Need for Evaluation of Irrigation Schemes and Irrigation Systems

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1 Introduction

Evaluation is a process of determining systematically and objectively the relevance, effectiveness, efficiency, and effect of activities in light of their objectives. It is an organizational process for improving activities still in progress and for aiding management in future planning, programming, and decision-making [1]. Evaluation in the rural development programs is associated with the assessment of effects, benefits or disbenefits, and impacts, on the beneficiaries.

Evaluation focus on: who or which group has benefited (or has been adversely affected), by how much (compared to the situation before the activity), in what manner (directly or indirectly), and why (establishing causal relationships between activities and results to the extent possible). While monitoring is a continuous or regular activity, evaluation is a management task that takes place at critical times of the life of a scheme or program. Evaluation can be executed [2]:

- during project planning (ex-ante): to assess the potential impact
- during project implementation (ongoing): to evaluate the performance and quality
- at project end (ex-post): to define the successful completion
- some years after completing (impact): to evaluate its final impact on the development

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- The main objective of monitoring and evaluation (M&E) design and process is to ensure that the program or project fulfills the stated goals and objectives within the financial supports that are set at the beginning.

The objectives of an irrigation scheme can be grouped into six categories [3, 4]:

- Production and productivity
- Profitability
- Equity
- Rational utilization of the resource
- Sustainability
- Non-agricultural objectives.

Irrigation systems may or may not be well designed and properly used. The basic concepts and terms for system evaluation described in this chapter are specified for evaluating actual operation and management and for determining the potential for more efficient and economical operation. This is vital to provide direction to manage in deciding whether to continue existing practices or to improve them [5].

Improvement of water management on the farm may conserve water, soil, and labor and may increase crop yields. A system evaluation should show and measure the existing irrigation practice effectiveness. Careful study of the system evaluation will indicate whether improvements can be made and will provide information for management with a reasoned basis for selecting possible modifications that may be both economical and practical.

Most modifications suggested for irrigation systems improvement require only simple changes in management practices. Evaluations frequently indicate the need for estimates of soil moisture deficiency and for better maintenance practices for systems. These often save water, labor, and working hours. Sometimes it is worthwhile to invest the capital necessary to mechanize or even automate an irrigation system.

Operation of sprinkler irrigation systems may be improved greatly by such simple changes as altering operating pressures, nozzle sizes, heights of risers, and water application durations; operating at different pressures at alternate irrigations; using alternate set sequencing; obtaining larger sized lateral pipes; and by tipping risers along the edge of the field.

For border and strip furrow irrigation systems, any of the following simple changes may greatly improve performance: use of larger, smaller, or cutback streams; irrigation at a different soil moisture deficiency; using different spacing or shape of furrows; revising strip width or length; using supplemental pipelines and portable gated pipe; and using return-flow systems to recover runoff water. Capital investment for such projects as grading the land to provide a smoother surface or more uniform slope and soil conditions, constructing reservoirs, increasing capacity for water delivery, and automation or semi-automation often proves profitable where it improves labor and water efficiency.

Basin irrigation systems may be improved greatly by relocating a dike conforming to changes in the surface texture of the soil; grading land more carefully to achieve, as nearly as possible, a level surface and uniform intake; or changing the basin area so that it more nearly matches the volume of water from the available stream.

Trickle irrigation systems may require a different duration of application, a different frequency of irrigation, additional infiltration, or a higher density of emitters.

Possibilities for saving water and labor usually are best when the water supply is flexible in frequency, rate, and duration. Flexibility in frequency means that the water is available on or near the day when it is needed to match the moisture demands of the crop. Flexibility in the rate means that the rate of supply can be changed to match different sizes of fields, to cutback sizes of streams, to accommodate varied rates of infiltration, and to smooth out the irrigators workload. Flexibility in duration means that the water can be turned off as soon as the soil moisture deficiency has been supplied and requirements for leaching have been satisfied. These types of flexibility are necessary for achieving efficient use of water.

A principal cause of low efficiency is over-irrigation. When either furrow or border-strip irrigation is used, a chief part of any excess water is runoff, which may be recovered by using a return-flow system. Most excess water, used in the basin, basin check, sprinkler, and trickle systems, infiltrates and adds to the groundwater supply. Such water may be recovered from wells, but it may cause a drainage problem if the subsurface flow is restricted at a shallow depth.

2 Basic Concepts and Terms

Certain concepts are implicit in the design and operation of every irrigation system and irrigation schemes. Likewise, certain terms and their definitions are basic in describing these systems and in evaluating their operation. Some of the most frequently used terms are listed and briefly explained here and are explained in detail.

Evaluation is the analysis of any irrigation system based on measurements that have been taken in the field under the conditions and practices normally used. It also includes on-site studies of possible modifications such as changing sprinkler pressures, having larger or smaller streams in furrows, and changing the duration of application. Measurements needed for analysis include soil moisture depletion before irrigation, the rate of inflow, uniformity of application and infiltration, duration of application, the rate of advance, soil conditions, rates of infiltration, and irrigation adequacy [6].

As for indicators concerning irrigation schemes, indicators are the tools that measure the substantial progress toward the goal achievement such as the targets or standards to be met at each stage. They provide an objective basis for monitoring progress and evaluation of final achievements. A good indicator should define the level of achievement, specifically: how much? (quantity), how well? (quality), by when? (time). This can be demonstrated in the steps below [7]:

Step 1: **Identify indicator**: Small farmers increase rice yields

Step 2: **Add quantity**: A total of *5000* farmers *with landholdings of 1 acre or less* increase their rice yields *by 30%*
Step 3: **Add quality**: A total of *5000* farmers with landholdings of 1 *acre* or less increase their rice yields by 30% *while maintaining the same rice quality existing in the 2000 harvest*
Step 4: **Specify time**: A total of *5000* farmers with landholdings of *1 acre* or less increase their rice yields by 30% *between June 2000 and June 2008* while maintaining the same rice quality existing in the 2000 harvest. One set of indicators needs to be formulated to monitor and evaluate the process.

