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SIMULATION-BASED IRRIGATION SCHEDULING AS A WATER MANAGEMENT TOOL IN DEVELOPING COUNTRIES[†]

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ABSTRACT

An Irrigation District Decision Support System (IRDDESS) is described and applied to a large irrigation scheme in the Middle Awash Valley of Ethiopia. Crop yields are simulated over a 12-year period in order to determine which of 12 separate irrigation schedules in use meet certain specified objectives. IRDDESS is a crop growth and irrigation district simulation model capable of predicting biomass development and yields for fields varying in soil type and irrigation management scenarios. IRDDESS also tracks water demand in the distribution system. Results show which of the 12 schedules will meet specific objectives of maximizing yields or minimizing water use and illustrate the potential of such decision support system in evaluation and management of large irrigation schemes. Copyright © 2001 John Wiley & Sons, Ltd.

KEY WORDS: irrigation scheduling; irrigation water management; irrigation decision support system; crop growth simulation

RÉSUMÉ

Un Système d'Aide à la Décision pour Districts d'Irrigation (IRDDESS) est décrit et appliqué à un projet d'irrigation important dans la Vallée Moyenne de l'Awash en Ethiopie. Les rendements sont simulés sur une période de douze ans afin de déterminer lesquels des douze programmes d'irrigation utilisés atteignent certains objectifs fixés au préalable. IRDDESS est un modèle de croissance de culture et de simulation de district d'irrigation capable de prédire le développement de biomasse et les rendements pour des exploitations à types de sols et à scénarios de gestion d'irrigation variables. IRDDESS enregistre également la demande en eau dans le système de distribution. Les résultats montrent lesquels des douze programmes vont atteindre les objectifs fixés et maximiser les rendements ou minimiser l'utilisation d'eau. Ces résultats illustrent également le potentiel d'un tel système d'aider à la décision pour l'évaluation et la gestion de projets d'irrigation à grande échelle. Copyright © 2001 John Wiley & Sons, Ltd.

MOTS CLÉS: établissement du programme d'irrigation; gestion de l'eau d'irrigation; systèmes interactifs d'aide à la décision d'irrigation; simulation de croissance de collecte

INTRODUCTION

The performance of irrigation systems in many parts of the world is generally perceived to be poor compared to design intentions and investment expectations (World Bank, 1990). In many parts of the world, irrigation is based on traditional methods of water distribution and application. Often, traditional irrigation methods fail to meet the variable water demands of different crops due to inadequate management of soil water (Gardner, 1992). Many irrigation systems were laid

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out when land and water appeared unlimited. Rehabilitation of schemes and design of new ones continue to be based on old concepts of unlimited water resources in many parts of the world (World Bank, 1990). Recent advances in irrigation technology and knowhow now make it possible to maintain nearly optimal soil water conditions (Hillel, 1990). However, the infrastructure, resources and expertise to install, operate and maintain advanced irrigation systems such as drip, and surge flow, are not available in many developing countries.

Alternative ways for improving water management practices are needed. One option is to utilize data on such variables as climate, soils, hydrology, agriculture and management, commonly collected in many irrigation areas, and formulate decision support tools to develop water delivery strategies which more closely meet crop water requirements. The growth of computer technology provides the opportunity to move beyond record keeping. Advances in the understanding of the physical, chemical, and biological environment of the soil–plant–atmosphere continuum, and environmental monitoring technology offer us the opportunity to base crop performance and assessment on sounder scientific principles (Jones and Ritchie, 1990).

In this paper, we demonstrate the potential use of such a decision support system to analyze current irrigation scheduling and to determine which schedules meet specified objectives. We illustrate this process in an analysis of cotton production in a large irrigation scheme in the Middle Awash Valley of Ethiopia using the Irrigation District Decision Support System (IRDDESS), a crop growth, irrigation scheduling and district simulation model developed at Texas A&M University (Endale, 1995).

Background

The Middle Awash located in the Middle Awash Valley of East Central Ethiopia (latitude 9°16′ North and longitude 40°9′ East) is one of the most intensely irrigated parts of the country with cotton as the dominant crop. It lies at about 740 m above mean sea level in an area with semiarid climate with temperatures ranging from 15–30 °C in December to 25–40 °C in May/June (World Bank, 1977). The "long rains" occurring from July to September account for 49% of the 550 mm annual rainfall. The "short rains" from February to April account for 29%. December is the driest month with little or no rain. Potential evapotranspiration varies from 5.5 mm day^{-1} in January to 8.7 mm day^{-1} in June. The soils have been grouped under alluvia and vertisol, for practical purposes of irrigation.

