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Statistical methods for irrigation system water delivery performance evaluation

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Abstract. There are several different parameters that can be measured and used to describe the performance of water delivery service; flow rate, volume, duration, pressure, and frequency. The proper one(s) to consider depends on the project conditions and objectives. The overall performance of an irrigation water delivery system can be broken down into two components; the delivery schedule and operations. The performance of the delivery schedule can be evaluated by looking at the ratio of intended to required water (volume, rate, duration, etc.) and the performance of operations by the ratio of actual to intended water. The overall performance is expressed by the product of these two ratios; the actual divided by the required water. Statistical relations are provided to express equity, adequacy and reliability from measurement of these ratios.

Introduction

The performance of an irrigation system can be viewed from a number of different perspectives. This view depends upon the background and experience of those conducting the evaluation, and the objectives of the irrigation project that are evaluated. If the irrigation project is a single, large farming operation, project objectives should be relatively easy to define. However, for irrigation projects that are publicly funded and operated to distribute water to a large number of independent farmers, the objectives may not be so easy to define. Irrigation project objectives usually include such things as; economic return, augmenting crop production, betterment of the general population, rural development, etc., and more recently developing a sustainable agriculture and minimizing the impact of the project on the environment (i.e., water quality issues). Some of these objectives are relatively easy to evaluate, while others may be very difficult. In any case, the above types of objectives can only be viewed as long-term objectives. Measurements or indicators for evaluating these objectives can be measured seasonally or yearly at best (Biswas 1990).

In the initial stages of project formulation, decisions are made regarding 1) the method for allocating water, and 2) the method for physically distributing water. The method for allocating water is often referred to as the delivery schedule. Examples include demand, arranged, and rotation schedules (Zimbelman 1987). The method for distributing water (operations) is a combination of the physical facilities, the physical water control strategy and the operating plan (management). Examples of control strategies and physical facilities are upstream control in canals with manually operated check gates and pressurized closed pipe deliveries with regulated pressure (Zimbelman 1987). The conditions (both in project operation and in farm irrigation) assumed during project development may be considerably different from those which currently exist. Changes in irrigation practices and crops may suggest changes in this plan.

Evaluation of project water delivery performance, should focus on evaluating these two parts of the water delivery plan. The first, an evaluation of the delivery schedule, should be done periodically (e.g., every ten years) or when major rehabilitation is being planned. The second, an evaluation of water delivery operations, can be an on-going activity (see Seckler et al. 1988). Unfortunately, the data needed for these evaluations is not typically collected during routine irrigation project operations.

This paper is focused on methods to evaluate how well the irrigation system distributes water to users. Decisions on the control of water are made daily, and water is only one component of the agricultural production system. Thus it can be very difficult to see the influence of water control decisions on the overall long-term project objectives discussed above. The purpose of this paper is to describe

- the type of data that needs to be collected in evaluating water delivery operations,
- the statistical methods for analyzing the data, and
- how to interpret the results.

These indicators can be used by project management to identify strengths and weaknesses in their operations (areas of high and low performance). Such indicators give a relative measure of quality of service. Areas of low performance identified will provide guidance to where changes need to be made. A next step is to determine the exact influence of these indicators on the project objectives, but such issues are not the focus of this paper. The discussion and examples focus mainly on water delivery operation, although the delivery schedule can also be evaluated with these techniques.

Delivery statistics

Past evaluations of delivery performance have identified the concepts of adequacy, equity and dependability as being important considerations

(Mohammed 1987). Dependability and consistency can also be considered as word descriptions of performance. At any point in time, one can measure the discharge, Q, or the pressure, P, at various delivery points within the system. Over specified periods of time, one can examine the duration of a delivery, D, the total volume of water supplied, V, and the frequency with which water is delivered, F, at a given farm turnout or offtake. These are the usual quantities of interest that can be measured. The question is, how can these measurements be made into expressions of adequacy, equity and reliability? In addition one might ask, 'how can these expressions be related to overall project performance?' and 'how can one establish target values for these expressions that can be used by project management to improve performance?'

When measurements of one of these physical quantities (for example, volume) are taken at any point in the system, there are three values that should be considered:

- the actual volume of water delivered (measured), V_A,
- the volume that the operators intended to supply, V_I, and
- the volume required by the system downstream, V_R.

The actual volume delivered, V_A, can be obtained from project records, however, on some projects such measurements are imprecise, taken too infrequently to be representative, or missing altogether. It is important to verify the suitability of these existing records for evaluation purposes. The intended volume, V_I, can be determined from project records of either the seasonal plan for rigid delivery schedules, or water orders for the more flexible delivery schedules. The volume required, V_R, can be obtained from agronomic considerations, the requirements of the crops and irrigation efficiencies associated with farm irrigation systems, and conveyance losses from seepage and evaporation. (A similar set of terms can be defined for Q, P, D and F).

The three terms defined above can be related as follows

$$\frac{V_A}{V_R} = \frac{V_I}{V_R}\frac{V_A}{V_I} \qquad (1)$$

Similar equations can be written for each of the other variables (Q, P, D, F). The first term, V_A/V_R, is a measure of the overall project performance; the actual volume delivered divided by the required volume. It indicates the relative amount of extra (or insufficient) water delivered. The inverse of this ratio (required volume divided by actual volume) can be considered as an efficiency term. Efficiency terms of this kind are used to quantify terms in a project water balance and do not necessarily reflect a value judgement on performance (Bos 1979). The statistics associated with this ratio provide additional information about overall performance.

