IRRI RESEARCH PAPER SERIES
NUMBER 62 JUNE 1981

A SOIL MOISTURE-BASED YIELD MODEL OF WETLAND RAINFED RICE

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ABSTRACT

A water balance and crop simulation model (PADI-WATER) was developed to predict the yields of the drought-prone second rainfed wetland rice crop in Iloilo Province, Philippines. The model was developed from data collected from 2 years of planting date trials in that province. The only data required to operate the completed model were those on daily rainfall. The model was validated against farmers' crop yields for 6 years and against the yields for 4 years from experimental crops grown in the province. During the model verification, a term found to be essential was groundwater contribution. Excluding the term resulted in a 30% underestimation of actual yield at the 4 t/ha level and a 90% underestimation at the 1 t/ha yield level. It is in this yield range that decisions are made on whether a second rice crop should be grown. Sensitivity tests on the model showed that the model was most sensitive to changes in pan evaporation rate and to the rate of canopy development, as determined by the transpiration-to-evapotranspiration ratio. The model terms pan factor, spillway height, and net seepage and percolation rate which receive considerable attention in water balance studies of irrigated rice, were found to be less sensitive.

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The advent of modern short-duration rice varieties (less than 120 days) has encouraged double-cropping in rainfed rice growing areas where the monsoon lasts more than 6 months (200 mm/month). Like the traditional long-duration single crop, the first crop in this pattern will not normally encounter severe drought stress because it matures before the monsoon recedes. The second rice crop, however, matures as the monsoon recedes and therefore its yields are routinely reduced by drought. To determine whether a given rainfed rice area can support a successful second rice crop it is necessary to have an estimate of the average expected yield and the variability of that yield. Because the late monsoon is noted for rainfall variability yield estimates would normally require long-term field trials. An alternative method of delineating areas for double-cropping rice is to run field trials over a few crop seasons, characterize the crop response to a full range of environments in these trials, and build a crop model from the data base. Although this approach may be less accurate, it results in an earlier decision on when to double-crop rice. Modeling rainfed rice is, however, confounded by two factors:

- a dearth of literature on the unsaturated mode of the water balance for rainfed wetland rice; and
- lack of well-equipped meteorological stations in rainfed rice areas. Commonly the only dependable data for these areas are those on rainfall.

This restriction automatically precludes the use of sophisticated, and largely exploratory, models such as those of Iwaki (1975) and Van Keulen (1976, 1978). On a simpler level, predictive equations based on the accumulation of stress days (days without standing water) have been successfully used for determining the benefits of irrigation (Wickham 1971), but have been of less value when applied to rainfed areas (Cablayan and Wickham 1977). Estimates of low yields with these equations will not be accurate because the stress-day concept does not take into account the intensity and precise timing of the drought stress.

The principle used in the PADIWATER model we describe is that crop transpiration decreases as soil moisture is depleted and the transpiration rate is known to closely parallel dry matter accumulation. The value of this relationship for modeling a rainfed crop is that it holds true even for a drought stressed crop and does not change appreciably with varietal or fertility differences.

MODEL DESCRIPTION

A flow chart of the PADIWATER yield simulation model is in Figure 1. Modeling was from data from 2 years of planting date trials in Tigbauan, Iloilo Province, Philippines. The trials were on two farmers' fields -- one higher-lying with low fertility and prone to drought, the other low-lying with more fertile soil and less prone to drought. Depending on moisture availability, rice was planted up to eight times on alternate weeks in the late wet season at four fertilizer rates.

