Modeling the Irrigation Requirements for an Experimental Site in Northern Alberta, Canada

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A combined methodology of the Root Zone Water Quality Model (RZWQM), the generation of stochastic rainfall realizations, and an historical meteorological record were used to determine the supplementary irrigation requirement for an experimental site located in northern Alberta. The site receives an annual rainfall of approximately 500 mm yr^{-1}, and contains a fluctuating water table. The simulated results showed maximum irrigation requirements of 270 mm, however, half that amount can be required during an average or wet growing season of mean rainfall of 350 and 500 mm, respectively. The irrigation requirements were influenced by rainfall amount and distribution, downward flux and the subsequent fluctuation of the water table and the depth of water table at the beginning of the growing season, which was influenced by the winter season precipitation. The simulated results suggested that a water table less than 2 m deep from the ground surface can significantly reduce the irrigation requirements. Therefore, the winter precipitation and initial depth of the water table are suitable indicators of the likely requirement of irrigation during the growing season.

Keywords: RZWQM, soil water, water table, stochastic rainfall, irrigation.

Northern Alberta, Canada has abundant water resources and receives an average annual rainfall between 300 and 500 mm yr^{-1}. Although most rainfall there occurs during the growing season that extends from May to mid-September, irrigation may still be considered as supplementary to reduce soil water deficits during critical periods of the growing season. Also, irrigation with treated industrial and municipal effluents provides an alternative for disposing wastewater directly in surface waters. Both purposes require a reliable determination of the irrigation requirements in terms of amount and timing of the application of the allocated irrigation water.

Methods based on potential evapotranspiration and appropriate crop coefficients are sufficient for the scheduling and the determination of the total irrigation requirements (Allen et al. 1998; Popova et al. 2006; Sensoy et al. 2007). However, the management of supplemental irrigation requires the consideration of the temporal variation in soil moisture contents. Models based on soil water balance have been used as a tool for improved irrigation management. For example, one-dimensional soil water models were used in combination to determine the spatial variability of potato irrigation requirements in northeast Portugal (Sousa and Pereira 1999) and cotton monthly irrigation in the costal plain of Georgia, USA (Guerra et al. 2007).

The Root Zone Water Quality Model (RZWQM) was suitable for this study because of its ability to predict the temporal soil moisture variations and water table fluctuations and also because it has been fitted with an irrigation module that allows fixed irrigation scheduling as well as automatic water application based on a depletion criterion of soil water content (Hanson et al. 1998).

The RZWQM model was extensively studied and verified for its ability to predict soil moisture dynamics (Hanson et al. 1999). Starks et al. (2003) obtained a reasonable agreement between predicted and observed average soil water in the upper 0.60 m of soil profile by calibrating some soil hydraulic properties. For an intensive irrigation system under arid climate conditions, the RZWQM simulated soil water contents close to observed data (Stulina et al. 2005), and for a double cropping system, the RZWQM was able to simulate the soil water pattern. Furthermore, researchers have also found that the RZWQM outperformed similar models such GLEAMS and CERES-Wheat in simulating soil water content (Chinkuyu et al. 2004; Saseendran et al. 2004; Hu et al. 2006).

The objective of this research was to determine the supplementary irrigation requirement for a site in northern Alberta, Canada which was also an experimental site for the use of effluent water from a nearby pulp mill plant in the irrigation of poplar trees and forages. Irrigation requirement was assessed using the stochastic generation of rainfall realizations and the RZWQM to simulate the soil water content.

METHODS

Site

The experimental site, approximately 4 ha in area, is located at latitude 54° 52' N and longitude 112° 51' W (approximately 120 km northeast of Edmonton, Alberta, Canada). The site was planted with hybrid poplar trees and inter-planted with a forage mixture of reed canarygrass, alsike clover and timothy (Patterson et al. 2008). A preliminary surficial soil textural analysis showed that the average clay content in the experimental site is approximately 35–45%. The surficial loam to sandy loam soils are underlain by clay to clay loam layers that have higher soil water content than the upper soil layers (Table 1), thus raising the concern over poor drainage and excessive water table buildup.

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Neutron probe measurements were conducted during the rainfall season, April to September 2003 and 2004, to determine the soil water in the upper 0.8 m of the soil profile, while the groundwater level was monitored through piezometers. The average water table depth was observed to be 2 m below the ground surface (bgs), with seasonal fluctuations in the water table levels between 0.5 to 4 m bgs, depending on the topographic location and the soil physical characteristics.

Calibration of the Root Zone Water Quality Model

The RZWQM was calibrated to simulate the seasonal soil water changes and the fluctuation of the shallow water table. The soil profile was initially divided into eight layers for the upper 3.0 m of the profile following the soil textural sampling (Table 1). The loam surface layer represented the upper 0.4 m of the soil profile, followed by sandy loam and sandy clay loam layers, each 0.2 m in depth. A sandy loam layer at a depth interval of 1.5-2.0 m below ground surface was sandwiched between clay loam and sandy clay loam layers at depth intervals of 0.8-1.5 m and 2.0-2.5 m, respectively. The eighth clay layer was subdivided into two layers of 0.35 and 0.15 m, respectively, for better control of the water depth at the beginning of each simulation.

The RZWQM uses the Brooks and Corey saturation – pressure relationship expressed as (Sumner 2000):

$$\frac{\theta - \theta_r}{\theta_s - \theta_r} = \left(\frac{h}{h_e}\right)^{-\lambda} \qquad (1)$$

where θ is volumetric soil water content (V/V), θ_s is the saturated soil water content (V/V), θ_r is the residual soil water content (V/V), h is the pressure head (L), h_e is the bubbling pressure (L), and λ is a fitting parameter of the Brooks–Corey relationship, usually interpreted as the pore size distribution index. The parameter λ is of special importance because it determines the soil water contents at field capacity (FC) and permanent wilting point (PWP), which were used to determine the quantity of the irrigation water and the timing of the application. The higher λ is, the lower FC and the PWP are. The calibrated inputs included the parameters of Brook and Corey equation (Eq.1), and the water table leakage rate (cm h^{-1}) set as the lower boundary condition at the bottom layer.

