Performance assessment of irrigation water management of heterogeneous irrigation schemes: 1. A framework for evaluation.

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Abstract: Studies of the performance assessment of irrigation schemes have gained momentum since the late 1980s due to the common perspective that the resources (land and water) in irrigation schemes are not being managed appropriately. In this paper "irrigation water management" is considered as one of the activities of the irrigation scheme. Three phases of irrigation water management namely planning, operation and evaluation are identified. A framework for the performance assessment of irrigation water management in heterogeneous irrigation schemes is proposed in this paper, based on earlier studies made in this direction. The paper presents two types of allocative measures (productivity and equity) and five types of scheduling measures (adequacy, reliability, flexibility, sustainability and efficiency), together with the methodologies for estimating these for the scheme as a whole during different phases of irrigation water management.

Keywords*:* irrigation water management, performance assessment, productivity, equity, adequacy, reliability.

Introduction

Developing countries have made huge investments in infrastructure for irrigation in the form of irrigation schemes over the last half century, realizing its importance for food production for the growing population. This investment, together with improved crop production technologies such as use of fertilizers, hybrid varieties, plant protection techniques etc, has enabled many countries to move towards achieving self-sufficiency in food production. Nevertheless there is also a perception that many irrigation schemes do not perform up to expectations or achieve the goals.

Irrigation performance is the result of a large number and variety of activities such as planning, design, construction, operation of facilities, maintenance and application of water to the land (Small and Svendsen, 1990) or agricultural production, irrigation, land settlement, maintenance, construction, water users' organization etc. (Nijman, 1992). Management of the application of water to land or "Irrigation Water Management" is important within each irrigation scheme for achieving the benefits of the earlier activities and investment in creating the irrigation potential. It is also important at the catchment/basin and national levels, where increasing attention is being focused on efficient management of water resources to meet growing challenges: the increasing demand for irrigation to meet the growing food demands of the population; the competition for water allocation from high priority non-agricultural sectors; the limitation to the development of new water resources due to rapidly increasing cost, technical infeasibility and environmental concern.

This paper considers the assessment of irrigation water management (IWM) on heterogeneous irrigation schemes, particularly those in developing countries. These typically have extensive systems of branched canals with numerous outlets along their length, distributing water over large areas with various soil types, for use by farmers with differing sizes of landholdings, growing a variety of crops. This heterogeneity is a major complication for irrigation water management.

Irrigation water management within irrigation schemes involves three phases: planning, operation and evaluation. In the planning phase, the pre-determined objectives/targets for the irrigation scheme are used to develop an allocation plan for distribution of land and water resources to different crops up to tertiary level and hence water delivery schedules in terms of timing and amount of water delivery. In the operation phase, the plan finalised at planning stage is implemented or modified and implemented. In the evaluation phase, operation data are collected and analysed to determine the performance (Molden and Gates, 1990 and Gorantiwar, 1995). The success of irrigation water management in the irrigation scheme depends on appropriateness of all these processes. If the allocation plans are not according to the objectives of the scheme, the performance of the entire irrigation process in the scheme will not be according to the objectives. If the water delivery schedules are not prepared according to the allocation plan and are not followed during the operation of the scheme, farmers may not get the scheduled supply and the yields may be lowered.

As no single assessment of performance can involve all the facets (Small and Svendsen, 1990 and Nijman, 1992), we present in this paper a framework for evaluation of the performance of irrigation water management in the irrigation scheme. The proposed framework does not consider the performance of other activities.

Performance of irrigation water management

Definition

Lenton (1986) described irrigation performance as knowing the extent to which an irrigation scheme achieved established objectives. According to Abernethy (1989) the performance of an irrigation scheme is represented by "its measured levels of achievement in terms of one, or several, parameters which are chosen as indicators of the system's goals." While reviewing and proposing different methodologies for assessing performance of irrigation and drainage schemes, Bos et al (1994) commented, "performance assessment is, despite its apparent simplicity, a very complex task" and cited the definition of performance proposed by Murray-Rust and Snellen (1993) as "the degree to which an organization's products and services respond to the needs of their customers or users, and the efficiency with which the organization uses the resources at its disposal". The performance of irrigation water management can be stated as "the extent to which the land and water resources in the irrigation schemes planned for allocation to different users and their spatial and temporal distribution in planning and operation stages follow the objectives of the irrigation scheme".

Characteristics of Performance Measures

Abernethy (1989) pointed out that performance indicators should provide irrigation managers with the answer to the following three questions.

(1) “Does the quantity of water provided meet the growth needs of the crops planted in a given season?

(2) How fair is the water distribution among multiple users of the delivery system?

(3) Does the water delivery timing match the growth needs of the crop and expectation of the farmers?”

Bos (1997) presented the properties of performance indicators. These are that those should be scientifically based, quantifiable, have reference to target values, provide information without bias, provide information on reversible and manageable processes and be easy to use and cost-effective.

It is important to have reliable means of estimating the performance measures. The appropriate sets of parameters or priorities will vary depending on the physical, economic and social environment in the irrigation scheme. But the satisfactory performance measures require the following characteristics besides those included above from Abernethy (1989) and Bos (1997).

- a set of performance measures and their indicators describing system behaviour in relation to a set of specific objectives.
- identification of the deviation of the actual performance from the desired performance.
- identification of how and where to improve the performance of the irrigation scheme, thus its spatial and temporal distribution (as the objective of the

performance assessment should not be just to know the performance of the irrigation in the scheme).

Different Performance Measures

The study of performance assessment has gained momentum since the late 1980s, with initial work by C. Abernethy, M.G. Bos, R.K. Sampath and the International Irrigation Management Institute, though many others contributed later. The performance measures addressed by various researchers are presented in Table 1. The definitions of various performance measures are discussed below and summarised in the other tables, but for detail on the researchers' findings, readers are advised to refer to their original publications.

Types

Previous research on performance measures summarized in Table 1 indicates that these measures relate to the different processes involved in irrigation water management. These are allocation of the resources (e.g. productivity, equity etc) and scheduling of the resources (e.g. adequacy, reliability etc). Hence in this paper these are referred to as allocative type and scheduling type of performance measures. The studies related to performance measures indicate that some researchers focused on scheduling type (Malhotra, 1984 and Makin et al, 1991) and some on both allocative and scheduling types (Abernethy, 1989; Small and Svendsen, 1990 and Nijman, 1992). These performance objectives/measures are linked in the sense that if irrigation water management performs satisfactorily in achieving allocative objectives, then scheduling objectives can be achieved and when scheduling objectives are achieved, the irrigation water management in a scheme has performed satisfactorily for the allocative objectives.

Allocative type performance measures

The allocative type performance measures are those which need to be attended primarily during the allocation of the resources at the planning stage. Allocation of the resources influences production, area to be irrigated, net return, distribution of the resources to the users based on certain considerations, or combinations of these. Hence we classify the performance measures as

1. Productivity
2. Equity

Scheduling type performance measures

The irrigation schedule (consisting of the temporal or intraseasonal distribution of the resources to different users) needs to be prepared for the allocation plans developed according to the objectives of the scheme. Depending on these objectives, the schedule should be such that water deliveries may need to be adequate both in planning and operation, reliable when in operation considering all the complexities in the irrigation scheme, flexible and sustainable. Depending on the objectives of the scheme we propose following five scheduling type performance measures.

1. Adequacy
2. Reliability
3. Flexibility

4. Efficiency
5. Sustainability

These two allocative and five scheduling type performance measures could also be grouped as follows:

- Economic: Productivity
- Social Equity
- Environmental: Sustainability
- Management Reliability, adequacy, efficiency and flexibility

The different types of performance measures in the process of irrigation water management are shown in Figure 1.

Different phases of performance

It is evident from past research studies that many irrigation schemes are planned and operated for multiple objectives. These objectives often conflict with each other. Therefore it is necessary to have a proper trade off amongst these objectives and this calls for an appropriate system to quantify these performance objectives. As many irrigation schemes are characterized by variability in soils, cropping patterns, irrigation efficiencies and climate, multiple users, water scarcity and complex network of canals, it is necessary to know the temporal and spatial variation in these performance measures over each irrigation scheme. Pointing out that the main function of the irrigation scheme is to provide irrigation, Abernethy (1986) argued that the yardstick for the evaluation of the irrigation management must be whether it fulfils its function i.e. the delivery of water where and when it is wanted, reliably and in the right quantities.

