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DRAFT IRRIGATION EFFICIENCY AND PRODUCTIVITY MANUAL

TOOLS FOR IRRIGATION PROFESSIONALS AND PRACTIONERS

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Raising Irrigation Productivity And Releasing Water for Intersectoral Needs

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Definitions of terms

Conventional irrigation efficiency (CIE) is the efficiency of measured using conventional or traditional methods of measuring efficiency. In this method irrigation efficiency is defined and measured using irrigation efficiency indicators of conveyance efficiency, distribution efficiency, water application efficiency and some times the distribution uniformity coefficient or equity ratio.

Duration of water in fields (DWF) is the total number of day's water is maintained in paddy fields from transplanting until harvesting.

Field operation and management efficiency (FOME) is the management of water in the field related wetting fields, water depths maintained in fields, delays of water from upstream to downstream users and the number of days water spends in fields.

Integrated water resource management (IWRM) is the management of water resources that takes into account all users and beneficiaries and emphasises its management in an integrated manner.

Irrigation efficiency (IE) is the ratio of the amount of water consumed by the crop to the amount of water supplied through irrigation (surface, sprinkler or drip irrigation).

Irrigation situation efficiency (ISE) is the efficiency of an irrigation system determined at a particular period of time that takes into account the micro-efficiencies of irrigation water use.

Nested system efficiency (NSE) is the efficiency of two or more connected system depending on a single source of water supply.

Net water requirement (NWR) is the amount of water required to replenish evapotranspiration and deep percolation/seepage or root zone soil moisture deficit.

Gross water requirement (GWR) is the actual amount of water supplied to meet crop evapotranspiration and or percolation/seepage observed under field conditions.

Nested system productivity indicator (NSPI) is the indicator of water productivity for the two or more connected systems of water use.

Nested system wetting days (NSWD) are the total number of days used for wetting the soils for land preparation especially for paddy crop for connected systems of water use.

Productivity of water (PW) is the ratio of output (physical, economical or social) to the amount of water depleted in producing the output.

Nested System Productivity (NSP) is the productivity of water for a nested system of water use

Relative nested system productivity (RNSP) is the productivity of water in comparison to a standard measure of productivity in two or more nested water systems.

Standard rice water productivity (SRWP) is the ratio of practical rice yield achieved under control to the net annual paddy water requirement.

Water depth efficiency (WDE) is the efficiency of water use when expressed in terms of the ratio of required to actual water depths maintained in paddy fields.

Water use efficiency (WUE) is defined as the ratio between the amount of water that is used for an intended purpose and the total amount of water supplied within a spatial domain of interest.

Whole system efficiency (WSE) is the efficiency of water use for the entire defined system.

Whole system productivity indicator (WSPI) is the water productivity indicator for the entire system of water use.

Preface

This manual is aiming to provide irrigation professionals in Tanzania and Eastern Africa two approaches for evaluating irrigation efficiency and productivity. These approaches are the traditional or conventional irrigation efficiency (CIE) methods and the irrigation situational efficiency (ISE). The ISE approach have been developed to address some of the important factors of measuring and assessing irrigation efficiency which cannot be addressed by the CIE

The manual is divided into four sections. Section one deal with evaluation of irrigation efficiency using the conventional or traditional methods. It also gives some key measurement parameters important for evaluating irrigation efficiency under this method and gives an example of the method for irrigation schemes based on design specification. Finally the section gives/outlines some important issues (demerits) which are not addressed in the CIE method.

Section two is about the evaluation of irrigation efficiency and productivity using the ISE approach. It is important to note the inclusion of irrigation productivity as one of the important factor in the evaluation of efficiency under this methodology. Definitions, key measurement parameters and ISE indicators are dealt with giving examples from a case study drawn from Usangu Plains in Tanzania.

Section three of the manual is about the determination of irrigation efficiency and productivity using the irrigation situational efficiency approach. Primary measurement of efficiency parameters and secondary indicators under ISE framework is clearly outlined and described in detail.

Section four outlines some of the important aspects of improving irrigation efficiency and productivity in irrigation systems based on ISE evaluation. Potentials for water saving and intersectoral water allocations are also briefly discussed.

1. Determination of irrigation efficiency using conventional methods

A range of indicators is used when defining irrigation efficiency (IE) using conventional or traditional methods. Common definitions of irrigation efficiency indicators are given by Bos *et al*. 1978-1992; Burman *et al*. 1983 and Heermann *et al*. 1992.

The measurements of CIE parameters are difficult and time consuming. Therefore a rare measurement of IE exist based on physical measurement of the factors affecting IE. Difficulties in measurement of efficiency parameters force evaluation of irrigation efficiency by irrigation professionals to base on efficiency factors that were obtained or measured during scheme designs. Changes in scheme configurations such as size of the distribution systems (canals) may result into fault values of efficiency.

Conventional irrigation efficiency as derived from design process

Useful definitions of components of CIE are given in Box 1. Different symbols are often used to label efficiency factors (Bos *et al.* 1982; Burman *et al.* 1983; Wolters 1992; and Heermann *et al*. 1992). Factors of CIE which are cited in Box 1 below were specifically used by Merwe (1997).

BOX 1: Definitions of important CIE components *(Source: Merwe, 1997)*

Efficiency is expressed in (%) or fraction and is defined as output of a specific operation in relation to the input.

Transportation efficiency (η_t), is the efficiency of transportation of water from the source to the irrigation dam or draw-off point on the farm boundary.

Distribution efficiency (η_d), is the distribution of water from the irrigation dam or draw-off point on the farm boundary through the irrigation system to the point where it leaves the distributor. Losses from the irrigation dam are included here.

Conveyance efficiency (η_c), is the combination of the two above and is defined as the efficiency of conveyance of water from the source to the point where it leaves the point of distribution.

Application efficiency (η_a), is the efficiency with which the water leaving the distribution point of the irrigation system falls onto the soil surface.

System efficiency (η_s), is the efficiency with which water from the irrigation dam or draw-off point on the farm boundary is delivered through the irrigation system to the point where it falls onto the soil surface.

Storage efficiency (η_o), is the efficiency with which the water that falls onto the soil surface, infiltrates the soil and becomes available in the root zone of the plant.

Field application efficiency (η_f), is the efficiency with which the water leaving the distribution point, infiltrates the soil and becomes available in the root zone of the plant.

Irrigation efficiency (η_i), is the efficiency of the total process of irrigation from the source of the water to the point where the water becomes available in the root zone of the plant.

During the design process of irrigation systems, several factors affecting the conventional irrigation efficiency are identified (Step 1 in Figure 1). These factors are used to produce efficiency indicators (Step 2). The indicators in Step 2 are multiplied to form indicators in Step 3. The two remaining factors (in Step 3), the conveyance efficiency and field application efficiency, are the variables in the equation used to analyse irrigation efficiency (BOX 2). For surface irrigation systems, system efficiency (η_s) determined using this approach is normally in the range of 0.4 to 0.6 and even much less some times.

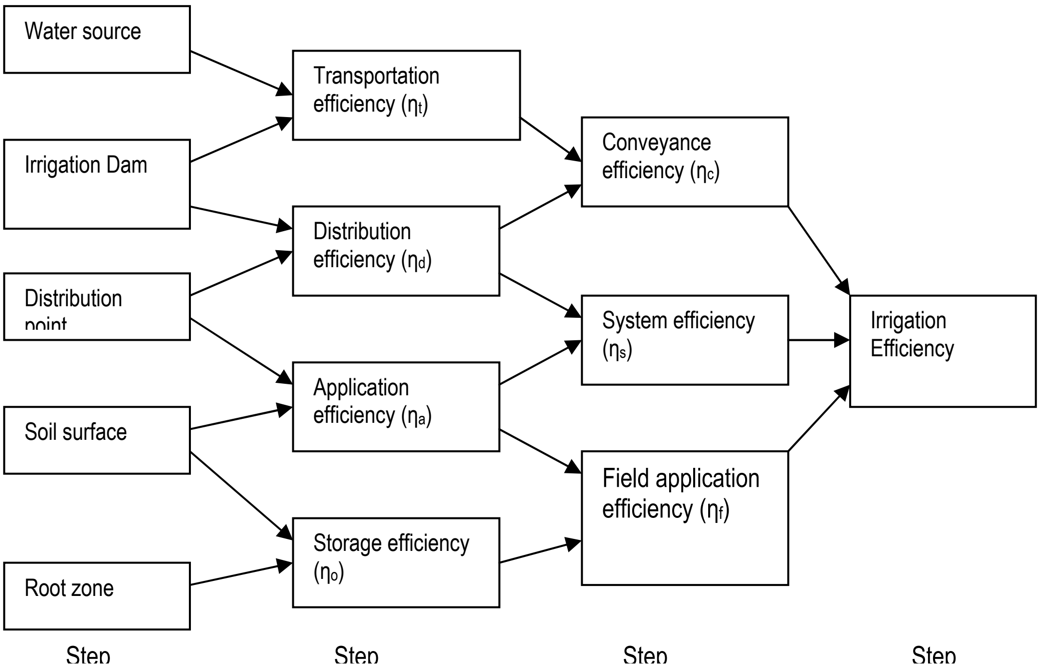

Figure 1: Key factors in the determination of conventional efficiency of an irrigation system (*Source: Merwe, 1997*)

BOX 2: An example of estimating IE during design of flood irrigation systems using CIE (Case of Kapunga Scheme)

Three efficiency indicators are considered to give the overall scheme efficiency;

1. Conveyance efficiency (η_c), for lined canal this is assumed at 0.9, but for unlined could be down to 0.7 (Halcrow *et al*. 1992).

2. System efficiency (η_s), this is assumed to be 0.6 (Merwe 1997, Halcrow *et al*. 1992).

3. Field application efficiency (η_f), is assumed at 0.7 to 0.9

Taking the mean values for the ranges, the irrigation efficiency (η_i) is calculated

$$(\eta_i) = (\eta_s) \times (\eta_c) \times (\eta_f) \qquad (1)$$

$$= 0.6 \times 0.8 \times 0.8$$
$$= 0.38 = 38\% \text{ or approximately } 40\%$$

1.2 The demerits of CIE

This section describes some of the disadvantages of irrigation efficiency measured using the conventional means.

a) Boundaries do not allow for re-use of water

The expression or equation for calculating overall efficiency as a product of conveyance, distribution and application efficiencies (Doorenbos and Pruit 1992) implies that the efficiency will reduce as the domain of interest increases from farm to block to field**.** Such simplistic perception neglects the proportion of the seepage and percolation from the water distribution system that is recycled within the whole irrigation system or basin. In many watersheds, where water recycling and reuse are fully implemented, the ratio of evapotranspiration to the water input (i.e., Ei) actually increases as one scales up from field scale to the watershed. Thus, improving the local irrigation efficiency may not necessarily mean more water is “saved” to irrigate new land or to put into other uses. This argument has also been made by various authors who argue that re-use generates further agricultural production. Often in these re-use scenarios, water percolates into groundwater from where it is extracted again.

b) Factoral design over-sensitise it to measurement errors and single measurements

Related to the previous point about boundary conditions, is the fact that the overall irrigation efficiency of an irrigation system is defined as the ratio of water used by the crop to water released at the headworks. In this definition, the efficiency figure is a product of conveyance, channel and application efficiencies, which implies that the efficiency decreases factorally as the domain of interest increases. The three factors combined to give the efficiency carries errors in its measurement that are then compounded in the ultimate efficiency figure obtained. Also the factors are obtained from single measurement results in canals, which somehow obscure water use, and losses that take place within the field.

c) Depend on difficult measurements of water flows in canals or assumption of figures

The parameters that are used for determining efficiency are rarely measured and therefore, forces assumptions from literature thus making them too general. This is due to the fact that measurement of irrigation efficiency is difficult and time consuming. For example to get representative values of efficiency for irrigation system one would require a measurement of:

- The amount of net or gross inflows into the system;
- Losses in the distribution system;
- Field water losses;
- Amount of water consumed by the crop (crop evapotranspiration); and
- Amount of water returned to its source river.

These measurements need to capture different scenarios such as wet and dry season scenarios, wet and dry year scenarios and at different climatic conditions. This would require a considerable length of time, effort and resources.

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d) Time boundaries are not defined or well incorporated into the conventional method

The role of time in both the timing element and duration of water use is not adequately addressed in efficiency figures derived by using the CIE methodology. However, late timing of water lowers productivity because of seasonal effects such as photosensitivity and fluctuating market prices. Secondly, the method does not compare well between a field that spends much time (duration) covered with water compared to a field that is irrigated only during the most productive growth phases of the crop.

2. Alternative approaches to evaluating irrigation efficiency and productivity

2.1 Introduction to definitions

The new approach for evaluating irrigation efficiency and productivity comes in the wake of conditions common in irrigated semi-arid but not well addressed in the conventional approach for evaluating irrigation efficiency. These conditions, among others, include the water reuse process downstream of irrigated farms, timing and duration of water supply between upstream and downstream-irrigated farms and price fluctuation of harvested rice.

From these perspectives, efficiency and productivity need to be defined as a multi-faceted collection of indicators varying in space and time. In such water systems, efficiency and productivity needs to consider crop water consumption, re-use of water, domestic water use, livestock and animal water use, micro enterprises water use (e.g. brick making), and livelihood benefits derived from water use, etc. In this case, therefore, **no single indicator** can explain the efficiency /productivity of these areas. Rather a combination of different water and non-water management indicators can give a better and more accurate picture. In order to define the efficiency and productivity, four key terms need to be defined and differentiated as discussed in the next sections.

