5}$$

Where:

$\lambda = 2.501 - (0.002361T)$ (MJ/kg), (5.1)
E_{tr} = potential evapotranspiration (MJ/m^2/day),

$$C_t = \frac{1}{38 - \left(2.0\frac{H}{305}\right) + 7.3\left(\frac{5.0}{e_2 - e_1}\right)} \quad (°\mathrm{C}^{-1}), \tag{5.2}$$

$$T = \frac{Tmax + Tmin}{2} \quad (°\mathrm{C}), \tag{5.3}$$

$$Tx = -2.5 - 1.4(e_2 - e_1) - \frac{H}{550} \quad (°\mathrm{C}), \tag{5.4}$$

R_s = total incoming solar radiation (MJ/m^2),
H = elevation (m), and
(e_2-e_1) = saturation vapour pressure in kPa, at mean Tmax and Tmin for the warmest month.

Local calibration values for Vauxhall, AB, are $C_t = 0.0202$ and $T_x = -6.96$. The Jensen-Haise equation uses alfalfa as a reference crop.

PE equation assessment

Temperature and solar radiation-based equations were compared to modified Penman-Monteith and daily disc atmometer PE data to determine the most appropriate equation for estimation of daily PE in southern Alberta.

Modified Penman-Monteith (alfalfa-reference). The five PE equations were compared to PE values calculated from meteorological data for May 1 to September 30, 1986 to 1998 at Vauxhall, AB, using the modified Penman-Monteith equation (Jensen 1995):

$$Et_r = \frac{0.408\Delta(Rn-G) + (\gamma\left(\frac{1700}{T+273}\right) U_2(e_a-e_d)}{\Delta+(\gamma\ (1+(0.40U_2))} \qquad (6)$$

Where:

Et_r = potential evapotranspiration (mm/day),
$\Delta = (0.200(((0.00738T) + 0.8072)^7)) - 0.000116$ (kPa/°C), (6.1)
Rn = net radiation (MJ/day),
G = 0 (MJ/m^2/day),

$$\gamma = \frac{c_p P}{0.622\lambda} \quad (\text{kPa/°C}), \qquad (6.2)$$

$$T = \frac{Tmax + Tmin}{2} \quad (°\text{C}), \qquad (6.3)$$

$U_2 = (W_2 0.01157407)$ (m/s), (6.4)
e_a-e_d = mean daily vapour pressure deficit (kPa),
$c_p = 0.001013$, (MJ/kg/°C),

$$P = 101.3\left[\frac{(T+273.16) - (0.0065H)}{T+273.16}\right]^{5.256} \quad (\text{kPa}), \qquad (6.5)$$

$$Rn = \left[\frac{0.63Rs1000000}{43200}\right] - 40 \quad (\text{W/m}^2), \qquad (6.6)$$

$$Rn = \frac{Rn_{(W/m^2)}43200}{1000000} \quad (\mathrm{MJ/m^2}), \tag{6.7}$$

R_s = total incoming solar radiation (MJ/m^2),

$$Satvp = \exp(52.58 - \frac{6790.5}{TK} - (5.031n(TK))) \quad (\mathrm{kPa}), \tag{6.8}$$

$$Dailyvp = \frac{(Satvp)(RHmean)}{100} \quad (\mathrm{kPa}), \tag{6.9}$$

Vpd = Satvp - Dailyvp (kPa),
$TK = T + 273$ (°K), (6.10)
H = elevation (m),

$$RHmean = \frac{a.m.\ relative\ humidity\ +\ p.m.\ relative\ humidity}{2} \quad (\%), \tag{6.11}$$

$$W_2 = W_1 \left(\frac{Z_2}{Z_1} \right)^a \quad (\mathrm{km/day}), \tag{6.12}$$

W_1 = measured wind at Z_1 (km/day),
W_2 = estimated wind at height Z_2 (km/day),
Z_1 = measured wind height (m),
Z_2 = estimated wind at 2 m, and
a = 0.2 (Jensen 1974).

Actual incoming solar radiation data for 1986 to 1998 were used, as required in two of the five equations. The integrity of historical relative humidity and solar radiation data at Vauxhall, AB, was checked according to procedures specified by Allen (1996). Solar radiation data prior to 1986 did not meet the standard and were not used. Relative humidity data appeared to be offset in a few years, or portions of a year, and were corrected to more realistic values (Allen 1996).

Disc atmometer standard. Latent evaporation measurements with an Alundum disc atmometer from May 1 to September 30, 1962 to 1975, were obtained from the AAFC substation in Vauxhall, AB, for use as a standard to which all five PE equations were compared. Solar radiation was estimated for this time period.

Statistical analysis

The concordance correlation coefficient index (Lin 1989) was used to compare daily data from each PE equation to disc atmometer and modified Penman-Monteith data. This index evaluates the degree to which data pairs fall on a 45° line (1:1) through the origin. The concordance correlation coefficient contains measurements of precision and accuracy. A concordance correlation coefficient of 1 indicates that the pairs lie on the line. Any departure from this line would produce a concordance correlation coefficient < 1, even though the Pearson correlation coefficient is equal to 1 (Lin 1989).

Linear regression analysis was also used with selected PE equations to determine locally calibrated values for constants when the necessary data were available.

PE database

A PE database was created after the selection and local calibration of the most appropriate PE equation. The database contained daily PE values from 1920 to 1995 for the 57 nodes in the GRIPCD. A PE isopleth map was subsequently created for the SSRB using "Surfer® for Windows" by Golden Software Inc. Only data for the frost-free period (last -2°C in the spring and first -2°C in the fall) were used.

RESULTS AND DISCUSSION

PE equation evaluation

Examination of the five PE equations in relation to modified Penman-Monteith data revealed that the Priestley-Taylor equation had the highest Pearson and concordance correlation coefficients (Table 1). The location shift for the Priestley-Taylor equation was relatively low compared to the other equations, but the scale shift was 0.77, indicating a somewhat steeper slope than the 1:1 line. The Blaney-Criddle equation ranked second highest in Pearson and concordance correlation coefficients. Location shift was extremely low for this equation, but the amount of location shift was higher than to the other four equations. Concordance correlation coefficients were the lowest for the Jensen-Haise and Baier-Robertson 1. These two equations also had the highest amount of location shift. The Hargreaves equation had a scale shift equal to 1 and a location shift of 0.91.

Table 1. Comparison of five PE equations to modified Penman-Monteith PE data (1986 to1998).

Equation	Pearson correlation coefficient (r)	Concordance correlation coefficient (cc)	Location shift (1:1 line has 0)	Scale shift (1:1 line has 1)
Baier-Robertson 1	0.80	0.54	0.97	1.04
Blaney-Criddle	0.76	0.74	0.03	1.26
Hargreaves	0.81	0.57	0.91	1.00
Priestley-Taylor	0.83	0.79	0.18	0.77
Jensen-Haise	0.81	0.39	1.45	0.93

Comparison of the five PE equations to daily disc PE data indicated that the Priestley-Taylor equation provided the best fit to the daily disc atmometer PE data set (Table 2). This equation had the highest concordance correlation coefficient, with the least amount of location and scale shift compared to the other four equations. The Pearson correlation coefficient for the Priestley-Taylor equation was similar to that of the other four equations. Location shifts for the other four equations were relatively large compared to the Priestley-Taylor equation. Scale shifts for all but the Blaney-Criddle equation were close to 1. Hargreaves, Jensen-Haise and Baier Robertson 1 PE equations had scale shifts close to 1, but had high location shifts and low concordance correlation coefficients. The Blaney-Criddle equation had low a concordance correlation coefficient, and exhibited high location and scale shifts.

Table 2. Comparison of several PE equations to daily disc atmometer PE data for Vauxhall (1962 to 1975).

Equation	Pearson correlation coefficient (r)	Concordance correlation coefficient (cc)	Location shift (1:1 line has 0)	Scale shift (1:1 line has 1)
1. Priestley-Taylor α=1.7, estimated R_n	0.79	0.76	0.11	0.78
2. Hargreaves c=0.0023, estimated R_A	0.81	0.52	1.07	0.99
3. Jensen-Haise, estimated R_s	0.82	0.44	1.31	0.93
4. Blaney-Criddle	0.73	0.36	1.24	1.95
5. Baier-Robertson 1	0.84	0.53	1.08	1.01

The Priestley-Taylor and Hargreaves equations were selected for local calibration. Linear regression analysis with daily disc atmometer PE data, wherein location shifts were forced through the origin, resulted in an adjustment of the α coefficient in the Priestley-Taylor equation from 1.7 to 1.66, and in modification of the c coefficient in the Hargreaves equation from 0.0023 to 0.00285. Pearson correlation coefficients, concordance correlation coefficients, and scale shifts were similar for the two modified PE equations (Table 3). Changing the α coefficient in the modified Priestley-Taylor equation had minimal effect on the Pearson correlation or concordance correlation coefficients, but improvements in location shift were achieved. Increasing the c constant in the modified Hargreaves equation improved the concordance correlation coefficient from 0.52 to 0.79, but the resulting scale shift decreased from 0.99 to 0.78 (Tables 2 and 3).

The modified Priestley-Taylor equation was chosen for development of an historical PE database for southern Alberta because it provided a slightly lower location shift and slightly higher scale shift than the modified Hargreaves equation when compared to daily disc atmometer PE data.

Table 3. Comparison of modified Priestley-Taylor and modified Hargreaves equations to daily disc atmometer PE data (1962 to 1975).

Equation	Pearson correlation coefficient (r)	Concordance correlation coefficient (cc)	Location shift (1:1 line has 0)	Scale shift (1:1 line has 1)
1. Priestley-Taylor $\alpha = 1.66$, estimated R_n	0.79	0.77	0.01	0.80
2. Hargreaves $c = 0.00285$, estimated R_A	0.81	0.79	0.02	0.78

PE database

The modified Priestley-Taylor equation was used to generate daily PE values from May 1, 1920 to September 30, 1995. Mean seasonal PE values within the SSRB ranged from about 460 mm at the headwaters of the Red Deer River Basin to about 820 mm in southeastern Alberta (Fig. 2). All of the irrigation districts had mean seasonal PE values greater than 700 mm during the 76-year period. These values were similar to those reported by Steed and Ulrickson (1971) (Table 4). Grid stations nearest each location were used for the comparison. Differences in PE values may be related to methodology used in the development of the GRIPCD, or to the limited number of years of temperature data available when the original work by Steed and Ulrickson (1971) was carried out. The mean seasonal PE calculated for the grid station nearest Lethbridge (BD43) was also comparable to PE values derived by Grace and Quick (1988). The mean PE value for grid station BD43 (783 mm) was similar to the mean PE value of 769 mm for 1983, 1984, and 1985.

Table 4. Comparison of modified Priestley-Taylor PE values to Steed and Ulrickson (1971).

	Steed and Ulrickson		Modified Priestley-Taylor (mm)		
Grid CD station	Nearest location	Seasonal consumptive use factor (F) (mm)	Mean	Range	SE[†]
BD67	Brooks	729	769	578-900	8
BD71	Calgary	661	691	480-863	8
BD33	Cardston	699	739	546-917	10
BD41	Cowley	579	686	477-869	10
BD37	Foremost	773	825	591-1008	9
BD73	Gleichen	708	750	517-905	8
BD43	Lethbridge	734	783	522-954	8
BD59	Medicine Hat	799	811	575-977	9
BD45	Taber	772	776	648-921	8
BD57	Vauxhall	749	788	654-924	7

[†] SE = standard error.