We identify planning, operation and evaluation as three phases in irrigation water management during which the performance should be measured, so as to know and continuously improve the performance of the irrigation water management according to the set objectives. These are considered in turn below

Planning

The allocation plan and corresponding water delivery schedule need to be prepared to achieve the set objectives of the irrigation scheme during the planning phase of irrigation water management and then these need to be followed during the operation. It is possible to estimate all the performance measures at the planning stage except reliability and efficiency. But if the allocation plans and water delivery schedules are prepared without considering the heterogeneity in the scheme, the characteristics of the water delivery schedules and the appropriate efficiencies at several levels and places, then this will reduce the reliability.

Operation

The chosen allocation plan is put into the operation and the manager then needs to monitor the performance of this plan when in operation, to allow for continuous assessment and improvement of performance of irrigation water management of the irrigation scheme. Allocation plans and schedules are prepared for historical data or synthetic climatological data series on various assumptions. In practice however the irrigation scheme may not behave according to these plans, firstly because of spatial and temporal variation in climate, secondly because of the inappropriate consideration of complexity and variability in the physical aspects of the scheme (different characteristics of the water distribution network, variable soils etc) and managerial aspects (on demand/continuous/rotational water supply, etc.) while developing the allocation plan and thirdly due to different types of interventions. The performance assessment under simulated and actual operation will enable the irrigation manager to review the allocation plan of the same irrigation year or subsequent irrigation years.

Simulated Operation: Before subjecting the plan to actual operation, if the performance of the irrigation plan is modelled through simulated operation, the irrigation authorities can make an accurate prediction of the performance of the irrigation plan when the plan is put in actual operation. Similarly the simulated operation acts as a useful research tool for studying the different irrigation strategies and plans. This is done with the help of historical and generated data series related to water supply and demand. The simulated operation is possible now a days as the irrigation authorities of many irrigation schemes maintain these data in proper format (for example, Khadakwasla Major Irrigation Scheme and some 100 minor irrigation schemes in Maharashtra State, India). In this case it is assumed that the allocation rule defined in the allocation plan is followed exactly. The performance of the selected irrigation plan will provide information to the management about the influence of climatological variability on supply and demand and will thus be helpful to the management in actual operation.

The estimation of the performance measures through simulated operation is also helpful to identify the potential effects and limitations of different allocation plans under ideal conditions. This will enable irrigation authorities to review and modify the allocation plan, if it is not performing according to the objectives, and also to develop robust allocation and scheduling rules which are stable over the years.

Actual Operation: In actual implementation of these rules while the scheme is in operation, there may be some deviation from the plan due to some unforeseeable reasons e.g., some additional demands due to famine etc, political reasons, theft of water, unusual year (variation in supply and demand), the canal network not behaving according to what is assumed etc. The performance assessment at this stage should help explain why the scheme is not performing according to the expectations.

The performance measures to be addressed during operation are productivity, equity, adequacy, flexibility and sustainability. Additionally reliability needs consideration during actual operation.

Evaluation

The comparison of the planned performance (or during simulated operation) and the actual performance at the end of the irrigation season will enable the irrigation authorities to diagnose whether the deviation from the expected performance is due to climatological variability, inappropriate considerations to different aspects of the scheme, management aspects or combinations of these, and will provide the management with insight to improve the performance. During evaluation the manager needs to measure the performance measures such as irrigation efficiency which cause the expected performance to deviate from the actual. Actual measurement of these parameters will enable the authorities to know the trend of variation and whether deviation of actual performance from the anticipated during the planning is due to their improper consideration. The inclusion of actual measurements will also enable these parameters to be included appropriately during further planning.

Spatial and temporal variation of performance measures

It is necessary to consider the performance of the irrigation scheme both over space and time. It may be necessary to know the allocative type performance measures (productivity and equity) over the season or year for the entire irrigation scheme or part of irrigation scheme. However the variation of the scheduling type of performance measures may need to be considered over space and some time.

Productivity

The productivity is related to output from the system in response to the input added to the system and there are several indicators of productivity. The principle output of the scheme is the crop produce or its economic equivalence and the area irrigated. These need to be assessed seasonally or annually. The productivity can be indicated by measuring these outputs in gross terms or relative to input utilized. The inputs of interest in irrigation are land, water and finance. The productivity is relevant when the outputs are measured in terms of whichever input is scarce. Lenton (1986), Chambers (1988), Abernethy (1989), Steiner (1991), Burton (1992) and Hales (1994) listed various indicators of productivity.

All these can be summarized as total production, total net benefits and total area irrigated in gross terms, and total production or benefits or area irrigated per unit of water utilized or area available or under crop. The water utilized is measured at various levels in the irrigation scheme i.e. from the headworks to the root zone of the crop. The productivity indicators are easy to quantify and included in all studies related to performance of an irrigation scheme. Some of these studies are reviewed in Table 2. The productivity indicators used in these studies have been adopted here in a generalized from, as discussed below.

Measurement of Productivity

Allocation plans are obtained for the maximization of outputs in different forms. Hence we propose to measure the productivity by all those forms or indicators through which it can be included while obtaining the allocation plans. The different parameters that should be measured to quantify the productivity indicators are:

Gross term

- total net benefits
- total area irrigated
- total crop production for the single crop case

Efficiency term (relative to input utilized)

- net benefits per unit area irrigated
- crop production per unit of area irrigated for a single crop
- crop production per unit of water used for a single crop

net benefits per unit of water used

maximum irrigated area per unit of culturable command area

It is proposed to measure the productivity using the above indicators relative to certain standards. Certain standards may be for example a target value, or the value associated with no limitations on water or land, or the value associated with the management option which gives maximum output.

Indicators of Productivity

The different indicators (relative to certain standards) proposed for measuring productivity are presented in Equations (1) and (2). As in some of the earlier studies (Table 1) higher productivity was found in the upper reaches, it would be interesting to know the spatial distribution of the productivity.

Scheme level-gross term

$$\Pr g = \frac{Oa}{Ot} \qquad (1)$$

where,

Prg = productivity (gross)

Oa = actual output

Ot = targeted output or output of management strategy with maximum output

Output may be total net benefit, total area irrigated or total crop production.

Scheme level-efficiency term

$$\Pr i = \frac{\left(Oa/Ia\right)}{\left(Ot/It\right)} \qquad (2)$$

where,

Pri = productivity

Ia = actual input utilized to obtain actual output

It = input proposed to be utilized to obtain targeted output or input utilized for the management option giving maximum output

Similar terms would be used at a lower level within the scheme. For example measures of productivity at the allocation level would be calculated from the outputs and inputs obtained/utilized for the allocation unit (outlet or farm).

Equity

Water is a scarce resource in many tropical countries and some may argue that it is advisable to achieve the maximum productivity in its use. However in these countries, the objective of social justice in the irrigation scheme may also be important and many people's livelihoods may depend on their irrigation supplies. Thus the allocation of water to achieve the maximum productivity is not the only objective but to allocate those resources such as water and area equitably according to the prevailing equity objectives is necessary to ensure social justice. In general, the price of irrigation water is relatively low and does not impact on demand and equity issues.

Some authors (Abernethy, 1986 and Khepar et al 2000) have argued that the equitable distribution of water is also necessary for maximizing productivity. They argue that the farmers at the head of the system generally apply more water than needed for potential yield and excess water will not improve the productivity but will reduce it. If instead the excess water were diverted to another part of the scheme receiving less water than needed to produce potential yields, then the production would have increased. However we feel that when water is scarce and managed optimally, the productivity and equity become conflicting issues, as observed by Gorantiwar (1995) and Kalu et al. (1995). In this case, in the process of achieving equity, water allocated to more productive areas (e.g. the head of the system with lower conveyance losses) gets diverted to less productive areas (e.g. the tail of the system with higher conveyance losses) and the production decreases.

