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AN INDEX TO EVALUATE THE EFFECT OF WATER SHORTAGE ON THE YIELD OF WETLAND RICE

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AN INDEX TO EVALUATE THE EFFECT OF WATER SHORTAGE ON THE YIELD OF WETLAND RICE[1]

ABSTRACT

Economic evaluation of existing or potential investments in irrigation can be enhanced by a direct measure of the effect of water on yields of wetland rice. A stress day index has been used to estimate this effect. In this paper we report on efforts to develop an improved index suitable for use in estimating water-related yield reductions of wetland rice grown in nonexperimental fields.

The literature on previous efforts to develop growth-related moisture indices consistent with knowledge of plant-soil-water relationships is reviewed, and alternative formulations of a water shortage index (WSI) are specified. Data from five data sets from the Philippines are used to test the alternatives, and to compare them with the standard stress day index.

The index proposed is based on daily measurements of the depth to the perched water table. Perforated tubes placed in the paddy to a depth of about 50 cm serve as observation wells from which these measurements can be taken. Daily values of the depth to standing water, scaled from 0.0 to 1.0, are multiplied by daily pan evaporation to give daily water shortage factors. The water shortage index is calculated by summing these daily factors from the day of transplanting to 20 days before harvest. For analysis involving data from a single crop season, for which pan evaporation shows little daily variation, the inclusion of pan evaporation in the formulation of the index is not necessary.

Although the proposed index performs modestly better than the stress day index, the resulting estimates of yield reduction remain fairly specific to the pattern of water shortage from which they are derived. The water shortage index is thus most appropriately used as a device to assess the effect of water shortage on rice yields in specific situations.

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AN INDEX TO EVALUATE THE EFFECT OF WATER SHORTAGE ON THE YIELD OF WETLAND RICE

Economic evaluation of investments in irrigation is often hampered by the difficulty of identifying the effect of such investments on yields. A common approach is to compare yields in the area of a project before and after the investment is made. Alternatively, comparisons are sometimes made between yields in a project area and yields in some nearby <u>comparable</u> area. In both cases, the difference in yields -- sometimes adjusted for differences that can be attributed to variables not related to irrigation -- are assumed to be due to the irrigation investment. Any effects of unmeasured variables may cause a bias of unknown magnitude and direction in the resulting estimate of the effect of the irrigation investment.

An alternative approach is to obtain a more direct measure of the effect of irrigation on yields through the use of a water shortage index, to which both yields and irrigation flows are related. Such an index needs to be conceptually sound -- incorporating known plant-soil-water relationships -- and empirically feasible -- utilizing variables that can be measured over large areas by irrigation project field personnel with relatively little training. In this paper, we report on efforts to develop such a water shortage index.

CONCEPTUAL APPROACH

For several decades, scientists in many disciplines have attempted to establish functional relationships between water and the growth and yield of agricultural plants. Two broad approaches can be identified, based on the nature of the variable used to represent the effect of water. One approach is to use water itself as the input variable. Most efforts to use this approach have been limited to analyses of experimental data (Hexem and Heady 1978, Hogg and Vieth 1977, Minhas et al 1974). Although this analytical approach is attractive in its simplicity, it has serious practical and conceptual drawbacks, particularly because of the role of atmospheric conditions in affecting the amount of water needed to obtain maximum yield and the role of the timing of water application on yield.

The alternative approach is to incorporate into the production function one or more variables reflecting the degree of moisture adequacy or moisture stress encountered by the crop. Such a variable may be called a moisture-related growth index, or a moisture stress index. An ideal index would incorporate information on five items:

- the intensity of stress;
- the rate of recovery when stress of a given intensity ends;
- the effect (either positive or negative) of stress in one growth stage on the crop's ability to withstand stress in a later growth stage;
- the effect of stress in one growth stage on the crop's ability to grow and develop in stressed conditions in a later growth stage; and
- growth stage differences in the crop's susceptibility to stress.

Most stress indices are limited to the first item of information (the intensity of stress). There is a considerable body of literature -- reviewed by Salter and Goode (1967) -- on growth stage differences in the response of plants to moisture stress; however, only a few investigators (Knetsch 1959, Dale and Shaw 1965, Hiler and Clark 1971, Mapp and Fidman 1976) have attempted to incorporate growth stage effects into a moisture stress index. The other three items have generally not been considered.

Most attempts to develop an agriculturally useful moisture stress index are based on the concept that plant growth is a function of the ratio of the actual transpiration or evapotranspiration (ET_a) of the crop to the potential rate (ET_p). In much of the early work, it was assumed that plant growth would not be limited by moisture stress as long as ET_a was equal to ET_p, but that growth would cease whenever ET_a dropped below ET_p (van Bavel 1953, van Bavel and Verlinder 1956, Knetsch 1959, Dale and Shaw 1965, Flinn and Musgrave 1967, Alles 1969). Penman (1962) presented experimental evidence supporting this assumption and suggesting that, at least for grass crops, growth was in proportion to the total ET_p occurring during periods of no water stress (i.e. when ET_a was equal to ET_p). Because all of these studies focus on the duration of water stress (or duration during a critical growth stage) as the measure of the stress intensity, they may be called, using the term introduced by van Bavel (1953), <u>drought day</u> studies, with a drought day occurring when ET_a falls below ET_p.

In the early work, it was assumed that the ET_a-ET_p ratio was a function of soil moisture content only. Furthermore, van Bavel (1953), van Bavel and Verlinder (1956), Knetsch (1959), and Alles (1969) all assumed that ET_a remains at the potential rate until the soil moisture content falls to some critical value, at which point ET_a falls to zero. This assumption is consistent with the early work of Thornthwaite (1948), who proposed a moisture index for climatic classification. Penman (1962) also used this assumption. But as Denmead and Shaw (1962) pointed out, many investigators observed that the ET_a-ET_p ratio declined with increasing soil moisture tension, rather than remaining constant until some critical value was reached and then dropping to zero. By 1955, Thornthwaite had modified his moisture index to incorporate the assumption that the ET_a-ET_p ratio was a linear function of the ratio of actual soil moisture content to the soil moisture content at field capacity (Thornthwaite and Mather 1955).

Other work has suggested that the ET_a-ET_p ratio is a function of both soil moisture and evaporative demand. Closs (1958) and Lowrey (1959), as cited by Flinn (1971), suggested that for any given plant-soil complex, there is a functional relationship between the maximum rate at which the plants can remove moisture from the soil (termed E_m), and the soil moisture content. This suggests that the ET_a-ET_p ratio is a function of ET_p and soil moisture content, since.

$$ET_a = ET_p \quad \text{if } ET_p \leq E_m$$

$$ET_a = E_m \quad \text{if } ET_p > E_m$$

Using evidence from greenhouse experiments with maize, Denmead and Shaw (1962) suggested that the ET_a-ET_p ratio is a function of both soil moisture content and evaporative demand. Although Ritchie (1973) presented results indicating that in the field, the form of this functional relationship may differ considerably from the results of Denmead and Shaw (1962), the basic concept that the ET_a-ET_p ratio is a function of both soil moisture tension and evaporative demand was not challenged. The approach of Denmead and Shaw (1962) was used by Dale and Shaw (1965) to determine the number of drought days occurring in a maize crop during a 9-week period around tasselling. The period was chosen because it was believed to represent the critical growth stage for maize with respect to moisture stress. They introduced the term *nonstress days* for the number of days during this period that were not drought days. Flinn and Musgrave (1967) followed a similar approach.