The Nash-Sutcliffe Efficiency coefficient (EF) was used as an objective criterion for the goodness of fit between the observed and the simulated, expressed as:

$$EF = 1 - \frac{\sum_{i=1}^{n}\left(P_i - O_i\right)^2}{\sum_{i=1}^{n}\left(O_i - \overline{O}\right)^2} \quad (2)$$

where P and O represent the predicted and observed values, respectively, and the overbar denotes the average of n observations.

The calibration was conducted in two stages. In the first stage feasible ranges of input variables were established (Table 2) from the typical values of the corresponding textural classes. A uniform distribution was assumed for all the feasible ranges, which were sampled using a Latin Hypercube of 20 divisions. Each division was sampled 5 times to produce 100 sets of input variables, representing 100 scenarios of the soil profile. After running the RZWQM for all the scenarios, the feasible ranges of the input variables were redefined by ±5% of the scenario that produced the best fit in terms of EF. This process was repeated several times and was enhanced by using a stepwise multiple regression to linearly optimize the inputs within the narrowly defined range of ±5% of the inputs of the best performing set.

In the second stage, the best 20 performing sets from stage 1 were selected and split into two groups according to the EF coefficients. A methodology similar to that described by Duan et al. (1992) was used to improve the calibration. The inputs of the best performing scenario in the group were assumed to be the averages of the average normal Gaussian distributions. The standard deviations were calculated from all the inputs in the group. The normal distributions were randomly sampled to produce three new input sets. Two additional input sets were generated using two techniques suggested by Duan et al. (1992) and expressed as:

$$R = 2g - u \tag{3}$$

and

$$c = \frac{g + u}{2} \tag{4}$$

where R is the new set of input variables known as the reflection set, g is the simple average of all the input sets, *u* is the worst scenario and *c* is the new set of input variables known as the contraction set.

A newly generated scenario was included when it outperformed any of the scenarios in the group and the worst performing scenario was excluded to maintain a constant number of scenarios in each group. This process was repeated five times and then all the scenarios were shuffled and split into two groups. The second stage of the calibration continued until a satisfactory calibration was reached.

Rainfall Generation

Random rainfall realizations were generated using a Markov chain series to represent the probability of rainfall occurrences on any given day combined with a Gamma Probability Density Function (PDF) as a predictor for the daily rainfall depth.

Three possible states were considered in the construction of a Markov chain transitional matrix: a wet state, indicating a rainfall > 0.2 mm; a dry state, indicating no rainfall occurrences; and a low-wet state of rainfall ≤ 0.2 mm. The analysis of the historical rainfall record for the Athabasca weather station (54° 49' N, 113° 32' W, approximately 44 km southwest of the site) extending from 1953 until 2003, indicated that for any given day during the calendar year, there is a good transitional probability from dry to high wet state and visa versa. However, a rainfall of ≤ 0.2 mm was not observed in the historical record; therefore, the transitional probabilities to or from the low wet state to the other two states were set to zero. Thus, rainfall occurrence is probable year round with a lower truncation limit of 0.2 mm, provided that rainfall occurs when the generated probability exceeds the Markov chain transitional probability. The generation of daily rainfall distribution was handled through a Gamma PDF with the following mathematical form:

$$f(x) = \frac{\lambda^{\beta} x^{\beta-1} e^{-\lambda x}}{\Gamma(\beta)} \tag{5}$$

with:

$$\lambda = \frac{\bar{x}}{s_x^2} \;; \qquad \beta = \frac{\bar{x}^2}{s_x^2}$$

where Γ is the Gamma function, x is the stochastic property or unknown, s_x^2 is the variance of the property x, and $\bar{x}$ is mean of the property x.

Random 10^4 realizations representing the daily precipitation depth for the period of April to October were generated. Separate Gamma PDFs were evaluated for each month. Each PDF was used to generate random rainfall realizations for the corresponding month. The stochastic generation was carried out by generating a uniformly distributed random number between 0 and 1, and then transforming the random number into a random variable of the required PDF. The transformation was accomplished by setting the uniformly distributed random number as a value on the cumulative distribution function (CDF) curve and choosing the corresponding stochastic variable (Carnahan et al. 1969).

Simulation of Irrigation Requirement

The hypothetical scenarios used to evaluate the irrigation requirement considered orchard grass as the crop planted at the beginning of the simulation period, and allowed to grow to a height of 0.20 m. The simulation period extended from May 1 to September 30. A dry soil albedo of 0.15, wet soil albedo of 0.05 and plant maturity and residue albedo of 0.15 and 0.1, respectively, were used. Daily shortwave radiation was determined from the maximum and minimum temperature according to the method described by Allen et al. (1998).

Irrigation management utilized an irrigation criterion defined as 50% of the allowable depletion, further defined as the difference in soil water contents between FC and PWP.

The simulations considered two scenarios: (1) a soil depth of 0.59 m and the water table was excluded; the lower boundary was controlled by unit gradient flow. The water leaving the horizon at the lower boundary was considered to be deep percolation or flux into the groundwater table, and (2) a soil depth of 3.0 m with a fluctuating water table, set initially at a depth of 3.0 m bgs.

The irrigation requirements for each scenario were evaluated using two sets of meteorological and rainfall inputs. The first set included stochastically generated rainfall seasons. Each season started on Apr. 1 and ended on Oct. 15. The initial soil water contents (SMC) were established from the soil water measurements, which showed average SMC of 0.25 cm^3 cm^{-3} at the beginning of April for the upper 0.5 m of the soil profile. The irrigation started on or after May 3, which allowed a period of re-initialization of the SMC before starting the simulation of the irrigation requirements.

The stochastic 10^4 rainfall realizations were divided into ten rainfall intervals. From each interval, 30 seasonal realizations were randomly selected, however, the ninth and tenth intervals only included 10 realizations, and thus a total of 250 realizations were used in the determination of the approximate irrigation requirements. For simplicity, only rainfall was stochastically generated, and the meteorological variables of 2003 were substituted for the other meteorological variables in the model.