A major portion of the irrigation infrastructure was constructed from 1970 to 1985 under the guidance of international consultants. A number of separate institutions operated portions of the 10300 ha net irrigated area developed during this period. The three primary institutions were the State Farms (8000 ha), the Settlement Farm (2000 ha) and the Research Farm (300 ha). The project office through its consultants also advised these entities on farm operations including irrigation scheduling and management.

Institutional accountability led to the development of different estimates of crop water requirements and irrigation schedules for cotton. There were at least 12 separate irrigation schedules implemented for cotton during this period (AIP, 1984). As would be expected, yields were highly variable among the farms. Rapid rise of the groundwater level during this period also added to problems of water management. In order to insure long-term viability of irrigation, it was vital to identify which of the competing irrigation strategies minimized return flow and percolation while maintaining economically viable yields.

METHODS

IRDDESS, a generic crop growth and irrigation district simulation model, was used to analyze the cotton water demand and yield relationships under the 12 most common irrigation schedules.

Model summary

IRDDESS can simulate potential crop production and corresponding water demand of various crops under different irrigation alternatives while assessing the ability of the supply system to meet this demand. Only the growth simulation module is described and utilized in this paper. The simulation uses a generic crop model (can be used for different crops) similar to that described in Driessen and van Diepen (1986), and Driessen and Konijn (1992). The approach is to predict daily dry matter production at a series of hierarchical levels. At the highest level, dry matter production is determined by radiation, temperature and crop genetics. This represents the highest potential production for a specific crop at a location. At the next level, this highest potential is reduced by an amount equivalent to any water stress experienced by the crop. Other stress factors such as nutrients, pests etc., are similarly considered at subsequent levels. Daily dry matter production is calculated at the first two levels only in IRDDESS. Pests and diseases are assumed to be under optimal control and nutrients under optimal supply.

The crop model includes equations and functions for a number of crop growth processes, including photosynthesis, respiration and biomass partitioning into plant parts, to predict daily dry matter production, yield and root zone development which are then integrated over time. The effect of soil water stress is taken into account by adding to the potential production analysis a soil water balance algorithm that accounts for water fluxes to and from the root zone that include precipitation, irrigation, surface storage, infiltration, capillary rise, evaporation, transpiration and percolation. An empirical relationship suggested by Rijtema (1965) is used to describe the relationship between soil hydraulic conductivity and soil matric suction. Soils are considered homogeneous within a field but can vary from field to field. The ratio of actual to potential evapotranspiration indicates the level of the water stress. Dry matter production is curtailed in proportion to this stress factor (de Wit, 1958). Water stress scenarios can be considered under natural rainfall only (dryland production) or under irrigation based on critical soil water, management-allowed depletion, or pre-established irrigation schedule. The latter is used for the analysis in this paper. Input data required for the crop model for management, crop and soil, and weather are given in the Appendix. Default coefficients found in the literature are used for the required crop and soil parameters. These can easily be replaced with known local values which can improve prediction of dry matter production.

IRDDESS has been evaluated for three cases. The model prediction was compared to experimental data from Greece for maize and cotton kindly provided by Danalatos (1993). IRDDESS predicted maize dry matter production and yield within 6% of measured values for one maize variety and 14% for a second. Cotton dry matter and yield were predicted within 8% of measured values (Endale, 1995). It produced reasonable and consistent results for dryland cotton yields in the Rio Grande Valley of Texas and determined the effects of water stress by both excessive and insufficient soil water levels (Endale, 1995; Fipps and Endale, 1996). The model also predicted reasonably well cotton yields under actual irrigation in the Middle Awash which is discussed later.