Several researchers have defined equity from different perspectives. Abernethy (1986) defined equity as spatial uniformity of water distribution and stated that it ought to be one of the principle aims of the managers of any irrigation scheme that supplies water to multiple users. According to Chambers (1988), equity is not just equality in the sense of providing equal amount of resources to users over different periods. Equity implies equality, fairness and even-handed dealing. Equity deals with the distribution of water amongst users (Sampath, 1989). According to Sampath (1988) and Kalu et al. (1995), equity refers to fairness in water distribution whereas Oad and Sampath (1995) defined equity of water distribution among various outlets in an irrigation scheme as “the spatial uniformity of water deliveries”.

Though the meaning of equity is simple it is a complex issue. The performance measure of equity is the source of debate and is complex because equity depends on one's concept of what is fair, to whom it is fair and in what way it is fair, and this may vary greatly in the irrigation scheme. Another reason, as Abernethy (1989) pointed out, is that equity is multidimensional, which takes into account varying circumstances of farmers such as size of land holding, soil type or value of land, its closeness to the headworks and many more. The equity according to one parameter (say land holding) may be in fact inequity with respect to another parameter (say family size). Depending on the circumstances existing in the irrigation scheme, either equity or inequity in certain ways might be desirable. Therefore we define equity as "the distribution of input resources in the irrigation scheme (area and water) or the resulting output (crop production or net benefits) among the users (farmers, outlet) in a fair manner which is prescribed in the objectives of the irrigation scheme in the form of social welfare." Equitable or fair distribution of water to the farmers in the command area of the irrigation scheme has always been a major concern of the management of the irrigation scheme and accordingly many researchers focused on the issue of equity. Some of these studies are reviewed in Table 3.

Most of the studies related to equity tried to distribute the water proportional to the land holding as observed in the northern India Warabandi system (Malhotra 1982). However it may be possible that in a scheme with inequitable distribution of water, land towards the head of the system will have a high land price and as a result farmers are likely to have lower land holdings at the head end than the tail end farmers who may be able to buy more land with the same funds (Abernethy, 1986). In this case allocating water according to the land holding may not be fair. According to Levine and Coward

(1989), for water allocation, the equity may be based on seniority of water rights of the irrigator, severity of water needed by crops, time or resource sharing on a canal, allocation based on land holdings and water allocation based on family size.

Thus the issues in equity in irrigation water management are multiple: whether there should be equity or inequity; the resources to be targeted for equity (whether it should be area irrigated, water delivered or expected returns in terms of crop production or net benefits) and the base of equity (land holding, water rights, water requirement of the area, land price, family size etc).

Measurement of equity

The issues in equity do not end with different views on the concept of equity. There are a number of indicators and methods to measure equity.

Resources to be targeted for equity measurement

Investigation here measured equity in various ways. Malhotra et al (1984) and Sampath (1988) assumed the ratio of total wetted area (sum of the area wetted by each irrigation over the irrigation season) to cultivable command area as the parameter. Seckler et al (1988) used total wetted area. Bos et al (1991) argued using the flow rate for measuring the performance while El-Awad et al (1991) used volume. Bos et al (1994) used discharge in the form of delivery performance ratio for equity measures.

The choice of parameter should depend on the resource for which equity is targeted, availability of data and simplicity in data collection while the scheme is in operation. Depending on the objectives of irrigation water management in the irrigation scheme, equity can be for:

- Area to be irrigated (planning) or area irrigated (operation)
- Water allocated (planning) or delivered (operation)
- Crop production expected (planning) or crop production obtained (operation) for monocrop irrigation scheme.
- Benefits expected (planning) or generated (operation)

These may be referred to as equity in area allocation, water allocation, crop production and benefits generation, respectively. The parameter to be considered for equity in water allocation may vary: depth, volume and discharge. However as the depth and discharge need to be associated with area and duration of supply, we propose to use volume of water allocated or delivered for equity in water allocation. The parameter, volume of water, also provides the link from planning to the operation phase.

Base for equity measurement

Equity should be measured in terms of intended and planned resources (planning) and delivered resources (operation). Intended resources may be proportional to land holding, water requirement of the land holding, family size, land price etc (for equity) or disproportional to have a bias towards water rights or farmers with small land holdings if this is an objective of the scheme.

Parameter for measurement of equity

Because the characteristics of each allocation unit (outlet, farm) or the value of the parameter to which equity should be proportional for each allocation unit is different, it is not desirable to measure the equity directly by the quantity of the parameter (area irrigated, water delivered, crop production or benefits generated from each allocation unit) by which equity is to be measured. For example, culturable command area of each allocation unit is different. To overcome this effect, it is proposed to compute the contribution of the parameter by which equity is measured towards each allocation unit with reference to the contribution of the parameter to which equity should be proportional for the corresponding allocation unit. This is called the allocation ratio and is computed as the ratio of the actual allocation proportion and the desired allocation proportion. It is proposed to measure the equity for allocation ratio. The procedure is explained in Equations (3) and (4).

Indicator for measurement of equity

Like the equity concept, there are different views on equity measurement. Equity should enable us to know the degree of variation in the allocation of the resources to different allocation units/farms in the irrigation scheme and also the variation in allocation of the resources in different reaches of the scheme (head, mid and tail). There is no single best measure to estimate equity. The several ways used in equity measurement are reviewed in Table 4.

In general the following equity measures are extensively used.

1. Christianson Coefficient
2. Inter-quartile ratio
3. Modified inter-quartile ratio
4. Coefficient of variation
5. Theil's Index
6. Gini Coefficient

The modified interquartile ratio is the "average depth of water received by all land in the best quarter, divided by the average depth received in the poorest quarter" (Abernethy, 1986). Its value varies from 1 to infinity. However for better understanding and comparison, the value of equity indicator should vary from 0 to 1, 1 for perfect equity and 0 for total inequity. Therefore we propose to use the modified interquartile ratio proposed by Abernethy in modified form as interquartile allocation ratio (IQAR) and define it as "the average allocation ratio of the poorest quarter divided by the average allocation ratio of the best quarter." The formula proposed is given by Equation (6).

Computation of equity indicators

It may be necessary to know the temporal and spatial variation of equity or its estimates. The indicators for measuring temporal and spatial equity are described below through Equations (3) to (6).

Allocation ratio

$$Ra_i = \frac{\lambda a_i}{\lambda d_i} \tag{3}$$

where

Ra_i = allocation ratio of i^{th} allocation unit

λa_i = actual allocation proportion for i^{th} allocation unit

λd_i = desired allocation proportion for i^{th} allocation unit

$$\lambda d_i = \frac{\Delta d_i}{\sum_{i=1}^{na} \Delta d_i} \tag{4}$$

where

Δd_i = the value of the parameter to which equity should be proportional, assigned to i^{th} allocation unit.

na = total number of allocation units

Δd_i can be equal to the culturable command area of i^{th} allocation unit (ha). In this case $\sum_{i=1}^{na} \Delta d_i$ = is culturable command area of irrigation scheme.

$$\lambda a_i = \frac{\Delta a_i}{\sum_{i=1}^{na} \Delta a_i} \tag{5}$$

where

Δa_i = value of parameter by which equity is measured, computed for i^{th} allocation unit

The value of the parameter by which equity is measured can be area allocated, water allocated (at various levels) or crop production or benefits generated. Thus

$\Delta a_i = A_i$ (area allocated)

$\Delta a_i = V_i * A_i$ (water allocated)

$\Delta a_i = Y_i * A_i$ (crop production)

$\Delta a_i = Nb_i * A_i$ (Net benefits generated)

where

A_i = Area allocated for irrigation or irrigated of i^{th} allocation unit

V_i = Volume of water allocated or delivered to the i^{th} allocation unit

Y_i = Yield expected or obtained from the i^{th} allocation unit

Nb_i = Total net benefits expected or generated from i^{th} allocation unit

Interquartile allocation ratio

$$Ei = \frac{\overline{Ra^{pq}}}{\overline{Ra^{bq}}} \quad (6)$$

where

Ei = measure of equity for the irrigation scheme based on IQRA

$\overline{Ra^{bq}}$ = average of allocation ratios of the best quarter

$\overline{Ra^{pq}}$ = average of allocation ratios of the poorest quarter

The equity of different regions of the irrigation scheme (say, head, tail etc.) can be computed by considering the allocation units in those regions.

