

# Estimation of water use by four potato (*Solanum tuberosum* L.) cultivars for irrigation scheduling

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Boisvert, J.B., Dwyer, L.M. and Lemay, M. 1992. Estimation of water use by four potato (*Solanum tuberosum* L.) cultivars for irrigation scheduling. Can. Agric. Eng. 34:319-325. Potato (*Solanum tuberosum* L.) is sensitive to water deficit and requires irrigation for stable production in many areas of central and eastern Canada. Estimates of water use were calculated with a soil moisture budget calibrated for potato using field data on four cultivars (Jemseg, Norchip, Superior and Kennebec) collected over three years under rainfed control (CON) and irrigated (IRR) conditions at Ottawa, Canada. Analysis of soil moisture measurements in the top 0.40 m indicated crop coefficients ( $k$ ) varied with plant phenological stage and the proportion of roots in the measured zone. A sensitivity analysis on two cultivars (Jemseg and Superior) showed that average  $k$  values (0.88 at stage 3 and 0.67 at stage 4) were appropriate for all cultivars and treatments. Validation using independent Norchip data suggested that soil drying rate coefficients ( $z$ ) were best fitted to site-specific data. Weather-based simulations using the calibrated budget indicated that sprinkler irrigation was more efficient than trickle irrigation, when evaporation was not considered, and that both timing and amount of water applied were important to maximize potato water use.

Les pommes de terre (*Solanum tuberosum* L.) sont sensibles aux déficits hydriques et ont besoin d'irrigation pour maintenir une production stable dans plusieurs régions du centre et de l'est canadien. Les quantités d'eau requises ont été estimées à l'aide d'un bilan hydrique calibré pour la pomme de terre. Pour le calibrage, des données ont été collectées durant trois ans sur quatre cultivars (Jemseg, Norchip, Superior et Kennebec), dans des champs sans irrigation (CON) et avec irrigation (IRR) à Ottawa, ON. L'analyse des teneurs en humidité du sol mesurées jusqu'à 0.4 m de profondeur a indiqué que les coefficients des plantes ( $k$ ) variaient en fonction de leur stade phénologique et de la proportion de racines dans la zone mesurée. Une analyse de sensibilité sur deux cultivars (Jemseg et Superior) ont montré que les valeurs moyennes pour  $k$  (0.88 au stade 3 et 0.67 au stade 4) étaient appropriées pour tous les cultivars et tous les traitements. Une validation faite à partir de données indépendantes (cultivar Norchip) a indiqué que les coefficients pour le taux de séchage du sol ( $z$ ) étaient mieux ajustés aux données spécifiques au site étudié. Des simulations avec le bilan hydrique calibré et des données climatologiques ont indiqué que l'irrigation par aspersion était plus efficace que l'irrigation goutte à goutte, lorsque l'évaporation n'était pas considérée, et que le moment d'application et la quantité appliquée importaient afin de maximiser l'utilisation de l'eau par les plantes.

## INTRODUCTION

Irrigation reduces the annual variability in potato (*Solanum tuberosum* L.) production even in relatively humid areas (Marra et al. 1987). Economic benefits of irrigation vary with cultivar (Martin and Miller 1980) and market destination (Salter and Goode 1967), as a result of differential sensitivity to water stress for specific cultivars (Wilcox and Ashley 1982) and growth stages (Nelson and Hwang 1975; Van Loon 1981). Efficient irrigation scheduling therefore requires quantified relationships between potato growth stage and water use. Visual estimates of growth stage are relatively easy, but estimating water use is more difficult. One approach has been to model the soil moisture budget beneath the crop (Jensen et al. 1970; Rao 1987).

The objectives of the present study were: (i) to calibrate coefficients of an existing soil moisture budget (Baier et al. 1979; Dyer and Mack 1984; Boisvert and Dwyer 1987; Boisvert et al. 1990) for potato using measured field data, (ii) to use model estimates of actual evapotranspiration to compare water use at different growth stages under irrigated and rainfed conditions, and (iii) to compare the effects of different irrigation scheduling strategies on water use. The model was validated on independent data and a sensitivity analysis was performed.

