Modeling Yields from Rainfall and Supplemental Irrigation

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Abstract: Frequently, the area of good soils suitable for irrigation far exceeds that for which adequate water is available for maximum crop production. Decisions and/or policies are often required relative to how much land should be irrigated with limited water supplies or the level of deficit irrigation desirable. The use of crop-yield models provides a tool for determining how best to combine benefits from rainfall and irrigation. Some developments are described that facilitate the modeling of crop yields. A method that requires only temperature measurements for reliable estimates of potential evapotranspiration facilitates modeling at many locations where more complete climatic data are not available. A weather simulation procedure that provides good results without local calibration and requires only monthly climatic input makes it possible to develop a worldwide climatic data base for use with the existing crop-yield models that otherwise require the availability of daily climatic data. Estimated probable relative yields for rain-fed agriculture, and with one irrigation and with two irrigations, are calculated with a yield model operated with actual daily data and with data synthesized from a monthly climatic data base. The difference in yields calculated from historical data and synthesized data varies from 0 to 17%.

Introduction

Throughout much of the world, irrigation is supplemental to rainfall. The areas of good quality lands for crop production frequently far exceed the area that can be irrigated from developed or developable water supplies. Those responsible for the planning and designing of irrigation projects may need a method or criteria for deciding the most acceptable degree of deficit irrigation or the probable benefits from irrigation supplemental to rainfall.

Hargreaves and Samani (1984) found that the economic benefits from deficit irrigation are strongly influenced by the percentage of total water requirements provided by rainfall. Agricultural development planning can be significantly improved by providing crop growth and development models to be used for comparing probable yields from rain-fed agriculture with those indicated when one, two, or more supplemental irrigations are applied.

Decisions relative to the land area to be irrigated with limited water supplies should be largely based upon predetermined goals and an evaluation as to the most efficient means of accomplishing the desired goals. The following are suggested as possible objectives:

- Promoting the production of the maximum amount of food.
- Maximizing economic returns from the investment.

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- Producing a large increase in opportunities for rural employment.
- Benefiting large numbers of the rural poor.
- Generating foreign exchange earnings.

When the goals or objectives have been clearly defined, it is frequently difficult to quantify the influence of various design or operating decisions on yields, profits, or numbers of persons benefited in various ways. However, crop-yield models can provide a useful tool for evaluating relative benefits from different crop production practices.

Many crop-yield models have been developed. Most of the more reliable of these require the use of daily rainfall or water availability and other daily climatic data. Recent research and development of Utah State University, described by Samani et al. (1987), has resulted in an improved procedure for estimating crop water requirements and for synthesizing daily climatic data, thereby simplifying computations and greatly reducing the data requirements for modeling crop yields.

Hargreaves et al. (1985) proposed an equation for potential evapotranspiration (ETP) that requires only measured values of temperature. Hargreaves and Samani (1985) compared the ETP equation with measured values from lysimeters planted to cool-season grass and concluded that the temperature-based equation provided a better fit with the monthly lysimeter values than other equations in nearly all cases. Keller (1982, 1987) developed a weather-maker model simulation procedure (WMAKER model) for generating daily values from a monthly climatic data base.

Zuniga (1987) evaluated the WMAKER model by comparing predicted yields of corn generated from actual (measured daily) climatic data with the yields from generated WMAKER data derived from a monthly climatic data base. Yields from the Hanks (1974) plant growth (PLANTGRO) and the Jones and Kiniry (1986) crop-environment resource synthesis (CERES)-Maize models were calculated with both actual and simulated data. The yields estimated from the two models from both actual and simulated data were quite similar and in each case adequate for purposes of planning and policy decisions.

Water available to the crop depends upon rain, irrigation, the crop rooting and growth characteristics, and the capacity of the soil to store available water within the crop root zone. The various yield models estimate relative or potential yields for known or assumed crop and soil conditions. A version of the CERES-Maize model calculates the assimilation of nitrogen thereby indicating how fertility influences crop yields.