Adequacy

Adequacy deals with water supply to the crop relative to its demand. The measure of adequacy, relative water supply (RWS), proposed by Levine (1982) is the most comprehensive. RWS is the ratio of supply due to irrigation and effective rainfall to the demand due to evapotranspiration and other needs,. This indicator in itself or in little modified form (to account for variation in supply and demand) was used or proposed by many (Keller, 1986; Moya and Walter, 1988; Oad and Padmore, 1988; Weller, 1991; Sakthivadivel et al, 1993 and Bos et al 1994). Some of the studies based on these definitions of adequacy are presented in Table 5.

We have proposed two separate measures for describing supply of water in relation to demand. These are: adequacy and excess. Based on earlier studies (Table 5), we define adequacy as "the ratio of the water allocated or supply from all the sources (irrigation, effective rainfall, capillary water etc.) and the demand due to all the processes (consumptive use, losses, land preparation, leaching for draining accumulated chemicals or salts, other special needs etc) over a specific time period for a specific crop grown in a specific area".

For the purpose of estimating demands, it is proposed to consider consumptive use by following two approaches.

1. Approach-1: Applying water equivalent to maximum crop evapotranspiration. The water is supplied according to demand estimated by considering maximum crop evapotranspiration (ETm) as consumptive use. This approach is useful for estimating adequacy for "on-demand" irrigation schemes.

2. Approach-2: Applying water equivalent to fill the root zone to filed capacity for a specified irrigation interval: The Approach-1 may not be suitable for estimating adequacy for the irrigation schemes under rotational water supply. In such schemes, as the water is supplied at fixed interval, consumptive use is estimated according to the depth of water needed to fill the root zone to field capacity (d) for a specified irrigation interval.

It is noted here that often the water supplied or allocated equivalent to α ETm or α I (where α is a parameter which depends on crop and soil parameters and possess value less than 1.0) is adequate for particular irrigation. But over the season for adequate irrigation, this reduced application of water either reduces the irrigation interval or causes more water to apply for next application.

When the supply matches demand (due to all the processes defined above) exactly, adequacy is one, however when supply exceeds demand, adequacy will be more than one. Hence the water supplied or allocated in excess of demand (if any) should not be considered for estimating the adequacy. This excess amount of water supplied, which is not advisable, is not beneficial. As the measure "adequacy" in this study is proposed to indicate the beneficial supply in relation to demand, a separate parameter called "excess" is also proposed to indicate excess supply in relation to demand. The excess is defined as the "ratio of supply in excess of demand and demand". Adequacy ranges from 0 to 1, the minimum values of excess is zero with no upper limit. When supply is equal to or less than the demand, excess is zero.

The different crops have different maximum water requirement over different intraseasonal periods and over different regions (due to differences in soil types, irrigation layouts and different water transmission efficiencies). Therefore demands vary over different intraseasonal periods and regions. Supply may also vary over different periods and regions. Hence the adequacy (and excess) has both temporal and spatial dimensions. The adequacy is not only limited by the strategy adopted but also by the characteristics of the water delivery systems (for example, the capacity of the canal network may not be sufficient to carry water for the "full irrigation" strategy). Thus it would also be interesting to know the value of adequacy if the supply of maximum demands is restricted by the water delivery systems.

Every farmer in the irrigation scheme is interested to obtain the adequate supply of water. However in the water scarcity regions, maximum adequacy cannot be achieved over the entire area. In the process of achieving maximum adequacy for some allocation units or farms, there will not be any water supply remaining for some allocation units/farms. This will cause lower equity and also widen the horizon of conflicts from managers-farmers to farmers-farmers. Full irrigation or deficit irrigation may be followed while developing the allocation plans. The adequacy may be reduced with deficit irrigation as less water may be delivered than the maximum crop water requirement or the interval between irrigation water deliveries may be prolonged (Gorantiwar and Smout, 2003). However with deficit irrigation other performance parameters may be improved.

The above discussion leads to estimation of adequacy/excess according to the following criteria.

A) Stage: (1) Planning (2) Operation

B) Basis

(1) Area: Based on whole culturable command area/total Demand

Based on area allocated for irrigation/irrigated

(2) System capacity: Based on system capacity influencing supply

Based on system capacity not influencing supply

C) Distribution

(1) Temporal: (i) Intraseasonal (ii) Seasonal (iii) Irrigation year

(2) Spatial (i) Scheme (ii) allocation unit/farm (iii) intermediate units

The formulas proposed for these terms for adequacy and excess are elaborated below (Equations 7 to 13).

Measurement of Adequacy (without considering the system capacity while estimating the maximum demands)

Intraseasonal-Allocation unit

$$AQia_{ji} = \min\left(\frac{Va_{ji}}{Vr_{ji}}, 1\right) \tag{7}$$

where

$AQia_{ji}$ = adequacy during j^{th} irrigation for i^{th} allocation unit

Va_{ji} = volume of water allocated to i^{th} allocation unit during j^{th} irrigation

Vr_{ji} = volume of water needed according to maximum demand to i^{th} allocation unit during j^{th} irrigation

Seasonal-Allocation unit

$$AQa_i = \left(\frac{\sum_{j=1}^{J} \min\left(Va_{ji}, Vr_{ji}\right)}{\sum_{j=1}^{J} Vr_{ji}} \right) \qquad (8)$$

where

AQa_i = adequacy for i^{th} allocation unit

J = total number of irrigations during the irrigation season/year

Intraseasonal-Scheme

$$AQi_i = \left(\frac{\sum_{i=1}^{na} \min\left(Va_{ji}, Vr_{ji}\right)}{\sum_{i=1}^{na} Vr_{ji}} \right) \qquad (9)$$

where

AQi_{ii} = adequacy during i^{th} irrigation for the scheme

na = total number of allocation unit

Scheme

$$AQ = \left(\frac{\sum_{i=1}^{na} \sum_{j=1}^{J} \min\left(Va_{ji}, Vr_{ji}\right)}{\sum_{i=1}^{na} \sum_{j=1}^{J} Vr_{ji}} \right) \tag{10}$$

where

AQ = Adequacy for the irrigation scheme

Measurement of Adequacy (Considering the system capacity while estimating the maximum demands)

The Vr_{ji} in Equations (7) to (10) should be replaced by Vs_{ji} (Deliverable volume of water needed according to maximum demand to i^{th} allocation unit during j^{th} irrigation) to compute $AQSia_{ji}$ (system restricted adequacy during j^{th} irrigation for i^{th} allocation unit), $AQSa_{ji}$ (System restricted adequacy for i^{th} allocation unit), AQS_{ii} (System restricted adequacy during i^{th} irrigation for the scheme) and AQS (System restricted adequacy for the irrigation scheme). Equation (10) can be used to know the adequacy of different regions (say, head, tail etc) in the irrigation scheme, by selecting the allocation units accordingly.

Measurement of excess

Intraseasonal-Allocation unit

$$EXia_{ji} = \max\left(\frac{Va_{ji} - Vr_{ji}}{Vr_{ji}}, 0 \right) \tag{11}$$

where

$EXia_{ji}$ = excess during j^{th} irrigation for i^{th} allocation unit

Seasonal-Allocation unit

$$EXa_i = \left(\frac{\sum_{j=1}^{J} \max\left(Va_{ji} - Vr_{ji}, 0\right)}{\sum_{j=1}^{J} Vr_{ji}} \right) \qquad (12)$$

where

EXa_{ji} = excess for i^{th} allocation unit

Intraseasonal-Scheme

$$EXi_i = \left(\frac{\sum_{i=1}^{na} \max\left(Va_{ji} - Vr_{ji}, 0\right)}{\sum_{i=1}^{na} Vr_{ji}} \right) \qquad (13)$$

where

EXi_{ii} = excess during i^{th} irrigation for the scheme

Scheme

$$EX = \left(\frac{\sum_{i=1}^{na} \sum_{j=1}^{J} \max\left(Va_{ji} - Vr_{ji}, 0\right)}{\sum_{i=1}^{na} \sum_{j=1}^{J} Vr_{ji}} \right) \qquad (14)$$

where

EX = Excess for the irrigation scheme

Equation (14) can be used to know the excess in different regions (say, head, tail etc) in the irrigation scheme, by selecting the allocation units accordingly.

Based on whether demand is estimated from Approach-1 or Apprach-2, adequacy and excess are termed as Adequacy (1) and Excess (1) (when Apprach-1 is used) and Adequacy (2) and Excess (2) (when Approach-2 is used). Accordingly the notation, AQ in Equations (7) to (10) will be AQ(1) or AQ(2) and notation, EX in Equations (11) to (14) will be EX(1) or EX(2).

