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AN APPROACH TO ESTIMATING THE POTENTIAL BENEFITS FROM IMPROVED IRRIGATION WATER MANAGEMENT FOR RICE**

BY

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Table of Contents

List of Tables

Introduction

Economic evaluation of efforts to improve the management of irrigation systems is often limited by the twin difficulties of identifying (1) the effect of the change in management procedures on the resulting pattern of irrigation water deliveries, and (2) the effect of changes in water deliveries on production. A common approach used to circumvent these difficulties is to compare yields before and after a change in management is made. Alternatively, comparisons of yields may be made between a project area and some nearby "reasonably comparable" area. In either case, the difference in yields, perhaps adjusted for differences that can be attributed to variables not related to irrigation, are assumed to be due to the improvement in irrigation. Effects of unmeasured variables may cause a bias of unknown magnitude and direction in the resulting estimate of the effect of the irrigation improvement.

In this paper we present an alternative approach to dealing with the second of the two difficulties noted above.[1] The approach, which is applicable where flooded paddy rice dominates the cropping pattern, also permits an *ex ante* estimation of the potential for increasing production through improvements in allocation of a given water supply. The results of our attempt to apply this approach to a Philippine irrigation system are reported.

[1]This paper does not deal with the problem of identifying the effect of an improvement in management on the deliveries of irrigation water, which is largely one of hydraulic modelling and of data collection.

Conceptual Framework

From the perspective of economic theory, the value of irrigation water can be conceptualized by means of a production function in which water is one of the inputs with a functionally defined effect on production. Translating this concept into operationally useful methods for evaluating actual irrigation projects requires both empirical estimates of the water-output functional relationship and field measurements of the amount of water input. Several researchers have investigated the nature of the production function for water for various crops (Hexem and Heady; Hogg and Vieth; Minhas et al). But the ability to obtain appropriate measurements of the actual water input under the field conditions that prevail in most LDC irrigation projects designed for flooded paddy rice production is severely limited.

These measurement problems are of two general types. First, several practical difficulties associated with the instrumentation necessary to obtain field measures of water flows limit the availability of such measurements to a small number of points within an irrigation system. The water that is measured at any one of these points serves a relatively large area (generally 30 hectares or more). Such meausrements do not permit the identification of the amount of water delivered to any individual field for which data on other inputs and outputs are obtained.

The second type of measurement problem relates to the potential for the existence of large differences between the amount of water delivered to an individual field and the amount of water available to the plants. Under field conditions, especially when significant amounts of rainfall may occur during the cropping season, a substantial proportion of the water delivered to an individual field may not be available to the plants because of surface runoff. In contrast to the situation with an input such as fertilizer, the amount of water which can be stored on the field for future use by the plant is very small relative to the total amount of the input which is needed for unstressed plant growth during an entire cropping season. Thus even if it were feasible to measure the amounts of water delivered to individual fields, these measurements would not necessarily correlate well with the actual water input into the biological production process.

Given these difficulties, much of the research dealing with functional relationships between water and yield has followed an approach that incorporates 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. Many of these indices are based on some modification of the concept, introduced by van Bavel, of "drought days." Although early work focused on moisture stress indices for crops grown under dryland conditions, Wickham and his colleagues at the International Rice Research Institute developed a similar index applicable to "wetland" rice production (Wickham; International Rice Research Institute, pp 60-61). This index was further modified by Small et al.[2]

Several studies have successfully incorporated a moisture stress index into production functions for wetland paddy rice (Herdt and Mandac; Small et

[2]See Small et al for a more detailed review of the literature on the development of moisture stress indices.

al; Wickham). In these functions, the coefficient of the stress index has a negative value, indicating that the greater the amount of moisture stress, the lower the resulting yield. Although a non-linear relationship between yield and moisture stress would be expected, the empirically estimated production functions do not generally show a statistically significant non-linear term.