The ratio V_I/V_R is a measure of how well the intended operation matches the downstream requirements. For a rigid rotation system, it might be a measure of the performance of the schedule for water delivery or the system design. It may also be a measure of the adquacy of the supply. V_I could be considered as either the design volume for the season or the volume intended for the supply available, depending on what is being evaluated. For a flexible arranged delivery system, V_I/V_R is a measure of the farmers' and water purveyor's abilities in ordering the correct amount of water. The statistics associated with this ratio can be used to evaluate the delivery schedule part of the delivery plan. Determining the real downstream water requirement may be difficult. If evaluating the entire project, one would use crop water use plus management uses such as leaching. If evaluating only the water delivery part, then total farm water requirement could be used (including farm inefficiency).

The ratio of actual volume of water delivered to volume of water intended, V_A/V_I, is a measure of the delivery system's ability to supply water according to their schedule (operations). The statistics associated with this ratio can be used to evaluate the ability of the system and its' management at delivering water. These statistics will not determine whether physical system limitation, operational problems, or management are the main cause of poor performance. This can only be identified by analysis of the delivery system functioning. Diagnostic Analysis (Clyma & Lowdermilk 1988), part of a Management Improvement Process (Dedrick et al. 1989), is one method of identifying the causes of the problem. Here we are concerned with quantifying the magnitude of the problem.

The latter two ratios can be used to examine 1) how well does the delivery schedule match the needs and 2) how well is the schedule being carried out. The performance of the operating staff is concerned with how well the schedule is being carried out. Evaluation for rehabilitation is concerned with both.

Operations

Suppose we are interested in evaluating the ability of a lateral (secondary) canal with fixed structures to distribute a flow of water to farm (tertiary) canals. In evaluating the ability of the structures to distribute water, we need to know the flow rate intended to be delivered at each outlet, Q_I, measure the actual rate of flow at each outlet, Q_A, and then compute the ratio of the two, $Q_{A/I} = Q_A/Q_I$. Along the lateral canal, there will be a range of values observed for this ratio, which can be represented by a frequency distribution, as shown in Fig. 1. We can characterize the distribution by its mean value, $M_{QA/I}$, and standard deviation, $S_{QA/I}$ (Till & Bos 1985). If we choose a large enough random sample, we need not measure every outlet within the project to determine these two parameters.

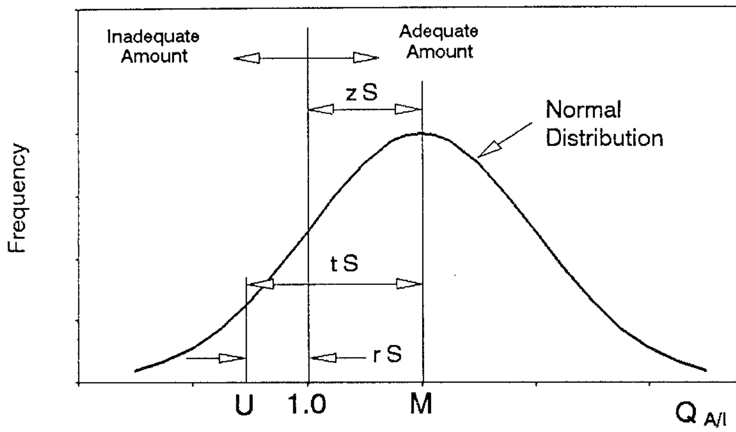

Fig. 1. Frequency distribution of actual to intended flows.

Any particular value of $Q_{A/I}$ can be related to the mean and standard deviation by the following expression (without subscripts).

$$Q = M - z\,S \tag{2}$$

where z represents the number of standard deviations from the mean. The value of z can be related to the proportion of the samples that receive a rate equal to or greater than the amount Q. The adequacy of delivery, A, is defined as the portion of outlets (or area) that receive at least the intended (sufficient) rate (or volume, etc.). Thus if the rate Q is the intended rate, then z is directly related to the adequacy, A. The relation between z and A for a normal distribution is given in Table 1.

At z equal to zero, the actual flow rate is equal to the intended flow rate ($Q_A = Q_I$, $Q_{A/I} = 1.0$). Then 50% of the outlets receive more than the intended rate while 50% receive less than the intended rate (adequacy = 0.5, Table 1). Equation 2 can be rearranged to read (with Q = 1)

$$M_{QA/I} = 1 + z\,S_{QA/I} \tag{3}$$

and since $M_{QA/I} \simeq M_{QA}/M_{QI}$

$$M_{QA} \simeq (1 + z\,S_{QA/I})\,M_{QI} \tag{4}$$

Equation 4 represents the trade off between the number of outlets receiving an adequate rate and the average rate delivered. From Table 1, if a higher adequacy is desired, z will have to be higher, making the mean value of Q_A higher, requiring more water delivered to the lateral.

Table 1. Statistical tables for Gaussian (Normal) Distribution, where M is the mean value of the distribution, I is the value of interest, U is the centroid of the distribution below I, and values are given in terms of the number of standard deviations.

	Relative distance		
Adequacy A	From M to I z	From M to U t	From I to U r
0.50	0.000	0.798	0.798
0.55	0.126	0.879	0.753
0.60	0.253	0.966	0.713
0.65	0.385	1.058	0.673
0.70	0.524	1.159	0.635
0.75	0.674	1.271	0.597
0.80	0.842	1.399	0.557
0.85	1.037	1.554	0.517
0.90	1.282	1.754	0.471
0.95	1.645	2.061	0.416
0.955	1.695	2.106	0.411
0.960	1.751	2.154	0.403
0.965	1.811	2.207	0.396
0.970	1.881	2.267	0.386
0.975	1.960	2.336	0.376
0.980	2.054	2.419	0.365
0.985	2.170	2.522	0.352
0.990	2.327	2.661	0.334
0.995	2.575	2.883	0.308

If too many outlets receive an inadequate supply, there are likely to be complaints. If too many complaints are received (A and z are too low), there are only two alternatives. First, the flow rate into the lateral can be increased. Ditchriders often supply more water to lateral canals than is intended at the outlets. They have learned to do this through experience to minimize complaints. Second, changes in operations (hardware or management) can be implemented to reduce the variation in $Q_{A/I}$, described by $S_{QA/I}$. Equation 4 is simply a mathematical expression to explain these relations.

