Performance Measure for Improving Irrigation Management

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ABSTRACT

A MEASURE TO evaluate performance in irrigation systems is formulated using the mean square prediction error concept. In the context of irrigation systems, the term error means the deviation of actual performance from a reference performance. The measure analyzes performance in terms of the management objectives of adequacy, dependability and equity of water delivery. It provides an understanding of the management capacity to schedule and distribute water in an irrigation system. Application of the performance measure is demonstrated by evaluating performance of an irrigation system in the North-West Frontier Province of Pakistan.

RESEARCH BACKGROUND AND OBJECTIVES

Reliable measures of system performance are extremely important for improving irrigation policymaking and management decisions. Several researchers have proposed a number of performance measures (Seckler et al. 1988; Oad and Podmore 1989; Sampath 1989; Abernethy 1986). Sampath (1989) analyzed these measures and suggested that most indicators violate some properties desired in a performance measure. There is a consensus on the management objectives that need to be evaluated, but inconsistency is observed in the selection of performance measures that appropriately describe those management objectives.

This paper reports our research to formulate a measure that can evaluate the level of managerial performance in terms of achieving the objectives of an irrigation system.

ANALYSIS

The research premise is that performance evaluation is meaningful only in terms of certain management objectives, and these must be defined for a given social and economic context. Then,

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some key variables that describe these management objectives are formulated and used to develop a performance measure. Analysis of the existing system performance, using this performance measure, can identify required improvements.

Irrigation Management Objectives

Barker et al.(1984) propose that an irrigation system, consisting of a water delivery and a water use subsystems, can be conceptualized to have two sets of objectives. One set relates to the outputs from its irrigated area, and the second set relates to the performance characteristics of its water delivery system. They state that "...inherently, the two sets of objectives are linked. If the water delivery performance objectives are met, then the output objectives should be achieved." This argument implies that one needs to only analyze water delivery subsystem performance for understanding performance of the whole irrigation system. The authors suggest the following most common management objectives of water delivery systems.

Adequacy in water delivery systems may be defined as the ability to deliver the amount of water to meet farmers' irrigation needs. Farmers' irrigation needs can be based on the knowledge of a crop consumptive use and/or social norms of equity. Dependability is defined as the delivery of a relatively uniform amount of water over time. Dependability reflects the combined effect of reliability and predictability and describes the arrival of a scheduled amount of water at a given place in a given time. The concept of equity deals with the distribution of irrigation water among users in a fair and just manner.

Water Delivery Performance Indicators

There are two properties that the irrigation water delivery variables should satisfy. The variables should represent both the farm and the water delivery system, and be subject to management control so that they can be manipulated to improve system performance (Merriam 1987).

In gravity flow irrigation, the variable that satisfies the two properties is the flow rate. Also, if the duration of a certain flow rate at a control point is known, then any other form such as water volume or depth can also be used. Denoting Q as water flow measured at a point x in the system at a time t, we define water flow required by the farmers to be $Q_r(x,t)$. Also, we can define Q_s (x,t) as the flow rate scheduled or planned for delivery and $Q_a(x,t)$ as the flow rate actually delivered by the system management.

Formulation of the Performance Measure

The performance measure analyzed in this research, called the performance error, is based on the mean square prediction error theory proposed by Theil (1966) and adapted by Sampath (1989) and Seckler et al. (1988). Theil (1966) states that if we have n number of pairs $(P_i A_i)$ of corresponding predicted and achieved forecasts, then the seriousness of a given forecast error can be measured by:

$$e^2 = \frac{1}{n} \sum_{i=1}^{n} (P_i - A_i)^2 \qquad (1)$$

In Equation (1), e^2 is the mean square prediction error for the set of n observations, and its square root gives us a measure of performance.