Not all investigators have accepted the concept that plant growth proceeds at the maximum rate until ET_a drops below ET_p, at which point growth ceases. Taylor (1952) developed a moisture stress index based on soil moisture tension measurements, which he successfully related to yields. His work led him to reject the commonly accepted hypothesis that moisture is equally available to plants for growth throughout the entire plant growth range from field capacity to permanent wilting percentage." Moore (1961) developed a plant growth index based on the assumption that growth decreased in proportion to the increase in soil moisture tension. Reutlinger and Seagraves (1962), using the assumption of Thornthwaite and Mather (1955) that the ET_a-ET_p ratio is equal to the ratio of the actual soil moisture content to the soil moisture content at field capacity, assumed that growth would not be substantially reduced as long as the ET_a-ET_p ratio had a value greater than 0.5. Between this value and zero, growth was assumed to decrease linearly to zero. Flinn (1971), using an ET_a-ET_p ratio estimated on the basis of the approach of Denmead and Shaw (1962), assumed that growth is reduced linearly from the nonstress level to zero as ET_a-ET_p ratio drops from 1.0 to 0.5. Hiler and Clark (1971) proposed a similar stress index, with the assumption that growth is linearly reduced to zero as the ET_a-ET_p ratio goes from 1.0 to zero.

With the exception of the Taylor (1952) study, all of these approaches are equivalent to the use of weighted drought days, where the weight for a given day represents reduction in growth, expressed as a fraction of the stressed growth, expected to occur on that day. Consideration is thus given to both the duration and the intensity of stress on each day, with the latter measured in terms of the ET_a-ET_p ratio.

The assumption that stress intensity on a given day is related to both soil moisture tension and atmospheric demand, coupled with the difficulty of determining ET_a, has led some investigators to attempt to incorporate separate variables for soil moisture and atmospheric demand into a stress index. Nix and Fitzpatrick (1969), working with wheat and sorghum in Australia, developed a stress index by dividing the amount of water in the root zone at the beginning of a critical period by the mean ET_p during that period. Hiler and Clark (1971) suggested that if data on ET_a are not available, stress intensity might be approximated by a multiplicative relationship between ET_p and soil moisture tension. Mapp and Eidman (1976) incorporated soil moisture deficits and evaporative demand as separate additive variables reflecting stress intensity, assuming linear relationships between yield reduction and the absolute amount of soil moisture depletion, and between yield reduction and pan evaporation in excess of a threshold value.

In contrast to the above studies, which developed indices that could be calculated without data on ET_a, Stewart and Hagen (1973) considered only ET_a, which they measured experimentally. They reported a linear relationship between yields of maize and sorghum and total ET_a of the crop, up to the point where water is no longer a limiting factor in crop growth. Moisture stress is thus defined on a seasonal basis as the difference between the amount of evapotranspiration necessary to achieve maximum yields, and the ET_a of the given crop. The difficulties of determining ET_a in the field, however, would seem to limit the extent to which this approach can be used.

A water shortage index for rice

All the studies reported above were conducted on crops grown in dryland soils, i.e. the soils contained structural aggregates and were reasonably well drained. The work focused on soil moisture-plant relationships between field capacity and the permanent wilting point. But this work is of limited applicability to wetland rice, which is grown generally on puddled flooded soils. In these soils, the soil aggregates have been deliberately broken down in the puddling process. A well-puddled soil will initially have water in excess of field capacity, so that there should be concern with relationships of soil moisture and plant from the saturated condition to field capacity, as well as from field capacity to wilting point. Furthermore, the water-release characteristics of a structureless puddled soil may be considerably different from those of dryland soils.

Work on the development of a water shortage index for rice has been limited mostly to that of Wickham and his colleagues at IRRI (Wickham 1971, IRRI 1973). Building on the work of Dale and Shaw (1965), Wickham attempted to develop a stress day concept that would include the total duration of water stress, the stress intensity during each stress period, and the effects of different growth stages on the susceptibility of the crop to stress. The duration of stress was based on the assumption that a stress period began on the fourth consecutive day with no standing water on the paddy, and continued until the paddy was flooded again.[2] During each stress period, soil hardness, rather than soil moisture tension, was used as a proxy for stress intensity, due to difficulties of measuring the latter on farmers' fields; however, efforts to incorporate this intensity information into the stress index were unsuccessful. Growth stage effects were considered by incorporating 1 variable reflecting stress during the vegetative phase (from transplanting to 60 days before harvest (DBH), and another reflecting stress during the reproductive stage, from 60 to 30 DBH. In later work at IRRI, these variables were called early and late stress days, respectively (IRRI 1973). But this approach to the incorporation of growth stage effects was not entirely successful, because usually only one -- not both -- of the two stress day variables was found to be significant. In part, this may be attributed to the high correlation between water shortage in the reproductive stage and water shortage in the vegetative stage in the available data. Attempts to treat water shortage as two independent variables are, therefore, likely to produce inconsistent and misleading results. Although attempts were thus made to include separate measures of the effects of duration, intensity, and growth stage on stress, the stress day approach actually incorporates only the duration of water shortage. Despite this limitation, the concept has been used successfully in several IRRI studies involving production functions (Tabbal and Wickham 1978, Rosegrant 1978, Herdt and Mandac 1981). The concept has proved useful, and is attractive because of the simplicity of the measurements involved. This latter factor is an important consideration for any stress index used in the evaluation of water conditions in large irrigation projects in rice-growing regions of Asia.

The objective of the work we report here was to develop, building on the stress day work, an improved water shortage index (WSI) for irrigated rice that could be used in nonexperimental fields (e.g. in large irrigation projects) to estimate the yield losses attributable to water shortage. We attempted to incorporate into the WSI measures of the duration of water shortage, of the intensity of shortage during each day period, and of the relative susceptibility of the crop to water stress at different growth stages.

Following Hiler and Clark (1971), we define the water shortage index in general terms as follows:

$$WSI = \sum_{i=1}^{n} (WSF_i)\,(CS_i) \qquad (1)$$

where n is the number of growth stages,

WSF_i is the water shortage factor for growth stage i, and

CS_i is a factor reflecting the relative susceptibility of the crop in growth stage i to water shortage.

From our review of literature we feel that the ideal variable to use as the water shortage factor (WSF_i) would be based either on ET_a, or on the ET_a-ET_p ratio. For rice grown in flooded paddies, many studies on the relationship between pan evaporation and ET_a have been conducted (see Tomar and O'Toole 1979a). But in flooded paddies, there is no water stress and the ET_a-ET_p ratio equals 1.0. It appears that until recently there were no published field studies that provide data on the behavior of this ratio during periods of drought (Wickham and Sen 1978). Bolton (1980) presents data for two soils in Iloilo, Philippines, that suggest a linear relationship between the ET_a-ET_p ratio and soil moisture content between saturation and the point at which transpiration ceases. Angus (1979) developed a rice growth simulation model by assuming that the ET_a-ET_p ratio declines at an exponentially decreasing rate as soil moisture content falls from saturation to the point at which transpiration ceases.

As we are unable to use either ET_a or the ET_a-ET_p ratio for the water shortage factor, we have modified the suggestion of Hiler and Clark (1971) that stress intensity could be approximated by a multiplicative relationship between ET_p and soil

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[2] The figure of 3 days prior to the onset of stress can in part be justified on the grounds that at typical rates of evapotranspiration, the amount of *free water* in the saturated puddled soil (i.e. the amount in excess of field capacity), is enough to last for about 3 days.

moisture tension and defined the water shortage factor for growth stage i in general terms as:

$$WSF^{i} = \sum_{j=1}^{d_i} (ED_j)\ (SW_j) \qquad (2)$$

where d_i is the number of days in growth stage i,

ED_j is some variable reflecting the environmental water demand on the plant during day j, and

SW_j is a variable reflecting the supply of water in the soil available to the plant on day j.

Considering only plant-soil-water relationships, it appears from the literature that it would be best to use ET_p for ED_j and either integrated soil moisture tension or soil moisture content for SW_j. Considering the difficulties of field measurement, however, we propose using pan evaporation to represent environmental demand, and scaled depth to the perched water table to represent the water supply in the soil. More specifically, our proposal for the water shortage factor for growth stage i is:

$$WSF_i = \sum_{j=1}^{d_i} (PAN_j)\ (DSW_j) \qquad (3)$$

where PAN_j is the pan evaporation on day j, and

DSW_j is the scaled depth to the perched water table on day j.