Theoretically when using a ratio of two normally distributed parameters, it is not appropriate to use a normal distribution for the ratio without first making a transformation. There are two reasons for this. The first is that the standard deviation of Q_A/Q_I is different from the standard deviation of Q_I/Q_A ($S_{A/I}$ is not equal to $S_{I/A}$). For example, $1-9/10 = 0.1$, while $10/9-1 = 0.111$. If the standard deviation is less than 20% ($S_{QA/I}<0.20$) then this error is not significant. If the standard deviation is more than 20%, the implication made from the statistics will be somewhat in error. Such high standard deviations indicate a significant problem with the distribution of water and the exact numbers for the statistics are not that important (e.g., indicates need for major changes rather than minor adjustments in operations).

The second problem with the use of ratios has to deal with what happens to the statistics of the ratio when the numerator or denominator take on the value of zero (or are restricted to positive numbers). Consider the ratio Q_A/Q_I. If no flow is intended for a particular area, then $Q_I = 0$. Any flow, Q_A that is received would cause the value of the ratio to be infinity. The statistics in this case are meaningless. To avoid this problem, the statistical relations presented in this paper should only be used when water is intended to be delivered. Unauthorized diversions of water are considered as a loss. If flow is intended at a site and none is delivered, then the value of the ratio is zero. This sample point should be included in the statistical analysis since it represents poor distribution of water. This produces no major concern for the statistical procedure unless there are a significant number of these samples. If the standard deviation of the ratio is more than 0.4, then presence of zero values causes the distribution to be non-gaussian (i.e., not following a normal distribution). The standard deviation is still a useful number, but the other measures of performance derived from it are in error. If conditions are such that the standard deviation is greater than 0.4, then either serious water distribution problems exist, or the measured variable is not a good reflection of conditions. The above argument is the reason that the ratio Q_A/Q_I is used, rather than the reciprocal, Q_I/Q_A.

The relation between values of $Q_{A/I}$ and the fraction of offtakes receiving an actual flow which is equal to or greater than the intended flow times this $Q_{A/I}$ value is shown in Fig. 2 for $M_{QA/I} = 1.2$, $S_{QA/I} = 0.2$. For example, if $Q_{A/I} = 1.5$, only 16% of offtake received at least this ratio (16% received at least 1.5 times intended supply). At $Q_{A/I} = 1.0$, 84% received a flow greater than intended.

Assuming that the statistics are reasonable, we can use Eq. 4 and Table 1 to determine the proportion of tertiary canals not receiving an adequate supply, 1-A. In addition, we can also determine the average relative amount these tertiary canals are receiving, from

$$U_{QA/I} = 1 - S_{QA/I}\, r \qquad (5)$$

where r is found from Table 1. The proportion of the required water supplied by the secondary canal (analogous to storage efficiency) can be found as

$$E_S = A + (1 - A)\, U_{QA/I} \qquad (6)$$

The distribution efficiency (Bos 1979) of the secondary canal can also be found as

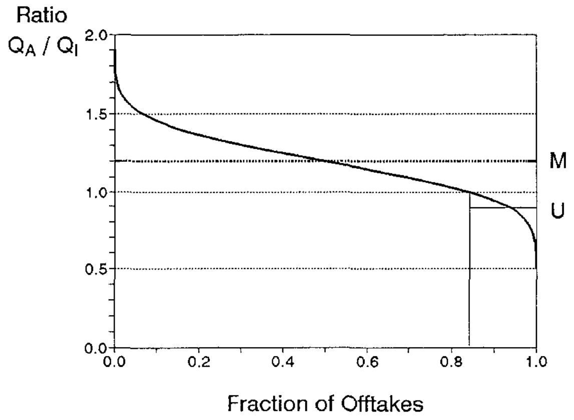

Fig. 2. Relation between $Q_{A/I}$ and the fraction of off takes that have values of $Q_{A/I}$ which are greater than or equal to this value. For this figure $M_{QA/I} = 1.2$, $S_{QA/I} = 0.2$.

$$E_D = \frac{E_S}{[1 + z\, S_{QA/I} + (\text{relative losses})]} \tag{7}$$

where the relative losses are losses such as seepage and evaporation relative to the total canal flow. The z and $S_{QA/I}$ terms represent excess water delivered to the farm. All losses that are not delivered to the farm, including end of canal spills, would be included in the relative loss term.

The parameter $S_{QA/I}$ gives a measure of spatial *equity* of operations and z (A and $U_{QA/I}$) gives us a measure of *adequacy* of operations. We can also look at these ratios temporally over the season. The temporal variation in the supply at any given location is a measure of the *reliability* of operations. To examine whether certain areas have more temporal variation than others, we can examine the covariance of the ratio over space and over time. In open canals, we must also be concerned with the *consistency* of the flow rate in the canals. When water is introduced into a canal, a certain amount of time is required to fill the canal. Open-channel flows are transient in nature causing fluctuations in delivery flow rates (Clemmens & Dedrick 1984). The standard deviation of flow rates, S_Q, or the coefficient of variation of flow rates (S_Q/M_Q), C_Q, sampled periodically, can be used as a relative measure of equity to users (or fields) sharing the water over time downstream. Of course, this is only a relative measure since adjustments can be made to make the system more equitable. The time measurements of flow variation should be made on the same scale as the time distribution of water to users or fields.

