Water Budgets to Schedule Irrigation for Vegetables

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Summary. Instrumented rainfall- and groundwater-protected irrigation shelters were used to establish relationships (daily crop factors) between pan evaporation and daily water use for several vegetables. Use of these daily crop factors (water use/pan evaporation) and pan evaporation data for scheduling irrigations are described. Snap bean (*Phaseolus vulgaris* L.) is used to illustrate irrigation scheduling by this method. A table of the model output with columnar headings of age, root depth, date, pan evaporation, crop factor, daily water use, cumulative water use, allowable water use, rainfall, and irrigation is presented. When irrigation was applied according to the model, soil water tension was held below 25 db at 6-inch (15-cm) soil depth. With varying irrigation rates under a line-source irrigation system, marketable pod yields were maximized at 100% of the model rate. Marketable yields of summer squash also were maximized when irrigation was applied at 100% of the model rate. Marketable yields of sweetpotato were not affected by irrigation rates ranging from 1% to 177% of the model rate.

Ease of use and availability of measurement data are important criteria in the selection of a method for scheduling irrigations. Soil and plant water measurements have been used to determine when to irrigate, but they have not been used extensively for irrigation scheduling models (Bruce et al., 1980; Haise and

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Hagan, 1967; Hansen et al., 1980; Stegman et al., 1980).

Estimation of evapotranspiration (ET) by climate-based methods often is used in irrigation scheduling models, but calibration for specific crops and local conditions often has been required. Climate-based methods of estimating ET incorporate measurements of air temperature, air movement, solar radiation, and relative humidity. Pan evaporation (E_p) combines these climatic conditions and has been used to estimate ET (Jensen and Middleton, 1970). A single adjustment of E_p data for estimation of ET was used, but the single-crop factor value often caused excessive water applications during the early stages of crop growth when water use by the crop was low.

Model development. The irrigation scheduling model uses the water balance technique described by Stegman et al. (1980). The water balance technique simply states that irrigation is applied when the sum of the daily soil water depletions is equal to the allowable soil water depletion. The irrigation scheduling model for snap beans (Smittle et al., 1990) is used to illustrate the development of a simple irrigation scheduling model.

The allowable soil water depletion is determined by the volume of the rhizosphere (root zone) and the fraction of the available water to be removed from it before irrigating. Root growth began 6 days after planting snap bean seeds 1 inch deep, then the root depth increased one-half inch per day until a maximum root depth was attained. Maximum root depth for snap bean is ≈ 16 inches in the Coastal Plain of the southeastern United States (Bruce et al., 1980), but may exceed 36 to 48 inches in areas where physical or chemical conditions of the soil do not inhibit root growth (Mack and Varseveld, 1982). Soil compaction and tillage methods may alter dramatically the maximum root depth. Although our data generally show that yields and water-use efficiency were maximized when snap beans were irrigated at 25 cb (Stansell and Smittle, 1980), we allowed a depletion of 50% of the available soil water (ASW) due to substantial water use at soil water contents above field capacity (Hansen et al., 1980). The allowable soil water depletion (inches) is calculated as:

$$0.5 (a - 4) \times 0.5ASW$$

where a is the number of days after planting.

The sum of the daily water depletions requires the addition of the daily ET, calculated as E_p times the daily crop factor value, and the subtraction of the rainfall since the last irrigation, or rainfall in excess of the allowable soil water depletion. Daily crop factor values for snap beans irrigated at soil water tensions of 25 cb (Stansell and Smittle, 1980) are calculated as:

$$\text{Daily ET} = E_p (0.31 + 0.01a).$$

The irrigation scheduling model for snap beans is represented by the equation:

$$0.5 (a - 4) \times 0.5ASW = D_{a-1} + [E_p(0.31 + 0.01a) - P - I]_a,$$

where crop age (a) is days after planting; effective root depth is $0.5 (a - 4)$ with a maximum of 16 inches; usable water (inch³ per inch³ of soil) is 0.5 ASW, soil water deficit on the previous day is D_{a-1} ; daily depletion is E_p times $0.01a + 0.31$; rainfall (inches) is P ; and irrigation (inches) is I .