## MATERIALS AND METHODS

Potato cultivars were grown under sprinkler irrigation (IRR) and rainfed control (CON) conditions in 1987, 1988 and 1989 on a well-drained sandy loam soil of the Uplands association (Typic Haplorthod) at the Central Experimental Farm, Ottawa, ON (45°22' N, 75°43' W). Cultivars 'Kennebec' and 'Superior' were grown in all three years; 'Norchip', 'Jemseg' and 'Russet Burbank' were grown in 1988 and 1989. Cultivars were randomized in six replicate blocks, half of which were irrigated and half rainfed. Plant spacing was approximately 0.25 m between plants and 0.90 m between rows. A 10-m buffer zone separated IRR and CON blocks to avoid sprinkler drift. Further details of the planting design appear in Dwyer and Boisvert (1990). Fertilizer (commercial analysis 18-18-18) was banded preplanting at a rate of 800 kg·ha<sup>-1</sup>. Planting occurred when the soil temperature reached 10°C, within a week of 1 May, in all three years.

Soil moisture content was measured twice weekly from 0 to 0.40 m (from the soil surface before hilling) using the time domain reflectometry technique (TDR, Topp et al. 1980) with vertical rods. Rods were not covered during hilling. In 1987 three pairs of rods were installed in 'Kennebec' and 'Superior' cultivars in IRR and CON treatments and the three readings were averaged. In 1988 one pair of rods was installed in 'Superior', 'Norchip' and 'Jemseg' plots in IRR and CON treatments, and in 1989 one pair of rods was installed in 'Superior', 'Kennebec' and 'Jemseg' in IRR and CON treatments. Irrigation (approximately 20 mm of water applied over a 1.5 hour period) occurred when measured mean soil water content in IRR plots was  $\leq 50\%$  available water (AW) (Meyer and Green 1980; Dwyer et al. 1987; Tan 1988) where available water was approximately 40 mm in the top 0.40 m.

Phenological stage was noted weekly. In 1987 root depths were measured at the beginning of flowering, at maximum flowering and during senescence. Maximum rooting depth was determined by excavating soil pits with one face perpendicular to the row, centred on a plant and extending midway to rows on each side ( $N=3$  for each treatment in 'Kennebec' and 'Superior'). In 1988 and 1989 root depths were measured at tuber initiation and at maximum flowering for all cultivars.

Field measurements were used to calibrate crop and soil coefficients of a simplified version of the Versatile Soil Moisture Budget (Baier et al. 1979; Dyer and Mack 1984; Boisvert et al. 1990). Because soil water content was not measured in 'Russet Burbank' plots, phenology and rooting depths of this cultivar did not contribute to model validation. Soil moisture was estimated in the 0 to 0.40 m depth by subtracting the evapotranspiration (*ETA*) from the rooting depth and by adding rainfall and irrigation water to existing soil moisture. Excess water was assumed to drain from the 0 to 0.40 m zone in one day. Rainfall and irrigation were measured at the site. *ETA* was limited to the available water (AW) in the rooting depth and was computed from:

$$ETA = ETP \cdot k \cdot z \quad (1)$$

where:

- ETP* = potential evapotranspiration,
- k* = crop coefficient (changes daily with phenological stage), and
- z* = soil drying rate coefficient which changes with fraction of AW in rooting depth on previous day.

*ETP* was estimated daily using method 1 of Baier and Robertson (1965) and daily maximum and minimum air temperatures measured at the Ottawa CDA climatological station located within 0.5 km of the site.

The *z* coefficient was linearly related to the fraction of available water in the estimated rooting depth and was calculated from Dyer and Baier (1979):

$$z = w/z_r \quad (2)$$

where:

- $z_r$  = constant between 0 and 1 based on soil texture (with the lightest texture represented by the lowest value), and

*w* = ratio of actual AW to maximum AW. When *w* is larger than  $z_r$ ,  $z=1$ .

