Irrigation Systems Performance Monitoring and Evaluation: Reliability, Resiliency, and Vulnerability Criteria for Assessing the Impact of Water Shortage on Rice Yield

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A simple and low-cost methodology for measuring the field-level water adequacy and equity of distribution in lowland rice irrigation systems has been successfully developed at the International Irrigation Management Institute. The method consists of measuring the inflow and outflow of water from the irrigation command area, and installing perforated PVC tubes to monitor the fluctuations of the perched water level in paddy fields. Indices for measuring the frequency, duration, and intensity of water shortage have been developed. These three indices, termed reliability, resiliency, and vulnerability, respectively, correlate very well with crop yield from sample irrigation systems in Indonesia, Sri Lanka, and the Philippines. The methodology appears applicable across countries, seasons, and sites. This paper briefly presents the methodology and the summary of results from the three countries.

Detailed discussions of the methodology and its application as a management tool for continuous monitoring and evaluation of the performance of irrigation systems are included in an IIMI Research Report.

Conceptual Approach

Irrigation development may generate efficiency and equity benefits, as well as improve the environment and human conditions. The efficiency benefits may derive from increase in yield per hectare in area already planted and/or in the expansion of new area for cropping. Yield increase may come from the direct effect of improved water conditions to crop, or from the use of additional inputs such as fertilizers that are complementary to water. In addition to increased production, irrigation development is likely to also reduce the variability of yields over time and space, thus contributing towards a more stable and equitable food supply.

To measure the direct effect of improved water conditions on yield, we need a variable that reflects water conditions and is functionally related to yield. The conventional approach is to use water itself as the variable in a production function (Hexem and Heady 1978). This approach, however, is more suitable for analyzing experimental data rather than field data.

An alternative approach, which we adopt, is to relate yield to some index of water shortage derived empirically from the field (Small 1985). Ideally, such an index (or indices) would incorporate information on the frequency, duration, and intensity of water stress throughout the crop's various growth stages.

The extent to which yield is depressed due to moisture stress conditions, or conversely, the benefits gained from improved water conditions, can then be estimated from the functional relationships between yield and these indices. This, in turn, allows estimation of the aggregate gain in production from, or the loss thereof from the lack of, new or further irrigation investment.

Empirical Method

The technique consists of measuring the inflow and outflow of water from the irrigation system, and installing vertical perforated PVC tubes in representative parts of its command area to monitor the daily fluctuations of the perched water table in paddy fields. These perforated tubes, which act as observation wells for the water level in paddy fields, measure 5-10 cm in diameter and 100 cm in length. They are installed to a depth of 50 cm below the soil surface in sample paddy plots. Readings of the water level in these tubes are taken daily from the date of transplanting to harvest. Yield from the sample paddy field is estimated by crop cuts. Additional data such as fertilizer applications can be collected, if so desired, from a farm survey to estimate the complementary effects of other inputs to water on crop yield.

Data on depth to standing water in paddy fields from the date of transplanting to 20 days before harvest are used to compute three indices called Reliability, Resiliency, and Vulnerability. These three indices are descriptors which reflect, respectively, the frequency, duration, and intensity of water shortage experienced at each sample paddy plot (perforated tube).

Reliability describes how likely a system is to fail or violate a performance threshold, in this case, how frequent water level in the paddy field falls below a performance standard that defines stress condition for the crop; Resiliency, how quickly it recovers from such failure, i.e., the expected time duration of moisture stress once it occurs—the shorter the time, the more resilient it is; and Vulnerability, how severe the consequences of failure may be, i.e., the expected maximum severity of moisture stress once it occurs (see also Hashimoto et al. 1982). These three performance indicators refer to the operation of the water delivery system causing the moisture stress and not simply to the stress condition itself.

It is conventional in irrigation design to derive the crop water requirements figure based on soil, climatic, and evapotranspiration (ET) demands—which is about 600-800 mm per crop for paddy rice. In practice, however, the amount of water actually used to grow a paddy crop in many irrigation systems in Asia is much more—typically 1,500 mm or more, eliciting suggestions of "wasteful" or "inefficient" use of water.