The second data set combined the historical data and weather data during the monitoring period. Complete meteorological records were available from 1959 Sep. 01 till 2005 Nov. 25.

RESULTS AND DISCUSSION

RZWQM Calibration

The calibrated soil physical properties are given in Table 3. The comparisons between the simulated and observed SMCs are shown in Figures 1, 2 and 3. The model successfully simulated the seasonal variation in the surface layer (Fig. 1) and resulted in an EF of 0.62. The observed data showed a decreased variation in the SMC in the second layer (Fig. 2), and the SMC became almost static in the third layer (Fig. 3) The minimal variations of the SMC in the subsurface layers could be attributed to the intermediate position of these layers that transformed them into a buffer zone for the upward and downward fluxes. This effect was also reflected in the simulated results (Fig. 2 and 3), but was also associated with lower EF values of 0.30 and 0.01 because the observed SMC data were close to the seasonal average. This in turn resulted in minimal sum squares of error for the alternative model defined in Nash-Sutcliffe EF coefficient (Eq. 2) as the average of the observed data, and narrowed the margin of improvement over the alternative model. The observed SMC averages were 0.230, 0.286 and 0.342 $cm^3 cm^{-3}$, which compared well with the simulated SMC averages of 0.232, 0.283, and 0.341 $cm^3 cm^{-3}$ for the first, second, and third layers, respectively.

The RZWQM simulation of the water table (Fig. 4) was acceptable (EF of 0.52), although it did not predict the sudden rises that occurred during July 2003 and spring 2005. The sandy loam layer located at depths of 1.5–2 m and beneath the clay loam and sandy clay loam layers (Table 1) may have contributed to the discrepancy between the simulated results and observed results. The water in the clay loam and sandy clay loam layers was held at higher capillary tensions than in the sandy loam layer. This created an unsaturated zone between the interface of the sandy loam and the clay loam that acted as a barrier and restricted the downward water movement. The water buildup in the clay layer may have caused a temporary rise of a perched water table, followed by downward drainage caused by a newly developed pressure head. This effect was not replicated by the RZWQM because the model only allows an upward development of the water table from the bottom layer; however, the simulated SMCs showed that the clay loam and sandy clay loam layers were near saturation during the periods of the sudden water table fluctuations. The observed data showed a rise in the water table level from an average depth of 2.80 m bgs in 2003 to an average depth of 2.36 m during 2004, indicating a steady buildup of the water table above the bottom clay layer, an effect that was reasonably simulated by the RZWQM.

Rainfall Generation

The Gamma PDFs for each month are given in Fig. 5. A comparison between the predicted statistics, i.e., the statistics of the randomly generated realizations, and the statistics of the historical record showed that the Gamma distribution function suitably described the rainfall probability distribution (Table 4). The observed average daily precipitation depth and the monthly average were re-generated by the 10^4 randomly obtained realizations as indicated by a linear regression correlation coefficient (R^2) of 0.997. The stochastic generation accurately predicted the average depth of a single rainfall (R^2=0.967) and average number of rainfall events (R^2=0.959). The CDF of the generated realizations was also close to the CDF of the historical record, but with some over-prediction associated with the higher CDF values. In fact, the maximum values of the generated record were higher than those found in the historical record, while the minimum values of the generated record were lower than the observed. This is an expected outcome, however, since the historical record is relatively short compared to the thousands of realizations that were randomly generated. Hence, the generated record is more likely to include more extreme events than the historical record.

Average precipitation during the period April to October, inclusive, for the period 1953–2003 at the Athabasca weather station was 376 mm, and the yearly totals were 332, 443, 246, 429 and 312 mm for 2001–2005, inclusive. The CDFs for these years were

0.28, 0.83, 0.02, 0.78 and 0.18, respectively. Thus, the 2003 rainfall season was a rather rare event. In contrast, during the same period, 2002 and 2004 had high CDFs.

Irrigation Requirements: Stochastic

The simulation results, obtained for an irrigation period that extended from the beginning of May until mid September, are summarized in Tables 5 and 6.

The actual evapotranspiration remained fairly constant for all scenarios with an average value of approximately 372 mm, close to the potential evapotranspiration of 379 mm (data not shown), likely because the irrigation criterion of 50% allowable depletion ensured sufficient soil moisture to meet the crop water requirements.

The deep percolation (DP, Table 5) was defined as downward flux past the 0.50 m root zone. The average DP was approximately 125 mm and increased as the rainfall scenarios shifted from dry to wet. The proportional relationship between rainfall and DP was the result of the low soil retention in the loam and sandy loam soil emphasized by a soil porosity index (λ) of 0.5 and 0.64 for the first and second layers, respectively (Table 3). According to equation (1) 70% of the soil water storage for the upper 0.5 m of the soil profile is between saturation and FC, thus, leaving significant amounts of infiltrated rainfall susceptible to rapid drainage.

The simulated average irrigation requirement was 142 mm for the first soil profile scenario, assuming a depth of 0.59 m and no water table (Table 5). In contrast, the average simulated irrigation requirement for the second soil profile that considered the presence of a water table was 98 mm. The results (Table 6) showed a negative water flux, indicating an upward movement from the water table to the root zone, thus offsetting a portion of the irrigation requirement. The rising water table also acted as a reservoir for the rainfall water percolated through the loam and sandy loam layers, which further reduced the need for irrigation.

As anticipated, the irrigation requirements were inversely related to the total rainfall amounts (Fig. 6). The simulated irrigation averages for the lowest rainfall increment were 248 and 212 mm for the first and second soil profiles, respectively. As the simulations shifted from dry to wet rainfall seasons, the irrigation requirements decreased gradually. However, the reductions were not linearly proportional to the increase in total rainfall, especially for seasonal rainfall that exceeded the annual seasonal average of approximately 376 mm. The reduction in irrigation requirement between rainfall increments dropped from approximately 35 mm to about 10 mm as the simulation shifted through the wettest rainfall scenarios (Tables 5 and 6). One to three irrigation events, each of an average depth of 29 mm (the mean depth of irrigation from Tables 5 and 6), were simulated for the wettest rainfall increment of an upper limit of 736 mm, almost twice the annual average. Furthermore, the upper and lower limits of the irrigation depths for each scenario (Fig. 6) suggested that the irrigation requirement during a wet season could be close to that of an average season.

