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INDICATORS OF THE PERFORMANCE OF IRRIGATION WATER DISTRIBUTION SYSTEMS

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INTRODUCTION

This paper aims to review and discuss some of the principal criteria that have been proposed for measuring and evaluating the performance, or level of success, of canal water delivery systems. No new indicators of performance are proposed, because those that have already been put forward in the existing literature seem to offer a sufficient range of choice. The final section of the paper makes recommendations for a limited set of indicators which IIMI might adopt as standard in order to ensure consistency in its own field studies.

GENERAL CHARACTERISTICS TO BE MEASURED

Malhotra, Raheja and Seckler (1984) say that the following statement "would describe the goal of an irrigation system nearly perfectly:"

To supply the required quantity of water at the right time to the right farmers.

Statements of this kind set out ideal results. We may safely say that these ideal results are never, or virtually never, achieved. Performance measurement entails measuring the extent of departures from ideal results.

There is a growing consensus in the literature, reflected in statements such as the above quotation, that a good irrigation water supply must be judged by three primary characteristics:

adequacy
timeliness
equity

Indicators of these three characteristics should enable us to answer, in respect of any given irrigation system, three questions framed on the following lines:

- to what extent does the quantity of water provided suffice for the growth needs of the crops that are planted?
- does the timing of the water deliveries match the growth needs of the crops and the expectations of the farmers?
- is it distributed fairly among the multiple users of the system ?

The above three factors may not be sufficient in systems which experience difficulties with water quality. In many systems, the content of salinity or sediment in the water is another important consideration in management. These quality factors will not, however, be brought within the scope of the present review. We must first determine how to reflect, in indicators, the above three major dimensions, in a clean, low-salinity system. Only when that has been achieved will we be ready to assimilate the fourth dimension, water quality.

We should also note the relationship of water management to the overall goals for which irrigation systems are created. These goals can be summarized in five major categories: productivity; equity; profitability; sustainability; and the quality of life (Abernethy, 1989).

The management of water is not, in itself, one of these system goals. It is a subordinate objective. Good water management is a necessary condition, but not a sufficient condition, for attaining system goals.

As we have noted, actual performance in water management will always differ from the ideal, and the significance of these deficiencies has to be measured in terms of the impact of such deficiencies on achievement of system goals, especially productivity of crops.

It is therefore necessary to look for indicators that connect water distribution to the overall system goals. The literature on this is remarkably sparse, and in this review we shall look at such indicators only in respect of productivity, not the other four system goals identified above.

It is necessary to distinguish between the two major styles of irrigation management, appropriate respectively to rice and non-rice crops. Much of the available literature on performance indicators refers to rice-producing systems. This is not only because they are widespread, but also because rice is usually grown as a mono-crop, and this makes it much easier to analyze the data, since planting dates and crop water needs have a homogeneity that is absent from mixed-crop systems. But we should beware of the assumption that indicators suitable to a rice environment will also be suitable in non-rice systems.

ADEQUACY

Early methods of assessing the adequacy of water supplies used simple concepts like the "water duty" of the system, which in spite of many recent improvements in both theory and practices remains a most influential idea. It originated as a planning and design parameter, especially suited to water deficient environments like the Indus basin. The duty is expressed as a ratio between irrigated area and water discharge rate (e.g. acres per cusec), which can readily be interpreted as a depth of water supplied per day. This is a convenient parameter for determining, at design stage, the necessary sizes of channels.

From this origin, it has been adapted in some countries as an operational target parameter. When used in this mode, it is sometimes differentiated according to the specific crops that are being irrigated; it may also be given different values in different seasons.

The duty parameter, however, is a crude one that is related only approximately to the actual water needs of crops. In places where water is scarce, duty is deliberately fixed at values well below the optimum for crop growth.

During the 1950's and 1960's our understanding, and quantitative evaluation, of the water needs of specific crops increased rapidly, especially following the pioneering work of Penman and others that clarified evapotranspiration processes. This led to the development of indicators that relate the amount of water supplied to the potential evapotranspiration of the crop.

The principal candidates are irrigation efficiency, on which the definitive work was presented by Bos and Nugteren (1982) and relative water supply, proposed by Levine (1982). In principle these are the reciprocals of each other:

$$\text{irrigation efficiency} = \frac{\text{water required}}{\text{water supplied}}$$

$$\text{relative water supply} = \frac{\text{water supplied}}{\text{water required}}$$

but there are important differences.