A Monthly Climatic Data Base

The data required for the WMAKER model are the mean monthly values of potential evapotranspiration (ETP), temperature, number of rainy days, rainfall amounts, and the standard deviations of each of these values. For purposes of evaluating the WMAKER model and crop-yield and development models a monthly data base was created for each of several locations from daily climatic data.

Daily data are more difficult and expensive to obtain than monthly values and in many cases are not available. The use of daily values with crop-yield models also requires more effort. For these reasons it was considered de-

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TABLE 1. Example of Monthly Climatic Data Base Compiled from 85 Years of Monthly Data from Quixeramobim, Brazil (Lat 5°18′ S; Long 39°18′ W; Elev 199.0 m)

Values (1)	January (2)	February (3)	March (4)	April (5)	May (6)	June (7)	July (8)	August (9)	September (10)	October (11)	November (12)	December (13)
TMAX	34	32	31	30	30	30	31	32	33	34	34	34
TMIN	26	26	25	25	24	24	23	24	25	25	25	26
ETP	150	128	129	113	105	103	118	136	147	167	155	154
TEMC	28	28	27	27	26	26	26	27	28	28	28	29
SDT	0.9	1.2	1.1	1.0	1.0	1.2	1.1	0.9	0.7	0.6	0.5	0.6
PM	61	107	172	159	109	50	29	9	3	2	7	21
RPAR	0.8	1.1	2.7	3.6	1.7	1.0	0.6	0.3	0.2	0.2	0.3	0.3
SDPM	59	90	94	84	77	48	33	15	6	5	14	32
RDAY	6.4	9.0	14.9	12.6	10.7	8.0	6.0	1.6	0.9	0.4	1.1	2.5
SDRD	3.3	4.7	4.4	4.1	4.6	4.1	4.1	1.9	1.1	0.6	1.0	2.2

Note: TMAX – mean daily maximum temperature (°C), TMIN – mean daily minimum temperature (°C), ETP – potential evapotranspiration (mm), TEMC – mean daily temperature (°C) (the average of TMAX and TMIN), SDT – the standard deviation of TEMC (°C), PM – mean monthly precipitation (mm), RPAR – the gamma factor for monthly precipitation, SDPM – the standard deviation in the amount of monthly rainfall, RDAY – the mean number of rainy days, and SDRD – the standard deviation in the number of rainy days.

sirable to develop and publish a monthly climatic data base. Because of the food shortages in Africa and the attention being given to that continent, it was decided to first prepare a monthly data base for Africa and proceed with data from Latin America and other areas.

Worldwide climatic data are available from the National Oceanic and Atmospheric Administration (NOAA) on computer tapes. These data were supplemented with values from Food and Agriculture Organization of the United Nations (FAO 1984, 1985) and from *Tables of Temperature, Relative Humidity and Precipitation for the World, Part I* (Her Majesty's Stationery Office 1980), *Part II* (1978), *Part IV* (1983), and *Part V* (1978). From these data monthly climatic data-base tables were prepared for Africa, Latin America, and selected Asian countries. Table 1 illustrates the data content and format of the monthly climatic data-base tables.

Daily climatic data from Brazil and El Salvador were used to prepare monthly climatic data-base tables for the purpose of comparing predicted yields from synthetic data with those from the actual daily values.

Samani et al. (1987) compared relative probable yields of corn grain estimated by the PLANTGRO model for assumed planting dates and soil conditions for rainfed production at four locations (two in El Salvador and two in Brazil). For one location yield estimates were also made assuming one irrigation applied 70 days after planting. Differences in estimated probable yields from the actual daily climatic data and daily data generated from the monthly data base tables and the WMAKER model varied from zero to about 17%.

METHODOLOGY

The data presented in Table 1 are adequate for use with the WMAKER model with the exception of the standard deviation of ETP (SDETP). Some methods for estimating ETP are temperature-based. It was assumed that SDETP may be correlated with the standard deviation of temperature (SDT).