For a water shortage index for rice, pan evaporation (as measured by a Class A pan) appears to be a good proxy for potential evapotranspiration. Although there is disagreement in the literature concerning the details of the relationship between pan evaporation and potential evapotranspiration, there is general agreement that the two are highly correlated (Tomar and O'Toole 1979a, Yoshida 1978, Wickham and Sen 1978). The absolute magnitude of pan evaporation relative to ET_p need not concern us, as we need only a relative measure of environmental demand.

The use of depth to standing water as a proxy for soil water is more problematic. We have chosen to use it because it appears to be a feasible measure to obtain over large areas in field conditions. Obtaining and analyzing soil samples from dry and cracked paddies for soil moisture content do not seem feasible on a large-scale basis. Difficulties with the use of tensiometers in heavy, cracking clay soils led Wickham (1971) to conclude that widespread field measurements of soil moisture tension with tensiometers were not feasible. As noted above, his approach was to measure soil hardness with a penetrometer, but the resulting data were not successfully incorporated into his stress day analysis. Depth to the perched water table is a relatively easy variable to measure. The reading is made using a perforated tube installed in the ground after land preparation has been completed. The bottom of the tube should be at some reasonable depth with respect to the rice root zone (such as 50 cm below the surface of the ground). This tube serves as an observation well.

In our analysis, depth to the perched water table was scaled from zero (perched water table at or above the ground surface) to 1.0 (perched water table at or below the bottom of the perforated tube). Thus, the daily contribution to the water stress factor is zero on any day when there is standing water on the paddy, or when the paddy is completely saturated (i.e. when the perched water table is at the surface). When the perched water table is at or below the bottom of the perforated tube, the contribution to the water shortage factor is equal to the pan evaporation for the day. This implicitly assumes that the effect of soil moisture stress on the plant reaches a maximum when the perched water table has dropped to the bottom of the perforated tube.

Little work has been done on the question of how the rice plant varies in its susceptibility to water stress at different growth stages; however, there is general agreement that the most critical period relative to water stress occurs in the reproductive growth stage (Salter and Goode 1967, Matsushima 1962, 1966; Yoshida 1975; Neales 1976; De Datta et al 1973; Reyes and Wickham 1973; IRRI 1973, 1974; Murakami 1975; Tomar and O'Toole 1979b; Namuco et al 1980). Some investigators (Matsushima 1962, Yoshida 1975) have suggested that the reduction division stage is the most critical; other work has suggested that the critical period centers on flowering (Namuco et al 1980). In either case, the period from about 20 days before flowering to 10 days after flowering would include this critical period.

The above discussion suggests the possibility of using three growth stages in the stress index. The first stage would cover the vegetative and early reproductive period, from transplanting to about 20 days before flowering. The second stage would be the late reproductive stage, from 20 days before flowering to 10 days after flowering. The third stage would be the ripening stage, beginning 11 days after flowering

DATA AND PROCEDURES

In the development of a water shortage index, we have made use of several data sets generated by IRRI researchers in the Philippines (Table 1). Two of these data sets came from experiments in rainfed fields at Iloilo, and were provided by Bolton (1980). A third data set, which came from IRRI's Irrigation Water Management Department, was collected in the command area of Lateral C of the Peñaranda River Irrigation System in Central Luzon (Tabbal 1975, Tabbal and Wickham 1978). Two other data sets were from an irrigated experiment

Table 1. Information on the data sets analyzed.

Data set	Season	Type of data	Number of observations in the analysis	Variety	Data used to construct alternative water shortage indices
Iloilo plain	1977-78 dry	Experimental	32	IR36	1) Depth to standing water (cm from ground surface) in observation wells inserted into ground soil to 120-cm depth (daily) 2) Soil moisture content (mm per 30 cm) based on volumetric readings (daily) 3) Presence or absence of standing water in the paddy (daily) 4) Pan evaporation (mm/day) (daily)
Iloilo plateau	1977-78 dry	Experimental	28	IR36	Same as Iloilo plain
Lateral C	1973-74 dry	Farm	200	Mostly IR20	1) Depth to standing water (cm from ground surface) in observation wells inserted into ground soil to 25-cm depth (daily) 2) Presence or absence of standing water in the paddy (daily) 3) Pan evaporation (mm/daily)
Central Luzon 1978	1977-78 dry	Experimental	90	IR36	1) Soil moisture content (% dry weight)(daily) 2) Pan evaporation (mm/day) (daily)
Central Luzon 1979	1978-79 dry	Experimental	30	IR36	Same as Central Luzon 1978

in Central Luzon, and were provided by the IRRI Irrigation Water Management Department.

The Iloilo data are for the two rainfed sites where Bolton had experiments in 1978-79 on the effects of different planting dates and nitrogen levels on rice yields. The experiment at the low site (the plain) involved 8 transplanting dates between 1 September and 30 November 1978. For each planting date, 4 treatments for nitrogen (0, 30, 60, and 90 kg N/ha) were established. IR36 was grown in all cases and the plots were harvested 89 days after transplanting. The treatments on the high site (plateau) were identical to those on the plain, except that only 7 planting dates were used, because plateau soils were too dry to permit transplanting 30 November.

At the plain site, the fields had standing water through 30 November and then were without standing water through 13 December. Rainfall at that time flooded the fields again from 14 December through 31 December. Beginning 1 January 1979, the fields were continuously without standing water. At the plateau site, standing water remained on the fields only through 20 November. The rainfall in December resulted in standing water on the fields from 15 December through 19 December, after which the fields were continuously without standing water.

Two alternative measures of the water supply in the soil were available from the Iloilo data provided by Bolton. The first was the depth to standing water in observation wells inserted into the soil to a depth of 120 cm. These wells did not have perforations above the soil surface and the depth to water in the observation well at the time standing water first disappeared from the surface of the paddy was 75 cm in both sites. We scaled the water depth readings between 75 and 120 cm linearly from 0.0 to 1.0. Multiplying these depths by the daily pan evaporation values (mm/day), and summing over the appropriate period, gave water shortage factors based on depth to standing water.

The second measure of soil water conditions available was the soil moisture content. Although field measurement of soil moisture content in irrigation projects in Southeast Asia is probably not generally feasible, soil moisture is presumably a better proxy for availability of moisture to the plants than is the depth to standing water. For this reason, we used these data to evaluate certain alternative formulations of the water shortage index. Bolton measured the soil moisture content on a volumetric basis at several points in time after the field was no longer flooded. We obtained daily values by interpolating between the dates on which actual measurements were taken. The daily water shortage factor was given a scale value of zero when the soil moisture content was at saturation. A scale value of 1.0 was assigned to represent the soil moisture content prevailing at the time the crop was essentially dead. Multiplying the resulting daily scaled depths to standing water by the daily pan evaporation values (mm/day), and summing over the appropriate period, gave the water shortage factors, as defined by equation 2, based on soil moisture content.

The third data set used in the development of the water shortage index involved farm data in 5,700 ha in the command area of Lateral C of the Peñaranda project in Nueva Ecija. Using a grid, Tabbal and Wickham (1978) selected sample paddies, in each of which they installed a perforated tube to a depth of 25 cm.[3] They used crop-cut samples to determine yield and interviewed farmers to get information on the amount of nitrogen used. We used the data generated from the 1973-74 dry season, for which the total number of sample paddies was 284. After eliminating cases with missing values, we had a data set based on observations for 200 paddies. According to Tabbal (1975), more than 90% of the area from which these paddies were sampled was planted to IR20.

The final two data sets came from experiments in the 1978 and 1979 dry seasons at sites in Bulacan and Nueva Ecija in Central Luzon. Data were available for three sites in 1978 and two sites in 1979. In both years the variety grown was IR36. The experiment involved five water treatments. Control plots were continually flooded and plots of the remaining treatments were drained and kept unflooded for 12, 19, 26, and 33 days (11, 24, 31, and 38 days at 1 site). All the stress treatments in a given site were reflooded on the same date, which was about 30 DBH. Three management levels each involving a group or package of techniques were superimposed on each treatment. Two of these management packages were determined by the researchers, and differed primarily in the amount of fertilizer used. The third management treatment was based on decisions of the local participating farmer. The major differences between his treatment and the others were in fertilizer use and pest control. All treatments were replicated 3 times, resulting in 45 observations per site.