2.1.1 The water use efficiency

Water use efficiency is a measure of efficiency of water use for a defined user type with specified boundaries, and is expressed without units (i.e. as a percentage) requiring the formulation of the net and gross amount of water utilised for the activity under study. This explains efficiency of different uses/users (e.g. fisher people, irrigators) in an irrigation system of which there can be many and they may differ in demand of water for the same activity. We need to evaluate efficiency of water use by the nested users.

2.1.2 The productivity of water

Productivity of water is a measure of the economic, livelihood or biophysical outputs derived from the use of a unit of water. Such outputs could be brick making, crop production, fishing, livestock watering etc. Units are jobs per m^3, $\$/m^3$, total biomass ($kg/m^3$), families per command area etc. The productivity of water in an irrigation system is more than what comes from the intended or unintended products within the total command area i.e. water diverted for irrigation system can be used for many other uses e.g. domestic purposes, fishing, brick making etc. Water productivity is therefore a wider consideration of the products that comes from the diverted water for the irrigation system.

2.1.3 Irrigation efficiency

Irrigation efficiency is a special case of the water use efficiency. It is the measure of efficiency for irrigation given specified boundaries. There are many ways of measuring efficiency, some of which are conventional and well-known, others which are new and attempt to capture efficiency for the whole system and the temporal elements of efficiency. Unlike productivity (which has units), however, efficiency is expressed as a %, being a measure of net to gross water use or net days of irrigation to gross days of irrigation.

2.1.4 Irrigation productivity

Irrigation productivity is a measure of the economic or biophysical gain from the use of a unit of irrigation water in crop production and is expressed in productive crop units of kg/ha, kg/m^{3}or \$/m^3. As the name portrays, this is the product that is obtained from the irrigated crop to which the diverted water was planned for. Here we just consider our product from irrigation process but do so in ways that capture the whole system of water use and re-use. We include irrigation products from drain water use and rice ratoon products, if any, because they originated from irrigation.

The main difference between efficiency and productivity is that efficiency refers only to physical quantities of water, both in the denominator and the numerator. It does not capture differences in the value of water in alternative uses. Gains in basin efficiency can make an important contribution to gains in productivity.

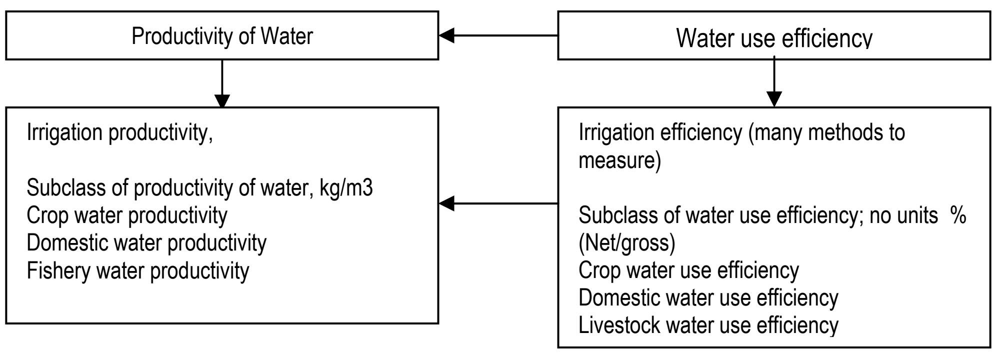

Figure 2. Relationship between irrigation efficiency, irrigation productivity, water use efficiency and the productivity of water

An increase in irrigation productivity (Figure 2) can occur without necessarily an increase in irrigation efficiency (as can occur when more water is volumetrically consumed, or when yields are increased by use of fertiliser etc).

3 Measurement of efficiency and productivity using the ISE Methodology

3.1 Measurement of irrigation efficiency and irrigation productivity

Based on the conditions explained above for semi-arid situations, a meso-scale concept of irrigation efficiency that encapsulates micro-level inefficiencies and water productivity, and macro-scale efficiencies is presented. It is tentatively dubbed Irrigation Situation Efficiency (ISE).

There are many situational efficiency indicators emphasised in the ISE approach which include the following: net and gross water use by the nested systems; difference in transplanting time between nested systems (timeliness and delay of water to the downstream users); swing of prices between early (upstream) and late (downstream) harvested rice products; comparison of water supply hydromodules; productivity (crop per drop); annual depths of water maintained in fields; and number of days water spent in fields. These situation efficiency indicators can be categorized into primary and secondary (nested) indicators as outlined in the next paragraphs and also further discussed under the section 3.1.2.

In total, ISE use nine measures to define six efficiency and productivity indicators. The interaction between primary measured factors and secondary (efficiency/productivity) indicators are shown in Table 2. The derived irrigation efficiency indicators will define specific situations in the savannah plains. One indicator can address many issues and may well not be applicable in some areas. The primary efficiency measurements that are considered by ISE are:

1. Water inflow and use of the whole system,
2. Measurement of amount of water used in nested systems,
3. Delay of drain water from one nested system to another,
4. Crop productivity in each nested system,
5. Rice price fluctuations in nested systems caused by limited water supply at the beginning of the season leading to delayed transplanting and harvesting,
6. Measurement of the length of time the irrigation water spent in each nested system,
7. Measurement of the length of time the paddy stay with water,
8. Measurement of mean annual depths kept in paddy fields from transplanting to harvesting.

Table 1: Measurement of ISE primary efficiency indicators

ISE parameter	How to measure	Equipment to be used
1	See appendix 3	Current metres,
	See appendix 3	flumes, weirs,
	See appendix 3	floating object,
	See appendix 3	bucket,
	See appendix 3	Calibrated shaped materials
2	See appendix 4	Lysimeters
	See Section 3.1.1	Water balance
3	Monitor the difference in transplanting time between the upstream and the downstream farmers	Field observation and monitoring
4	See appendix 5	GIS, Wheel race meter, or measuring tapes
5	See appendix 6	Weigh balance, moisture meter, measuring tape, sickle, pegs, rope
6	Monitor and record price fluctuations, at harvesting, between upstream and downstream farmers	Field observation and data record
7	Daily observation on field water status	Physical observation
8	Count and record the number of days paddy stay with water for the whole season	Daily counting and recording
9	See appendix 7	Ruler

There are five efficiency and productivity indicators (Figure 3) that come out of the nine primary measurements. These are listed below and further discussed in sections 3.1.2 .1 to 3.1.2.5.

(i) The nested system efficiency (NSE) expressed in ratio of net to gross water use (%)
(ii) The whole system efficiency (WSE) expressed in ratio of net to gross water use (%)
(iii) The nested system productivity indicator (NSPI) measured in (kg/m^3)
(iv) The whole system productivity indicator (WSPI) measured in (kg/m^3)

(v) The field operation and management efficiency (FOME) that include four components: the pre-saturation, mean annual depths maintained in fields (ratio of standard depths to actual depths), water delays, and the ratio of net days paddy require water to reach maturity to gross days water has spent in the fields. Both expressed in (%).

Table 2: Nested system, whole system and FOME efficiency/productivity indicators

Secondary productivity indicators	Primary measurements						
	1	2	3	4	5	6	7
NSE	√						
NSPI	√		√				
FOME		√			√	√	√
WSE	√	√		√			
WSPI	√	√	√	√			

Key: 1 = measurement of net and gross water use in nested systems, 2 = delay of drain water from one nested system to another, 3 = rice productivity in each nested system, 4 = rice price fluctuations between nested systems caused by delayed water supply to downstream users at the beginning of the season leading to delayed transplanting/harvesting, 5 = measurement of amount of water used and duration for presaturation of fields, 6 = measurement of mean annual depths kept in paddy fields from transplanting to harvesting, 7 = measurement of length of time the fields stay with water

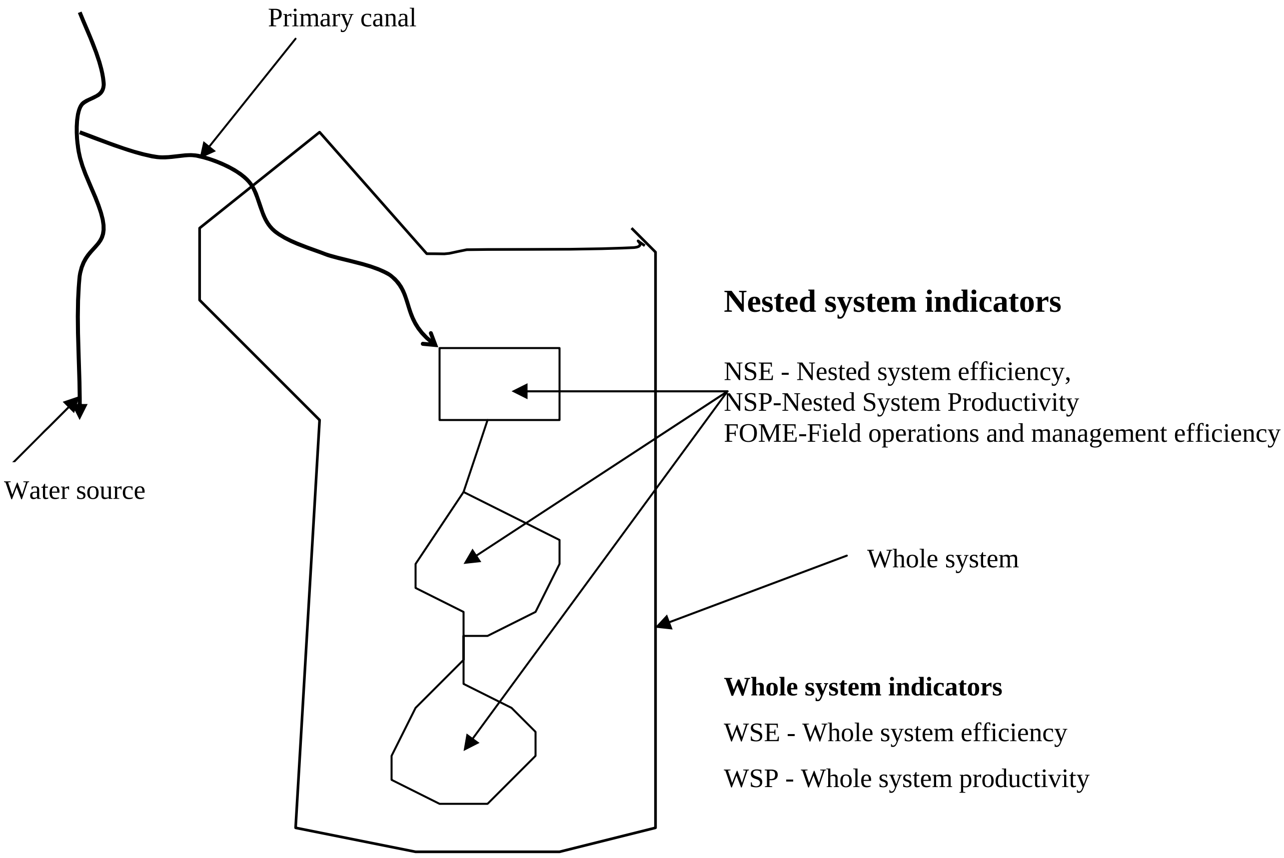

Figure 3: Nested and whole system indicators

The Nested system efficiency (NSE) sub method

The IE analysis using NSE involves the determination of annual or seasonal net and gross water requirement. The NSE is then calculated as the ratio of net to gross demand (Eqn 4). Net water requirement is the amount of water required to replace evapotranspiration and deep percolation/seepage) or root zone soil moisture deficit. Gross water requirement is the practical or actual amount of water supplied to meet crop evapotranspiration and or percolation/seepage observed under field conditions. The net water requirement can be determined from field measurement of the following parameters:

(i) Evaporation;
(ii) Transpiration;
(iii) Deep percolation and or seepage losses

The net water requirement can then be calculated using equation (2).

$$NWR = ETcrop + Dp - R \qquad (2)$$

Where:

NWR = Seasonal or Annual Net Water Requirement (mm)
ETcrop = Seasonal or Annual Crop evapotranspiration (mm)
Dp = Seasonal or annual deep percolation losses (mm)
R = Seasonal or annual effective rainfall (mm)

Because of the difficulties in measurement of all the parameters for the gross water requirement, which are sometime dependent, modelling techniques can be used to determine the gross water requirement of an irrigation system. The Modelling requires the estimation of Eto from Penman-Monteith method and the application of crop factors to determine actual crop evapotranspiration (Etc). The model equation (3) can be used to estimate seasonal or annual gross water requirements. Physical measurements for deep percolation can be done by lysimetry method, N-type apparatus (Odhiambo and Murty, 1996), or derived from farmer interviews (asking how many times do they have to refill the paddy basin, or by asking whether they notice seepage losses or contribution into the paddy fields).

$$GWR = (E + T + Dp + Ro + (Lp + S)) \qquad (3)$$

Where:

GWR = (R+I) = annual or seasonal rainfall and irrigation water (mm)
E = Annual or seasonal evaporation (mm),
T = Annual or seasonal transpiration (mm),
Dp = Annual or seasonal deep percolation (mm),
Ro = Annual or seasonal runoff from the field (mm),
(*Lp* + ∗s) = Annual or seasonal lateral percolation and subsurface movement of water in the field (mm).
The nested system efficiency, based on annual or seasonal water use (net and gross), can then be calculated using the following equation (4):

$$NSE = \frac{Net\ annual\ or\ seasonal\ paddy\ water\ use}{Gross\ annual\ or\ seasonal\ paddy\ water\ use} \qquad (4)$$

Examples of nested system efficiency calculations

Tables 3 and 4 give examples of NSE for the nested system of Kapunga Irrigation farm (KIF), Kapunga Smallholder Scheme (KSS) and Kapunga

Peri-smallholder schemes (KPSS). The KPSS reuse water from both KIF and KSS. Calculation of efficiency is based on results of field experiments in sample locations from KIF, KSS and KPSS for two crop seasons (dry and wet year).