In this study, we use the water shortage index (WSI) developed by Small et al. This index is calculated by summing daily water shortage factors from the time that the crop is transplanted until 20 days before harvest, which is about when flooded fields are drained in preparation for harvest. The daily water shortage factors reflect both the environmental demands on the crop (measured by pan evaporation) and the availability of water in the soil (measured by the depth below the soil surface to the free standing water associated with the perched water table). As with other moisture stress indices, the larger the value of the WSI, the greater the degree of water stress.

Given the utilization of a water shortage index in the production function, estimation of the effect of irrigation water on yield requires that a relationship between the amount of water available and the amount of moisture stress be established. We postulate the existence of a functional relationship between weekly water supplies to a given area and the corresponding amount of moisture stress in this area. We expect the relationship to be non-linear, with the water shortage index approaching some maximum value at extremely low levels of water supply, and approaching zero with abundant supplies of water (Figure 1).

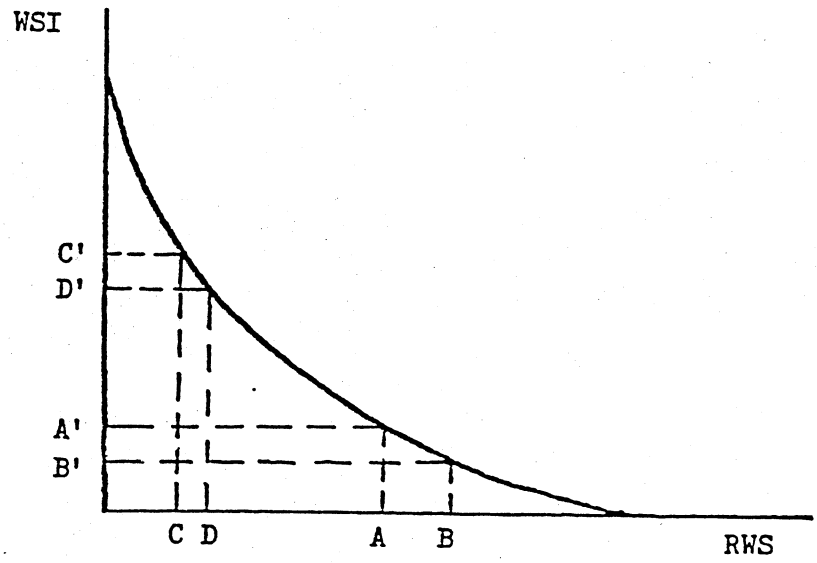

Figure 1. Hypothesized Relationship between Weekly Relative Water Supply (RWS) and Weekly Water Shortage Index (WSI).

A difficulty with identifying this hypothesized relationship between moisture stress and water supply is that it is likely to be affected by differences among fields in the environmental demand for water. In particular, fields may differ substantially in the amounts of lateral seepage and deep percolation (S&P) that occur when they are flooded. An amount of water which might result in very little stress in situations with low S&P could result in a substantial degree of stress in situations where these rates are high.

One approach to dealing with this problem is to restate the hypothesis in terms of <u>relative</u> rather than <u>absolute</u> water supply. Following Levine, relative water supply (RWS) is defined as the total amount of water available from rainfall and irrigation (expressed in mm over the area served by the irrigation water) divided by the environmental demand for water associated with the production of an unstressed crop. This environmental demand is taken to equal evapotranspiration plus S&P. Since both the water supply and the environmental demand are expressed in the same units (mm), RWS is a dimensionless ratio for which a value greater than (less than) 1.0 implies that the amount of water available is greater than (less than) the minimum amount needed to produce an unstressed crop, assuming no losses in the distribution and use of the water.

Because the RWS concept includes the absolute water supply as one of its components, the previously noted difficulties of measuring water flows apply to the measurement of RWS. In particular, it is not feasible under field conditions to measure RWS for individual paddy fields. It is therefore necessary to relate RWS for a given area to the average amount of water shortage within that area. The advantage of relating RWS to water shortage rather than to yield is that it is possible to obtain values on both RWS and water shortage for periods of time which are short enough so that most of the water needed for unstressed crop growth can be stored in the field, either as soil moisture or as standing water on the field. This should result in a much closer relationship between RWS and moisture stress than would exist between yield and the RWS for the entire season.

