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AN OVERVIEW OF INTEGRATED THEORY OF IRRIGATION EFFICIENCY AND UNIFORMITY AND CROP WATER USE EFFICIENCY

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ABSTRACT

The irrigation efficiency, crop water use efficiency, and irrigation uniformity evaluation terms that are relevant to irrigation systems and management practices currently used in India, and around the world.The definitions and equations described can be used by crop consultants, irrigation district personnel, and university, state, and private agency personnel to evaluate how efficiently irrigation water is applied and/or used by the crop, and can help to promote better or improved use of water resources in agriculture. As available water resources become scarcer, more emphasis is given to efficient use of irrigation water for maximum economic return and water resources sustainability. This requires appropriate methods of measuring and evaluating how effectively water extracted from a water source is used to produce crop yield. Inadequate irrigation application results in crop water stress and yield reduction. Excess irrigation application can result in pollution of water sources due to the loss of plant nutrients through leaching, runoff, and soil erosion. The efficiency of irrigation water use varies across in India. In areas where water is limited, available water is used more carefully. Whereas, in areas of abundant water, the value put on conserving water is less and the tendency to over irrigate exists. Efficient use of water is also influenced by cost of labour, ease of controlling water, crops being irrigated, type of irrigation system, and soil characteristics. Various terms are used to describe how efficiently irrigation water is applied and/or used by the crop. Incorrect usage of these terms is common and can lead to a misrepresentation of how well an irrigation system is performing. In India as per the land use statistics 2013-14, the total geographical area of the country is 328.7 million hectares, of which 141.4 million hectares is the reported net sown area and 200.9 million hectares is the gross cropped area with a cropping intensity of 142 %. The net sown area works out to be 43% of the total geographical area. The net irrigated area is 68.2 million hectares. In practice, it is seldom possible to deliver every drop of irrigation water to the crop due to water losses between the source and the delivery point. Irrigation water losses include spray droplet evaporation, weed water use, soil evaporation, furrow evaporation, leaks in pipelines, seepage and evaporation from irrigation ditches, surface runoff, and deep percolation. The magnitude of each loss is dependent on the characteristics and management of each type of irrigation system.In India, the main beneficial use of irrigation water is to meet crop evapotranspiration (ET) requirements. Another beneficial use is water used for chemigation. In some areas, leaching of salt from the soil is also an important beneficial use. Perhaps the most non-beneficial use of water is evaporation from water and soil surface, which does not contribute to crop productivity. Irrigation efficiency is generally defined from three points of view: (1) the irrigation system performance, (2) the uniformity of water application, and (3) the response of the crop to irrigation. These irrigation efficiency measures are interrelated and vary on a spatial and temporal scale. The spatial scale may be defined for a single field, or on a larger scale up to a whole irrigation district or catchment. The temporal scale can vary from a single irrigation event to a longer period such as part of the growing season, or a period of years. In understanding and characterising irrigation efficiency, the conventional (or classical) approach and the International Water Management Institute (IWMI) is a non-profit, scientific research organization focusing on the sustainable use of water and land resources in developing countries. IWMI works in partnership with governments, civil society and the private sector to develop scalable agricultural water management solutions that have a real impact on poverty reduction, food security and ecosystem health. Headquartered in Colombo, Sri Lanka, with regional offices across Asia and Africa. Research at the Institute focuses on improving how water and land resources are managed, with the aim of underpinning food security and reducing poverty while safeguarding vital environmental processes.'effective efficiency' (neoclassical) approach hold true in various situations as long as the terms, circumstances and purposes of those situations are carefully defined. However, given the need to bridge these two views and engage with the specifics affecting efficiency, a theoretical framework of 'integrated irrigation efficiency' is proposed the relationship between efficiency and timing; and the coupling of net requirements and recovered and unrecovered losses. The discussion introduces the term 'attainable efficiency' and discusses the persistence of classical irrigation efficiency, hypothesising that it persists because it reflects observations made by irrigation professionals and farmers that local efficiencies and recovered losses critically affect water management and productivity in a river basin system.

Key words: Irrigation efficiency, crop water use efficiency, irrigation uniformity evaluation, Water Use Efficiency,Surface Irrigation, Sprinkler Irrigation, Drip Irrigation or Micro Irrigation, productivity, Irrigation Water Use Efficiency,water management, assessment, and performance, Christiansen's Uniformity Coefficient (Cu), Low-Quarter Distribution Uniformity (D_U).

Introduction

Irrigation efficiency is a critical measure of irrigation performance in terms of the water required to irrigate a field, farm, basin, irrigation district, or an entire watershed or catchments or drainage basin. The value of irrigation efficiency and its definition are important to the societal views of irrigated agriculture and its benefit in supplying the high quality, abundant food supply required to meet our growing world's population. "Irrigation efficiency" is a basic engineering term used in irrigation science to characterize irrigation performance, evaluate irrigation water use, and to promote better or improved use of water resources, particularly those used in agriculture and turf/landscape management.

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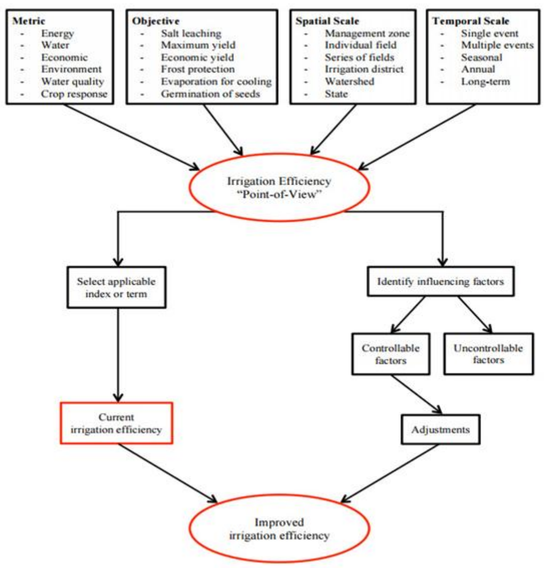
Irrigation efficiency affects the economics of irrigation, the amount of water needed to irrigate a specific land area, the spatial uniformity of the crop and its yield, the amount of water that might percolate beneath the crop root zone, the amount of water that can return to surface sources for downstream uses or to groundwater aquifers that might supply other water uses, and the amount of water lost to unrecoverable sources (salt sink, saline aquifer, ocean, or unsaturated vadose zone).