Middle Awash irrigation schedules

Details of the 12 most common irrigation schedules are given in Table Ia and b. International consultants proposed various irrigation schedules (schedules 1–5) which were modified over time, based on feedback from new farms, in order to improve production and water management. Operating entities sometimes adopted some of these schedules. Schedules 6–8 were usually independently practiced by State Farms while schedule 9 was the Settlement Farm's established practice. The Research Farm proposed schedules 10–12 based on research on small fields. These schedules varied in the number and amount of, as well as the interval between, irrigations. Opinions on pre-irrigation strategies also differed. The Research Farm proposed planting first then irrigating immediately afterwards. In the Settlement and State Farms the first irrigation occurred 2 days

Table I. Details for schedules 1–6 (a) and 7–12 (b) of the 12 most common irrigation schedules used in the Middle Awash, Ethiopia, during the period 1970–83

Irrigation number	Irrigation schedule*											
(a)	1		2		3		4		5		6	
	day	mm	day	mm	day	mm	day	mm	day	mm	day	mm
Pre-irrigation	−15	200	−12	200	−12	200	−8	200	–	–	–	–
1	3	100	3	98	3	91	20	91	3	91	3	70
2	24	100	30	98	30	91	41	91	24	91	18	70
3	45	100	51	98	51	91	55	91	38	91	33	70
4	66	100	65	98	65	91	69	91	52	91	48	70
5	87	100	79	98	79	91	83	91	66	91	63	70
6	108	100	93	98	93	91	104	91	87	91	78	70
7	–	–	114	98	114	91	125	91	108	91	93	70
8	–	–	135	98	135	91	–	–	129	91	108	70
9	–	–	–	–	–	–	–	–	–	–	123	70
Total irrigation		800		984		928		837		728		630

(b)	7		8		9		10		11		12	
	day	mm	day	mm	day	mm	day	mm	day	mm	day	mm
Pre-irrigation	–	–	–	–	–	–	–	–	–	–	–	–
1	3	50	3	91	3	105	1	150	1	125	1	150
2	13	50	18	91	24	105	15	75	22	125	22	75
3	23	50	33	91	45	105	29	75	43	125	36	75
4	33	50	48	91	66	105	43	75	65	125	50	75
5	43	50	63	91	87	105	57	75	86	125	64	125
6	53	50	78	91	108	105	71	75	107	125	85	125
7	63	50	93	91	129	105	85	75	128	125	106	125
8	73	50	108	91	–	–	99	75	–	–	127	125
9	83	50	123	91	–	–	113	75	–	–	–	–
10	93	50	–	–	–	–	127	75	–	–	–	–
11	103	50	–	–	–	–	–	–	–	–	–	–
12	113	50	–	–	–	–	–	–	–	–	–	–
13	123	50	–	–	–	–	–	–	–	–	–	–
14	133	50	–	–	–	–	–	–	–	–	–	–
Total irrigation		700		819		735		825		875		875

* Day is irrigation date considering planting date as day 1; mm is the irrigation amount in mm. Schedules 1–5 are by consultants. Schedule 6 is by State Farms. Schedules 7 and 8 are by State Farms. Schedule 9 is by the Settlement Farm. Schedules 10–12 are by the Research Farm. There was no pre-irrigation for schedules 5–12.

after planting. Consultants were generally strongly in favor of pre-irrigation partly on the grounds that it helped fill the soil water reservoir to field capacity and flush salts out of the root zone. Schedule 5, however, had no pre-irrigation. The need for irrigation immediately after planting (2–3 days) when fields have been pre-irrigated was also questioned by operating entities. Clearly these series of variations in irrigation practices reflected the prevailing water management problem in the Middle Awash. While some of the problems could be attributed to institutional and logistical constraints, there was also lack of decision aid tools that could be utilized to analyze the complex factors that come into play in crop production under irrigation.

Yield and water use analysis

Yield prediction by IRDDESS in the Middle Awash was first compared against actual yield as follows. Data for average yield were available for 1983 for four farm units varying in area from 364 to 487 ha (total 1671 ha). There were from 21 to 33 individual fields in each unit. Yields had been consistently good in these units since their commissioning in the previous 1–2 years. The measured average yield from all four units in 1983 was 3553 kg ha^{-1} (varying from 3232 to 3864 kg ha^{-1} among units). Cotton was hand harvested in two to three pickings. The third picking was considered uneconomic if it was less than 600 kg ha^{-1} and was not carried out. Thus the actual yield from these units was closer to 4000 kg ha^{-1}. Simulations were run for 1983 for 15 fields with a total area of 226 ha comprising 2 each from two units, 5 from the third and 6 from the fourth unit. The soil type was similar in all 15 fields. Although their planned irrigation regime was the same, the actual irrigation varied due to management constraints. The actual planting dates and irrigation schedules for each field were used in the simulation. The predicted yield from each of these 15 fields varied from 3128 to 4953 kg ha^{-1}. The mean, standard deviation and coefficient of variation were 4212 kg ha^{-1}, 489 and 11.6%, respectively. The closeness between actual average and predicted yields was considered reasonable. Fertility levels in the virgin and newly commissioned fields were high as were pest and weed control which support the model assumption of optimal nutrient levels and pest and weed control.