Maximum AW is the difference between field capacity ( $0.195 \text{ m}^3 \cdot \text{m}^{-3}$ ) and permanent wilting point ( $0.065 \text{ m}^3 \cdot \text{m}^{-3}$ ), estimated from both field soil water content measurements and laboratory measurements.

When the soil was at field capacity and the rooting depth was less than or equal to 0.40 m, *k* and *z* were assumed to be 1.0 and  $ETA = ETP$ ; when the rooting zone was deeper than 0.40 m, the *k* coefficient was less than 1.0 and expressed the fraction of effective roots between 0 and 0.40 m.

A sensitivity analysis was performed on the *k* coefficients for phenological stages 3 and 4 to assess the significance of cultivar and treatment differences on these coefficients using 'Jemseg' and 'Superior' 1988 and 1989 data. A mean *k* coefficient was calculated for stage 3 and stage 4. These coefficients were varied by 15% and the standard errors of estimate (SEE) and the coefficients of determination ( $R^2$ ) of the fit were compared for different *k* coefficients as well as the mean cumulative *ETA* from June to harvest. The same approach was used for the  $z_r$  coefficients.

The *k* coefficient value for each stage was validated against an independent data set collected at l'Assomption, Quebec in 1988 and 1989 on a sandy soil (Achigan Series) planted in 'Norchip'. The 2.7 ha field was irrigated with a fixed sprinkler system in 1988 except for a 0.7 ha CON area. One pair of rods was installed from 0 to 0.40 m in both the IRR and CON treatments. In 1989, a 3.2 ha field was not irrigated and only one pair of rods was installed. Soil moisture readings were taken a minimum of once a week both years.

The mean cumulative water used (*ETA*) by 'Jemseg', 'Kennebec' and 'Superior' cultivars in each treatment was calculated from planting to harvest. The effects of irrigation scheduling strategies on water use were investigated using IRR treatments of 'Jemseg' and 'Superior' in 1988 and 1989 from June to harvest. The CON and IRR treatments were compared to the strategies usually associated with sprinkler and trickle irrigation. Sprinkler irrigation with emitters spaced approximately 5 m apart was scheduled independently for each cultivar when the soil moisture was at 50% AW and the irrigation water was the amount of water needed to bring the soil to field capacity; surface trickle irrigation was applied every day the soil AW was less than 95% of the maximum AW and the amount corresponded to the *ETA* loss of the previous day. Irrigations were applied between 0600 and 0800 hours when winds were calm. The average water use for stages 3 and 4 was assessed for 'Jemseg' and 'Superior' assuming that the maximum water needed by the plant corresponded to the daily *ETP* multiplied by *k*.

## RESULTS AND DISCUSSION

The *k* coefficients corresponded to five phenological stages. The length of each stage, determined by minimizing the residual mean square, varied somewhat with cultivar (Table I). In model calculations of 'Superior', 'Norchip' and 'Kennebec' water use, stage 1 continued from approximately 0 to 40 days, stage 2 from 40 to 75 days, stage 3 from 75 to 100

**Table I. First date of phenological stages (in Julian calendar days) for four cultivars grown at Ottawa.**

Cultivar	Phenological Stage						Harvest
	S1 Planting	S2 Tuber Initiation	S3 Flowering	S4 Tuber Bulking	S5 Senescence		
Jemseg							
1988	124	153	172	202	254	252	
1989	115	152	171	201	253	221	
Norchip							
1988	124	166	207	224	254	252	
Superior							
1987	128	168	203	228	258	259	
1988	124	164	199	224	254	252	
1989	115	155	190	215	295	260	
Kennebec							
1987	128	173	208	233	258	259	
1988	115	160	195	220	250	257	

days, stage 4 from 100 to 130 days and stage 5 from 130 days to harvest. Note that harvest often occurred before senescence as plants were sprayed to kill above ground growth. Stages for the earlier cultivar 'Jemseg' were shorter: 0 to 30 days (stage 1), 30 to 50 days (stage 2), 50 to 80 days (stage 3), 80 to 120 days (stage 4) and 120 days to harvest (stage 5). The *k* coefficients were interpolated linearly between periods. Based on field observations, roots were assumed to increase linearly with depth during stage 1 and reached 0.40 m at the beginning of stage 2 which corresponded to tuber initiation.