The volumes of the water for the various irrigation components are typically given in units of depth (volume per unit area) or simply the volume for the area being evaluated. Irrigation water application volume is difficult to measure, so it is usually computed as the product of waterflow rate and time. This places emphasis on accuratelymeasuring the flow rate. It remains difficult to accuratelymeasure water percolation volumes groundwater flowvolumes, and water uptake from shallow groundwater.

1.0 Irrigation Efficiency "Point-of-View": Irrigation efficiency can be evaluated by various perspectives or metrics, including water, energy, economic, environment, water quality, crop response, operation, and management of the irrigation system. Unfortunately, being efficient in one manner does not necessarily translate to another. An irrigation system can be more energy efficient than another; however, depending on fuel type and cost, a less-energy efficient system can be more economical. The "scale" used should also be considered when evaluating the impact(s) of enhancing efficiency on water resources and crop productivity. One can evaluate a single irrigation event or cumulative irrigation events over a growing season as well as a single field as compared to an irrigation district. Irrigation system efficiency enhanced on a field scale may result in water conservation, but the impact on overall water balance of the watershed or a basin may not be affected to the same or similar magnitude as those on a field scale. Establish an irrigation efficiency "point-of-view" by outlining what metric on which the irrigation system will be evaluated, the objective or purpose of irrigating, and the time and spatial scale of interest. A flow diagram for establishing an irrigation efficiency "point-of-view" along with proceeding steps to evaluate and potentially improve irrigation efficiency is presented in Figure 1.



1.1 Evaluating Irrigation System Performance: Irrigation system performance describes the effectiveness of the physical system and operating decisions to deliver irrigation water from a water source to the crop. Several efficiency terms are used to evaluate irrigation system performance. These include water conveyance efficiency, water application efficiency, soil water storage efficiency, irrigation efficiency, overall irrigation efficiency,and effective irrigation efficiency.

1.2 Impacts of Irrigation Efficiency: Depending on the "point-of-view," irrigation efficiency can be influenced by a number of factors, including pump efficiency, engine, irrigation system type and capacity, management practices, crop type and development, climate, soil physical and chemical properties, and fuel price, among others. These influencing factors can be divided into two categories: controllable and uncontrollable. Controllable factors can be adjusted or influenced by the producer to improve irrigation efficiency, and uncontrollable factors cannot be adjusted. Table 1 lists various controllable and uncontrollable factors that can impact irrigation efficiency. Certain controllable factors are more easily modified than others, and in some cases adjusting factors to improve efficiency is not economical. We recommend consulting an irrigation equipment expert prior to major adjustments or upgrades.

Table 1: Primary Controllable and uncontrollable factors that can impact irrigation efficiency

Controllable factors	Uncontrollable factors
1	2
Irrigation System	Climate and weather
Irrigation Uniformity	Soil properties
Irrigation Scheduling	Field size and geometry
Pump	Fuel price
Pumping Pressure	Pumping lift
Engine and fuel type	Water availability
Crop type	
Land and crop management	

1.3 Definition of Various Efficiencies: Irrigation efficiency is used to evaluate how effectively the available water supply isused for crop production. Water is conveyed through canal system, water courses,and field channels to the fields. Irrigation water is stored in the effective root zone of the soil. A considerable loss of water occurs from the source to the point of actual usage by the crop. The performance of an irrigation system is determined by the efficiency with which water is stored in the surface reservoir at the head works, diverted and conveyed to the irrigated area through the conveyance system and applied to the field and by the adequacy and uniformity of the water application in each field. The overall performance of an irrigation system is defined as the percent of water supplied to the farm that is beneficially used for irrigation on the farm. The extent of water loss in this process determines the irrigation efficiencies. Less the water losses higher the irrigation efficiencies. The tube well commands have higher irrigation efficiency than the canal commands. The efficiency provides a measure for comparing various systems or methods of water application, i.e. sprinkler compared in surface method. Presently, the irrigation efficiency in surface method of irrigation is very low (about40%) which means that about 60% water is either wasted and flows as runoff or goes back to the aquifer from where it is pumped again requiring high amount of energy. Irrigation efficiency in surface method of irrigation can be easily increased to 60 % by proper design and operation of the system. However, irrigation efficiency is considerably high in case of pressure system of irrigation. However, it has many limitations in terms of its use under specific set of conditions.

Depending on the condition of the infrastructure, the length of the canals and the climate, there are during the transport in the canal system: Percolation into the ground, seepage through the canal bunds, spilling over the bunds and through holes in the bunds, uptake by weeds on the bunds or banks and evaporation from the water surface. A decisive factor regarding losses is the material of the canals. In earthen canals, losses are higher than in lined canals. In lined canals, losses depend on the ` of the lining. The losses can be estimated and/or measured and allow to assess the conveyance efficiency (Ec) in percent.

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For evaluating the overall performance of the irrigation system, it is essential to examine the efficiency of each component of the system which helps to identify the components which are not performing well and take suitable measures to improve them. The overall irrigation efficiency may be expressed as follows:

$$Ei = \left(\frac{Er}{100}\right)\left(\frac{Ec}{100}\right)\left(\frac{Ea}{100}\right)x100 \qquad (1)$$

Where,

Ei = Overall irrigation efficiency (%);

Er = Reservoir storage efficiency (%);

Ec = Water conveyance efficiency (%); and

Ea = Irrigation application efficiency (%).

i. Reservoir Storage Efficiency (Er):

It is defined as the efficiency with which water stored in a reservoir and is expressed as

$$Er = \left(1 - \frac{Ve + Vs}{Vi}\right) x\ 100$$

$$= \left(\frac{Vo + \Delta s}{Vi}\right) x\ 100 \qquad (2)$$

Where,

Ve = Evaporation volume from the reservoir;

Vs = Seepage volume from the reservoir; and

Vi = Inflow to the reservoir during a time interval

Vo= volume of out flow from the reservoir

ΔS = change in reservoir storage

Illustrative Example: 1 *Compute the reservoir storage efficiency for a 24-hr period when 5795 lit/min of water are diverted from reservoir based on the following data,*

Reservoir inflow rate = 6425 lit/min and ΔS = 715 m^3.