During the field trials, rainfall and Class A pan evaporation were measured daily at each site. When standing water was present the water depth was measured on a sloping gauge (1 cm on the gauge represents 1 mm depth of water). When less than 50% of the field was covered with standing water, soil cores were taken to 30 cm depth from parts of the field without standing water and volumetric moisture content was estimated. The average water depth in parts of the field with standing water at

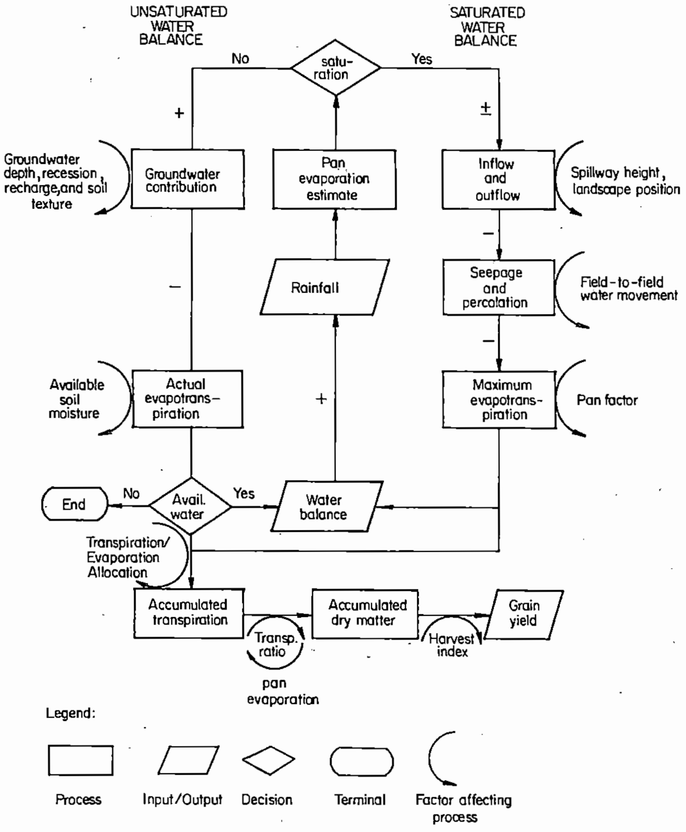

Fig. 1. Flow chart for the PADIWATER yield simulation model of the second rainfed rice crop.

50% coverage was about 30 mm. Groundwater depth was recorded in perforated dip-wells. Evapotranspiration rates were recorded from plants growing in tanks (120 cm in diameter and 40 cm deep), buried in the paddy with at least 10 m uniform crop border. Evaporation was also measured with small pans (20 x 20 cm and 10 cm deep) placed between hills of transplanted rice. Within-canopy evaporation was assumed to be equal to evaporation loss from these pans.

Grain yield and total dry matter were recorded at harvest.

Soil water balance

The basic water balance equation for a rice crop in standing water may be summarized:

$$\underline{WD}_t = \underline{WD}_{t-1} + \underline{RF}_t - \underline{ET}_t - \underline{S}_t - \underline{P}_t + \underline{IF}_t - \underline{OF}_t$$

where: $\underline{WD}$ is water depth,
$\underline{RF}$ is rainfall,
$\underline{ET}$ is evapotranspiration,
$\underline{S}$ is lateral seepage through the dikes,
$\underline{P}$ is percolation,
$\underline{IF}$ is inflow from higher fields over the spillways,
$\underline{OF}$ is outflow or surface drainage from the paddy over the spillway, and
$\underline{t}$ is the time interval between measurements.

The spillway height in the field trials was 135 mm for low-lying fields and 100 mm for the high-lying fields. For a paddy without standing water the water balance is similar to that for dryland fields and may be expressed as:

$$\underline{SM_t} = \underline{SM_{t-1}} + \underline{RF_t} - \underline{ET_t} + \underline{CP_t}$$

where: $\underline{SM}$ is soil moisture in the root zone, and

$\underline{CP}$ is capillary rise from a shallow water table into the root zone.