An inspection of the monthly data-base tables for Africa and other regions indicates little correlation between mean monthly temperature (TEMC) and

SDT. At Marrakech, for the frost-free months (March–November) linear regression produced a value of r^2 (coefficient of determination) of only 7%. There is, however, a fairly good correlation between SDT and latitude. At the equator SDT averages about 0.5° C. SDT increases linearly with departure from the equator up to about 30° north or south and then there is little or no change in mean SDT with increasing values of latitude. There is significant variation in the increase and additional evaluation may indicate the importance of some factor other than latitude. An initial study of values of SDT for 18 locations in Africa from 4° south to 39° north indicated a minimum value of SDT of 0.5° C at 4° south with an increase of 0.020° C per degree of departure from 4° south. The coefficient of determination (r^2) for the linear regression was 87%.

An evaluation using more data from Africa and Latin America indicates that SDT averages about 0.5° C at the equator and increases with departure from the equator up to an average of about 1.2° or 1.3° C at 30° north or 30° south latitude.

The equation used to calculate ETP (Hargreaves et al. 1985; Hargreaves and Samani 1985) can be written:

$$ETP = 0.0023 \times RA \times (TEMC + 17.8) \times TD^{0.50} \qquad (1)$$

in which ETP and extraterrestrial radiation (RA) are in the same units (usually millimeters) of equivalent water evaporation; TEMC = mean temperature in degrees centigrade; and TD = TMAX − TMIN in degrees centigrade (mean maximum temperature minus mean minimum of the daily temperature range).

The data base presented in Table 1 does not include values of the standard deviation of ETP (SDETP). Monthly means of TMAX and TMIN from various locations in different climates and latitudes were used with Eq. 1 to compare the coefficients of variation (standard deviations in percent of mean values) of TEMC and ETP (CVT and CVETP, respectively). The data evaluated by Hargreaves and Samani (1988) indicated the following equation:

$$CVETP = CVT(2.30 - 0.027\,LD - 0.15\,KEL) \qquad (2)$$

in which LD = latitude departure from 4° south; and KEL = elevation, in km (1,000 m).

From limited data Hargreaves and Samani concluded that SDT is minimum at 4° south latitude. However, after completing the data base tables for Latin America and Africa, it appears that minimum values of SDT occur at the equator. Data from other locations do not confirm the correction for elevation. This indicates that Eq. 2 should be modified as follows:

$$CVETP = CVT(2.2 - 0.027\,LAT) \qquad (3)$$

in which LAT = latitude in degrees (either north or south). Additional evaluation of Eq. 3 indicates a good average relationship during the dry months when irrigation is required. However, the ratio of CVETP/CVT is usually significantly greater during months when rainfall is generally adequate for crop production.

SDETP is influenced by latitude, elevation, and rainfall. It therefore seems evident that where these conditions are similar, values of SDETP from one location can be used at a similar location where data are inadequate or are not available for the calculation of SDETP.

The indicated average relationships are recommended for use with the monthly data-base tables illustrated in Table 1 and other similar data until additional or improved analysis becomes available. Use of approximate average values of SDETP is expected to result in reasonable crop-yield values for comparisons and for agricultural planning and development However, additional evaluation of Eq. 3 is recommended together with studies to determine the degree to which errors in estimating CVETP influence the reliability of crop yields estimated by the crop-yield models.

Crop yields were estimated with the PLANTGRO model developed by Hanks (1974) with adjustment for the use of Eq. 1 for estimating ETP. The PLANTGRO model was operated with the historic daily data and also with data simulated from the monthly means and standard deviations.

The WMAKER model was used with a monthly data base to develop daily simulated values of climate to be used instead of the actual daily climatic data. The PLANTGRO model was operated with the simulated data and the results of predicted probable yields at various locations and conditions were compared with those obtained from the measured daily data.

The comparisons reported by Samani, et al. (1987) indicate that synthetic weather values generated by the WMAKER model can be used satisfactorily for predicting plant growth and development. Probable relative yields estimated by crop models from 20 to 30 years of generated daily weather values are of the same order of magnitude as those estimated from the actual historical measured daily weather values.