Solution:

We know,

$$= \left(\frac{Vo + \Delta s}{Vi}\right) x\ 100$$

Where,

$$Vi = 6425\ \text{lit}/min = \frac{6425x24x60}{1000} = 9252\ m^3$$

$$Vo = 5775\ \text{lit}/min = \frac{5775x24x60}{1000} = 8316\ m^3$$

Δs = 715 m^3

$$Er = \left(\frac{8316 + 715}{9252}\right) = 97.61\%$$

ii. Efficiency of water-conveyance (Ec): It is the ratio of the water delivered into the fields from the outlet point of the channel, to the water entering into the channel at its starting point. It takes the conveyance or transit losses into consideration, this may be expressed as:

$$Ec = \frac{Wf}{Wd} x\ 100 \qquad (3)$$

where Ec is the water conveyance efficiency (%), Wf is the volume of water delivered to the farm or irrigation field (m^3),and Wdis the volume of water diverted from the source(m^3).Ec also applies to segments of canals or pipelines, where the water losses include canal seepage or leaks in pipelines. The global Ec can be computed as the product of the individual component efficiencies, Eci, where i represents the segment number. Conveyance losses include any canal spills (operational or accidental) and reservoir seepage and evaporation that might result from management as well as losses resulting from the physical configuration or condition of the irrigation system. Typically, conveyance losses are much lower for closed conduits or pipelines compared with unlined or lined canals. Even the conveyance efficiency of lined canals may decline overtime due to material deterioration or poor maintenance.

iii. Efficiency of water- application: Water application efficiency relates to the actual storage of water in the root zone to meet the crop water needs in relation to the water applied to the field. It might be defined for individual irrigation or parts of irrigations or irrigation sets. Water application efficiency includes any application losses to evaporation or seepage from surface water channels or furrows, any leaks from sprinkler or drip pipelines, percolation beneath the root zone, drift from sprinklers, evaporation of droplets in the air, or runoff from the field. In case of surface irrigation evaporation losses are generally small but runoff and deep percolation are substantial. However, air losses (droplet evaporation and drift) can be very large if the sprinkler design or excessive pressure produces a high percentage of very fine droplets. Water application efficiencies expressed as:

$$Ea = \frac{Ws}{Wf}\ x\ 100 \qquad (4)$$

where Ea is the application efficiency (%), Ws is the water stored at the root zone of plant` at the source needed by the crop (m^3), and Wf is the water delivered to the field or farm (m^3).

The root zone may not need to be fully refilled, particularly if some root zone water-holding capacity is needed to store possible or likely rainfall. Often, Ws is characterized as the volume of water stored in the root zone from the irrigation application. Some irrigations may be applied for reasons other than meeting the crop water requirement (germination, frost control, crop cooling, chemigation, fertigation, or weed germination). The crop need is often based on the" beneficial water needs. In some surface irrigation systems, the runoff water that is necessary to achieve good uniformity across the field can be recovered in a "tailwaterpit" and recirculated with the current irrigation or used for later irrigations, and Vf should be adjusted to account for the "net" recovered tail water. Efficiency values are typically site specific. Table 2 provides a range of typical farm and field irrigation application efficiencies and potential or attainable efficiencies for different irrigation methods that assumes irrigations are applied to meet the crop need.

iv. Efficiency of water-storage: It is the ratio of the water stored in the root zone during irrigation to the water needed in the root zone prior to irrigation (i.e. field capacity – existing moisture content). The storage efficiency, it is expressed as:

$$\mathrm{Es} = \frac{Ws}{Wn} \mathrm{x}\ 100 \qquad (5)$$

where Es is the storage efficiency (%) and Was is the water stored at the root zone of plant` at the source needed by the crop (m^3), Wnis the water needed in the root zone prior to irrigation (m^3). The root zone depth and thewater-holding capacity of the root zone determine Wrz. Thestorage efficiency has little utility for sprinkler or micro irrigation because these irrigation methods seldom refill the root zone, while it is more often applied to surface irrigation methods.

v. Irrigation Efficiencyof water use: It is the ratio of the watervolume beneficially used, including leaching water, to the quantity of water delivered.The irrigation efficiency,it is expressed as:

$$\mathrm{Ei} = \frac{Wb}{Wd} x\ 100 \qquad (6)$$

where Ei is the irrigation efficiency (%) and Wb isthe water volume beneficially used by the crop (m^3). Wd issomewhat subjective,water delivered to the field, but it basically includes the required crop evapotranspiration (ETc) plus any required leaching water (Wl) for salinity management of the croproot zone.It is also expressed as ratio of crop yield to the amount of water depleted by crop in the process of evapotranspiration

Cropwateruseefficiency= $\frac{Y}{ET}$

where, Y = Crop yield, and

ET = The amount of water depleted by crop in the process ofevapotranspiration.

(a). Leaching requirement (or the leaching fraction): The leaching requirement, also called the leaching fraction, is defined as

$$Lr = \frac{Wd}{Wf} = \frac{ECi}{ECd} \qquad (7)$$

where Lr is the leaching requirement, Wd is the volume of drainage water (m3), Wf is the volume of irrigation (m3) applied to the farm or field, ECi is the electrical conductivity of the irrigation water, Decisiveness per metre(dS/m), or (640 mg /l)and ECd is the electrical conductivity of the drainage water (dS/m). The Lr is related to the irrigation application efficiency, particularly when drainage is the primary irrigation loss component. The Lr would be required "beneficial" irrigation;(Vl = LrWf), so only Wd greater than the minimum required leaching should reduce irrigation efficiency. Then, the irrigation efficiency can be determined by combining Equations. (6) and (7)

$$Ei = \left(\frac{Wb}{Wf} + Lr\right) x100 \qquad (8)$$

Burt et al. defined the "beneficial" water use to include possible off-site needs to benefit society (riparian needs or wildlife or fishery needs). They also indicated that Vf should not include the change in the field or farm storage of water, principally soil water but it couldinclude field (tailwater pits) or farm water storage (a reservoir) that wasn't used within the time frame thatwas used to define Ei.

vi. Waterdistributionefficiency: The effectiveness of irrigation may also be measured by its water distribution efficiency. The water distribution efficiency represents the extent to which the water has penetrated to a uniform depth, throughout the field. When the water has penetrated uniformly throughout the field, the

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deviation from the mean depth is zero and the water distribution efficiency is 1.0.