For lowland rice systems water is used, however, not only to fulfill ET

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requirements but also as a substitute for many other requirements, such as weed control. It is commonly observed that farmers become edgy when water in the paddy field falls below a certain level—which, in many instances, is well above the soil saturation point. Ng (1980, 1985) has used the notion of a ***"Critical Tolerance Level"*** (CTL) of water supply to refer to this threshold; farmers will tolerate more water above this threshold but not below it.

Thus, the CTL becomes a standard for evaluating water adequacy. To the farmer, the water supply system is ***reliable*** if the paddy water level (as observed in the perforated tube) does not fall below the CTL too often; ***resilient,*** if and when the water level goes below the CTL, it recovers quickly, i.e., it does not persist below the CTL for an extended period of time; and ***vulnerable,*** if and when the water level falls, it goes deep below the CTL.

In computing the reliability, resiliency, and vulnerability indices, no prior knowledge of the true CTL is assumed, however. Nor is it necessary. The true CTL is to be derived through simulations. A set of these three indices are computed using differentassumed CTL values (from levels above the soil surface to those below it); and the CTL which produces the reliability, resiliency, and vulnerability indices best correlated with crop yield is taken as the true CTL. (Simple scatter diagrams supplemented with simple or stepwise regression techniques—see Gomez and Gomez (1984)—are sufficient to determine which CTL produce the best fit between yield and these indices.) This CTL value, obtained through simulation, is then cross-checked with the farmers in the field to determine its empirical validity.

Sample Calculations of Indices

Figure 1 shows the time series plot of paddy water level from the date of transplanting to 20 days before harvest in one sample paddy (perforated tube) WT11406 from the Cirebon Irrigation System in Java, Indonesia. The data from WT11406 and sample calculations of the reliability, resiliency, and vulnerability indices for CTL = 0 cm are included in Tables 1 and 2.

Figure 1. Time series of paddy water level for paddy WT11406 in Cirebon Irrigation System, Indonesia. 1980-81; critical tolerance level (CTL) = 0 cm.

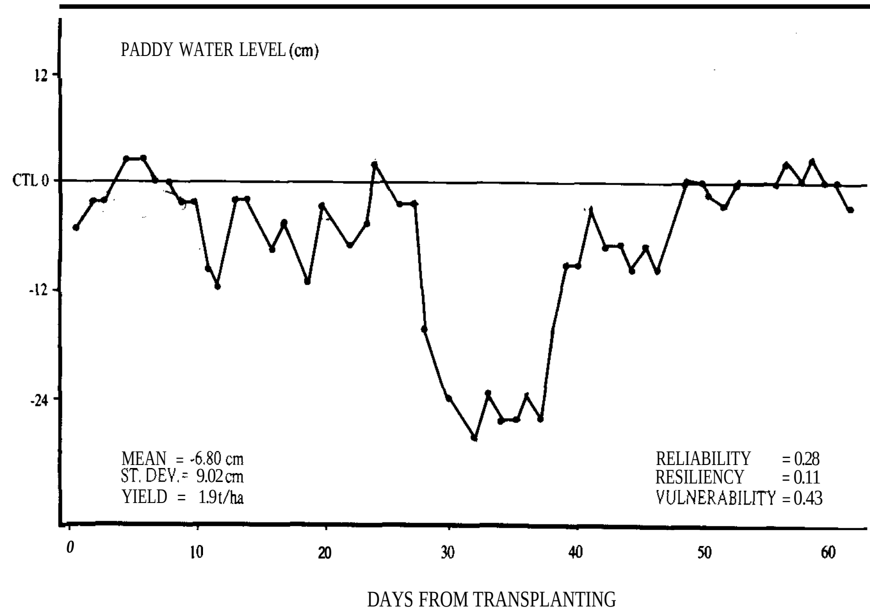


Table 1. Sample calculations of reliability, resiliency, and vulnerability indices for paddy WT11406, Cirebon Irrigation System, Indonesia: CTL = 0 cm