The rainfall distribution through the season appears to be as important as the total precipitation depth. Even during a wet season, some irrigation may be required to compensate for the deficiency in SMC occurring during the dry periods of the season. For example, the model simulations indicated that supplementary irrigation was not required for few rainfall scenarios of total water depth between 500 and 600 mm but 30 mm of irrigation water was simulated for rainfall scenarios between 400 and 736 mm in depth.

The irrigation requirements were not always eliminated by above average rainfall, thus creating a similarity between the wet and average scenario, and similarly between the average and dry scenarios. However, the differences were manifested in the maximum irrigation requirement anticipated for a specific rainfall scenario. For a slightly above average season of approximately 400 mm rainfall, the expected irrigation requirements varied between 30 and 150 mm, with 30 mm representing the maximum irrigation requirement for a wet season in excess of 650 mm in total rainfall.

Irrigation Requirements: Historical Record

Since the conditions were not known at the beginning of the historical record, an initiation period was considered. It is evident (Fig. 7) that two simulations initiated at different water table levels would equalize after a 12-yr simulation period and the effect of the initial conditions would have completely diminished for all results after 1972. Therefore, 33 years of simulation results were considered for the two soil profile scenarios.

The average and maximum irrigation requirements of 154 and 268 mm for the first soil profile were close to the 142 mm average and 248 mm maximum irrigation predicted using the stochastically generated rainfall scenarios.

The simulation results of the second soil profile showed a clear effect of the water table on the irrigation requirements (Fig. 7). Irrigation was not needed when the water table level at the beginning of the growing season was above 2 m bgs. As a result fewer irrigation events were simulated. In fact only five irrigation events were simulated between August 1990 and June 1993, and eight events between May 2001 and June 2004. The water table levels were influenced by snowfall during the winter. It is evident from the reported winter precipitation in Table 7 that the two periods in which irrigation was simulated were preceded by winter precipitation of < 100 mm, which is relatively low compared to the average and maximum winter precipitation of 155 and 230 mm, respectively. After summer 1993 the water table reached a level of 0.40 m bgs before it started to subside and drop to the levels observed in the field during the period that extended from 2002 till 2005. Of course, the simulations presented in Figure (7) were not meant as retroactive prediction of the soil water contents and water table fluctuations for the past four decades, since the crop cover was not known for that period. However, it indicated how much irrigation water probably could be applied to the site, and also that a fluctuating water table can offset much of the irrigation requirements, thus, reducing the need for irrigation.

CONCLUSIONS AND RECOMMENDATION

The maximum seasonal supplementary irrigation requirement, estimated at approximately 270 mm, would likely be needed during a dry growing season (i.e., May to September) of mean rainfall of 240 mm. However, for an average season of mean rainfall of 350 mm or a wet season of mean rainfall > 500 mm, irrigation requirements could be anywhere between 30 and 150 mm, associated with a slight probability the supplementary irrigation may not be needed during a wet season.

The predicted irrigation requirements for the wet and average seasons were similar due to the characteristics of rainfall; namely, poor distribution during some wet seasons.

The downward flux contributed directly to the water table and caused it to fluctuate; however, water table levels during the irrigation season were also dependent on the precipitation during the winter season which influenced the depth of water table at the beginning of the growing season. In general, an initial water table depth above 2 m bgs can reduce the need for irrigation. Thus, an initial assessment of the necessity for irrigation can be made at the beginning of the season using the winter precipitation and the depth of the water table as indicators.

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Table 1. Soil texture at the SW corner of the study site

Depth interval (m)	Soil texture	Clay (%)	Sand (%)
0.00-0.2	Loam	19	41
0.20-0.4	Loam	19	41
0.40-0.6	Sandy loam	19	57
0.60-0.8	Sandy clay loam	29	49
0.80-1.0	Clay loam	37	43
1.00-1.5	Clay loam	37	37
1.50-2.0	Sandy loam	19	59
2.00-2.5	Sandy clay loam	27	47
2.50-3.0	Clay	53	23

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Table 2. Feasible ranges of input parameters for the soil hydraulic properties

Depth interval (m)	θ_r[z]		θ_s[y]		λ[x]		h_e[w]		K_s[v]	
0.00–0.40	0.00	0.12	0.29	0.64	0.01	0.58	-1.0	-100.0	0.60	3.40
0.40–0.60	0.01	0.17	0.25	0.66	0.00	0.85	-1.0	-97.8	1.40	7.60
0.60–0.80	0.00	0.21	0.27	0.53	0.01	0.80	-1.0	-100.0	0.43	1.27
0.80–1.50	0.00	0.27	0.35	0.57	0.01	0.59	-1.0	-100.0	0.34	1.41
1.50–2.00	0.01	0.17	0.25	0.66	0.00	0.85	-1.0	-97.8	1.40	7.60
2.00–2.50	0.00	0.21	0.27	0.53	0.01	0.80	-1.0	-100.0	0.43	1.27
2.50–2.85	0.00	0.30	0.38	0.57	0.00	0.42	-1.0	-100.0	0.14	1.05
2.85–2.99[u]	0.00	0.30	0.38	0.57	0.00	0.42	-1.0	-100.0	0.14	1.05

[z]θ_r: Volumetric residual soil water content (V/V)

[y]θ_s: Volumetric saturated soil water content (V/V)

[x]λ: Pore size distribution index

[w]h_e : bubbling pressure (L)

[v]K_s: Saturated hydraulic conductivity (cm h^{-1}).