Reliability

As explained while describing “adequacy”, water allocation or supply may be less than maximum demand (estimated with potential crop water requirement). However, in operation it is necessary to match the water deliveries to allocations, which may be less than maximum demand, as in case of deficit irrigation. If water is delivered to the farmers in accordance with the schedules prepared during the planning process, the supply is considered to be reliable; otherwise the supply is unreliable. The reasons attributed to the unreliable supply are many: water availability in the irrigation scheme is lower than estimated during the allocation process, unexpected demands arise from sectors other than irrigation, inappropriate consideration of the capacity of the water distribution system, canal breakage and theft and management capacity or capability of the irrigation organization to deliver the scheduled supply.

Abernethy (1986) defined reliability as deliveries according to some schedule and according to him, unreliable water supplies are undesirable to a system's overall health. The successful results of the allocation plans depend on reliable supply. The maximum reliability of water supply is often more important than maximum adequacy. The farmers may be happier with a water delivery system in the irrigation scheme that delivers an inadequate supply which is reliable, than with the adequate supply which is not reliable. If the farmers are sure that the deliveries are according to the schedule communicated to them, they can plan their activities accordingly resulting in higher productivity. If the farmers think that the supply is unreliable, they cannot plan to use the water efficiently and instead will try to play safe (for example by adjusting their cropping plan), thus affecting the productivity, or will increase their demands for water, thus affecting the equity also. Some studies on reliability are reviewed in Table 6.

Based on these studies (Table 6), the reliability is defined as "the ability of the water delivery system and the schedule to meet the scheduled demand of the crop". This involves matching both the duration of supply or volume delivered to the planned duration of supply or volume to be delivered and the time during the season when these volumes were supplied to those planned times. As the reliability points to delivered water, it needs to be estimated during operation of the irrigation scheme. The reliability like adequacy has temporal and spatial attributes.

Measurement of reliability

The Equations (7) to (10) can be modified to compute the reliability by replacing Vr_{ji} in equations with Vd_{ji} (Delivered volume of water to i^{th} allocation unit during j^{th} irrigation) to compute Ria_{ji} (reliability during j^{th} irrigation for i^{th} allocation unit), Ra_{ji} (reliability for i^{th} allocation unit), R_{ii} (reliability during i^{th} irrigation for the scheme) and R (reliability for the irrigation scheme). Equation (10) can be used to measure the reliability of different regions (say, head, tail etc) in the irrigation scheme, by selecting the allocation units accordingly.

Flexibility

The water delivery schedules decided during planning are often subjected to changes. These changes are firstly due to variability in weather parameters, which cause the deviation of supply and demand during actual operation from those considered during planning. Secondly, there are different types of interventions when the scheme is in operation. The irrigation authorities are interested to know the influence on the outputs of any change in water delivery schedules during the operation. These outputs are in the form of allocative types of performance measures i.e. productivity and equity and scheduling type of performance measure i.e. adequacy. Once the areas are allocated to different crops for irrigation and the operation of the scheme has begun, any changes in the water delivery schedules should cause minimum reduction in the output or tend to recover towards the intended output. In short it is necessary to know how flexible are these schedules to take in these changes. We define flexibility as “the ability of the water delivery schedule of the allocation plan to recover from any changes caused in the schedule”. This needs consideration during planning of the irrigation water management. The schedules based on a management strategy of full or over irrigation are normally more flexible than those based on deficit irrigation. Achieving high flexibility in water delivery schedules may require compromising on other performance measures. Depending on water rights, flexibility may not be desirable or feasible.

Flexibility was not given importance during earlier studies of irrigation performance. It is a multidimensional measure to estimate, as Figure 2 shows. The irrigation system outputs are influenced by changing the amount of water application and the frequency of application (delaying the irrigations). In each of these two categories, their magnitude, sequence and level are important. Magnitude is referred to as the percentages by which the volume of application is changed and the period between irrigations is extended or shortened. The sequence refers to the number of irrigations during which the amount and/or frequency is changed. The level refers to whether it is the first change (first level) or is preceded by changes during previous irrigations. The procedure suggested to estimate the flexibility is described in Equation (15).

$$Fx_{tmsl} = Fx_{tms(l-1)} + \frac{(Pa - Pa_{tmsl})}{Pa_a}$$

$$Fx_{tms(0)} = 0 \qquad (15)$$

where

Fx_{tmsl} = the flexibility of the water delivery schedule t^{th} type is changed by m^{th} magnitude during s^{th} irrigation at l^{th} level

Pa = the output without change

Pa_{tmsl} = the output when water delivery schedule of t^{th} type is changed by m^{th} magnitude during s^{th} irrigation at l^{th} level

Sustainability

Sustainability is the performance measure related to upgrading, maintaining, and degrading the environment in the irrigation scheme. According to Abernethy (1986), the sustainability is the most difficult factor to encompass and refers to the issue of leaching, drainage and salinisation which if not attended to properly, may shorten the system's life. Though a lot of work has been published on the indicators of performance measures like productivity, equity, adequacy etc, few efforts have been made to define the indicators for sustainability. The indicators should enable the irrigation authorities to know which management strategy or option is more sustainable or environmentally friendly and how the chosen management strategy performed for sustainability while the scheme was in operation.

Inefficient irrigation leads to deep percolation. For a heterogeneous irrigation scheme with rotational water supply it is difficult though not impossible to produce allocation plans which will not cause any return flow or percolation deep in to the groundwater. However it should be noted that the return flow is desirable when the salt accumulated in the crop root zone needs to be leached away (as defined in the term demand explained in adequacy Section). The experience on these schemes show that deep percolation over the years will cause the groundwater table to rise into the root zone of crop (if adequate drainage systems are not adopted) for example Smedema and Ochs (1998) reported that total seriously affected area due to waterlogging and salt problems is around 20–30 million ha, out of the World's total of some 250 million ha of irrigated land. Experiences in the Indian subcontinent suggest that serious waterlogging and salinity problems typically arise within some 20–50 years after irrigation development and seriously affects between 5–10% of the developed area (IPTRID 1993).

This will throw the land out of cultivation due to water logging. The problem is further aggravated if the groundwater has a high salt content, bringing salt in to the root zone causing the problem of salinisation. Thus the allocation plans need to be produced and operated such that these should not cause the problems of water logging and salinisation. At the same time if the water supply from the irrigation canal system is not reliable farmers tend to pump the water excessively from the aquifer to supplement the irrigation. If the level of pumping exceeds the recharge, there will be groundwater overdraft and its associated disadvantages of mining (falling groundwater tables, increased cost of pumping, salinisation etc).

The indicators/measures proposed/used for sustainability by some of the past researchers are presented in Table 7. In this paper we propose the following five indicators for sustainability related to irrigation water management in the irrigation schemes. These are:

1. Crop occupancy sustainability: This refers to the area irrigated over the years compared to the area originally irrigable. It is proposed to use average crop occupancy ratio as the indicator. Crop occupancy ratio is defined as

$$COR_i = \frac{AI_i}{AOI} \qquad (16)$$

Where

COR_i = crop occupancy ratio for ith month

AI_i = Area irrigated during ith month

AOI = Area originally irrigable

2. Irrigated area sustainability: This refers to the % change in irrigated area over the period of years of concern.

3. Groundwater (rise) sustainability: This refers to the rise in groundwater table over the period of years. If the management strategy chosen brings the groundwater table in to the root zone of the crop, the chosen strategy is not sustainable. It is proposed to use the number of years after groundwater starts reaching into the soil root zone, as the indicator.

$$Sgr = N \quad \text{when} \quad \overline{Dw} \leq \overline{Ds} \tag{17}$$

where

Sgr = indicator of groundwater (rise) sustainability

N = number of years

$\overline{Dw}$ = the average depth of groundwater from the surface

$\overline{Ds}$ = the average depth of soil root zone in the command area

4. Groundwater (fall) sustainability: This refers to the drop in groundwater table over the years. If the chosen management strategy is causing the farmers in the area to overdraw groundwater over the years, the level may drop below the safe level specified for pumping. It is proposed to use number of years after the groundwater starts falling below the safe level, as the indicator.