One key difference is that Bos and Nugteren divide the irrigation efficiency into various components, so that the efficiencies associated with different elements of the water delivery system (such as main canals, minors, field channels, fields) can be separately stated; and for the conveyance sectors they adjust the above definition to:

$$\text{irrigation efficiency} = \frac{\text{water delivered from the sector}}{\text{water supplied into the sector}}$$

The idea of irrigation efficiency is most useful in describing the performance of the water conveyance system. Thus the ratio of water supplied at minor canal heads to water taken in at the main canal head gives a clear measure of the success of the main system in transmitting water towards the ultimate user. Similar ratios can define the performances of the various levels of a complex canal network: minor channels, field channels, etc, and these can all be multiplied together to give an overall performance indicator of the water delivery system.

Matters become less satisfactory when we try to incorporate into this the water requirements of the crop.

Bos and Nugteren define the field application efficiency as "the ratio between the quantity of water needed to maintain the soil moisture at the level required for the crop and the quantity of water furnished at the point of delivery to the field."

The main objection to this is that, if the quantity of water that is furnished is very much less than would be required to re-supply the root zone, the efficiency will be substantially more than 100%. In the extreme, efficiencies much greater than 100% would rapidly lead to loss of crop yield. There is nothing intrinsically wrong with this; but it is surprising, and goes against normal understanding of the word "efficiency," to find that very high values can be associated with crop failure.

The communication role of indicators needs to be stressed. They are not just for use between researchers, but should be easy to explain at many levels, if they are to influence the organizational culture. In this respect, the relative water supply is clearer. As Levine puts it, there are "value connotations inherent in the term efficiency", whereas "the relative water supply variable presents a neutral view of the relationship between the amount of water delivered and the amount utilized for crop production".

As with the irrigation efficiency parameter, relative water supply can be expressed at any of several different levels of the canal network. In every case, the denominator is the amount of water required for crop growth; but the numerator may be the amount of water delivered to the field, or to the minor, or into the main canal, etc. Any of these are legitimate uses of the relative water supply concept; but it is essential (for interpretation of the information) that the level in the canal hierarchy is always clearly declared.

Levine defines the relative water supply as "the ratio of water supply to the water demand associated with the crop actually grown, with the cultural practices actually used, and for the actual irrigated area". (This, in Levine's terminology, is the "actual relative water supply": he also defines a "theoretical" value, in which optimized crop pattern, cultivation practices and planted area are substituted for observed values of these.)

Although the principles of the relative water supply or the irrigation efficiency concepts are easy to understand, there are major difficulties in applying them. The definitions cited above for Levine and Bos and Nugteren contain ambiguities that are far from trivial. It is important, for IIMI and for the research community in general, to develop a consistent approach to these. The principal problems concern the ways of treating;

a. percolation
b. rainfall

in the calculations. Since each of these parameters may quite commonly have values in the range half to double the crop evapotranspiration, variations in the way of treating them make great changes in the calculated relative water supply.

The definition used by Bos and Nugteren makes it clear that percolation is to be regarded as part of the water demand. This does not necessarily follow from Levine's definition, but in his papers he also incorporated field percolation into the crop demand. Thus, in both methods, demand is equal to crop evapotranspiration plus percolation.

There are two objections to the inclusion of percolation as part of the demand. One is practical : field percolation is difficult to measure, so it is usually represented by rough estimates. This is especially true for non-rice systems; but even in rice systems, acceptable estimates of percolation rates are difficult to obtain at larger aggregate or system-scale.

The second objection is more theoretical: it is that the incorporation of percolation losses into the demand affects the meaning of the relative water supply (or irrigation efficiency) as a management indicator. For example, if percolation-reducing practices, such as puddling for rice, are not used, then the demand is higher and so the relative water supply is lower and apparently indicates better management, which is not the true case.

For these reasons, there seems to be a good case for defining the "demand" element simply as the amount needed to satisfy crop evapotranspiration.

Rainfall presents other difficulties. The commonest way of treating it is to add, to the water supply side, an amount called the "effective rainfall." However, some authors instead deduct this from the demand side. The "effective" concept is based on the observation that not all rainfall can be captured and used by the crop: if the rainfall is very intense, much of it will run off, and if it is very light, much of it will evaporate directly to atmosphere. Empirical formulas are available which claim to quantify these aspects. But it is clear that the proportion of rainfall that is detained in the field and is made available to the crop can be increased by appropriate management and cultivation practices. Our performance indicator should be designed so that it reflects the impact of management, upon rainfall capture as well as canal water use.