These indicators might be, for example, credit repaid amount, the cultivated crops, rate of the farmers' participation, attendance of the training, etc. Another set of indicators needs to be formulated to monitor and evaluate the effect of the program activities. These indicators could be, for example, yield increase, income gains, environmental effects, changes in workload, relationship between benefits and investment, etc. A set of indicators can of course also include both of the above at the same time.

Indicators should disaggregate the information by gender and various socio-economic groups. This means that instead of monitoring the number of farmers, data need to be gathered on the number of male and the number of female farmers from the different socio-economic groups participating. Equally, information on yield increases should be distinguished based on the gender of the household head, large versus small farmers, etc. The purpose of collecting gender-disaggregated monitoring data is that it may yield valuable information that can lead to measures to improve the program, especially the performance of specific groups of farmers [2].

Because of the difficulties in collecting information in the field, and because of the related costs, the number of indicators should be kept to the minimum required. A few key indicators should be selected that will adequately fulfill the objective of assessing the conditions of the scheme and identifying causes for failure or success. In this chapter, some common indicators are given for each type of performance, from which key indicators can be selected.

For the calculation of indicators, a certain number of parameters have to be measured in the irrigation scheme. The choice of these parameters has to be judicious. They should be easily measurable and remeasurable, at low cost, preferably by the farmers themselves. Some examples of indicators associated with related parameters are given in Table 1.

Examples of indicators to monitor and evaluate the technical and agronomic performance of smallholder irrigation scheme are listed down [2].

To these objectives, so-called performance indicators are mentioned down. For an irrigation scheme, the values of these obtained indicators should be compared to comparative values in order to evaluate the performance level concerning the irrigation scheme. For their calculation, performance indicators call upon a certain number of parameters that have to be measured in the irrigation improvement project (IIP) [8].

The first objective is to intensify and increase agricultural production on irrigated land.

Table 1 Examples of indicators associated with related parameters [2]

Indicators	Parameters	Expression
• Yield Y	• Harvest per season H (kg) • Area cultivated A (acre)	• $Y = H/A$ (kg/ha)
• Gross or net production per quantity of water applied P_{gIr} or P_{nIr}	• Harvest H (kg) • Volume of water applied W (m^3)	• P_{gIr} or $P_{\mathrm{nIr}} = H/W$ (kg/m^3)
• Cropping intensity CI	• Area harvested per year AH (= sum of the areas harvested per season) (acre) • Area cultivable CA (acre)	• CI = AH/CA × 100 (%)
• Overall project efficiency E_{p}	• Quantity of water entering the conveyance canal V (m^3) • Net irrigation requirements IR$_n$ (m) • Actual irrigated area AIA (acre)	• $E_{\mathrm{p}} = 100 \times (\mathrm{AIA} \times 4000 \times \mathrm{IR}_n)/V$ (%)

The first indicator: Increase in average production

This indicator will measure the average increase that is being obtained in the demonstration phase as compared to the national averages and/or the production averages in the project area before the demonstration phase. The required data for its application are:

The average percentage of increase or decrease in production (CP) for all the crops is the indicator proposed for agricultural production:

$$\mathrm{CP} = 100 \times \sum_{1}^{N} \left[\frac{P(N) - A(N)}{A(N)} \right]^{\frac{1}{N}} \tag{1}$$

where

CP = Crop production increase or decrease (percentage)
P = Project crop production average
A = National crop production average
N = Number of crops

The second indicator: Cropping intensity

This indicator will provide an evaluation as to what extent second and third crops may take place in a year. The indicator (CI) is defined as follows:

$$\mathrm{CI} = \frac{A(C1) + B(C2) + C(C3)}{\mathrm{CA}} \tag{2}$$

where

$A(C1)$ = Total area harvested in the first season
$B(C2)$ = Total area harvested in the second season
$C(C3)$ = Total area harvested in the third season
CA = Cultivable area

The third indicator: Increase in planted area

The intensive use of irrigation water is a good indication that the change toward an intensive agriculture is taking place in an effective manner. Therefore, this indicator aims at evaluating to what extent this change is taking place. For this purpose, the increase in planted area from one season to the next (expressed in percentage) is a relevant indicator (IPA):

$$\mathrm{IPA} = 100 \times \frac{[\mathrm{AP}(S1) - \mathrm{AP}(S2)]}{\mathrm{AP}(S2)} \tag{3}$$

where

IPA = Increase in planted area (percentage)
AP($S1$) = Area planted during the current season
AP($S2$) = Area planted during the past season

The second objective is to improve the performance of existing schemes through on-farm irrigation technology.

The fourth indicator: Overall irrigation efficiency

Overall irrigation efficiency is a value that constantly varies through the year and is affected by the efficiency of the actual water distribution and farmers' ability to apply water effectively. Still, it is always a good reference for how efficiently irrigation water is utilized.

The following indicator is proposed:

$$\mathrm{OIE} = 100 \times \frac{(\mathrm{AIA} \times 4000 \times \mathrm{CWR})}{(\mathrm{FI} \times 3600 \times 30 \times N)} \tag{4}$$

where

OIE = Overall irrigation efficiency (percentage)
AIA = Actually irrigated area during peak month (acre)
CWR = Crop water or net irrigation requirement for the peak month (mm/month)
FI = Average flow of main intake in the peak month (l/s)
N = Number of irrigation hours per day

The above indicator will give the efficiency of the water use in the peak month. It is desirable to determine it for every month of the year in order to indicate the variations of the OIE along the year. This indicator will be particularly relevant when rehabilitation and improvements works have been undertaken, as the greater physical efficiency of the system must be reflected in higher values of OIE.