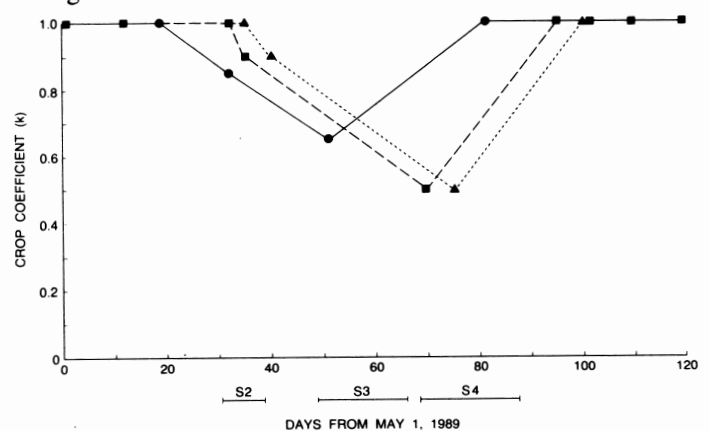
The *k* coefficients from the 5 stages were fit using the Marquardt algorithm (Marquardt 1963). Different *z<sub>r</sub>* constants were also tested and the solution giving the minimum residual sums of squares for a treatment and a cultivar were retained. The fitted values which resulted in the smallest standard errors of estimate (SEE) are presented in Table II with coefficients of determination (*R*<sup>2</sup>). Water use during stage 1 was all from 0 to 0.40 m and the *k* coefficient, which expressed the contribution of the 0 to 0.40 m zone, was at a maximum value of 1. Water use during stages 2, 3 and 4 was also from deeper depths and *k* coefficients decreased (Fig. 1). The low *k* coefficient for stage 4 can be attributed to the combined effect of low soil evaporation due to foliage cover and low plant transpiration due to aging. By stage 5, the plant had senesced and the major contribution to *ETA* came from the soil surface which resulted in the *k* coefficient increasing to 1 (Table II).

For 'Jemseg', 'Superior' and 'Kennebec', the *k* coefficient at the beginning of stage 4 (beginning of tuber bulking) was higher when irrigated (Table II). This indicated that more water from 0 to 0.40 m was used in IRR than in CON plots during the tuber bulking period and it could be explained by the greater amount of water available. This supports the

assumption of Feddes et al. (1988) that water from lower layers is not used if the upper layers are providing the necessary water. Seeding was done at different locations each year and this contributed to the annual variation in the *z<sub>r</sub>* parameters.

The significance of differences between cultivars in the values of the *k* and *z<sub>r</sub>* coefficients was investigated using a sensitivity analysis. Several scenarios were simulated using the eight treatment x cultivar combinations. The original *k* and *z<sub>r</sub>* coefficients were replaced by their mean values and then varied by 15%. Length of each stage was also varied from a mean value ( $\pm 15\%$ ).

A variation of 15% around the mean values of *k* and *z<sub>r</sub>* had no significant effect on water use or statistics for CON and



**Fig. 1. Examples of the contribution of the 0 to 0.40 m zone to total water use during phenological development of Jemseg (●), Superior (■) and Kennebec (▲) in 1989. Beginning of stages S2, S3 and S4 indicate the range in development rates.**

IRR treatments. Use of fitted and mean values gave similar results so it appeared reasonable to use average  $k$  values (0.88 for  $k_3$  and 0.67 for  $k_4$ ) for all cultivars and treatments. However, CON plots were more sensitive to overestimation of  $k_4$  and water use was also overestimated; IRR plots seemed to be sensitive to underestimation of both  $k_3$  and  $k_4$ . Varying  $k$  and  $z_r$  had different effects on the water use of cultivars and treatments depending on the original fitted values. Underestimating  $z_r$  tended to overestimate ETA in both CON and IRR plots.