$$Sgf = N \quad \text{when} \quad \overline{Dw} \geq Df \tag{18}$$

where

Sgf = indicator of groundwater (fall) sustainability

$\overline{Ds}$ = the safe depth of groundwater for the command area

5. Problematic area sustainability: This refers to the change in problematic area (saline, alkaline and saline alkaline) within the culturable command area of the irrigation scheme over the period of concern. It is proposed to use the number of years after the soils in the culturable command area start becoming problematic as the indicator.

$$Spa = N \quad \text{when} \quad Q \geq Qf \tag{19}$$

where

Spa = indicator of problematic area sustainability

Q = the soil properties characterizing the problematic soil (electrical conductivity, pH, exchangeable sodium percentage etc) of the culturable command area or part of culturable command area

Qf = the safe limit the soil properties characterizing the problematic soil

It takes several years to judge the sustainability of the selected management strategy. Therefore it is important that the different management strategies or the selected management strategy are evaluated for the sustainability (groundwater and problematic area) in the simulated operation. The simulation model used for the evaluation needs to be updated every year by correlating the estimated and actual ground water/salinity or/and alkalinity levels. The groundwater (fall) sustainability needs to be evaluated on the basis that there may be groundwater withdrawal by farmers for irrigation for the areas or fraction of areas in culturable command area of irrigation scheme, which are not allocated with irrigation water from the canal system. As the change in planned and actual irrigated area is the result of the actual management of the irrigation scheme including interventions, the irrigated area sustainability cannot be evaluated during simulated operation.

Efficiency

Allocation plans are developed using estimated efficiencies of water flow at various stages and time and if these allocation plans are implemented properly, most of the performance measures described above will be good indicators irrespective of whether the efficiency of the network is good or bad. However deteriorating efficiency over the years will reduce the performance of the irrigation schemes over this period. Hence though the efficiency is related to the maintenance of the physical infrastructure of the water distribution network it needs to be evaluated as performance of the irrigation scheme when it is in actual operation. This helps to show the causes of performance deviating from the desired standard.

Efficiency is important in two ways. Firstly, appropriate optimum allocation plans cannot be developed if proper consideration is not given to efficiency. Inaccurate or simplified estimates also have a major influence on other performance parameters such as productivity, adequacy, equity and reliability. Secondly, the inspection of efficiencies over space and time at different levels enables the irrigation authorities to learn which part of the scheme is inefficient, where it is inefficient and how it is deteriorating. It is necessary to define and use efficiencies at different levels in the scheme, as the measures to improve these efficiencies are different at these levels.

The efficiency measures used by past researchers are reviewed in Table 8. These studies indicate the importance of efficiency as it is the performance measure of irrigation water management when the scheme is in actual operation. A comprehensive methodology has been proposed by Bos et al (1994) and Bos (1997) for evaluating the efficiencies at different levels in the irrigation scheme. The efficiencies to be considered at different levels in the irrigation scheme are described below.

Application efficiency or field application ratio: This efficiency indicates how efficiently the water delivered to the field is applied in the field

Distribution Efficiency or tertiary ratio: This is the efficiency of the water distribution canal network in the allocation unit supplying water up to the individual field

Conveyance efficiency or conveyance ratio: Conveyance efficiency is the efficiency of canal networks from the reservoir or river diversion to the offtakes of the AU.

Project efficiency (overall consumed ratio): This is the overall efficiency and is the ratio of crop irrigation water consumption and total inflow into canal system.

Conclusion

Irrigation water management in irrigation schemes is complex due to their heterogeneity. Three phases of irrigation water management namely planning, operation and evaluation were identified. Previous studies on the performance assessment of irrigation scheme have provided the conceptual framework for performance measurement. This has been extended in this paper for the qualitative and quantitative evaluation of performance during every phase of irrigation water management. Two types of performance measures were proposed in this paper: the allocative type comprising productivity and equity; and the scheduling type comprising adequacy (excess), reliability, flexibility, sustainability and efficiency. These performance measures are described with different attributes in this paper. The methodologies to estimate these measures explained in this paper provide the irrigation authorities with the information on the performance of irrigation water management in the scheme, their management capability, the response of the irrigation water management to variations in climatological, physical and management aspects and insight to improve the performance during different phases of the of irrigation water management.

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Table 1. Performance measures addressed by various researchers.

Researcher(s)	Performance Measures
Abernethy (1986)	Equity, regularity, reliability and durability
Chambers (1988)	Productivity, equity and stability
Uphoff (1988) and Steiner (1991)	Productivity, equity, harmony, environmental sustainability and economic sustainability or cost effectiveness
Abernethy (1989)	Productivity, equity, profitability, sustainability and quality of life
Plusquellec et al (1990)	Water availability, water use efficiencies (conveyance, field application and overall efficiencies), equity of water distribution, cropping intensity and crop yields and project economic rates of return
Molden and Gates (1990)	Adequacy, efficiency, dependability and equity at different levels in the water delivery systems
Goldsmith and Makin (1991)	Adequacy, equity, reliability, productivity and equity
Makin et. al. (1991)	Water delivery performance parameters such as actual versus targeted water supply along with equity, reliability and adequacy
El-Awad et. al. (1991)	Adequacy, water losses (distribution efficiency), equity, cost (annual operating cost of system per unit area), water users convenience and durability
Kaushal et al (1992)	productivity, equity and adequacy
Mujumdar and Vedula (1992)	reliability (matching water release from the reservoir in particular period with total irrigation requirement of all the crops in that period), resiliency (likelihood of the system recovery from a failure once a failure occurs) and productivity
Bos et al (1994)	water supply performance (conveyance indicators, maintenance indicators, utility of water supplied, and equity), agricultural performance (area indicators and production indicators) and economic, social and environmental performance (economic viability, social viability and environmental sustainability and drainage)
Purkey and Wallender (1994)	water supply and deliveries, water conveyance, on-farm irrigation and the environmental sustainability
Meinzen-Dick (1995)	timeliness of irrigation (cumulative deficit in water deliveries over the crop season and cumulative excess in water deliveries over the crop season)
Oad and Sampath (1995)	adequacy, dependability (reliability and predictability) and the equity
Kalu et al (1995)	productivity (agronomic efficiency-the total quantity of crop production under irrigated agriculture and economic efficiency-the total net benefits) and equity
Makadho (1996)	adequacy, equity and timeliness
Small and Rimal (1996)	productivity (conveyance efficiency, physical productivity of water, physical productivity of land, economic productivity of water) and equity

Bos (1997)	40 multidisciplinary performance indicators, which cover water delivery, water use efficiency, maintenance, sustainability of irrigation, environmental aspects, socio-economics and management
Sarma and Rao (1997)	water supply-requirement ratio, irrigation intensity, crop productivity and change in cropping pattern
Makombe et al (1998)	deviation of actual water supply from the desired supply as measured by the crop water requirement adjusted with the effective rainfall (how accurately the water management system is achieving the desired supply).

Table 2. Productivity indicators used by different researchers

Researcher	Productivity indicators
Plusquellec et al (1990)	Cropping intensity, yield and project economic rate of return
Steiner and Walter (1993)	Relative yield (per cent of potential yield)
Bos et al (1994)	Area indicators (irrigated area performance as the ratio of actual area irrigated to target area and cropping intensity performance as the ratio of actual cropping intensity and target cropping intensity) and production indicators (production performance as the ratio of total production to target production, yield performance as the ratio of actual yield to target yield and water productivity performance as the ratio of actual water productivity to target water productivity).
Purkey and Wallender (1994)	Modified irrigated area performance (the ratio of irrigated area during the periods of reduced deliveries to the irrigated area when the deliveries are according to the requirement or allocations).
Small and Rimal (1996)	Conveyance efficiency (the ratio of the amount of water delivered at the turnouts of the main irrigation conveyance network to the total amount of water diverted into the irrigation scheme), physical productivity of water (the ratio of physical quantity of crop production to the volume of water used), physical productivity of land (crop yield), economic productivity of water (value of the irrigated crop production divided by the quantity of water used)
Sarma and Rao (1997)	Irrigation intensity, crop production and change in cropping pattern cropping pattern

Table 3. The equity considerations used by different researchers

Researcher	Equity considerations
The rotation system of water distribution to the farmers in north west India and Pakistan (Warabandi) (Malhotra, 1982)	Water available in the irrigation scheme is distributed to the farmers such that the duration of water supply available to the farmer in each turn is proportional to his land holding. However the conveyance loss in the network of canals within in the outlet is not considered while allocating the duration of water supply to each farmer
Malhotra (1982)	The watercourse may be divided in to three or four reaches and the farmers may be allotted time proportional to his land holding on the basis of actual flow in each reach.
Rajput (1989), Latif and Sarwar (1994) and Khepar et al (2000)	Duration of water delivery to each farmer should be distributed proportional to his land holding considering the conveyance losses.
Bos et al (1991)	Proposed equity in terms of misallocation of water calculated as the volume actually supplied minus the intended volume if water were to be divided over the tertiary units in accordance with the water rights.
Oad and Sampath (1995)	Compared sanctioned discharge (outlets' entitlement based on certain considerations) with actual discharge; sanctioned discharge with design discharge (flow capacity of the outlet) and design discharge and actual discharge for equity measurement
Small and Rimal (1996)	Used equity as the distribution of water in proportion of land area

Table 4. The equity indicators proposed and used by different researchers.