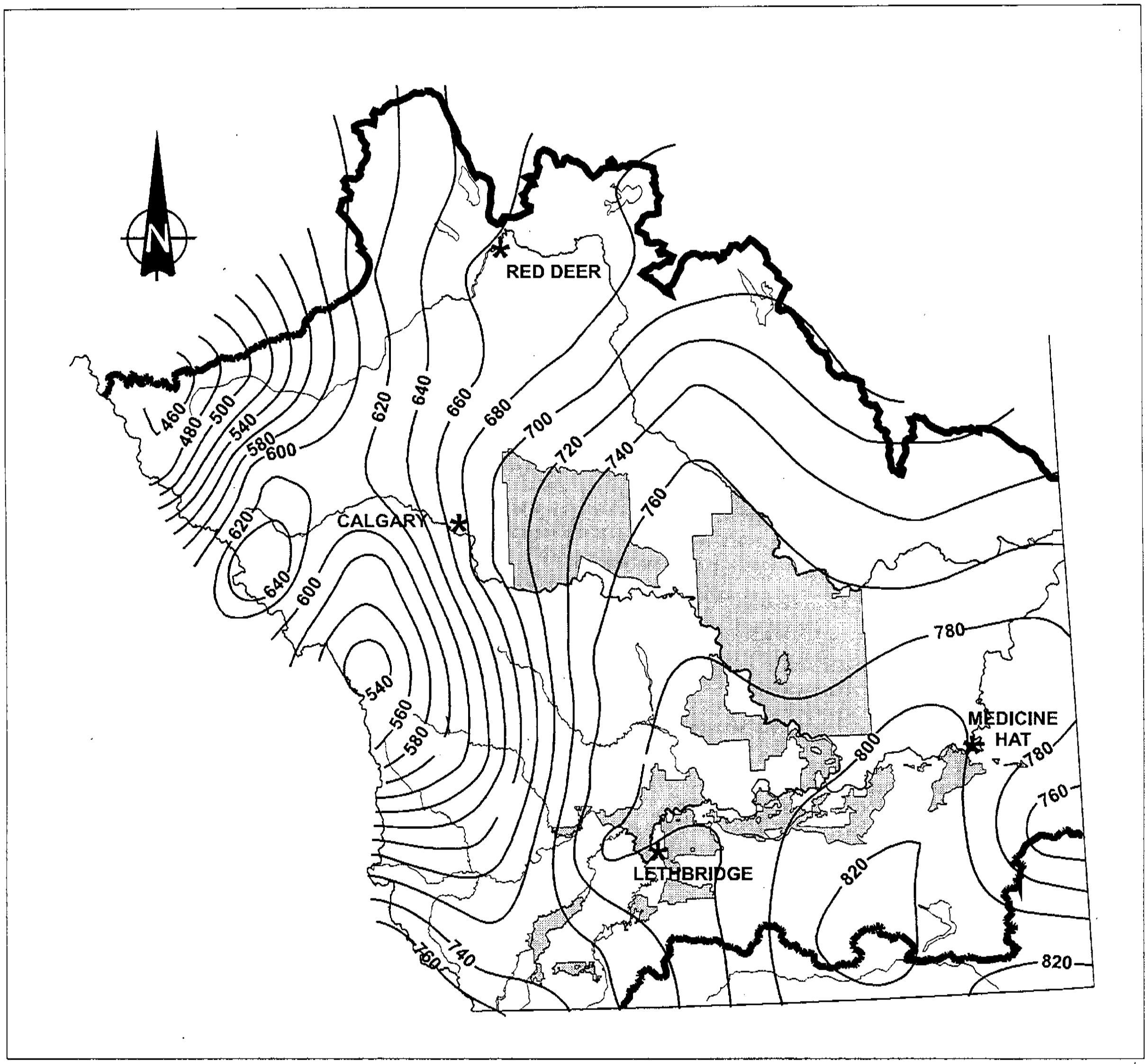

Fig. 2. Mean PE values (mm) for the killing frost-free period in the South Saskatchewan River Basin.

CONCLUSIONS

Limited meteorological data available prior to 1955 (temperature and precipitation) restricted the choice of equations for determination of historical PE. Selection of the most suitable PE equation for historical PE was dependant on the input parameters required for each of the different methods. A modified Priestley-Taylor equation, using estimated R_s and calibrated with an α coefficient equal to 1.66, compared most favorably to daily disc atmometer PE data. The modified Priestley-Taylor equation was used to create a daily historical PE database. Mean seasonal PE values ranged from about 460 mm at the headwaters of the Red Deer River Basin to about 820 mm in southeastern Alberta. Mean seasonal PE values were greater than 700 mm for all of the irrigation districts in the SSRB.

The historical PE database allows users to look at average and extreme conditions, and to assess these impacts on future irrigation development. The historical PE map for the SSRB allows irrigation districts, water resource planners, and regulators to make more informed decisions regarding irrigation expansion, crop water requirements, and on-farm water management in southern Alberta.

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Volume 2 On-Farm Irrigation Water Demand

II. Current irrigation management practices, 1996-2000

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EXECUTIVE SUMMARY

Water supplies in southern Alberta are at, or near, full allocation. Alberta Agriculture, Food and Rural Development (AAFRD), in conjunction with the 13 irrigation districts, the Prairie Farm Rehabilitation Administration, and Alberta Environment, initiated a major irrigation review in 1996 to assess current and future water allocation in the South Saskatchewan River basin. Irrigation is the largest consumptive user of water in the basin; thus, it was considered essential to evaluate on-farm irrigation practices of producers as part of the study.

This study was conducted from 1996 to 2000 to evaluate the current level of on-farm irrigation water management and to answer questions relating to crop water use, irrigation amounts, timing of irrigation, and irrigation efficiencies. The assessment included measures of crop water requirements, irrigation amounts and timing, under-irrigation (crop water stress), over-irrigation (excess water applied), and the ability of the irrigation system to meet crop water demands. During the five-year study, 306 fields were monitored. The most prevalent crops studied were alfalfa, wheat and canola.

Of the crops monitored, alfalfa and sugar beets were the greatest consumers of water, requiring an average of 500 mm of water per growing season for evapotranspiration. Grain and oilseed crops had very similar annual water use, averaging 310 to 360 mm. Crop water use was lowest in the northern areas around Strathmore and Brooks, and highest around Medicine Hat and Bow Island.

Measured irrigation application amounts were largest for alfalfa and sugar beets. In all districts, except Strathmore, consumptive use requirements were primarily fulfilled by irrigation applications, with minor contributions from rainfall and stored soil moisture. In the Strathmore area, precipitation constituted 53 to 68 percent of the crop water requirements.

Surface irrigation methods applied the largest annual irrigation amounts, followed by pivot irrigation and then wheel-move systems. Pivot irrigators applied an average of 23 mm more than irrigators operating wheel-move systems.

All of the surface-irrigated fields, 34 percent of the fields irrigated with wheels and 11 percent of the fields with pivots were over-irrigated at least once during the growing season. Of the fields over-irrigated, 69 percent were due to operator error and 31 percent were due to system design problems. Over-irrigation of surface irrigated fields varied from 98 to 260 mm. Of the extra water applied, deep percolation accounted for an average of 83 percent, and runoff accounted for an average of 17 percent. Measured irrigation application efficiencies of surface irrigated fields were generally low, ranging from 0.20 to 0.51.

More than 50 percent of the fields using wheel-move or pivot irrigation systems and 20 percent of the surface-irrigated fields were under-irrigated at least once during the irrigation season. Of the fields under-irrigated, 93 percent were attributed to operator error and 7 percent due to system problems. An additional 55 mm would be required on 70 percent of the fields monitored to avoid under-irrigation during the growing season. Not all under-irrigation situations were avoidable.

Irrigation application amounts should decrease in a few districts as surface-irrigation systems are converted to sprinkler systems. Many of the problems identified with surface-irrigation systems are primarily a consequence of the method of irrigation. Efficiencies can be improved marginally with operational and/or design changes, but conversion of surface systems to pivot or other sprinkler systems will significantly improve on-farm and irrigation district efficiencies. On the other hand, conversion of wheel-move to center pivot irrigation systems may slightly increase the irrigation application amounts of most districts.

AAFRD technicians that monitored the fields reported that 65 percent of the producers did a good job in management of their systems, a fair job was done by 18 percent and 17 percent were rated as doing a poor job. Seventy-nine percent of the producers that received previous irrigation training by AAFRD personnel were rated as having done a good job in management of irrigation water. This compared to 56 percent for irrigators who received no formal training. Irrigation training has been shown to be beneficial in irrigation management, particularly when using center pivot systems.

Simulation of crop water demands suggests that crop water requirements could potentially increase if irrigation management levels increase. For all crops, the average measured consumptive use was 84 percent of simulated estimates. The average deficit between measured and simulated consumptive use values was 54 mm. It was felt that the simulated crop water use values for alfalfa were practically unobtainable, and those for sugar beets were too low.

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INTRODUCTION

Alberta Agriculture, Food and Rural Development (AAFRD), in conjunction with the 13 irrigation districts, the Prairie Farm Rehabilitation Administration, and Alberta Environment, initiated a major irrigation review in 1996 to assess current and future water allocation in the South Saskatchewan River basin. The need for this information has become more critical as water supplies in southern Alberta are at, or near, full allocation. Irrigation is the largest consumptive water user in the basin, therefore, determination of the present level of water use by the irrigation districts is critical to properly assess current water demands and to estimate future demands for this limited resource.

Irrigation district have been active in increasing overall water use efficiencies by minimizing or eliminating seepage and/or evaporation from their distribution systems by installing pipelines and/or rehabilitating canals. Improved water management through the use of improved technology and training has reduced return flows and has increased overall efficiencies. However, poor management or design of the on-farm component of the irrigation network may offset all gains by the irrigation districts. The level of irrigation water management practiced by the irrigation farmer is one component that can dramatically change water demand for the irrigation district. Determination of the present level of on-farm irrigation management is essential to manage the irrigation system and to plan future water allocations and management in the region. A small change in the level of on-farm water management can have a significant effect on the total demand for water.

History of irrigation water management in Alberta

AAFRD has been assisting irrigators with irrigation water management since 1958. The "District Irrigation Gauge" was the first system used by the Colonization Branch, Alberta Department of Agriculture, to promote better use of irrigation water. Gauge boards were set up near post offices or in other high traffic locations throughout the irrigated area. Department staff posted weekly crop water use and soil moisture levels on the boards. Crop water use estimates were based on measured evaporation from Bilaney cups and provided general irrigation information for the surrounding area or district.

The District Irrigation Gauge board was later modified to make irrigation-specific recommendations for an individual irrigator's field. For an annual fee of $3.00, a government technologist would take soil samples to determine available water holding capacity and soil moisture levels prior to the irrigation season. The irrigator would receive a weekly mailing of crop water use and soil moisture levels for the farm. With this subscription, the irrigator received recommendations on irrigation management specific to the field sampled.

In 1961 and 1962, plots were established within sugar beet fields and were irrigated according to the Irrigation Gauge recommendations (Steed 1974). This study reported that these plots received higher yields than fields irrigated according to the more general District Irrigation Gauge recommendations.

In the late 1970's, Gen atmometers were used to estimate evapotranspiration in combination with periodic, in-field soil moisture checks. These soil moisture determinations showed some discrepancies between the field measurements and the estimated soil moisture level. It was apparent that existing programs needed to be improved with more accurate soil moisture predictions. This prompted the next major change in irrigation management promotion in southern Alberta. The newly created Irrigation Division focused on two areas: field soil moisture measurements and modeling to estimate soil moisture content.

In 1979, the Irrigation Division initiated producer training with a program called, "The Irrigation Scheduling Program". The initial design of the program was for an AAFRD technologist to take weekly soil moisture readings in the fields included in the program and to make recommendations to producers regarding irrigation timing and amounts. The Irrigation Scheduling Program was solely a service and did not include irrigation producers in the irrigation management decisions, and did not provide the irrigation producers with the necessary knowledge manage irrigation water effectively and efficiently.

In 1983, the program was revised and was called the Alberta Irrigation Management (AIM) Program, with a new emphasis on education of the irrigator to do his/her own irrigation scheduling. The irrigator was taught to use the hand-feel method for soil moisture determinations. During a two-year period of weekly meetings with a technologist from AAFRD, the irrigator was trained to understand the water holding characteristics of the soil, crop water use and to determine irrigation timing and amounts for themselves.

The AIM program has recently been privatized and is now offered in a modified format by technologists of agri-businesses. These technologists, trained and supported by the Irrigation Branch, assist irrigators with irrigation scheduling information and recommendations.

Arguably, the most significant influence to date on the level of irrigation management is the type of irrigation system used. In 1970, 30 percent of irrigated land was irrigated by sprinkler systems, compared to 80 percent by 1995 (Chinn 1996). As wheel-move systems replaced surface irrigation and as center pivots replaced wheel-move systems, the irrigation application efficiency increased. During this period, the level of irrigation management also increased, necessitating timely and accurate information regarding soil moisture status.

The Irrigation Branch is currently calibrating and validating the Alberta Irrigation Management Model (AIMM) computer model. The AIMM model assists irrigators with irrigation management by estimating soil moisture use by various crops based on certain meteorological inputs. The model assists the irrigator in making decisions on timing and amounts of irrigation application based on the crop grown and system used.

The Irrigation Branch is also testing soil moisture sensors for suitability for use by individual irrigators. The latest in technology is also being tested, which combines computer modeling, soil moisture metering, telemetry, weather station and pivot controls to automate irrigation scheduling and center pivot operation.

Irrigation management has a significant influence on the profitability of a crop and efficiency of water use. Yields are increased when the crop is neither under- nor or over-irrigated, and water use efficiency can be maximized when water is not lost to evaporation, surface relocation, surface runoff, nor percolation beyond the depth of the root zone.