[u]Water table leakage rate : 10^{-5} – 10^{-1} cm h^{-1}

Table 3. Calibrated soil hydraulic properties

Depth interval (m)	θ_r[z]	θ_s[y]	λ[x]	h_e[w]	θ_{FC}[v]	θ_{pwp}[u]	K_s[t]
0.00–0.40	0.03	0.61	0.50	-30.5	0.20	0.05	1.07
0.40–0.60	0.09	0.52	0.64	-57.8	0.23	0.10	4.39
0.60–0.80	0.10	0.37	0.16	-83.5	0.32	0.22	1.14
0.80–1.50	0.00	0.54	0.16	-69.0	0.42	0.23	0.90
1.50–2.00	0.07	0.66	0.27	-10.4	0.30	0.15	1.77
2.00–2.50	0.05	0.53	0.71	-34.8	0.14	0.05	0.54
2.50–2.85	0.08	0.38	0.01	-39.8	0.37	0.37	0.99
2.85–2.99[s]	0.14	0.54	0.19	-43.5	0.41	0.28	0.15

[z]θ_r: Volumetric residual soil water content (V/V)

[y]θ_s: Volumetric saturated soil water content (V/V)

[x]λ: Pore size distribution index

[w]h_e : bubbling pressure (L)

[v]θ_{FC}: Volumetric soil water content at field capacity (V/V)

[u]θ_{PWP}: Volumetric soil water content at permanent wilting point (V/V)

[t]K_s: Saturated hydraulic conductivity (cm h^{-1}).

[s]Water table leakage rate: 2.408 x 10^{-4} (cm h^{-1})

Table 4. Comparison between the observed[z] and predicted statistics of the seasonal rainfall (depth or number of events); for the period extending from April till October at Athabasca weather station

	April		May		June		July		August		September		October	
	O[y]	**P[x]**	**O**	**P**	**O**	**P**	**O**	**P**	**O**	**P**	**O**	**P**	**O**	**P**
Min depth (mm)	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Max depth (mm)	31.0	91.6	46.6	82.0	55.5	146.5	84.8	148.9	65.0	83.5	44.8	76.9	21.0	39.2
Avg. depth (mm)	3.8	3.16	5.0	3.8	6.5	5.5	6.8	5.9	5.4	4.5	4.2	3.8	3.1	2.5
Min Month (mm)	1.4	0	5.9	3.0	15.0	14.6	11.7	17.0	21.0	5.8	5.8	4.9	3.0	0.5
Max Month (mm)	66.4	150.7	112.5	139.6	172.0	280.5	237.4	272.1	134.1	179.5	147.6	133.9	75.4	87.7
Avg Month (mm)	24.1	23.9	44.8	44.5	84.8	88.4	96.4	96.0	63.6	62.6	41.1	39.9	21.7	20.9
Min events[w]	1	0	4	3.0	6.0	8.0	4.0	7.0	6.0	5.0	4.0	4.0	1.0	2.0
Max events	12	17	17	21.0	21.0	25.0	21.0	24.0	20.0	22.0	21.0	20.0	13.0	16.0
Avg. events	6.4	7.6	8.9	11.8	13.1	16.1	14.2	16.2	11.8	13.9	9.8	10.6	7.1	8.5
70%[v]	>0.2	>0.2	>0.2	0.5	1.8	1.9	2.0	1.8	1.0	0.9	0.4	0.4	>0.2	>0.2

80%[v]	0.3	0.5	1.4	1.5	3.8	4.0	4.2	3.9	2.3	2.4	1.5	1.3	0.5	0.5
90%[v]	2.2	2.0	4.3	4.9	9.0	14.6	10.8	14.4	6.9	7.7	4.1	3.9	2.2	1.9
99%[v]	15.3	13.9	20.9	22.9	35.7	39.0	40.8	42.5	24.8	28.3	19.0	22.2	11.5	12.1

[z] The observed record extended from 1953 to 2003

[y]O: Observed

[x]P: Predicted

[w] Number of events refers to the number of days with rainfall occurrences

[v] Exceedance probability

Table 5. Summary of the anticipated supplementary irrigation requirement, for the first soil profile scenario of 0.59 m depth and without the presence of a water table

Rainfall increments (mm)	ETA[z] (mm)	Irrigation (mm)	DP[y] (mm)	ΔS[x] (mm)	N[w]	Average depth (mm)
163.3–220.6	370.3	247.6	36.6	-0.8	9.0	27.4
220.6–277.9	370.5	211.8	51.3	0.6	7.7	27.5
277.9–335.2	371.5	175.6	60.81	0.6	6.4	27.4
335.2–392.5	371.7	154.2	84.9	3.8	5.7	27.4
392.5–449.8	372.3	123.0	108.5	3.1	4.5	27.6
449.8–507.2	372.7	112.6	144.3	2.6	4.1	27.5
507.2–564.5	372.8	98.3	172.7	5.5	3.6	27.6
564.5–621.8	373.4	81.8	212.5	3.1	3.0	27.6
621.8–736.4	373.8	77.0	253.6	8.1	2.8	27.5
Average	372.1	142.4	125.0	3.0	5.2	27.5

[z]ETA: actual evapotranspiration

[y]DP: deep percolation

[x]ΔS: change in soil water storage; negative values indicate that the soil profile contained less water at the end of the simulation than the beginning

[w]N is the average frequency

Table 6. Summary of the anticipated supplementary irrigation requirement, for the second soil profile scenario of 3.0 m depth and a shallow water table

Rainfall increments (mm)	ETA[z] (mm)	Irrigation (mm)	WT[y] (cm)	WF[x] (mm)	ΔS[w] (mm)	N[v]	Average depth (mm)
163.3–220.6	370.2	211.6	297.2	-25.7	25.6	6.9	30.7
220.6–277.9	370.6	163.4	297.2	-21.6	24.9	5.3	30.6
277.9–335.2	371.6	134.7	290.6	-16.5	36.8	4.4	30.6
335.2–392.5	372.1	100.6	272.9	-8.7	43.5	3.3	30.8
392.5–449.8	372.7	79.4	269.7	-2.0	69.6	2.6	31.0
449.8–507.2	373.3	58.7	255.0	0.4	91.9	1.9	30.9
507.2–564.5	373.3	52.4	232.8	-0.4	132.1	1.7	30.8
564.5–621.8	374.1	42.9	217.6	-1.4	177.4	1.4	30.6
621.8–736.4	374.4	33.8	189.7	1.1	216.9	1.1	30.8
Average	372.5	97.5	258.1	-8.3	91.0	3.2	30.8

[z]ETA: actual evapotranspiration

[y]WT: the average minimum water table depth below the ground surface

[x]WF: downward water flux

[w]ΔS: change in soil water storage; negative values indicate that the soil profile contained less water at the end of the simulation than the beginning

[v]N is the average frequency

Table 7. Summary of the anticipated supplementary irrigation requirement, for the first soil profile scenario of 0.59 m depth and without the presence of a water table, and using the meterological inputs of the historic record.