Because paddies are not completely level there are times when the field is only partially covered with water. Field measurements of soil moisture in the parts of partially flooded fields without standing water indicate that soil moisture does not decline significantly below saturation until virtually all standing water is lost. Therefore, in the model it is assumed that the unsaturated water balance model (second equation) does not start until all standing water is lost. The saturated water balance model (first equation) may again be used if rainfall for a given day is greater than that required to return the soil to saturation. It is common for the intermittent late-season rains to cause the water balance to pass through several such cycles of wetting and drying. A further assumption in the model was that at times when no standing water was present there was no percolation. However, when the field was partially flooded percolation continued, implying that the drained portion of the fields continued to lose water through percolation. This assumption, although appropriate for this soil type and for the wet-to-dry season transition, may not be correct for lighter soils and for the dry-to-wet season transition in deeply cracked soils (see Zandstra et al 1980). The veracity of the approach could not be determined because the model is relatively insensitive to seepage and percolation rates below 2 mm/day, as we indicate later.

Most moisture extraction by wetland rice grown in puddled soil takes place within 30 cm of the soil surface (Hasegawa et al 1979). In our field trials 90% of the root axes counted, even at 20 days after transplanting, were in the top 20 cm of a 30-cm core, which is consistent with previous field measurements for wetland rice (IRRI 1977). This is the justification for using a 30-cm root zone in the model. In the trials soil was saturated by 150 mm water in the top 30 cm of the soil for the high fields and 175 mm in 30-cm soil for the low fields.

The 2.5-year record of pan evaporation from the field site was used to calculate the monthly evaporation rate. These rates may be used directly in the model. To capture year-to-year variations, however, it was found more accurate to predict pan evaporation rate using its relationship with current and the past month's rainfall that was derived from the available record. This relationship also allows determination of evaporation rates for nearby sites where only rainfed records exist. The relationship, however, is probably site specific and would have to be reevaluated for rainfed areas in different rainfall regimes. To obtain potential evapotranspiration rates, a 0.93 pan factor was used. This was the rate measured in the tank lysimeter when standing water was present. When no standing water was present evapotranspiration rate was determined from the soil moisture content of the 30-cm effective root zone (Fig. 2). Although it is recognized that this relationship is demand sensitive, particularly for heavier soils with lower conductivities, there were too few data points to form a functional relationship. The values for actual evapotranspiration rate (ET_A) were determined in the field according to the following equation:

$$ET_A = \underline{SM_t} - \underline{SM_{t-1}} + \underline{RF_t} + \underline{CP_t}$$

Capillary rise is computed from measured groundwater depths and the corresponding rates of upward ater movement computed for various soil textures by Doorenbos and Pruitt (1975).

Net seepage and percolation was determined by the Giron and Wickham (1976) subsidence technique, which may be summarized as follows:

$$\underline{SP_t} = \underline{WD_t} - \underline{WD_{t-1}} - \underline{ET_t} + \underline{RF_t}$$

Net seepage and percolation rates used in the model were determined in the field trials as 0.5 mm/day for the low-lying paddies and 0.7 mm/day for the higher-lying fields. In the Philippines, Wickham and Singh (1977) reported that net seepage and percolation rates generally lie between 0 and 3 mm/day in the wet season, the rate increasing with the relative elevation of the paddy within the landscape (Wickham and Singh 1977).

Surface drainage is one of the most visible components of the water balance in rice culture. The gain to fields low in the landscape bottomlands and waterways is considerable in rainfed rice areas with sharp relief. The net gain to most fields in the landscape, however, is not as great as it would first appear; before inflow occurs the reference field will already be about full to spillway height. The reason for this is: assuming rainfall and evapotranspiration rates are equal across the landscape and allowing for lower rates of seepage and percolation in low-lying fields, these fields will overflow into bottomlands and waterways before there is inflow from the fields above. The limited net gain is largely the result of the time lag between cessation of rainfall and inflow; after rainfall, inflow continues and may compensate for evapotranspiration, seepage, and percolation losses in subsequent days. Therefore, in a simulation it is necessary to know how many days inflow compensates for field water requirement. For this purpose all spillways in and out of the study fields were equipped with wooden gates. Each day the increase in water depth behind the gates was measured before release. Inflows and outflows over spillways were thus recorded for two crop seasons in the field trials. During this time five discrete inflow events were recorded. On all these occasions it was observed that inflow ceased the same day as rainfall in the higher-lying fields but continued for about 2 days after the last heavy rainfall (greater than 10 mm) in the low fields.