It is anticipated that the WMAKER model and modifications and crop yield models will become increasingly useful for estimating extreme rainfall amounts, watershed and hydrologic modeling, agrotechnology transfer, and the estimation of the performance of various cultivars. However, for irrigation it is anticipated that the principal use will be that of evaluating the probable benefits possible from providing one or more irrigations supplemental to rainfall.

The influence of irrigation supplemental to rainfall was modeled for various locations in Brazil, Africa and El Salvador. For La Union, El Salvador, the soil was assumed to be of medium texture. The effective root depth of a corn crop was assumed to be 60 cm. A Planting date of May 1 was used. Crop yields were modeled for rainfed production and for one and two supplemental irrigations applied at 75 and 85 days after planting. Irrigation amounts were sufficient to fill the 60 cm depth of soil to the field capacity.

RESULTS

Fig. 1 was produced with the PLANTGRO model using daily or historical data from La Union, El Salvador, and WMAKER data for rain-fed production, with one irrigation and with two irrigations. The maximum differences between the yields predicted from the historical data and the synthesized data is for the rain-fed corn production. The maximum difference in yields indicated by the two data sets is about 13%.

The results presented in Fig. 1 illustrates the value of the WMAKER model. The difference between yields predicted from the actual and the WMAKER data at the various locations evaluated usually varied from 0 to 17%. Many years of yield trials in the field would be required to define optimum planting dates and the potential benefits from one or more irrigations applied at var-

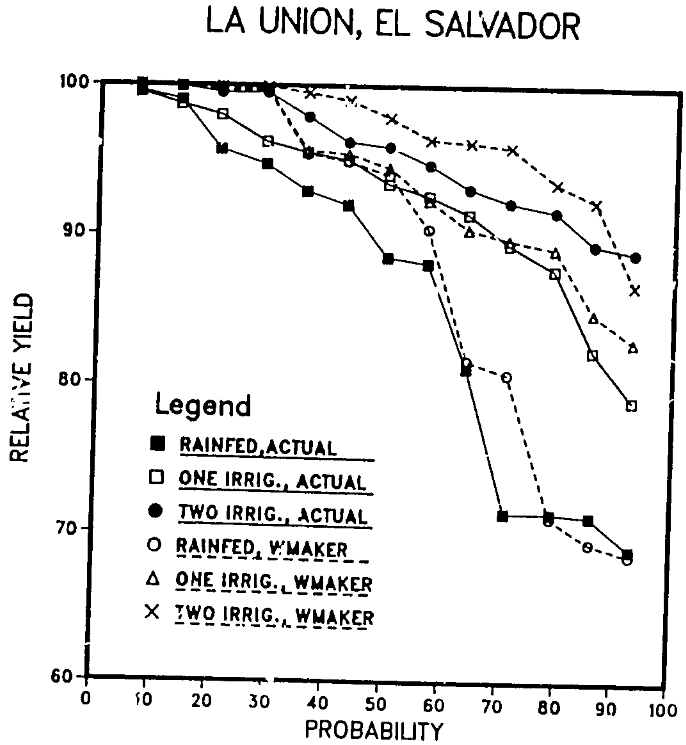

FIG. 1. Probable Relative Yields of Corn Grain at La Union, El Salvador

ious times. The described procedure requires historical monthly records of sufficient length so as to provide a monthly data base as indicated in Table 1. This data base can then be used to provide as much information on the probable yields from various practices as could be obtained from many years of field experiments.

Practical Application

For rain-fed agriculture, yields are largely determined by the amount and distribution of water available to the crop. Hargreaves and Samani (1984) indicate that supplemental irrigation for maximum yields is seldom economical. In areas where crops can be grown during both the dry season and the rainy season, irrigation projects are frequently designed based on the maximum area that can be irrigated during the dry season by accepting some degree of deficit during years of low rainfall. However, during the rainy season a much larger land area can be irrigated with the same amount of water.