The measure of the supply of soil moisture available for these data sets was the soil moisture content, which was recorded daily during the period when a plot was without standing water. Although some measurements of the depth to standing water were taken, the close proximity of the various water treatments within a given replication made it impossible to obtain meaningful water depth information on individual treatments.

Preliminary analysis of the data from both the 1978 and 1979 irrigation experiments in Central Luzon revealed that in one site (Santa Cruz) there were no statistically significant differences in yield among the water treatments. Furthermore, all treatments showed low values for the various water shortage indices tested. The apparent reason for this was that subsurface water flows from a nearby canal at the site defeated the experimental attempt to impose any substantial degree of water stress on the plots. With no significant degree of water stress imposed at the Santa Cruz site, it was not possible to use the Santa Cruz data to test the relative merits of alternative formulations of a water shortage index. As a result, data from that site were not included in the analysis.

We also observed that the yields obtained on the plots that were managed at the farmer's input level tended to be considerably lower than would otherwise be predicted from the stress and fertilizer treatments. This can be attributed to considerably poorer insect and disease control under the farmer's management level. The farmer's management level generally involved less fertilizer than the other two management packages, resulting in a tendency for a negative relationship between fertilizer use and pest damage. With no explicit measure of pest damage in the yield equation, this introduced a bias in the estimated coefficients. In the 1978 data set, we were able to deal with this satisfactorily by including an intercept-shifting dummy variable in the response equation. The variable took on a value of one if the plot involved the farmer's management level, and zero if otherwise. In the 1979 data set, even with the inclusion of the dummy variable, the estimated equations appeared to give an unreasonably low intercept and an unreasonably large coefficient to nitrogen. For this reason, the farm-level management plots were dropped from the analysis of the 1979 data. The analysis reported below is thus based on 90 observations from 1978 (45 from Maburak and 45 from Camachilihan), and 30 from 1979 (from Maburak, excluding the farmer-managed plots). The data for the two sites in 1978 were pooled after an individual analysis of each site showed no significant difference in the estimated coefficients of the water shortage index.

We began our analysis of the five data sets to develop a water shortage index by hypothesizing the following functional relationship between yield ($\underline{Y}$), nitrogen ($\underline{N}$), and the water shortage index ($\underline{WSI}$):

$$\underline{Y} = \underline{a} + \underline{b_1N} + \underline{b_2N^2} + \underline{b_3WSI} + \underline{b_4WSI^2} + \underline{b_5N \cdot WSI}$$

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[3] This depth was probably shallower than desirable for the water shortage index. In more recent work at IRRI, 40-cm depth was used for observation wells (Early 1980; Alagcan, 1981, pers. comm.) and a 50-cm depth was used in related work in West Java (Pasandaran, Gadja Mada University, 1981, pers. comm.).

In the estimated equations, none of the coefficients for either quadratic term were ever significant; these terms were, therefore, dropped. For three data sets -- Iloilo plain, Lateral C, and Central Luzon 1978 -- the coefficient for the interaction term between nitrogen and water shortage was not significant and was also dropped. For the other two data sets -- Iloilo plateau and Central Luzon 1979 -- the estimated coefficients for the nitrogen-water shortage interaction term was usually significant, and the term was retained throughout the analysis of these data sets.

In developing a water shortage index, we had to deal with several issues. For each issue, except soil texture, we considered alternative formulations of the index. In each case the analytical procedure was to calculate the values for the alternative indices being considered, and then to use those data to estimate a series of regression equations. The equations in each series were identical in form, number, and type of variables included. The only difference was in the formulation of the water shortage index. We then evaluated the relative merits of the various formulations of the index by considering both how well the equations fit the data, as measured by the R^2 values, and how precisely the equation estimated the yield loss due to water shortage, as measured by the size of the confidence interval for the point estimate of this loss.[4]

RESULTS

The first issue we had to deal with in the development of the water shortage index is the determination of the appropriate time over which the index is to be calculated. The index is calculated by summing daily water shortage values beginning at the date of transplanting, and continuing to some appropriate cutoff date. One possibility is to continue the calculation up to the date of harvest. But moderate levels of water stress during the last 10 DBH are not likely to reduce yield, as the photosynthates have already been produced by that time and need only to be translocated to the grains. Where farmers have control over the water, a common practice is to drain the paddy field at least 10 days before maturity, so that it will be dry at harvest.

We tested four alternative cutoff points for the water shortage index: 30 DBH, 20 DBH, 10 DBH, and 0 DBH (Table 2). For the data from the Iloilo plain site, the index based on 20 DBH gave the highest R^2, and the index based on 0 DBH gave the lowest. However, the differences in the R^2 were small among the indices using 10, 20, and 30 DBH as the cutoff points. Both the estimated yield reduction at the mean stress level and the confidence interval around this estimate increased as the cutoff point approached the date of harvest, with the largest increases occurring between the index using 10 DBH and that using 0 DBH. For the Iloilo plateau site, there was little difference in the R^2 of the 4 alternatives, although the indices based on 20 and 30 DBH gave a slightly higher R^2. As in the case of the plain, the plateau index based on summations to 0 DBH gave a somewhat higher estimate of the reduction in yield caused by stress and a wider confidence interval.

For the Lateral C data set, there were no differences in the R^2 for indices based on 10, 20, and 30 DBH. All stress treatments in the data sets from the Central Luzon experiments ended by 30 DBH, therefore, no information could be obtained from these data sets on the performance of alternative cutoff points. Given these results, and considering that the critical period for sensitivity to water shortage presumably ends about 10 days after flowering, which for most modern varieties is about 20 days before maturity, we conclude that the water shortage index should be calculated at least until 20 DBH, but should not extend beyond 10 DBH.

A second issue in the formulation of a water shortage index is the determination of the crop susceptibility factors for the various growth stages (the CS_i in equation 1). None of the work reported in the literature on the differential growth stage effects of water stress was designed to give quantitative estimates of these crop susceptibility factors; however, a few of the studies shed some light on this matter. In Matsushima's (1962) study, the yield reduction from water stress in the critical period around flowering was three to five times the amount of reduction of a presumably similar stress imposed in the vegetative phase. A field experiment at IRRI with IR20 resulted in stress during the reproductive stage reducing yields by slightly more than twice as much as when stress was imposed during the vegetative stage (Reyes and Wickham 1973; IRRI 1973). In an experiment by Tomar and O'Toole (1979b,c), the yields of three cultivars (IR20, Kinandang Patong, and IR6115-1-1-1) stressed during the reproductive stage were reduced 2 to 5 times as much as the yield reduction of IR1529-680-3-2 stressed in the vegetative stage. No firm conclusions about the relative susceptibility of different growth stages to water stress can be made, however, because in no case was the same cultivar stressed in both growth stages. Although far from definitive, these studies suggest that in the reproductive stage, the yield loss from water stress may be two to five times the loss for a comparable amount of stress in the vegetative stage. No information could be found that could be interpreted in a similar fashion for the ripening stage.

For convenience, we chose a value of 1.0 for the crop susceptibility factor for the vegetative

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[4] We also considered the F-tests for the significance of the equations and the standard errors of the estimate of Y. All equations were significant at the .001 level, and for all equations being compared, larger F-values and smaller standard errors of the estimate were associated with larger R^2 values. We do not, therefore, report the F-values or the standard errors of the estimate of Y in this paper.

stage (from transplanting to 51 DBH), and then tested values ranging from 1.0 to 5.0 for the presumed critical reproductive period (50 to 20 DBH). The ripening period (from 19 to 10 DBH) was either excluded from the analysis (Table 3) or included with a weight to 1.0 (Table 4). For the Iloilo plateau and the Lateral C data sets, there is a tendency for slight improvement in the R^2 of the estimated production function as the weight on the reproductive period increases from 1.0 to about 3.0. No improvement in the R^2 occurs with the other data sets. The estimates of yield reduction due to water stress are stable with the alternative weights. Although some changes in the confidence intervals occurred as the weights increased, no consistent pattern in these changes is apparent. We are thus unable to find any empirical basis for using a different crop susceptibility factor for the reproductive growth stage.