Researcher	Equity indicators
Abernethy (1986)	Christianson co-efficient (Christianson, 1942), standard deviation (Till and Bos, 1985), interquartile ratio (Abernethy, 1984), Gini coefficient and Shannon-Wiener. However preferred modified interquartile ratio (the average depth of water received by all land in the best quarter, divided by the average depth received in the poorest quarter)
Sampath (1988)	Relative mean deviation, the variance, the coefficient of variation, the standard deviation of logarithms, the Gini coefficient and Theil's information measure (Theil, 1967). Preferred Theil's information measure.
Molden and Gates (1990) and Kalu et al (1995)	Coefficient of variance (Cv) of spatial water distribution to field plots as a measure of inequity and thus (1-Cv) as measure of equity.
Steiner (1991)	Relative mean deviation, coefficient of variation, inter-quartile comparison and Gini coefficient
El-Ewad et al (1991)	Absolute average deviation
Bird (1991)	Inter quartile ratio
Goldsmith and Makin (1991)	A normalized equity index called inter quartile ratio (Abernethy, 1986).
Kaushal et al (1992)	Christiansen uniformity coefficient, coefficient of variation, modified IQR and Theil index
Bhutta and Van der Velde (1992)	Inter quartile ratio (Abernethy, 1986)
Bos et al (1994)	modified interquartile ratio (Abernethy, 1986) for overall equity and Head: Tail equity ratio (Vander Velde, 1991) for looking at the difference between head and tail of the canal.

Table 5. Adequacy measures defined by different researchers.

Researcher	Adequacy measures
Lenton (1984) and Abernethy (1986)	Termed adequacy as the regularity and defined as the supply according to some time schedule that matches the water needs of the crops and ensures that the necessary water is always accessible in the root zone
Abernethy (1986)	proposed to present adequacy (regularity) in terms of relative yield (the yield relative to what would be achieved if the delivery and demand matched precisely) or relative productivity.
Wijayaratna (1986)	Used water availability index for adequacy.
Molden and Gates (1990)	Proposed three measures of adequacy in terms of the arithmetic ratios over the space and time. These are: 1 ratio of actual amount delivered by the system to amount of water required for consumptive use, leaching, land preparation and the conveyance losses, 2 ratio of amount deliverable and the amount scheduled and 3 the ratio of the actual amount delivered and amount deliverable. In fact the first ratio indicates the adequacy, the second indicates the adequacy associated with structural characteristics of the water delivery systems and the third indicates the adequacy associated with the management characteristics.
Bos et al (1991)	The ratio of volume of water intended to be supplied to the tertiary units over the volume of water actually supplied on seasonal and monthly basis.
El-Ewad et al (1991)	Defined adequacy as how well the system is able to supply the water indent.
Sakthivadivel et al (1993)	Cumulative RWS (CRWS), which they defined as the cumulative value of the ratio of supply to the demand, computed over short intervals of time starting from a particular time of the seasons alongside RWS. They felt the necessity of both as RWS describes the adequacy for a specific period of time whereas CRWS describes the nature of adequacy for whole season.
Oad and Sampath (1995)	Defined adequacy in water delivery system as the ability to deliver the amount of water required to meet farmers' irrigation demand (crop consumptive use + additional water requirements for land preparation, salt leaching etc. + application losses).Compare actual flow with scheduled or required flow at different points in water delivery system by Theil's performance measure
Meinzen-Dick (1995) and Makadho (1996)	"TIMELY" (ratio of sum of intraseasonal deficit in water deliveries from maximum water requirement to sum of intraseasonal maximum water requirement over the crop season and "SURPLUS" (ratio of sum of intraseasonal excesses in water deliveries over the maximum water requirement to sum of intraseasonal maximum water requirement over the crop season).

Sarma and Rao (1997)	The water supply-requirement ratio
Makombe et al (1998)	Match desired supply with actual water supply. They computed the desired supply as the crop water requirements adjusted downwards by rainfall where relevant. They used the Theil measure of accuracy described by Marikar et al (1992) to compute the error committed by each scheme in matching water supply and demand

Table 6. Reliability measures defined by different researchers.

Researcher	Reliability measures
Molden and Gates (1990)	Defined reliability in the form of dependability as temporal uniformity of the ratio of the delivered amount of water to the required or scheduled amount of water. They provided three indicators in the form degree of temporal variability in the ratio of amount delivered to amount required (reliability), amount deliverable to amount scheduled (reliability associated with structural characteristics) and amount delivered to amount deliverable over a region (reliability associated with management characteristics).
Makin et al (1991)	Applied the reliability index developed by Francis (1989). This reliability index is the difference in cumulative percentage of locations at which percentage deviation of observed flows from target flows is +10 and cumulative percentage of locations at which percentage deviation of observed flows from target flows is –10. Thus the operational limits for the flow to be regulated or delivered at different locations are +-10 %. They assumed the target flows as demand equal to weekly crop water requirement.
Marikar et al (1992)	Matched the supplied and required quantity of water to the fields by Theil's mean forecast error concept
Mujumdar and Vedula (1992)	Used reliability as equalling the water release from the reservoir to total irrigation requirements of all crops in that period.
Purkey and Wallender (1994)	'Delivery performance' which is the ratio of water delivered to contractors to total contractual obligations.
Bos et al (1994) and Bos (1997)	Used the reliability in two forms viz. water delivery performance and predictability. Water delivery performance compares actual discharge/volume with intended or targets discharge/volume. The predictability proposed by them concerns both the actual duration of water delivery compared to plan duration (dependability of supply) and the actual interval between deliveries or actual irrigation interval compared to the planned interval or intended irrigation interval (regularity of the deliveries)
Oad and Sampath (1995)	Compared sanctioned discharge (outlets' entitlement based on certain considerations) with actual discharge; sanctioned discharge with design discharge (flow capacity of the outlet) and design discharge and actual discharge by Theil's mean square forecast error concept.
Oad and Sampath (1995)	Reliability is one of the two dimensions of dependability (other being predictability), which they defined as "the delivery of a relatively known amount of water over time as expected by the water users." They related reliability to supply rate consistent with farmers' expectations and predictability to timing of water supply.

Table 7. Sustainability measures defined by different researchers.

Researcher	Reliability measures
Bos et al (1991)	Monthly ratio of evapotranspiration to the diverted canal water and the average monthly changes in groundwater levels
Purkey and Wallender (1994)	The maps of salinity and depth to water below the ground surface
Bos et. al. (1994)	Sustainability of irrigated area (ratio of current irrigable area to initial irrigable area), rate of change of depth to groundwater (ratio of the difference between new depth and old depth and old depth) and impact of flooding (ratio of area subject to flooding and total irrigable area).
Bos (1997)	Sustainability of irrigation, depth of groundwater, pollution of water, salinity, organic matter, biological pollution and chemicals

Table 8. Efficiency measures defined by different researchers.