Models also have been developed for summer squash, sweetpotato, greens (turnip and mustard), and muskmelon. The irrigation model for summer squash is represented by the equation:

$$0.5 (a - 4) \times 0.5ASW = D_{a-1} + [E_p(0.14 + 0.015a) - P - I]_a,$$

where the maximum root depth is 15 inches. The irrigation model for sweetpotato is represented by the equation:

$$3 + 0.5 (a - 3) \times 0.5ASW = D_{a-1} + [E_p(0.12 + 0.023a - 0.00019a^2) - P - I]_a$$

where the maximum root depth is 12 inches. The irrigation model for greens (turnip and mustard) is represented by the equation:

$$0.5 (a - 3) \times 0.5ASW = D_{a-1} + [E_p(0.365 + 0.0154a - 0.00011a^2) - P - I]_a,$$

where the maximum root depth is 12 inches. The irrigation model for muskmelon is represented by the equation:

$$0.5 (a - 4) \times 0.5ASW = D_{a-1} + [E_p(-0.064 + 0.025a - 0.0002a^2) - P - I]_a,$$

where the maximum root depth is 16 inches.

Data have been collected to establish daily crop factor values for broccoli, cauliflower, lima bean, onion, pepper, and southern pea.

Model validation. The snap bean irrigation scheduling model was validated under solid-set and center-pivot irrigation systems in 1980 (Smittle and Johnson, 1982). A line-source irrigation system, as described by Bauder et al. (1975) and Hanks et al. (1976), was used to verify the snap bean irrigation scheduling model in 1985 and 1986. The line-source irrigation system consisted of a single line of sprinklers spaced 20 feet (6.1 m) apart to provide uniform water application parallel to the irrigation line and continuously decreasing water application with increasing distance from the irrigation line.

The same general cultural practices were used in 1985 and 1986. A rye cover crop was incorporated to a depth of 6 inches (15 cm) before moldboard plowing to a depth of 12 inches (30 cm). Fertilizer at (lb/acre) 25N, 21P, 152K (28kg N, 24 kg P, 170 kg K/ha) and phenamiphos at 6.0 lb a.i./acre (6.7 kg a.i./ha) were incorporated to a depth of 4 inches (10 cm) immediately before seeding. 'Greencrop' snap beans were seeded 1.5 inches (3.8 cm) apart in 36-inch(91-cm) rows on 6-foot (183-cm) beds on 10 Apr. 1985 and 25 Mar. 1986. Metalochlor at 2.9 lb a.i./acre (3.2 kga.i./ha) was applied to the soil surface immediately after seeding and was incorporated with 0.5 inch (13 mm) of irrigation. The N sidedress was split, with half applied at expansion of the first trifoliate leaf and the remainder at expansion of the fourth trifoliate leaf. Sidedress rates in 1985 were 50%, 75%, 100%, 125%, and 150% of the recommended total N rate of 100 lb/acre (112 kg/ha) for Georgia. Total N rates in 1986 were 50%, 100%, and 150% of the recommended rate (Granberry et al., 1986).

Split-plot designs with five N rates and two replications and three N rates and four replications were used in 1985 and 1986, respectively. The N plots were 20 $\times$ 48 feet (6.1 $\times$ 14.6 m) with seven irrigation depth plots within each N plot. The irrigation depth plots were 20 feet (6.1m) of a bed 6 feet (1.83m) wide. The beds were parallel to the irrigation line, and irrigation amounts decreased as distance from the irriga-

tion line increased. The irrigation line was placed on a central guard bed and the third bed from the line received irrigation according to the model. The amounts of water applied to each bed on both sides of the irrigation line were measured at each irrigation. Soil water tensions at 6 inches (15 cm), 12 inches (30 cm), and 18 inches (46 cm) in the first, third, fifth, and seventh beds were monitored with cylindrical gypsum block sensors using a Delmhorst Model KS-1 meter.