The term error, in the context of water delivery performance, may be defined as the deviation of actual amount of water delivered from the required or scheduled amount of water. For a given time period, therefore, Equation (1) can be written in terms of flow rate variables, Q_r, Q_s and Q_a. This error in actual flow rate may be due to reasons such as inadequate water supply, inappropriate scheduling and lack of physical capacity. When actual flow rate (Q_a) is equal to the required flow rate (Q_r), the error is zero and the system is performing perfectly. If no water is delivered in the system, that is Q_a=0, then e^2 is equal to one. Thus, the higher the value of e^2, the higher the error in water delivery and the lower the system performance.

Since we want to evaluate performance in terms of adequacy, equity and dependability, the total error can be decomposed into corresponding terms as follows:

$$\frac{(1)■}{R} \; R \; [Q_r(X) - Q_a(X)]^2 = (MQr - MQa)2 + (SQr - SQa)^2 + 2(1-r)SQr.\ SQa \qquad (2)$$

where MQr and MQ^a are arithmetic means (over a region R) of required and actually delivered flow rates, SQr and SQa are the standard deviations of Qr and Qa, and 'r' is the correlation coefficient of Qr and Qa.

The statistical properties, means and standard deviations are calculated by standard procedures shown in the notes at the end of this paper.

In Equation (2), the first right side term which we call error in water adequacy (E_a), is a measure of water shortage. For a given time period at a control point, the difference in arithmetic means of actual water flow from the required flow indicates the level of inadequacy in system water supply. The second right hand side term in Equation (2) is the error due to unequal variations in actual water flow compared to the required flow and is, therefore, a measure of the spatial nonuniformity. At the outlet level, unequal variations of the delivery canal flow will cause unequal variations in the outlet discharges. For the outlet level performance, therefore, the term indicates inequity of water distribution among various farmers' groups. As such, the second term is defined as error in water distribution equity (E_e).

The third right side term in Equation (2) is the error due to incomplete covariance of required (Q_r) and actual (Q_a) irrigation water flows. This is a measure of the management capability to implement a scheduled irrigation water delivery pattern. The management capability is conceptually a function of the physical capacity of the system and the organizational procedures. If the scheduled water flow rates are derived from the requirement and water is distributed according to the schedule, then Q_a=Q_r and the correlation coefficient of Q_a and Q_r is unity, and the third term will be zero. A positive value of the term will indicate either an inadequate system physical capacity to deliver water according to the schedule, and/or inappropriate organizational procedures. We define the third right side term as error in management capacity (E_m).

It is desirable to divide the right side terms of Equation (2) by the sum of squares of the total error to get a proportional contribution of each error term as follows:

$E_a = (M_Q\ r - M_Q\ a)^2$ /right side of Equation (2)

$E_e = (S_Q\ r - S_Q\ a)^2$ /right side of Equation (2)

$E_m = 2(1-r)\ S_Q\ r.S_Q\ a$/right side of Equation (2) so that, $E_a + E_e + E_m = 1$

RESULTS AND DISCUSSION

Data Source

The application of the performance measure formulated in the previous section is illustrated by using data from an irrigation system in North Pakistan. The Warsak Lift Canal (WLC) irrigation system is jointly managed by the farmers and the Department of Irrigation. The design discharge of the main canal is 5.67 m^3/s at the source, but during the study period (Nov–Dec, 1989) the discharge at the source was 4 m^3/s. The design agricultural command area is about 14,000 ha, but the Irrigation Department targets a command area of about 12,000 ha for water delivery. The command area is served through 108 watercourse outlets or water users' groups. The watercourse outlets are ungated pipe outlets which flow continuously whenever there is water in the main canal. Irrigation water below the outlet is managed by the farmers' groups and this includes water distribution among themselves. In the main canal, it is managed by the Irrigation Department.

Management Objectives and Performance Indicators

The Irrigation Department has two water management objectives: to maintain an adequate water flow and depth in the main canal, and to distribute water equitably among various outlet groups. The objectives are related and have the common goal of delivering each outlet its fair share of irrigation water. If an adequate flow, and correspondingly an appropriate flow depth is maintained along the canal length, then the pipe outlets can withdraw their fair share.