To summarize, the simple conceptual model consists of two functional relationships: between yield and a water shortage index, and between weekly water shortage and weekly relative water supply. Estimation of the marginal and average products of irrigation water becomes possible by combining these functional relationships with the definitional relationships between weekly water shortage and the seasonal water shortage index, and between the weekly relative water supply and the amount of irrigation water.

If the total amount of irrigation water available in a given irrigation system is constant, then aggregate production can be maximized if the marginal products of irrigation water are equal in all parts of the system. Furthermore, if storage capacity permits temporal shifts in the allocation of the water over the season, then maximizing production also implies equality of the marginal product of irrigation water in each time period within the season.

Data on the actual performance of an irrigation system can be used to give empirical estimates of the two functional relationships in the model. These results can then be used to estimate the water allocation pattern which would maximize total production by equating the marginal products of water in both time and space throughout the irrigation system. By comparing this estimated maximum production with similar estimates of production based on the actual water distribution pattern, the maximum potential increase in production that could accrue from improved allocation of the available irrigation water can be estimated.

Two additional points should be emphasized here. First, equating the marginal product of irrigation water is not the same as equating the amount of moisture stress that occurs on the various fields. To the extent that fields vary in the amount of S&P to which they are subject, equality of the marginal product of irrigation water implies differences in the amounts of water shortage on the various fields. In particular, on fields with high rates of S&P, an incremental unit of irrigation water will have a smaller impact on RWS than it will on fields with low rates of S&P. For the marginal products of irrigation water to be equal in the two situations, the smaller increment of RWS must have a larger impact on water shortage, which implies a greater amount of water shortage for fields with high S&P.

This point can be illustrated by reference to Figure 1. Assume that one field with low rates of S&P has an initial RWS of "A", that another field with higher rates of S&P has an initial RWS of "C", and that each field then receives an equal increase in the amount of irrigation water. The new values of the RWS for the two fields are "B" for the field with the low S&P, and "D" for the field with the high S&P. The increase in RWS for the first field (AB) is greater than for the second field (CD) because of their differences in rates of S&P; however, the effect on the WSI (A'B' in the one case, and C'D' in the other) is equal. Equal increments of water for the two fields thus result in equal increments in yields, but only because the field with the low level of S&P has less water shortage than the other field.

The second point is that equating the marginal products of irrigation water implies that effective use is made of rainfall. The amount of rainfall at any given location and time period is taken as given, and all irrigation water is assumed to be incremental to this rainfall. As a result, the marginal product of the first unit of irrigation water can vary across time and space because of differences in rainfall.

An Empirical Application

The approach outlined above was applied to data from the Lower Talavera River Irrigation System (LTRIS) in the Central Luzon region of the Philippines. With a command area of about 2,500 ha, LTRIS is one sub-system of the Upper Pampanga River Integrated Irrigation System (UPRIIS), reservoir-based gravity flow system operated by the National Irrigation Administration (NIA). In 1977 a two-year study was undertaken jointly by the NIA and the International Rice Research Institute (IRRI) to improve the distribution of water throughout the LTRIS command area (Early). Implementation of the improved procedures began in the 1977 wet season. Data on water flows, water shortage, and yields were collected in 1977 and again in 1978 for both the wet and dry seasons.

The data generated by the project permit the application of the conceptual approach outlined above for the period of time subsequent to the introduction of the improved management procedures. We have used these data to attempt to estimate the remaining potential for further improvement in the distribution of water in LTRIS. Unfortunately, lack of comparable data prior to the introduction of the improved management methods precludes estimating the potential benefits existing at the time the NIA-IRRI study was initiated.