Objectives

The objectives of this study were:

(1) to collect information on actual crop water use for a variety of crops;
(2) to observe irrigation management practices throughout all irrigated areas of southern Alberta;
(3) to identify the potential for future changes in crop water use and management practices.

This study was conducted to evaluate the current level of on-farm irrigation management and to answer questions related to crop water use, irrigation amounts, timing of irrigation and irrigation efficiencies. In this study, each field was specifically monitored for crop water use while the irrigation water management practices of the farmer were observed. These results were compiled for various crop types and regions throughout southern Alberta. At the same time, the crop water use and irrigation applications were simulated using a locally calibrated computer model to determine how irrigation water requirements might change if irrigation water management levels improved and crop water use increased in relation to potential crop water demand.

METHODS

The assessment of current irrigation management practices included measurement of crop water requirements, irrigation amounts and timing, under-irrigation (crop stress), over-irrigation (excess water applied), and the ability of the irrigation system to meet crop water demands. In addition, computer simulations of optimum irrigation water management were completed to help predict how water management levels could change in the future.

Site selection

Fields participating in the study were selected in the spring of each year. Each field selected was required to meet the following criteria prior to field sampling and equipment installation:

a) site has irrigation rights and is expected to be irrigated during the year.
b) site was within 50 km of a weather station, i.e. collection of daily minimum and maximum temperature, wind and solar radiation.
c) crop to be grown must be one of the 14 modeled by the Lethbridge Research Station Irrigation Management Model (LRSIMM).
d) a maximum of three fields of any one crop to be selected by a district office.

If a field did not meet the selection criteria, it was rejected and an alternate field was chosen. Each of the six, Irrigation Branch, district offices selected 10 fields for monitoring each year. During the five year study, 306 fields were selected for monitoring (Table 1). The most commonly represented crops in the study were alfalfa, wheat and canola.

Table 1. Number of fields monitored in each year for each crop from 1996 to 2000.

Crop	**1996**	**1997**	**1998**	**1999**	**2000**	**Total**
Alfalfa	14	16	15	15	15	75
Barley	7	6	6	4	8	31
Barley Silage	6	3	3	2	4	18
Canola	10	11	13	11	9	54
Soft Wheat	8	6	6	1	5	26
Sugar Beet	5	7	5	6	5	28
Wheat	7	8	8	17	22	62
Other Crops	3	3	3	1	2	12
All Crops	*60*	*60*	*59*	*57*	*70*	*306*

The majority of irrigators in the study irrigated with center pivot irrigation systems (Table 2). Wheel-move irrigation systems were less common and only the Brooks district office monitored fields irrigated using surface methods.

Table 2. Number of each system type in each area.

Location	Pivot	Wheels	Surface
Bow Island	48	4	0
Brooks	27	11	10
Lethbridge	27	20	0
Medicine Hat	48	2	0
Strathmore	44	6	0
Taber	33	4	0

Site measurements

All sites were equipped with three 1.2 or 1.5 m aluminum access tubes for monitoring soil moisture, a 3.0 m polyvinyl-chloride tube for monitoring depth to water table and one standard rain gauge placed outside the irrigated area to measure rainfall. Fields irrigated with center pivot or wheel-move systems were equipped with three additional standard rain gauges positioned at each of the access tubes to measure irrigation amounts (Fig. 1). In addition, flow tests were done on each sprinkler irrigation system to determine the volume of water applied to each field.

Irrigation amounts applied to surface-irrigated fields were estimated using the continuity equation:

Where $Q=AV$ (1)

Q - discharge ($m^3\ s^{-1}$)

A - cross-sectional area of hydraulic radius (m^2)

V - velocity of flow ($m\ s^{-1}$)

Cross-sectional flow area and velocity were measured on both the supply and drain ditches during irrigation events from 1996 to 1999. During 2000, calibrated RBC flumes instrumented to digitally record stage readings (water level) every 15 min were placed in the supply and drain ditches prior to an irrigation event.

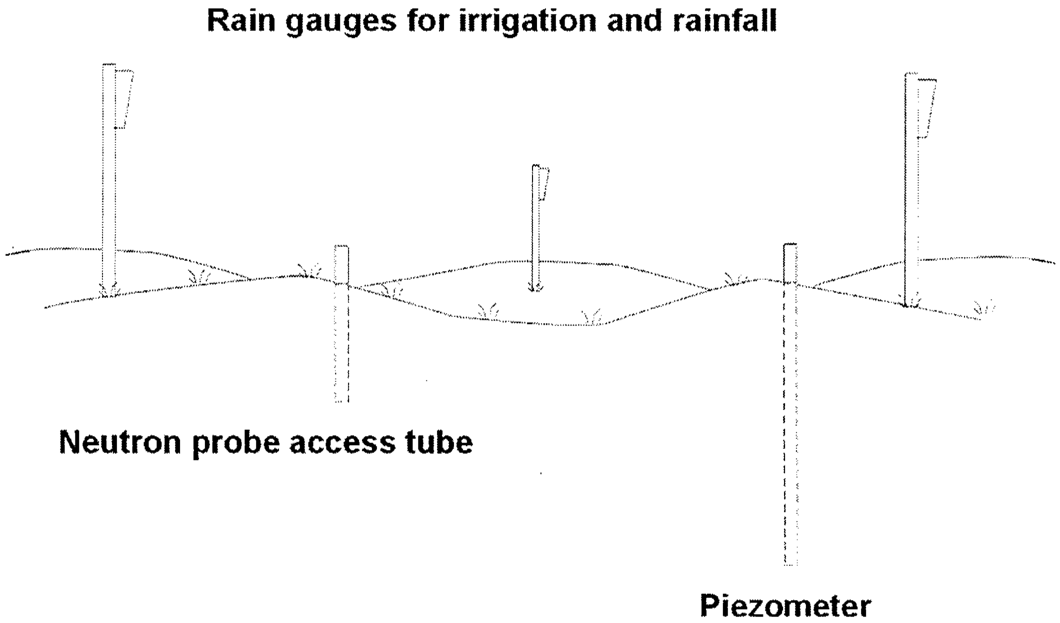

Fig. 1. Typical site setup for sprinkler irrigated fields.

At the start of each year, detailed information was obtained as to the soil type, water holding capacity of soil, starting soil moisture conditions and crop stand. Weekly monitoring of irrigation, rainfall, water-table level and soil moisture content commenced as soon as the crop was planted and continued until harvest or until the first killing frost. Weekly soil moisture measurements were taken using a neutron probe soil moisture instrument (CPN International, Inc., Martinez, California) and hand-feel moisture sampling was done intermittently throughout the season. After the crop was harvested, rain gauges were re-installed in the field and fall irrigation amounts were recorded.

Weekly crop water use (evapotranspiration) was calculated from a general soil moisture balance equation ($Et=(P+I)-R-D\pm\Delta S$): (2)

Where Et - Evapotranspiration (mm)
P - Rainfall (mm)
I - Irrigation (mm)
R - Runoff (mm)
D - Deep percolation (mm)
ΔS - Soil moisture (change) (mm)

Daily meteorological data (temperature, wind, incoming short-wave solar radiation, relative humidity) were obtained from a weather station near the monitoring site. Other information recorded included ratings on crop condition, weed problems, disease problems and overall irrigation management. Each of these subjective ratings were determined by the technologist in the field.

After a site was selected and permission was obtained, the irrigator was not contacted again during the growing season. This was done to ensure data collected met the requirements of the project and to prevent irrigation management practices from being influenced by the AAFRD technologist. Each farm operator was contacted after the irrigation season to discuss irrigation practices and to recommend changes where required. Some of the fields selected were eliminated from the final data set due to high water tables, hail damage, improper crop selection, and irrigation system mechanical problems.

Simulation of irrigation demand

Simulations were done using the Lethbridge Research Station Irrigation Management Model (LRSIMM) to determine the upper limits or "optimum" irrigation scheduling for crop water use and irrigation applications (Foroud and Hobbs 1983). The simulations included local weather conditions and actual seeding and harvest dates for each field. Daily evapotranspiration for optimum irrigation scheduling was obtained from the LRSIMM computer model. Simulated irrigations on the center pivot fields were applied in 25 mm increments to maintain soil moisture between 70 and 100 percent of available. Soil moisture was maintained between 50 and 100 percent of available for wheel-move and surface-irrigated fields. Precipitation volumes from on-site rain gauges were used in the simulation. Comparisons were made between measured and modeled (optimum) irrigation applications and crop evapotranspiration for each crop, district office and year.

The LRSIMM computer model is based on a model developed by Jensen et al. (1971) at Kimberly, Idaho. LRSIMM uses a modified Jensen-Haise equation, modified by Foroud et al. (1989) to calculate potential evapotranspiration for southern Alberta conditions. The potential evapotranspiration is adjusted for each of 14 crops using crop coefficients developed from data collected at the Agriculture and Agri-Food Canada (AAFC) research substation at Vauxhall, Alberta (Hobbs and Krogman 1983). Crop coefficients are available for alfalfa, grass, wheat, oats, barley, flax, canola, peas, sugar beets, potatoes, corn, sorghum, faba beans, and soybeans. Inputs to the model include: meteorological data, total available moisture in the soil profile (mm), starting soil moisture depletion (mm), depletion allowed (mm), date of planting, date of effective cover, irrigation efficiency (set to 100 percent for optimum simulations), and constants required for the Jensen-Haise evapotranspiration equation. The model was verified in the field by Foroud et al. (1992) and Dill et al. (1995).

Irrigation training

The Irrigation Branch of AAFRD provided an irrigation management (AIM) training program for individual producers from 1983 to 1996. In this training program, producers were taught how to determine available soil moisture and to calculate when to irrigate and how much irrigation water to apply to meet crop water requirements. Irrigators participating in this study included those trained previously and those not trained by AAFRD personnel. To assess whether irrigators from the training program performed better at irrigation management than irrigators that were not trained, comparisons using an unpaired t-test ($p<0.05$) were performed for each district office and for each crop.

RESULTS

Climate

Annual precipitation received during the growing season (May through September) is presented in Fig. 2. During the five years of monitoring, there was a fairly good representation of above and below normal annual precipitation observed for most locations. The only exception was Bow Island, which reported below normal precipitation in all five years of the study. During the 2000 growing season, all locations received markedly lower precipitation than normal. Monthly precipitation and temperature from 1996 to 2000 and long-term (30 year) normals can be found in Appendix A. Temperature was also well distributed throughout the study period, with above and below normal monthly temperatures reported. For most districts, with the exception of Strathmore, average temperatures for the month of August were above normal for all years of the study.

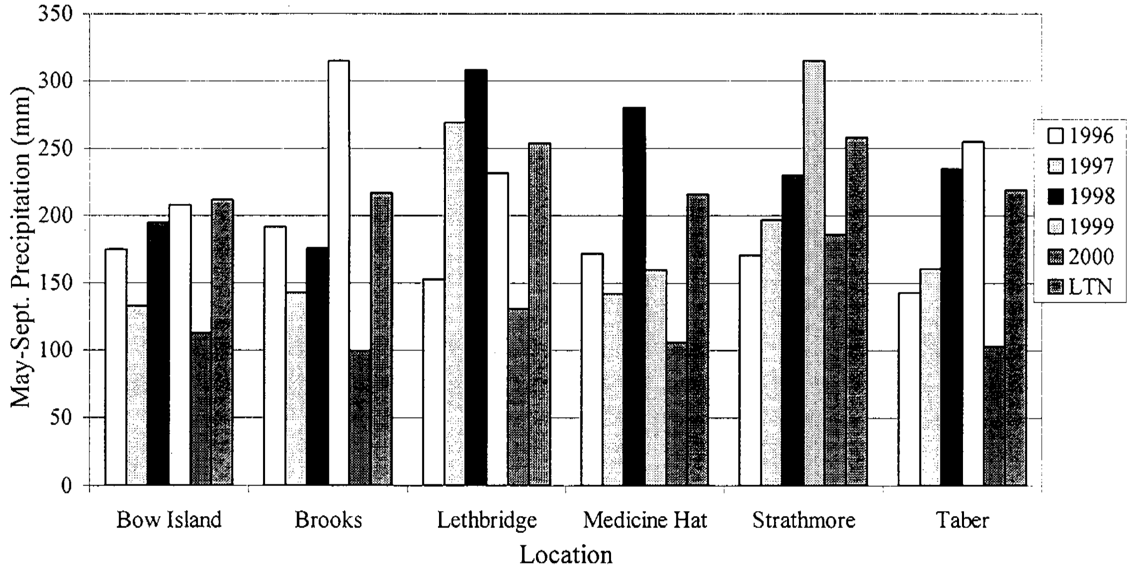

Fig. 2. Season (May to Sept.) precipitation for all locations from 1996 to 2000.