Table 3: Nested system efficiency (NSE) for 1999/2000 season (dry year)

Site Name	Gross water used (mm)	Net water required (mm)	Nested system efficiency (%)
KIF	2038.15	984.51	48
KSS	1992.79	988.94	50
KPSS-top	1668.30	1150.76	69
KPSS-end	1789.00	999.43	56

Table 4: Nested system efficiency (NSE) for 2000/2001 season (wet year)

Site Name	Gross water used (mm)	Net water required (mm)	Nested system efficiency (%)
KIF	3009.52	1063.27	35
KSS	2326.99	986.31	42
KPSS-top	1721.83	1094.62	64
KPSS-end	1730.40	975.98	56

Whole system efficiency (WSE)

The whole system efficiency sub method is a result of water reuse processes within the nested systems of the whole system. The IWMI and ISE theory on water reuse, with particular reference to the Usangu irrigation systems, are discussed next and their distinction pointed out.

IWMI and ISE theory of water reuse process

Figure 4 is a hypothetical representation of the water reuse process in the IWMI framework. It represents a situation whereby water is reused in three different nested systems. The whole system efficiency and whole system productivity could be obtained as explained below:

If, say, ***X*** units of water were diverted from the source river to farm A, which operates at ***a%*** efficiency, theoretically this mean that ***(X -Xa)*** of the abstracted water would move to the next farm, and only ***aX*** units will be used in farm A. If the next farmer B is operating at ***b%*** efficiency, it means that ***b(x-ax)*** units will be spent in that farm. The amount that will move ahead to farm C will be ***(X-aX) - b(X-aX)***. In farm C the amount that will be spent there is ***c((X-aX) - b(X-aX)*** and the amount leaving that farm, the return to sink in this case is ***{(X-aX) - b(X-aX)} - c((X-aX) - b(X-aX))***.

Figure 4: Hypothetical IE calculated using IWMI whole system sub methods

Hypothetically the overall usable units from the three reuse systems would be the sum of all the units spent in A, B and C. This is given as follows:

$$UsableUnits = ax + b(x - ax) + c\{(x - ax) - b(x - ax)\} \qquad (5)$$

The whole system hypothetical efficiency (WSHE) would be as given in equation (7).

$$WSHE = \frac{aX + b(X - aX) + c\{(X - aX) - b(X - aX)\}}{X} \qquad (6)$$

$$WSHE = a + b - ba + c - ac - bc + abc$$

$$WSHE = a + b + c - (ba + ac + bc) + abc \qquad (7)$$

The hypothetical efficiency obtained in equation (7) demonstrates that the reuse process increases both efficiency and productivity of irrigation water. However, under real situations, many operational as well as natural phenomenon affect the water reuse process. The ISE theory considers these operational as well as natural phenomenons in its analysis as described in Figure 5.

The main difference of the ISE from IWMI theory is that, IWMI define irrigation efficiency and productivity at large scale, reuse concept, in the same way is defined in the ISE framework, but the six key factors illustrated by Figure 6 are not included in the IWMI framework.

Figure 5 illustrate chronologically how the efficiency and productivity of irrigation water can be affected in the water reuse process, something, which is not, tackled in both CIE and IWMI approaches. The figure demonstrates that efficiency and productivity of reused water are a function of delay of water for reuse to downstream users and their timing. These factors, together, contribute to series of crop production constraints to the downstream users. These constraints reduce both productivity and efficiency of reused water and the supplied water in general.

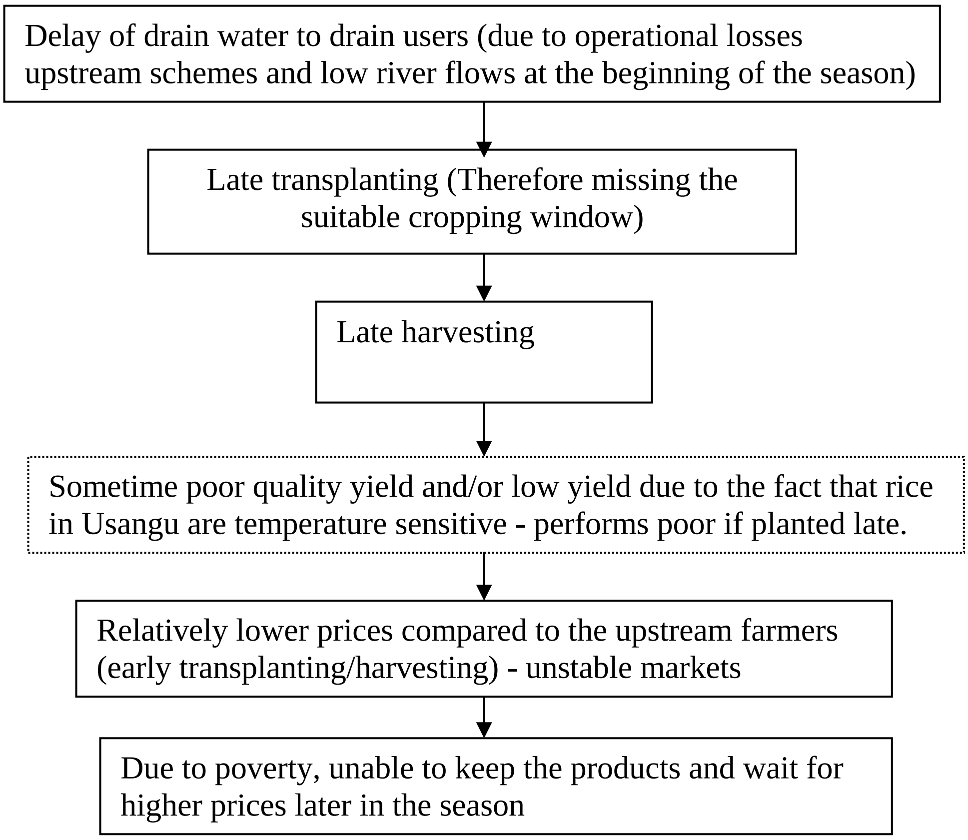

Figure 5: Efficiency and productivity as affected by the reuse process of water

Therefore, in the ISE theory, irrigation efficiency and productivity of irrigation water under water reuse processes (Eqn 8) is a function of water delays from upstream water users, the timing upon which the drain-water becomes available for reuse by downstream farmers, price fluctuation of harvested crop by drain-water users at the time of harvesting and poverty issues that in one way or another position farmers to directly depend on drain-water.

$$IE / PW\ of\ reused\ water = f\begin{Bmatrix} Delays\ of\ drain\ water\ to\ drain\ users, water\ quality \\ Poor\ quality\ yield, market\ prices, and\ poverty \end{Bmatrix} \quad (8)$$

Because the factors in equation (8) affect both efficiency and productivity of reused water, in the ISE, the efficiency of reused water is given as:

$$IE\ of\ reused\ water = r\{NSE\} \quad (9)$$

Whereas productivity of reused water is given by equation (10)

$$PW\ of\ reused\ water = r\{NSP\} \quad (10)$$

Where:

IE = Irrigation efficiency
PW = Productivity of irrigation water
NSE = Nested system efficiency
NSP = Nested system productivity
r = is a factor relating the prices of rice at harvest between upstream and downstream schemes. It is obtained by dividing the price of rice at the downstream scheme (drain users), to the price of rice at upstream scheme when the harvesting commences.

If (r) factor is therefore introduced in the hypothetical equation (7) of the water reuse process, the real usable units, using ISE concept, will be as given in equation (11)

$$UsableUnits = aX + r_1 b(X - aX) + r_2 c\{(X - aX) - b(X - aX)\} \quad (11)$$

The whole system efficiency of such systems would, therefore, be calculated as follows:

$$WSE = \frac{aX + r_1 b(X - aX) + r_2 c\{(X - aX) - b(X - aX)\}}{X}$$

$$WSE = a + r_1 b - r_1 ba + r_2 c - r_2 ac - r_2 bc + r_2 abc \quad (12)$$

Equation (12) is a general equation that represents the whole system efficiency using ISE framework. However, there are many scenarios with regard to the equation as elaborated in the sections below.

(i) First scenario

If it happens that the operating efficiencies (a, b and c) of the three farms reusing water are equal, equation (12) can be rewritten as:

$$WSE = a + r_1 a + r_2 a - r_1 a^2 - 2r_2 a^2 + r_2 a^3 \qquad (13)$$
$$where: \quad a = b = c$$

(ii) Second scenario

When r_1 equals r_2, it means that there was no significant delay in both the water arrival and the transplanting between the middle (second) users and the tail (third) users, though it might not be the case for different rice crop varieties. The equation (12) can be adjusted to address this situation as follows:

$$WSE = a + 2ra - 3ra^2 + ra^3 \qquad (14)$$
$$where: \quad a = b = c \quad and \quad r_1 = r_2 = r$$

(iii) Third scenario

When a = b = c and r_1 equals r_2 and also is equal to unity this implies several possibilities.

Firstly, it implies that perhaps there were no delays in the water arrival between the top users, middle users and end users, leading to the same periods for transplanting and harvesting.

Secondly, this might mean that there were early and sufficient rains, enabling same time of transplanting for the top, middle and end users.

Thirdly, this could mean that the downstream users do not directly depend on harvested rice yields and are capable of to keep their harvests to wait for a good price later in the season.

Fourthly, this might indicate that the market was stable throughout the season and did not fluctuate. In other words, the price was similar for farmers regardless of when they sold.

When these situations occur, Equation 14 becomes:

$$WSE = 3a - 3a^2 + a^3 \quad (15)$$
$$where: \quad a = b = c \quad and \quad r_1 = r_2 = r = unity$$

Equations 12 to 15 are the possible ISE whole system efficiency, which changes according to the situation available in the area at each pointing time. Also, at known nested systems efficiency the ISE whole system efficiency (WSE) is given by equation (16).

$$WSE = NSE + r_1\{NSE_1\} + r_2\{NSE_2\} \quad (16)$$

Where:
NSE = Nested system efficiency of the upstream water user
NSE_1 = Nested system efficiency of the first drain water user
NSE_2 = Nested system efficiency of the second drain water user
r_1 and r_2 = are factors relating the prices of rice at harvest between upstream and downstream schemes. It is found by dividing the price of rice at the downstream schemes, schemes one and two, when the harvesting commences, by the price of rice at the upstream scheme when harvesting commences.

Examples on whole system efficiency (WSE) calculation

Tables 4 and 5 shows the examples of calculating the “r” variable using the (1999/2000 and 2000/2001 seasons data) from the Kapunga Water System (KWS) while Table 6 shows how the “r” variable can be applied to calculate whole system efficiency. Once the factors are calculated they are used in table 6 on equation (16) to calculate the WSE for the two seasons. For the KWS reuse, the NSE_1 is the efficiency for KIF, NSE_2 is for KPSS-top and NSE_3 is for KPSS-end. See **Appendix 1** for description of acronyms and the layout of the KWS which will often be referred in this manual.

Table 4: Transplanting/harvesting date and the respective "r" value for 1999/2000

Site	Transplanting dates	Harvesting dates	Days to Maturity	Variety	% of normal price[1]	"$r_1 = r_2$ ="r"$_{1999/2000}$ = ($\frac{100\%}{180\%}$)
KIF	23/11/1999	29/04/2000	156	Kilombelo	180	1
KSS	20/01/2000	01/072000	161	Kilombelo	100	0.56
KPSS-top	06/01/2000	30/05/2000	144	India rangi	100	0.56
KPSS-end	10/02/2000	12/07/2000	152	India rangi	100	0.56

Table 5: Transplanting/harvesting date and the respective "r" value for 2000/2001

Site name	Planting Date	Harvesting date	Days to maturity	Varieties	% of normal price[1]	"r_1 = r_2 = "r"$_{2000/2001}$ = $(\frac{100\%}{150\%})$
KIF	17/11/2000	04/17/01	150	Subamati	150	1
KSS	18/11//2000	04/29/01	161	Macho ya Tanga	150	1
KPSS-top	06/01//2001	05/27/01	141	India rangi	100	0.67
KPSS-end	27/01//2001	06/28/01	151	India rangi	100	0.67

Table 6: Efficiency as calculated by whole system efficiency sub method

Year	NSE	NSE_1	NSE_2	r_1	r_2	$WSE = NSE_1 + r_1\{NSE_2\} + r_2\{NSE_3\}$
1	0.48	0.69	0.56	0.56	0.56	**73%**[1]
2	0.35	0.64	0.56	0.67	0.67	**72%**[2]

[1] Results from the first season 1999/2000
[2] Indicate results from the second season 2000/2002

Importance of determining irrigation efficiency in each nested system as well as the whole system

(i) Can allow for the assessment of the benefit of improving water allocation in different parts of the water systems (equity);
(ii) Identification of means to water reallocation to other nested systems based on identified potential of water saving, this may not be an easy task;
(iii) Allows understanding of how different nested users in river basins use and manage water;
(iv) Useful in transferring knowledge on better management of water from one nested system to another.