Year	PPT_w[z] (mm)	PPT_g[y] (mm)	PET[x] (mm)	AET[w] (mm)	I[v] (mm)	DP[u] (mm)	ΔS[t] (mm)	N[s]
1972	216.9	248.1	374.3	342.0	188.9	76.9	10.8	7
1973	136.6	362.2	377.2	345.5	112.8	80.5	49.8	4
1974	334.4	339.1	358.9	328.4	136.3	140.5	9.3	5
1975	129.2	386.4	359.3	327.7	145.7	176.2	26.8	5
1976	130.6	312.5	373.6	341.1	185.0	109.4	48.0	6
1977	153.6	454.1	355.4	324.9	74.1	159.7	42.7	2
1978	144.1	468.5	373.3	340.7	110.7	154.4	81.9	4
1979	166.7	343.3	377.5	345.2	81.1	94.1	-13.5	3
1980	103.1	354.9	365.8	333.8	157.8	122.8	56.4	5
1981	160.6	248.2	412.3	376.1	208.0	64.1	16.5	7
1982	199.6	279.4	377.2	344.3	171.8	79.1	0.5	6
1983	115.2	463.4	364.9	333.3	155.0	222.7	62.8	5
1984	112.4	448.0	361.0	329.5	102.2	166.2	56.3	3
1985	230.0	179.9	379.2	345.0	220.8	40.7	12.3	8
1986	190.7	314.2	370.7	337.7	137.6	139.4	-26.4	5
1987	152.6	287.0	385.7	352.3	182.2	89.5	29.0	6
1988	91.1	410.4	378.8	345.9	161.8	185.6	41.5	5
1989	115.9	347.4	370.8	339.2	126.9	98.1	37.4	4
1990	158.6	233.1	397.9	363.7	191.4	61.1	-1.5	7
1991	93.5	280.0	397.8	362.4	183.5	56.8	45.2	6
1992	178.1	293.0	383.5	349.3	161.5	81.1	23.5	6
1993	160.9	456.8	367.1	335.0	111.7	219.9	17.0	4
1994	224.1	346.6	378.0	345.2	106.6	103.0	12.5	4

1995	146.8	369.1	373.7	340.7	175.9	175.2	26.6	6
1996	209.1	392.4	345.8	317.0	54.1	102.6	23.2	2
1997	209.2	360.8	374.8	342.1	110.2	104.6	22.9	4
1998	96.5	201.7	427.4	389.5	266.1	40.9	37.1	9
1999	217.0	259.3	375.4	342.9	160.9	67.9	9.6	6
2000	90.7	349.7	348.0	317.8	101.5	92.8	40.8	3
2001	78.1	395.7	376.3	343.8	132.3	157.0	28.5	4
2002	147.2	237.8	398.7	360.5	222.3	98.3	2.3	8
2003	112.0	206.7	379.4	354.1	268.3	88.3	32.9	9
2004	123.8	363.7	351.7	315.5	121.5	118.8	49.3	4
2005	120.2	206.3	363.8	345.2	191.4	56.4	-39.0	7
Average	154.38	329.40	375.15	342.86	153.47	112.49	25.68	5.26

[z]PPT_w: winter season precipitation from mid September to the end of April

[y]PPT_g: growing season precipitation from beginning of May till mid September

[x]PET: Potential evapotranspiration

[w]AET: Actual evapotranspiration

[v]I: simulated irrigation requirement

[u]DP:Deep percolation

[t]ΔS: Change in storage

[s]N: Number of irrigation events

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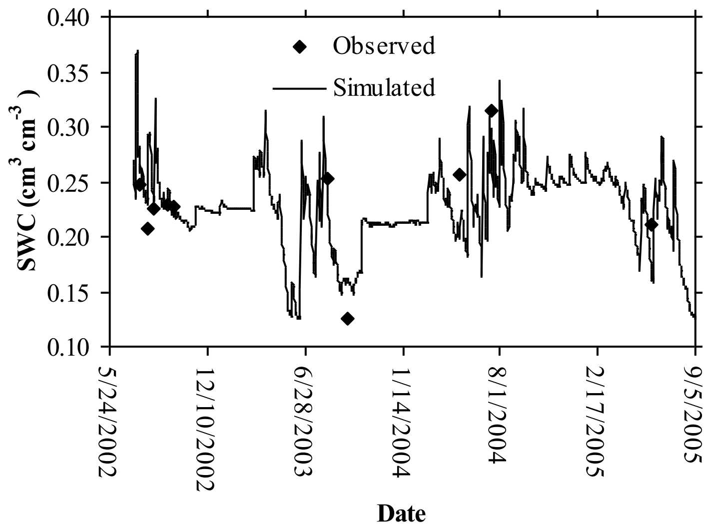

Fig. 1. The simulated and observed soil water contents for the first layer of the soil profile, 0–0.40 m. EF = 0.62.