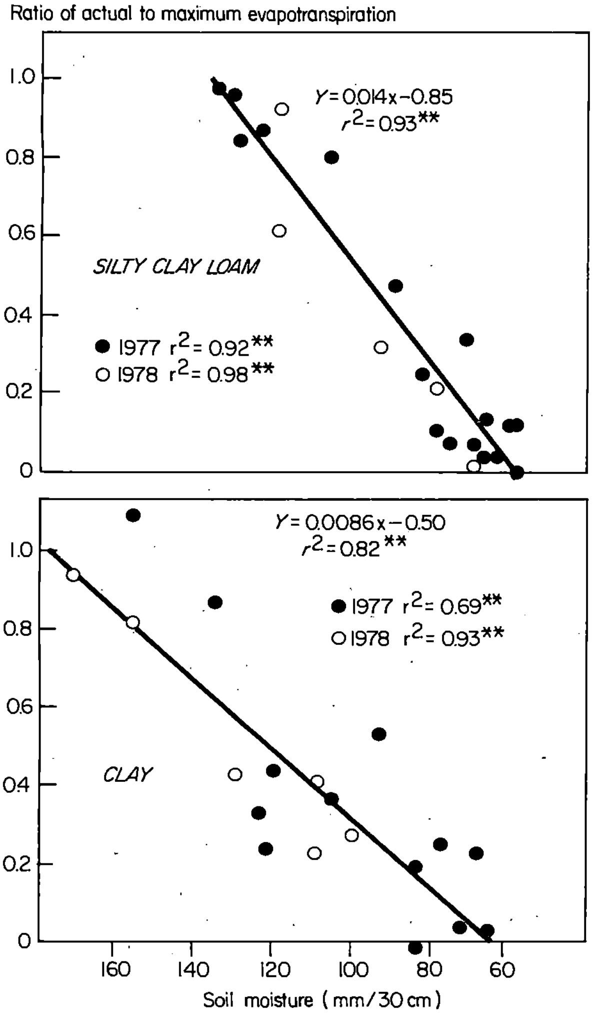

Fig. 2. The relationship of actual upon maximum evapotranspiration to soil moisture for a silty clay loam (above) and clay (below). Crop years 1977 and 1978, Iloilo.

Because of the dearth of literature on the subject, the initial logic was that groundwater contribution would be a minor component in the water balance for wetland rice. However, on the first runs of the simulation it became apparent that on the basis of the functional relationships prepared by Doorenbos and Pruitt (1975), in some years the capillary rise could represent up to a third of the input to water balance. It was also found that ignoring groundwater contribution led to a significant underestimation of observed yield. Such a situation could be created by light but frequent rains that maintained the soil near saturation and the groundwater within a meter of the surface.

Groundwater level beneath the root zone is required for use in the Doorenbos and Pruitt curves. In the simulation, therefore, groundwater depth is increased 2 cm/day for each rainless day in the low fields, and 4.3 cm/day for the higher fields. These values were based on those recorded in the field, but with the former figure changed from the measured value of 3.1 cm/day during tuning. The estimated value for groundwater depth is reduced on rainy days by a height proportional to the amount of rainfall received, again a relationship derived from field data. There was no attempt to link deep percolation rates to groundwater recharge in the equations for the water balance because this relationship is more a function of catchment hydrology and, therefore, too complex to incorporate in a simple water balance model of a paddy. Groundwater contribution is then computed from these simulated groundwater levels according to the graph of Doorenbos and Pruitt (1975).

Crop growth and yield

Transpiration rate closely parallels the rate of dry matter accumulation (De Wit 1958; Arkley 1963; Sugimoto 1971, 1973). Sugimoto reported that the relationship breaks down for rice at low temperatures but remains stable for the tropical environment. In the Philippines, based on data from Wu (1966), this relationship was confirmed over a range of solar radiation levels and soil moisture tensions down to 10 bars (1 M Pascal). Because of this close correspondence under a wide range of environments, and because drought stress is by far the major determinant of second rice crop yield, this relationship was selected to link the water balance and crop growth simulations. This relationship also has a low information requirement when compared to other processes.