The fifth indicator: Costs of operation and maintenance

Operation and maintenance costs referred to the irrigated hectares are themselves already a good indicator of how efficiently the financial resources are being utilized:

$$\mathrm{OM} = \frac{\mathrm{TC}}{\mathrm{AIA}} \tag{5}$$

where

OM = Costs of operation and maintenance per acre
TC = Total annual costs incurred in O&M
AIA = Actually irrigated area (acre)

Once operation and maintenance costs have been determined, one can get an indication of the farmers' capacity to pay them by referring these costs to the farmers' income through the following equation:

$$\mathrm{IFI} = 100 \times \frac{\mathrm{TC}}{\mathrm{FI}} \tag{5.1}$$

where

IFI = Impact of costs operation and maintenance in farmer's income (percentage)
TC = Total annual costs incurred in O&M
FI = Farmers' income (assessed on the bases of a representative sample). For values of IFI greater than 10%, difficulties can be expected in the collection of fees

The third objective is to demonstrate technologies and methods of irrigation expansion.

The sixth indicator: Percentage of farmers that adopted the irrigation technology

A simple indicator is the percentage of farmers over the total participants in the demonstration area that have adopted the technological package:

$$\mathrm{AT} = 100 \times \frac{\mathrm{FAT}}{\mathrm{TNF}} \tag{6}$$

where

AT = Farmers that adopted the technology (percentage)
FAT = Number of farmers that adopted proposed technology
TNF = Total number of farmers of the demonstration area

The apparent simplicity of this indicator is constrained by the fact that is not so simple to clear whether or not a farmer has adopted a technology. As the technological packages will likely be different in each country or demonstration area, the criteria for determining the adoption by farmers must be developed locally.

The seventh indicator: Water use at farm level

One important aspect of the demonstration phase is the efficient application of water at the farm level. By this term, we mean that water is applied at suitable intervals (which will depend on the technology used) and the amounts necessary to satisfy the crop water requirements. If irrigation water is not applied with a minimum of technical bases, it is clear that the intended increases in crop production will not be reached. Therefore, it is of great importance to document how irrigation water is applied.

As the number of farmers participating in a scheme can be relatively large, it will be practically impossible to monitor the water use by every farmer as this will be time-consuming and costly. The only feasible way will be to do it on sample bases. The sample should be statistically representative, but this is again costly when the number of farmers is large.

The eighth indicator: Farm irrigation efficiency

The determination of the irrigation schedules mentioned for the seventh indicator implies the application of the farmer's efficiency in applying the irrigation water. The tendency is often to apply this figure based on empirical or personal experience. In the field, it can be carried out following standard procedures [2, 9]. It will be useful to determine these efficiencies yearly and monitor any progress made by farmers. However, as with the previous indicator it is an expensive indicator to be determined. More information on irrigation efficiencies is given in this chapter.

The fourth objective is to improve the capacity of staff and local community for self-management and develop institutional base for irrigation expansion.

The ninth indicator: Self-management

The aim of this indicator will be to assess the degree of self-management that has been achieved. The underlying assumption is that an effort was made to establish a WUA, and through the criteria proposed below, the degree of self-management is assessed as given in Table 2.

The tenth indicator: Training activities carried out

The number of training activities that have been done, the type of activity, its duration, and number of participants should be reported here. The number of participants should be related to this potential number to have an indication of what percentage has been covered.

As for soil moisture depletion, it (hereafter called SMD) is expressed numerically as a depth (in cm) indicating the dryness of the root zone at the time of measurement. This depth is identical to the water depth to be replaced by irrigation under normal management. For this reason, the idea of moisture deficit in the root zone is preferable

Table 2 Assessment of self-management degree

Self-management	Degree
The WUA functions satisfactorily and 80–90% of the water rates are collected	Fully independent
The WUA is established, the water distribution is effected by farmers at tertiary level but secondary canals and upward are operated by government staff, only minor maintenance works are carried out by farmers, and 65–80% of water rates are collected	Semi-independent
The WUA has been established but acts mainly as a consultative and information body. Decisions are still made by government officials, and 50–65% of water rates are effectively collected	Low degree of independence
The WUA has been established on paper, but none of its tasks are carried out in practice	Dependent, it needs explanation
The WUA has not been established	Needs justification

to the commonly used concept of water depth currently in the soil. Knowledge is needed of how dry the soil should be before irrigation and is related to the soil moisture tension at that SMD and to how well the crop will grow under that stress. Some plants produce better when they are kept moist by frequent irrigations, but they may be more subject to diseases and insect pests under such a regime. Other plants may produce more efficiently when the soil is allowed to become quite dry. Infrequent irrigating also reduces costs of labor and generally increases efficiency.

Management allowed depletion (hereafter called MAD) is the desired SMD at the time of irrigation. MAD is an expression of the degree of dryness that the manager believes the plants in a given area can tolerate and still produce the desired yield. The MAD is related to SMD and resulting in crop stress. It may be expressed as the percent of the total available soil moisture in the root zone or the corresponding depth of water that can be extracted from the root zone between irrigations to produce the best economic balance between crop returns and costs of irrigation.

Evaluation of furrow and border-strip irrigation systems should be made at about MAD, since infiltration rate, water movement, and duration of the irrigation are greatly affected by soil moisture deficit because the MAD appreciably affects all these factors, and small variations in the MAD become a useful management tool for improving the operation of certain surface irrigation systems, especially the border-strip system.

Efficient operation of an irrigation system depends as much or more on the capability of the irrigator as on the quality of the system. Any system may be properly used or misused. To determine what is the best use requires a thorough evaluation of the system or appreciable experience combined with shortcut evaluation procedures. The two following questions must always be considered to obtain the maximum efficiency from any given system:

- Is the soil dry enough to start irrigating?
- Is the soil wet enough to stop irrigating?

The irrigator must carefully estimate the SMD; if it is the same as MAD or greater, the soil is dry enough to start irrigating. The simplest method for evaluating SMD is field observation of the soil. This requires comparing soil samples taken from several depths in the root zone (preferably to the full rooting depth) with Table 3 This chart indicates the approximate relationship between field capacity and wilting point. For more accurate information, the soil must be checked by drying samples of it. The descriptions at the top of each textural column correspond to the condition of zero soil moisture deficiency, i.e., field capacity. Those descriptions at the bottom of a column describe a soil having the maximum deficiency, i.e., wilting point. The soil moisture deficiency at this condition is numerically equal to the available moisture range of the soil.