Very little water shortage occurred in any of the four seasons during which the study was undertaken. Of the four, water shortage was greatest during the 1977 wet season. Furthermore, this season had the fewest data problems associated with missing observations. We therefore have used it to illustrate the application of our conceptual approach. The empirical application is limited, however, because even in that season problems of missing observations were severe.

To estimate the relationship between yield and WSI, data on yield, WSI and nitrogen from 139 sample fields were analyzed. Data on other inputs were not available. Several functional forms were tested, but in all cases the fit was poor. The best results were obtained with an additive model incorporating nitrogen and WSI for the season (WSI_s) in linear form. The equation, with the standard errors of the estimates in parentheses, is given below, with yield in tons per ha and N in kg of elemental nitrogen per ha.

$$\text{Yield} = 4.09 + \underset{(.003)}{.008N} - \underset{(.00008)}{.00004}\ WSI_s \qquad [1]$$

The R^2 of this equation was only 0.06, and the coefficient on the WSI variable was both trivial in magnitude and statistically insignificant.

Although this equation provides a lower bound estimate of zero for the effect of water shortage on yield during the 1977 wet season, the lack of data on other imputs may have been responsible for the failure to identify a significant non-zero relationship. We therefore considered the results of two other studies done in the Philippines to estimate an upper bound on the effect of water shortage (Herdt and Mandac; Small et al). These studies estimated the yield loss in terms of a stress day index, with the estimates ranging from 15 to 50 kg/ha per stress day. To convert these estimates of loss based on stress days to losses based on WSI, we developed a conversion ratio from the LTRIS data for the 1977 wet season. The mean number of stress days in this data set was 2.29, while the mean value of the WSI was 6.16, giving a ratio of about 0.37 stress days for each unit of WSI. Using this ratio of 0.37, the results of the other studies imply yield losses ranging from roughy 6 to 19 kg of paddy per ha per unit of WSI. We have therefore used the 19 kg figure as the upper bound on our estimates of the effect of water shortage on yield.

The relationship between WSI and RWS was estimated using weekly data from the 1977 wet season. Because the amount of water standing on flooded fields at the beginning of a week could be a significant part of the total amount of water available for that week, total water supply for the weekly RWS was defined to include this initial stock of standing water in addition to the weekly rainfall and flow of irrigation water. The RWS data were measured at the head of each of the six lateral canals of the LTRIS. The potential data set for estimating this relationship thus consists of six observations for each week during the cropping season. Missing data presented a serious problem, however, and the final data set consisted of only 15 observations: five weeks for Lateral A; four weeks for Lateral C; one week for Lateral D; five weeks for Lateral F; and none for laterals B and E. The resulting estimated equation, with an R^2 of 0.59 was:

$$WSI_w = 1.952 - \underset{(0.36)}{1.56}LNRWS_w \qquad [2]$$

where WSI_w is the weekly subtotal of the seasonal water shortage index and $LNRWS_w$ is the natural logarithm of the weekly RWS. The standard error of the coefficient is given in parenthesis. The marginal product of irrigation water in any given short-period is given by the following equation:

$$MP_{ir_w} = \partial Y/\partial IR_w = (\partial Y/\partial WSI_s)(\partial WSI_s/\partial WSI_w)(\partial WSI_w/\partial RWS_w)(\partial RWS_w/\partial IR_w) \qquad [3]$$

where Y is the yield per ha, IR_w is the weekly water supply, and the other variables are as defined previously. The marginal product of irrigation water is thus the product of four terms. The first of these is the partial derivative of yield with respect to WSI for the entire season. Based on other studies which have found this relationship to be linear in WSI with linear interaction terms between WSI and nitrogen, and between WSI and solar radiation (Herdt and Mandac; Small et al.), this partial derivative is equal to a constant "k". The second term is the partial derivative of the seasonal WSI with respect to the weekly WSI. Because the WSI is additive, a change in the WSI for any week creates an exactly equal change in the seasonal WSI, so that this term is equal to 1.0. The third term is the partial derivative of the weekly WSI with respect to the weekly RWS. From equation [2], this derivative is $-1.56/RWS_w$. The final term is the partial derivative of the weekly RWS with respect to the weekly irrigation flow. By definition,