Previous attempts to relate solar radiation to the transpiration coefficient have proved inadequate when applied to humid and arid sites in similar radiation regimes. Some form of humidity index has often been included to improve the relationship. Bierhuizen and Slatyer (1965) demonstrated a close relationship between vapor pressure deficits, radiation level, and the transpiration coefficient. Sugimoto reported that dry season transpiration coefficients for 5 Asian countries averaged 419 when midday vapor pressure deficits can be up to 25 mbars, but only 332 in the wet season when deficits are about 50% lower. Because daily estimates of vapor pressure deficit are not available for most rainfed areas, pan evaporation above the wet season minimum of 5.3 mm/day was used in the simulation as a substitute for vapor pressure deficit in modifying the transpiration coefficient. Hignett (1973) demonstrated a strong linear relationship between pan evaporation and the vapor pressure deficit for four contrasting sites in southern Australia. Doyle and Fischer (1979) reported a linear relationship between pan evaporation and the transpiration coefficient. The coefficient at wet season minimum was estimated in the field to be 250. The dry season maximum was set in the model close to that reported by Sugimoto (1971), generally about 570, but because it is linked to pan evaporation rate this value varies from year to year. Naturally, dry season field determination of the transpiration coefficient is not possible in a rainfed rice area.

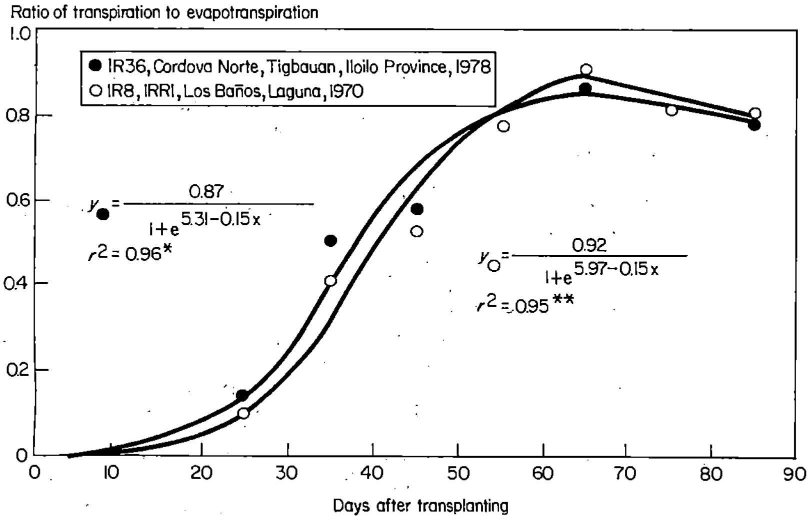

Fig. 3. The relationship between estimated transpiration-to-evapotranspiration ratios and crop age.

In the simulation model, transpiration is accumulated and translated daily into terms of dry matter by this modified transpiration coefficient. To determine the proportion of evapotranspiration allocated to transpiration, curves similar to those in Figure 3 are used; these treat transpiration as a residual of evapotranspiration and free-water evaporation from beneath the canopy (after Sugimoto 1971, IRRI 1971). The coefficients for the curve depend on variety, field duration of that variety, and nutrition level. For example, the slope of the curve will be shallower for longer-duration varieties; the peak value for the ratio of transpiration to evapotranspiration will be greater for leafy varieties and smaller for nutrient-deficient crops.

Transpiration rates when there is no standing water may be estimated by the method described by Ritchie (1972).

Grain yield is computed from the estimated total dry matter production at harvest using a harvest index estimated according to the relationship given in Figure 4. The close relationship of dry matter and harvest index, with data from two seasons and a number of planting dates within each season, is probably due to increase in drought stress as the dry season approaches.