Nested system productivity (NSP) sub method

[1] *"Normal rice price" is the price that exist in an irrigation system when reasonably amount of rice have been harvested by both upstream and drain water users. This period occur between June and August. The normal price for the bag of 85 kg in the KWS for the two seasons was found to be about Tsh. 15,000/=.*

The NSP looks at the crop yield per unit volume of water expressed in (kg/m^3 or \$/m^3) and it is obtained using the following equation:

$$NSP = \frac{Yield\ \ in\ kg\ or\ \$}{Gross\ \ annual\ \ or\ seasonal\ \ water\ \ use} \qquad (17)$$

The NSP can be compared to the standard paddy water productivity of 0.7kg/m^3 using the relative nested system productivity (RNSP), which is the percentage of the ratio between NSP and SRWP (equation 18).

$$RNSP = \frac{NSP\ (kg\ /\ m^3)}{0.7\ (kg\ /\ m^3)}\ X\ 100 \qquad (18)$$

The standard water productivity (0.7kg/m^3) is calculated using the following assumptions:

(i) Good rice yields under fully controlled irrigation with high inputs ranges from 6-8 ton/ha (unpolished rice at 15-20% moisture content);
(ii) Net annual/seasonal water requirement of paddy in the tropics and subtropics is about 1100mm, which is the same as 1.1m of water.

Standard water productivity for paddy is = maximum grain yield (8000kg)/Annual or seasonal volumetric water requirement for paddy (1.1m x 10000m^2)=0.7kg/m^3).

Example of nested system productivity (NSP) calculations are given below

Formula:

$$NSP = \frac{Yield\ \ in\ kg\ or\ \$}{Gross\ \ annual\ \ water\ \ use} \qquad (Eqn\ \ 5)$$

The relative nested system productivity (RNSP) in percentage is obtained by comparing the NSP with standard rice yield (0.7 kg/m^3) as follows:

$$RNSP = \frac{NSP\ (kg\ /\ m^3)}{0.7\ (kg\ /\ m^3)}\ X\ 100 \qquad (Eqn\ \ 6)$$

Table 7: Nested system productivity (NSP)

Seasons	KIF (kg/m^3)	KPSS-top (kg/m^3)	KPSS - end (kg/m^3)
1999/2000	0.18	0.22	0.14
2000/2001	0.16	0.18	0.27

Table 8: Relative nested system productivity (RNSP)

Seasons	KIF (%)	KPSS-top (%)	KPSS - end (%)
1999/2000	26	31	20
2000/2001	23	26	39

Whole system productivity sub method

It was argued under the ISE theory that productivity of drain water is guided by variable "r". The ISE whole system productivity (indicator) equation, based on (r) variable, was derived as indicated by equation 19.

On the other hand, at known standard rice water productivity (SRWP), the ISE relative whole system productivity (RWSP) can be given as per equation (20).

$$WSP = NSP1 + r_1\{NSP_1\} + r_2\{NSP_2\} \qquad (19)$$

$$RWSP = \frac{WSP}{SRWP}. = \frac{WSP}{0.7} * 100\% \qquad (20)$$

Where:

NSP = Nested system productivity of the upstream water user
NSP_1 = Nested system productivity of the first drain water user
NSP_2 = Nested system productivity of the second drain water user
SRWP = Standard rice water productivity (which is 0.7 kg/m^3)
Example on whole system productivity (WSP) calculation

Formula:

$$WSP = NSP_1 + r_1\{NSP_1\} + r_2\{NSP_2\} \qquad (Eqn\ 17)$$

While the nested system productivity (NSP) in the equation (17) and Table (10) is for KIF, the NSP_1 is for KPSS-top and NSP_2 is for KPSS-end (**see** also **Appendix 1** for acronym definitions).

Table 9: Whole and relative system productivity

NSP	NSP_1	NSP_2	r_1	r_2	$WSP = NSP + r_1\{NSP_1\} + r_2\{NSP_2\}$	$RWSP = \frac{WSP}{SRWP} . = \frac{WSP}{0.7} * 100\%$
0.18	0.22	0.14	0.56	0.56	0.38	**55%**
0.16	0.18	0.27	0.67	0.67	0.46	**66%**

Field operations and management efficiency (FOME)

This is the measure of how the system utilizes water during in-field operations. It is expressed both in (mm), requiring the formulation of how much water was used to do a particular activity, and in (days) requiring the formulation of how long the activity was done.

Four different in-field operations are studied under FOME. These are pre-saturation process, water depths maintained in fields through out the growing season, delay of drain water from upstream water users to the drain users downstream, and the number of days water reside in paddy fields annually.

3.1.5.1 Pre-saturation

It is argued that water for pre-saturation in rice fields can account up to 40% of gross annual water use (Small, 1992). However, recently it has been argued that this amount is not lost because it is reused downstream, when is drained off the upstream fields (Keller, 1996; Perry, 1999, Molden et al., 2003). The major challenge with the reuse concept is that if water is not properly managed, much of it might be depleted through evaporation and deep percolation and not reach the drain users. A two step approach is taken to arrive at a realistic definition of presaturation in a water reuse system is given. First the amounts of water used by different water users in the reuse process are determined and secondly the duration of pre-saturation for each of the users is determined. The efficient pre-saturation is then defined based on two factors. One, based on minimal but realistic amount of water required for pre-saturation and two minimal and realistic number of days required for pre-saturation.

3.1.5.2 Water depths in fields

It has been cautioned that maintaining high water depths decrease yields (Doorenbos et al. 1986) and sometime causes diseases (Wei et al., 1989) in rice irrigated agriculture. Further, Hoek et al. (2001) stressed that continuous flooding of rice fields results in increased water demand and health problems (particularly a mosquito borne disease -Malaria). Hoek continued suggesting that a way that annual mean water depths could be reduced is through a wet and dry method which accounts for up to 40% water saving. However, Walker et al. (1984) raised a concern that the reason why farmers keep high depths is for security as the timing of the next water supply is often uncertain. He, however, acknowledged the fact that high depths maintained in fields are responsible for more losses through bunds. Since some of these losses are never picked up for reuse, the practice might be influencing efficiency and it is therefore necessary to understand the extent of depths maintained in irrigated fields as compared to the standard depths.

The above arguments suggest that there is potential to analyse water depths efficiency (WDE). As suggested by Walker et al., (1984) and Wei et al., (1989), with a depth of not more than 50 mm in rice fields, water losses through bunds and diseases are minimal. Although the 50 mm is scientifically proven, farmers and agricultural officers, interviewed, argue that 120 mm is a suitable depth in Tazania due to higher temperature conditions. The argument is based on the fact that that 50 mm would require so many irrigation frequencies per annum and would take much of their time. Due to these contradicting views between farmers and scientists, the analysis of WDE should be based on two criteria i.e. according to what farmers/scientist say is sufficient and efficient in relation to what was measured from the fields. Equations 22 and 23 are therefore used to analyse the two cases.

$$WDE_1 = \frac{\text{Standard Depth (according to farmers - 120 mm)}}{\text{Mean annual measured depth}} \qquad (22)$$

$$WDE_2 = \frac{\text{Standard depth (according to scientists - 50 mm)}}{\text{Mean annual measured depth (mm)}} \qquad (23)$$

3.1.5.3 Delays of water arrival to the drain water users

In order to be able to model the number of days in which the downstream users delay to start their activities, it is necessary to monitor the start of transplanting in all the farms of a nested system. Several surveys and transect walks needs to be conducted in order to be able to model the cropping calendar for each of the farms in a particular system.

3.1.5.4 Number of days water spend in fields

Monitoring of the period from transplanting to harvesting is important in order to account the numbers of days water reside in fields. It is documented that a long maturing rice variety in Tanzania requires about

160 days. It is however reported that in rice fields water can be drained out off 2-3 weeks prior to harvesting without effect on yield (Wei et al.1989). Thus, the effective number of days for water to be spent in fields could be cut down to 140 days for long maturing varieties. This is important because in so doing, the water which would otherwise evaporate at the end of the season is released downstream to irrigate late transplanted crops and thus improving productivity and efficiency at system level. The efficiency is likely to improve because the gross water use, upstream, is reduced while productivity could improve due to timely and probably sufficient water supply downstream.

The efficiency based on this criterion, the duration of water in fields (DWF), is then calculated by comparing the actual number of days the rice plant would require to stay with water, from planting to maturity, and the number of days water actually spent in fields in each nested system. This can be calculated as follows:

$$\text{DWF} = \frac{\text{Standard number of days paddy needs water}}{\text{Actual days water stay in fields}}$$

$$\text{DWF} = \frac{\text{140 days}}{\text{Actual days water stay in fields}} \qquad (24)$$

Summary of the FOME sub method

The combined efficient FOME for each nested system is defined based on the above four assessment criteria. The combined equation for FOME is given next.

$$\text{FOME} \Rightarrow \text{Pre - saturation} + \text{WDE} + \text{Water delays} + \text{DWF} \qquad (25)$$

Where:

Pre-saturation = [efficient amount (mm) + efficient duration (days)]
WDE = water depth efficiency (mm)
Water delays = efficient water delays (days)
DWF = efficient duration of water in fields (days)

Examples on field operation and management efficiency (FOME) calculations

(a) Based on water depths from the KWS

Formula:

$$\text{WDE}_1 = \frac{\text{Standard Depth (according to farmers - 120 mm)}}{\text{Mean annual measured depth}} \qquad (Eqn.22)$$

$$\text{WDE}_2 = \frac{\text{Standard depth (according to scientists - 50 mm)}}{\text{Mean annual measured depth (mm)}} \qquad (Eqn.23)$$

Table 11: Mean water depths (mm) kept in fields for the two seasons

Site	1999/2000	2000/2001
KIF	121	101
KSS	119	139
KPSS	116	138

Table 12: Water depth efficiencies (WDE) in fields

Site	Scientists definition (50 mm)		Farmers definition (120 mm)	
	1999/2000	2000/2001	1999/2000	2000/2001
KIF	41%	50%	99%	119%
KSS	42%	36%	101%	86%
KPSS	43%	36%	103%	87%

(b) Based on the number of days water stay in the paddy fields in the KWS

Formula:

$$DWF = \frac{140\ Days}{Actual\ \ Days\ Water\ Spent\ in\ System} \qquad (Eqn.\ 24)$$

Table 13: Duration of water in fields and efficiencies

Irrigation system	Average days spent	Net days	Average DWF efficiency
KIF	200	140	70%
KSS	165	140	85%
KPSS	165	140	85%

Water use efficiency and water productivity

As well as irrigation use of water, we can also look at the efficiency and productivity of water when it is used for non-irrigation purposes. This can be done using equations (26) and (27) given below:

3.2.1. Water use efficiency

$$WE = \frac{Net\ \ annual\ \ or\ \ seasonal\ \ \ water\ \ use\ \ (NWU\ )}{Gross\ \ annual\ \ or\ \ seasonal\ \ \ water\ \ use\ \ (GWU\ )} \qquad (26)$$

Where:

WE = Water use efficiency for defined use/user type
NWU = is the net water requirement of the specified user type in a water system which may include domestic, irrigation, fishing, brick making etc.
GWU = is the gross water supplied for the specified water use.

Note: The efficiency of the diverted water in a given system must, therefore, include the efficiencies of all uses.

3.2.2. Water productivity

This measures the productivity of water in all its uses within a water system. The uses might include domestic, irrigation, fishing, brick making etc.

$$WP = P_1 + P_2 + P_3 + ... \qquad (27)$$

Where:

WP = Combined water productivity
P = Productivity for distinctive water use
1,2,3 … Water uses in the system

Productivity for distinctive water uses can be measured in terms of physical, economic or social values. The physical measurements represent the physical output such as yield of crop per amount of water depleted in producing this yield, economic measure is when the physical output is transformed or equated into a value of shilling or dollar under market conditions and the social productivity is when the value of water is equated into social benefits gained by having or using water in the community such as the number of jobs created as a result of presence of water or the value of good health maintained by good sanitation using water.

4. Improving efficiency and productivity based on ISE framework

It is now generally accepted that Integrated Water Resources Management (IWRM) is a necessary factor to be considered when planning water resources use in any river basin. The inter-dependence of users necessitates a clear understanding of each user in relation to the location, the water demand, and the duration of water need. An understanding of these factors, together, is very important for the management of the basins without which, it is argued that, the competition and conflict between users become increasingly high. As an example of this, ISE analyses both nested users and whole system water demand. The potential of ISE analysis in improving water management and allocation is discussed in the next sub sections.

4.1. Potential for water saving within a river system

There is potential for water saving within a river system when analysing IE and productivity by using ISE method. Different water users and uses in a river system can be evaluated. We can question why X nested system is using more water than Y system, located in the same basin, for the same use. Also, based on other indicators and characteristics from other nested system we can make water savings in the X system and then transfer it to another system or user that is getting less water. We can, in this way, improve the water productivity, increase equity, adequacy and eventually the efficiency and productivity of the water system and basin can be improved.