Average corn heat units (CHU) and frost-free period (FFP) from 1996 to 2000 were comparable to long-term normals (Fig. 3). All locations except Strathmore reported higher corn heat units and a longer frost-free period for all five years compared to the long-term normal (LTN). Of particular interest is the shorter growing season observed in Strathmore, where the least number of frost-free days were observed in four of five years (Appendix A).

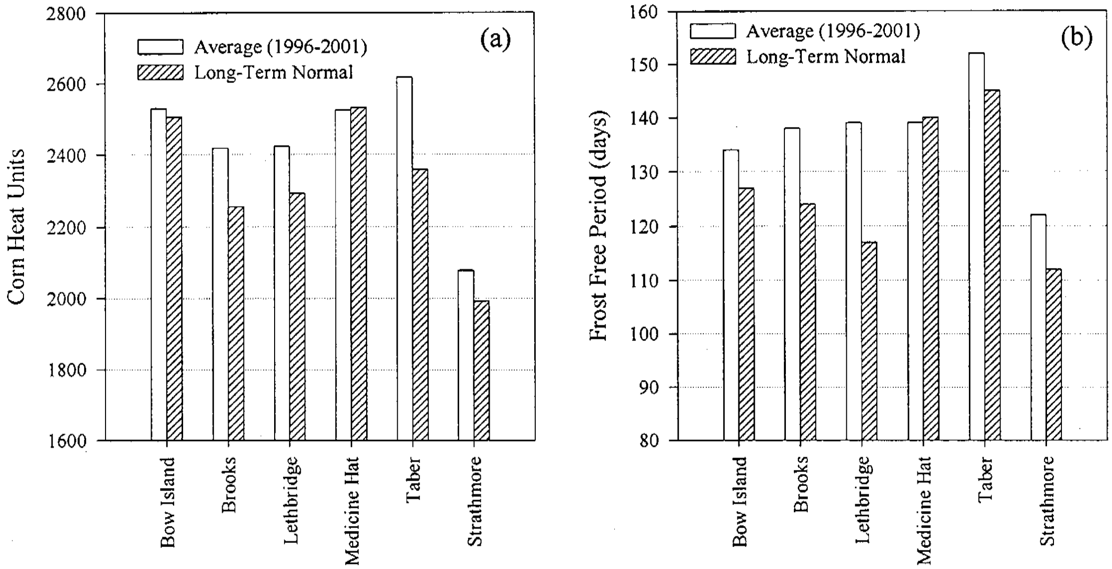

Fig. 3. Average (a) corn heat units and (b) frost-free period measured during the growing season compared to long-term normal values.

Observed irrigation practices

Variation by area and crop type. Variation in irrigation application amounts and crop water use by location is shown in Table 3. Annual crop water use and irrigation amounts for each crop and each location can be found in Appendix B. The crops with the highest irrigation application amounts and crop water use were alfalfa and sugar beets. The cereal crops and canola exhibited similar crop water use. Crop water use numbers were generally lowest for the Brooks and Strathmore districts, and highest for the Medicine Hat and Bow Island areas.

Among districts, crop water use was derived from varying proportions of irrigation, precipitation, and soil moisture (Table 3). All of the areas, except Strathmore, derived the majority of their crop water requirements from irrigation, with minor contributions from precipitation and soil moisture. Conversely, Strathmore was the only area where precipitation was the greatest contributor to crop water requirements. The Brooks area was the only area where the combined irrigation application and precipitation amounts were greater than measured crop water use.

Table 3. Average crop water use (CU), irrigation amount, and precipitation from 1996 to 2000 (mm).

Alfalfa	CU	Irrigation	Rainfall	Number of Fields	Irrigation as % of CU	Rainfall as % of CU	% of CU obtained from soil moisture
Bow Island	594	397	184	10	67%	31%	2%
Brooks	453	327	168	13	72%	37%	-9%
Lethbridge	465	297	160	13	64%	34%	2%
Medicine Hat	586	395	177	17	67%	30%	2%
Strathmore	383	176	224	16	46%	58%	-4%
Taber	509	345	169	9	68%	33%	-1%
All Offices	494	317	182	78	64%	37%	-1%

Barley	CU	Irrigation	Rainfall	n	Irrigation as % of CU	Rainfall as % of CU	% of CU obtained from soil moisture
Bow Island	357	186	145	4	52%	41%	7%
Brooks	312	205	104	13	66%	33%	1%
Lethbridge	335	187	131	7	56%	39%	5%
Medicine Hat	297	151	91	4	51%	31%	19%
Strathmore	272	127	145	6	47%	53%	0%
Taber	344	167	153	2	49%	44%	7%
All Offices	315	178	122	36	57%	39%	5%

Barley Silage	CU	Irrigation	Rainfall	n	Irrigation as % of CU	Rainfall as % of CU	% of CU obtained from soil moisture
Bow Island	261	149	54	1	57%	21%	22%
Brooks	248	195	105	1	79%	42%	-21%
Lethbridge	310	136	102	6	44%	33%	23%
Medicine Hat	277	178	75	1	64%	27%	9%
Strathmore	274	101	167	7	37%	61%	2%
All Offices	285	128	126	16	45%	44%	11%

Canola	CU	Irrigation	Rainfall	n	Irrigation as % of CU	Rainfall as % of CU	% of CU obtained from soil moisture
Bow Island	358	208	124	10	58%	35%	7%
Brooks	291	189	111	3	65%	38%	-3%
Lethbridge	334	151	139	9	45%	42%	13%
Medicine Hat	391	209	159	13	53%	41%	6%
Strathmore	258	80	176	12	31%	68%	1%
Taber	345	188	118	8	54%	34%	11%
All Offices	334	167	144	55	50%	43%	7%

Soft Wheat	CU	Irrigation	Rainfall	n	Irrigation as % of CU	Rainfall as % of CU	% of CU obtained from soil moisture
Bow Island	419	223	142	4	53%	34%	13%
Brooks	322	173	132	4	54%	41%	5%
Lethbridge	348	236	102	2	68%	29%	3%
Medicine Hat	370	209	118	4	56%	32%	12%
Taber	354	213	97	12	60%	27%	12%
All Offices	361	201	113	26	56%	31%	13%

Table 3. continued from previous page...

Sugar Beets	CU	Irrigation	Rainfall	n	Irrigation as % of CU	Rainfall as % of CU	% of CU obtained from soil moisture
Bow Island	554	372	171	9	67%	31%	2%
Lethbridge	496	301	149	8	61%	30%	9%
Taber	496	329	144	12	66%	29%	5%
All Offices	514	334	154	29	65%	30%	5%

Wheat	CU	Irrigation	Rainfall	n	Irrigation as % of CU	Rainfall as % of CU	% of CU obtained from soil moisture
Bow Island	389	229	112	14	59%	29%	12%
Brooks	350	248	126	14	71%	36%	-7%
Lethbridge	392	143	234	2	36%	60%	4%
Medicine Hat	426	211	170	11	50%	40%	11%
Strathmore	252	86	144	9	34%	57%	9%
Taber	345	194	120	9	56%	35%	9%
All Offices	360	200	136	59	56%	38%	7%

Variation in irrigation amounts by system type. The average annual irrigation application for each irrigation system type is shown in Fig. 4. The large standard deviations for sprinkler irrigation are a reflection of varying precipitation among districts and among years for the same district. Pivot irrigators applied an average of 23 mm more than irrigators that operated wheel-move systems.

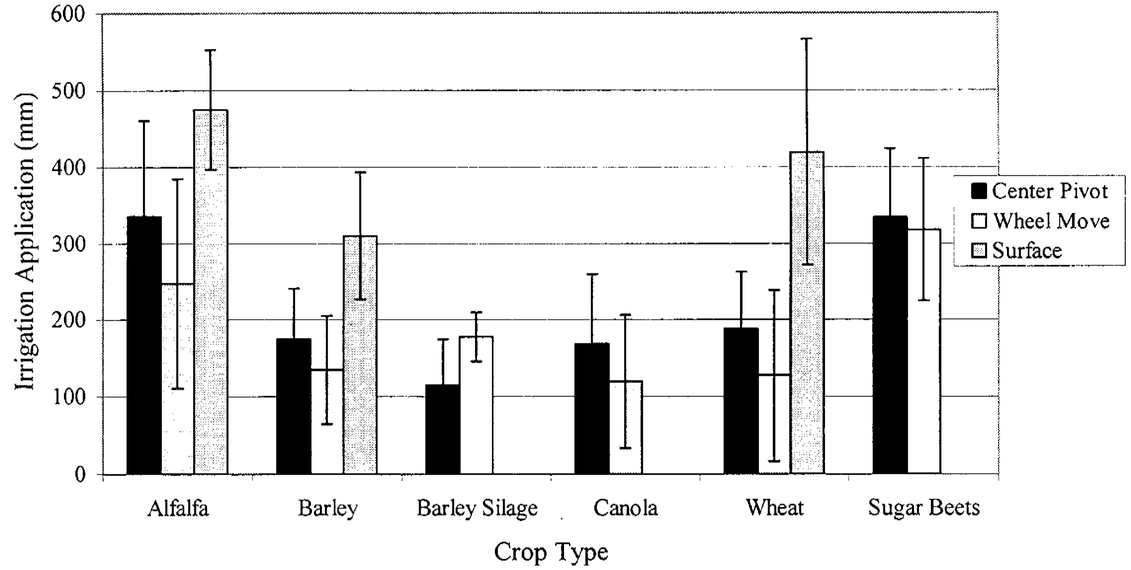

Fig. 4. Irrigation application by system type.
Note: Error bars indicate one standard deviation from mean value.

Surface irrigation methods applied the largest annual irrigation amounts. However, the standard deviation is not consistently greater than that of sprinkler systems for a similar crop type. This result highlights the difficulty of applying small amounts of water via surface irrigation methods to meet soil moisture deficits. Even with properly designed fields, it is difficult to apply less than 200 mm per application using surface irrigation methods.

Over-irrigation. All surface irrigated fields, 34 percent of the fields irrigated with wheels, and 11 percent of the fields with pivots were over-irrigated at least once during the growing season (Table 4).

Table 4. Average over-irrigation by system type.

	Surface	Wheel-move	Center pivot
Number of monitored fields	10	50	248
Fields over-irrigated	10	17	27
% of fields over-irrigated	100%	34%	11%
Average mm over	158	39	23

Of the fields over-irrigated, 69 percent were due to operator error and 31 percent were due to system design problems. Operator error was due mainly to irrigation applications of too long of duration, whereby the soil's water holding capacity was exceeded. In the case of surface irrigation methods, a common operator error was to irrigate more borders than the available water could cover in a reasonable time. System problems included: too long of border lengths; too wide of borders for the available stream size; wrong nozzle package; or poor design for soil hydraulic conditions.

Surface irrigation efficiencies - Ratios of soil moisture deficit prior to irrigation to gross application for surface irrigation systems were generally low, varying from a low of 0.20 to a high of 0.51 (Table 5). Over-irrigation of surface-irrigated fields varied from 98 to 260 mm. Of the extra water applied, deep percolation accounted for an average of 83 percent and runoff accounted for an average of 17 percent.

Table 5. Summary of gravity irrigation systems from 1996 to 2000.

Year	Field	Irrigation number	Gross application (mm)	Soil moisture deficit prior to irrigation (mm)	Excess (mm)	Deep percolation (mm)	Tailwater (mm)	Ratio of soil moisture deficit to gross application
1996	1	1	439	179	260	215	45	0.41
	2	1	286	116	170	149	21	0.41
		2	214	92	122	111	11	0.43
	3	1	209	80	129	73	56	0.38
		2	198	100	98	77	21	0.51
	4	1	192	93	99	84	15	0.48
		2	200	63	137	94	43	0.32
1997	1	1	275	55	220	193	28	0.20
		2	275	56	219	176	43	0.20
	2	1	213	60	153	115	38	0.28
		2	223	78	145	125	20	0.35
1998	1	1	244	102	142	132	10	0.42
		2	218	73	145	118	27	0.33
2000	1	1	302	130	172	169	3	0.43
		2	263	89	174	168	6	0.34
	2	1	227	80	147	107	40	0.35

Under-irrigation. More than 50 percent of the fields using wheel-move or pivot irrigation systems and 20 percent of the surface irrigated fields were under-irrigated at least once during the irrigation season (Table 6). The average annual under-irrigation amount was 55 mm.

Table 6. Average under-irrigation by system type.