For these reasons it seems desirable to incorporate the actual rainfall into the water supply, as Levine does. It has to be recognized, however, that this means that, even with equally high standards of management, the expected values of relative water supply in rainy environments should be greater than in arid environments.

What are the desirable target levels of the relative water supply? This question has to be treated differently at the farm level and at the system level. The farmer wants enough water to ensure that, on all parts of the field, he can satisfy crop needs plus percolation; if his field is poorly levelled, so that the amount provided is non-uniform, he wants more water so that the higher points still get enough. Generally, to satisfy these losses and non-uniformities, he may look for an excess of say 30 - 50% above plant requirements; a relative water supply of 1.3 - 1.5.

At the system level, the same problems of losses and non-uniformity of distribution also arise. The management objective may be (for example) to ensure that all fields in the system receive a necessary minimum, say a field relative water supply of 1.2. In that case, the system relative water supply must be greater than this. The excess is principally a function of the inequity of the distribution arrangements.

It does not seem appropriate to set independent targets for relative water supply and for equity. The interactions between them are too numerous. Wade has observed that, when system relative water supply is low, competition for water intensifies, which must drive inequity upward. Levine suggests that systems should have relative water supplies in the range 1.5 - 2.5, depending on their internal control arrangements, with the high values of relative water supply corresponding to weak control (i.e. high inequity).

EQUITY

The literature on equity in distribution networks is even more scarce than that on adequacy. This seems to be due mainly to the measurement difficulties. Measurement at numerous locations is necessary in order to derive a single estimate of inequity, and until recently appropriate equipment to perform this reliably was not available.

Equity of water distribution involves some concept of fairness among the system's users. There are different ways of interpreting this. The simplest is to identify equity with equality, and say that each hectare in the system ought to receive the same. Many variants are (at least in theory) possible. For example, if there are difficulties in delivering equal supplies to all parts, this may be reflected in lower land prices in those parts that receive less water, or (as in the system described by Yoder, 1989) in a communal system those farmers' labor inputs for system maintenance may be reduced. Where such adjustments occur, it is quite possible for a system to be unequal, yet equitable. However, the stage has not been reached where these refinements can be incorporated in any generic indicator. As noted above, the literature is still small and it seems appropriate at present to take the simple approach and treat equity as synonymous with equality.

Sampath (1986, 1988) analyzes various possible measures from a theoretical standpoint. He considers, among others, the Gini coefficient (which originates in inequity studies in the economic field, such as inequity of personal incomes or wealth); the normal and logarithmic standard deviations; and some other less attractive ones, before deciding in favor of Theil's information measure, which is:

$$T = \sum_{i=1}^{n} y_i \log (ny_i)$$

where n is the number of land units considered and yi is the fraction, of the total water available, delivered to the ith unit.

A difficulty with this is that its maximum value (representing severe inequity) is log n, so it gets bigger if there are very many land units; but it can readily be transposed to a zero to one range, by dividing by log n.

Abernethy (1986) proposes the use of an inter-quartile ratio, defined as the ratio between the volumes of water delivered respectively to the most favored 25% and the least favored 25% of the area. He argues for this measure that it is a concept easy to grasp, and therefore has a higher communication value than other measures that might be more acceptable in a purely statistical sense.

Rao (1987), noting that Abernethy's measure took no account of the central 50% of the data, adapts the idea somewhat. He continues to use a ratio between the best-off and worst-off groups, but instead of defining these arbitrarily as the upper and lower quartiles, he proposes that middle (roughly satisfactory) range should be defined as those who get within + 10% of their proportionately fair amount. He then calculates the amounts of water received (per hectare) by those who get more and less, respectively, than this. The ratio between these is Rao's relative equity ratio.

Numerous other measures have been proposed, but many are designed with a particular type of situation in view. The cases that have attracted more attention are rice irrigation, and water-deficient irrigation. Some of the indicators that have been proposed respond to the difficulty or expense of water discharge measurement by using instead wetness observations. This is of course rather rough, but easier in rice.