Next IRDDESS was used to predict yield under each of the 12 irrigation schedules for the period 1970–83, excluding 1979 and 1982 because of incomplete weather data. In the analysis, crop growth simulations began at emergence, assumed 7 days after planting, on May 10. The initial soil water was adjusted to take into account any irrigation prior to emergence. Simulated yield data were analyzed with the General Linear Models of SAS (SAS Institute, 1990).

RESULTS

The mean annual seed cotton yields over the 12 years from each schedule with statistical differences are presented in Figure 1. The 12 schedules could be placed into 6 groups based on statistical differences of mean yields over 12 years. Means were different between but not within groups.

The first group (schedule 7) produced up to 47% significantly more yield than the other groups. The second group (schedule 10) produced up to 34% significantly more yield than subsequent groups. Mean yield from group 3 (schedules 6 and 8) significantly exceeded that from group 4 and 6 by up to 28%. Group 4 (schedules 5 and 12) produced up to 17% significantly more yield than groups 5 and 6. The five schedules in group 5 (2, 3, 4, 9, 11) produced about 10% significantly more yield than schedule 1 which is in group 6. Yield under any one schedule varied from year to year. The range over the 12 years varied from 1121 for schedule 7 to 2701 kg ha^{-1} for schedule 4.

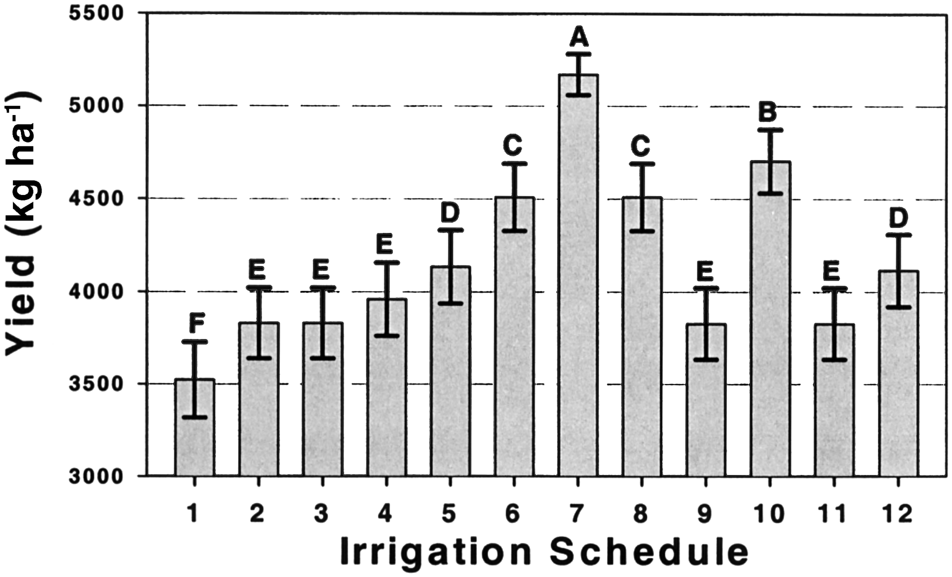

Figure 1. Simulated mean annual cotton yield with standard error bars under 12 irrigation schedules in the Middle Awash, Ethiopia, for 12 years during 1970–83. Mean yields with the same letter are statistically not different at alpha = 0.05