Having established that in the field 20 DBH is an acceptable cutoff date, and that a crop susceptibility factor of 1.0 for all growth stages gives results comparable to those obtained when the reproductive stage is given a larger weight, we now turn to a comparison of our measures of water shortage with the traditional stress day concept. This comparison is complicated by the fact that

Table 2. Comparison of alternative cutoff points for the water shortage index on production function estimates of yield loss due to water shortage.[a]

Cutoff points[b]	R^2 of estimated production function			Estimated yield reduction at mean levels of stress and N (point estimate and 95% confidence limits) (t/ha)		
	Iloilo plain	Iloilo plateau	Lateral C	Iloilo plain	Iloilo plateau	Lateral C
30 DBH	.81	.86	.24	.78 ± .14	.79 ± .39	.35 ± .11
20 DBH	.84	.86	.24	.90 ± .15	.77 ± .39	.36 ± .11
10 DBH	.81	.84	.24	.95 ± .17	.80 ± .44	.39 ± .12
0 DBH	.76	.85	.23	1.07 ± .21	.91 ± .47	.42 ± .14

[a] The water shortage indices for the Iloilo plain and plateau are based on the summation (over the period from transplanting to the cutoff date) of the product of daily soil moisture content values and daily pan evaporation values. The index for Lateral C is the same except that daily depths to standing water were used instead of daily soil moisture content values, which were not available. [b] DBH = days before harvest.

Table 3. Effects of different crop susceptibility factors for 50-20 days before harvest (DBH) on production function estimates of yield loss due to water shortage (water shortage index calculated from transplanting to 20 DBH).[a]

Factor susceptibility factor for reproductive period (50-20 DBH)[b]	R^2 of estimated production function					Estimated yield reduction at mean levels of stress and N (point estimate and 95% confidence limits) t/ha				
	Iloilo plain	Iloilo plateau	Lateral C	Central Luzon 1978	Central Luzon 1979	Iloilo plain	Iloilo plateau	Lateral C	Central Luzon 1978	Central Luzon 1979
1.0	.84	.86	.24	.76	.55	.90±.15	.77±.39	.36±.11	.76±.16	.84±.35
2.0	.84	.88	.25	.76	.54	.89±.15	.82±.37	.37±.11	.78±.17	.85±.32
3.0	.84	.89	.25	.76	.54	.89±.14	.84±.32	.35±.10	.79±.17	.85±.34
4.0	.84	.89	.25	.76	.54	.89±.14	.85±.35	.34±.09	.78±.18	.85±.37
5.0	.84	.90	.24	.76	.54	.88±.15	.86±.39	.33±.11	.79±.16	.85±.40

[a] The water shortage indices for the Iloilo plain and plateau and for the Central Luzon experiments for 1978 and 1979 are based on the summation (over the period from transplanting to the cutoff date) of the product of daily soil moisture content values and daily pan evaporation values. The index for Lateral C is the same except that daily depths to standing water were used instead of daily soil moisture content values, which were not available. [b] Vegetative phase (from transplanting to 51 DBH) is given a crop susceptibility factor of 1.0.

the traditional stress day analysis involves the calculation of two separate variables -- early stress days and late stress days. In analyzing the various data sets, it became apparent that regardless of whether the traditional stress day measure or one of the indices we developed was used, attempts to separate the measure of water shortage into two separate variables for early and late stress led to difficulties in estimation. The problem was caused by the lack of independence between the values of the early and late stress variables. In some of the data sets the Pearson correlation coefficient between these variables was greater than 0.9. This lack of independence can be expected in many field situations which are not experimentally controlled, however, it also occurred in all of the experimental data sets which were available to us. We conclude that in the absence of experiments specifically designed for separating the effects of early and late stress, it is empirically difficult to separate a stress index into two separate variables. In the following comparisons between the water shortage indices we developed and the stress day approach, we have modified the latter to incorporate early and late stress into a single variable. The stress day index referred to in this section is defined as the total number of days between transplanting

Table 4. Effects of different crop susceptibility factors for 50-20 days before harvest (DBH) on production function estimates of yield loss due to water shortage (water shortage index calculated from transplanting to 10 DBH).[a]

Crop susceptibility factor for reproductive period (50-20 DBH)[b]	R^2 of estimated production function			Estimated yield reduction at mean levels of stress and N (point estimate and 95% confidence interval) (t/ha)		
	Iloilo plain	Iloilo plateau	Lateral C	Iloilo plain	Iloilo plateau	Lateral C
1.0	.81	.84	.24	.95 ± .17	.80 ± .44	.39 ± .12
2.0	.84	.87	.25	.94 ± .15	.84 ± .43	[illegible]8 ± 11
3.0	.84	.88	.25	.92 ± .15	.85 ± .36	.26 ± .10
4.0	.84	.89	.25	.92 ± .15	.86 ± .38	.35 ± .10
5.0	.84	.89	.25	.91 ± .15	.86 ± .42	.34 ± .10

[a] The water shortage indices for the Iloilo plain and plateau are based on the summation (over the period from transplanting to the cutoff date) of the product of daily soil moisture content values and daily pan evaporation values. The index for Lateral C is the same except that daily depths to standing water were used instead of daily soil moisture content values, which were not available. [b] Vegetative phase (from transplanting to 51 DBH) and ripening phase (19-10 DBH) are given crop susceptibility factors of 1.0.

Table 5. Comparison of performance of water shortage indices based on alternative measures of water shortage, Iloilo plain.[a]

Measure of water shortage	Estimated regression coefficients[b]			R^2	Mean value of WSI	Estimated yield reduction at mean stress level (point estimate and 95% confidence limits) (t/ha)
	Constant (t/ha)	Nitrogen (t/kg N)	WSI			
SMC * PAN[c]	3.84	.0103*** (.0033)	-.0313*** (.0026)	.84	28.7	.90 ± .15
DSW * PAN[d]	4.01	.0103*** (.0038)	-.0262*** (.0025)	.80	40.7	1.07 ± .20
Stress days[e]	4.19	.0103*** (.0048)	-0851 (.0113)	.68	14.6	1.24 ± .36

[a] All indices based on a cutoff point of 20 days before harvest (DBH) and a crop susceptibility factor for the reproductive period of 1.0. [b] Figures in parentheses are standard errors of the estimates. [c] Index based on summation from transplanting to 20 DBH of the product of daily soil moisture content values and daily pan evaporation values. [d] Index based on summation from transplanting to 20 DBH of the product of daily depth to standing water values and daily pan evaporation values. [e] Index based on summation from transplanting to 20 DBH of the number of days without standing water, less the first 3 days in each dry period. ***Significant at the 1% level.

and 20 DBH that the paddy is without standing water, excluding the first 3 days of each dry period.

For the Iloilo data set, it is possible to compare indices of water shortage based on three alternative measures: 1) daily scaled soil moisture content values multiplied by daily pan evaporation values (SMC*PAN); 2) daily scaled depth to standing water values multiplied by daily pan evaporation values (DSW*PAN); and 3) the stress day index (SD). For the plain, the index based on SMC*PAN gave the highest R^2 (.84), whereas the index based on DSW*PAN gave an R^2 of .80. Both were improvements over the stress day index, which gave an R^2 of .68 (Table 5). For the plateau, there was little difference in the R^2 of the three alternatives, although the DSW gave the highest value (Table 6). At both sites, the stress day index gives somewhat larger point estimates of the yield reduction due to water shortage. The confidence interval around these point estimates is considerably larger for the stress day index (Table 5 and 6).