	Gravity	Wheels	Pivot
Number of monitored fields	10	50	246
Fields under-irrigated	2	30	139
% of fields under-irrigated	20%	60%	57%
Average mm under	64	57	44

Of the fields under-irrigated, 93 percent were attributed to operator error and 7 percent to system problems. Operator error included starting too late or quitting early. System problems were due to poorly designed or installed systems, which could not supply sufficient water. In no case did the irrigation district delivery system cause an over- or under-irrigation to occur in the field.

System design. Of the sprinkler systems tested, 82 percent met or exceeded AAFRD design standards for system flow rate per irrigated area. In this study a sprinkler irrigation system is considered designed properly if the measured flow was greater than 0.98 L s^{-1} ha^{-1}.

Nine of the 10 surface irrigated fields included in the study were surveyed for land leveling and designed for irrigation application by AAFRD personnel prior to 1983. These designs were based on the infiltration properties of the soil and the hydraulics of water flow. Unfortunately, many of the fields were not constructed according to the design. The design often included a cross ditch to shorten border lengths or recommended narrow border widths to increase irrigation efficiency. These features were generally not included when the field was constructed.

Overall rating. During the five-year study, the irrigation technologist rated each field on the level of irrigation management practiced. This rating looked at the operation of the irrigation system and the ability of the producer to manage the crop being grown with that system (Table 7). These field observations indicated that 65 percent of the producers did a good job of managing their systems, a fair job was done by 18 percent, and 17 percent were rated as doing a poor job.

The poorest ratings for irrigation management were on fields of alfalfa, wheat and canola. Sugar beets and barley silage had the highest ratings. The ratings for five canola fields with wheel-move irrigation were fair or poor.

Irrigation training. Producers who had previous AIM training managed 108 of the 306 fields monitored in the five years of the study. Seventy-nine percent of the producers that received the AIM training were rated as doing a good job in the management of their irrigation water. This compared to 56 percent for irrigators who received no formal training. All of the previously trained irrigators included in this study irrigated using sprinkler irrigation. Ninety-eight producers irrigated using center pivot systems and 10 used wheel-move systems.

The differences in irrigation application between AIM-trained and non-trained irrigators were not significant ($P<0.05$) for all crops except barley. AIM-trained irrigators applied more water for all crops monitored. The amount of extra water applied by AIM-trained irrigators ranged from 10 mm for durum wheat to 91 mm for alfalfa.

Table 7. Irrigator ratings by system and crop.

Crop	System	Good	Fair	Poor	% Rated as good
Alfalfa	Pivot	29	6	16	57%
	Wheels	11	4	3	61%
	Gravity	2	1	-	-
Barley	Pivot	18	6	-	75%
	Wheels	4	2	-	67%
	Gravity	1	1	1	-
Barley Silage	Pivot	11	-	1	92%
	Wheels	1	1	1	-
Canola	Pivot	28	11	6	62%
	Wheels	-	2	3	0%
Wheat	Pivot	40	12	12	63%
	Wheels	3	-	1	-
	Gravity	1	1	1	-
Sugar Beet	Pivot	16	1	1	89%
	Wheels	7	-	-	100%

Simulated crop water use and irrigation amounts

Measured crop water use compared to "optimum" simulated crop water use is illustrated for each field in Fig. 5. For most crops, the cluster of data points is located above the 1:1 reference line, indicating that measured crop water use amounts were generally lower than simulated amounts. The average difference between simulated and measured water use amounts ranged from 144 mm for alfalfa to only 11 mm for sugar beets. Average results for each year of the study can be found in Appendix B. Overall, measured crop water use values for alfalfa were the lowest relative to simulated values at 80 percent, while sugar beet values were the highest, at 99 percent. Measured crop water use for all crops combined was 84 percent of that simulated by LRSIMM.

The variation of measured crop water use was much greater than that of modeled crop water use for most crops. This was most evident for sugar beets and wheat. Measured crop water use for wheat varied from 150 to 500 mm whereas the modeled values varied from 300 to 500 mm.

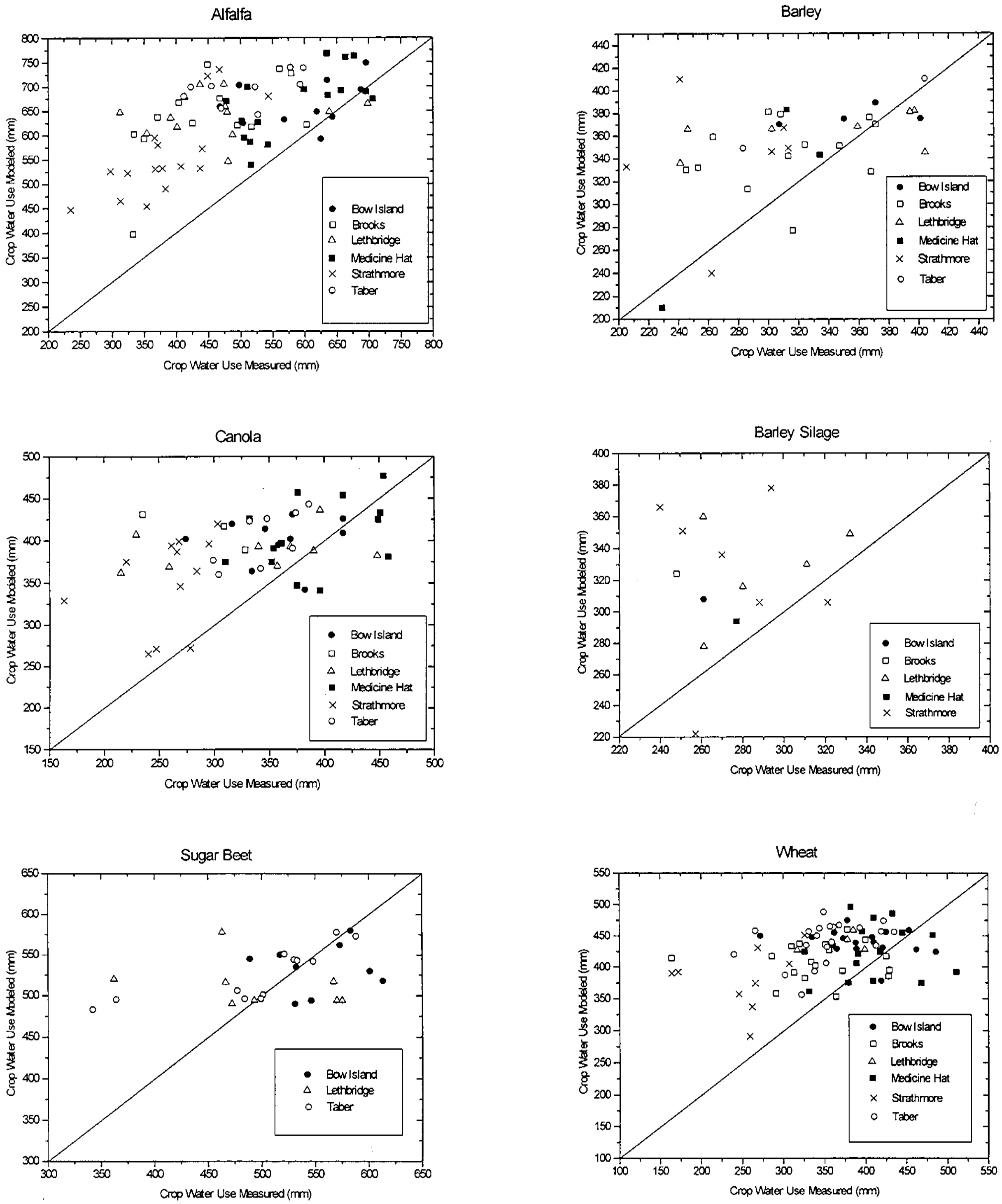

Fig. 5. Measured crop water use compared to simulated crop water use.

Measured and modeled crop water use for each study area is shown in Fig. 6. Measured crop water use was again lower than the simulated optimum conditions. This difference ranged from 35 mm at Bow Island to 117 mm at Strathmore. In other terms, measured crop water use at Bow Island and Strathmore were 93 and 72 percent of simulated values, respectively. The crop mix of a particular district in this study was not the same as the crop mix actually found in the area. Consequently, differences in average crop water use values among locations included variations in crop mix as well as climate. The average measured consumptive use for all fields throughout the entire study are was 396 mm.

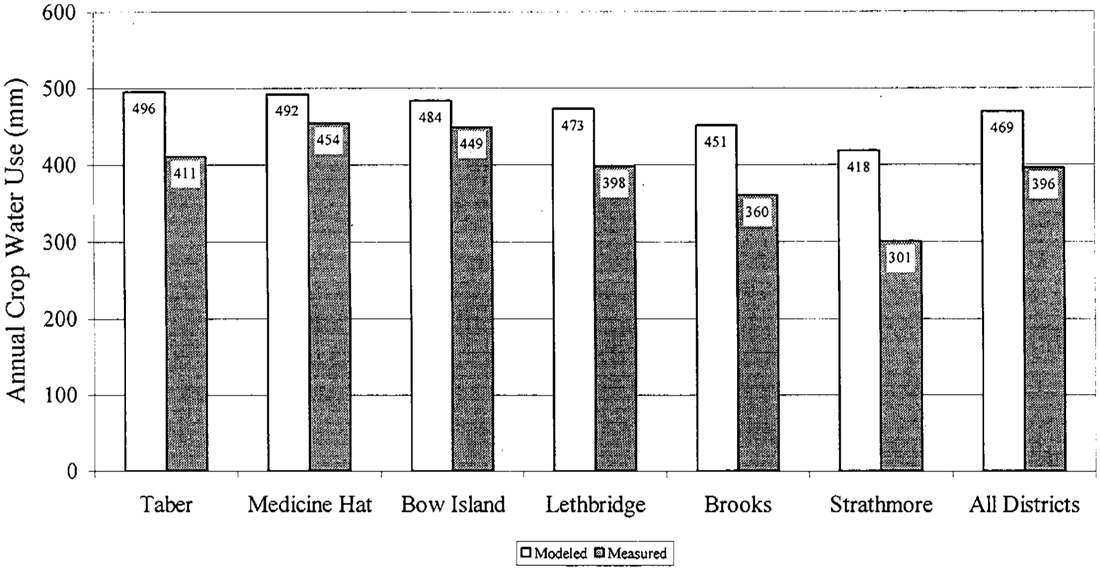

Fig. 6. Average simulated and measured crop water use for each study area.

Measured and simulated irrigation amounts for each field can be seen in Fig. 7. Modeled irrigation application amounts for "optimum" irrigation scheduling were typically higher than measured application amounts for most crops and districts. Exceptions were typically the surface-irrigated fields monitored from the Brooks district office and sugar beet fields. Fig. 8 shows measured and simulated irrigation applications for each general area. The average difference between measured and simulated irrigation application amounts for all districts was 127 mm. Simulations were ended at the harvest date, and therefore fall irrigations were not included. In many cases, the irrigator applied fall irrigations to increase soil moisture levels, but these were not accounted for in the modeled nor in the measured amounts. The average irrigation application amounts observed in each district are only representative of the crop mix selected in this study and may not accurately represent the actual application numbers of that geographical area.