Intermediate soil moisture deficiency descriptions occur opposite corresponding numerical values of inches of water per foot of depth at which the soil is deficient. This chart describes a specific group of soils, and though it has been found to have general application, it may not apply to many other groups. Where this is the case, new descriptions will need to be prepared corresponding to particular soil moisture deficiency, feel, and appearance relationships.

Other methods for estimating SMD include the use of tensiometers when MAD values are low (high moisture situation) and resistance blocks or similar equipment when MAD values are high (low moisture content). Weighing and drying soil samples are precise, but slow and cumbersome and neutron soil moisture probes are expensive.

Water budgets based on the depth of evaporation from a pan and other methods for estimating the water consumed by the plants (potential evapotranspiration) are also satisfactory for estimating SMD. The SMD estimated from water budgets should occasionally be checked by field observations of the lower part of the root zone to see that SMD is not accumulating. Such checks show deficient irrigation, but unfortunately do riot reveal over-irrigation [10].

The second question, namely, when is soil wet enough to stop irrigating, is equally important because all water applied to the root zone after the SMD and leaching requirements have been satisfied is completely wasted. A probe, typically a 15/40-cm or 10/20-cm steel rod about 1.2 m long having a somewhat bulbous (not pointed) tip and a tee handle, can be used in most soils to quickly check the depth of penetration of irrigation at numerous points throughout the field. Such a probe easily penetrates to a moderate depth (about 90 cm) through the nearly saturated soil being irrigated, but it encounters considerable resistance when it meets plow pans or drier soil below the wetted soil. The proper depth of probe penetration is appreciably less than the desired final depth of water penetration because water continues to percolate deeper after the irrigation stops. This requires that the depth to which the probe penetrates during irrigation be calibrated later with depth penetrated after an adequate irrigation.

Alternately, to anticipate when the soil will be wet enough to stop dividing the SMD by the minimum rate of application at the soil surface. This will give the duration of irrigation needed to replace the SMD.

Table 3 Soil moisture and appearance relationship chart [2]

Soil texture					
Available soil moisture	Soil moisture conditions	Coarse fine sand; loamy fine sand	Moderate coarse sandy loam; fine sandy loam	Medium sandy clay loam; loam; silt loam	Fine clay loam; silty clay loam
0–25	Dry	Loose. Will hold together if not disturbed. Loose sand grains on fingers	Forms a very weak ball[a]. Aggregated soil grains break away easily from ball	Soil aggregations break away easily. No moisture staining on fingers. Clods crumble with applied pressure	Soil aggregations easily separate. Clods are hard to crumble with applied pressure
25–50	Slightly moist	Forms a very weak ball with well-defined marks. Light coating of loose and aggregated sand grains remains on fingers	Forms a weak ball with defined finger marks. Darkened. color. No water staining on fingers	Forms a weak ball with rough surfaces. No water staining on fingers. Few aggregated soil grains break away	Forms a weak ball. Very few soil aggregations break away. No water stains. Clods flatten with applied pressure
50–75	Moist	Forms a weak ball with loose and aggregated sand grains remaining on fingers. Darkened color. Heavy water staining on fingers Will not form into a ribbon[b]	Forms a ball with defined finger marks. Very light soil water staining on fingers. Darkened color. Will not slick	Forms a ball. Very light water staining. Darkened color. Pliable. Forms a weak ribbon between thumb and forefinger	Forms a smooth ball with defined finger marks. Light soil water staining on fingers. Ribbons form with thumb and forefinger

(continued)

Table 3 (continued)

Soil texture					
Available soil moisture	Soil moisture conditions	Coarse fine sand; loamy fine sand	Moderate coarse sandy loam; fine sandy loam	Medium sandy clay loam; loam; silt loam	Fine clay loam; silty clay loam
75–100	Wet	Forms a weak ball. Loose and aggregated sand grains remain on fingers. Darkened color. Heavy water staining on fingers. Will not ribbon	Forms a ball with wet outline left on hand. Light to medium water staining on fingers. Makes a weak ribbon between thumb and forefinger	Forms a ball with well-defined finger marks. Light to heavy soil water coating on fingers. Ribbons form	Forms a ball. Uneven medium to heavy soil water coating on fingers. Ribbon forms easily between thumb and forefinger
Field capacity (100)	Wet	Forms a weak ball. Light to heavy soil–water coating on fingers. Wet outline of soft ball remains on hand	Forms a soft ball. Free water appears briefly on surface after squeezing or shaking. Medium to heavy soil–water coating on fingers	Forms a soft ball. Free water appears briefly on soil surface after squeezing or shaking. Medium to heavy soil–water coating on fingers	Forms a soft ball. Free water appears on soil surface after squeezing or shaking. Thick soil water coating on fingers. Slick and sticky

[a] A “ball” is formed by squeezing a soil sample firmly in one’s hand
[b] A “ribbon” is formed by squeezing soil between one’s thumb and forefinger

Several devices for sensing soil moisture can indicate when to start and stop irrigating, but none is less expensive and easier to understand and use than the auger and simple probe described above. Some electrical or mechanical sensing devices may be connected to turn the irrigation system on and off automatically. However, their operation must be correlated with soil moisture values at the sensing point, which, in turn, must be related to values representative of the entire field under control.

The rate or volume of the application by sprinkler and trickle irrigation systems is usually known. When the application is reasonably uniform, the depth of application can be controlled easily by controlling the duration of the irrigation. However, under all the methods of irrigation field conditions must be checked to assure that the desired depth of application has been reached and that no excess water is being applied.

Information about soils and crops is fundamental to all planning for irrigation. Optimum MAD depends on the specific soil, crop, and depth of root zone, climate, and system of irrigation. The MAD should be established because it affects the depth, duration, and frequency of irrigation.