The department has established some monitoring points along the main canal where it wants to maintain a certain flow rate, which may be called the scheduled or required flow (Q^r). This required flow is based on the considerations of agricultural command area below that point and an assumed cropping pattern in that area. In our study of the irrigation system, we measured actual flow (Q_a) at the monitoring points. These two flow variables, Q_r and Q_a, will be used to analyze the system performance at the main canal level.

Towards the objective of equity, each farmers' group is allocated a flow rate through its outlet called the sanctioned discharge (Q_s). The sanctioned discharge of an outlet is primarily a representation of the agricultural land serviced by that outlet and the system would be fair if the actual discharge through all outlets equals their sanctioned discharge.

In this study, ten outlets were selected and the flow through these outlets was measured (actual discharge, Q_a). In addition to the sanctioned and actual discharge, we need one more flow variable which will indicate the discharge capacity of the outlets as determined by their hydraulic design. This may be called the outlet design discharge (Q_d). The design discharge of an outlet is determined by hydraulic factors such as pipe size, its setting and hydraulic head over the pipe. A proper engineering design of an outlet would determine its size and setting based on its ability to deliver the sanctioned discharge. That is, if an irrigation delivery canal is managed close to its design condition, then the actual, design and sanctioned discharges of an outlet are essentially equal.

A qualification about the data is that the actual measurements reflect the system behavior during a two-month time period. Results of the analysis, therefore, may not truly reflect the long-term average behavior of the system, which is not the purpose of this analysis. The purpose of using these data is only to illustrate field application of the methodology.

Analysis of Performance at the Main Canal Level

The results of actual and required flow measurements at the monitoring points along the main canal are presented in Figure 1. The actual flow at all points is much less than the flow scheduled by the system management and there is serious shortage of water in the downstream sections. Water barely reaches km 36 compared to the targeted length of 45 km and the total canal length of 57 km.

Using the methodology of mean prediction error (Equation 2), we estimated the contribution of water adequacy, equity and the management capacity to the error in system performance (deviation of actual from required performance). The relative error terms for adequacy, equity, and management capacity are presented in Table 1. The high value of the correlation coefficient (r=0.97) indicates that the actual flow consistently deviates in the same direction, from the required flow (actual flows are always less than the required flows). Also, about 84 percent of the performance error is explained by the error in water adequacy (E_a). The results indicate that the system management is unable to maintain its target or required flow at the key monitoring points.

Figure 1. Water delivery pattern in the main canal.