Plants from 5 feet (1.52 m) × 6 feet (1.83 m) areas of each plot were removed, counted, and weighed. Pods were removed and a 2-lb (0.9-kg) sample was graded to remove non-marketable pods, and marketable pods were weighed.

Data were analyzed by regression analyses using the general linear models procedure of SAS (SAS Institute, 1982).

Results and discussion

For ease of use and record-keeping, a tabular format, with column headings of age, root depth, date, E_p , crop factor, daily water use, cumulative use, allowable use, irrigation, and rainfall was used. In this format, data for age, root depth, crop factor, and allowable use were calculated when the table was developed. Data entries for 15- to 30-day-old snap beans are presented in Table 1. On 9 Apr. 1986,

data for date and E_p (0.18 inch) were entered. The value for E was multiplied by the crop factor (6.47) to give a daily use of 0.08 inch. The daily use is added to the cumulative use on day 14 (0.09 inch) and the cumulative use value of 0.17 for day 15 is recorded. The cumulative use value is less than the allowable use; therefore, irrigation was not required on 9 Apr. An E of 0.36 inch on 10 Apr. produced a daily water use of 0.12 inch and a cumulative use of 0.34 inch. The cumulative use exceeded the allowable use of 0.30 inch for 16-day-old snap beans; therefore, the snap beans were irrigated with 0.34 inch of water on 10 Apr. Water measurement showed that the model rate plots received 0.35 inch of irrigation. Pan evaporation of 0.24 inch on 11 Apr. produced daily and cumulative water use of 0.12 inch. Daily water use of 0.06 inch and rainfall of 0.10 inch on 13 Apr. reduced cumulative water use by 0.04 inch. During this 15-day period when rainfall of 0.10 and 0.05 inch occurred on days 19 and 25, irrigations with 0.35, 0.42, 0.58, and 0.72 inch of water were applied on days 16, 21, 26, and 30, respectively.

For a Tifton loamy sand soil having an ASW capacity of 0.1 inch per inch of soil depth, the allowable soil water deficit increased 0.025 inch (0.64 mm) per day until the maximum al-

lowable use of 0.80 inch of water was attained 36 days after seeding. If the model were used for a soil having an ASW of 0.21 inch of water per inch of soil depth, as in Oregon (Mack and Varseveld, 1982), the allowable water use would be 210% of the values for the Tifton soil. The maximum allowable water use would be < 0.80 inch if tillage systems (Smittle and Threadgill, 1982) or soil compaction (Smittle and Williamson, 1977) reduced the maximum root depth.

In 1985, the model scheduled six irrigations with a total of 3.94 inches (100 mm) of water (Table 2). The snap beans received a total of 5.83 inches (148 mm) of rainfall on seven dates. In 1986, the snap beans intercepted 1.22 inches (31 mm) of rainfall, with 0.87 inch (22 mm) occurring 49 days from seeding (Table 2). The model called for 11 irrigations totaling 7.72 inches (196 mm) of water (Table 2).

The number of irrigations and the amount of water applied in 1985 and 1986 were less with the model than with the method presently recommended in Georgia. Using Georgia irrigation recommendations of two or three applications of 0.3 to 0.5 inch water/week (Granberry et al., 1986), 13 to 16 irrigations with a total of 6.5 to 8.0 inches of water would have been applied in 1985 and 15 to 20 irrigations with a total of 7.5 to 9.0 inches of

Table 1. *Tabular format of the snap bean irrigation scheduling model $0.05(a - 4) \times 0.5ASW = D_{a-1} + [E_p(0.31 + 0.01a) - P - I]/a$. 'Soil, Tifton loamy sand (0.1 inch/inch ASW).*