For Lateral C, data are available only for the water shortage index based on DSW*PAN and for the stress day index (Table 7). Compared to the stress day index, the DSW*PAN index increased the R^2 from .15 to .24, and gives a slightly higher estimate of the yield reduction due to water shortage,

Table 6. Comparison of performance of water shortage indices based on alternative measures of water shortage, Iloilo plateau.[a]

Measure of water shortage	Constant (t/ha)	Nitrogen (t/kg N)	WSI	N*WSI	R^2	Mean value of WSI	Estimated yield reduction at mean levels of stress and N[c] (point estimate and 95% confidence limits) (t/ha)
SMC * PAN[d]	2.65	.0098*** (.0028)	-.0118*** (.0022)	-.000084** (.00004)	.86	49.3	.77 ± .39
DSW * PAN[e]	2.70	.0102*** (.0026)	-.0105*** (.0018)	-.000076** (.00003)	.89	60.3	.84 ± .37
Stress days[f]	2.75	.0112*** (.0032)	-0327*** (.0067)	-.0026** (.00012)	.85	21.1	.94 ± .50

[a] All indices based on a cutoff point of 20 days before harvest (DBH), and a crop susceptibility factor for the reproductive period of 1.0. [b] Figures in parentheses are standard errors of the estimates. [c] Mean value of N was 45.0 kg/ha. [d] Index based on summation from transplanting to 20 DBH of the product of daily soil moisture content values and daily pan evaporation values. [e] Index based on summation from transplanting to 20 DBH of the product of daily depth to standing water values and daily pan evaporation values. [f] Index based on summation from transplanting to 20 DBH of the number of days without standing water, less the first 3 days in each dry period. ***Significant at the 1% level. **Significant at the 5% level.

Table 7. Comparison of performance of water shortage indices based on alternative measures of water shortage, Lateral C.

Measure of water shortage	Estimated regression coefficients[a]			R^2	Mean value of WSI	Estimated yield reduction at mean stress level (point estimate and 95% confidence limits) (t/ha)
	Constant (t/ha)	Nitrogen (t/kg N)	WSI			
DSW * PAN[b]	2.30	.0103*** (.0026)	-.00564*** (.00088)	.24	64.7	.36 ± .11
Stress days[c]	2.21	.0109*** (.0020)	-.0123*** (.0031)	.14	25.0	.31 ± .15

[a] Figures in parentheses are standard errors of the estimates. [b] Index based on summation from transplanting to 20 days before harvest (DBH) of the product of daily depth to standing water values and daily pan evaporation values. [c] Index based on summation from transplanting of 20 DBH of the number of days without standing water, less the first 3 days in each dry period. ***Significant at the 1% level.

and a slightly narrower confidence interval around this estimate.[5]

For the Central Luzon sites in 1978 and 1979, data are available for a comparison only of the water shortage index based on SMC*PAN and that based on stress days (Tables 8 and 9). Again, the index based on SMC*PAN results in somewhat higher R^2 values than the stress day index. Furthermore, for the 1978 data, the SMC*PAN index gives a lower point estimate of the yield reduction due to stress, and a narrower confidence interval.

Another question to be considered in the formulation of the water shortage index is that of the benefit of including pan evaporation in the calculation of the daily water shortage factors used in the index. The results from equations estimated for water shortage indices which incorporate the daily pan evaporation values are compared to those estimated for indices which do not incorporate pan evaporation in Table 10. It is apparent that for these only marginal gains in the R^2 are obtained by incorporating pan evaporation into the index. This might not be true, however, for data sets that involve both wet and dry seasons, where variability in pan evaporation would be greater.

For the Lateral C data set, we attempted to incorporate information on differences in soil texture into our equations. Of the 284 paddies cropped in the 1973-74 dry season, 188 are heavy clay soils (from 55 to 88% clay in the upper 15 cm of soil), and another 54 are either clay, or clay loam with a minimum of 35% clay. The remaining 42 paddies are classified as sandy clay loams.

We hypothesized that the yield reduction per unit of "water shortage" (as measured by the water shortage index) might be less in heavy-textured soils than in light-textured soils because at any given depth to standing water, a greater amount of moisture would be available to the plants in the heavier-textured soils. To test this hypothesis, we created a "slope-shifting" dummy variable that took on a value of 0 if the percentage of clay was below a specified level, and a value equal to the water shortage index if the percentage of clay was equal to or greater than the specified level. The effect of this variable in the equation is to group the soils into two categories, and to allow the coefficient for the water shortage index to differ between the two. We tested alternative percentages of clay ranging from 35 to 60 as the specified level used to group the soils into two categories. In no case was the estimated coefficient of the dummy variable significantly different from zero. We also tried incorporating the percentage of clay as a separate continuous variable in the regression equation, along with nitrogen and the water shortage index. Again, the estimated coefficient was not significant.

We conclude that for the Lateral C data set, at least, either the differences in the texture of the surface soils are unimportant for explaining differences in yields and in yield loss due to water shortage, or else the effect of these differences is already incorporated (via the depth to standing water) in the water shortage index.

To further evaluate the relative merits of the proposed water-shortage index and the stress day index, we compared the estimates of yield reduction across sites. An ideal index that fully incorporates all the effects of water shortage on yield should result in similar estimates of yield reduction, when these estimates are expressed as a percentage of the estimated stressed yield.[6] For each of the equations reported in Tables 5-9, we calculated the yield reduction per unit of stress as a percentage of the stressed yield at the mean nitrogen level (Table 11). To facilitate comparisons among the sites, the yield reductions for each site are also expressed as percentages of the corresponding figure for the Iloilo plain (Table 11).

Although there are differences in the estimated rates of yield reduction among the data sets, the most striking difference is between the estimated rate for the Lateral C data set and the rates for the others. The 0.46% yield reduction per stress day for Lateral C is less than half as large as the corresponding figure for any of the other data sets, and is only 25% as large as the 1.83% for the Iloilo plain. This result can be explained on the basis of the differences in the intensity of stress per stress day, and in the extent to which the duration and the intensity of stress were correlated in these data sets. It is likely that the average intensity of stress imposed on the experimental sites per stress day was greater than that encountered on the Lateral C plots, since one of the objectives of the experiments was to observe the yield effect of severe stress. Furthermore, by the nature of the experimental treatments, duration and intensity of stress were highly correlated in the experimental sites, so that the estimated coefficients for stress days on these sites tend to reflect intensity as well as duration. In the controlled farm conditions of Lateral C, the correlation between duration and intensity was less so that the coefficient of the stress day variable was less likely to reflect the yield effect of intensity. For example, a given number of stress days might occur in a single period of stress (high intensity) on some fields, whereas the same number of days might have resulted from several short (low intensity) periods of stress on another farm.

To the extent that the proposed water shortage index is able to incorporate the effect of stress

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[5] The low R^2 obtained with the Lateral C data set reflects the fact that the data represent farm rather than experimental conditions, with many uncontrolled and unmeasured factors (unrelated to water conditions) affecting yield.

[6] This implies that the number of units of stress resulting in a zero yield would be the same at all sites.

intensity on yield, the difference between the results for Lateral C and the other data sets should be reduced. The estimated yield reduction for the index based on DSW*PAN shows Lateral C to be still considerably less than the other sites for which a comparison is possible; however, with the figure for Lateral C which is 36% of that for the Iloilo plain, the discrepancy is less than in the case of the stress day index.[7] These results again suggest that although far from being ideal, the proposed water shortage index is a modest improvement over the stress day index.