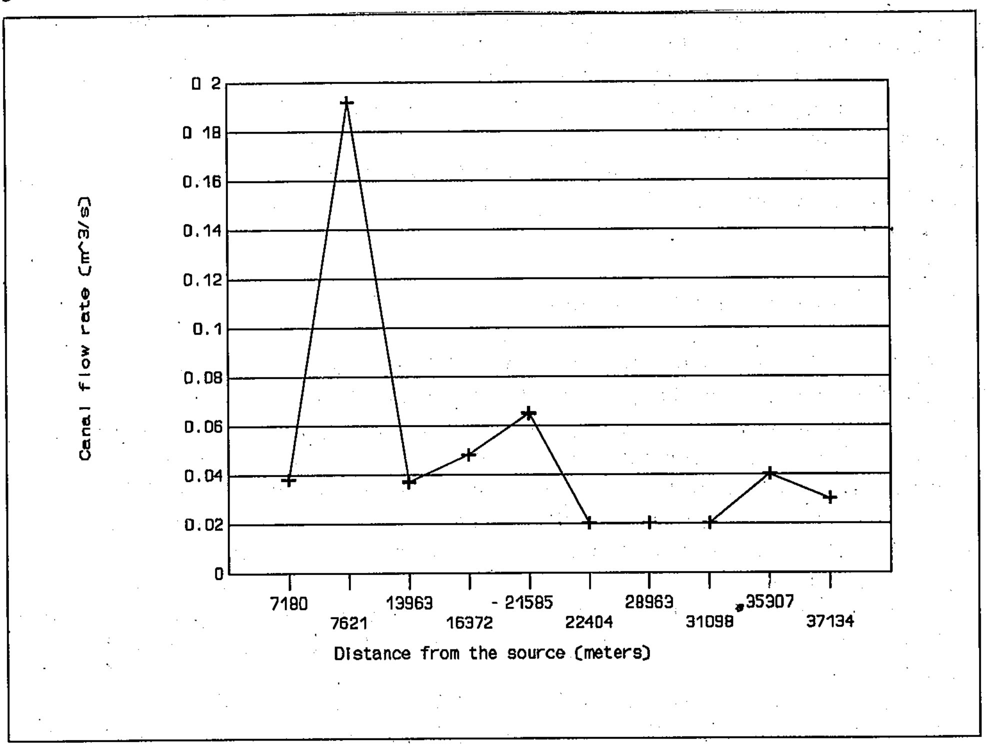

Table 1. Performance error in water delivery canal.

Distance from source(m)	Required flow (m^3/s)	Actual flow (m^3/s)	Performance error terms
80	3.95	3.95	Correlation coffefficient = 0.97
7,000	3.64	2.6	Error in adequacy (E_a)
14,500	3.13	2.5	Error in equity (E_e)
19,800	2.3	1.17	Error in management capacity
23,500	1.68	0.84	
30,500	1.23	0.42	
33,500	1	0.3	
37,000	0.75	0.01	
43,500	0.5	0	

Analysis of the error terms can provide possible explanations for this low performance. Note that the remaining two error terms, E_e and E_m, are small. The implication of the E_e term being small is that variation of the actual flow rate along the canal is the same as variation of the required flow. The fact that the management capacity term is small indicates that the physical capacity of the canal is not limiting. Also, available and required flows at the source are equal and seepage losses were measured to be none.[21]

All these results indicate that the reasons for the low performance are somewhat external to the system. Using the methodology of participant observation and informal interviews, the reasons were identified. In the upper sections of the canal, there are water withdrawals in excess of the planned use causing water shortages in the canal. This observation is supported by the flow measurement results in Figure 1 which indicate the sections in which excess withdrawals occur: in section 0–7 km and in section 14–20 km. The excess withdrawals are mainly due to additional water use by Afghan immigrants from across the border.

Analysis of Performance at the Outlet Level

The analysis of water flow in the main canal showed that the canal flow and the resulting water surface level are not maintained as planned. This finding and the fact that the outlets are ungated pipes indicate that the actual outlet discharge will not equal the design and the sanctioned discharge. That is, water distribution among various outlets may not be equitable. A comparison of the actual and sanctioned discharge of ten selected outlets confirm the inequity of water distribution (Figure 2). In the upstream and middle sections, outlets receive 140 to 200 percent of their due share, which means that either no water or little water for the downstream users (about 30 percent of their due share) will be available.

Using the methodology of mean prediction error, we calculated the three error components to explain the performance error in actual discharge with reference to the sanctioned discharge

21 This is explained by the fact that the canal runs on a contour with higher lands on one side. The water loss due to seepage on the lower side is compensated for by the incoming seepage from the lands on the higher side.

(Table 2). The Table also shows performance error components when sanctioned discharge is compared to the design discharge and when actual discharge is compared to the design discharge.

Comparing actual and sanctioned discharges, the error terms for equity (E_e) and the management capacity (E_m) explain about 87 percent of the total error. Water distribution among various outlets is certainly not equitable. The primary cause for this appears to be the management capacity (E_m=53 %) and not water adequacy (E_a=12 %). Recall that the error term for management capacity reflects the combined effect of the management decisions and the structural capacity of the system. In the context of ungated pipe outlets, no discharge regulation or other management decisions are involved. This implies that an explanation for the inequitable water distribution can be provided by the hydraulic features of the outlet.