Water distribution efficiency

$$E_d = 100 \text{ x } \left(1 - \frac{d}{D}\right) \qquad (9)$$

Where,D = Average depth of precipitation along the run off during irrigation, d = Average numerical deviation from –D

Water distribution efficiency indicates uniformity in distribution of water over the entire rootzone.

According to FAO between 60 - 95 % conveyance efficiencies (see Table 1) and 60 - 90 % field application efficiencies apply (Table 2).

Water losses on-farm or on the field are caused by deep percolation to soil layers below the crop root zone, by surface run-off, by use of weeds and by evaporation from the soil surface between the crops. Another important factor is the farmer's training and knowledge with regard to agriculture and irrigation.

vii. Effective Irrigation Efficiency (Ee): Reuse of runoff water decreases the amount of waterpumped from a source and can improve overall irrigation efficiency. Effective irrigation efficiency (Ee) is theoverall irrigation efficiency corrected for runoff anddeep percolation water that is recovered and reused orrestored to the water source without reduction in waterquality. It is expressed as:

$$Ee = [Eo + (FR) \times (1.0 – Eo)] \times 100 \qquad (10)$$

FR = fraction of surface runoff, seepage, and/or deep percolation that is recovered

Eo = overall irrigation efficiency (%)

In some areas, water regulations prohibit irrigation water pumped from groundwater to leave the field asrunoff. Producers are, therefore, more motivated to reuse irrigation runoff to prevent it from leaving the field. Irrigatorswho do not have reuse systems often reduce the stream size in the furrow to minimize runoff. While this practice can reduce runoff, it generally results in poorer distribution of water and deeper percolation. Another way to reduce runoff while improving water distribution is to use surge-flow irrigation. Blocking the furrow ends is yet another way of reducing runoff. Losses due to wind drift, evaporation, and transpiration by weeds cannot be recovered.

Table 2: Indicative values of field application efficiencies

Irrigation method	Field application efficiency
1	2
1. Surface irrigation	
Furrow (conventional)	45% - 65%
Furrow (surge)	55% - 75%
Furrow (with tail water reuse)	55% - 75%
Basin (with or without furrow)	60% - 75%
Basin (paddy)	40% - 60%
Precision level basin)	40% - 60%
2.Sprinkler irrigation	
LEPA	80% - 90%
Side roll	65% - 85%
Hand move	65% -80%
Travelling Gun	60% -70%
Centre Pivot &Linear	70% -95%
Solid set	70% -85%
3.Drip or Micro irrigation	
Bubbler (low head)	80% -90%
Micro spray	85%- 90%
Point source emitters	75% -95%
Line source emitters	70% -95%
Subsurface drip	>95
Surface drip	85% -95%

Source: Raghuvanshi, 2013& FAO

Table 3: Indicative values of conveyance efficiencies for adequately maintained canals

Canal length	Earthen canals/ Soil type			Lined canals
	Sand	Loamy	Clayey	
1	2	3	4	5
1.Long (>2000 m)	60%	70%	80%	95%
2.Medium (200 - 2000 m)	70%	75%	85%	95%
3.Short (< 200 m)	80%`	85%	90%`	95%

Source: Food and Agriculture Organization of the United Nations (FAO)

Once the conveyance and field application efficiency have been determined, the scheme irrigation efficiency (Ei) can be calculated, using the following formula:

$$Ei = \left(\frac{Ec}{100}\right)\left(\frac{Ea}{100}\right) \text{x } 100$$

Where,

Ei = scheme irrigation efficiency (%)

Ec = water conveyance efficiency (%)

Ea = field application efficiency (%)

A scheme irrigation efficiency of 50-60% is good; 40% is reasonable, while a scheme Irrigation efficiency of 20-30% is poor. It should be kept in mind that the values mentioned above are only indicative values.

***Illustrative Example**:2 Determine the project irrigation efficiency for a scheme with a long canal system. The canals are constructed in heavy clay and the irrigation method is furrow irrigation. Maintenance of the canals is adequate.*

Solution:

The conveyance efficiency, using Table 1: Ec = 80%.

The field application efficiency, using Table 2: Ea = 60%.

Calculate the scheme irrigation efficiency, using the formula:

$$\mathrm{Ei} = \left(\frac{Ec}{100}\right)\left(\frac{Ea}{100}\right) \text{x } 100$$

$$\mathrm{Ei} = \left(\frac{80}{100}\right)\left(\frac{60}{100}\right) \text{X } 100 = 48\%$$

Thus, the scheme irrigation efficiency Ei = 48% or approximately 50%. This is considered a fairly good scheme Irrigation efficiency, for a surface Irrigation system.

***Illustrative Example: 3** A stream of 160 litters per second was delivered from a canal and 120 litters per second were delivered to the field. An area of 1.9 hectares was irrigated in 8 hours. The effective depth of root zone was 1.8 m. The runoff loss in the field was 436 m^3.the depth of water penetration varied linearly from 1.8 m at the head end of the field to the 1.2 m at the end of the tail end. Available moisture holding capacity of the soil is 20 cm per meter depth of soil. Determine the water conveyance efficiency, water application efficiency, water storage efficiency and water distribution efficiency; irrigation was started at a moisture extraction level of 50 per cent of the available moisture.*

Solution:

We know Equation (3)

i Efficiency of water-conveyance,

$$\mathrm{Ec} = \frac{Wf}{Wd} \text{x } 100$$

$$= \frac{120}{160} \text{x } 100 = 75\%$$

We know Equation (4)

ii. Water application efficiency

$$\mathrm{Ea} = \frac{Ws}{Wf} \, x \, 100$$

Water delivered to the field

$$= \frac{120\text{x}60\text{x}60\text{x}8}{1000} = 3456 \text{ m}^3$$

Water stored in the root zone = (3456-436) = 3020 m^3

Water application efficiency

$$\mathrm{E_c} = \frac{3020}{3456} \text{x}100 = 87.38\%$$

We know Equation (5)

iii.Water storage efficiency

$$\mathrm{Es} = \frac{Ws}{Wn} \text{x } 100$$

Water holding capacity of the root zone = 20x1.8 = 36 cm

Moisture required in the root zone = 36-(36x50)/100) = 18 cm

$$= \frac{18}{100} \text{x}1.9\text{x}10000 = 3420 \text{ m}^3$$

$$\mathrm{Es} = \frac{3020}{3420} \text{x } 100 \quad = \ 88.30\%$$

We know Equation (9)

iv. Water distribution efficiency

$$\mathrm{E_d} = 100 \text{ x } \left(1 - \frac{\mathrm{d}}{\mathrm{D}}\right)$$

$$\mathrm{D} = \frac{1.8 + 1.2}{2} = 1.5$$

Numerical deviation from depth of penetration:

At upper end = 1.8 - 1.5 = 0.3

At lower end = 1.5 - 1.2 = 0.3

Average numerical deviation = (0.3+0.3)/2 = 0.3

Water distribution efficiency

$$\mathrm{E_d} = 100 \text{ x } \left(1 - \frac{0.3}{1.5}\right) = 80\%$$

1.4 Irrigation uniformity:The fraction of water used efficiently and beneficially is important for improved irrigation practice. The uniformity of the applied water significantly affects irrigation efficiency. The uniformity is a statistical property of the applied water's distribution. This distribution depends on many factors that are related to the method of irrigation, soil topography, soil hydraulic or infiltration characteristics, and hydraulic characteristics (pressure, flow rate, etc.) of the irrigation system. Irrigation application distributions are usually based on depths of water (volume per unit area); however, for micro irrigation systems they are usually based on emitter flow volumes because the entire land area is not typically wetted.

1.5 Water Use Efficiency (WUE): The previous sections discussed the engineering aspects of irrigation efficiency. Irrigation efficiency is clearly influenced by the amount of water used in relation to the irrigation water applied to the crop and the uniformity of the applied water. These efficiency factors impact irrigation costs, irrigation design, and more important, income cases, the crop productivity. Water use efficiency (WUE) has been the most widely used parameter to describe irrigation effectiveness in terms of crop yield. Water use efficiency is defined as yield of marketable crop produced per unit of water used inevapotranspiration.It is expressed as:

$$\mathrm{WUE} = \frac{\mathrm{Y}}{\mathrm{ET}} \qquad (11)$$

Where,WUE = Water use efficiency (kg/ha/mm or kg/m^3 of water), Y = marketable yield (kg/ha or gm/m^2), ET= Evapotranspiration (mm). Water use efficiency is usually expressed by the economic yield, but it has been historically expressed as well in terms of the crop dry matter yield (either total biomass or aboveground dry matter). These two WUEbases (economic yield or dry matter yield) have led to some inconsistencies in the use of the WUE concept. The transpiration ratio (transpiration per unit dry matter) is a more consistent value that depends primarily on crop species and the environmental evaporative demand, and it is simply the inverse of WUE expressed on a dry matter basis.

If yield is proportional to ET, water use efficiency has to be constant but it is not so. Actually, Y and ET are influenced independently by crop management and environment. Yield is more influenced by crop management practices, while ET is mainly dependent on climate and soil moisture. Fertilization and other cultural practices for high yield usually increase in water use accompanying fertilization is often negligible. Crop production can be increased by judicious irrigation without markedly increasing ET. Under optimum water supply, ET is not dependent on kind of plant canopy provided the soil is adequately covered with crop. Increasing the amount of plant canopy has therefore little or no effect on ET. Obviously, any practice that remotes plant growth and more efficient use of sunlight in photosynthesis without causing a corresponding increase in ET will increase WUE.

Factors affecting Water Use Efficiency (WUE):

i. Nature of the plant: There are considerable between plant species to produce a unit dry matter per unit amount of water use resulting in widely varying values of WUE.

Table 3:Water use efficiency of different crops:

Crop	Water Requirement in mm	Grain Yield (kg/ha or kg/m^2)	WUE (kg/ha/mm or kg/m^3)
1	2	3	4
1. Rice	2000	6000	3.0
2. Sorghum	500	4500	9.0
3. Bajara	500	4000	8.0
4. Maize	625	5000	8.0
5. Groundnut	506	4680	9.2
6. Wheat	280	3534	12.6
7.Finger millet	310	4137	13.4

There is also difference in WUE between varieties of the same crop. Selection of properly adopted crop, with good rooting habit, low transpiration rates increase. WUE

ii. Climatic Conditions:

Weather affects both Y and ET. Manipulation of climate to any extent is possible at present. However, ET can be reduced by mulching, use of antitranspirant etc. To limited extent, but may not be economical or practical. Weed control is the most effective means of reducing ET losses and increasing the amount of water available to the crop thereby increasing WUE.

iii. Soil Moisture Content:

In adequate supply of soil moisture as well as excess moisture supply to the crop have an adverse effect on plant growth and production and therefore conductive to low WUE. For each crop combination of environment conditions, there is a narrow range of soils moisture level at which WUE is higher than with lesser or greater supply of water, proper scheduling of irrigation will increase WUE.

iv. Fertilizers:

Irrigation improves a greater demand for plant nutrients. Nutrient availability is highest foremost of the crops when water tension is low. All available evidences indicate that under adequate irrigation suitable fertilization generally increase yield considerably, with a relatively small increase in ET and therefore, markedly improve WUF.

v. Plant population:

Higher yield potential made possible by the favourable water regime provided by irrigation, the high soil fertility level resulting from heavy application of fertilizers and genetic potentialof new varieties and hybrids, could be achieved only with appropriate adjustments of thepopulation. The highest yields and WUE are possible only through optimum levels of soilmoisture regime, plant population and fertilization.