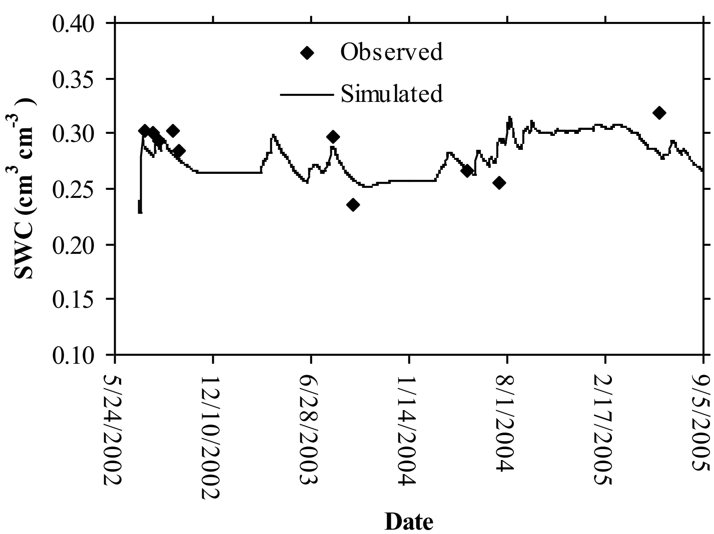

Fig. 2. The simulated and observed soil water contents for the second layer of the soil profile, 0.40–0.60 m. EF = 0.30.

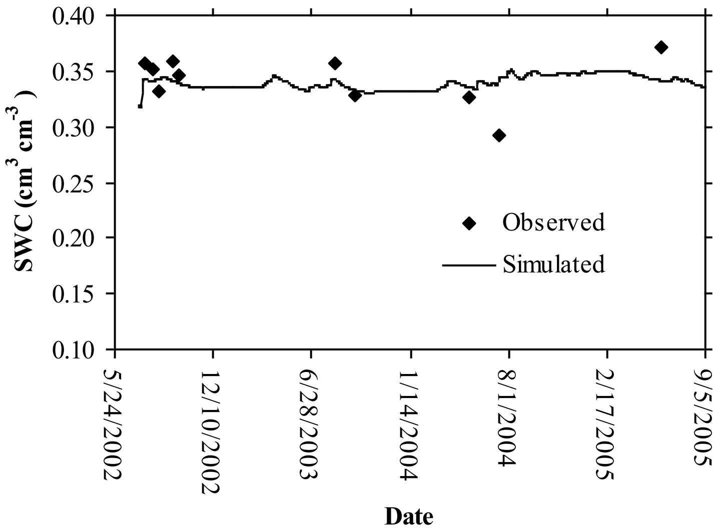

Fig. 3. The simulated and observed soil water contents for the third layer of the soil profile, 0.4–0.8 m. EF = 0.01.

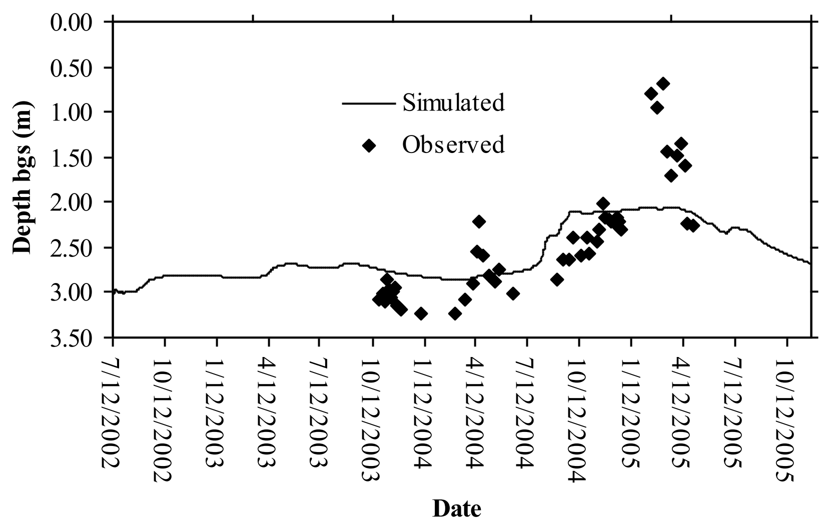

Fig. 4. The simulated and observed water table depths. EF= 0.52.