The available moisture, rate of infiltration, adaptability of method, and choice of crop are all related to soil texture; but depth of root zone, rate of intake, lateral wetting, perched water tables, and adaptability to land grading are mostly affected by soil profile and structure. The uniformity of soil in a field is important because it affects the uniformity of infiltration and therefore the choice of method of irrigation. Field surveys must thoroughly investigate soil uniformity. For all methods of irrigation in fields having more than one type of soil, the frequency and depth of irrigation should be governed by the soil that permits the lowest MAD.

Sprinkler or trickle irrigation is best for fields that have varied soils and topography because the depth of application of the water is independent of surface variations. For the areas where the rate of intake is slowest, the rate of application should be less than the basic rate of infiltration to prevent runoff.

Reasonable uniformity of soil surface is important to assure efficiency of furrow, border strip, or basin irrigation. It must be fully appreciated that the basic objective of land grading is to improve irrigation, not merely to produce a plane surface. The possibility of improving the uniformity of the soil within each field should not be overlooked during land grading. In basin and basin-check irrigation, uniformity of the intake rate is even more important than in-furrow and border-strip irrigations. However, uniformity of intake often can be improved by making boundaries of the basin conform to boundaries of areas having uniform soil texture. Low ridges can be formed over or temporarily removed as needed, and the shapes or sizes of basins may be varied as required [11].

To avoid confusion with certain similar but more general terms, three important terms used have been renamed. Irrigation System Efficiency is now called Potential Application Efficiency is now called Application Efficiency of the Low Quarter, and Distribution Efficiency has been changed to Distribution Uniformity.

3 Irrigation Methods

There are seven basic techniques or methods of irrigation, most of which have several variations. Each technique and variation has characteristics that are adaptable to different locations and crops [2, 6]. The basic component and operation for each of the seven techniques are:

3.1 Basin

A level area of any size or shape bounded by borders or ridges retains all the applied water until it infiltrates. Any loss of water results from either deep percolation or surface evaporation.

3.2 Basin Check

A fairly level area of any size or shape bounded by borders and with no depressions which cannot be readily drained. The borders (or ridges) retain all the applied water for a sufficient time to obtain a relatively uniform depth of infiltration over the area, and then, the remaining water is drained off the surface and used to irrigate an adjacent border check. Water is lost chiefly by deep percolation and evaporation.

3.3 Border Strip

A sloping area, usually rectangular, is bounded by borders or ridges that guide a moving sheet of water as it flows down the bordered strip. There should be little or no slope at right angles to the direction of flow. The on-flow of water is usually cut off when the advancing sheet has flowed six- to nine-tenths of the distance down the strip. Water is lost chiefly by runoff and deep percolation.

3.4 Furrow or Corrugation

A small sloping channel is scraped out of or pressed into the soil surface. For high uniformity of wetting, the irrigation stream should reach the end of the channel in about one-fourth of the time allotted for the irrigation; but the stream is not shut off until the root zone soil at the lower end of the furrow is adequately irrigated. Water in the soil moves both laterally and downward from the channel. Water is lost chiefly by deep percolation and runoff.

3.5 Sprinkler

Water discharged from a sprinkler should infiltrate the soil where it falls, but it should not wet the soil surface. For high wetting uniformity, the spray patterns from adjacent sprinklers must be properly overlapped. Evaporation, wind drift, and deep percolation are chief causes of loss of water.

3.6 Trickle (or Drip) Emitter

A device used in a trickle (or drip) irrigation for discharging water at some very low rate (less than 69 L per hour) through small holes in tubing placed near the soil surface. Water moves through the soil both sideways and downward away from the point of application to form a “bulb” of wet soil. Typically, only a portion of the soil mass is kept quite moist by very frequent or continuous application. Water loss is mainly by deep percolation.

Table 4 summarizes and compares the major physical characteristics that affect the adaptability of each of the six basic irrigation techniques. It also evaluates the probable Potential Application Efficiency of Low Quarter (PELQ) of a well designed and properly used system, employing each technique where appropriate. Most systems can be mechanized or even automated in order to reduce labor. This table leaves no allowance for such items as salinity and control of microclimate and takes no account of the costs or personal preferences of the irrigator.

4 Efficiency and Uniformity of Irrigation

The infiltrated water, evaporation from the plant and free water surfaces, wind drift, and runoff water must equal the total depth of applied (rain or irrigation) water. Furthermore, the sum of the transient and stored water, deep percolation, transpiration, and evaporation from the soil surface must equal the depth of infiltrated water. A growing crop may transpire transient water in the soil root zone before it is lost to deep percolation. However, some deep percolation is usually necessary to maintain a satisfactory salt balance since evaporation and transpiration (the only other ways to remove water from the root zone) leave the dissolved salts in the root zone. Transpiration and evaporation are interrelated and depend on atmospheric, plant, and soil moisture conditions.

Terms used to designate or rate the efficiency with which irrigation water is applied by a given system have been widely defined. To avoid confusion, the three primary terms that are used in field evaluation procedures (Distribution Uniformity, Application Efficiency of Low Quarter, and Potential Application Efficiency of Low Quarter) are defined below. These terms differ from those used in the first edition of this work and in some other publications; they should help avoid confusion with other terms and their definitions. The numerators and denominators of the definitions are expressed in equivalent depths of free water (volumes per unit area) for surface and most sprinkler-irrigated fields. However, water volume may be a more appropriate measure for trickle and sprinkler systems, which give only partial coverage.