4.2. Potential for inter-sectoral water allocation

Intersectoral water allocation may be a necessary part of river basin management where inequities of supply and timing exist. We assess different water uses and users, in which the potential of each use is a function of time, location and season. We therefore need a careful assessment to be able to know what is happening at one location and how much water is being supplied and how much is required during different periods (Figure 5). The knowledge of efficiency, provided by ISE, would allow us to take appropriate amount of water from a location at non-critical time, and transfer it to another location where it is critically required during that period. For example, water kept in upstream rice fields with matured rice, which is just evaporating, could safely and timely be taken to the downstream to meet environmental demands. This could be a more productive way of using water in river basins.

Other examples would be supplying water for domestic uses when there are low river flows. Because domestic water is a necessary priority, if provided will reduce the time spent for water fetching. The reduced time can be used for other productive activities. It is therefore wise to understand the water demand situations that happen during different times in a river system. These situations are best assessed by ISE in the nested and whole system analysis.

4.3. Potential for improving IE and decision making

With knowledge of how each nested system in a river basin manage water and practices water use, we can make decisions with regard to nested systems as well as the whole basin. In the water reuse systems of the semi arid savannah plains we cannot judge how efficient the irrigation system is without understanding the operations of the nested systems. When we understand, for example in rice irrigation systems in Usangu, that the poor downstream users harvest or sell for less, because they are delayed in transplanting, we can then focus on causes of this. The potential of the ISE method to analyse irrigation water uses in relation to CIE method is illustrated by Figure 7.

In order to exemplify Figure 7, an example is taken from the Kapunga irrigation farm (KIF) in the KWS whereby a gross amount of 2500 mm is annually used to grow paddy. While only about 1000 mm is actually transpired by the paddy crop, the movements of the remaining amount of water (1500 mm) is not clearly mapped when CIE method is used to measure efficiency. In this case, using CIE becomes difficult to understand the process by which this water is lost. Furthermore, it is difficult to think of any management or improvement of that water.

On the other hand, ISE demonstrates that the proportion of gross annual water that is not used by crop undergoes three processes (Figure 8). Some is used to meet net paddy water requirements (A); some is drained and reused in the downstream (B - C); some is lost but the losses can be managed or improved (D - G), and some is lost which it is not possible to manage or improve (H - I). The details of these processes are described next.

	An average gross annual water is used by an irrigation system	CIE	IWMI-P	ISE
I H	Not reused and cannot be managed or improved	✓	X	✓
G F E D	Not re-used but can be managed and improved	X	O	✓
C B	Drain water but reused downstream	X	✓	✓
A	Net Crop Water Requirement (variable)	✓	✓	✓

Key

I	*Field seepage to deep percolation which is unrecoverable*
H	*Canal losses (ET + unrecoverable seepage) and spillage*
G	*Excessive depth of water, evaporated at the end of season in paddy basins, also related to poor uniformity of field water depth*
F	*Excessive wetting up, e.g. KIF fields resulting in unrecoverable seepage or ET_o during long field preparation delays*
E	*Losses of water from poor field definition and irregular boundaries*
D	*Excessive irrigation at the beginning and end of season and after harvest (evaporated at end of season)*
C	*Drain water but reused downstream*
B	*Field seepage but reused (Movement of water from one field to another across bunds)*
A	*Net crop water requirement*

✓	*Acknowledged by method*
O	*Ignored by method*
X	*Contains errors in method*

Figure 7: Potential of the three tested methods to analyse irrigation water use

A: - This is the net paddy water requirement. This is the fixed amount of water for any crop type in a specific ecological zone and can rarely be changed, although it can slightly vary, for example, between short and long duration varieties. The ISE tells us that for the paddy varieties currently available and which were tested in KWS this amount is circa 1000 mm.

B-C: - This is the amount of water, which is used in one field and then seep across bunds and is reused in the next fields within KIF or is drained off and reused in KPSS. This is exactly what the water reuse process does. Much of this water becomes potentially available downstream. This water is therefore not lost but can be managed in terms of movement to make sure it arrives as early as possible in the KPSS to time the correct cropping window.

D-G: - This is the amount of water which is non-productively depleted but can be managed and made productive. This is a target window for improvement in KIF. There are four ways in which this water is lost from KIF as follows:

(D): Excessive irrigation at the end of the season and after harvest, the water which ends up by evaporating. Irrigation in KIF continues even when the paddy is matured and most of the fields are harvested in water. This creates unnecessary water demand and delays in the water going to KPSS. Also, some farmers do not close their gates after harvesting. As water will be passing when going downstream to irrigate late crops in (KPSS) and will accidentally irrigate harvested fields whose gates are open. This water eventually gets depleted through evaporation and deep percolation and is lost from the system.

(E): Losses of water from poor field definition and irregular boundaries. This is a serious problem when only one hectare is cropped but the whole area of six hectares has been irrigated. Or you find a small nursery often (300 - 500 m^2) in a six hectares plot, all of which has been irrigated (see Figure 8). Actually this is very critical as every six hectare area has its nursery and the problem is that during this time (November) river flow is at its lowest and temperature is at its highest evaporation losses are therefore higher. The practice in the KSS and KPSS is very different. Here, the whole small bunded basin is cropped and the nurseries are prepared at special places (often under trees) to minimize evaporation losses. Supplementary irrigation of nurseries is done by using hand cans when too much moisture is depleted from the soil.

(F): Excessive wetting of KIF fields result on excessive and unrecoverable seepage or ET_o during long field preparation delays.

The sunken canals allow deep percolation of water during pre-saturation. Water also stays too long (up to three weeks) in KIF fields just for puddling and weed suffocation. This causes wastage of water both through deep percolation and evaporation.

(G): Excessive depth of water evaporated at the end of season in paddy basins, is also related to poor uniformity of field water depth. Excessive water depths and continuous flood (at an average of 230 mm) in KIF also cause water losses through evaporation and percolation.

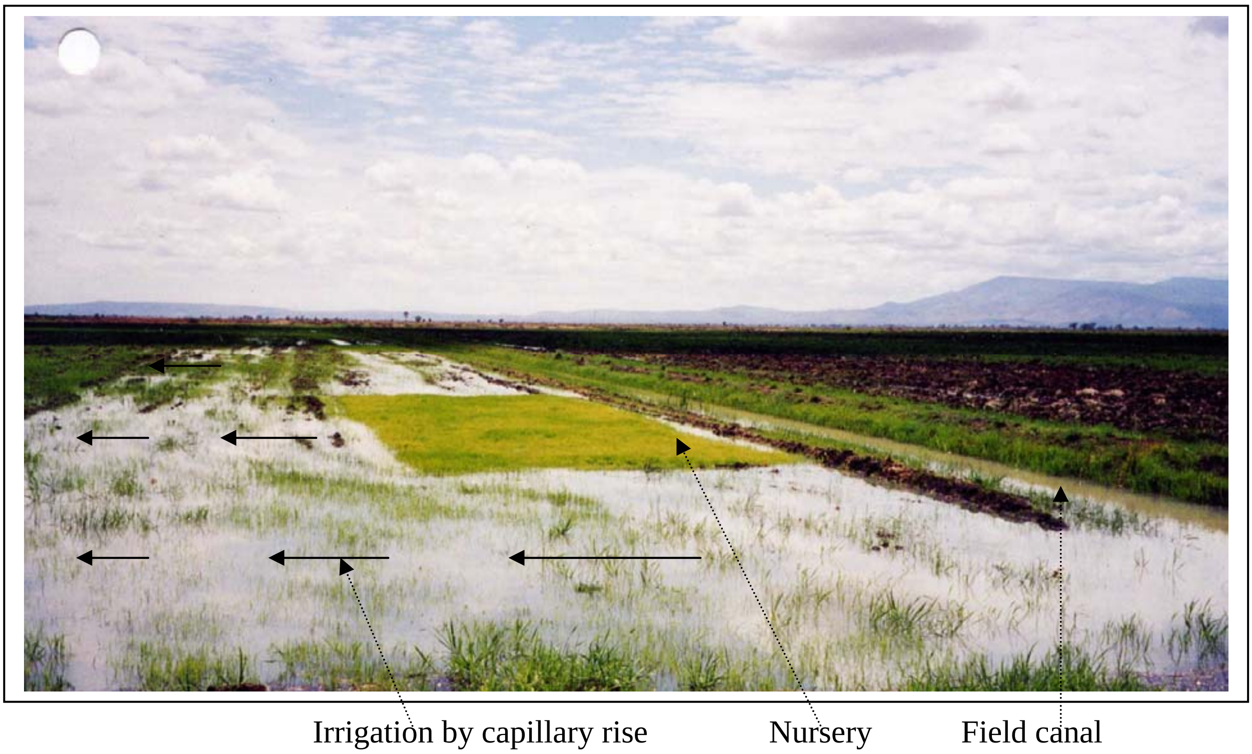

Figure 8: Nursery irrigation in KIF

H-I: Not reused and cannot be managed or improved. This portion includes seepage from fields, which cannot be recovered. It also includes canal losses; evaporation from canals and unrecoverable seepage in canals that occur in open earth channels. Although some literature argues that losses in earth canals are highly reduced by lining, this is sometimes true and sometimes not. In some situations, like the KWS, where some recharge was recorded in the primary canals, lining would prevent such recharge. This recharge would end up deep percolating, evaporating or irrigating grasses. Money might be spent to line the canals and instead of improving the efficiency it is actually lowered. Physical measurement is therefore required before the decision to line the canals is reached.

4.4. ISE can inform how much water can realistically be saved or improved

Based on the earlier analyses (Figure 8) it should be possible to save a significant amount of water from an irrigation system, e.g. the Kapunga irrigation farm (KIF) in four ways:

1. Reduce the excessive depth of water evaporated at the end of season in paddy basins related to poor uniformity of field water depths,
2. Reduce excessive pre-saturation which results in unrecoverable seepage or ET_o during long field preparation,
3. Reduce losses of water from poor field definition and irregular boundaries, and
4. Reduce excessive irrigation at the beginning and end of the season and after harvest (evaporated at the end of the season).

If say, for example, the gross water requirement of KPSS is assumed to apply all over the KWS, it means that about 1700 mm of water will be used in KIF annually. This is a saving of 900 mm from a KIF average gross annual use of about 2600 mm. The gross save of 900 mm annually over an area of 3233 ha (KIF cropped area in 2000/2001 season), for example, is equivalent to about 29 MCM. This means that the released 29 MCM from KIF could be made available for inter-sectoral or intra-sectoral allocation.

Again, if KIF reduces from 2500 mm to 1700 mm - this implies that its current efficiency of 35% will increase to about 64%. Its productivity (kg/m^3) will also increase because instead of using 2500 mm would be producing the same yield using only 1700 mm. This means that the productivity would rise from the current 0.17 kg/m^3 to about 0.27 kg/m^3 assuming that everything else remains constant.

In addition to the efficiency and productivity improvements that should be possible within KIF, there could be reduction in the delays of water delivery downstream. This would improve the efficiency and productivity of the KIF water reuse subsystem. Reduction of delays would allow more area to be cropped downstream and within correct transplanting window (November - March) which then increases yields. This was observed in the KSS water reuse subsystem where movement of water between neighbour schemes takes about three to four days. A delay of that magnitude was shown here to be insignificant since harvesting can take place on the same day.

This may also give some improvement to price fluctuations. A reduction of the transplanting gap between KIF and KPSS might bring the price fluctuation into some kind of stability. If KIF and KPSS farmers harvest at a similar time, it is possible that they will be able to sell their rice at a similar price.