Total water use over the 12 years from precipitation and irrigation, including pre-irrigation, varied from the lowest 11 083 mm by schedule 6 to the highest 15 331 mm by schedule 2. Compared to schedule 6, water uses were higher in other schedules as follows: 8% (# 7), 11% (# 5 and # 9), 18% (# 1), 20% (# 8), 21% (# 10), 22% (# 4), 26% (# 11 and # 12), 32% (# 3) and 38% (# 2). Schedules promoted by consultants were among the highest group of water users primarily because of pre-irrigation. There was no pre-irrigation in schedules 5 and above. Schedule 7, which gave the highest yield, was the second lowest water user. Analysis of 10-day water supply showed that schedule 7 had the least variability with at least 50 mm per 10-day period (data not shown). The other schedules showed variability from no supply to over twice that of schedule 7 during any single 10-day period. Excessive irrigation has a detrimental effect on plant growth by affecting the oxygen supply to roots which is predicted by IRDDESS.

DISCUSSION

Operating institutions had accountability to sometimes unforgiving higher authorities. So while higher yields, less water use, etc., were aspired for, farming operations usually gravitated to meeting minimum standards as a result of sometimes enormous institutional constraints. A long-term yield of 2500 and 3000 kg ha^{-1} was expected from Settlement and State Farms, respectively, that was used to partially justify international funding for irrigation development in the Middle Awash (World Bank, 1977).

Yields were grouped in six statistically different groupings. By selecting those schedules with the least amount of applied water from each of these groups, we can further narrow the choice of schedules and study how they meet further objectives. Table II presents details for these six selected irrigation schedules. Schedule 7, whose water use was the second lowest, maximized the yield. It had, however, the highest number of irrigations and the smallest irrigation interval, and would require more resources to implement. Schedule 6, whose yield was the third highest, minimized the water use. It would require less resources than schedule 7 since irrigation was less

Table II. Irrigation detail, average annual yield in ascending order, and total water use, including from rainfall, over 12 years, for the six schedules with the least amount of applied water from each of the six groups with statistically different yields

Irrigation schedule	Organization	Average annual yield (kg ha^{-1})	Total water use (mm)	Irrigation*		
				number	mm	interval
1	Consultant	3522	13 123	6	100	21
9	Settlement Farm	3827	12 343	7	105	21
5	Consultant	4134	12 259	8	91	14,21
6	State Farm	4509	11 083	8	70	15
10	Research Farm	4703	13 423	10	75	14
7	State Farm	5170	11 923	13	50	10

* Numbers of irrigation, amount in mm per irrigation, and irrigation interval in days.

frequent. Schedule 1 produced the minimum yield of 3522 kg ha^{-1}, which was 17% above the expected long-term mean. It used 18% more water than schedule 6. It had the smallest number of irrigations and the longest irrigation interval. The choice of the "best" schedule would depend on how well the operating entities were able to implement it as specified.

Minimizing excess irrigation become an important issue as more land was developed because of rising groundwater level and associated problems such as salinity, yield reduction and siltation of canals. In a 1984 report (Halcrow, 1984) consultants recommended a 16% reduction in water application from their earlier proposed schedules. The correlation between water use and yield of Table II is very low ($r^2 = 0.21$). As indicated by schedule 6, water use could be reduced without reducing yield.

CONCLUSIONS

Simulation models are powerful tools for analyzing the effect of the amount and timing of irrigation and rainfall on yield. Twelve years of yield analysis in the Middle Awash, Ethiopia, indicated that the 12 common irrigation schedules could be placed in six statistically different groups with respect to mean yield over 12 years. Water use between and within groups varied. Six schedules that had the least water use in each group were then chosen for further analysis. Multiple objectives are usually common in irrigation schemes. Operating entities based the choice of the "best" irrigation schedule not only on yield and/or water use but also (usually more importantly) on the resource required to implement the schedule.

Schedule 1 with its smallest number of irrigations and longest interval probably met this multi-objective criteria best in the Middle Awash. Schedule 7 maximized yield with 18% more water use than the lowest water user. Its accurate implementation was not realistic, especially on a large scale, because of resource limitations. Schedule 6 used the least amount of water and produced the third highest mean yield. Its frequency fell between that of schedules 1 and 7 which was probably manageable in the Middle Awash. This schedule would be the choice in response to concerns of overirrigation. The consultant's recommendation to reduce water application by 16% at the end of the period of this analysis is clearly supported by the analysis through IRDDESS which found that their earlier recommendations were among the highest water users but among the lowest producers. Further analysis could reveal new schedules that would further reduce water use without reducing yield from each existing schedule. The 12 irrigation schedules were practiced irrespective of planting dates. A late planted cotton (late June to early July) would have the benefit of the main rains earlier in its cycle than the early (early May) planted cotton. One would expect different irrigation schedules in this case. Modeling allows us to make the distinction and develop different schedules. Maintaining a sustainable salt balance in the root zone is critical in irrigation. The leaching requirements to achieve this could be included in the analysis of different water use scenarios.