High efficiency in the operation of an irrigation system is not necessarily economical, but a manager must evaluate the efficiency of any system in order to rationally decide whether he should merely modify his operation or adopt a different system. Efficiencies computed from ordinary field data are seldom more accurate than to

Table 4 Physical requirements and potential application efficiencies of the low quarter for the basic irrigation techniques [5]

Irrigation method	Physical requirements at site					PELQ
	Soil uniformity	Infiltration rate	Ground slope	Water supply	Labor intensity	
Basin	• Uniform within each basin	• Any	• Level, or graded to level	• Large intermittent	• High or infrequent intervals	• 60–85
Basin check	• Uniform within each basin	• All but extreme	• Fairly smooth with no depressions	• Large intermittent	• High or infrequent intervals	• 60–80[a]
Border strip	• Uniform within each strip	• All but extreme	• Mild and smooth	• Large intermittent	• High or infrequent intervals	• 70–85[a]
Furrow or corrugation	• Uniform along each furrow	• All but very rapid	• Mild or contour	• Medium to large intermittent	• High or infrequent intervals	• 70–75[a]
Sprinkler	• Soils may be intermixed	• All but very slow[b]	• Any farmable slope	• Small continuous	• High to very low daily[c]	• 65–85 • Depending on variance
Trickles (drip or subsurface)	• Soils may be intermixed	• Any	• Any farmable slope	• Small continuous	• Very low daily	• 75–90

[a] Values of 90% can be attained under ideal conditions if runoff water is reused

[b] Except for the center pivot and traveling sprinklers, which are best suited to use on soils that have medium and high infiltration rates?

[c] Labor inputs range from high intensity for hand move, moderate for the mechanical move, to low for automatic sprinkler irrigation systems

the nearest 5%. Therefore, variations of less than 5% in computed efficiency values are not significant except where identical data are being used for comparisons of alternative operational procedures [12, 13].

Distribution Uniformity (hereafter called DU) indicates the infiltration uniformity throughout the field.

$$\mathrm{DU} = \frac{\text{depth infiltrated in the lowest one quarter of area} \times 100}{\text{average depth of water infiltrated}} \tag{7}$$

The average low quarter depth of water infiltrated is the lowest one-quarter of the measured or estimated values where each value represents an equal area. For sprinkler and trickle irrigation, the depth infiltrated is presumed equal to the depth applied or caught on the soil surface if there is no runoff.

The DU is a useful indicator of the magnitude of distribution problems. A low DU value indicates that losses due to deep percolation are excessive (and that the water table is likely to be too high) if adequate irrigation is applied to all areas. Although the concept of a low DU is relative, values less than 67% are generally considered as unacceptable. For example, if the desired depth of infiltrated water is 10 cm and the DU is 67%, the average depth infiltrated must be 15 cm and the deep percolation loss will be 5 cm. However, if deep percolation is limited by reducing the applied depth and the DU value is low, any area that receives the low quarter depth of irrigation will be seriously under-irrigated.

Application Efficiency of Low Quarter (hereafter called AELQ) achieved in the field indicates how well a system is being used.

$$\mathrm{AELQ} = \frac{\text{average low quarter depth of water stored in the root zone} \times 100}{\text{average depth of water applied}} \tag{8}$$

When the average low quarter depth of irrigation water infiltrated exceeds the SMD, which is the storage capacity of the root zone, AELQ can be expressed as follows:

$$\mathrm{AELQ} = \frac{\mathrm{SMD}}{\text{Average depth of water applied}} \times 100 \tag{9}$$

The average low quarter depth of water infiltrated and stored in the root zone is the average of the lowest one-fourth of the measured or estimated values where each value represents an equal area of the field. Thus, about one-eighth of the irrigated area receives less than the average of the low quarter. “Irrigated area” means the area receiving water; for most systems, this is the entire field. However, where, a limited area is being wetted, the term refers only to that part of the area receiving water.

Implicit in AELQ is a measure of uniformity, but it does not indicate adequacy of the irrigation. It merely shows that, for any value greater than zero, all the area is receiving water. Low values for AELQ indicate problems in management and/or use of the system. Additional factors, which will be presented later, must be considered when any field is intentionally under-irrigated.

Potential Application Efficiency of Low Quarter (hereafter called PELQ) indicates a measure of system performance attainable under reasonably good management when the desired irrigation is being applied.

$$\text{PELQ} = \frac{\text{average low quarter depth infiltrated when equal to MAD} \times 100}{\text{average depth of water applied when MAD just satisfied}} \tag{10}$$

The PELQ is the precise value of AELQ when the low quarter depth of water infiltrated is just sufficient to satisfy the SMD when SMD = MAD in all parts of the field. Low PELQ usually is associated with inefficient system design, but may be intentional for economic reasons. The difference between PELQ and AELQ is a measure of management problems, whereas low values for AELQ merely indicate the possible existence of such problems.

Modifications of systems or methods can be compared meaningfully only by comparing values of PELQ. Such comparisons must be made when applying similar MAD depths. Economic comparisons should include costs of irrigation and crop production as well as expected returns.

$DU_{a,}$ AELA, and PELA may be used in place of DU, AELQ, and PELQ, respectively, to denote the use of absolute minimum depth instead of the average low quarter infiltrated. For convenience in the evaluation of surface irrigation systems, the depth of infiltration at the downstream end of the furrow (or borders) is often used in place of the average low quarter depth. This depth would be the absolute minimum depth infiltrated if the soil infiltration and furrow (or border) characteristics were uniform throughout the field. The absolute minimum should not be used for method comparisons [14, 15].

5 Essential Deficit Irrigation

Irrigation systems are usually managed to fill the SMD throughout the root zone at each irrigation; however, this should not always be the objective. Sometimes the interval between irrigations is extended to reduce the rate of water use below peak volumes by using a high MAD. This practice is used to aid other agricultural practices, to reduce requirements for system capacity, and/or to obtain maximum crop yields per unit of water or per unit of capital cost and is called stress irrigation. Another variation is to replace less than the SMD leaving the bottom portion of the root zone somewhat drier and is called limited irrigation. This type of intentional under-irrigation may be imposed rather uniformly throughout the field, or only in areas receiving minimum infiltration, or selectively. Intentional under-irrigation also enables better utilization of rainfall than full irrigation.

