Modelling irrigation strategies to minimize deep drainage for two different climatic regions of Canada

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Abstract

Irrigation is a vital part of agriculture in certain regions of Canada including the interior of British Columbia. In this study we examined the use of a soil water budget model for efficient irrigation management in two contrasting climatic regions of British Columbia: Abbotsford (AD) and Osoyoos (OS). The average annual precipitation at AD and OS are 1573 and 318 mm, respectively. The soil types (AD – silt loam and OS – sand) and major crops (AD – raspberry and OS – apple) are also quite different between the two regions. We used the Simultaneous Heat and Water (SHAW) model to estimate the amount of deep drainage and soil water content under different irrigation management strategies. The SHAW model integrates detailed physics of vegetative cover, snow, residue and soil into one simultaneous solution. The model was run on a daily basis for 28 and 32 years for AD and OS regions, respectively. Different combinations of crop and irrigation conditions were run for each region. Based on this study, the "best" irrigation management strategy involves triggering every irrigation event when the soil water content (estimated by SHAW) in crop's rooting zone reaches a prescribed amount below field capacity. At that time, 40 mm of irrigation is added as rainfall. Other strategies involved adding more irrigation and a constant weekly irrigation regardless of rainfall and soil water content. In conclusion, while most of deep drainage in the dormant seasons (no irrigation) cannot be controlled, it can be well controlled to a minimum level in the growing seasons by "best" irrigation management practice.

Keywords: irrigation modelling, minimize drainage, Canadian conditions.

WIT Transactions on Ecology and the Environment, Vol 112, © 2008 WIT Press
www.witpress.com, ISSN 1743-3541 (on-line)
doi:10.2495/SI080181

1 Introduction

Irrigation of field crops is required in certain regions of Canada to maintain consistent crop yield and quality. In the province of British Columbia (BC), approximately 190,000 hectares were under irrigation in 1995 [1]. Forage crops were grown on about 85% of the irrigated land with tree fruits, vegetables, and berries together comprising about 11%. The focus of this study is on a tree fruit (apple) and a berry (raspberry) as they are high-value, intensively grown crops.

Water-use efficiency (WUE) is an important consideration in terms of designing an irrigation management system. In fact, improving agricultural WUE is a key element in coping with future water demands [2]. Excessive irrigation has been cited as a possible contributing factor to elevated levels of nitrate in some domestic wells in the two regions of BC selected for this study (Abbotsford, AD and Osoyoos, OS) [3]. The goal of this study was to investigate WUE for these two regions of BC using a model to estimate the relative amount of drainage under various irrigation management strategies. The "best" irrigation scheduling strategy is assumed to minimize the amount of drainage yet still provide sufficient available soil water for plant growth.

The Simultaneous Heat and Water (SHAW) model is a one-dimensional physical-process model, which simulates detailed heat and water movement through the vegetative cover, snow, residue cover and soil [4]. The model enables detailed simulation of water and energy flux at the atmospheric-soil interface and within the soil profile, and includes the effects of vegetation, snow, crop residue cover and soil freezing. It has been used for many applications including estimating soil water budgets and temperatures, snowmelt dynamics, components of net all wave radiation, and timing manure application [5–8]. To our knowledge, it has never been used to assess WUE of different irrigation management strategies. The SHAW model was chosen for this study as it is physically-based and includes the effects of freezing and thawing processes on water movement, which is an important selection criterion for non-growing season conditions in most of Canada.

The main objective of this study was to use the SHAW model to estimate the amount of drainage under efficient and less-efficient irrigation management systems for two vastly different climatic regions of British Columbia, Canada.