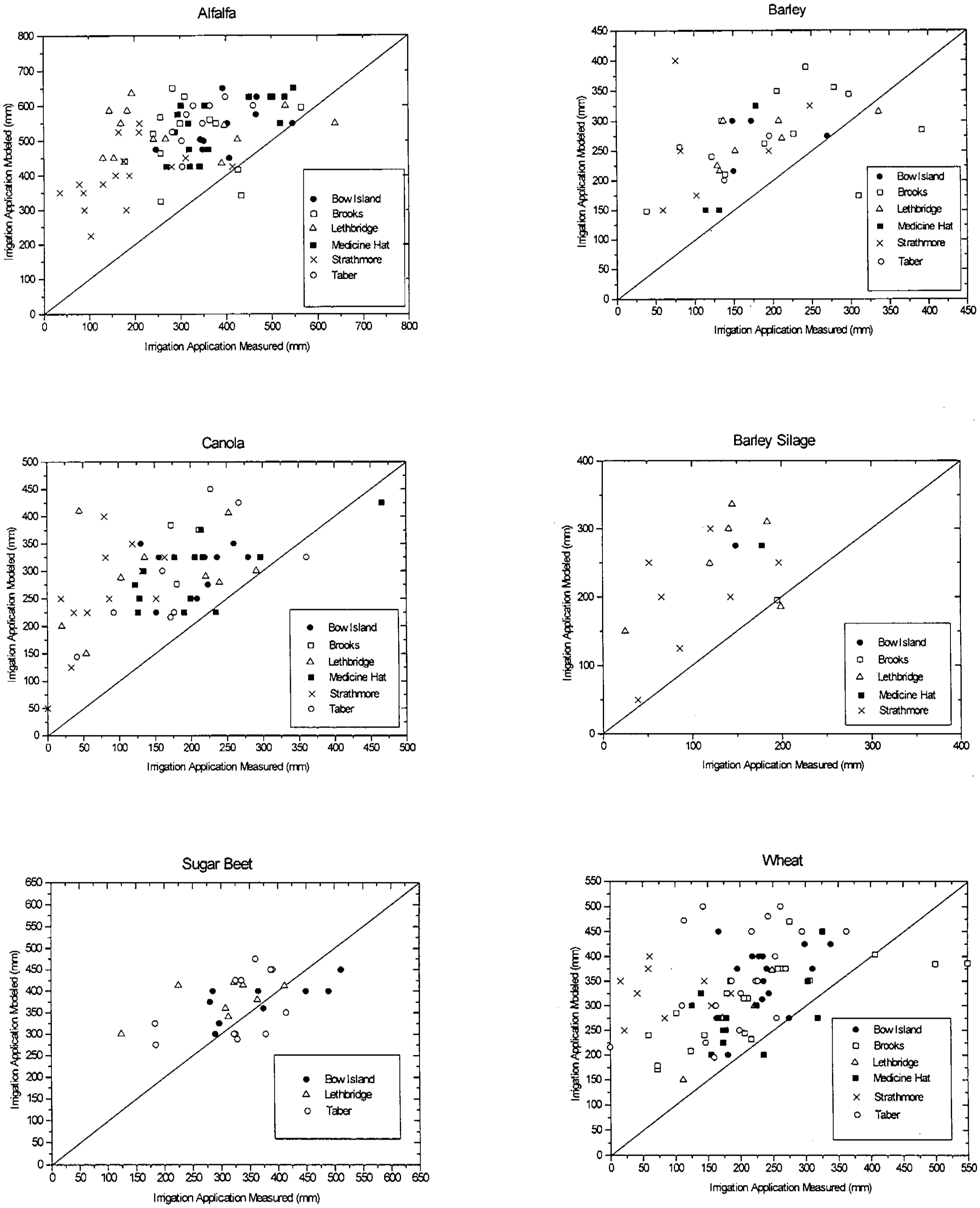

Fig. 7. Measured irrigation application compared to simulated "optimum" irrigation application.

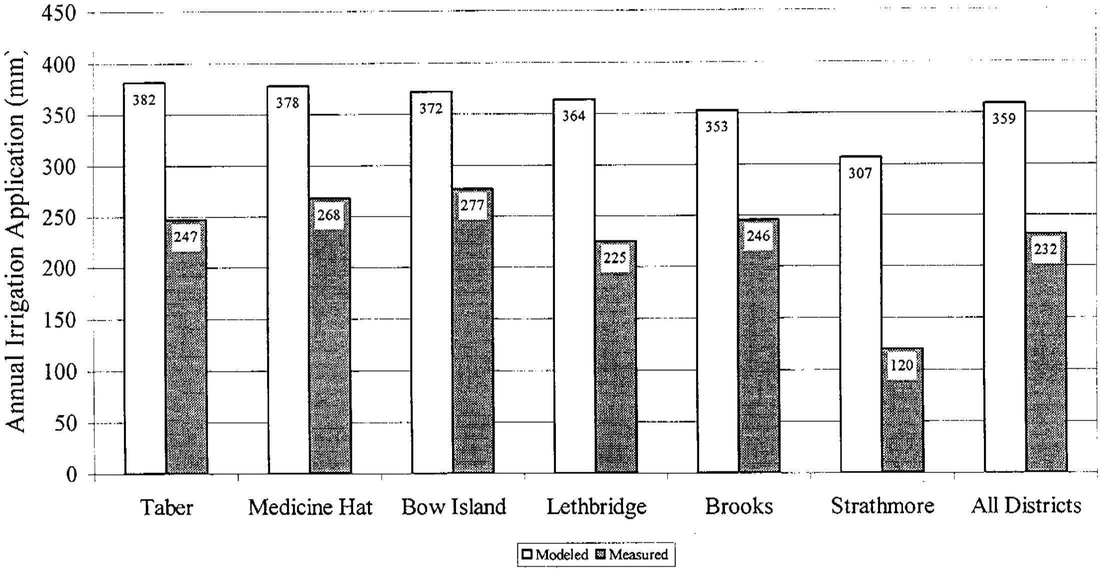

Fig. 8. Average simulated and measured irrigation application for each study area.

DISCUSSION

Assessment of current irrigation practices

Regional variations in irrigation management. Variation in irrigation application amounts among districts (Table 3) is primarily a reflection of differences in management (i.e. alfalfa 2-cut vs. 3-cut), amount of rainfall received during the growing season and irrigation system types (i.e. more surface irrigation rather than sprinkler).

Consumptive use of alfalfa was the lowest in the Strathmore, Brooks and Lethbridge areas. This can, in part, be attributed to the fact that alfalfa producers in the Strathmore and Brooks areas typically manage alfalfa for only two cuts during the season. Three cuts are only obtained during years receiving above average heat units and a longer than normal frost-free period. Three-cut alfalfa is normal for the Medicine Hat, Taber, and Bow Island areas, and some of the Lethbridge area. Alfalfa fields managed for three cuts rather than two cuts will have higher irrigation application amounts and crop water use.

Strathmore recorded the lowest irrigation application amounts for all crops monitored and the lowest crop water use for all crops except silage barley (Table 3). The Strathmore district also had the lowest corn heat units for all years of the study. Long-term normal precipitation is higher in the Strathmore area, but yearly rainfall was not always the highest during the five years of the study. Since evaporative demand is lower in this area and precipitation is generally higher, irrigation is typically managed to supplement natural precipitation rather than the primary source of precipitation for crop water use. This is supported by data in Table 3 that indicates that precipitation amounts in the Strathmore area constituted 53 to 68 percent of total measured crop water use.

The Brooks district office is the only office that monitored fields irrigated via surface irrigation. Irrigation application amounts for barley and wheat were highest for the Brooks district office, reflecting the presence of surface-irrigated fields. As indicated in Table 5, the minimum irrigation application amount for grain fields under surface irrigation was greater than 200 mm.

Performance of irrigators by system type. Fields irrigated with pivot irrigation had higher irrigation application amounts compared to fields irrigated with wheel-move systems (Fig. 4). Wheel-move systems are typically managed for two or three applications during the growing season and the entire soil profile is used to supply crop water demand. Conversely, center pivot irrigators typically ensure soil moisture in the top part of the soil profile is adequate to meet crop water needs. Therefore, center pivot irrigation requires more frequent irrigations of lesser amounts than wheel-move. Management-allowable depletion of soil moisture is greater for wheel-move than for center pivot systems.

Over-irrigation. Over-irrigation with wheel-move or pivot irrigation is primarily a result of applying irrigation water for too long and exceeding the soil moisture deficit of the soil. Over-irrigation with surface systems is a design and an operational problem.

Unlike wheel-move or pivot irrigation systems, it is very difficult to apply irrigation water with a gravity irrigation system to just meet the soil moisture deficit since the soil surface is used to convey as well as infiltrate the applied water. For many soils in southern Alberta, the water holding capacity in the upper 1 m of the root zone is less than 200 mm. Irrigating when the soil moisture drops to 50 percent of available means that the irrigator can add somewhat less than 100 mm of water to fill the root zone to achieve maximum efficiency. The highest efficiencies should be realized when the soil moisture deficit prior to irrigation is the largest (Burt 1995). Unfortunately, it is seldom practical or desirable to allow the soil moisture to decrease much below 50 percent of available before irrigating.

Typical problems with surface irrigation operation included: too wide of border widths, too long of field lengths, allowing spill water to discharge from the end of the field for extended lengths of time, and irrigating more borders than the size of stream allowed. Efficiencies can be improved with surface irrigation systems by: shortening border widths and field lengths, minimizing tail water discharge, and irrigating only the number of borders that the irrigation water can cover in a reasonable time.

Under-irrigation. Under-irrigation was defined as any time during the growing season that the available soil moisture in the top 1 m of the soil profile dropped below 50 percent. Under-irrigation often occurred at the start and end of the growing season, before irrigation had started for the season, or when the field was being dried down for harvest (Fig. 9). Another factor that contributed to the number of under irrigations is that a soil profile depth of 1 m was used as the monitoring depth. After seeding, the top 0.50 m or less of the root zone may have had sufficient moisture for germination, but the available moisture of the deeper soil zone was below 50 percent. In Fig. 10, the top 0.40 m of the profile had sufficient moisture but the total available moisture for the entire 1 m root zone was below 50 percent and would have been considered an under-irrigation.

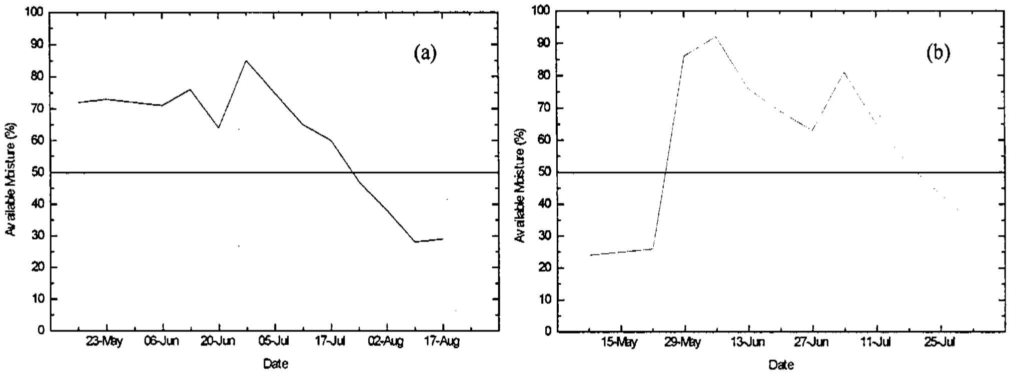

Fig. 9. a) Wheat field under center pivot irrigation and b) barley field under wheel-move.

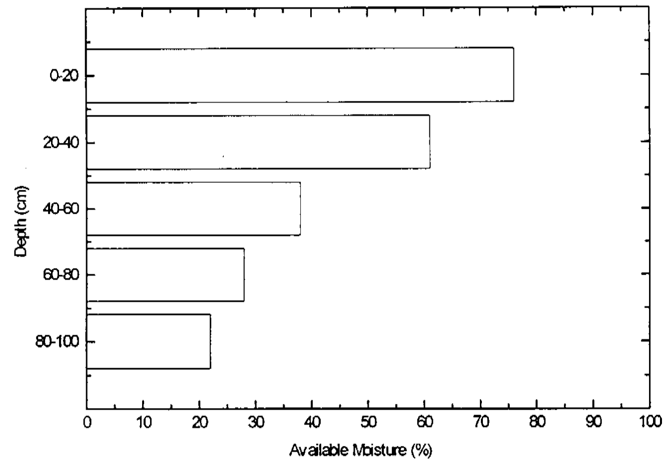

Fig. 10. Soil moisture profile of a wheat field under center pivot irrigation, May 15, 2000.

Effect of irrigation training. On average, irrigators with previous AIM training were rated as doing a good job more frequently than irrigators without formal training. However, 88 percent of previously trained irrigators operated center pivots. Irrigation management is different for a center pivot system than it is for wheel-move and is certainly different from surface irrigation. With surface irrigation, and to a lesser degree with wheel-move, the entire root zone is filled to field capacity or above and then slowly depleted from the soil surface downward as the crop uses the stored soil moisture for transpiration. This management necessitates a larger application amount per irrigation and fewer irrigations during the growing season compared to fields irrigated using center pivot systems.

Center pivot irrigation systems are not designed to fill the root zone to field capacity with each application, but rather to supply smaller applications more frequently. Therefore, after each irrigation application, only the top part of the root zone is at field capacity and the lower soil profile is somewhat below field capacity. In order to meet peak crop water demands, center pivot irrigators must build up soil moisture reserves early in the spring so that additional moisture will be available later in the season when plants require it. Irrigators using center pivot irrigation systems benefit from having knowledge about the water holding characteristics of their soils, as well as the operational parameters of their irrigation systems.

Simulated irrigation requirements. In this study, the purpose of simulating crop water and irrigation applications at "optimum" levels was to gain some insight as to what might be expected if a high level of irrigation management was practiced. This comparison also provided the opportunity to contrast actual crop water use values and irrigation amounts to simulated values for the purpose of identifying areas where water requirements might be expected to increase in the future. In order to maximize the benefit of such a comparison, the difference between observed and simulated values was evaluated to determine whether it would be reasonable to expect crop water use to increase to the levels suggested by the simulations.