Limited irrigation is any of a group of procedures which result in under-irrigation to conserve water but do not reduce yields. If the root zone is full of moisture at the beginning of the period of peak water use, limited under-irrigation by not fully replacing SMD on the whole area can improve the efficiency of water use without reducing crop yields. However, yields can be maintained only if the period of peak use is relatively short and is followed by either a period of less use or by harvest. Moisture stored deep in the root zone from early or off-season irrigation, and rainwater is consumed during periods of under-irrigation. This plus of the irrigation water are available for crop production. This practice reduces losses from deep percolation if DU is high but allows a cumulative SMD to develop in the bottom portion of the root zone. Depletion of deep moisture augments the limited irrigation supply. Frequent checks of the SMD are essential for obtaining the maximum benefit from this practice and to avoid the danger of running out of deep moisture reserves and stressing a crop at a critical period, such as maize at tasseling. The area of land irrigated should not exceed what can be irrigated economically with the limited supply of irrigation water plus the available reserve of deep soil moisture [16, 17]. Another means for maximizing the efficiency of water use and reducing required system capacity without reducing yields are to irrigate only part of the area at any one time. This method is effective in orchard or vineyard irrigation by furrows, emitters, or orchard sprinklers because trees and vines have extensive root systems. The full soil profile throughout the area should be wet annually from rain or early season irrigation. During the period of deficient water supply, irrigation should be restricted to applying the SMD to a reduced area near each plant. This substantially reduces the loss of water by surface evaporation and thereby increases the percentage of irrigation water transpired by the crop. High AMD in the area wetted stresses the crop slowly as it draws moisture from the areas of the unirrigated areas and the lower root zone. Location of the area watered is relatively unimportant because root systems in a mature orchard of vineyard are extensive. This technique of limited irrigation utilizes the available supply of water very efficiently. Certain cultural practices such as harvesting and propping trees suggest modification in planning and managing irrigation; this may result in using limited irrigation. For example, depth of the pre-harvest irrigation can be reduced by spreading the limited amount of available water wider and shallower. This permits the large mass of roots near the surface to function normally and thus reduces crop stress and improves crop quality. Sometimes the area is reduced since furrows cannot be plowed close to trees because of low branches or props. Often sprinklers have to be placed only in the tree row to reduce foliar interception.

A common practice in young orchards under basin, furrow, sprinkler, or trickle irrigation is to irrigate only the area immediately adjacent to the trees until their root systems become extensive. Even in mature orchards, much of the surface area is left dry to improve trafficability. In fact, ability to do this is a prime advantage of trickle and furrow irrigation, which is never intended to wet the total soil area of an orchard. The planned reduction of the area to be wetted is compensated by more frequent irrigation in inverse proportion to the wetted area [5, 6]. For example, if only half area is to be wetted, it is wetted at twice the normal frequency; this is a prime example of limited irrigation. However, great caution should be exercised if one plans to design a system to irrigate less than one-third of the volume of potential root soil. An excellent variation of limited irrigation is the use of alternate side irrigation. In this practice, all or part of the area on one side of the plant is wetted at a time, i.e., the full SMD is replaced on half the field. At the next irrigation, the SMD is replaced on the other side of the plant. At each irrigation, only half the usual application is applied but at half the usual frequency.

Stress irrigation applies to any of a number of practices which result in under-irrigation to conserve water at the expense of some reduction in potential yields. Irrigation procedures that are likely to stress a crop can be combined with alternate side irrigation to reduce the maximum stress.

Maximizing crop production from a limited amount of water is important either when the water supply is inadequate or when the value of water is measured by crop production per unit of water. In such areas, operating at a high MAD extends the interval between irrigations. This practice of stress irrigation may reduce yields per unit area but may produce total crop per unit of water on an enlarged area and thereby produce a greater net return.

Except for some of the special variations mentioned below, intentional under-irrigation puts a premium on having high values of DU and AELQ to reduce losses of water and results in a higher percentage of the irrigation water being transpired by the crop.

Reducing system capacities as discussed above, and/or accepting a lower DU enables the reduction of capital investment. When a system that achieves only low DU is used, the SMD may not be fully replaced in portions of the field even when the water supply is adequate. In such areas, management simply plans to accept a reduced yield from the dry portions of the field. Such systems require careful management, logical design, checks of SMD, and periodic evaluations of the success of the operation.

The above design logic anticipates moderate to low values of DU and AELQ as a trade-off for reducing the costs of system development. Wide spacing of sprinklers and operation at low pressures may reduce costs, but they may also cause deficiencies of soil moisture to cumulate in the drier spots. The dry spots may produce fewer crops, but profits may be increased because of the reduced cost of capital more than offset the crop losses. To eliminate the dry spots, abnormally large quantities of water must be applied which may be uneconomical or cause drainage problems.

For furrows and border strips, reduced land grading or use of longer-than-normal lengths of run is possible means for decreasing costs for capital and labor. However, these practices should be used only where resultant reductions in cost substantially exceed the losses resulting from reduced production at the under the irrigated end of the furrow or strip. Furthermore, salt accumulated in dry areas, which are not leached by occasional rainfall, may become a hazard.

Before using any of these forms of stress irrigation, a manager should determine that the resulting savings in capital, labor, water, and management will more than offset the value of the estimated decrease in crop yield per unit area.

6 High-Frequency Irrigation

Movable and permanent solid set (or full coverage) sprinklers, center pivot, and trickle (or drip) systems are normally managed to apply light frequent irrigations. High-frequency irrigation is used to achieve any or all of three major objectives: (1) to maintain a continuous low-stress high level of soil moisture to produce high yields or better quality of crops; (2) to avoid the runoff that often accompanies high rates of application; and (3) to control temperature, humidity, and/or wind erosion. Under some conditions, high-frequency irrigation may be conducive to diseases or excessive vegetative growth.

Under high-frequency irrigation, depth of each application is usually less than 3 cm unless an area is being intentionally under-irrigated; the SMD would also be less than 3 cm. It is practically impossible to estimate the SMD precisely enough for it to be useful in determining whether the soil is dry enough to require irrigation when the MAD is so low.