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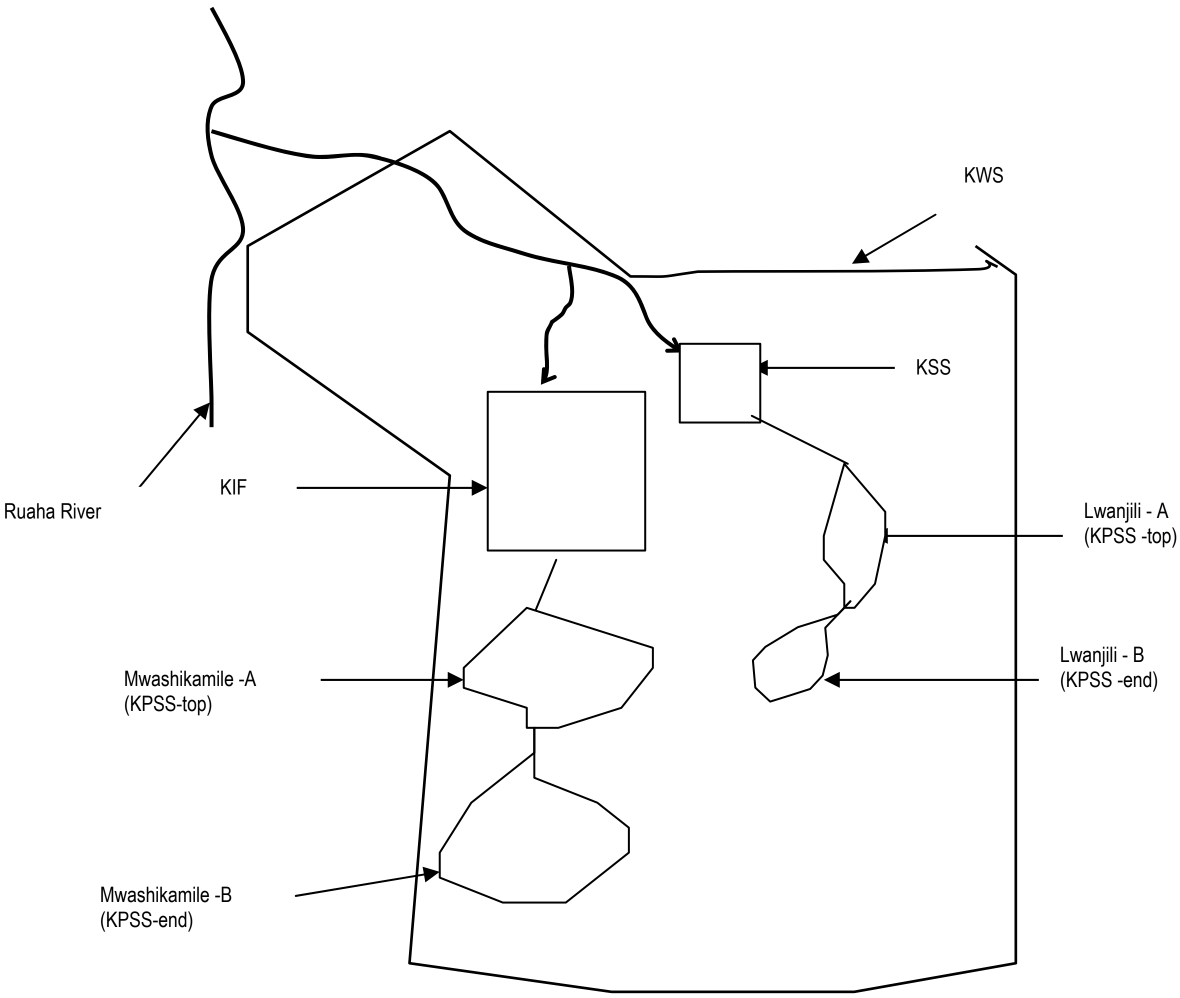
Appendix 1: Kapunga Water System

This section provides a brief description on the background of worked examples on irrigation efficiency and productivity used in the texts above. The examples are drawn from three different irrigation schemes for the period of two years (1999/2000 and 2000/2001). The 1999/2000 year was dry with rainfall amount of about 300 mm while the 2000/2001 was wet with rainfall of about 800 mm. The three irrigation schemes are Kapunga irrigation farm (KIF), Kapunga smallholder scheme (KSS), Kapunga peri-smallholder schemes (KPSS). The combination of the three schemes is what is known as Kapunga water system (KWS). The KPSS are the schemes, which reuse water from both KIF and KSS. It is further divided into KPSS-top (first user of drain water) and KPSS-end (second user of drain water). The KWS is illustrated by the figure below.



Appendix 2: Conversion Table

Length			Weight			Area			Capacity		
meters	m/ft	feet	grammes	g/ozs	ounes	sq cms	Sq cms/sq ins	Sq ins	litres	Litres/US gals	US gals
0.30	1	3.28	28.35	1	0.04	6.45	1	0.16	3.79	1	0.26
0.61	2	6.56	56.70	2	0.07	12.90	2	0.31	7.57	2	0.53
0.91	3	9.84	85.05	3	0.11	19.35	3	0.47	11.35	3	0.79
1.22	4	13.12	113.40	4	0.14	25.81	4	0.62	15.14	4	1.06
1.52	5	16.40	141.80	5	0.18	32.26	5	0.78	18.93	5	1.32
1.83	6	19.68	170.10	6	0.21	38.71	6	0.93	22.71	6	1.58
2.13	7	22.97	198.50	7	0.25	45.16	7	1.09	26.50	7	1.85
2.44	8	26.25	226.80	8	0.28	51.61	8	1.24	30.28	8	2.11
2.74	9	29.53	255.20	9	0.32	58.06	9	1.40	34.16	9	2.38
3.05	10	32.81	283.50	10	0.35	64.52	10	1.66	37.94	10	2.64
6.10	20	65.62	567.00	20	0.71	129.03	20	3.10	75.88	20	5.28
9.14	30	98.42	850.50	30	1.06	193.55	30	4.65	113.82	30	7.92
12.20	40	131.20	1134.00	40	1.41	258.06	40	6.20	151.76	40	10.56
15.24	50	164.00	1417.50	50	1.76	322.58	50	7.75	189.70	50	13.20
18.29	60	196.90	1701.00	60	2.12	387.10	60	9.30	227.64	60	15.84
21.34	70	229.70	1984.50	70	2.47	451.61	70	10.85	265.58	70	18.48
24.38	80	262.50	2268.00	80	2.82	516.13	80	12.40	303.52	80	21.12
27.43	90	295.30	2551.50	90	3.17	580.64	90	13.95	341.46	90	23.76
30.49	100	328.10	2835.00	100	3.53	645.16	100	15.50	379.40	100	26.40
centimetres	cm/ins	inches	kilogrammes	kg/lbs	pounds	cu metres	cu m/cu ft	cubic feet	litres	litres/gals	gallons
2.54	1	0.40	0.45	1	2.21	0.03	1	35.32	4.55	1	0.22
5.08	2	0.80	0.91	2	4.41	0.06	2	70.63	9.09	2	0.44
7.62	3	1.20	1.36	3	6.61	0.08	3	105.90	13.64	3	0.66
10.16	4	1.60	1.81	4	8.82	0.11	4	141.30	18.18	4	0.88
12.70	5	2.00	2.27	5	11.02	0.14	5	176.60	22.73	5	1.10
15.24	6	2.40	2.72	6	13.23	0.17	6	212.00	27.28	6	1.32
17.78	7	2.80	3.18	7	15.43	0.20	7	247.20	31.28	7	1.54
20.32	8	3.20	3.63	8	17.64	0.23	8	282.50	36.37	8	1.76
22.86	9	3.50	4.08	9	19.84	0.25	9	317.80	40.91	9	1.98
25.40	10	3.90	4.54	10	22.05	0.28	10	353.20	45.46	10	2.20
50.80	20	7.90	9.07	20	44.09	0.57	20	705.30	90.92	20	4.40
76.20	30	11.80	13.61	30	66.14	0.85	30	1059.40	136.40	30	6.60
101.60	40	15.80	18.14	40	88.19	1.13	40	1412.60	181.80	40	8.80
127.00	50	19.70	22.68	50	110.20	1.42	50	1765.80	227.30	50	11.00
152.40	60	23.60	27.22	60	132.30	1.70	60	2119.00	272.80	60	13.20
177.08	70	27.60	31.75	70	154.30	2.00	70	2472.10	318.20	70	15.40
203.20	80	31.50	36.29	80	176.40	2.27	80	2825.30	363.70	80	17.60
228.60	90	35.40	40.82	90	198.40	2.55	90	3178.40	409.10	90	19.80
254.00	100	39.40	45.36	100	220.50	2.83	100	3531.60	454.60	100	22.00
kilometers	km/miles	miles	Metric tones	tonnes /ton	ton	hactares	ha/acres	acres	US gals/US gals	Imp gals	Imp gals
1.61	1	0.62	1.02	1	0.98	0.41	1	2.47	1.20	1	0.83
3.22	2	1.24	2.03	2	1.97	0.81	2	4.94	2.40	2	1.67
4.83	3	1.86	3.05	3	2.95	1.21	3	7.41	3.60	3	2.50
6.44	4	2.49	4.06	4	3.94	1.62	4	9.88	4.80	4	3.33
8.05	5	3.11	5.08	5	4.92	2.02	5	12.36	6.00	5	4.16
9.66	6	3.73	6.10	6	5.91	2.43	6	14.83	7.21	6	5.00
11.27	7	4.35	7.11	7	6.89	2.83	7	17.30	8.41	7	5.83
12.88	8	4.97	8.13	8	7.87	3.24	8	19.77	9.61	8	6.66
14.48	9	5.59	9.14	9	8.86	3.64	9	22.24	10.81	9	7.49
16.09	10	6.21	10.16	10	9.84	4.05	10	24.71	12.01	10	8.33
32.19	20	12.43	20.32	20	19.68	8.09	20	49.42	24.01	20	16.56
48.28	30	18.64	30.48	30	29.53	12.14	30	74.13	36.03	30	24.98
64.37	40	24.86	40.64	40	39.37	16.19	40	98.84	48.04	40	33.30
80.47	50	31.07	50.80	50	49.21	20.23	50	123.60	60.05	50	41.63
96.56	60	37.28	60.96	60	59.05	24.28	60	148.30	72.05	60	49.96
112.70	70	43.50	71.12	70	68.89	28.33	70	173.00	84.06	70	58.29
128.70	80	49.71	81.28	80	78.74	32.38	80	197.70	97.07	80	66.61
144.80	90	55.92	91.44	90	88.58	36.42	90	222.40	108.08	90	74.94
160.90	100	62.14	101.60	100	98.42	40.47	100	247.10	120.09	100	83.27

Appendix 3: Flow Measurements

Appendix 3a: Measurement of flows using current meter

Equipment:

1. Current meter rod
2. Timer
3. Measuring tape
4. Meter or propeller
5. Two ranging rod or wood poles

Procedure:

1. Select an appropriate fair straight river/stream section for measurement
2. Measure the width of the stream or canal conveying the inflow or outflow water
3. Divide the width into equal cross-sections
4. Select the method to use depending on average depth of the flowing water (0.6 or 0.8 method) – 0.6 method for shallow depths.
5. Measure and record the counts or revolutions (revs) of the meter for known or set time period in seconds for each cross section area
6. Calculate the number of counts (rev/sec) for each cross section as the ratio of number of revolutions to time recorded in (4) above
7. Calculate the velocity (m/s) for each cross section using the standard current meter equation
8. Calculate the mean sectional velocity as the average velocity of the two adjacent vertical depths
9. Calculate the cross-sectional area for the each of the sections divided in (2) above
10. Calculate flow rate (product of 7 and 8) for each cross-section
11. Calculate the flow rate for the stream, river or canal as the average of the cross-sectional flow rates

Example on measurement of flows using current meter

Date: 26/03/2002
Canal: Igomelo
GPS Points:
Starting time: 13.45pm
End time: 14.05pm

Current metre: Pygmy SEBA No. 1258
Propeller No. 100.405
Discharge measurement method: 0.6 method

Table 1A: Discharge calculation from current meter measurements

Width (m)	Depth (m)	Revs (counts)	Time (sec)	Revs/sec (n)	Vel (m/s)	Mean Vel sect. (m/s)	Area (m^2)	Discharge (m^3/s)	Discharge (l/sec)
5.15	0	0							
5.35	0.12	30	40	0.75	0.0852	0.0568	0.012	0.001022	1.0224
5.55	0.18	80	40	2	0.2117	0.14845	0.03	0.006351	6.351
5.75	0.18	89	40	2.225	0.23447	0.223085	0.036	0.008441	8.44092
5.95	0.18	88	40	2.2	0.23194	0.233205	0.036	0.00835	8.34984
6.15	0.18	75	40	1.875	0.19905	0.215495	0.036	0.007166	7.1658
6.35	0.19	73	40	1.825	0.19399	0.19652	0.037	0.007178	7.17763
6.55	0.18	73	40	1.825	0.19399	0.19399	0.037	0.007178	7.17763
6.75	0.19	69	40	1.725	0.18387	0.18893	0.037	0.006803	6.80319
6.95	0.14	59	40	1.475	0.15857	0.17122	0.033	0.005233	5.23281
7.25	0	0	40	0	0.0093	0.083935	0.021	0.000195	0.1953
Average							**0.315**	**0.057917**	**57.91652**

Appendix 3b: Measurement of flows using weirs (portable)

Equipment:

Weir gauge or ruler

Procedure:

1. Set the weir at the lower end of a long pool sufficiently wide and deep to give an even, smooth current with a velocity of approach of not more than 0.15m/s (practically still water)
2. Fix the gauge of the weir approximately at a distance four times the height of weir crest on one side of the weir (normally upstream face of the weir). The zero mark of the gauge should coincide with the crest of the weir
3. Measure the average depth of water (H) above the crest of the weir for an inflow or outflow of water into or out of the field
4. Calibrate the weir using standard equation depending on the type of the weir (rectangular, trapezoidal or triangular)
5. Obtain several measurements of H to get several values of flow into the weir.