1.6 Improving the efficiencies for water use: The efficiencies of individual on farm water systems need to be improved to ensure that water withdrawn from the natural system, after considerable use of resources is used in an efficient way. Proper levelling of farms could improve the water application efficiencies by over 20% Laser levelling may be employed on large scale to level the irrigation layouts to improve water use. Proper designing offarm layouts would also improve the water application anduse efficiencies. A relook on the water pricing and realistic values could promote efficient use of natural resources. Automation, computer-controlled decision support systems, on demand irrigation through creation of level pools in canals, using real time soil moisture data to decide irrigation doses etc. are important means of improving efficiency. Use of modern irrigation methods such as micro-irrigation should be promoted to enhance water use efficiency. Recent researches have shown that surface seeding or zero-tillage establishment of upland crops after rice gives similar yieldsto when planted under normal conventional tillage over adiverse set of soil conditions. This reduces costs ofproduction, allows earlier planting and thus higher yield, results in less weed growth, reduces the use of natural resources such as fuel and steel for tractor parts, and shows improvements in efficiency of water and fertilizers. Availability of assured prices and infrastructure could createa situation for better utilization of groundwater. Policiesshould to be evolved that would encourage farmers toenrich organic matter in the soil and thus improve soilhealth such as financial compensation/incentive for greenmanuring.

1.7 Evaluating the Uniformity of Water Application: All irrigation systems apply water nonuniformly to a varying degree. The irrigation system performance efficiency terms described previously do not directly account for the uniformity or nonuniformity of irrigation application within a given field. Yet, the nonuniformity of the applied water can significantly affect irrigation performance. Nonuniform irrigation application results in areas that are under-watered or over-watered. Crops may experience water stress in areas that are under-watered, and oxygen stress in areas that are waterlogged for several days. Over-watering also may cause surface runoff and/ or leaching of nutrients below the root zone. Thus, both under- and over-watered areas may experience yield reduction. With favourable climate conditions, optimum crop growth and yield are obtained with high uniformity of irrigation application in which each plant has an equal opportunity to access the applied water and nutrients. The uniformity of irrigation application depends on many factors that are related to the method of irrigation, topography, soil (infiltration) characteristics, and the irrigation system’s pressure and flow rate. For a sprinkler irrigation system, nonuniformity can be due to numerous factors: (1) improper selection of delivery pipe diameters (sub-main, manifolds, and lateral), (2) too high or too low operating pressure, (3) improper selection of sprinkler heads and nozzles, (4) inadequate sprinkler overlap, (5) wind effects on water distribution, (6) wear and tear on system components with time, such as pump impellers, pressure regulators, or nozzle size, and (7) nozzle clogging. For surface irrigation, nonuniformity can be caused by: (i) differences in opportunity time for infiltration caused by advance and recession, (ii) spatial variability of soil-infiltration properties, and (iii) non-uniform grades. For micro-irrigation, nonuniformity can be due to: (i) variations in pressure caused by pipe friction and topography, (ii) variations in hydraulic properties of emitters or emission points (from clogging or other reasons), (iii) variations in soil wetting from emission points, and (iv) variations in application timing. For all irrigation methods, poor management also can cause nonuniformity. Generally, irrigation uniformity is calculated based on indirect measurements. For example, the uniformity of water that enters the soil is assumed to be related to that collected in catch cans for sprinkler systems, to intake opportunity time and infiltration rates for surface systems, and to emitter discharge for micro irrigation systems. The common uniformity measures for sprinkler, surface, and micro irrigation systems are illustrated below.

i. Sprinkler Irrigation: In this method of irrigation, water is applied to the crop in the form of rainfall. Water is distributed through a system of pipes with pressure of 2-3 kg/cm' (20-30 m head of water) by pumping. It is then sprayed into the air through sprinklers so that it breaks up into small water drops which fall to the ground. The system consisting of, a pump, water storage tank, main and lateral pipes, water filters, fertilizer applicator and sprinklers ensures uniform application of water. The desired depth of water depending upon water requirement can be applied at different times ensuring, considerable high-water application efficiency (75-80%). The fertilizer and pesticidescan also be efficiently applied along with irrigation water. This is a portable system and can be moved to cover large area with a small setup. However, precautions need to be taken during high winds. In order to overcome this problem, the irrigationmay be applied during night time when wind velocity is minimum for uniform water application.

ii. Surface Irrigation:Depending upon the crop, soil type and topography, surface methods of irrigation such as border, check basin and furrow methods of irrigation are generally used. For most of the cereal crops, border method of irrigation which consists of strips of certain width and length with a uniform slope is used. This method requires a certain amount of field levelling as water flows by gravity from upstream to downstream by providing a uniform slope depending upon the soil conditions. For crops which require standing water like rice and vegetables, check method of irrigation which consists of number of small bunded fields is generally used. For row crops such as cotton, sugarcane and some vegetable crops, furrow irrigation is an ideal method. In hilly areas with undulating topography contour furrows are used. During rainy season, it helps in not only moisture conservation but serves the purpose of drainage also. Surface irrigation is the most widely used irrigation method all over the world due to its simplicity, less cost and minimum requirement of instrumentation. At most of the places, surface irrigation efficiency is very low resulting in huge water losses which is not only the wastage of scarce and costly water resource but leads to soil degradation in terms of water logging and drainage as well. It is therefore, absolutely essential that proper surface irrigation method should be selected suiting the existing conditions as outlined above which should be properly designed for high irrigation efficiency.

iii. Drip or Micro Irrigation: Drip irrigation, also known as trickle irrigation or micro-irrigation is an irrigation method which minimizes the use of water and fertilizer by allowing water to drip slowly to the roots of plants, either onto the soil surface or directly onto the root zone, through a network of valves, pipes, tubing, and emitters. It is becoming popular for row crop irrigation. This system is used in place of water scarcity as it minimizes conventional losses such as deep percolation, evaporation and run-off or recycled water is used for irrigation. Small diameter plastic pipes fitted with emitters or drippers at selected spacing to deliver the required quantity of water are used. Drip irrigation may also use devices called micro-spray heads, which spray water in a small area, instead of dripping emitters. These are generally used on tree and vine crops with wider root zones. Subsurface drip irrigation (SDI) uses permanently or temporarily buried dripper line or drip tape located at orbelow the plant roots. Pump and valves may be manually or automatically Irrigation Methods operated by a controller. The modem technology of drip irrigation was invented in Israel.