Tuning, validation, and sensitivity tests

Each component in the model was tuned separately, from the best understood parameters to the least understood. For instance, the hierarchy of tuning of the water balance was seepage and percolation first, then evapotranspiration, then groundwater contribution. Tuning of the water balance simulation made negligible difference to the predicted water balance values for both seasons and both sites, suggesting that the processes in the simulation are satisfactory. Figure 5 illustrates one of the four verification runs comparing the tuned

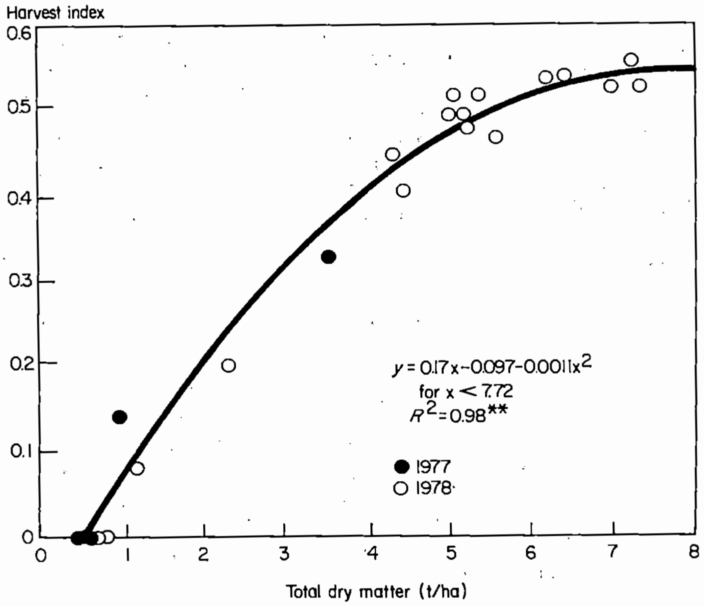

Fig. 4. The relationship between harvest index and total dry matter of IR36. Crop years 1977 and 1978. Cordova Norte, Tigbauan, Iloilo, Philippines.

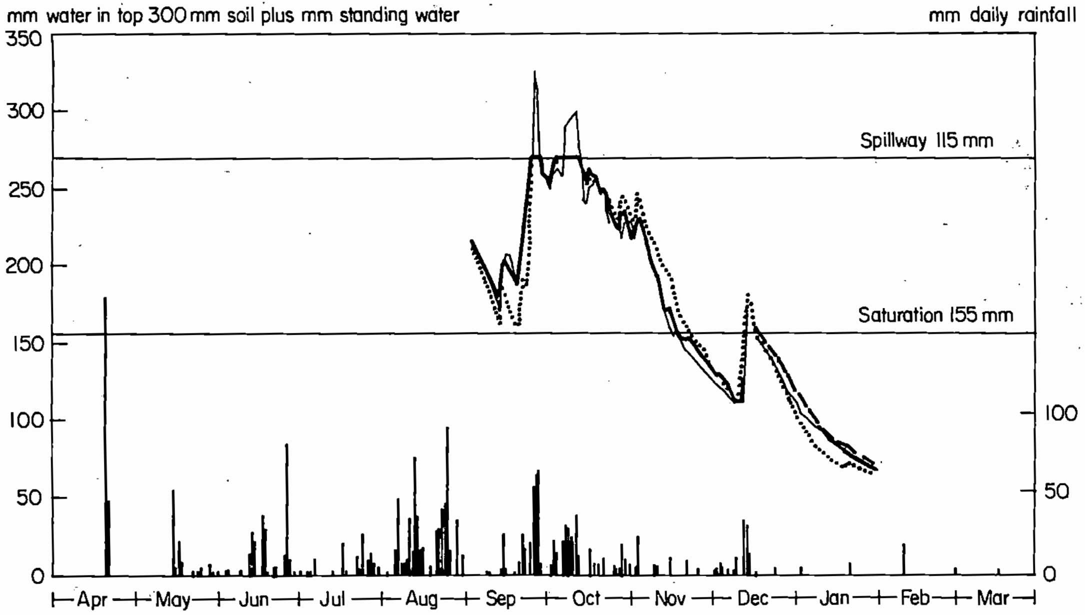

Fig. 5. The tuned (dashed line) and untuned (dotted line) simulated water balance, compared with the observed water balance (solid line). Plateau, crop year 1978.