Estimates of the rate of a crop's use of water give a reasonable basis for scheduling high-frequency irrigation. A crop's use of water can be estimated from weather data, taken from measurements from evaporation pans, or can be based on experience. Except where under-irrigation is intended, ideal system management would exactly replace the water consumed in the areas that receive the minimum application.

It is impractical to attempt to estimate exactly the volume of water consumed between irrigation. Since over-irrigation is difficult to measure, it is good management to under-irrigate slightly when using systems other than trickle irrigation. The SMD can be checked periodically to spot areas where deficits of soil moisture have been cumulative. For such areas, scheduling of irrigation can be corrected accordingly. This practice of under-irrigation should not be risked if only a small portion of the root mass is irrigated as in trickle irrigation.

High-frequency irrigation is particularly well suited for use in conjunction with limited irrigation where the deep soil moisture is being gradually depleted over a whole area, as sometimes happens under center pivot and other automatic sprinkler irrigation systems. Light frequent watering of the topsoil plus the gradual withdrawal of moisture from the subsoil can produce optimum crop yield when the irrigation system capacity is limited. However, where subsoil moisture is inadequate, light frequent irrigation, causing heavy moisture losses from evaporation, may be an inefficient use of a limited supply of water and also increase salinity. Therefore, less frequent deeper irrigations may produce better crops [18].

While using supplemental irrigation in areas that receive high rainfall, it is good practice to apply shallow irrigation frequently while maintaining an SMD between 3 cm and 6 cm in the lower part of the root zone. Thus, the soil always has some storage capacity for rain but also has plenty of water for the crop.

7 Uniformity, Efficiency, and Economics

The efficiency of any operation, including irrigation, is a measure of how well its performance compares with some ideal level of performance. The following evaluation procedures usually imply that full irrigation with high DU and AELQ is the desired ideal. The concept of full irrigations in the areas receiving the average low quarter depth of application is useful for standardizing evaluation procedures in the field. However, this concept may provide a poor basis for evaluating and managing a system to optimize profit or any other value such as production per unit of land, production from a given quantity of water, or production per unit of energy input [12, 13].

Intentional under-irrigation of areas that are receiving the average low quarter depth of application may provide the optimum profitability. Rather than replenishing the water in almost all of the area, as is implied by PELQ, it may be more economical to leave a substantial area under-watered. This would be especially true for deep-rooted crops, low-value crops, and for crops growing in humid regions.

8 Conclusions

Basic concepts and terms of indicators of the technical and agronomic performance of smallholder irrigation schemes that used is very significant for monitoring and evaluating. Essential deficit irrigation between limited and stress irrigation and high-frequency irrigation depends on soil moisture depletion (SMD), management allowed depletion (MAD), irrigation methods, efficiency, and uniformity of irrigation.

9 Recommendations

For an irrigation scheme evaluation, the values of performance indicators should be applied in order to evaluate the performance level concerning the irrigation scheme. For their calculation, performance indicators call upon a certain number of parameters that have to be measured in the areas of irrigation schemes for the progressive elaboration.

A detailed study is needed to optimize profit which would be beyond the scope of the following evaluation procedures described here. In addition to evaluation of system performance in the field, which indicates the location and magnitude of water losses, such a study would require a thorough knowledge of system costs, plus the relation between water and crop production in the area studied.

References

1. Casley DJ, Kumar K (1990) Project monitoring and evaluation in agriculture. London
2. FAO (2002) Monitoring the technical and financial performance of an irrigation scheme. Irrigation Manual 14, Harare, Zimbabwe
3. IIMI (1996) Méthodologie d'évaluation des performances et de diagnostic des systèmes irrigués. Projet Management de l'irrigation au Burkina Faso, Novembre, p 1996
4. Sally H (1995) Performance assessment of rice irrigation in the Sahel: major indicators and preliminary results from Burkina Faso and Niger. Paper presented at Workshop on irrigated rice in the Sahel: prospects for sustainable development, 27–31 Mar 1995
5. Merriam JL (1978) Farm irrigation system evaluation: a guide for management
6. Merriam JL (1966) A management control concept for determining the economical depth and frequency of irrigation. Trans ASAE 9(4):492–498
7. Fao SAFR (2000) Socio-economic impact of smallholder irrigation in Zimbabwe: case studies of ten irrigation schemes. Harare, Zimbabwe
8. Abd El-Hafez SA, El-Bably AZ (2006) Irrigation improvement project (IIP), on-farm water management (OFWM), Kafr El-Sheikh and El-Behira Directorates, Final report
9. FAO (1992) CROPWAT: A computer programme for irrigation planning and management. FAO Irrigation and Drainage Paper No. 46. Prepared by: Smith M Rome, Italy
10. SCS National Engineering Handbook (1976) Planning Farm Irrigation Systems, Chapter 3, Section 15, USDA, Washington, DC, July 1967
11. Smerdon ET, Glass LI (1965) Surface irrigation water distribution efficiency related to soil infiltration. Trans ASAE 8(1):1965
12. Griddle WD, Sterling D, Claude HP, Dell GS (1956) Methods for evaluating irrigation systems. Agricultural handbook No. 82, SCS, USDA, Washington
13. Merriam JL (1968) Irrigation system evaluation and improvement. Blake Printery, San Luis Obispo, California
14. Willardson LS, Bishop AA (1976) Analysis of surface irrigation application efficiency. J Irrig Drain Div ASCE 93(No. IR2), June 1967
15. Beaudoux E, de Crombrugghe G, Douxchamps F, Gueneau M, Nieuwkerk M (1992) Supporting development action from identification to evaluation. Macmillan Education Ltd
16. FAO (1989) Guidelines for designing and evaluating surface irrigation systems. FAO Irrigation and Drainage Paper No 45. Developed by: Walker, W.R. Rome, Italy
17. Casley DJ, Lury DA (1981) A handbook on monitoring and evaluation of agriculture and rural development projects. World Bank
18. United Nations ACC Task Force on Rural Development Panel on Monitoring and Evaluation (1984) Guiding principles for the design and use of monitoring and evaluation in rural development projects and programmes. Rome