Day	Paddy Water Level (cm)	Journey below CTL	Duration of Journey (days)	Maximum Severity (cm)	Water Stress State, Xi
1	-4.5				
2	-3.0	1st	4	-4.5	X2
3	-2.5				
4	-1.0				
5	2.0				
6	1.5				
7	0.2				
8	0.2				
9	-2.0				
10	-3.4				
11	-8.4				
12	-11.5				
13	-2.0				
14	-3.U				
15	-4.5				
16	-6.0	2nd	15	-13.0	X3
17	-4.3				
18	-8.0				
19	-13.0				
20	-1.5				
21	-3.6				
22	-8.0				
23	-5.1				
24	1.6				
25	1.1				
26	-1.9				
27	-3.0				
28	-17.0				
29	-22.0				
30	-24.5				
31	-27.5				
32	-28.0	3rd	22	-28.0	x4
33	-24.5				
34	-25.2				
35	-27.5				
36	-25.0				
37	-25.5				
38	-17.0				
39	-6.5				
40	-9.0				
41	-0.5				
42	-6.0				
43	-8.0				
44	-9.0				
45	-8.3				
46	-9.5				
47	-4.7				
48	0.3				
49	0.5				
50	-0.6				
51	-0.9	4th	2	-0.9	X2
52	0.5				
53	0.5				
54	0.5				
55	1.0				
56	1.5				
57	1.0				
58	1.4				
59	0.6				
60	0.4				
61	-0.4	5th	1	-0.4	X2

*(Table **1. continued)***

Summary of Data for Paddy WTI1406:.

Total number of days from transplanting,	**N = 61**
Total number of sojourns below CTL,	**J = 5**
Total number of days below CTL (failures),	**F = 44**

Definitions of Terms:

WL = **Perched water table in the perforated tube, in centimeter;**
= **zero cm. when the paddy water level is at the soil surface;**
= **negative value, when water level is below the soil surface.**

CTL = **Critical Tolerance Level;**
= **Performance standard defining water shortage condition;**
= **Minimum acceptable level of water supply.**

Reliability = **Frequency Measure;**
= **Percent Occurrence of water level (WL) above CTL**
= **(N - F)/N**
= **(61 - 44)/61**
= **0.28**

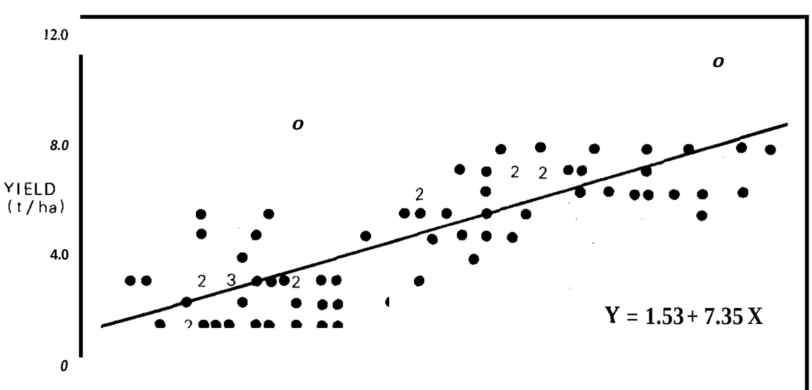
Resiliency = **Duration Measure;**
= **How quick recovery is expected from each journey below CTL;**
= **Inverse of average duration per journey;**
= **Inverse of (F divided by J)**
= **5/44**
= **0.11 (or 8.8 days expected per journey)**

Vulnerability = **Intensity Measure;**
= **Expected maximum severity for each journey below CTL;**
= **(Severity Indicator of Xi) * (Probability of Xi)**
= **0.166(0) + 0.333(0.6) + 0.500(0.2) + 0.666(0.2) + 0.833(0) + 1.0(0)**
= **0.43 (using Linear Severity Indicators from Table 2)**

Table 2. Definition of moisture stress states and their corresponding severity indicators and frequencies of occurrence at paddy WT11406

Stress State		Paddy Water Level (WL)	Frequency of Occurrence	Probability Occurrence	Severity Indicators, Si Linear	Square	Exponential
XI	**200**	● WL➤= **0**	**0**	**0**	**0.166**	**0.027**	**0.105**
x 2	**0**	● WL➤= **-10**	**3**	3/5 = **0.6**	**0.333**	**0.111**	**0.230**
x 3	**-10**	➤ WL➤= **-20**	1	1/5 = **0.2**	*0.500*	**0.250**	**0.377**
X4	**-20**	● WL➤= **-30**	**1**	1/5 = **0.2**	**0.666**	**0.444**	**0.551**
X5	**-30**	● WL➤= **-40**	**0**	**0**	**0.833**	**0.694**	**0.757**
X6	**-40**	● WL➤= -200	**0**	**0**	1.000	**1.000**	**1.000**
	Summation	=	5				

Figure 2. Correlation between yield and reliability of water supply in Cirebon Irrigation System, Indonesia, 1980-81; pooled data file WT 1c; early dry season (April-August); **CTL** = 0 cm.