1.1 Background information

The location and climate normals for the two study sites (AD: 49°02' N, 122°22' W, 59 m a.s.l.; OS: 49°02' N, 119°26' W, 297 m a.s.l.) are given in Table 1. As discussed previously these two sites were chosen because of their vastly different climatic regimes yet irrigation of intensively-grown crops is a common practice in both regions. The average annual precipitation at AD is nearly five times that at OS; however, due to relatively low amount of summer rainfall, irrigation is still generally required at AD. The average annual temperature at the two sites is essentially the same even though summer and winter season temperatures are normally higher and lower, respectively at OS. These differences in precipitation, and to a lesser extent temperature, should lead to significant differences in the amounts of drainage even without irrigation for the two regions; the SHAW model results will confirm\deny this hypothesis.

Table 1: A comparison of some monthly climate normals for 1971–2000 for the two study sites.

Month	Precipitation (mm)		Average Daily Temperature (ºC)	
	Abbotsford	Osoyoos	Abbotsford	Osoyoos
January	198	28	2.6	-2.1
February	160	26	4.7	1.1
March	146	23	6.8	6
April	120	24	9.5	10.8
May	99	37	12.5	15.1
June	79	36	15.1	18.7
July	50	24	17.5	21.7
August	49	21	17.7	21.3
September	76	16	15	16.2
October	145	17	10.2	9.8
November	241	32	5.7	3.5
December	209	34	2.8	-1.2
Average Annual	1573	318	10.0	10.1

2 Methodology

Estimates of deep drainage under different irrigation management strategies and a control were determined using the SHAW model. The control model runs were completed under local soil and climatic conditions with no crop planted and zero irrigation applied. The first irrigation management strategy (I40) was designed to minimize the amount of drainage yet maintain enough available soil water to sustain the crop grown in each region. For both regions, 40 mm (roughly equal to the amount of available water in the top 100 cm of each soil profile assuming a reasonable deficit coefficient) of irrigation was applied as additional daily rainfall when the soil water content decreased to a prescribed level as estimated by the SHAW model under a raspberry crop at AD and apple trees at OS. Soil volumetric water contents of 0.15 and 0.10 triggered irrigation at AD and OS, respectively. Irrigation increased the soil water content to about 0.19 and 0.15 in the respective regions, which are slightly below field capacity of the two local soils providing good growing conditions while presumably minimizing drainage losses. As a test of the efficiency of I40 a second strategy (I60) was tested for the AD region only by adding 60 mm to the rainfall input file of SHAW instead of 40 mm when irrigation was required according to the model estimate of soil water content as discussed previously. A third irrigation strategy was tested only in the semi-arid OS region; this strategy (IW40) applied 40 mm of irrigation to the apple trees each week regardless of the soil water content.

The main inputs to the SHAW model include: initial soil temperature and water content profiles, daily weather conditions, and parameters describing the vegetative cover, snow, plant residue and soil. General site information includes slope, aspect, latitude, and surface roughness parameters. Plant residue or litter properties include residue loading, thickness of the residue layer, percent cover and albedo. Input soil parameters are dry bulk density, saturated hydraulic conductivity, coefficients for the matric potential-water content relation, and the albedo-water content relation. Some of the physical properties of the soils selected to represent the two study regions are given in Table 2.

Table 2: Select soil physical properties used in the SHAW model to represent local soils at the two study regions.

Depth (cm)	Texture		% Clay		% Silt		% Sand		% OM		WP		FC	
	AD	OS	AD	OS	AD	OS	AD	OS	AD	OS	AD	OS	AD	OS
0-20	SiL	Lsa	15	10	65	6	20	84	1.0	1.0	0.11	0.09	0.30	0.18
20-50	SiL	Sa	15	10	65	6	20	84	0.5	0.5	0.11	0.09	0.28	0.16
50-B	Sa	Lsa	6	6	4	4	90	90	0	0	0.06	0.06	0.15	0.12

Depth (cm)	ASWC		Porosity		BD		AE (cm)		PSDI		Ksat	
	AD	OS	AD	OS	AD	OS	AD	OS	AD	OS	AD	OS
0-20	19	8.8	0.53	0.41	1.21	1.50	-47	-18	3.60	4.08	16	3.9
20-50	17	7.6	0.46	0.39	1.37	1.56	-48	-14	3.86	4.11	1.6	2.6
50-B	9.4	5.9	0.41	0.40	1.52	1.52	-18	-18	2.97	2.97	10.9	10.9