and untuned model. When untuned the crop growth routine overestimated low yields. It was necessary to cease dry matter accumulation below a given soil moisture value -- 115 mm for the low field and 90 mm for the high -- low yields were overestimated. The difference in values is probably a function of soil texture. In terms of moisture tensions these values are equivalent to 5 and 10 bars, which are tensions associated with very low rates of evapotranspiration, photosynthesis, and dry matter accumulation (Kamoto et al 1974).

Sensitivity tests were conducted on the model using rainfall data from a typical year, 1978, with simulated plantings on alternate weeks for a low-lying field. The plantings were started from the middle of the wet season (September) and continued until no standing water remained (mid-December). That resulted in estimated yields ranging from 7 t/ha to complete failure. The most sensitive parameter was evaporation; an alteration of 10% in mean monthly rates resulted in a 20% change in yield (Table 1). In the rainfed area of the field trials the dry season pan evaporation rates were 20% higher than for irrigated areas 20 km distant. This model sensitivity to evaporative demand highlights the need for accurate estimation of evaporation rates at the wet-to-dry season transition, as was mentioned in the section on the soil water balance. Selection of different transpiration - evapotranspiration curves within the envelope defined by the 95% confidence intervals on coefficients for the regression equation in Figure 3 also resulted in a 20% change in yield estimate (Table 2).

Table 1. Effects of pan evaporation sensitivity tests on estimated grain yield (t/ha), using 1978 Iloilo rainfall data.

Planting date	% change in mean monthly pan evaporation -20	-10	0	+10
1 Sep	8.5	7.0	6.2	5.5
15 Sep	8.1	6.6	5.7	5.1
30 Sep	7.6	6.2	5.4	4.7
15 Oct	5.7	4.6	3.8	3.0
30 Oct	5.0	4.0	2.9	2.1
14 Nov	4.1	2.9	1.9	1.3
29 Nov	2.5	1.5	1.0	0.4
14 Dec	1.2	0.4	0.1	0.0
Mean yield	5.3	4.1	3.4	2.8
% change	+56	+21	-	-18

Table 2. Effects on estimated grain yield (t/ha) of sensitivity tests on transpiration-to-evapotranspiration curves according to stage of crop development, using 1978 Iloilo rainfall data.

Planting date	Coefficients of T/ET curves[a] 3.1/0.2	4.5/0.2	7.5/0.2	3.1/0.1
1 Sep	6.8	6.2	4.7	5.3
15 Sep	6.3	5.7	4.3	4.8
30 Sep	6.0	5.4	4.0	4.6
15 Oct	4.5	3.8	2.2	3.0
30 Oct	3.7	2.9	1.5	2.2
14 Nov	2.6	1.9	0.6	1.0
29 Nov	1.6	1.0	0.1	0.5
14 Dec	0.4	0.1	0.0	0.0
Mean yield	4.0	3.4	2.2	2.7
% change	+18	-	-19	-21

[a] The standard curve in Figure 2 was $y = 0.92/(1 + e^{5.3 - 0.15x})$, the 95% confidence limits on the coefficients being 5.3 ± 2.2 and 0.15 ± 0.05, the values 4.5 and 0.2 representing the tuned coefficients.