For water-deficient systems, where in general there is not enough water to irrigate all the available land in any one watering (as is common in the warabundi systems of Pakistan or NW India, outside of the monsoon season), Malhotra, Raheja and Seckler defined "allocative efficiency" as the coefficient of determination between the wetted area (after a watering) on each farm, and the farm area. This will be 1.0 when there is perfect equity, in the sense that every farmer receives a share proportional to the size of his holding. Seckler, Sampath and Raheja (1988) elaborated this to form an indicator of "management effectiveness" defined as

$$E = 1 - \sqrt{\frac{(Aw - Aw^*)^2}{Aw^{*2}}}$$

in which Aw, Aw* are respectively the actual and the target wetted areas on each holding

This has evident similarities to a coefficient of variation of the ratio of area wetted.

Faced with such diverse options, what parameter might we choose as its standard, if any? It seems clear that measures based on volumetric water measurement ought to be preferred where possible. It is true that the cost (or, in very flat terrain like the Egyptian systems, the technical difficulty) of water measurement will quite often mean that surrogate variables like wetted area are the only primary data that can in practice be obtained. In such circumstances, Seckler's management effectiveness will sometimes be useful. It will not work, however, in the important case where the water is just slightly scarce. If, say, the relative water supply to the system is close to 1.00, there will be intense competition for the water. It is likely that farmers who lose out in this, and secure a personal relative water supply of, say, 0.8 or so, will irrigate all their holding, but with sub-optimal qualities of water. That is, in the Seckler index, $Aw = Aw^*$, and so $E = 1.00$. Thus it seems that the Seckler index can represent inequity only for seriously water deficient areas, such as the systems in Sind where relative water supply may be under 0.5 in the rabi season.

In the more satisfactory case where volumetric water measurement can be done, the writer continues to prefer the inter-quartile ratio. However, we need more sets of data for real systems, in order to see how the various proposed parameters behave in practice. Sampath says, correctly, that "one of the fundamental problems is that we have absolutely no idea about the characteristics of water distribution functions". Until that need can be satisfied, from empirical data, we should probably suspend any final judgement as to which parameter is most informative, most useful to managers and so on. This writer guesses that the most likely underlying statistical distribution is the log-normal, but that remains to be proven.

What target values should be set for an inequity variable such as the inter-quartile ratio? The number of studies so far available is too small to supply any clear answer. System design methods that are in common use assume (usually implicitly) values very near to 1. Field data, such as it is, often suggests actual values in excess of 3.

The target value cannot, in any case, be selected independently from the adequacy parameter. If relative water supply is high, equity of distribution will not be a high objective, and inter-quartile ratios of 3 or 4 may be quite tolerable; but where water is scarce (as in Pakistan) such values would seem much too high.

TIMELINESS

There are two quite distinct aspects to the question of the timing of water deliveries. We can distinguish these by the terms "timeliness" and "reliability".

Timeliness means the correspondence of water deliveries to crop needs. It can be considered on the basis of the accuracy of fit between two time-history curves, one of which represents the evapotranspiration needs of the crop throughout its season, while the other represents the actual deliveries of water.

Reliability, on the other hand, means the degree to which the irrigation system and its water deliveries conform to the prior expectations of its users. Can the farmer feel certain that he knows whether water will come to his field channel on a given day, and in what depth and quantity it will flow?

Reliability is a most important aspect, affecting the efficiency of various field activities. It does not however seem to have been systematically studied, and the writer is not aware of any numerical parameters that have yet been proposed. This discussion will therefore focus on timeliness, which a number of workers have considered.

No one appears to have attempted to treat timeliness as a fully independent parameter, and indeed it would not be easy or perhaps useful to do so. Some writers have proposed that timeliness be assessed in terms of its impact on productivity, and these are reviewed in the next section.

Others, particularly those dealing with rice systems, propose that it be linked to observations of soil wetness.

Thus Small, Capule and Oallares (1984) propose a water shortage index, Sw, based on a summation of daily products of pan evaporation and depth from land surface to standing water:

$$Sw = \sum_{i=1}^{N-20} Ei\ di$$

where Ei is the pan evaporation rate on day i

di is the depth from land surface to standing water on day i

i = 1 on the date of transplanting

N is the number of days from transplantation to harvest.

If water is standing above the surface, di = 0. Thus if the crop is grown in a continuously flooded field Sw = 0 for the season; but if there are erratic water deliveries the field will dry out and Sw takes some positive value that reflects the number of dry days, weighted by their consumptive demands. Small et al included in their initial formulation a further weighing factor to represent differential water needs at different crop stages, but found in practice that their results indicated this was not distinguishable from 1.0.