Drip irrigation is the slow, frequent application of water to the soil though emitters placed along a water delivery line. The term drip irrigation is general, and includes several more specific methods. Drip irrigation applies the water through small emitters to the soil surface, usually at or near the plant to be irrigated. Subsurface irrigation is the application of water below the soil surface. Emitter discharge rates for drip and subsurface irrigation are generally less than 12 litters per hour. Bubbler irrigation is the application of a small stream of water to the soil surface. The applicator discharge rate (up to 250 litters per hour) exceeds the soil's infiltration rate, so the water ponds on the soil surface. A small basin is used to control the distribution of water. Micro-spray irrigation applies water to the soil surface by a small spray or mist. Discharge rates are usually less than 120 litters per hour.

iv. Christiansen's Uniformity Coefficient (Cu) for Sprinkler Systems:Christiansen's Uniformity Coefficient (Cu) is commonly used to describe uniformity for stationary sprinkler irrigation systems and is based on the catch volumes (or depth):

$$C_u = \left[1 - \frac{(\sum Xi - Xm)}{\sum Xi}\right] x100 \qquad (12)$$

C_u = Christiansen's uniformity coefficient (%) Xi = measured depth water in equally spaced catch cans on a grid arrangement (mm) Xm = mean depth of water of the catch in all cans (mm) ∑ = indicates that all measured depths are summed (mm)

The Cu method assumes that each can represents the depth applied to equal areas. This is not true for data collected under centre pivots where the catch cans are equally spaced along a radial line from the pivot to the outer end. For centre pivot systems, it is necessary to adjust and weigh each measurement based on the area it represents.

v. Adjusted Uniformity Coefficient (Cu(a)) for Centre Pivot `Systems: The adjusted uniformity coefficient for centre pivots reflects the weighted area for catch cans that are uniformly spaced and, thus, represent unequal land areas:

$$Cu(a) = \left\{1 - \left[\frac{\sum Si\left[Vi - \left(\frac{\sum ViSi}{\sum Si}\right)\right]}{\sum (ViSi)}\right]\right\} x100 \qquad (13)$$

Cu(a) = adjusted uniformity coefficient for centre pivots (%)

Si = distance from the pivot to the *i*th equally spaced catch container (m)

Vi = volume of the catch in the *I*th container (mm)

vi. Coefficient of Design Uniformity (CUd) forMicro irrigationSystems: Another parameter commonly used to evaluate the uniformity of water distribution in micro irrigation systems is the coefficient of design uniformity (C_{Ud}), whichis based on the emitter discharge rate deviations from the average rate:

$$C_{Ud} = \left[\left(1 - 0.798(C_{vm})\mathrm{n}^{-1/2}\right)\right] x100 \qquad (14)$$

C_{Ud} = coefficient of design uniformity (%)

C_{vm} = manufacturer's coefficient of uniformity

n = the number of emitters per plant

vii. Low-Quarter Distribution Uniformity (D_U) for SurfaceIrrigation Systems:The distribution uniformity is more commonly used to characterize the irrigation water distribution over the field in surface irrigation systems, but it also can be applied to micro and sprinkler irrigation systems. The low-quarter distribution uniformity (D_U) is defined as the average depth infiltrated in the low one-quarter of the field divided by the average depth infiltrated over the entire field. It is expressed as:

$$D_U = \left(\frac{D_{lq}}{D_{ay}}\right) x100 \qquad (15)$$

D_U = distribution uniformity (%)

D_{lq} = average depth of water infiltrated in the low one quarterof the field (mm)

D_{ay} = average depth of water infiltrated over the field (mm).

Typically, D_U is based on the post-irrigation measurement of water depth that infiltrates the soil because it can be more easily measured and better represents the water available to the crop. However, using post-irrigation measurements of infiltrated water to evaluate D_U ignores any water intercepted by the crop and evaporated, and any soil water evaporation that occurs before the measurement. Any water that percolates below the root zone or the sampling depth also will be ignored. A low D_U (<60%) indicates that the irrigation water is unevenly distributed, while a high D_U (<80%) indicates that the application is relatively uniform over the entire field.

viii. Emission Uniformity (EU) for Micro irrigation Systems:For micro irrigation systems [trickle (surface drip), subsurface drip, micro spray], both C_U and D_U`conceptsare impractical because the entire soil surface is not wetted. Micro irrigation uniformity is affected by the variability in emitter discharge rates. Variability can because by manufacturing variations in orifice size and shape, clogging of the orifices, topographic factors, and hydraulic characteristics of the irrigation system. Uniformity of irrigation water application in micro irrigation systems is defined by emission uniformity (EU) expressed by the empirical formula:

$$E_U = \left\{\left[1 - 1.27(C_{vm})n^{-\frac{1}{2}}\right]\left(\frac{q_{min}}{q_{avg}}\right)\right\}x100 \qquad (16)$$

E_U = emission uniformity (%)
C_{vm} = manufacturer's coefficient of uniformity (unitless)
n = the number of emitters per plant
qmin = minimum emitter discharge rate at minimum systempressure (m^3/sec)
qavg = average emitter discharge rate (m^3/sec)

The definition of E_U is based on the ratio of the discharge rate for the lowest quarter of emitters to the average discharge rate, and includes the influence of multiple emitters per plant so that each may have a flow rate from population of random flow rates based on the emitter variations from manufacturing.