support scheduling sprinkler irrigation at 50% AW (Meyer and Green 1980; Dwyer et al. 1987; Singh 1969) but practical aspects, e.g. wind, water availability, human resources and technical limitations, affect irrigation scheduling. To overcome these practical constraints, water use was simulated with theoretical thresholds accurately applied for each cultivar. Trickle irrigation, on the other hand, is based on a different water management concept than sprinkler irrigation. A drip irrigation system is usually operated on a daily basis, replenishing each day the exact amount of soil water

**Table II. Crop coefficients ( $k$ ), soil parameters ( $z_r$ ), standard errors of estimate (SEE) and coefficients of determination ( $R^2$ ) generated from the best fits to soil moisture data. N represents the number of soil moisture measurements fit.**

Cultivar	$k$ -coefficient for each stage					$z_r$ parameter			SEE %	$R^2$ %	N
	S1	S2	S3	S4	S5	1987	1988	1989			
<b>Jemseg</b>											
CON	1.0	1.0	0.85	0.65	1.0		0.20	0.30	1.52	88.1	36
IRR	1.0	1.0	0.85	0.95	1.0		0.43	0.55	1.55	89.5	43
<b>Norchip</b>											
CON	1.0	1.0	0.80	0.65	1.0		0.30		1.16	94.5	25
IRR	1.0	1.0	0.80	0.65	1.0		0.30		2.41	86.0	26
<b>Superior</b>											
CON	1.0	1.0	0.90	0.50	1.0	0.60	0.21	0.38	1.76	89.0	74
IRR	1.0	1.0	0.90	0.60	1.0	0.50	0.54	0.43	2.47	84.3	77
<b>Kennebec</b>											
CON	1.0	1.0	0.90	0.50	1.0	0.60		0.38	1.24	91.2	49
IRR	1.0	1.0	0.90	0.60	1.0	0.67		0.43	2.63	55.0	54

Table III shows accumulated  $ETA$  and statistics from the model validation on independent data collected at l'Assomption. Mean  $k$  and  $z_r$  values along with the fitted 'Norchip'  $k$  values from Table II and the  $z_r$  values fitted to l'Assomption data were used in different combinations. Once again there were no significant differences between the mean  $k$  value and fitted values. However, it was found preferable to fit the  $z_r$  value to data as close to the site as possible; this was particularly obvious from the SEE data in the IRR treatment. Figure 2 shows the observed and estimated data from combinations 1 (fitted  $k$  and  $z_r$ ) and 3 (mean  $k$  and  $z_r$ ). Combination 3 tended to underestimate the soil moisture from 0 to 0.40 m, particularly in the IRR treatment, since the fitted  $z_r$  was greater than the mean  $z_r$ .

Accumulated  $ETA$  for 'Jemseg', 'Kennebec' and 'Superior' were computed from 1989 CON and IRR treatments. The six curves are shown in Fig. 3. The differences in the curves are due to soil drying characteristics ( $z_r$ ) and cultivar specific phenology ( $k$ ). For all cultivars, the rate of accumulation of  $ETA$  tended to decrease earlier in CON treatments, around 60 days from seeding (or at tuber bulking). The larger accumulation in IRR is consistent with the larger leaf area and later senescence noted by Dwyer and Boisvert (1990).