Results and Discussions

Empirical evidence from the Philippines, Indonesia, and Sri Lanka show that the critical tolerance level (CTL) is season and location-specific, and linked to soil types and the varieties of rice planted. One CTL usually produces one or more water shortage indices, viz, Reliability, Resiliency, and Vulnerability, that are better correlated with yield for each location and season. And for any one site, the CTL may vary from season to season. See the last column in Table **3** below.

Three sample correlation plots between yield and the reliability, resiliency, and vulnerability indices are shown in Figures 2, 3, and **4.** These three indices predict up to **63%** of the variations in farm-level yield in simple linear regression models at the 99.9% level of confidence with data from four inter-connected Indonesian irrigation systems in Cirebon, West Java. Incorporating fertilizer application and quadratic terms in multiple regression improves the coefficient of determination further. Equally good correlations (R-squared values as high as 85%) are also obtained with data for three seasons from two very different irrigation systems (Devahuwa and Kalankuttiya) in the North Central Province of Sri Lanka. The general form of regression equations between yield and these three indices appear similar in all the systems from Indonesia and Sri Lanka.

Only one season of data from the Lateral C of the Perananda System in the Philippines is available for testing this methodology. This set of data had previously been processed and used by IRRI scientists to develop several varieties of paddy water-stress indices (Tabbal 1975; Tabbal and Wickham 1978; Small et al. 1981). The pre-processed data (raw data no longer available) limit the number of simulations that can be performed to three. Even with these limitations, the three indices generated from this methodology are still better than those obtained earlier at IRRI in terms of their ability (R-squared values of **28%** compared to 14 and **24%**) to predict the impact of water shortage on rice yield.

Whereas the paddy water-stress indices previously developed generally show low correlation with yield, and work in only limited seasons and sites, the reliability, resiliency, and vulnerability indices developed from this methodology show high correlation with yield for all seasons (wet and dry) in every site that the methodology has been tested to date. The detailed results are presented in Ng (forthcoming).

The general applicability of the methodology and the high predictive power of these three indices would seem to suggest a ***breakthrough*** in methodology. This has been achieved by using farm level data to predict the impact of water shortage on yield in lowland rice irrigation systems.

Table **3.** Empirical critical tolerance levels **(CTL) of** water supply in sample irrigation systems in Indonesia, Philippines and Sri Lanka.

Observation Units #	Cropping Season	Irrigated Area (ha)	Number of Tubes	Rice Variety	Average Yield (t/ha)	Best CTL (cm)**
Cirebon System, Indonesia (64,116 ha):						
WT1c	1-Dry 1980	6123	90	3-month	4.71	0
WT2c	2-Dry 1980	3740	40	do	5.13	1
WT3c	Wet 1980/1	6123	122	do	6.03	1
Perananda System (C), Philippines (18,500 ha).						
PLI113c	Dry 1973/4	5,700	**208**	3-month	2.39	-10 (Provisional)
Devahuwa System, Sri Lanka (1,215 ha):						
SL31c	Dry 1986	499	29	mostly 3-mo	2.58	1
SL41c	Wet 1986/7	644	96	mostly 4-mo	5.96	-15
SL413		216	34		5.96	-15
SL415		131	30		6.61	-15
SL416		105	14		5.24	-20
SL418		192	18		5.42	-20
Kalankuttiya System, Sri Lanka (2,023 ha).						
SL22c	Wet 1985/6	372	38	mostly 3-mo	4.69	-5
SL225c		252	21	do	4.71	-5
SL2264		49	8		4.54	
SL2272		71	9		4.74	
SL32c	Dry 1986	372	58	mostly 3-mo	3.36	0
SL325c		252	34	do	3.24	0
SL3264		49	9		3.54	
SL3272		71	15		3.52	
SL42c	Wet 1986/7	372	121	mostly 3-mo	4.89	0
SL425c		252	75	do	5.00	1
SL4252		77	21		4.90	1
SL4253		104	33		4.92	1
SL4254		71	21		5.22	-5
SL4264		49	18		5.05	-5
SL4272		71	28		4.49	0

\# The four digits in the identification code indicate in order the Season, **Site.** Block/Tract, and Distributary for the Observation Unit. "c" means "combined or pooled data for analysis, e.g., WT1c includes all the observations from 4 inter-linked systems in Cirebon, West Java for Season No. 1.