Table 8 contains the average deficit between simulated and measured crop water use and irrigation amounts for each crop. Alfalfa represents the largest difference, while sugar beets represent the smallest difference. The difference between simulated and observed crop water use would suggest that more water is required from irrigation, precipitation, or stored soil moisture. This table can be used in conjunction with Fig. 5 to identify areas where crop consumptive use may increase. For instance, if the simulated values in Fig. 5 represent an achievable target, we would expect that a percentage of the irrigators would actually meet or exceed the simulated values, given the random field selection procedures used. The percentage of irrigators expected to surpass these results would likely vary according to the irrigation management difficulty level of that crop and the value of that crop. In other words, if only a few irrigators met or exceeded the simulated results, then it could be concluded that the simulated values were not an achievable target. On the other hand, if an abnormally high proportion of irrigators met or exceeded the demand then perhaps the simulated values were too low. From examination of alfalfa in Fig. 5, only six of the irrigators could meet the simulated demand. Conversely, 41 percent met the simulated water use for sugar beets. As for the other crops, 14, 18, and 25 percent of wheat, canola, and barley fields, respectively, met simulated values. From this analysis, it appears that target levels may be unattainable for alfalfa, and may perhaps be too low for sugar beets.

Table 8. Difference in water requirements as predicted by simulated and measured results.

	Alfalfa	Barley	Barley Silage	Canola	Sugar Beets	Wheat
Crop Water Use (mm)	144	37	37	56	11	64
Irrigation Application (mm)	192	87	101	124	38	125

The simulated irrigation application values exceeded measured values by a considerable amount for all crops except sugar beets (Table 8). The differences in simulated vs. measured irrigation application numbers are larger than those of crop water use. Under the "optimum" conditions modeled, soil moisture was brought up to 70 percent of available at the end of the growing season, whereas many of the fields monitored were allowed to dry to below 50 percent of available moisture.

Measured crop water use was closer to simulated crop water use in some locations than in others (Fig. 6). This may be due to differences in system types, crop mixes, common practices, or the ability of the model to accurately simulate the requirements of a particular area.

Some of the differences in system types that may have affected the results of this study were that Brooks had all of the surface irrigation fields, and the majority of the wheel-move fields were found in Brooks and Lethbridge. Center pivot irrigation was the major system type monitored in the other areas.

Some areas in the study may have had a larger proportion of a certain crop that came closer to meeting simulated values. For example, all of the sugar beet fields were in Bow Island, Taber and Lethbridge. Given that measured values were very close to simulated values for this crop, the average values for the entire area would be influenced.

Common irrigation practices may also be very different in each area of the study. Areas that receive more precipitation may view irrigation as supplemental to precipitation, or may withhold irrigation due to concerns of disease or field trafficability issues. These situations are not always avoidable, and cannot be accurately simulated.

The other relevant factor is that the computer model used may better simulate growing conditions in one area versus another. The crop coefficients for the LRSIMM computer model were developed and validated in the Lethbridge and Vauxhall areas. There is some evidence to suggest that it performed better in these geographical areas than it did in the Brooks and Strathmore areas. Jensen et al. (1990) suggest adjustments may be necessary to account for local variations in crop development and correction factors may have to be used to adjust the evapotranspiration equation for local conditions. Burman (1994) cautions that conditions should be the same or similar at the location of development of the calibrated evapotranspiration equation and crop coefficients as at the location of application. For the Strathmore district, the difference between the simulated optimum and the measured amounts for both crop water use and irrigations were higher than the other districts. This may be the result of the model over-estimating crop water use in this area.

CONCLUSIONS

The intent of this project was to collect information on actual crop water use, irrigation application amounts, and on-farm irrigation management practices throughout southern Alberta. Computer simulation of crop water demand was used to predict how water requirements might change if on-farm water management levels were to increase.

Of the crops monitored, alfalfa and sugar beets were the highest water users and required an average of 500 mm of water per growing season for evapotranspiration. Grain and oilseed crops were very similar in their annual water use, averaging 310 to 360 mm.

Irrigation application amounts were the highest for alfalfa and sugar beets. In all districts, except Strathmore, crop water requirements were primarily fulfilled by irrigation, with minor contributions from precipitation and stored soil moisture. In the Strathmore area, precipitation made up 60 percent of crop water requirements while irrigation contributed 39 percent.

Irrigation application amounts were highest for surface irrigation systems, followed by center pivots, and then wheel-move systems. Accordingly, irrigation application amounts should decrease in some districts as surface irrigation systems are converted to sprinkler systems. In all districts, an increase in irrigation application amounts would be expected if more irrigators convert to center pivot irrigation systems.

Over-irrigation was a problem observed with all surface-irrigated fields, 34 percent of wheel-move irrigated fields, and 11 percent of center-pivot irrigated fields. In the majority of cases, over-irrigation was due to operator error.

An additional 55 mm would be required on 70 percent of the fields monitored to avoid under-irrigation during the growing season, but not all under-irrigation situations were avoidable. Application efficiencies of surface irrigated fields ranged from 0.20 to 0.51. These low ratios are primarily a consequence of the method of irrigation. Efficiencies can be improved marginally with operational and/or design changes, but conversion of surface systems to pivot or other sprinkler type systems will improve the on-farm and irrigation district efficiencies.

Irrigation training has been shown to be beneficial to irrigation management, particularly with center pivot systems. Irrigation scheduling should be based as much as possible on root zone soil moisture, and training for irrigators should emphasize the need to monitor soil moisture to avoid under-irrigation. Producers should have a good understanding of water requirements for the crops grown, the application rates of their irrigation systems, and the hydraulic properties of their soils.

Computer simulations of crop water requirements indicate that crop water use would increase if a higher level of irrigation management were practiced. Measured crop water use of all crops was 84 percent of that simulated by the model. The average deficit of measured crop water use compared to simulated crop water use was 58 mm. It is felt that the simulated crop water use estimates for most crops were reasonable, with the exception of alfalfa, which was over-estimated; and sugar beet, which was under-estimated.

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APPENDIX A

Climate Information

Table A1. Measured and long-term normal (LTN), monthly temperature and precipitation for each location.

		May		June		July		August		September		
		Temp.	**Ppt.**	**Temp**	**Ppt**	**Temp**	**Ppt**	**Temp**	**Ppt**	**Temp**	**Ppt**	**Total Ppt**
Bow Island	1996	10.3	29.0	17.7	31.0	19.9	28.0	20.4	11.0	12.4	76.2	175
	1997	13.0	42.0	16.9	49.0	19.2	11.0	19.6	23.0	16.8	8.0	133
	1998	15.4	29.0	15.9	109.0	21.9	21.0	21.8	15.0	16.6	21.0	195
	1999	10.4	43.0	14.6	95.0	16.5	30.0	19.1	36.0	12.1	4.0	208
	2000	11.9	8.0	15.4	51.0	20.6	11.0	18.9	16.0	13.0	27.0	113
	LTN	11.4	43.0	16.1	62.0	18.8	35.0	18.3	36.0	12.3	36.0	212
Brooks	1996	9.2	28.0	16.4	42.0	19.0	19.0	19.7	38.0	11.5	65.0	192
	1997	13.4	42.0	16.6	39.0	18.8	12.0	18.6	43.0	14.7	9.0	143
	1998	13.8	21.0	15.3	100.0	21.0	30.0	20.4	9.0	15.0	16.0	176
	1999	10.1	40.0	14.3	115.0	16.2	110.0	18.2	47.0	11.8	2.0	315
	2000	11.3	13.0	15.0	29.0	20.2	3.0	18.3	31.0	11.8	24.0	100
	LTN	11.4	39.0	15.9	65.0	18.4	38.0	17.5	37.0	11.6	38.0	217
Lethbridge	1996	11.5	8.1	15.7	52.9	18.4	17.3	19.6	4.8	11.1	70.0	153
	1997	11.4	95.7	15.9	100.6	18.1	31.8	18.5	32.8	15.8	7.6	269
	1998	13.7	53.0	14.4	148.0	20.3	57.0	20.1	36.0	16.0	14.0	308
	1999	10.3	58.0	14.5	65.0	16.4	64.0	18.7	39.0	12.8	6.0	232
	2000	12.1	11.0	15.4	45.0	19.8	6.0	18.7	27.0	13.1	42.0	131
	LTN	11.1	55.0	15.6	74.0	18.1	43.0	17.4	42.0	11.9	40.0	254
Medicine Hat	1996	9.3	27.0	16.0	62.0	18.8	23.0	19.7	14.0	11.4	46.0	172
	1997	11.4	22.0	17.7	68.0	18.9	5.0	19.2	40.0	16.4	7.0	142
	1998	13.9	35.0	14.8	142.0	21.5	65.0	21.3	19.0	16.1	19.0	280
	1999	10.4	38.0	14.7	59.0	16.7	36.0	19.0	21.0	11.6	6.0	160
	2000	12.2	23.0	15.4	43.0	20.9	10.0	19.4	12.0	13.2	18.0	106
	LTN	12.5	45.0	16.7	60.0	19.4	42.0	18.8	32.0	12.9	37.0	216

Table A1 (cont'd). Measured and long-term normal (LTN), monthly temperature and precipitation for each location.

		May		June		July		August		September		
		Temp.	**Ppt.**	**Temp**	**Ppt**	**Temp**	**Ppt**	**Temp**	**Ppt**	**Temp**	**Ppt**	**Total Ppt**
Strathmore	1996	7.8	20.0	13.9	46.0	17.4	26.0	16.5	32.0	10.6	47.0	171
	1997	10.1	54.0	14.6	49.0	16.6	14.0	16.6	26.0	13.5	54.0	197
	1998	13.3	30.0	14.1	88.0	19.4	52.0	19.0	42.0	13.9	18.0	230
	1999	9.5	80.0	13.1	114.0	14.5	68.0	16.8	45.0	11.0	8.4	315
	2000	8.2	19.0	11.8	34.0	16.1	36.0	14.9	41.0	9.4	56.0	186
	LTN	10.1	46.0	12.8	72.0	16.1	53.0	16.1	51.0	11.8	36.0	258
Taber	1996	9.5	23.0	16.6	41.0	19.4	15.0	19.7	3.0	11.6	61.0	143
	1997	12.2	51.0	16.4	73.0	18.7	8.0	19.1	26.0	16.4	3.0	161
	1998	14.3	37.0	14.8	138.0	21.0	42.0	21.2	11.0	16.2	7.0	235
	1999	10.6	41.0	14.7	124.0	16.9	46.0	19.0	40.0	13.0	4.0	255
	2000	12.5	11.0	15.9	47.0	20.4	2.0	18.7	12.0	13.1	31.0	103
	LTN	11.6	43.0	16.0	62.0	18.8	36.0	18.2	40.0	12.6	38.0	219

Table A2. Corn heat units (CHU) and frost free period (FFP) (days), as compared to long-term normal (LTN) values.

	1996		1997		1998		1999		2000		LTN	
	CHU	**FFP**	**CHU**	**FFP**	**CHU**	**FFP**	**CHU**	**FFP**	**CHU**	**FFP**	**CHU**	**FFP**
Bow Island	2566	137	2447	133	2899	155	2292	126	2439	120	2505	127
Brooks	2421	144	2388	133	2733	150	2217	128	2331	136	2256	124
Lethbridge	2295	135	2327	133	2797	154	2300	136	2401	136	2294	117
Medicine Hat	2337	136	2433	129	2938	156	2298	135	2620	137	2532	140
Taber	2635	136	2727	168	2977	181	2270	139	2475	136	2359	145
Strathmore	2001	104	2258	119	2562	150	1926	138	1648	101	1993	112

APPENDIX B

Irrigation Requirements

Table B1. Average measured and modeled crop water use amounts (mm).