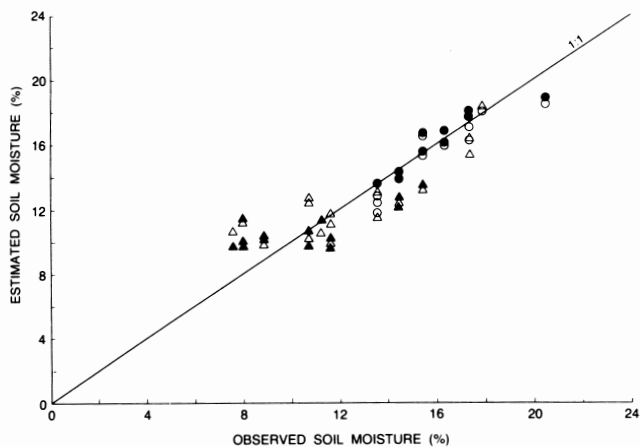
Sprinkler irrigation management can be based on either a fixed irrigation amount (e.g. 20 mm) or a soil water content level, such as in our experiment. Theoretical considerations

**Table III. Validation statistics for Norchip at l'Assomption, Quebec, using combinations of mean ( $k_3, k_4; z_r$ ) and fitted ( $k_3, k_4; z_r$ ) coefficient values. The number of soil moisture observations is 19 for CON and 13 for IRR.**

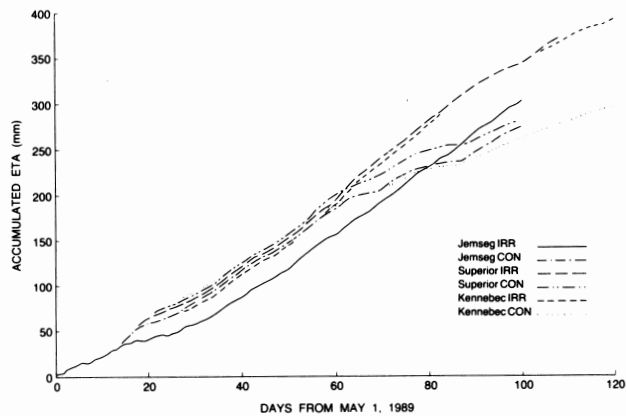
Combinations	CON		IRR	
	SEE (%)	$R^2$ (%)	SEE (%)	$R^2$ (%)
$k_3, k_4, z_r$	1.52	81.0	0.65	89.7
$\bar{k}_3, \bar{k}_4, \bar{z}_r$	1.56	80.8	0.74	88.0
$\bar{k}_3, \bar{k}_4, \bar{z}_r$	1.88	68.2	1.37	83.6
$k_3, k_4, \bar{z}_r$	1.90	67.2	1.15	86.0
$\bar{k}_3: 0.88$	$k_3: 0.80$			
$\bar{k}_4: 0.67$	$k_4: 0.65$			
$\bar{z}_r: 0.38$	$z_r: 0.11$ (CON 1988), 0.53 (IRR 1988, CON 1989)			

used by the crop the day before (Pleban and Israeli 1989). This amount can also be fixed and irrigations skipped by one or more days when rainfall occurs (Sammis et al. 1990).

Table IV shows the accumulated  $ETA$  and the statistics generated for four scenarios: 1) rainfed control; 2) actual scheduled irrigation; 3) sprinkler irrigation (addition of water to bring soil moisture to field capacity when soil moisture



**Fig. 2. Comparison of the observed and estimated soil moisture (%) at l'Assomption for CON ( $\Delta$ ,  $\blacktriangle$ ) and IRR ( $\circ$ ,  $\bullet$ ) treatments of 'Norchip' using fitted  $k$  and  $z_r$  coefficients (solid symbols) and mean  $k$  and  $z_r$  coefficients (open symbols).**



**Fig. 3. Estimated water use (mm) during the 1989 season for 'Jemseg', 'Superior' and 'Kennebec' under IRR and CON conditions.**

**Table IV. Accumulated ETA and water added (precipitation + irrigation) using different management strategies of irrigation. Based on Jemseg and Superior, 1988 and 1989, IRR data.**

Scenarios	Accumulated ETA (mm)				Water added (mm)			
	Jem 88	Jem 89	Sup 88	Sup 89	Jem 88	Jem 89	Sup 88	Sup 89
1. Rainfed	236	177	237	234	346	183	346	186
2. Actual schedule	347	246	340	287	518	329	518	333
3. Sprinkler irrigation <sup>1</sup>	387	274	350	285	566	322	527	275
4. Trickle irrigation <sup>2</sup>	388	287	362	290	609	393	593	371
Mean daily water used <sup>3</sup>	3.9	4.2	3.7	3.8				
PET <sup>4</sup>	411	307	411	341				

<sup>1</sup>Irrigation applied when fraction of available water was below 50%. Water added by irrigation was the amount required to bring the soil to field capacity.