Example 1: Variations in flow rate

Given:

A lateral canal with 20 farm canals, which covers an area of 200 ha. The design flow is 500 l/s. The current intended flow is 400 l/s, or 80% of the design flow. The system is intended to distribute water proportionately according to area. The areas and actual flows to 8 farm canals are given below. The flow rate measured for the lateral canal was 405 l/s.

Find:

1) $S_{QA/I}$, z, A for 80% of the design flow
2) What is the average Q_A/Q_I for those receiving insufficient water?
3) What is the distribution efficiency of the lateral canal?
4) What flow rate should be supplied to the lateral canal for 90% of the farm canals to receive 80% of the design flow on the average?

Farm canal area, ha	Actual flow l/s	Intended flow l/s	Q_A/Q_I
8	17	16	1.063
9	21	18	1.167
12	22	24	0.917
10	19	20	0.950
11	20	22	0.909
9	19	18	1.056
10	21	20	1.050
11	20	22	0.909
Sum	405	400	

1) The fourth column values have a standard deviation of $S_{QA/I} = 0.095$. The value of z can be found from Eq. 4.

$$z = [(405/400) - 1]/0.095 = 0.132$$

From Table 1, A = 0.552, or roughly 55% of the farm canals should receive the intended flow, 45% will not, on the average.

2) From Table 1, r = 0.751. From Eq. 5,
$U_{QA/I} = 1 - (0.095)*0.751 = 0.929$, or those canals not receiving an adequate supply would get an average of about 93% of the intended supply.

3) From Eq. 6 and 7

$$E_S = 0.552 + 0.448*0.929 = 0.968$$
$$E_D = 0.968\ (400/405) = 0.956$$

4) From Table 1 for A = 0.90, z = 1.282. From Eq. 1
Q_A = 400 (1+1.282*0.095) = 449 l/s for 80% intended flow or the lateral canal flow would have to be 449 l/s for 90% of the farm canals to get 80% of the design flow.

Delivery schedule

The previous discussion has focussed on the *performance of operations*. Consideration should also be given to the *performance of the delivery schedule*. A good example is the volume adequacy of the Waribundi rotational system as used in Northern India. The value of V_I/V_R in Eq. 1 is much less than unity by intention. It is also intended that V_A be augmented (above V_I) through the use of tubewells, thus achieving an acceptable ratio of V_A/V_R. The seasonal variation in volume required can be compensated for through the use of the tubewell flows by varying pumping durations over the season. If such a supply does not exist, then one must be concerned with how the ratio V_I/V_R varies over the season. A fixed frequency rotation schedule will have a very high $S_{VI/R}$ value temporally, since crop water requirements vary widely over the growing season. Such systems are thus susceptible to large shortages and/or poor efficiencies.

Example 2: Variations in duration

Given:
A rotation system that supplies water to 10 different geographical areas over 10 days. These areas have differing needs each season depending on the amount of fallow land. No attempt is made to adjust the duration or flow according to the amount of cropped area. The flow rate is adjusted to provide an adequate flow for the total cropped area. An extra 10% is added to the flow rate to allow for not adjusting durations.

Find:
What is the influence of not adjusting intended times on the distribution of water.

The standard deviation of the ratio D_I/D_R, $S_{DI/R}$, is 0.265. The ratio of total intended durations over total required duration is $M_{DI/R}$ = 240/218.2 = 1.10, reflecting the 10% extra water supplied. However, the average ratio for D_I/D_R is 1.15, which is 5% greater. Part of this difference results from statistical problems associated with ratios ($S_{DI/R}$ greater than 0.2). The other is

	Area, ha	Required duration hours	Intended duration hours	D_I/D_R
	8	19.64	24	1.22
	10	21.82	24	1.10
	8	17.45	24	1.38
	12	26.18	24	0.92
	6	13.09	24	1.83
	11	24.00	24	1.00
	10	21.82	24	1.10
	12	26.18	24	0.92
	11	24.00	24	1.00
	11	24.00	24	1.00
Sum	100	218.2	240	

related to how well the data fit a normal distribution. The fifth value in the Table, Area = 6 ha, is somewhat of an outlier. Figure 3 shows the frequency distribution for these data with a mean of 1.146. This distribution does not fit a normal distribution well (skewed right). For small samples like this, the mean and standard deviation of the underlying population (i.e., all deliveries over the district over space and time) are not accurately predicted. Thus any predictions made from these estimates can be in error. Equation 3 can be modified to read

$$M_{DI/R} = 1 + z\, S_{DI/R} \tag{8}$$

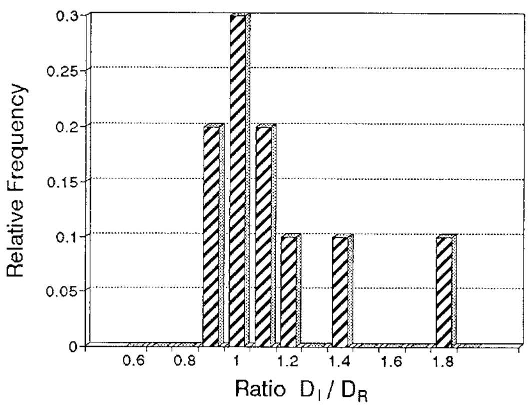

Fig. 3. Relative frequency distribution for $D_{I/R}$ from Example 2.