Age (DAP)	Root depth (inch)	Date (April)	E_p Evaporation (inch)	Crop factor	Daily use (inch)	Cumulative use (inch)	Allowable use (inch)	Irrigation (inch)	Rain (inch)
15	5.5	<u>9</u>	<u>0.18</u>	0.47	<u>0.08</u>	<u>0.17</u>	0.28		
16	6.0	<u>10</u>	<u>0.36</u>	0.48	<u>0.17</u>	<u>0.34</u>	0.30	<u>0.35</u>	
17	6.5	<u>11</u>	<u>0.24</u>	0.49	<u>0.12</u>	<u>0.12</u>	0.33		
18	7.0	<u>12</u>	<u>0.25</u>	0.50	<u>0.13</u>	<u>0.25</u>	0.35		
19	7.5	<u>13</u>	<u>0.12</u>	0.51	<u>0.06</u>	<u>0.21</u>	0.38		<u>0.10</u>
20	8.0	<u>14</u>	<u>0.16</u>	0.52	<u>0.08</u>	<u>0.29</u>	0.40		
21	8.5	<u>15</u>	<u>0.22</u>	0.53	<u>0.12</u>	<u>0.41</u>	0.43	<u>0.42</u>	
22	9.0	<u>16</u>	<u>0.16</u>	0.54	<u>0.09</u>	<u>0.09</u>	0.45		
23	9.5	<u>17</u>	<u>0.34</u>	0.55	<u>0.19</u>	<u>0.28</u>	0.48		
24	10.0	<u>18</u>	<u>0.20</u>	0.56	<u>0.11</u>	<u>0.39</u>	0.50		
25	10.5	<u>19</u>	<u>0.20</u>	0.57	<u>0.11</u>	<u>0.45</u>	0.53		<u>0.05</u>
26	11.0	<u>20</u>	<u>0.16</u>	0.58	<u>0.09</u>	<u>0.54</u>	0.55	<u>0.58</u>	
27	11.5	<u>21</u>	<u>0.24</u>	0.59	<u>0.14</u>	<u>0.14</u>	0.58		
28	12.0	<u>22</u>	<u>0.28</u>	0.60	<u>0.17</u>	<u>0.31</u>	0.60		
29	12.5	<u>23</u>	<u>0.34</u>	0.61	<u>0.21</u>	<u>0.52</u>	0.63		
30	13.0	<u>24</u>	<u>0.22</u>	0.62	<u>0.14</u>	<u>0.66</u>	0.65	<u>0.72</u>	

To operate the model, values for age (a) are recorded; values for root depth are calculated as $0.5(a - 4)$; values for crop factor are calculated as $0.31 + 0.01a$; values for allowable use are calculated as root depth times 0.5ASW; data for date and pan evaporation are recorded; pan evaporation data are multiplied by the crop factor values to calculate daily use; daily use value is added to previous day's cumulative use; and data for today irrigation and rainfall are subtracted from today cumulative use. Irrigation is applied when cumulative use approximates allowable use.

Table 2. **Water application rates to 'Greencrop' snap beans.**

Irrigation rate ^z	1985			1986		
	Inch	(mm)	Percentage of model	Inch	(mm)	Percentage of model
1	5.71	(145)	145	13.94	(354)	180
2	4.72	(120)	120	11.58	(294)	150
3	3.94	(100)	100	7.72	(196)	100
4	2.83	(72)	72	6.14	(156)	80
5	2.16	(55)	55	5.04	(128)	65
6	1.50	(38)	38	3.43	(87)	44
7	0.12	(3)	3	0.31	(8)	4
Rainfall	5.83	(148)		1.22	(31)	

^zAll plots received an additional 0.50 inch (13 mm) of irrigation after seeding. Irrigation rate 3 was determined by the irrigation scheduling model. Other rates reflect water application gradients produced by the line-source irrigation system.

water would have been applied in 1986. The line-source irrigation system provided irrigation amounts ranging from 4% to 180% of the model.