AD = Abbotsford; OS = Osoyoos; Lsa = loamy sand; Sa = sand; SiL = silt loam; OM = organic matter; WP = wilting point; FC = field capacity; ASWC = available soil water content (cmm^{-1}); BD = bulk density (gcm^{-3}); AE = air-entry pressure head (cm); PSDI = pore-size distribution index; Ksat = saturated hydraulic conductivity ($cmhr^{-1}$). B = 150 cm for Abbotsford and 200 cm for Osoyoos.

The SHAW model does not have an independent crop-growth module; it requires crop growth information as part of the input data set. The relevant crop-growth information for raspberry and apple crops grown at AD and OS, respectively as used in the SHAW model for this study are listed in Table 3. The daily climate data including maximum and minimum air temperatures, dew-point temperature, total wind run, precipitation, and sunshine hours (converted to solar radiation using the method given in [9]) were obtained from Environment Canada for the two regions. Climate data were available from 1971–1998 for AD and 1968–1999 for OS.

3 Results and discussion

3.1 Abbotsford (AD) Region

Table 4 gives average annual estimates of the water balance from SHAW for the AD region under different irrigation management strategies. Of the 351 mm of irrigation that is applied under the I40 system, it appears that only about 15% was lost as drainage increased by an average of 55 mm over the Control system.

Table 3: Crop-growth information used in this study as input for SHAW model for Osoyoos (OS) and Abbotsford (AD).

OS.

Stage of Development	Time Period	Dry biomass (kg/m^2)	LAI	Rooting Depth (m)
Initial	Apr 15 – May 5	1.0	0 - 1.0	1.0
Crop development	May 6 – Jun 24	1.0-1.5	1.0 - 2.0	1.0
Mid-season	Jun 25 – Sep 22	2.0	2.0	1.0
Late-season 1	Sep 22 – Oct 12	2.0-1.5	2.0 - 1.5	1.0
Late-season 2	Oct 13 - Nov 15	1.5-1.0	1.5 - 0	1.0

AD.

Day of year	Height (m)	Leaf width (cm)	Dry Biomass (kg/m^2)	LAI	Rooting depth (m)
91	1	0	1.3	0	1.0
120	1.5	6	1.9	3	1.0
165	2	6	2.7	4	1.0
193	2	6	3.7	4	1.0
212	2	6	3.4	4	1.0
227	2	6	3.2	4	1.0
262	2	6	2.6	2.5	1.0
273	2	6	2.4	2	1.0
319	1.5	0	1.9	0	1.0

LAI = leaf-area index.

On the other hand, on average, all of the increase in irrigation applied under system I60 was lost to drainage as estimated by SHAW. The average annual amount of evapotranspiration remained essentially the same for I40 and I60 suggesting that the additional irrigation applied under I60 did not increase plant growth.

The year-to-year variability is greatest for runoff (coefficient of variation > 100%); in fact the annual estimate of runoff ranges from 0 to 209 mm. The coefficient of variation for drainage is about 23% only slightly higher than precipitation at 16%; however, there is enough year-to-year variability to warrant caution when using long-term estimates of average drainage to guide water resource policy development for example (Figure 1). For every modelled year the SHAW-estimated drainage for I60 exceeds I40. As well, data shown in Figure 1 suggests that there is a reasonably strong correlation between annual precipitation and drainage. Since drainage is difficult to measure in the field it may be useful to be able to estimate it based on the annual amount of precipitation. Figure 2 shows that over 80% of the variability in annual drainage estimated by SHAW is explained by variability in annual precipitation, which suggests this simple approach to estimating annual drainage may be viable for the AD region.

Table 4: Summary of average (standard deviation in brackets) annual water balance components (all in mm) estimated by SHAW model for three irrigation systems at Abbotsford site.