Solving for z gives 0.377. For Table 1, this would indicate that on the average 65% of areas would receive adequate water, while 35% would not. The sample above indicates 80% would receive adequate water and 20% would not. The difference between these two estimates has to do with the poor fit of the sample to a normal distribution and the randomness of statistical sampling. This points out the other limitation of using these ratios. If in this example, the maximum area that could be cropped was 12 ha, then the distribution becomes skewed (more low extremes possible than high extremes). If the underlying population is felt to be normally distributed, then the 35% number should be used. A single small sample is not sufficient to determine the distribution type. If it is determined that the data fit another type of distribution, (e.g., log-normal, gamma, beta, etc.) then tables analogous to Table 1 would need to be made to determine the necessary parameters.

Example 3: Variations in frequency

Given:
A fixed frequency rotation is planned for a given area. The frequency is based on the average seasonal needs and average soil conditions. For this example, it is assumed that all fields have a full moisture profile at a given point in time after which three irrigations are planned at 14 day intervals. Six areas with different soils are considered having 100%, 120%, 70%, 90%, 110% and 110% of the average soil moisture holding capacity, respectively. The same crop is grown for each, and over the 42 day period, the average soil conditions would require irrigation intervals of 20, 10 and 12 days.

Find:
What is the influence of seasonal variations in evapotranspirative demand and variations in water holding capacity on the suitability of the frequency.

The relations for frequency are the reverse of all the other parameters, since a large number means less water received. Thus the reciprocal of the other ratios are used for frequency, e.g. F_I/F_A. If no water is delivered, this ratio goes to zero.

The standard deviation of F_I/F_R is $S_{FI/R} = 0.353$. From an irrigation system standpoint, this is a very high number, indicating a problem with the proposed distribution of water. Under such conditions, it would be important to have a supplemental source of water. Without another source, one would have to reduce the frequency over that required for average conditions to minimize the potential water stress to the crop. Equation 4 can be modified for this example to read

Area	Required frequency, days	Intended frequency, days	F_R/F_I
Irrig. #1 (20)			
1 (100%)	20.0	14	1.43
2 (120%)	24.0	14	1.71
3 (70%)	14.0	14	1.00
4 (90%)	18.0	14	1.29
5 (110%)	22.0	14	1.57
6 (110%)	22.0	14	1.57
Irrig. #2 (10)			
1 (100%)	10.0	14	0.71
2 (120%)	12.0	14	0.86
3 (70%)	7.0	14	0.50
4 (90%)	9.0	14	0.64
5 (110%)	11.0	14	0.79
6 (110%)	11.0	14	0.79
Irrig. #3 (12)			
1 (100%)	12.0	14	0.86
2 (120%)	14.4	14	1.03
3 (70%)	8.4	14	0.60
4 (90%)	10.8	14	0.77
5 (110%)	13.2	14	0.94
6 (110%)	13.2	14	0.94
Sum	252	252	

$$F_I = \frac{F_R}{(1 + z\, S_{FR/I})} \quad (9)$$

where F_R is the average required frequency (14 days in this example). In the case of Frequency, the intended value must be less than the required value in order to supply more water (the reverse of significance for rate duration and volume). To provide adequate frequency (on-time irrigation water) over 80% of the area (over time), would require z = 0.842 (Table 1), or from Eq. 9, an intended frequency of 10.8 days.

Selection of parameters

In terms of project objectives, the ratio of actual/required (A/R) is the most important. However, it is the product of the other two ratios. The A/R ratio could be evaluated separately. However, it might be misleading in that it would be difficult to identify the cause for the poor performance. It is particularly important to separate the performance of operations from the performance of the delivery schedule.

So far we have discussed five variables (Q, P, D, V, F), three ratios (A/R, A/I, I/R), two dimensions (space and time [seasonally plus short term for Q]), and three statistics (M, S, and z, plus interactions between space and time), for a total of about 120 parameters. A list of most of these parameters for the ratios A/I and I/R are given in Table 2 (see p. 361). For typical U.S. system with arranged schedules, the statistics on flow rate and volume have been the most useful (Palmer 1989). For a rotation systems with fixed flow rate, statistics on duration may be more relevant, provided that flow rates are indeed properly set. For high pressure pipe delivery systems, statistics on pressure may be most relevant. In general, the parameters to be chosen depend on:

- what aspects of the system are being evaluated (operators, structures, design, plan, etc.);
- site-specific conditions; and
- which of these parameters have the most relevance to achieving project objectives.

Some judgement is still required in determining which of these parameters is most appropriate for a particular project (or a particular unit within a project). Studies may have to be performed to determine which of these parameters are relevant indicators of overall project performance measures.

Discussion

One reason for using ratios in these statistics is the non-homogeneity of the samples. This also applies to the statistics of the ratio. For example, $S_{QA/I}$ of 0.1 indicates that the standard deviation of actual flow rates is 10% of the intended flow rate at a given location, regardless of the size of the canal or outlet. It is assumed here that this does not change with the mean actual flow rate supplied. It could be assumed that the standard deviation changes in proportion to the mean flow rate (analogous to a coefficient of variation). This would be analogous to assuming $S_{QI/A}$ remains constant (i.e., constant relative to Q_A). With our limited experience, we suggest that for open channel systems $S_{QA/I}$ remains nearly constant as used here, while for pressurized, closed pipelines $S_{QI/A}$ remains nearly constant. The relations described in Eq. 3 to 9 change somewhat for the latter case and are described in Clemmens (1991).

When making performance evaluations, we are usually dealing with a sample of all deliveries, either over space or time. Thus it can be misleading to use the results of the sample and apply it to the whole population (e.g., all water deliveries). In this paper, we use the assumption of a normal distribution to extend the results from the sample to that of the whole population. In cases where the water distribution is very poor, this is not a good assumption. However, the advantage of this assumption is that it allows one to estimate what the distribution of water would be with increases and decreases in water supplied. It also allows one to estimate the relative effects of changes in water volume and in water control (reduced standard deviation).