1.8 Evaluating the Response of the Crop to Irrigation: Irrigation system performance and irrigation uniformity parameters discussed previously evaluate the engineering and operational aspects of the irrigation system. Different parameters are used to evaluate the response of the crop to irrigation water. The three most commonly used parameters for evaluating the response of the crop to water are crop water use efficiency, irrigation water use efficiency, and water use efficiency.

i. Water use efficiency:Water use efficiency is a term commonly used to describe the relationship between water(input) and agriculture product (output). When used in this way the term is, strictly speaking, a water use *index*. Water use efficiency is also often used to express the effectiveness of irrigation water delivery and use.Barrett Purcell & Associates (1999) correctly point out that efficiency is in fact a dimensionless term obtained by dividing figures with the same units e.g. volume of water used (output)divided by a volume of water supplied (input). Consequently, the tonnes of produce per mega litre of water used is an *index*, not an *efficiency*. This common mis-usage of the term "water use efficiency" has created great confusion.

Adding to this confusion is the distinction between describing the agronomic performance of the crop (crop water use index) and the engineering aspects of the design and management of the system (irrigation index or efficiency).

A crop water use index compares an output from the system, such as yield or economic return, to crop evapotranspiration. In contrast, an irrigation index or efficiency often compares an output, such as yield, economic return or amount of water retained in the root zone to an input, such as some measure of water applied.

To reduce this terminology confusion, Barrett Purcell & Associates have suggested that water use efficiency be used as an umbrella term or as a generic label for a toolbox. Within this toolbox there are two compartments. The first compartment is a framework for the dimensionless efficiency measures, based on the calculation of a water balance, and the second compartment contains a suite of performance indices e.g. tonnes per mega litre or gross margins per megalitre. They state that:

"the term 'Water Use Efficiency' should be restricted to a generic label for any performance indicators used to study water use in crop production. This label, Water Use Efficiency, need not be defined but should be considered like a label on a toolbox. Inside the toolbox are many specific performance indicators that should be referred to as Water Use Indices. Any water use index (within this toolbox) should be clearly defined with specific units when used."

The engineering aspects of Irrigation efficiency is clearly influenced by the amount of water used in relation to the irrigation water applied to the crop and the uniformity of the applied water. These efficiency factors impact irrigation costs, irrigation design, and more important, in some cases, the crop productivity. Water use efficiency (WUE) has been the most widely used parameter to describe irrigation effectiveness in terms of crop yield. defined WUE as:

$$WUE = \frac{Y}{ET} \qquad (17)$$

where WUE is water use efficiency (kg/m^3), Y is the economic yield (g/m^2), and ET is the crop water use(mm). Water use efficiency is usually expressed by the economic yield, but it has been historically expressed swell in terms of the crop dry matter yield (either total biomass or aboveground dry matter). These two Wheelbases (economic yield or dry matter yield) have led twosome inconsistencies in the use of the WUE concept. The transpiration ratio (transpiration per unit dry matter) is a more consistent value that depends primarily on crop species and the environmental evaporative demand, and it is simply the inverse of WUE expressed on a dry matter basis.

ii. Crop Water Use Efficiency:The previous discussion of WUE does not explicitly explain the crop yield response to irrigation. Water use efficiency is influenced by the crop water use (ET), defined a term for WUE to characterize the influence of Crop Water Use Efficiency (CWUE)is mostly used to describe irrigation effectiveness in terms of crop yield (crop productivity). It is defined as the ratio of the massif economic yield or biomass produced per unit of irrigation water used in ET. It is expressed as:

$$\mathrm{CWUE} = \frac{(\mathrm{Y_i} - \mathrm{Y_d})}{(\mathrm{ET_i} - \mathrm{ET_d})} \qquad (18)$$

CWUE = crop water use efficiency (kg/ha-mm)
Yi = yield of the irrigated crop (kg/ha)
Yd = yield for an equivalent rained crop (kg/ha)
ETi = ET for irrigated crop (mm)
ETd = ET for rainfed crop (mm)

From the above definition, crop water use efficiency has units of production per unit of water used in ET.Units typically used are ton per ha-mm, kg perha-mm, or bushels per ha-mm

iii. Irrigation Water Use Efficiency (IWUE):Irrigation water use efficiency (IWUE) is used to characterize crop yield in relation to total depth of water applied for irrigation. It is expressed as follows:

$$\mathrm{IWUE} = \frac{(\mathrm{Y_i} - \mathrm{Y_d})}{\mathrm{IR_i}} \qquad (19)$$

IWUE = irrigation water use efficiency (kg/ha-mm)
Yi = economic yield of the irrigation level crop (kg/ha)
Yd = economic yield for an equivalent rainfed crop(kg/ha)
IRi = depth of irrigation water applied for irrigation(mm)

The CWUE is a better indicator when quantifying the efficiency of a crop production system because it directly reflects the amount of grain yield produced per amount of water used rather than per depth of water applied, which is the case with the IWUE. This is because not all irrigation water applied to the field is used for crop ET.

Thus, IWUE does not account for the irrigation application losses and actual water used by the crop.

iv. Crop Water Use Efficiency:Benchmark water use efficiency looks at the total amount of water used to produce the yield and is expressed as:

$$WUEb = \frac{Y_i}{(P_e + \mathrm{IR} + \triangle\ \mathrm{SW})} \qquad (20)$$

WUEb = benchmark water use efficiency
Yi = yield of irrigated crop (kg/ha)
Pe = effective rainfall (mm)
IR = irrigation applied (mm)
ΔSW = change in soil water content in the root zoneduring the growing season (mm)

The denominator of equation 19 is a surrogate estimate for the water used to produce yield. It neglects deep percolation losses, groundwater use, and surface runoff. Experienced irrigation practitioners use WUEb for a specific region and to identify differences between irrigation methods, irrigation management, or both.

Conclusion

Irrigation efficiency is described by several terms used to measure how efficiently irrigation water is applied tithe field and/or used by the crop. High irrigation efficiency translates into lower operating costs, improved production per unit of water delivered, and improved environmental benefit and management. Incorrect use of efficiency terms can lead to misrepresentation of how well an irrigation system is performing. Therefore, it is important for both producers and irrigation management professionals to selectthe appropriate efficiency and uniformity parameters when evaluating irrigation systems. Several adjustments

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can be made to the volume of water delivered to the field to increase irrigation efficiency or uniformity. However, efficiencies of100 percent are not always desirable or practical. The efficiency and uniformity indices described in this publication can provide the measure to achieve more efficient irrigation management that will lead to conserving water and protecting environmental quality unirrigated agriculture.

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