The recently developed monthly data-base tables and the crop-production and weather-generation models are recommended for the following purposes:

Comparing probable relative yields for various planting dates for rain-fed agriculture.

- Determining relative benefits from dry-season irrigation with those possible from supplemental irrigation during the rainy season.
- Decisions relative to the time and amount of water to be applied per unit of land area.
- Use with information on costs and benefits to develop economic models to aid in planning and management.

The Bureau for Science and Technology of the Agency for International Development is sponsoring a project for International Benchmark Sites Network for Agricultural Technology Transfer (IBSNAT). Four crop yield models are available from IBSNAT, the CERES models for wheat, soybeans, rice, and maize. Other models planned for future completion are for sorghum, millet, potatoes, barley, and field beans. The contractor for the IBSNAT project is the Department of Agronomy and Soil Science, College of Tropical Agriculture and Human Resources, University of Hawaii, associated with the Department of Agronomy and Soils, College of Agricultural Sciences, University of Puerto Rico.

The use of computers is advancing very rapidly in the developing countries. If suitable training in computer usage and crop modeling can be arranged, it is recommended that the weather-simulation procedure, the crop-yield models, and the monthly data base be placed on computer diskettes and made available for widespread use, particularly in the developing countries. However, it seems advisable that distribution of the required computer software not be made without adequate training in the use and significance of the models.

Crop-yield models utilizing monthly climatic data should be used together with costs of production and crop values to develop procedures for further definition of the economic considerations of the conjunctive use of rain and irrigation and of deficit irrigation.

Summary and Conclusion

Due to limited water supplies and the various areas where good lands are less limiting, it is frequently desirable that decisions be made relative to the permissible degree of deficit irrigation. The policy selected is often influenced by political considerations. Procedures are presented that provide relative evaluations of various combinations of the conjunctive use of rainfall and irrigation.

The improved evaluations described herein depend upon the two following important developments:

1. A reliable procedure for calculating potential evapotranspiration that requires only measured values of ambient air temperature.
2. A weather-simulation procedure that requires a monthly climatic data base for operating the more reliable and sophisticated of the crop-yield models.

Estimated relative yields for various locations and differing soils and climatic conditions were compared using models with daily (actual) data and with the monthly data base. Comparisons of probable yields are shown in this paper for two of the locations. Differences in resulting yields at the various locations and different conditions were usually in the range of 0–

17%. One or more irrigations were assumed and results compared both with daily and monthly data. The monthly data base appears to provide results that are within the limits of accuracy normally found in field irrigation research.

Monthly climatic data-base tables have been prepared for Africa, Latin America, and selected Asian countries and similar tables could be prepared for other areas from world-wide climatic data. The data-base tables were designed for use with the WMAKER model. With a suitable worldwide database publication and/or software and crop models for the basic food and other crops, probable increases in yields can be readily estimated for various levels of the conjunctive use of rain and irrigation.

APPENDIX I. REFERENCES

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Appendix II. Notation

The following symbols are used in this paper:

CVETP = coefficient of variation of ETP;
CVT = coefficient of variation of temperature in degrees C;
ETP = potential evapotranspiration with cool-season grass (Alta fescue) as reference crop, in mm;
KEL = elevation in km (1,000 m);
LD = degrees of latitude departure from 4° C;
PM = mean monthly precipitation in mm;
r^2 = coefficient of determination or variance predicted;
RA = extraterrestrial radiation in equivalent mm of water evaporation;
RDAY = average number of rainy days in month;
RPAR = gamma factor for monthly precipitation;
SDETP = standard deviation of ETP;
SDPM = standard deviation of PM;
SDRD = standard deviation of RDAY;
SDT = standard deviation of temperature in degrees C;
TEMC = mean air temperature in degrees C;
TD = mean daily maximum minus mean daily minimum temperature;
TMAX = mean daily maximum temperature in degrees C; and
TMIN = mean daily minimum temperature in degrees C.