Once the existing performance conditions are established, it is necessary to determine what represents an acceptable value for that particular performance parameter. This must be chosen according to the project benefits and costs associated with meeting this performance level. Often, there are unquantifiable factors that need to be considered.

One strategy for monitoring and evaluation is:

- Determine purpose of evaluation (design, operations, etc.).
- Select appropriate variables to study. Several variables may need to be studied initially to identify those that influence project performance.
- Develop sampling plan.
- Determine intended or required quantities (e.g., Q_I and Q_R).
- Take measurements.
- Make statistical analysis to determine actual values of statistical performance parameters.
- Determine which performance parameters are relevant (e.g., adequacy of delivery volume).
- Evaluate potential impact of given levels of these performance parameter on project objectives.
- Establish target levels for the relevant parameters.
- Identify causes of poor performance and improvements that could move actual performance toward the targeted performance. These improvements could be physical or management changes. (It is important to be sure that these improvements don't cause performance to worsen in other ways).
- Make changes in schedules or operations.
- Reevaluate performance periodically to determine whether changes have improved performance (If not, review appropriateness of chosen performance parameters).

Summary and conclusions

The two major components of the water delivery plan are the delivery schedule (water scheduling and ordering) and operations (physical facilities, operating rules, management, etc.). Three relations have been defined that compare the actual, intended and required supply of water. These relations can be used to separate the overall performance into its two component parts; delivery schedule performance and operations performance.

The ratio of actual to intended quantities (e.g., flow rate, volume, etc.) can be used as a measure of how well the project management is able to deliver water with existing facilities and management. The ratio of intended to required (by farm) flows is a measure of the suitability of the project's water delivery schedule. The product of these two ratios is a measure of overall water delivery performance. Statistical relations have been defined to mathematically describe adequacy, equity and reliability based on such ratios.

These statistics can be generated from measurements taken on flow rate, volume, delivery duration, pressure (in the case of pressurized systems) and frequency of delivery. Statistical parameters are defined for each of these measurements. The appropriate statistics to use depend on the type of project being studied and the key water management problems.

References

Biswas A.K. 1990. Monitoring and evaluation of irrigation projects. J. Irrig. and Drain. Engin., 116(2): 227–242.

Bos M.G. 1979. Standards for irrigation efficiency of ICID. J. Irrig. and Drain. Div., ASCE, 106(IR1): 37–43.

Clemmens A.J. & Dedrick A.R. 1984. Irrigation water delivery performance. J. Irrig. and Drain. Engin., 110(1): 1–13.

Clyma W. & Lowdermilk M. 1988. Improving the Management of Irrigated Agriculture: A Methodology for Irrigated Agriculture. WMS report 95, Water Management Synthesis Project, Colorado State University, 88 p.

Dedrick A.R., Clyma W. & Palmer J.D. 1989. A management improvement process to effectively change irrigated agriculture. Presented at the U.S. C.I.D. regional meeting, Aug. 24–26, Boise, ID, 44 pp.

Mohammed R.A. 1987. A theory for monitoring an irrigation conveyance system for management. PhD dissertation, Colorado State University, Fort Collins, CO, 182 pp.

Palmer J.D. 1989. Delivering appropriate quantities of water to the farm. ASAE paper number 892607, presented at the winter meeting, Dec. 12–15, New Orleans, LA, 11 p.

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

Till M.R. & Bos M.G. 1985. The influence of uniformity and leaching on the field application efficiency. ICID Bulletin 34(1): 32–35, 60.

Zimbelman D.D. (Ed). 1987. Planning, Operation, Rehabilitation and Automation of Irrigation Water Delivery Systems. ASCE, 381 p.

Table 2. Irrigation water delivery performance evaluation parameters.

Flow rate ratio, Q_A/Q_I – performance of operations	
$M_{QA/It}$	– Mean value of the ratio of actual over intended flow rate at a given site over time (season) – a measure of *efficiency* at a location
$S_{QA/It}$	– Standard deviation of the ratio of actual over intended flow rate at a given site over time (season) – a measure of *reliability*
$Z_{QA/It}$	– Number of standard deviations between unity and mean value of actual to intended flow rate ratio over time – a measure of temporal *adequacy* at a site
$M_{QA/Ix}$	– Mean value of the ratio of actual over intended flow rate at a given time over space (season) – a measure of *efficiency* at a given time
$S_{QA/Ix}$	– Standard deviation of the ratio of actual over intended flow rate at a given time over space – a measure of *equity*
$Z_{QA/Ix}$	– Number of standard deviations between unity and mean value of actual to intended flow rate ratio over distance – a measure of spatial *adequacy* at a given time
$S_{QA/Ixt}^2$	– Covariance between spatial and temporal effects on Q_A/Q_I – measure of interaction between *reliability* and *equity* of flow rates
$S_{QA/Id}$	– Standard deviation of the ratio of actual over intended flow rate for time intervals during an individual delivery – a measure of *consistency*?? – note $S_{QA/Id} = M_{QA/I}$ C_{QA} if Q_I is constant, where C_{QA} is the coefficient of variation of measured flow rates (mean over standard deviation)
$Z_{QA/Id}$	– Number of standard deviations between unity and mean value of actual to intended flow rate ratio during a delivery – measure of *adequacy* of delivery and uniformity of distribution among fields
Flow rate ratio, Q_I/Q_R – performance of plan or design	
$M_{QI/Rt}$	– Mean value of the ratio of intended over required flow rate at a given site over time (season) – a measure of *efficiency* at a location
$S_{QI/Rt}$	– Standard deviation of the ratio of intended over required flow rate at a given site over time (season) – a measure of *appropriateness*??
$Z_{QI/Rt}$	– Number of standard deviations between unity and mean value of intended to required flow rate ratio over time – a measure of temporal *adequacy* at a site
$M_{QI/Rx}$	– Mean value of the ratio of intended over required flow rate at a given time over space (season) – a measure of *efficiency* at a given time
$S_{QI/Rx}$	– Standard deviation of the ratio of intended over required flow rate at a given time over space – a measure of *equity*
$Z_{QI/Rx}$	– Number of standard deviations between unity and mean value of intended to required flow rate ratio over distance – a measure of spatial *adequacy* at a given time
$S_{QI/Rxt}^2$	– Covariance between spatial and temporal effects on Q_I/Q_R – measure of interaction between *appropriateness* and *equity* of flow rates

Table 2. Continued.