Systems simulation is based on answering many "what if" questions raised by producers and policy makers more quickly than by on-farm trials (IBSNAT, 1993). Arriving at the "best" irrigation schedule through experimental work consumes time, money and effort without guaranteeing answers in a specified time and for all specific scenarios. This is especially true in developing countries with limited resources. In addition to experimentation, the effect of different scheduling strategies can be effectively studied through modeling using actual or stochastically produced long-term weather data. Models must be tested and validated for specific crops and conditions if they are to be meaningfully used as analysis tools. The integrity of the assumptions must be maintained and the limitations recognized in interpreting the results.

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APPENDIX

Table III. Input data required for the crop model for (a) general and management parameters, (b) crop and soil parameters and (c) weather parameters

Type	Variable	Description
(a)		
General	DT	Simulation type step – taken as 1 day here
	WS	WS = 1, no water stress; highest potential yield WS = 2, water stressed; rain and/or irrigation included
	LAT	Latitude (degree)
Management	CROP	Crop type
	GDATE	Germination date
	PDEN	Planting density (kg ha^{-1})
	θ	Initial soil water content (cm^3 cm^{-3})
	IR	IR = 0, no irrigation; IR = 1, irrigation
	IRR	Irrigation regime based on: 1, MAD; 2, θ_{cr}; 3, a given schedule
	MAD	Management-allowed depletion (percent)
	SS	Initial surface storage (cm)
	ZT	Initial water table depth (cm)
	ASSC	Actual surface storage capacity (cm)
	PHI	Average slope of field (degree)
	SIG	Clod or furrow angle (degree – default 35°)
	DR	Furrow depth (cm)
(b)		
Crop	C	Photosynthetic pathway C3 or C4
	SLA_x	Maximum specific leaf area (m^2 kg^{-1})
	SLA_n	Minimum specific leaf area (m^2 kg^{-1})
	KE	Canopy extinction coefficient for visible light
	TH	Threshold temperature for development (°C)
	TLEAF	Heat unit required for full development of leaves (°C d)
	TSUM	Heat unit required for full development of crop (°C d)

Table III. (Continued)

Type	Variable	Description
	R_ORG	Relative maintenance respiration rate for plant organ: leaf, root, stem, or storage organ (kg kg^{-1} d^{-1})
	EC_ORG	Efficiency of assimilate conversion to plant organ: leaf, root, stem, or storage organ (kg kg^{-1})
	TCx	Maximum turbulence coefficient
	DRT	Drought tolerance group
	RDi	Initial rooting depth (cm)
	RDm	Maximum rooting depth (cm)
	RDSroot	Development stage at which root growth ceases
	H_{lf}	Critical leaf water potential (cm)
Soil	θ_{pwp}	Permanent wilting point (cm^3 cm^{-3})
	θ_{fc}	Field capacity (cm^3 cm^{-3})
	φ	Porosity (cm^3 cm^{-3})
	S_{o}	Standard sorptivity (cm $\mathrm{d}^{-0.5}$)
	K_{tr}	Hydraulic conductivity (m d^{-1})
	K_{s}	Saturated hydraulic conductivity (m d^{-1})
	h_{max}	Texture-specific suction boundary (cm)
	γ	Texture-specific constant (cm^{-2})
	α	Texture-specific geometric constant ($\mathrm{cm}^{-\mathrm{d}}$)
	β	Texture-specific empirical constant ($\mathrm{cm}^{-2.4}$ d^{-1})
(c)		
Weather	TMAX	Maximum daily temperature (°C)
	TMIN	Minimum daily temperature (°C)
	R	Daily precipitation
	RH	Average daily relative humidity (0 to 1)
	SUNH	Daily sunshine hours (h)
	Eo	Daily potential rate of evaporation (cm d^{-1})
	ETo	Daily potential rate of evapotranspiration (cm d^{-1})

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