In 1986, irrigation at 100% of the model rate maintained the soil water tension at the 6-inch (15-cm) depth below 25 cb unless the cumulative water use exceeded the allowable use (Table 3). The cumulative water use at the time of irrigation exceeded the allowable use by 0.11 inch (2.6 mm), 0.13 inch (3.2mm), and 0.21 inch (5.1 mm) on days 39, 47, and 54, respectively. Excessive cumulative uses of 0.13 inch and 0.21 inch on days 47 and 54 resulted in soil water tensions of 46 cb and 133 cb, respectively, when water was applied at the model rate. On day 46, the model showed a cumulative use of 0.71 inch (18 mm) of water. On this date, the soil water

tension at the 6-inch depth was 18 cb. With an allowable use of 0.80 inch of water, irrigation could have been applied, but it was not applied until day 47, to check the response to the model. The model called for an irrigation (0.77-inch cumulative use) on day 53. The soil water tension at the 6-inch depth was 34 cb on this day, but high wind required that irrigation be delayed 1 day to assure a uniform water application gradient with the line-source system. This delay resulted in the 133-cb water tension on day 54. These results and soil water tensions < 25 cb when the cumulative water use did not exceed the allowable use indicate that the model was effective in scheduling snap bean irrigations.

When water was applied at 180% of the model rate, soil water tension at the 6-inch soil depth exceeded 25 cb

only on day 54. The soil water tension at the 6-inch depth exceeded 25 cb at all irrigations when ≤ 65% of the model rate of water was applied.

In 1985, pod yield was higher, but marketable yield was little affected with water application rates > 100% of the model (Table 4). Water application rates greater than the model increased lodging of the plants and increased the nonmarketable pods due to decay. Total and marketable pod yields were lower when irrigations were applied at less than the model rate. Water application rates substantially less than the model also increased the percentage of nonmarketable pods.

In 1986, total and marketable pod yields were lower when water application rates were either greater or less than the model rate (Table 4). The magnitude of the yield response differences to irrigation rates in 1985 and 1986 was attributed to variations in total water intercepted by the crops. Total water (rainfall plus irrigation) intercepted by the snap beans ranged from 63% to 117% of the model rate in 1985 and from 22% to 166% of the model rate in 1986.

Pod yields were not affected by N fertilization in 1985, but in 1986 total N application of 50, 100, and 150 lb/acre produced marketable pod yield of 2.1, 2.7, and 2.9 tons/acre, respectively, when averaged across all irrigation rates. Maximum response to all N rates occurred when irrigation was applied at the model rate. Marketable

Table 3. **Rainfall and irrigation applied and soil water tensions during growth of 'Greencrop' snap beans in 1986.**

DAP	Water use (inch)		Water applied (inch)		Irrigation (% of model)			
	Allowable	Cumulative	Rainfall	Irrigation ^z	180	100	65	0
						<i>Soil water tension (cb)^y</i>		
14	0.19	0.25	0.08	0.25	---	---	---	---
16	0.26	0.34	---	0.35	---	---	---	---
19	0.34	0.23	0.10	---	---	---	---	---
21	0.40	0.41	---	0.42	---	---	---	---
25	0.51	0.45	0.05	---	17	18	27	32
26	0.54	0.54	---	0.58	16	16	34	119
30	0.66	0.66	---	0.72	16	15	42	118
36	0.80	0.87	---	0.89	19	21	49	148
39	0.80	0.91	---	0.95	16	22	28	210
43	0.80	0.81	---	0.88	18	18	57	210
47	0.80	0.93	---	0.99	24	46	57	210
49	0.80	0.34	0.86	---	18	18	17	12
54	0.80	1.01	---	0.99	91	133	137	55
56	0.80	0.12	0.17	---	18	18	17	127
59	0.80	0.71	---	0.70	22	23	29	139

^zIrrigation depth applied by the model rate (100%).

^ySoil water tension measured at 6-inch (15-cm) depth.