Volume ratio, V_A/V_I – performance of operations	
$M_{VA/It}$	– Mean value of the ratio of actual over intended Volume at a given site over time (season) – a measure of *efficiency* at a location
$S_{VA/It}$	– Standard deviation of the ratio of actual over intended Volume at a given site over time (season) – a measure of *reliability*
$Z_{VA/It}$	– Number of standard deviations between unity and mean value of actual to intended Volume ratio over time – a measure of temporal *adequacy* at a site
$M_{VA/Ix}$	– Mean value of the ratio of actual over intended Volume at a given time over space (season) – a measure of *efficiency* at a given time
$S_{VA/Ix}$	– Standard deviation of the ratio of actual over intended Volume at a given time over space – a measure of *equity*
$Z_{VA/Ix}$	– Number of standard deviations between unity and mean value of actual to intended Volume ratio over distance – a measure of spatial *adequacy* at a given time
$S_{VA/Ixt}{}^2$	– Covariance between spatial and temporal effects on V_A/V_I – measure of interaction between *reliability* and *equity* of Volumes
$S_{VA/Id}$	– Standard deviation of the ratio of actual over intended Volume delivered to individual field areas during an individual delivery – a measure of *consistency*?? – note $S_{VA/Id} = M_{VA/I}\ C_{VA}$ if V_I is constant, where C_{VA} is the coefficient of variation of measured Volumes (mean over standard deviation) – (this is not independent of farmer decisions)
$Z_{VA/Id}$	– Number of standard deviations between unity and mean value of actual to intended Volume ratio during a delivery – measure of *adequacy* of delivery and uniformity of distribution among fields (this is not independent of farmer decisions)
Volume ratio, V_I/V_R – performance of plan or design	
$M_{VI/Rt}$	– Mean value of the ratio of intended over required Volume at a given site over time (season) – a measure of *efficiency* at a location
$S_{VI/Rt}$	– Standard deviation of the ratio of intended over required Volume at a given site over time (season) – a measure of *appropriateness*??
$Z_{VI/Rt}$	– Number of standard deviations between unity and mean value of intended to required Volume ratio over time – a measure of temporal *adequacy* at a site
$M_{VI/Rx}$	– Mean value of the ratio of intended over required Volume at a given time over space (season) – a measure of *efficiency* at a given time
$S_{VI/Rx}$	– Standard deviation of the ratio of intended over required Volume at a given time over space – a measure of *equity*
$Z_{VI/Rx}$	– Number of standard deviations between unity and mean value of intended to required Volume ratio over distance – a measure of spatial *adequacy* at a given time
$S_{VI/Rxt}{}^2$	– Covariance between spatial and temporal effects on V_I/V_R – measure of interaction between *appropriateness* and *equity* of volumes

Table 2. Continued.

Pressure ratio, P_A/P_I – performance of operations	
$M_{PA/It}$	– Mean value of the ratio of actual over intended Pressure at a given site over time (season) – a measure of *efficiency* at a location
$S_{PA/It}$	– Standard deviation of the ratio of actual over intended Pressure at a given site over time (season) – a measure of *reliability*
$Z_{PA/It}$	– Number of standard deviations between unity and mean value of actual to intended Pressure ratio over time – a measure of temporal *adequacy* at a site
$M_{PA/Ix}$	– Mean value of the ratio of actual over intended Pressure at a given time over space (season) – a measure of *efficiency* at a given time
$S_{PA/Ix}$	– Standard deviation of the ratio of actual over intended Pressure at a given time over space – a measure of *equity*
$Z_{PA/Ix}$	– Number of standard deviations between unity and mean value of actual to intended Pressure ratio over distance – a measure of spatial *adequacy* at a given time
$S_{PA/Ixt}{}^2$	– Covariance between spatial and temporal effects on P_A/P_I – measure of interaction between *reliability* and *equity* of Pressures
$S_{PA/Id}$	– Standard deviation of the ratio of actual over intended Pressure delivered to individual field areas during an individual delivery – a measure of *consistency*?? – note $S_{PA/Id} = M_{PA/I}\ C_{PA}$ if P_I is constant, where C_{PA} is the coefficient of variation of measured Pressures (mean over standard deviation) – (this is not independent of farmer decisions)
$Z_{PA/Id}$	– Number of standard deviations between unity and mean value of actual to intended Pressure ratio during a delivery – measure of *adequacy* of delivery and uniformity of distribution among fields (this is not independent of farmer decisions)
Pressure ratio, P_I/P_R – performance of plan or design	
$M_{PI/Rt}$	– Mean value of the ratio of intended over required Pressure at a given site over time (season) – a measure of *efficiency* at a location
$S_{PI/Rt}$	– Standard deviation of the ratio of intended over required Pressure at a given site over time (season) – a measure of *appropriateness*??
$Z_{PI/Rt}$	– Number of standard deviations between unity and mean value of intended to required Pressure ratio over time – a measure of temporal *adequacy* at a site
$M_{PI/Rx}$	– Mean value of the ratio of intended over required Pressure at a given time over space (season) – a measure of *efficiency* at a given time
$S_{PI/Rx}$	– Standard deviation of the ratio of intended over required Pressure at a given time over space – a measure of *equity*
$Z_{PI/Rx}$	– Number of standard deviations between unity and mean value of intended to required Pressure ratio over distance – a measure of spatial *adequacy* at a given time
$S_{PI/Rxt}{}^2$	– Covariance between spatial and temporal effects on P_I/P_R – measure of interaction between *appropriateness* and *equity* of Pressures

Table 2. Continued.