Researcher	Reliability measures
El-Ewad et al (1991)	Project efficiency
Purkey and Wallender (1994)	Conveyance and distribution efficiencies
Bos et al (1994	Overall project efficiency, conveyance efficiency, distribution efficiency and field application efficiency as defined by Bos and Nugteren (1990)
Bos (1997)	Water balance ratios (overall consumed ratio, conveyance ratio, tertiary ratio and field application ratio, respectively), dealing with the volume of water deliveries within a set time period.
Small and Rimal (1996)	Conveyance efficiency (the ratio of the amount of water delivered at the turnouts of the main irrigation conveyance network to the total amount of water diverted into the irrigation scheme)

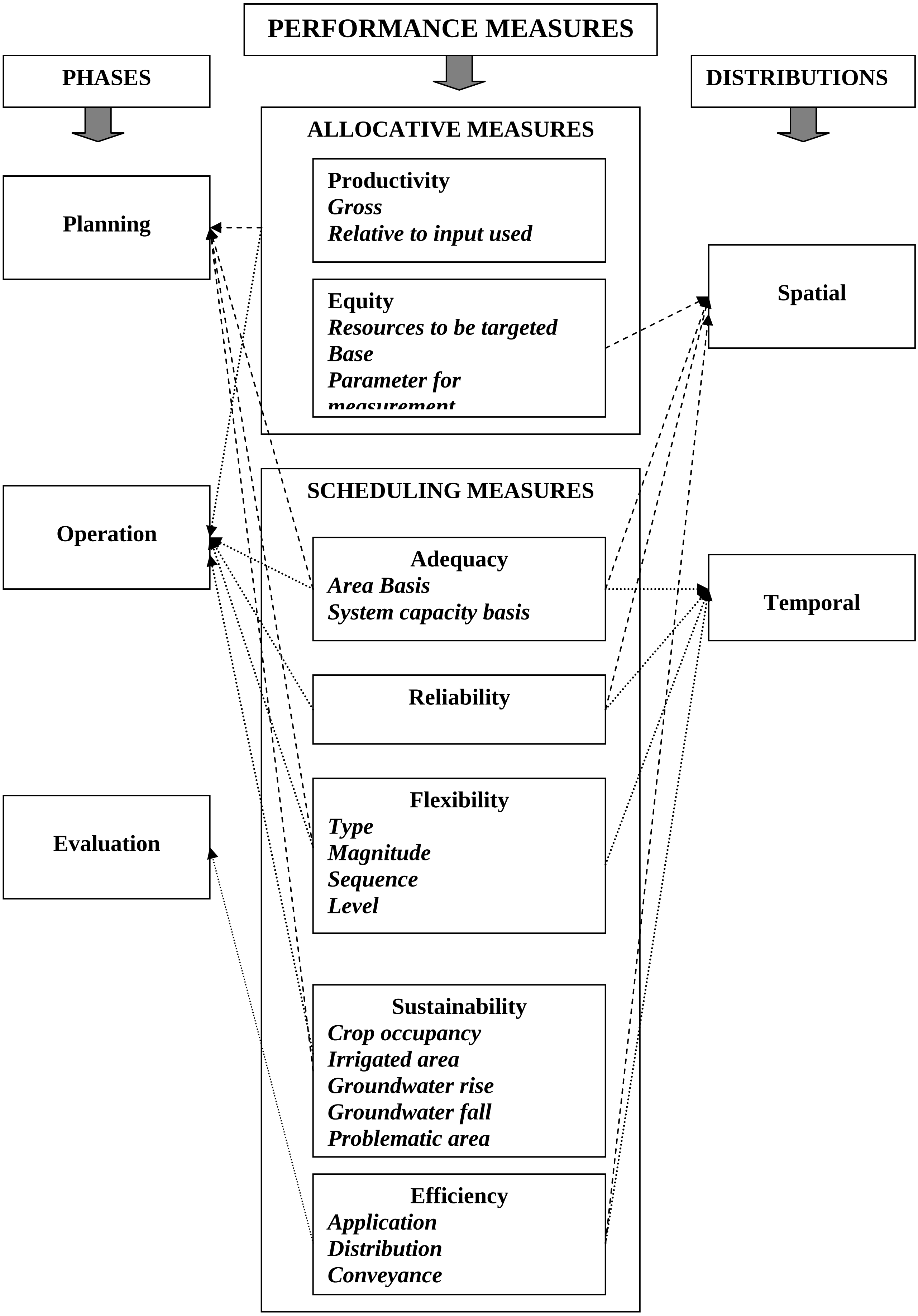

Figure 1. Performance measures of irrigation water management of irrigation scheme

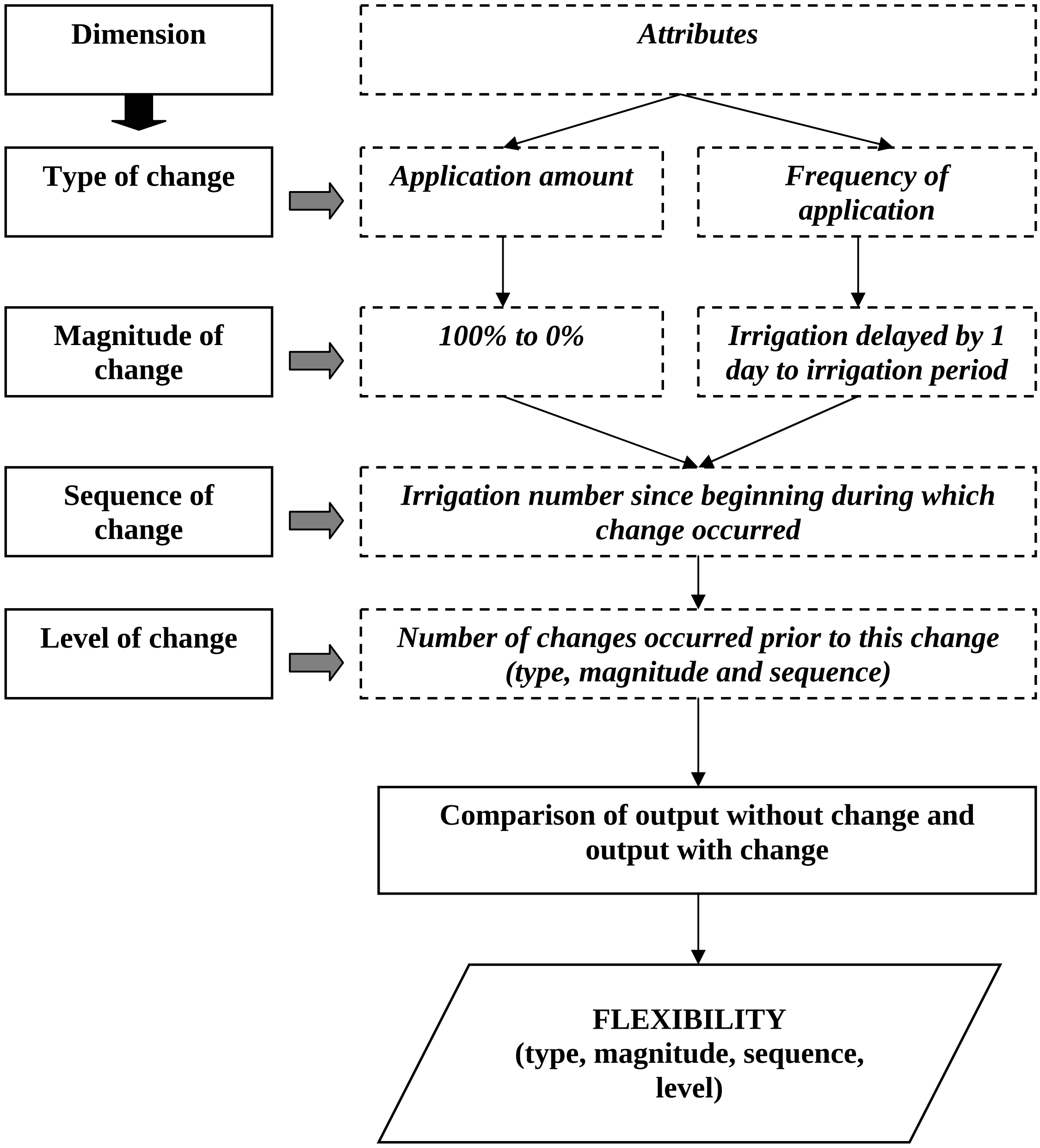

Figure 2. Flexibility and its different dimensions