Irrigation System	P	I	E+T	Drainage	Runoff
Control	1586 (253)	0	690 (62)	844 (222)	52 (60)
I40	1586 (253)	351 (97)	985 (48)	899 (217)	54 (68)
I60	1586 (253)	527 (146)	984 (48)	1076 (210)	54 (67)

P = precipitation; I = irrigation.; E+T = Evaporation + Transpiration.

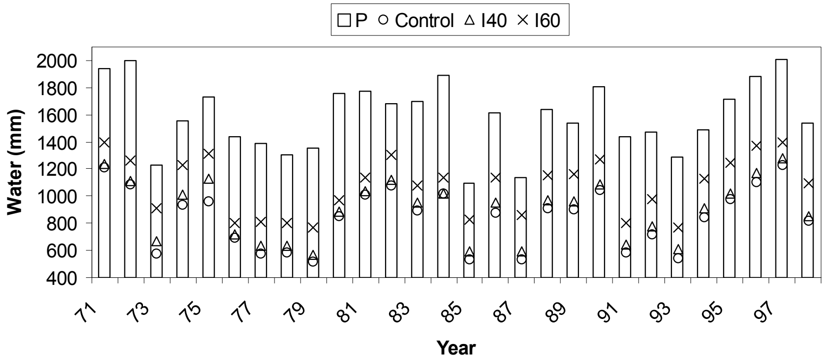

Figure 1: A comparison of annual precipitation and SHAW-estimated drainage for control, I40 and I60 irrigation systems in Abbotsford region. Note P = precipitation.

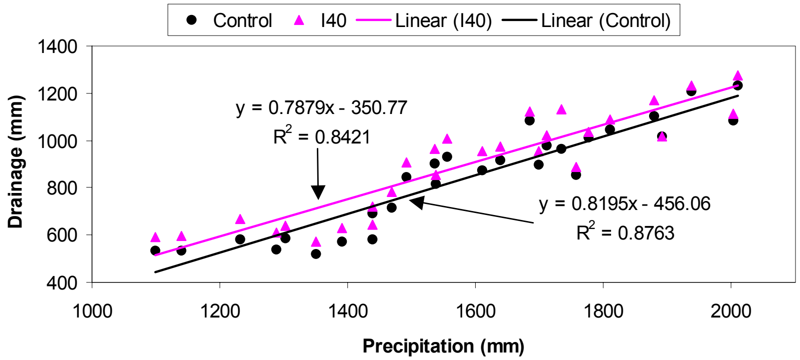

Figure 2: Relationship between annual drainage and precipitation for control and I40 irrigation system in Abbotsford region.

The SHAW model estimates that most deep drainage occurs in the winter and fall seasons; on average, the winter and fall account for 68% and 20% of total annual deep drainage, respectively (data not shown). Runoff usually occurs in the late winter\early spring seasons when the snow pack melts and a thin soil layer near surface is still frozen and thus the melted snow cannot infiltrate.

3.2 Osoyoos (OS) Region

The climate at OS is much drier than at AD; therefore, it is anticipated that the average annual drainage would be much less at OS – the SHAW model estimates bear this out (compare Tables 4 and 5). The SHAW-estimated amount of evapotranspiration at OS increased nearly 4-fold under the I40 system, which applied on average over 750 mm of irrigation per year, yet the estimated amount of drainage actually decreased in comparison to Control. On the other hand, about 84% of the additional amount of irrigation applied under IW40 (319 mm) was lost to drainage as SHAW-estimated average annual evapotranspiration only increased by 50 mm.

Table 5: Summary of average (standard deviation in brackets) annual water balance components (all in mm) estimated by SHAW model for three irrigation systems at Osoyoos.

Irrigation System	P	I	E +T	Drainage	Runoff
Control	318 (79)	0	290 (57)	25 (26)	2 (7)
I40	318 (79)	761 (107)	1062 (78)	12 (16)	4 (11)
IW40	318 (79)	1080 (0)	1112 (73)	279 (109)	5 (12)

P = precipitation; I = irrigation.; E+T = Evaporation + Transpiration.