Figure 2. Water distribution among outlets.

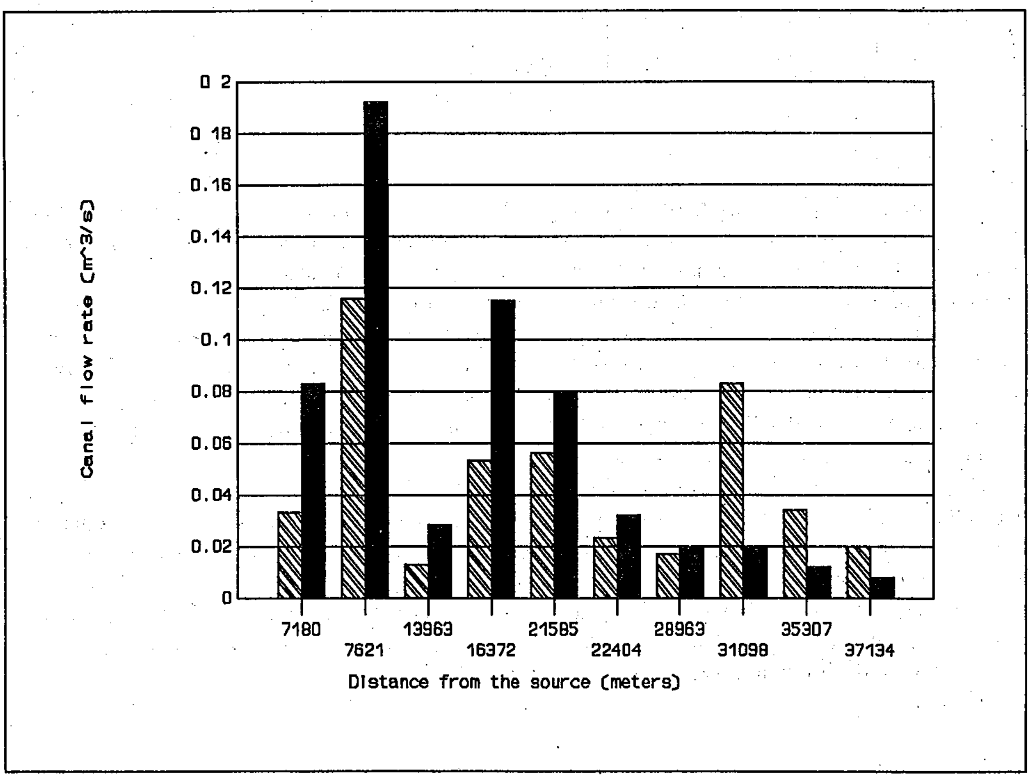

Table 2. Sanctioned, actual and design discharges of outlet.

Outlet	Discharges			Error terms			
Outlet location (m)	Q_s	Q_a	Q_d	Discharge variables	E_a	E_e	E_m
	(m^3/s)						
7180	0.03	0.08	0.04	Q_s and Q_a	0.12	0.34	0.54
7621	0.12	0.19	0.19				
13963	0.01	0.03	0.04	Q_s and Q_d	0.03	0.28	0.68
16372	0.05	0.12	0.05				
21585	0.06	0.08	0.07	Q_d and Q_a	0.08	0.06	0.86
22404	0.02	0.03	0.02				
28963	0.02	0.02	0.02				
31098	0.08	0.02	0.02				
35307	0.03	0.01	0.04				
37134	0.02	0.01	0.03				

As mentioned, actual discharge of an ungated pipe outlet is a function of water depth in the delivery canal and the pipe size. Since the flow rate and depth in the downstream sections of the delivery canal are less than the design, actual outlet discharge in those sections will be less than their design discharge. In Figure 2, we compare the outlet design discharge with the actual and sanctioned discharges. Note that in the upstream sections, design and actual discharges are generally equal, whereas in the downstream sections actual outlet discharge is consistently lower than the design discharge. An unexpected finding is that the design discharge for outlets does not equal their sanctioned discharge. The standard procedure is to design outlets by equating their design discharge to their sanctioned discharge.