Duration ratio, D_A/D_I – performance of operations	
$M_{DA/It}$	– Mean value of the ratio of actual over intended Duration at a given site over time (season) – a measure of *efficiency* at a location
$S_{DA/It}$	– Standard deviation of the ratio of actual over intended Duration at a given site over time (season) – a measure of *reliability*
$Z_{DA/It}$	– Number of standard deviations between unity and mean value of actual to intended Duration ratio over time – a measure of temporal *adequacy* at a site
$M_{DA/Ix}$	– Mean value of the ratio of actual over intended Duration at a given time over space (season) – a measure of *efficiency* at a given time (time during season)
$S_{DA/Ix}$	– Standard deviation of the ratio of actual over intended Duration at a given time over space – a measure of *equity*
$Z_{DA/Ix}$	– Number of standard deviations between unity and mean value of actual to intended Duration ratio over distance – a measure of spatial *adequacy* at a given time
$S_{DA/Ixt}{}^2$	– Covariance between spatial and temporal effects on D_A/D_I – measure of interaction between *reliability* and *equity* of Durations
$S_{DA/Id}$	– Standard deviation of the ratio of actual over intended Duration delivered to individual field areas during an individual delivery – a measure of *consistency*?? – note $S_{DA/Id} = M_{DA/I}\ C_{DA}$ if D_I is constant, where C_{DA} is the coefficient of variation of measured Durations (mean over standard deviation) – (this is not independent of farmer decisions)
$Z_{DA/Id}$	– Number of standard deviations between unity and mean value of actual to intended Duration ratio during a delivery – measure of *adequacy* of delivery and uniformity of distribution among fields (this is not independent of farmer decisions)
Duration ratio, V_I/V_R – performance of plan or design	
$M_{DI/Rt}$	– Mean value of the ratio of intended over required Duration at a given site over time (season) – a measure of *efficiency* at a location
$S_{DI/Rt}$	– Standard deviation of the ratio of intended over required Duration at a given site over time (season) – a measure of *appropriateness*??
$Z_{DI/Rt}$	– Number of standard deviations between unity and mean value of intended to required Duration ratio over time – a measure of temporal *adequacy* at a site
$M_{DI/Rx}$	– Mean value of the ratio of intended over required Duration at a given time over space (season) – a measure of *efficiency* at a given time (time during season)
$S_{DI/Rx}$	– Standard deviation of the ratio of intended over required Duration at a given time over space – a measure of *equity*
$Z_{DI/Rx}$	– Number of standard deviations between unity and mean value of intended to required Duration ratio over distance – a measure of spatial *adequacy* at a given time
$S_{DI/Rxt}{}^2$	– Covariance between spatial and temporal effects on D_I/D_R – measure of interaction between *appropriateness* and *equity* of durations

Table 2. Continued.

Frequency ratio, F_A/F_I – performance of operations		
$M_{FI/At}$	–	Mean value of the ratio of actual over intended Frequency at a given site over time (season) – a measure of *efficiency* at a location
$S_{FI/At}$	–	Standard deviation of the ratio of actual over intended Frequency at a given site over time (season) – a measure of *reliability*
$Z_{FI/At}$	–	Number of standard deviations between unity and mean value of actual to intended Frequency ratio over time – a measure of temporal *adequacy* at a site
$M_{FI/Ax}$	–	Mean value of the ratio of actual over intended Frequency at a given time over space (season) – a measure of *efficiency* at a given time (time during season)
$S_{FI/Ax}$	–	Standard deviation of the ratio of actual over intended Frequency at a given time over space – a measure of *equity*
$Z_{FI/Ax}$	–	Number of standard deviations between unity and mean value of actual to intended Frequency ratio over distance – a measure of spatial *adequacy* at a given time
${S_{FI/Axt}}^2$	–	Covariance between spatial and temporal effects on F_A/F_I – measure of interaction between *reliability* and *equity* of Frequencies
Frequency ratio, V_R/V_I – performance of plan or design		
$M_{FR/It}$	–	Mean value of the ratio of intended over required Frequency at a given site over time (season) – a measure of *efficiency* at a location
$S_{FR/It}$	–	Standard deviation of the ratio of intended over required Frequency at a given site over time (season) – a measure of *appropriateness*??
$Z_{FR/It}$	–	Number of standard deviations between unity and mean value of intended to required Frequency ratio over time – a measure of temporal *adequacy* at a site
$M_{FR/Ix}$	–	Mean value of the ratio of intended over required Frequency at a given time over space (season) – a measure of *efficiency* at a given time (time during season)
$S_{FR/Ix}$	–	Standard deviation of the ratio of intended over required Frequency at a given time over space – a measure of *equity*
$Z_{FR/Ix}$	–	Number of standard deviations between unity and mean value of intended to required Frequency ratio over distance – a measure of spatial *adequacy* at a given time
${S_{FR/Ixt}}^2$	–	Covariance between spatial and temporal effects on F_I/F_R – measure of interaction between *appropriateness* and *equity* of Frequencies

(Note: for I/R ratios, V, Q and D can not be looked at independently. There has to be assumptions made about which parameter(s) are fixed or known.)