Wijayaratna (1986) develops much the same line of reasoning, but avoids the need to make numerous daily observations of standing water depths below surface. His water availability index relies on observation of whether or not there is standing water in the field. If there is, it is assumed that the crop is satisfied and availability is equal to 1.0; but from the day on which the field is observed to dry out, water availability is assumed to decrease by 5% each day. The index is calculated by summation of daily values, first over the vegetative growth phase and then separately over the reproductive growth phase; finally a composite, whole-season index is derived, by assuming that the reproductive phase carries twice the weight of the vegetative phase. Wijayaratna related his index to crop yield, and found coefficients of correlation in the rane 0.35 - 0.75.

Indices like these reflect the joint effects of water adequacy and timeliness. They would not be useful in analysis of non-rice irrigation, where the presence of standing water is generally an undesirable feature rather than a positive indication of satisfaction. But for rice systems, Wijayaratna's index has the merit of being easy to evaluate over quite large numbers of fields.

PRODUCTIVITY

The Wijayaratna and Small et al indices are ways of assessing the extent to which a given water regime may fail to satisfy the needs of one specific crop, rice. The capacity to do this more generally was greatly enhanced by the publication of Doorenbos and Kassam (1979) which brought together much information on the effects of water deficits at different growth stages in a large number of economic crops.

Lenton's (1982) water delivery performance P is defined as

$$P = \Sigma Ki \frac{V_i}{V^*_i}$$

in which Vi, Vi* are the actual volumes and the required volume of water delivered in period i

Ki is a factor representing the crop's sensitivity to water deficiency in the period i; Ki values being scaled so that dki = 1.0 over the season.

Lenton treats excess supply (Vi > V*i) in an interesting way, suggesting that either we may then simply set Vi = V*i as a limit as others have done; or we may invert it, putting

$$P = Ki \frac{V^*_i}{V_i}$$

on oversupplied days, in order to indicate that over supply is potentially harmful to most crops.

Abernethy's (1986) index of potential productivity is essentially the same thing as this, through its treatment of over supply is less subtle. Each method produces a number, in the range 0 to 1, which represents the ratio of the yield (land productivity) that would be obtainable under some specific, imperfect water regime, to the yield that would be obtained, using the same farm practices, under a "perfect" water regime.

Thus these indices show the joint effect of any failings of adequacy and timeliness, in terms of crop loss.

Either index can quite readily be converted to a comparable index of water productivity, using the same input information, but with more specific emphasis upon any periods of over-supply.

A fully integrated indicator, incorporating all the three major water-supply characteristics identified at the outset (adequacy, equity, and timeliness) can be formulated from these. The water delivery performance or the potential productivity, refers to a single value, whether for one field or averaged over some set of fields supplied through a common facility. Over an irrigation system, parameters of this kind must vary. Their observed distribution can be analyzed for inequity in terms of any of the indicators that have been proposed for that. Thus we can calculate a Gini coefficient, or an inter-quartile ratio of water delivery performance.

An index of this sort would sum up, in one value, the system's performance in terms of meeting crop demands fairly among all users. It would be significantly better than an inequity measure based on water quantity alone, since it is often observed that "tail-end" farmers, as well as getting inefficient water, often get it especially erratically.

There are, however, quite formidable reasons why this kind of fully integrated indicator has not yet been adopted by system operators, nor indeed by researchers. The main reason is that the data collection involved is perceived as too difficult or too expensive.

These objections are reasonable. It is up to IIMI and other researchers, to demonstrate that benefits are obtained from measurement, exceeding the costs. That demonstration has not, hitherto, been done, at least not in any persuasive way. The most plausible benefits should come from the use of indicators as a tool in organizational control (say, as a basis for rewarding staff, or simply for communicating between the organization and its users). In theory at least, such uses of indicators ought to lead to enhancement of performance levels, thus justifying the data acquisition expenditure. This hypothesis awaits proof.

SUMMARY OF RECOMMENDATIONS

The following is a recommended list of indicators which could be adopted as the basis of standard assessment practices.

a. For main performance, from water source to field channel: conveyance efficiency.

b. For adequacy of water supply:

Relative water supply, with demand treated as crop potential evapotranspiration only (i.e., not including percolation) and supply treated as canal deliveries plus actual rainfall.

c. For equity of water distribution:
Inter-quartile ratio

d. For overall performance of a system (or of a system component such as a tertiary block):
Water delivery performance.

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