The comparison of the outlet design and sanctioned discharge (Table 2) confirms the performance error, that the design discharge is not correctly related to the sanctioned discharge. About 67 percent of the performance error is explained by the management capacity term alone. The most convincing information of the inadequate management capacity is obtained when the actual discharge is compared to the design discharge. Now, the management capacity term explains about 85 percent of the performance error which implies that the system is not managed in accordance with design conditions.

CONCLUSIONS

The irrigation system performance measure formulated in this research (the performance error) is derived from the methodology of mean prediction error proposed by Theil (1966). In the context of irrigation water delivery systems, performance error means the deviation of actual system behavior (canal flow, for example) from scheduled or required behavior.

The performance error methodology provides an estimate of the total error in water supply relative to the farmers' water requirements. The farmers' water needs can be derived from the crop and soil water requirements, and/or they may be based on the social norms of equity and fairness. The total error can be explained by three additive error components related to water adequacy, equity and management capacity. Since the error terms are additive and decomposable, their analysis is effective in identifying the sources and levels of low system performance.

Application of the methodology was illustrated by analyzing the performance of an irrigation system in Northwest Pakistan. It is seen that the methodology is effective in analyzing the system performance in reference to actual and required water deliveries. The methodology also indicated possible causes for error in the water delivery system performance. The methodology was also effective in analyzing water distribution equity among various water users' groups in the irrigation system. The performance error in actual discharge for selected outlets was evaluated in reference to their design and sanctioned discharge. The evaluation identified possible sources, both managerial and structural, as causes of the performance error.

Notes:

1. The arithmetic mean of Q_r and Q_a is defined as,

$$M_Q\,r = \frac{1}{R} \sum_R Q_r(X)$$

$$M_Q\,a = \frac{1}{R} \sum_R Q_a(X)$$

2. The standard deviation is defined as,

$$S_Q\,r = [\frac{1}{R} \sum_R (Q_r(X) - M_Q\,r)^2]^{1/2}$$

$$S_Q\,a = [\frac{1}{R} \sum_R (Q_a(X) - M_Q\,a)^2]^{1/2}$$

3. The correlation coefficient is defined as,

$$r = [\frac{1}{R} \sum_R (Q\,r(X) - M_Q\,r)\,(Q_a(X) - M_Q\,a)]/S_Q\,r.S_Q\,a$$

References

Abernethy, C.L. 1986. Performance measurement in canal water management: A discussion. ODI-IIMI Irrigation Management Network, International Irrigation Management Institute, Kandy, Sri Lanka.

Barker, Randolph, W. Coward, G. Levine, and L.E. Small. 1984. Irrigation development in Asia: Past trends and future directions. Cornell Studies in Irrigation, No. 1, Cornell University, Ithaca, New York.

Merriam, J.L. 1987. Symposium introduction. *In* Planning, operation, rehabilitation, and automation of irrigation water delivery systems, ASCE, New York.

Oad, R. and T. Podmore. 1989. Irrigation management in rice-based agriculture: Concept of relative water supply. ICID Bulletin vol.38, no. 1, pp. 1–12.

Sampath, R.K. 1989. Measures of managerial performance of irrigation systems. Irrigation and Power Journal, 46(4):93–112.

Seckler, D., R.K. Sampath and S.K. Raheja 1988. An index for measuring the performance of irrigation management systems with an application. Water Resources Bulletin, 24(4):855–860.

Theil, H. 1966. Applied economic forecasting. *In:* Studies in Mathematical and Managerial Economics, Volume 4, North-Holland Publishing Company, Amsterdam, The Netherlands.