** **CTL** = **0** cm at soil surface; negative CTL, below soil surface.

With this breakthrough, a proper technique for identifying gaps in performance of lowland rice irrigation systems and for evaluating the impact of investment to improve them is at hand. The technique is both simple and economical; it requires only minimum outlays of personnel and materials to implement it in the field.

We shall briefly illustrate how the methodology may be useful for monitoring and evaluating irrigation performance. Figure 2 shows the functional relationship between yield and reliability of water supplies in the Cirebon Irrigation System, Indonesia during the early dry season crop of 1980. Simulations performed indicate that the best critical tolerance level for this season was at the soil surface (CTL=0 cm). And 63% of the variations in yield could be explained by the reliability of water in a simple linear regression model.

The mean reliability for 90 sample paddies was 44% at this CTL, corresponding to an average yield of 4.71 t/ha. The graph shows that the yield could potentially be increased to 8.88 t/ha if the water were 100% reliable. In other words, the gap in yield performance was 4.17 t/ha; and 47% gain in yield for the Cirebon System could have been obtained if the water level in each of its paddy fields were maintained above the soil surface all the time from transplanting to 20 days before harvest.

Similarly, Figure 3 below shows the relationship between yield and resiliency. The mean resiliency for this season at CTL=0 was 0.27, which means each time the field paddy water-level fell below the soil surface ,it extended on the average 1/0.27 = 3.7 days before it "recovered" or returned to the soil surface again. If the average duration had been reduced to, say, ***2*** days (resiliency = ½ = 0.5), then the average yield would have been 6.72 t/ha. The yield loss at the system level was 6.72-4.71 = 2.01 t/ha, simply because the paddy water level, whenever it fell below the soil surface, was not prevented from extending on the average beyond 2 days.

This inference was not at all far-fetched because during the subsequent wet season, with better water supplies, the mean resiliency at CTL=0 for the Cirebon System was 0.54, giving an average yield of 6.03 t/ha. At this level of resiliency, the average yield could have been 6.72 t/ha during the dry season due to less cloud cover and better solar radiation.

The high correlation between yield and the reliability, resiliency, and vulnerability indices, which measure different aspects of the water shortage, make these three indices a valuable tool for evaluating the effects or benefits, if any, of design or management changes in irrigation projects. For example, if lining canal or changing the operating procedures to improve on-farm water deliveries is effective, the reliability and/or resiliency of water supplies at the farm level should increase, and the vulnerability decrease,

Evidence from the Indonesian and Sri Lankan systems suggests that the effects of design or management change could be monitored by installing about 20 perforated tubes to observe the fluctuations of the perched water level over a large area, 100 ha or more. Although 10 tubes may be sufficient to obtain correlation if variability in water supplies among them is large, 20 tubes appear to be the minimum optimal number for any size of command area to establish statistically significant correlation between yield and these three indices. The spatial distribution, and hence the equity distribution, of benefits can be determined if the tubes are distributed over an area representative of the entire irrigation system.

While installation of the tubes, computation of the indices, and performance monitoring can be done without finding out the true critical tolerance level (CTL) ***apriori*** through simulation, such calibration is necessary to avoid arbitrariness and for internal validity. The *context* of the data (reliability, resiliency, vulnerability, yield, etc.) may be as important as the data itself, and variations may be more revealing than the averages that are often the sole output of conventional survey studies. As shown in Table **3.** the CTL may be season and site-specific.

To have internal validity, the CTL and the three indices should be calibrated with the yield obtained in the local environment for at least two crop cycles. After calibration, the number of tubes as well **as** crop-cut samples of yield can be substantially reduced without compromising too much validity. The exact number of tubes required will depend, however, on the purpose of the monitoring exercise and the degree of accuracy needed.