CONCLUSIONS

The water shortage index we developed for wetland rice can be expressed as:

$$\underline{WSI} = \sum_{\underline{j} = \underline{DOT}}^{20\ \underline{DBH}} (\underline{PAN}_j)(\underline{DSW}_j) \qquad (4)$$

where DOT stands for the day of transplanting, 20 DBH stands for 20 days before harvest, $\underline{PAN}_j$ is the pan evaporation on day $\underline{j}$ serving as a measure of the environmental demand placed on the plants on that day, and DSW_j is the scaled depth to standing water in the perched water table serving as a proxy for the supply of water in the soil available to the plant on day $\underline{j}$. This formulation was based on the assumption that the intensity of water shortage would be measured by the multiplicative relationship between environmental demand and depth to standing water; however, the results indicate that within a single season stress intensity is measured equally well by the water depth

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[7] The fact that the measurements of the depth to standing water in the Lateral C data sets were limited to 25 cm below the ground surface reduced the extent to which the DSW*PAN index could measure intensity of stress. If the observation wells had been installed to a depth of 50 cm, the discrepancy in the yield reduction estimates probably would have been less.

Table 8. Comparison of performance of water shortage indices, based on alternative measures of water shortage, Central Luzon, 1978.[a]

Measure of water shortage	Estimated regression coefficients[b]				R^2	Mean value of WSI	Estimated yield reduction at mean WSI (point estimate and .95 confidence limits) (t/ha)
	Constant	Nitrogen	WSI	Management dummy			
SMC * PAN[c]	3.89	.0086*** (.0020)	-.0218*** (.0024)	-1.92*** (0.14)	.76	34.8	.76 ± .16
Stress days[d]	4.27	.0055*** (.0021)	-.0509*** (.0061)	-1.91*** (0.15)	.74	17.0	.86 ± .20

[a] Based on 90 observations at 2 sites (Maburak and Camachilihan). [b] Figures in parentheses are the standard errors of the estimates. [c] Index bases on summation from transplanting to 20 days before harvest (DBH) of the product of daily soil moisture content values and daily pan evaporation values. [d] Index based on summation from transplanting to 20 DBH of the number of days without standing water, less the first 3 days in each dry period. ***Significant at the 1% level.

Table 9. Comparison of performance of water shortage indices based on alternative measures of water shortage, Central Luzon, 1979.[a]

Measure of water shortage	Estimated regression coefficients[b]			R^2	Mean value of WSI	Estimated yield reduction at mean N and stress[c] (point estimate and .95 confidence limits) (t/ha)
	Constant	Nitrogen	N * WSI			
SMC * PAN[d]	1.85	.0146*** (.0045)	-.000139*** (.00003)	.55	47.2	.84 ± .35
Stress days[e]	1.85	.0145*** (.0048)	-.000396*** (.00008)	.48	16.4	.83 ± .33

[a] Based on 30 observations at 1 site (Maburak). [b] Figures in parentheses are standard errors of the estimates. [c] Mean level of N was 127.5 kg/ha. [d] Index based on summation from transplanting to days before harvest (DBH) of the product of daily soil moisture content values and daily pan evaporation values. [e] Index based on summation from transplanting to 20 DBH of the number of days without standing water, less the first 3 days in each dry period. ***Significant at the 1% level.

Table 10. Comparison of production functions using water shortage indices developed with and without data on pan evaporation.[a]

Data set and type of index	R^2 of estimated production function	Estimated yield reduction at mean stress level (point estimate and 95% confidence limits) (t/ha)
Iloilo plain		
DSW * PAN	.80	1.07 ± .20
DSW	.77	1.13 ± .23
Iloilo plateau		
DSW * PAN	.89	.84 ± .37
DSW	.89	.89 ± .39
Lateral C		
DSW * PAN	.24	.36 ± .11
DSW	.23	.35 ± .11
Central Luzon, 1978		
SMC * PAN	.76	.76 ± .16
SMC	.78	.78 ± .15
Central Luzon, 1979		
SMC * PAN	.55	.84 ± .35
SMC	.56	.82 ± .30

[a] All water shortage indices based on a cutoff point of 20 days before harvest (DBH), and with a crop susceptibility factor of 1.0 for the reproductive stage. DSW = depth to standing water, SMC = soil moisture content.

variable alone. Stress duration is incorporated through the summation of the daily water shortage factors between transplanting and 20 DBH. The index does not incorporate any growth stage effects because the data we used did not provide any clear basis for including such effects.

A comparison of the index we developed with the traditional stress day approach to measuring the effect of water shortage showed our index to give a somewhat higher R^2. Considering that the index is specifically designed for use on farm (i.e. nonexperimental) data, it is notable that the largest relative increase in the R^2 (from .14 to .24) occurred in the only data set based on farm conditions (Lateral C). Although we thus prefer the use of the index we have developed over the stress day measure, the improvement is modest, and where data for this WSI are not available, the stress day approach is a reasonable alternative. We suggest, however, that the stress day index be a single value based on the summation of the appropriate days from transplanting to 20 DBH because using early and late stress days as separate independent variables has led to inconsistent results.

We also tested the proposed WSI as defined in equation 4 against an alternative formulation which dropped pan evaporation from the calculation of the index. The results showed that for the data sets we used, incorporating pan evaporation into the index did little to improve it. This result is probably caused by the fact that each of the five data sets represents a single season only, within which there is relatively little variability in pan evaporation. For data sets involving both wet and dry season crops, the inclusion of pan evaporation would be more likely to improve the index. Because data on pan evaporation are generally collected for other purposes, excluding pan evaporation from the water shortage index would not

Table 11. Estimates of yield reduction per unit of water shortage, by site and type of index.[a]

Data set	Reduction as percent of nonstressed yield at mean nitrogen			Reduction as percent of reduction for Iloilo plain[b]		
	SMC * PAN	DSW * PAN	SD	SMC * PAN	DSW * PAN	SD
Iloilo plain	0.73	0.59	1.83	100	100	100
Iloilo plateau	0.50	0.44	1.36	68	75	74
Lateral C	n.a.	0.21	0.46	n.a.	36	25
Central Luzon, 1978						
Researchers' management	0.44	n.a.	1.00	60	n.a.	55
Farmers' management	0.74	n.a.	1.65	101	n.a.	90
Central Luzon, 1979	0.48	n.a.	1.37	66	n.a.	75

[a] Derived from the regresstion equations reported in Tables 5-9. [b] n.a. = data not available.

usually result in any reduction in the cost of data collection; however, excluding evaporation decreases the complexity of the calculation of the index. In cases where this is an important consideration, and where the analysis involves a single season, an index could be calculated simply on the basis of the depth to standing water.

The proposed water shortage index is most applicable to the analysis of the effects of water shortage for a specific time and place. The yield reduction coefficient estimated from a given data set -- whether expressed in absolute terms or as a percentage of the nonstressed yield -- is not likely to be highly generalizable, although this limitation is probably somewhat less severe than in the case of the stress day index, which totally ignores stress intensity. Factors that contribute to this specificity include variety, soil type, and the general pattern (timing and intensity) of water shortage. Coefficients developed from sites planted to relatively drought-tolerant varieties could be expected to be smaller than those developed from sites planted to less drought-tolerant varieties. Likewise, coefficients developed with data from a site with predominantly sandy soils may be larger than those derived from sites with heavy clay soils. The general pattern of water shortage is important because the water shortage index is only partially effective in incorporating the effects of differing intensities of water shortage. Concentrated periods of water shortage are likely to have a larger impact on yields than scattered periods of shortage which sum to the same value of the water shortage index. Although this lack of generalizability is an unfortunate limitation of the water shortage index, it should not detract from the usefulness of the index as a device to assess the effect of water shortage on yields in specific situations.

REFERENCES CITED

Alles, W. S. 1969. Drought incidence in relation to rainfed rice. Trop. Agric. 125:37-44.

Angus, J. F. 1979. Simulating production of rainfed rice. In Angus, J. F. Visit report: studies in adaptation of rice-based cropping systems to the physical environment. Multiple Cropping Department, International Rice Research Institute, Los Baños, Laguna, Philippines. (Also presented at a special seminar, IRRI, June 1979)

Bolton, F. R. 1980. Double cropping rainfed rice in Iloilo Province, Central Philippines. Unpublished Ph D dissertation, University of Reading.

Closs, R. L. 1958. Transpiration from plants with a limited water supply. Arid Zone Res. 11: 168:171.