Table 4. *Yield and quality responses of 'Greencrop' snap beans to irrigation rates.*

Irrigation rate ^z	Pod yield (tons/acre)			
	Total		Marketable	
	1985	1986	1985	1986
1	5.7	3.3	4.6	2.3
2	5.2	4.7	4.5	3.7
3	5.2	5.0	4.5	4.0
4	4.7	4.8	4.0	3.5
5	4.4	4.0	3.5	3.0
6	4.1	2.8	3.3	1.6
7	3.3	0.5	2.7	0.2
Significance ^y	L**Q**	L**Q**	L**Q**	L**Q**

^zIrrigation rate 3 was determined by the irrigation scheduling model. Rates 2 and 1 represent progressively greater water applications, and rates 4, 5, 6, and 7 represent progressively smaller water applications by a line-source irrigation system (see Table 1).

^yLinear (L **) and quadratic (Q*) significant at $P = 0.01$.

pod yields with the model irrigation rate and N rates of 50, 100, and 150 lb N/acre were 3.1, 4.3, and 4.6 tons/acre, respectively. Both maximum yield and the magnitude of the N response were lower when the irrigation rate was greater or less than the model rate.

The irrigation model for summer squash was tested under a line-source irrigation system during Spring 1986, 1987, and 1989. With rainfall representing about one-fourth of the total water applied at the model rate, marketable fruit yields of 'Dixie' summer squash showed both a linear and a quadratic response to the irrigation rates produced by the line-source irrigation system (Table 5). Marketable fruit yields were maximized when irrigation was applied at the model rate. Soil water tensions exceeded 25 cb at only one date when irrigation was ap-

plied at the model rate. When water was applied at less than the model rate, the soil water tension exceeded 25 cb on about half of the irrigation dates.

The irrigation model for sweetpotato was tested under a line-source irrigation system during 1988 and 1989. With rainfall representing about two-thirds of the total water applied at the model rate, marketable root yields of 'Jewel' sweetpotato were not affected by irrigation (Table 5). Soil water tensions in the upper 12 inches of soil did not exceed 25 cb when water was applied at 82% of the model rate. Soil water tension measurements indicated significant water extraction from soil depths of 18 inches by 'Jewel' sweetpotatoes 75 days after transplanting. The lack of a yield response to irrigation was attributed to the recharge of the soil profile by the rela-

tively frequent rainfall and to water use from soil profile depths greater than that controlled by irrigation at the model rate.

We have shown that the frequency and depth of irrigation for snap beans can be scheduled effectively with a simple irrigation model. The model maximized marketable pod yield of snap bean in years when rainfall was 1.22 inches (31 mm) and 5.83 inches (148 mm) during production of the snap bean crop and with N fertilization rates ranging from 50% to 150% of the recommended rate. The model for summer squash also effectively scheduled irrigations. Sweetpotato did not show a significant yield response to irrigation. Validation of irrigation models for turnip and mustard greens and for muskmelon are not complete at this time.

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Table 5. *Effect of irrigation rates on yield of 'Dixie' summer squash and 'Jewel' sweetpotato.*

Dixie summer squash ^z			Jewel sweetpotato ^y		
Irrigation rate		Marketable yield (tons/acre)	Irrigation rate		Marketable yield (tons/acre)
Percentage of model	Inches		Percentage of model	Inches	
148	11.4	12.3	177	19.5	10.9
127	9.8	13.6	166	18.3	10.3
100	7.7	14.4	143	15.7	9.6
86	6.6	13.6	121	13.3	10.2
69	4.9	11.5	100	11.0	10.2
50	3.9	11.3	82	9.0	9.3
6	0.5	6.6	63	6.9	9.2
			44	4.8	11.2
			24	2.6	10.8
			10	1.1	10.5
			1	0.1	10.2
Rainfall (inches)		4.5		19.2	
Significance ^x		L**Q**			NS

^zValues for 'Dixie' summer squash are averages of 1986, 1987, and 1989 seasons.

^yValues for 'Jewel' sweetpotato are averages of 1988 and 1989 seasons.

^xLinear (L**) and quadratic (Q**) effect of irrigation rate significant at $P = 0.01$ or nonsignificant (NS).

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