<sup>2</sup>Irrigation was applied when fraction of available water was below 95%. Water added was the actual evapotranspiration on the previous day.

<sup>3</sup>Time intervals: 2 June to 8 September (Jemseg, Superior 1988);  
3 June to 9 August (Jemseg 1989);  
3 June to 17 August (Superior 1989).

<sup>4</sup>Potential evapotranspiration.

< 50% AW); and 4) trickle irrigation (addition of water equal to *ETA* of previous day every day soil moisture < 95% AW). Scenario 4 (trickle simulation) was much more costly in water with little or no significant gain in *ETA* compared to scenario 3 (sprinkler simulation). This high water requirement is partly related to the problem of rainfall distribution that can cause overwatering in humid climates (Broner and Lambert 1989). A good manager could have reduced this simulated water added by taking into account rainfall forecasts. A different soil moisture threshold of 70% rather than 95% could also have reduced the water added closer to the amount from scenario 3, without significant reduction in *ETA*. When comparing our management (scenario 2) with the theoretical scenario 3, we reached the same *ETA* with 'Superior' in 1989 but with much more water. This can be explained by the fact that we irrigated when the mean deficit of the three irrigated plots was greater than 50% AW; the soil where 'Superior' measurements were made however had a greater maximum AW than the two others. The excess water did not bring any gain in terms of *ETA*. In 1989, for the same amount of water, scenario 3 had a higher accumulated *ETA* than our management for 'Jemseg' since irrigation sometimes had to be delayed due to practical constraints. The importance of irrigation timing was also demonstrated.

Table IV shows that in 1988, each 1 mm of supplemental water added could have resulted in about 1 mm of supplemental *ETA* for both cultivars. Using scenario 4, the fraction of available water remained between 0.95 and 1.0 through both seasons for both cultivars. Based on Eqs. 1 and 2, it appeared that the accumulated *ETA* from this scenario was the maximum estimated *ETA* that could be expected from the model as  $z_r$  in all cases was below 0.7. After dividing the accumulation of *ETA* from scenario 4 for each cultivar by the number of days, the mean daily water requirement for potato for the period June to August for these two cultivars was about 4.0 mm/day. This approximates recommendations of agronomists for the region (CPVQ 1983).

### CONCLUSION

Soil moisture budget models are sensitive to crop and soil coefficients. The  $k$  coefficients of the budget used in this study changed according to the phenological stage of the plant. In situations where the rooting zone was limited to a fixed depth, as in irrigation of horticultural crops,  $k$ -coefficients could be set to 1.0 as long as all roots were in the zone for which soil moisture was calculated;  $k$  coefficients decreased as the roots grew deeper than that zone. The sensitivity analysis for two potato cultivars showed that a mean  $k$  value that decreased linearly from 1.0 to 0.88 (day 50 or 75 from planting based on cultivar) then to 0.67 (day 80 or 100) and increased to 1.0 (day 120 or 130) gave reasonable results for study cultivars and treatments. By contrast, results from a validation site suggested that  $z_r$  coefficients should be fitted to data from the study site to get the most accurate results. Although it might not be practical to obtain site specific data, these results indicated the importance of using  $z_r$  coefficients from comparable sites.

Analysis of different strategies showed that both timing and the amount of water applied are important to optimize irrigation. Trickle irrigation as applied in the simulations led to an over use

of water compared to sprinkler irrigation. However, evaporation losses occurring with sprinkler irrigation were not quantified as would be necessary to optimize irrigation. In addition, trickle irrigation required more frequent addition of water. As a result, this method was more likely to apply water before a rainfall which could result in overwatering.

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