Dale, R. F., [illegible] R. [illegible] Shaw. 1965. Effect on corn yields [illegible] stress and stand at two fertili[illegible] Agron. J. 57(5):475-479.

De Datta, S. K., W. P. Abilay, and G. N. Kalwar. 1973. Water stress effects in flooded rice. Pages 19-36 in International Rice Research Institute. Water management in Philippine irrigation systems: research and operations. Los Baños, Laguna, Philippines.

Denmead, O. T., and R. H. Shaw. 1962. Availability of soil water to plants as affected by soil moisture content and meteorological conditions. Agron. J. 54(4):385-389.

Early, A. C. 1980. An approach to solving irrigation system management problems. Pages 83-113 in International Rice Research Institute. Report of a planning workshop on irrigation water management. Los Baños, Philippines.

Flinn, J. C. 1971. The simulation of crop irrigation systems. Pages 123-151 in J. B. Dent and J. R. Anderson, eds. Systems analysis in agricultural management. John Wiley and Sons, Australasia, Pty. Ltd.

Flinn, J. C., and W. F. Musgrave. 1967. Development and analysis of input-output relations for irrigation water. Aust. J. Agric. Econ. 2(1):1-19.

Herdt, R. W., and A. M. Mandac. 1981. Modern technology and economic efficiency of rice farmers. Econ. Dev. Cultural Change 29(2):375-399.

Hexem, R. W., and E. O. Heady. 1978. Water production functions of irrigated agriculture. Iowa State University Press, Center for Agricultural and Rural Development, Ames, Iowa.

Hiler, E. A., and R. N. Clark. 1971. Stress day index to characterize effects of water stress on crop yields. Trans. Am. Soc. Agric. Eng. 14(4):757-761.

Hogg, H., and G. H. Vieth. 1977. Method for evaluating irrigation projects. J. Irrig. Drainage Div. Am. Soc. Civil Eng. 103(IR1):43-52.

IRRI (International Rice Research Institute). 1973. Annual report for 1972. Los Baños, Philippines. p. 60-61.

IRRI (International Rice Research Institute). 1974. Annual report for 1973. Los Baños, Philippines. 266 p.

Knetsch, J. L. 1959. Moisture uncertainties and fertility response studies. J. Farm Econ. 41(1):70-76.

Lowrey, W. P. 1959. The falling rate phase of evaporative soil moisture loss. Bull. Am. Meteorol. Soc. 40:605-608.

Mapp, H. P. Jr., and V. R. Eidman. 1976. A bioeconomic simulation analysis of regulating groundwater irrigation. Am. J. Agric. Econ. 58(3):391-402.

Matsushima, S. 1962. Some experiments in soil-water-plant relationships in the cultivation of rice. Bull. 112. Division of Agriculture, Ministry of Agriculture and Cooperatives, Kuala Lumpur, Malaysia.

Matsushima, S. 1966. Some experiments and investigations on rice plants in relation to water in Malaysia. Pages 115-123 in Symposium on water resource utilization in Southeast Asia. Symposium Series III, Center for Southeast Asian Studies, Kyoto University.

Minhas, B. S., K. S. Parikh, and T. N. Srinivasan. 1974. Toward the structure of a production function for wheat yields with dated inputs of irrigation water. Water Resour. Res. 10(3):383-393.

Moore, C. V. 1961. A general hypothetical framework for estimating the production function for crops using irrigation water. J. Farm Econ. 43(4):876-887.

Murakami, Toshio. 1975. Physiological aspects of water control in the cultivation of Indian rice varieties. Pages 252-276 in Association of the Japanese Agricultural Scientific Societies. Rice in Asia. University of Tokyo Press, Tokyo.

Namuco, O. S., T. C. Tsiao, and J. C. O'Toole. 1980. Water stress sensitivity of rice at flowering. Paper presented at the 11th Annual Convention of Crop Science Society of the Philippines, 27-29 April 1980, Visayas State College of Agriculture, Baybay, Leyte, Philippines.

Neales, T. F. 1976. Crop physiology: its approaches to the determinants of economic yield. Paper presented at a Thursday seminar, 18 November 1976, International Rice Research Institute, Los Baños, Laguna, Philippines. (mimeo)

Nix, H. A., and F. A. Fitzpatrick. 1969. An index of crop water stress related to wheat and grain sorghum yields. Agric. Meteorol. 6(5): 321-337.

Penman, H. L. 1962. Weather and crops. Q. J. Roy. Meteorol. Soc. 88(377):209-219.

Reutlinger, S., and J. A. Seagraves. 1962. Estimating returns on investments in irrigation systems for flue-cured tobacco. Tech. Bull. 153. North Carolina Agricultural Experiment Station.

Reyes, R. D., and T. H. Wickham. 1973. The effect of moisture stress and nitrogen management at different growth stages on lowland rice fields. Paper presented at the 4th Scientific Meeting of the Crop Science Society of the Philippines, 21-23 May 1973, Cebu.

Ritchie, J. T. 1973. Influence of soil water stress and meteorological conditions on evaporation from a corn canopy. Agron. J. 65:893-897.

Rosegrant, M. W. 1978. Choice of technology, production and income for Philippine rice farmers: agricultural policy and farmer decision making. Unpublished Ph D dissertation, University of Michigan, Michigan.

Salter, P. J., and J. E. Goode. 1967. Crop responses to water at different stages of growth. J. Lonken Ltd., Poole, Dorset, Great Britain.

Stewart, J. I., and R. M. Hagen. 1973. Functions to predict effects of crop water deficits. J. Irrig. Drainage Div. Am. Soc. Civil Eng. 99 (IR4):421-429.

Tabbal, D. F. 1975. The distribution of water supply and water adequacy within a gravity irrigation system. Unpublished MS thesis, University of the Philippines at Los Baños, Laguna, Philippines.

Tabbal, D. F., and T. H. Wickham. 1978. Effects of location and water supply on water shortages in an irrigated area. Pages 93-101 in International Rice Research Institute. Irrigation policy and management in Southeast Asia. Los Baños, Philippines.

Taylor, S. A. 1952. Use of mean soil moisture tension to evaluate the effect of soil moisture on crop yields. Soil Sci. 74(3):217-226.

Thornthwaite, C. W. 1948. An approach toward a rational classification of climate. Geogr. Rev. 38(1):55-94.

Thornthwaite, C. W., and J. R. Mather. 1955. The water balance. Publications Climatol. 8(1). Drexel Institute of Technology, Laboratory of Climatology, New Jersey. 86 p.

Tomar, V. S., and J. C. O'Toole. 1979a. Evapotranspiration from rice fields. IRRI Res. Pap. Ser. 34. 15 p.

Tomar, V. S., and J. C. O'Toole. 1979b. Lower limit of available water and rice response to soil moisture during drought stress. Paper presented at a Saturday seminar, 17 November 1979, International Rice Research Institute, Los Baños, Laguna, Philippines.

Tomar, V. S., and J. C. O'Toole. 1979c. Personal communication of yield data for Figure 14 of Tomar and O'Toole, 1979b.

van Bavel, C. H. M. 1953. A drought criterion and its application in evaluating drought incidence and hazard. Agron. J. 45(4):167-172.

van Bavel, C. H. M., and F. J. Verlinder. 1956. Agricultural drought in North Carolina. Tech. Bull. 122. North Carolina Agricultural Experiment Station.

Wickham, T. H. 1971. Water management in the humid tropics: a farm level analysis. Unpublished Ph D dissertation, Cornell University, New York.

Wickham, T. H., and C. N. Sen. 1978. Water management for lowland rice: water requirements and yield response. Pages 649-666 in International Rice Research Institute. Soils and rice. Los Baños, Philippines.

Yoshida, S. 1975. Factors that limit the growth and yields of upland rice. Pages 46-71 in International Rice Research Institute. Major research in upland rice. Los Baños, Philippines.

Yoshida, S. 1978. Tropical climate and its influence on rice. IRRI Res. Pap. Ser. 20. 25 p.