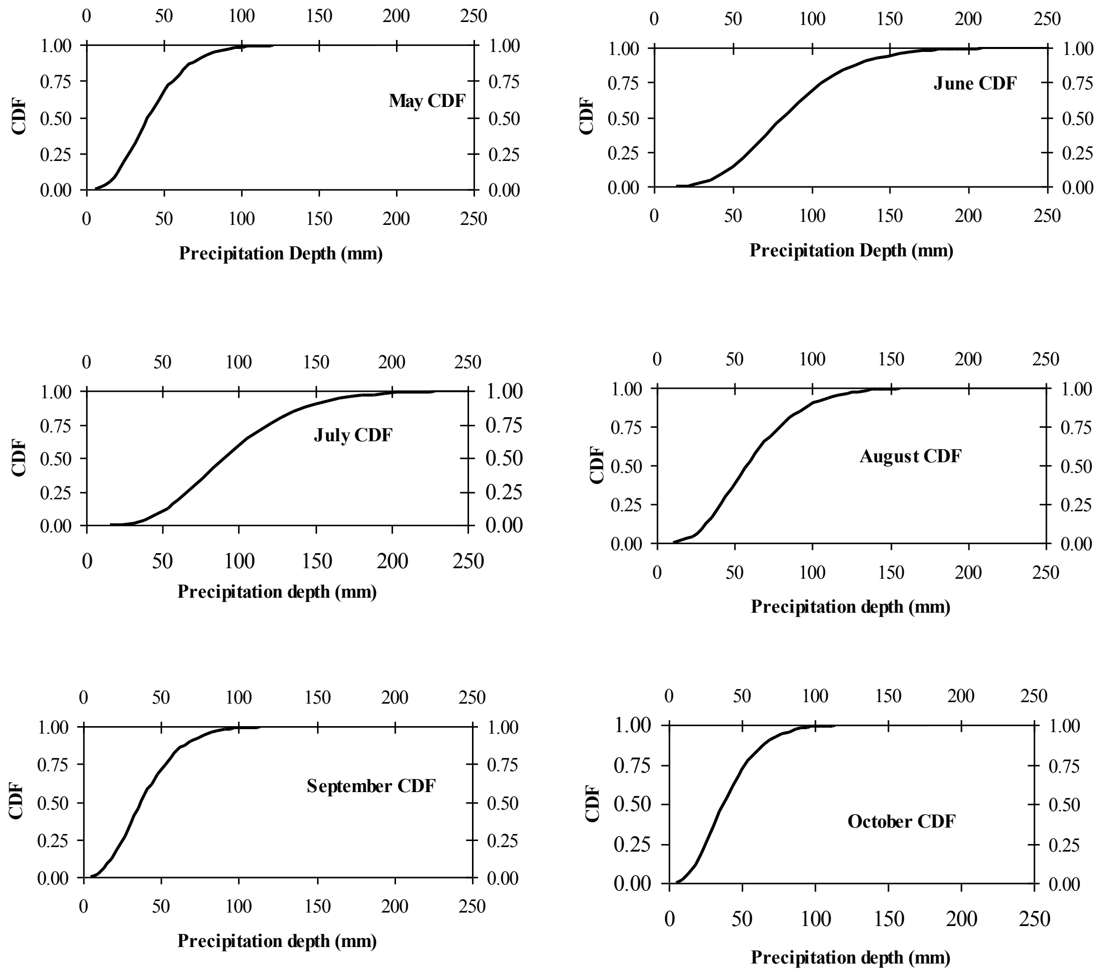

Fig. 5. The monthly cumulative distribution function (CDF) of the May to October precipitation.

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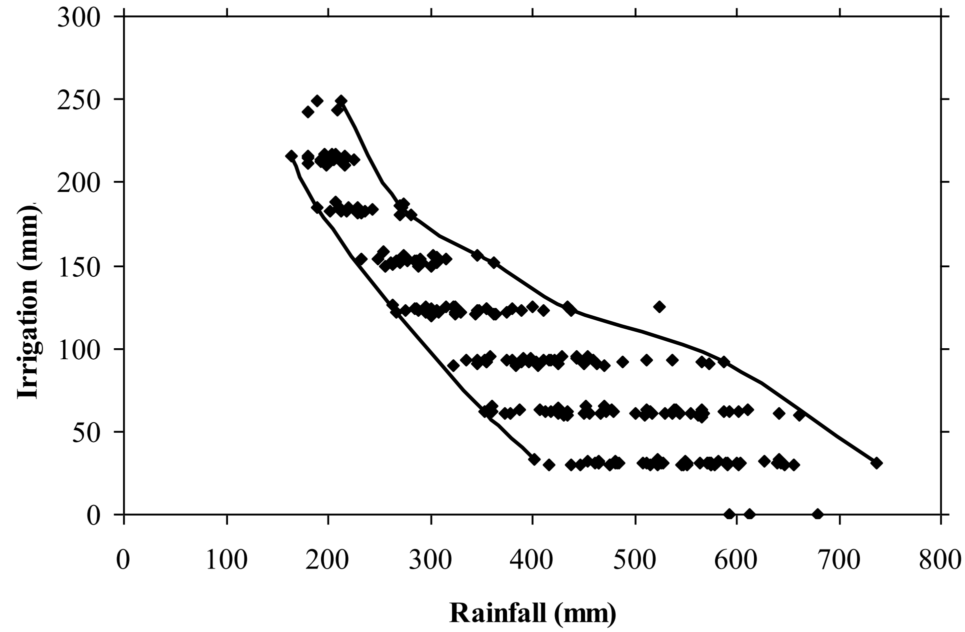

Fig. 6. The simulated irrigation for 250 stochastically generated rainfall seasons.

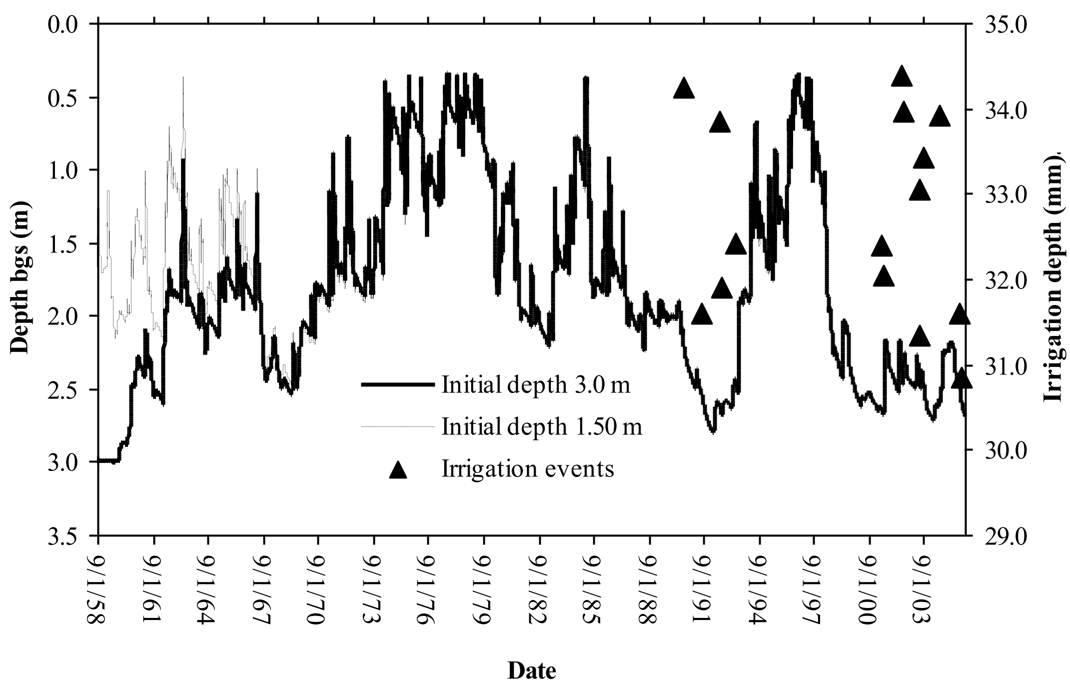

Fig. 7. The simulated water table fluctuation and the irrigation requirement using the meteorological input of the historical record.