Appendix 3c: Measurement of flows using floating materials

Equipment:

a. Measuring tape at least 5m long
b. Simple wooden stakes
c. Watch capable of measuring time in seconds or Telephone handset with stopwatch option (now-days)
d. Floating (bottle or stick)

Procedure:

1. Select a straight section of the stream at least 10m long. The shape of the stream along this section should be uniform as possible
2. Place a stake in the bank at the upstream end of the selected section (1) and measure 10m downstream
3. Place a stake at the downstream end of the selected section of the stream (3).
4. Place the floating object in the centre of the stream at least 5m upstream of section 1, and start timing when the object reaches section1
5. Stop timing when the floating object reaches section 3, and record the time in seconds
6. Repeat 4 and 5 at least four times in order to determine the average time necessary for the object to travel from section 1 to 3. The object should not touch the stream bank during the trial. If it does, repeat the run and do not include the time for the bad trial when calculating the average time.
7. Measure the following in the selected stream section: the stream bed width (b), the surface water width (a), and the water depth (h). The cross-section within the selected portion of the stream will usually not be regular, and so (b), (a) and (h) need to be measured in several places to obtain an average value
8. Calculate the average area of the stream cross-section (A), using the following formula:

$$A = \frac{(a+b)h}{2}$$

9. Calculate the average flow velocity (V):

$$V = \frac{L}{T}$$

T = the average travel time in seconds
L = the distance between section 1 to 3 in meters

10. Calculate the flow, Q in the stream, using the following formula:

Q = V.A (m^3/s)

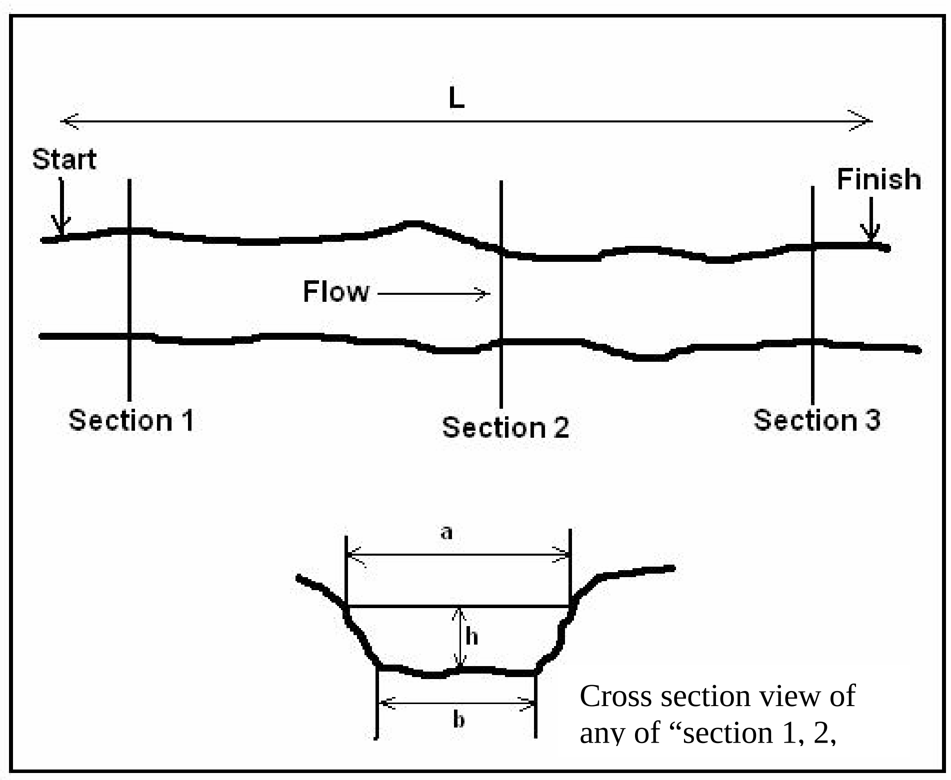


Figure 3c.1: Measurement of flows by floating object

Appendix 3d: Measurement of flows using buckets (Volumetric method)

Equipment:

a. Container of known volume
b. Stopwatch or wristwatch capable of measuring time in seconds
c. Furrow tube or conduit capable of conveying all the flow in the furrow
d. Hand hoe or spade for excavating a hole for placement of the container

Procedure

1. Excavate a hole at the end of the furrow (distribution or field inlet) for the placement of the container
2. Allow the flow and fill the volume (V) of the container
3. Record the time (t) required to fill the container
4. Calculate the flow rate by dividing the volume of the container (V) by the time (T) required to fill it as

$$Q = \frac{V}{T}(m^3/s)$$

Appendix 3e: Measurement of flows using calibrated materials (example of pipe conduit)

Equipment

a. Calibrated material of known dimension
b. Stopwatch or wristwatch
c. Ruler

Procedure

1. Install the measuring material to the respective location in the flow system
2. Measure the flow rates in the conveying canal at two points, (preferably 1 meter in distance apart) before and after water is diverted through the calibrated material system
3. Measure the height (h) of water at the different flow rates at the two selected points in the canal before diverting water into the calibrated material
4. Measure different (Q) at different (h) using methods explained in appendices (3a) or (3d)
5. Develop a rating table for the inlet water flow that is passing through the calibrated material
6. Develop a rating curve in relation to the discharge in the canal supplying water to the calibrated material
7. The difference in flow rates between the upstream and downstream points is equivalent to the amount of flow diverted through the calibrated material
8. Continue monitoring depth or head above the pipe and time water takes to flow into the field on irrigation days and use the depth (an average) to determine the amount of water flowed for irrigation into the field.

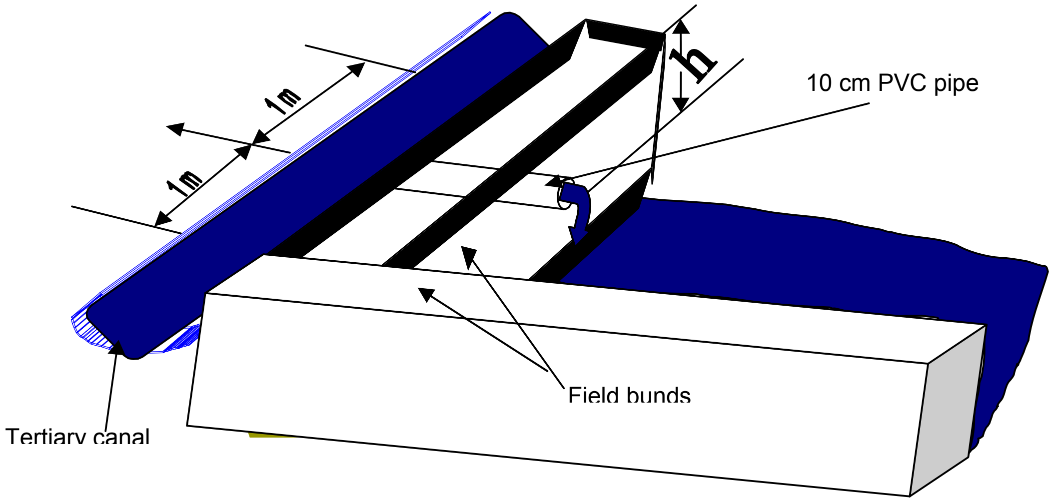


Figure 3e.1: Measuring inflow using calibrated PVC pipe

Appendix 4: Measurement of field water use (for flooded fields only e.g rice fields)

Note: For non flooded fields/crop please use ThetaProbe (For instructions on how to obtain and use visit www.delta-t.co.uk/frame/submenu/soil.html)

Equipment:

a. Lysimeter (Cylindrical drum)
b. Adjustable hook and hook holder
c. Standard measuring cylinder (preferably a 10mm cylinder)
d. Crop seedlings (paddy seedling)
e. Hand hoe or spade for soil excavatio

Procedure:

1. Select appropriate location in sampled field and excavate the soil (approx. half the height of the lysimeter) with the diameter equivalent to the diameter of the lysimeter
2. Refill the lysimeter with soil excavated material to half the depth of the lysimeter and then install the lysimeter in the excavated hole such that the filled soil level in the lysimeter is the same as in the main field
3. Transplant the crop seedlings (paddy seedling)
4. Fix the hook to appropriate height above the soil material in the lysimeter
5. Fill the lysimeter with water to a level which is equal to the level in the main field. Ensure the pointer of the hook is leveled with the filled water
6. Record the change in the level of water everyday preferably at 9.00 am using the standard measuring cylinder to determine the amount of water gained or lost in the lysimeter

7. An immersed hook indicate a gain of water while a protruding hook indicates that a loss has occurred
8. Use the measuring cylinder to refill or empty water from a lysimeter to the level that was set in the previous day
9. Set the level of water in the lysimeter according to the level of water in the main field
10. Adjust the adjustable hook to touch the surface of the newly set level of water ready for measurement in the next day (after 24hrs)

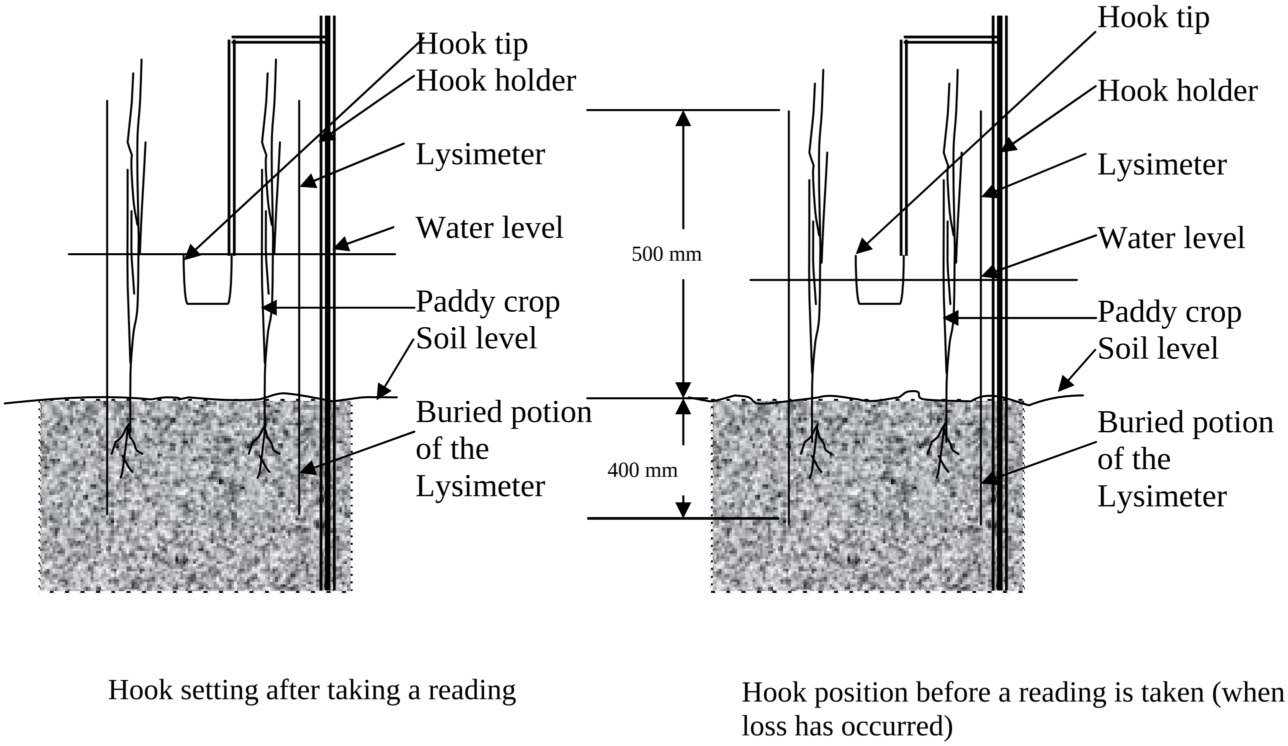


Figure 4.1: Cross sectional view of a lysimeter installed in a field

Appendix 5: Measurement of irrigated area

Equipment:

a. GPS
b. Measuring tape
c. Wheel race meter

Procedure:

1. Collect (mapping) the GPS points around cropped fields during the season
2. Download the GPS points after mapping
3. Process the downloaded points using appropriate software such as ArcView GIS program etc
4. Analyse the data and produce maps of irrigated area
5. From the maps use the software to calculate the cropped area
6. Area of small fields could be measured manually using a tape measure to determine the dimension of the field (length and width) and calculating the area depending on the shape of the field (rectangle, trapezoidal triangular). A wheel race meter may be used to measure the area of small fields too.

Appendix 6: Measurement of productivity of water

Equipment
a. Measuring tape
b. Pegs or sticks
c. Sickle
d. Balance (accuracy 0.05kg or higher)
e. Moisture meter

Procedure
1. Measure the annual or seasonal water use (m^3) for the field as explained under the ISE approach on water use
2. Select three sample area not less that $15m^2$ each (Machibya, 2003) in selected field plot and harvest the crop
3. Mark the sampled area with sticks or pegs
4. Harvest the crop using sickles
5. Measure the crop yield in kg
6. Measure the moisture content of the crop after harvesting and after drying
7. Extrapolate the equivalent yield per hectare from the sample yields obtained
8. Calculate the water productivity as the ratio of yield (kg) to equivalent water used (m^3)

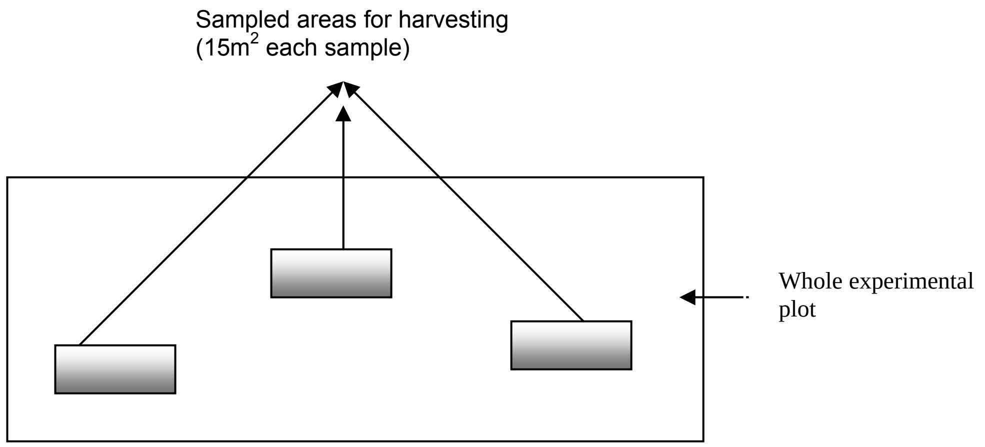


Figure 6.1: Appropriate sampling frame for measuring crop yield in the field.