$$RWS_w = (IR_w + RN_w + SW_w)/(EP_w + S\&P_w)$$

where RN stands for rainfall, SW for the initial amount of water standing on the surface of the field, and EP for the measure of evapotranspiration. This partial derivative is thus equal to the inverse of the environmental demands, or $1/(EP_w + S\&P_w)$. Substituting these four terms into equation [2] gives:

$$MP_{ir_w} = -1.56k/(RWS_w)(1/(EP_w + S\&P_w))$$

Replacing RWS_w by its definition and simplifying gives equation [4].

$$MP_{ir_w} = -1.56k(IR_w + RN_w + S\&P_w) \qquad [4]$$

This indicates that to equalize the marginal product of irrigation water, the absolute water supply (rainfall plus irrigation plus the initial amount of standing water) should be equalized.

A computer program was written to solve for the geographic and temporal allocation of irrigation water which would equate the marginal product of irrigation water in all locations and time periods, subject to the constraint that irrigation be non-negative. This constraint was necessary because in some cases rainfall was so great that equality of the marginal products could be achieved only by removing and reallocating some of the water which had been supplied by rainfall.

The resulting solution for the allocation of water in the LTRIS is presented in spatial terms in Table 1 and in temporal terms in Table 2. Table 3 presents the complete details of the spatial and temporal reallocation of water implied by the solution. These results show no tendency for the allocation of water to have favored the head reaches of the system over the tail portions. On the contrary, the production-maximizing solution calls for a reallocation of about 25,800 hectare-millimeters (ha-mm) of water from the lower portions of the system to the area served by Lateral A, the head-most lateral (Table 1). In temporal terms, the solution calls for the reallocation of about about 28,800 ha-mm of water, mainly by reducing deliveries in the first part of the season, and increasing deliveries in later weeks (Tables 2 and 3). As shown in the last column of Table 3, the maximum cumulative reduction in deliveries during the season was about 24,700 ha-mm, which occurred at the end of irrigation week number 14. Considering the spatial and temporal aspects together (Table 3), the solution calls for

Table 1. Spatial Allocation of Irrigation Water Within LTRIS: Comparison of Acutal with Estimated Deliveries Needed to Equate the Marginal Products of Irrigation Water, 1977 Wet Season.

Lateral	Actual Irrigation (ha-mm) (1)	Estimated Deliveries Needed to Equate the Marginal Products of Irrigation Water (ha-mm) (2)	Change from Actual (ha-mm) (Col.2-Col.1) (3)	Change as a Percentage of Actual (4)
A	40,954	66,730	+25,776	+63
C	13,643	9,883	-3,760	-28
D	8,433	0	-8,433	-100
F	36,351	22,768	-13,583	-37
Total	99,381	99,381	0	0

Table 2. Temporal Allocation of Irrigation Water in LTRIS: Comparison of Actual with Estimated Deliveries Needed to Equate the Marginal Products of Irrigation Water, 1977 Wet Season.

Irrigation Week No.	No. of Laterals for Which Data are Available	Actual Irrigation (ha-mm)	Estimated Deliveries Needed to Equate the Marginal Products of Irrigation (ha-mm)	Change from Actual (ha-mm) (Col. 3-Col. 2)	Change as a Percentage of Actual
	(1)	(2)	(3)	(4)	(5)
13	1	10,528	691	-9,837	-93
14	4	24,887	10,065	-14,822	-60
15	2	1,432	12,165	+10,733	+750
16	2	19,291	27,548	+8,257	+43
17	3	14,724	10,541	-4,183	-28
18	2	27,858	32,332	+4,474	+16
20	1	661	6,039	+5,378	+814
Total		99,381	99,381	0	0

Table 3. Estimated Changes in Water Allocation to Equate the Marginal Products of Irrigation Water, by Week and Lateral, LTRIS, 1977 Wet Season (ha-mm).