A term found to be essential to the model was groundwater contribution. Excluding it results in a 30% underestimation of yield at the 4 t/ha yield level and a 90% underestimation at the 1 t/ha yield level (Table 3). It is in this yield range that decisions are made on whether a second rice crop should be grown. Groundwater contribution is, therefore, an essential process in a model of rainfed rice, and yet no literature has been found that includes it as a component of the paddy-water balance, let alone detailing its simulation. The terms pan factor, spillway height, and net seepage and percolation rate, which receive considerable attention in water balance studies of irrigated rice, were found to be less sensitive in this rainfed rice model.

The model was validated against the actual yields of experimental cropping patterns for 4 seasons at the research site and against 6 seasons' yields from farmers' fields in a pilot project area for double-cropped rainfed rice, 20 km from the research site (Fig.6). Because of micro-relief and water management factors the actual yields for each site-year given in Figure 6 are variable; the 95% confidence interval on these average yields was ± 0.7 t/ha. This is the principal limit on interpreting model accuracy from Figure 6.

Table 3. Effects of groundwater contribution on estimated grain yield (t/ha), using 1978 Iloilo rainfall data.

Planting date	Groundwater contribution With	Without	Difference
1 Sep	6.2	6.1	-0.1
15 Sep	5.7	5.7	0
30 Sep	5.4	5.2	-0.2
15 Oct	3.8	2.7	-1.1
30 Oct	2.9	1.6	-1.3
14 Nov	1.9	0.9	-1.0
29 Nov	1.0	0.1	-0.9
14 Dec	0.1	0.0	-0.1
Av	3.4	2.8	-0.6
% change	-	-18	

CONCLUSION

The model we present may be used to determine whether to grow a second short-duration rainfed rice crop in a given rainfall regime. This is a considerable improvement to the alternative of long-term field trials in all sites where a second rainfed rice crop might be grown in a normal year. Although rice modeling does not remove the need for confirmatory trials it does permit quick initial screening of prospective sites. The difficulties encountered in building this model indicate that unlike irrigated rice, wetland rainfed rice and its environment remain poorly understood, particularly in terms of the groundwater contribution to the water balance and the crop response to drought stress. That suggests more attention should be paid to the edaphic factors determining yield.

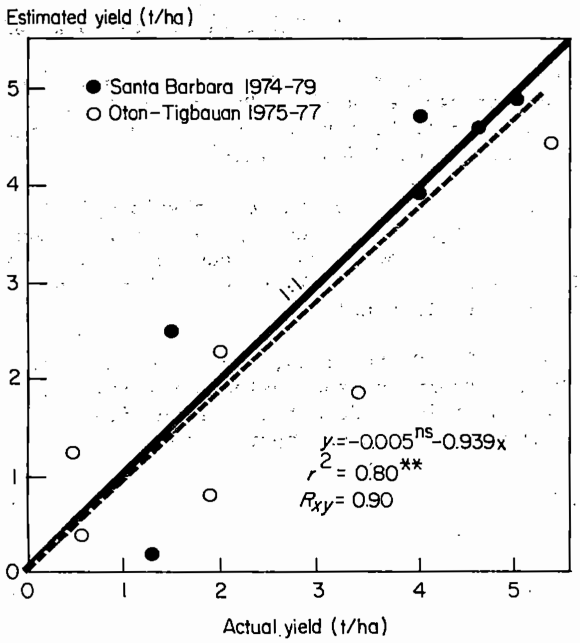

Fig. 6. Comparison of the yields estimated by the PADIWATER model and actual yields obtained in Santa Barbara, Oton, and Tigbauan, Iloilo, Philippines.

ACKNOWLEDGMENTS

We acknowledge the assistance of the staff of the jointly run Philippine Bureau of Plant Industries (BPI) and International Rice Research Institute (IRRI) Cropping Systems Outreach Site, Oton and Tigbauan, Iloilo Province, in the maintaining of the field trials and supplying the data on the cropping pattern trials. Dr. L. D. Haws kindly supplied the yield data from the pilot project for double-cropping rainfed rice in Santa Barbara, Iloilo Province. The assistance and encouragement of Roger Tayler, senior lecturer, Department of Agriculture and Horticulture at the University of Reading, is also gratefully acknowledged.

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