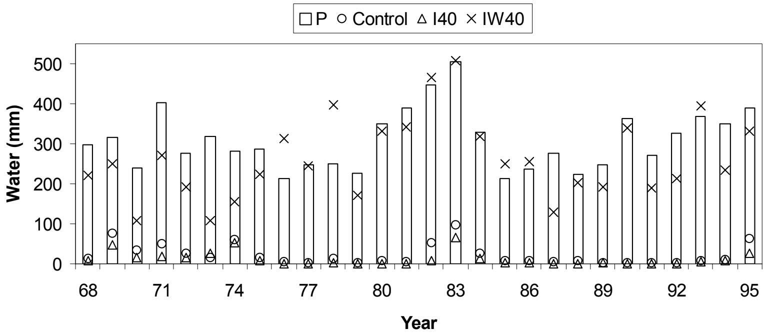

Figure 3: A comparison of annual precipitation and SHAW-estimated drainage for control, I40 and IW40 irrigation systems for Osoyoos. Note P = precipitation.

As discussed previously, over 80% of the variability in SHAW-estimated drainage for AD can be explained by the corresponding annual precipitation (Figure 2). However, at OS the linear relationship between SHAW-estimated

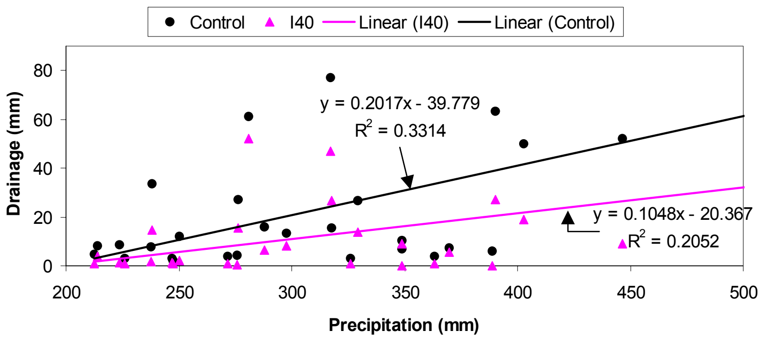

Figure 4: Relationship between annual drainage and precipitation for control and I40 irrigation system in Osoyoos region.

drainage and precipitation is much weaker (Figures 3 and 4). The weaker relationship at OS is probably related to the drier conditions for which much of the precipitation would remain in the soil profile as an increase in soil water content and not contribute to drainage. On the other hand, at AD, especially in the winter season, wetter soil conditions would result in a greater chance of drainage occurring during any precipitation (especially rainfall) event.

4 Conclusions

The SHAW model was run for about 30 years using daily climate data and local crop and soil conditions from two vastly different climatic regions in British Columbia, Canada. The model was run for bare soil\no irrigation, and efficient and less-efficient irrigation systems to compare water losses due to drainage under each scenario. Under the efficient irrigation system SHAW estimates less drainage loss than under bare soil for the drier region. For the wetter region, drainage loss was increased slightly under efficient irrigation and a raspberry crop over bare soil. On the other hand, the SHAW-estimated amount of drainage in both regions increased substantially using the less-efficient irrigation systems. In both regions the drainage that occurs during the non-growing season cannot be controlled; however, the modelling results from this study imply that drainage losses can be minimized during the growing season using SHAW or other water and energy balance models or by installing a water content or potential sensor in the plant root zone to determine when to irrigate the crops. Note that the issue of increasing salinity in the root zone due to minimizing irrigation has not been addressed in this research. Future research will examine the potential for build-up of salts in the soil profile under the efficient irrigation system using the solute transport module of SHAW.

Acknowledgements

Funding for this research was contributed by the Canadian Network of Centres of Excellence program through the Canadian Water Network. The authors wish to thank Ravindra Ramnarine for excellent assistance in checking and filling gaps in the climate data and David Fallow for translating raw climate data.

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