		1996			1997			1998			1999			2000		
	Crop	**Meas.**	**Mod.**	**Ratio**	**Meas.**	**Mod.**	**Ratio**	**Meas.**	**Mod.**	**Ratio**	**Meas.**	**Mod.**	**Ratio**	**Meas.**	**Mod.**	**Ratio**
Bow Island	Alfalfa	597	726	82%	594	640	93%	662	703	94%	565	609	93%	556	648	86%
	Barley	307	370	83%	401	375	107%	361	382	95%	-	-	-	-	-	-
	Barley Silage	-	-	-	-	-	-	-	-	-	-	-	-	261	308	85%
	Canola	394	429	92%	352	405	87%	367	415	88%	358	353	101%	322	402	80%
	Soft Wheat	402	466	86%	421	431	98%	453	459	99%	-	-	-	-	-	-
	Sugar Beets	558	558	100%	503	548	92%	573	562	102%	539	492	110%	607	524	116%
	Wheat	-	-	-	399	440	91%	362	455	80%	415	415	100%	375	440	85%
	All	467	525	89%	452	487	93%	463	497	93%	458	457	100%	418	467	90%
Brooks	Alfalfa	334	500	67%	390	658	59%	522	696	75%	456	654	70%	560	619	90%
	Barley	329	342	96%	266	348	76%	286	369	78%	-	-	-	339	338	100%
	Barley Silage	248	324	77%	-	-	-	-	-	-	-	-	-	-	-	-
	Canola	328	389	84%	309	417	74%	235	431	55%	-	-	-	-	-	-
	Soft Wheat	-	-	-	-	-	-	322	420	77%	-	-	-	-	-	-
	Wheat	401	440	91%	283	419	68%	-	-	-	327	376	87%	385	397	97%
	All	345	413	84%	313	469	67%	366	494	74%	382	495	77%	391	404	97%
Lethbridge	Alfalfa	456	588	78%	360	643	56%	456	705	65%	434	648	67%	605	653	93%
	Barley	-	-	-	-	-	-	246	366	67%	377	375	101%	336	357	94%
	Barley Silage	296	323	92%	372	339	110%	261	360	73%	-	-	-	261	278	94%
	Canola	215	362	59%	365	391	93%	313	422	74%	409	388	105%	308	370	83%
	Soft Wheat	317	427	74%	378	444	85%	-	-	-	-	-	-	-	-	-
	Sugar Beets	571	506	113%	414	518	80%	463	578	80%	472	490	96%	532	494	108%
	Wheat	-	-	-	-	-	-	385	459	84%	399	428	93%	-	-	-
	All	404	468	86%	376	487	77%	361	502	72%	414	467	89%	425	449	95%
Medicine Hat	Alfalfa	495	685	72%	521	571	91%	659	764	86%	515	614	84%	649	688	94%
	Barley	334	343	97%	229	210	109%	-	-	-	-	-	-	312	383	81%
	Barley Silage	277	294	94%	-	-	-	-	-	-	-	-	-	-	-	-
	Canola	357	386	92%	386	344	112%	416	463	90%	374	382	98%	411	428	96%
	Soft Wheat	386	440	88%	355	368	96%	-	-	-	-	-	-	-	-	-
	Wheat	394	421	94%	468	375	125%	408	491	83%	432	400	108%	446	465	96%
	All	387	454	85%	416	414	100%	505	583	87%	439	459	96%	511	547	93%

Table B1 (cont'd). Average measured and modeled crop water use amounts (mm).

		1996			1997			1998			1999			2000		
	Crop	**Meas.**	**Mod.**	**Ratio**	**Meas.**	**Mod.**	**Ratio**	**Meas.**	**Mod.**	**Ratio**	**Meas.**	**Mod.**	**Ratio**	**Meas.**	**Mod.**	**Ratio**
Strathmore	Alfalfa	335	513	65%	301	455	66%	486	712	68%	392	582	67%	397	533	74%
	Barley	276	389	71%	262	240	109%	313	349	90%	-	-	-	254	340	75%
	Barley Silage	273	365	75%	257	222	116%	255	351	73%	288	306	94%	321	306	105%
	Canola	258	386	67%	255	269	95%	277	404	69%	275	376	73%	216	338	64%
	Wheat	269	431	62%	261	314	83%	326	451	72%	307	405	76%	212	378	56%
	All	288	425	68%	271	326	83%	344	485	71%	332	458	72%	284	408	70%
Taber	Alfalfa	434	691	63%	473	699	68%	588	739	80%	499	649	77%	583	704	83%
	Barley	404	410	99%	-	-	-	-	-	-	283	349	81%	-	-	-
	Canola	353	428	82%	304	360	84%	357	379	94%	299	377	79%	367	435	84%
	Soft Wheat	350	462	76%	327	397	82%	328	435	75%	413	434	95%	358	465	77%
	Sugar Beets	530	544	97%	495	498	99%	579	576	101%	394	495	80%	534	545	98%
	Wheat	357	465	77%	-	-	-	332	403	82%	346	413	84%	360	449	80%
	All	396	509	78%	424	506	84%	449	514	87%	387	477	81%	407	487	84%
All Offices	Alfalfa	443	607	73%	428	604	71%	561	721	78%	472	624	76%	562	636	88%
	Barley	324	369	88%	282	311	91%	309	370	84%	386	366	105%	322	350	92%
	Barley Silage	277	332	83%	334	300	111%	257	354	73%	293	306	96%	281	297	95%
	Canola	327	401	82%	326	351	93%	337	420	80%	350	376	93%	332	397	84%
	Soft Wheat	370	452	82%	376	401	94%	345	436	79%	413	434	95%	358	465	77%
	Sugar Beets	557	534	104%	474	518	92%	549	573	96%	455	493	92%	554	525	106%
	Wheat	377	442	85%	330	393	84%	365	450	81%	381	401	95%	350	424	83%
	All	380	473	80%	373	447	83%	412	511	81%	407	468	87%	406	462	88%

Table B2. Average measured and modeled irrigation amounts (mm).

		1996			1997			1998			1999			2000		
	Crop	**Meas.**	**Mod.**	**Ratio**	**Meas.**	**Mod.**	**Ratio**	**Meas.**	**Mod.**	**Ratio**	**Meas.**	**Mod.**	**Ratio**	**Meas.**	**Mod.**	**Ratio**
Bow Island	Alfalfa	406	565	72%	408	525	78%	377	525	72%	327	463	71%	546	550	99%
	Barley	173	300	58%	270	275	98%	150	258	58%	-	-	-	-	-	-
	Barley Silage	-	-	-	-	-	-	-	-	-	-	-	-	149	275	54%
	Canola	270	338	80%	229	325	70%	178	313	57%	181	238	76%	181	325	56%
	Soft Wheat	231	344	67%	244	325	75%	174	275	63%	-	-	-	-	-	-
	Sugar Beets	403	380	106%	326	400	82%	281	375	75%	294	313	94%	501	425	118%
	Wheat	-	-	-	233	358	65%	164	275	60%	201	250	80%	254	407	62%
	All	297	385	77%	285	368	77%	221	337	66%	251	316	79%	326	396	82%
Brooks	Alfalfa	222	431	52%	232	544	43%	325	579	56%	231	409	56%	299	573	52%
	Barley	156	263	59%	118	243	49%	89	179	50%	-	-	-	239	328	73%
	Barley Silage	154	195	79%	-	-	-	-	-	-	-	-	-	189	311	61%
	Canola	173	384	45%	212	375	57%	181	276	66%	-	-	-	-	-	-
	Soft Wheat	-	-	-	-	-	-	128	231	55%	-	-	-	-	-	-
	Wheat	277	388	71%	179	342	52%	-	-	-	98	178	55%	258	378	68%
	All	196	332	59%	185	376	49%	181	316	57%	165	294	56%	246	397	62%
Lethbridge	Alfalfa	307	481	64%	174	603	29%	142	450	32%	206	527	39%	382	379	101%
	Barley	-	-	-	-	-	-	129	225	57%	142	233	61%	289	385	75%
	Barley Silage	163	305	53%	172	261	66%	25	150	17%	-	-	-	240	279	86%
	Canola	45	410	11%	237	348	68%	37	175	21%	214	313	68%	435	507	86%
	Soft Wheat	224	372	60%	222	300	74%	-	-	-	-	-	-	-	-	-
	Sugar Beets	388	396	98%	274	417	66%	124	300	41%	308	360	86%	156	294	53%
	Wheat	-	-	-	-	-	-	112	150	75%	173	275	63%	-	-	-
	All	225	393	57%	216	386	56%	95	242	39%	209	342	61%	300	369	81%
Medicine Hat	Alfalfa	277	550	50%	324	457	71%	369	608	61%	205	483	42%	516	617	84%
	Barley	131	150	87%	114	150	76%	-	-	-	-	-	-	179	325	55%
	Barley Silage	178	275	65%	-	-	-	-	-	-	-	-	-	-	-	-
	Canola	212	325	65%	200	240	83%	156	308	51%	255	242	105%	303	358	85%
	Soft Wheat	245	350	70%	173	238	73%	-	-	-	-	-	-	-	-	-
	Wheat	225	325	69%	319	275	116%	133	313	42%	185	219	84%	276	375	74%
	All	211	329	64%	228	272	84%	219	410	53%	215	315	68%	318	419	76%

Table B2 (cont'd). Average measured and modeled irrigation amounts (mm).

		1996			1997			1998			1999			2000		
	Crop	Meas.	Mod.	Ratio	Meas.	Mod.	Ratio	Meas.	Mod.	Ratio	Meas.	Mod.	Ratio	Meas.	Mod.	Ratio
Strathmore	Alfalfa	165	405	41%	126	400	32%	229	508	45%	75	308	24%	259	388	67%
	Barley	79	325	24%	102	175	58%	59	150	39%	-	-	-	222	288	77%
	Barley Silage	87	275	32%	86	125	69%	105	200	53%	39	50	78%	197	250	79%
	Canola	81	363	22%	139	325	43%	48	242	20%	13	63	21%	104	238	44%
	Wheat	61	400	15%	114	325	35%	84	275	31%	22	250	9%	94	344	27%
	All	95	354	27%	113	270	42%	105	275	38%	37	168	22%	175	301	58%
Taber	Alfalfa	340	588	58%	308	525	59%	364	613	59%	294	475	62%	460	600	77%
	Barley	196	275	71%	-	-	-	-	-	-	138	200	69%	-	-	-
	Canola	222	313	71%	172	216	80%	109	185	59%	93	225	41%	248	438	57%
	Soft Wheat	214	338	63%	202	250	81%	111	300	37%	199	250	80%	236	463	51%
	Sugar Beets	357	350	102%	328	296	111%	331	425	78%	232	300	77%	380	458	83%
	Wheat	187	350	53%	-	-	-	172	273	63%	82	258	32%	252	449	56%
	All	253	369	69%	253	322	79%	217	359	60%	173	285	61%	315	482	65%
All Offices	Alfalfa	286	503	57%	264	509	52%	301	547	55%	223	444	50%	410	518	79%
	Barley	147	263	56%	151	211	72%	107	203	53%	140	217	65%	232	331	70%
	Barley Silage	146	263	56%	129	193	67%	65	175	37%	39	50	78%	194	279	70%
	Canola	167	356	47%	198	305	65%	118	250	47%	151	216	70%	254	373	68%
	Soft Wheat	229	351	65%	210	278	76%	138	269	51%	199	250	80%	236	463	51%
	Sugar Beets	383	375	102%	309	371	83%	245	367	67%	278	324	86%	346	392	88%
	Wheat	188	366	51%	211	325	65%	133	257	52%	127	238	53%	227	391	58%
	All	213	360	59%	213	332	64%	173	323	54%	175	286	61%	280	394	71%

APPENDIX C

Definition of Terms

Active root zone: Depth of soil that contains roots: is limited to 2.0 m for alfalfa and 1.0 m for other crops.

Delivery problem: A loss-of-time problem that occurs as a result of something outside of the irrigator's control, e.g. irrigation district could not deliver water, energy company had a problem, lack of water in a river system.

Excess water: Water added to the site, not including irrigation applications, that increases the soil moisture content above field capacity, e.g. rainfall, breached ditch bank.

High water table: Occurs when the water table is within 2.0 m of the surface for alfalfa fields or within 1.0 m of the surface for all other fields.

Irrigation: The amount of water, applied through an irrigation system, which is measured in a rain gauge at plant canopy level.

Measured seasonal consumptive use: Irrigation + precipitation – excess water (runoff, deep percolation) ± (change in soil moisture).

Operation problem: A loss-of-time problem that occurs as a result of poor management by the producer, e.g. poor timing, long sets.

Over-irrigation: Water added, through the irrigation system, which increases the soil moisture content of the field (site) above field capacity.

Simulated irrigation: LRSIMM computer simulation using actual rainfall amounts collected in the field and manually inputting irrigations whenever the available moisture drops to 70% for pivots and 50% for wheel- and flood-irrigated fields.

System problem: A loss-of-time problem that occurs as a result of an under designed systems, incorrect nozzle package, or mechanical breakdown.

Under-irrigation: Occurs when the available soil moisture level drops below 50% in the active root zone.

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
	1.0 kilometre (km)	=	0.621 miles
Volume:	1.0 cubic metre (m^3)	=	35.315 cubic feet
	1.0 cubic decametre (dam^3)	=	0.811 acre feet
Rate of Flow:			
	1.0 cubic metre per second (m^3/s)	=	35.315 cubic feet per second
Yield:			
	1.0 kilogram per hectare (kg/ha)	=	0.893 pounds per acre
	1.0 tonne per hectare (t/ha)	=	0.446 tons per acre