Irrigation Week No.	Lateral A	Lateral C	Lateral D	Lateral F	Weekly Total	Cumulative Total
13	a	a	a	-9,837	-9,837	-9,837
14	+1,952	-5,551	-8,433	-2,790	-14,822	-24,659
15	+9,600	+1,133	a	a	+10,733	+13,926
16	+10,916	-2,659	a	a	+8,257	-5,669
17	-2,677	+3,317	a	-4,823	-4,183	-9,852
18	+5,985	a	a	-1,511	+4,474	-5,378
20	a	a	a	+5,378	+5,378	0
Total	+25,776	-3,760	-8,433	-13,583		

[a] No estimate available due to missing data.

the reallocation of 38,300 ha-mm of water, or roughly 39 percent of the total volume of irrigation water delivered during the season.

Although a substantial volume of water would need to be reallocated to achieve the distribution estimated to maximize production, the increase in production which such a change could be expected to produce is minimal. As noted previously, the lower bound on the estimate of the increase in production is zero. Using the upper bound estimate that each unit of WSI results in a decrease in production of 19 kg per ha, the upper bound estimate of the net increase in production over the 1,820 cropped ha served by the four laterals is only 3.8 tons, or less than one-tenth of one percent of the total actual production.

The reason for a rather large difference in water allocation between the actual and the estimated production-maximizing situations, even though there would be little change in production, is related to the fact that overall, water supplies were abundant during the 1977 wet season. At high RWS levels, the amount of water shortage is quite insensitive to changes in RWS, so that large changes in water allocation result in very modest changes in WSI, and thus in production.

These results suggest that given the total amount of water that was available in the 1977 wet season, distribution was quite satisfactory, with no significant reduction in production due to inadequate water distribution. Considering that there was even less water shortage during the subsequent three cropping seasons of the NIA-IRRI study, it is probable that the same conclusion applies to the other three seasons.

Given the relatively abundant water supplies available to the LTRIS during 1977 and 1978, virtually all of the potential benefits from improved irrigation water management within the LTRIS appear to have been achieved by the 1977 wet season. It is not possible, however, to draw conclusions about the potential benefits for further changes in management which could result in a reduction in water use within LTRIS, leaving more water to be used either in other sub-systems of the UPRIIS, or in other areas not currently served by irrigation. If, in years subsequent to 1978 less water were made available to LTRIS than was the case in 1977 and 1978, new water allocation problems could emerge.

Summary and Conclusions

Benefits from improved irrigation water management are frequently difficult to measure because they are in the form of increased yields that result when water stress on the crop is reduced through better allocation of the available water supplies. A conceptual framework to address this problem involves functionally relating weekly relative water supplies to weekly measures of water shortage; aggregating the weekly water shortage data into a seasonal water shortage index; and relating, by means of a production function, the seasonal water shortage index to crop yield. This framework permits the estimation both of the increase in production resulting from improved water management, and of the potential further increase in production associated with additional improvements in water allocation.

Data from a Philippine irrigation management improvement project were used to illustrate the application of the conceptual framework. A logarithmic relationship between weekly relative water supply and weekly water shortage was found. This, in combination with a linear relationship between yield and the seasonal water shortage index, implies that the given water supply will maximize production when the weekly total supplies of water per hectare (irrigation plus rainfall) are equal both throughout the irrigation system in any given week, and throughout the cropping season.

The results of this empirical application indicated that given the total amount of water available, there remain no significant benefits from further improvements in water management. The empirical validity of this application is limited, however, by problems of missing data. Furthermore, it is impossible to estimate the benefits that had already been achieved by the management improvement effort because the necessary data had not been collected prior to the initiation of the change in management.

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