Appendix 7: Measurement of Farm operation and management efficiency (*Daily water depths in paddy fields)*

Equipment:

Ruler (Approx. 2m long)

Procedure:

1. Sample appropriate locations at the centre and the two extreme ends of the field depending on the size of the field
2. Take the measurement of water depth above the soil surface at least once per day for the entire crop growth period (from transplanting until when water is drained off for harvesting)
3. Calculate the average depth maintained in the field for the entire crop growth period

Appendix 8: "Information, facts and calculations for managing Usangu irrigation"

General information on Usangu Irrigation

- The maximum irrigable area in the Usangu Plains is said to be **55 000 ha** – though this may be growing.
- The maximum irrigated land in year 2000 under rice was **42 000 ha**. This is grown during a normal-to-wet year.
- The core irrigated area found in a dry year is **16 700 ha**.
- The dry-season cropped area in year 2000 is **2500 ha**. This is for non-rice crops such as maize and beans.
- The main rice-growing season is now quite extended, and for the purposes of modelling water is from 1st dekad September to 2^{nd} dekad in August. This is **300 days**.
- The mean annual rainfall on the Plains is 729 mm, and **effective rainfall is 533** mm. This rain falls during the period November to May.
- The mean annual Penman-Montieth evapotranspiration is 1939 mm. The evapotranspiration during the 300 day growing season is 1623 mm. The water deficit between this and effective rainfall over this extended period is 1000 mm.
- The average field in Usangu spends about 200 days with water in it (from start of field preparation to end of residual watering after harvesting).
- In year 200, there were approximately **120 river offtakes** in the Usangu area, 70 of which are in the Mkoji catchment.
- In year 2000, these 120 offtakes account for an estimated maximum abstraction of **45 cumecs** when river flows are near their maximum.
- The average abstractable proportion is high, at **90% of** water, until the flow-rate capacity of the intakes is exceeded.

Irrigation system water requirements and productivity

- NAFCO farms account for 3 of the 120 river offtakes (2.5%), but can abstract a total of approximately 15-16 cumecs which is 34% of the total abstractive capacity in the Usangu Plains.

  Madibira. Approx 3000 ha rice, the intake total abstraction is 4.3 cumecs.

  Mbarali. Approx 3000 to 9000 ha. Intake capacity is about 6-7 cumecs.

  Kapunga. Approx 3000 ha. Maximum abstraction is about 5.0 cumecs.
- Net irrigation demand for global Usangu irrigation is approximately 1150 mm in a normal to wet year. (In other words, this is a weighted mean demand).
- Gross irrigation demand for global Usangu irrigation is approximately 1600 mm in a normal to wet year. (In other words, this is a weighted mean demand).
- NAFCO fields take approximately 800 mm to wet up, then 220 mm standing water, then a depth of water to replace a moisture deficit of about 1000 mm. This is approximately 2000 mm of water.
- In one hectare, this is 2000 x 10 = 20,000 cubic metres of water. If NAFCO yields are on average 2 tonnes (2000 kg) per hectare, then water use is 10 cubic metres of water per kg of rice. Alternatively expressed, the productivity of rice is 0.1 kg/cubic metre of water

Table 2A. Information used to determine gross irrigation demand of Usangu irrigation

Item no.	Item	Net Demand scenario	Gross demand scenario	Comments
1.	Start of rice field preparation	1st Nov	1st Sept	Early planting (stretching of the season) due to high rice prices and constrained resources
2.	Main season crop factor	1.10	1.10	No change in crop factor.
3.	End of season crop factor	0.00 (irrigation ceases)	1.10	In the net demand scenario, irrigation ceases altogether before harvesting. In gross demand scenario, the standing water layer remains.
4.	Withholding of water period length at end of season	20 days	0 days	In the net demand scenario, irrigation is withheld for 20 days before harvesting. In the gross demand scenario, water is supplied to the fields until harvest.
5.	Smallholder presaturation water	200 mm	220 mm	Smallholder water use (this depth has been estimated)
6.	NAFCO presaturation water	200 mm	800 mm	NAFCO water use is very high due to land prep and large fields (this depth has been measured)
7.	Duration of field wetting-up period in smallholder fields	7 days	10 days	Smallholders take about 7-10 days between first wetting and transplanting of rice.
8.	Duration of field wetting-up period in NAFCO fields	7 days	30 days	NAFCO allow fields to remain wet for a longer period (30 days) before transplanting due to method of land preparation
9.	Seepage rate of water below the root zone, lost to groundwater	2.5 mm/day	2.5 mm/day	No difference between net and gross demand scenarios
10.	Smallholder standing water layer	100 mm	180 mm	Water depth is reckoned to be ankle-high, whereas target depth should be 100 mm.
11.	NAFCO standing water layer	120 mm	250 mm	NAFCO water depth as recorded
12.	'Growing period' season length	150 days	160 days	The gross demand scenario has an increased period to account for varieties mix and delayed ripening
13.	Field wetting period after harvesting has been completed	0 days	20 days	20 days is added to end of season account for field-to-field distribution of water after harvesting.
14.	Average length of total wetting period		205	From field preparation to final drying out
15.	Area wetted after harvesting has been completed	0.0	0.5 of previous 10 day's area	Wetted area is a proportion of previous 10 days area of irrigation. Therefore, this area decreases by this amount each 10 day period
16.	Residual return flow from fields to drainage and back to rivers during most of the season	0%	2.0%	(Net demand precludes any return flow). The gross demand scenario accounts for water returning to rivers via seepage and some overland flow.
17.	Peak return flow % during the main part of the rainy season	0%.	10%	(Net demand precludes any return flow). Observations indicate that, although return flow is not a considerable amount, it does increase during the wet season.
18.	Period of peak return flow	Not applicabl e	Feb to May	The return flow occurs during peak rains and early harvesting period.

Table 3A: FACTS AND FIGURES FOR IRRIGATION AND WATER PLANNING

VOLUME

1 cubic foot		= 28.32 litres	= 0.02832 m^3
1 litre	= 1.76 pint	= 0.88 quart	= 0.2201 gallon
1 m^3	= 1000 litres	= 220.1 gallon	= 35.31 ft^3
1000 m^3	= 1 kilocume	= 1 million litres	= 220 080 gallons
1000 m^3	= 0.81 acre ft	= 10 ha cm	
1 ft water on 1 acre	= 1 acre ft = 12.1 cusec hrs	= 272 250 gals = 0.1234 ha m	= 1233.62 m^3
1 in water on 1 acre	= 1 acre in	= 22688 gallons	= 102.80 m^3 ≅ 1 ha cm
1 cm on 1 ha	= 1 ha cm	= 100 m^3	= 100 000 litres ≅ 1 acre in
10 cm on 1 ha	= 10 ha cm	= 1 million litres	≅ 10 acre in
1 mm water on 1 ha	= 10 000 litres	= 10 m^3	
1 litre on 1 m^2	= 1.0 mm		
1 m^3 on 1 m^2	= 1000 mm		

FLOWS AND RATES

1 cusec	= 1 ft^3/second	= 6.25 gals/sec	22500 gals/hr
1 cusec	= 28.32 l/sec	= 1699 l/min	102 m^3/hour
1 cusec for 1 hr	= 22500 gals	= 0.9917 acre ins	
1 cusec for 1 day	= 23.80 acre ins	= 1.984 acre ft	= 0.245 ha m
1 cusec for 30 days		= 59.59 acre ft	= 7.24 ha m
1 acrefoot/day	= 14.27 l/sec		
1 litre/sec	= 0.22 gals/sec = 13.2 gals/min	= 0.0357 cusecs	= 3.6 m^3/hr
1 litre/sec for 1 hr	= 3600 litres	= 0.36 mm on 1 ha	= 0.03 acre ins
1 litre/sec for 1 day	= 86400 litres	= 8.6 mm on 1 ha	= 0.84 acre ins
1000 litre/sec	= 1 m^3/sec	= 1 cumec	= 35.32 cusecs
1 cumec for 1 hr	= 3.6 million litres	= 0.36 ha m	= 2.92 acre ft
1 cumec for 1 day	= 86.4 million litres	= 8.64 ha cm	= 70.05 acre ft
1 m^3/hour	= 0.28 litres/sec	= 3.56 gals/min	
1 m^3/hour for 1 hr	= 1000 litres	= 0.10 mm on 1 ha	
1 m^3/hour for 1 day	= 24 000 litres	= 2.4 mm on 1 ha	
1 l/sec/ha	= 3.6 m^3/hr/ha		
1 mm/day	= 0.417 m^3/hr/ha		
1 cubic kilometre	= 1000 million cubic metres	= 1 milliard	

AREA

1 acre	= 4 840 yds^2	= 43560 ft^2	
1 acre	= 4048 m^2	= 0.4048 ha	
1 ha	= 10 000 m^2	= 2.47 acres	

TIME

1 min = 60 seconds 1 hour = 3600 seconds 24 hours = 86400 seconds

FLOW CALCULATIONS

Volume in m^3 = depth in mm x ha x 10 Thus: mm = m^3 / (ha x 10)
m^3/hr x hours = depth in mm x ha x 10
Litres/sec x hours = depth in mm x ha x 10
(Remember, one millimetre of water on one hectare is 10 cubic metres of water)

CONVERSIONS

1 m^3/day to litres/second. Multiply $m^{3/}$day by 0.01157
Litres/second to m3/day. Multiply litres/second by 86.4

Table 4A: More conversions and ways of calculating water management

Depth in mm = $\frac{m^3}{ha \times 10}$	Litres/ha = $mm \times 10000$
litres/second/ha = $\frac{m^3 \times 1000}{seoonds \times ha}$	mm/hour = $\frac{m^3 / hour \times 1000}{m^2}$
Litres/second = $\frac{mm \times ha}{minutes \times 6x10^{-3}}$	Litres/second = $\frac{mm \times ha}{hours \times 0.36}$
M^3/second = $\frac{mm \times ha}{minutes \times 6}$	M^3/second = $\frac{i\ (mm / hr) \times ha}{360}$
mm applied = $\frac{litres / s \times hrs \times 0.36}{ha}$	mm applied (effective) = $\frac{litres / s \times hrs \times 0.36 \times efficiency}{ha}$
hours of irrigation required = $\frac{mm\ applied \times ha}{efficiency \times l / s \times 0.36}$	Hectares irrigated = $\frac{litres / s \times hrs \times 0.36 \times efficiency}{mm\ applied}$
Efficiency % = $\frac{mm \times ha}{l / s \times hrs \times 0.36}$	Hydromodule (in litres/second/ha) = $\frac{mm / day \times 10000}{86400}$ Thus hydromodule = mm/day IWR $\times$ 0.1157
mm/day supplied = $\frac{l / sec}{ha \times 0.1157}$ where litres/second is on a 24 hour basis	

For example, taking last equation in last box

if flow is 2000 l/sec, and the hectares irrigated is 200 ha in that day, then the mm applied in that day is 86. 4 mm

or 2000 /(200 x 0.1157) = 86.4 mm applied

Calculating crop and field irrigation water requirements
There are a number of ways of presenting irrigation water requirements (irrigation need)
- As a depth equivalent (mm/day)
- As a total depth (mm per period)
- As a flow rate per unit area, called hydromodule if area = hectares, thus l/sec/ha
- As a flow rate per area farmed, ie in l/second, or cumecs, or m^3/day
- As a total volume per area farmed in a period (ie total litres, or cubic metres)

Steps in determining water demand

Starting from evapotranspiration, calculate the flow rate needed for 1000 hectares of rice in Usangu.

Average penman evaporation per day = 5.5 mm/day

Conversion factor to rice evaporation (x 1.10)

Rice evaporation per day = 5.5 x 1.10 = 6.05 mm/day

Effective rainfall = 2.5 mm/day, is subtracted from rice evaporation to derive crop irrigation need.

Crop irrigation need in depth equivalent (mm/day) = 6.05 - 2.5 = 3.55 mm/day

Field seepage = 2.5 mm/day, is added to crop irrigation need to derive field irrigation need

Field irrigation need (FIN) in depth equivalent (mm/day) = 3.55 + 2.5 = 6.05 mm/day

Conversion by multiplication of 0.1157 is used to derive litres/second per hectare = x 0.1157

Field irrigation need (FIN) in hydromodule (l/sec/ha) = 6.05 x 0.1157 = 0.699 l/sec/ha

Conversion by area multiplication to derive flow (FIN x ha), so FIN x 1000 if 1000 hectares

Field irrigation need in flow (l/sec) = 0.699 x 1000 = 700 l/sec

Conversion by efficiency division to derive gross irrigation need (divided by efficiency figure = 80%)

Gross irrigation need = 700 / 0.8 = 875 l/sec

Conversion factor to cumecs = divided by 1000

Gross irrigation need = 875 / 1000 = 0.87 cumecs