The findings that the CTL may be site specific have important implications for the way irrigation performance should be evaluated. The current prevalent practice of evaluating irrigation project performance is based on expert judgement, supplemented in some cases by survey data. Arbitrary norms or standards of efficiency and equity are typically used to pass a judgement on the level of performance achieved.

These norms (for instance about water requirements) seldom take into account local variabilities or the value of different levels of efficiency in the context of the local environment. As an example, more water and hence a higher CTL might have been necessary for control of weeds; and a lower CTL was possible because 4-month rice varieties could withstand prolonged periods without standing water (see Table **3).** Evaluation based on arbitrary norms usually gives only a "sense" of the problem rather than a definitive evaluation, as evidenced by the recurring lack of success in attempts at improvement. The methodology presented here is a response to dissatisfaction with the conventional approach.

More empirical studies are, however, still needed to validate the concept of a critical tolerance level (CTL) of water supply in lowland rice irrigation systems. With more empirical evidence. we will eventually be able to relate different values of CTL to different climatic, soil, cultural, and management characteristics. The locally derived CTL value, together with the computed reliability, resiliency, and vulnerability indices, can then provide the point of entry for identifying and evaluating the innovations that are needed to improve the management and performance of irrigation systems.

Figure **3.** Correlation between yield and resiliency of water supply in Cirebon Irrigation System, Indonesia, 1980-81. Pooled data file WT **lc;** early dry season (April-August); CTL = 0 cm.

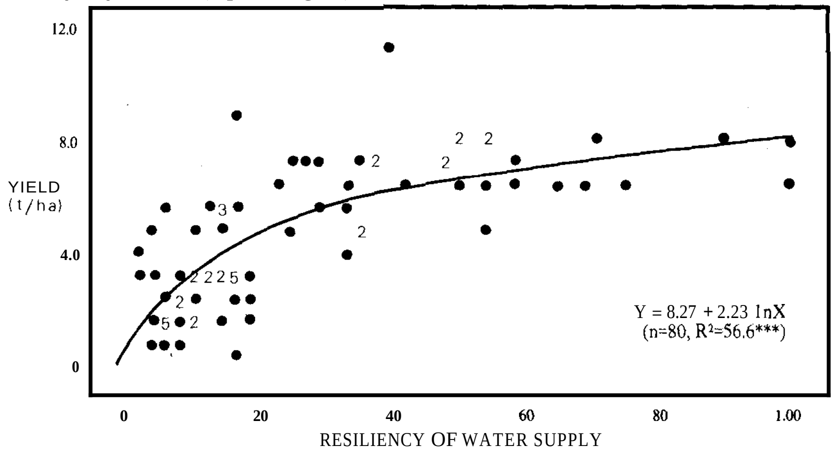
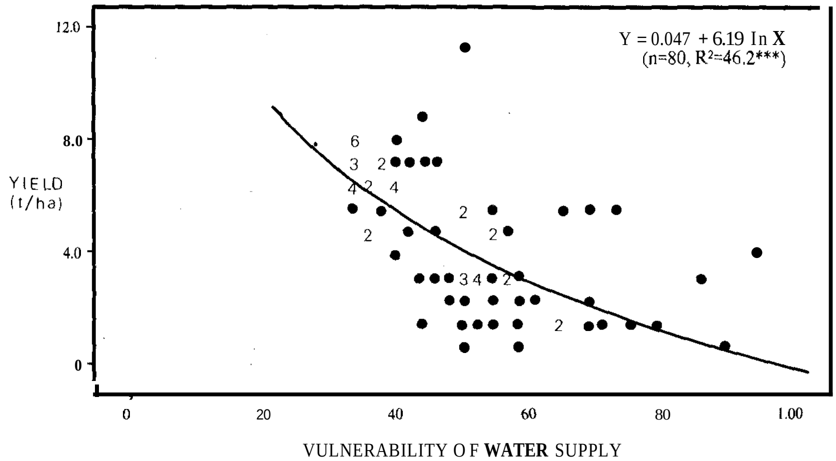


Figure **4.** Correlation between yield and vulnerability of water supply in Cirebon Irrigation System, Indonesia, 1980-81. Pooled data tile WT 1c; early dry season (April-August); CTL = 0 cm.



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