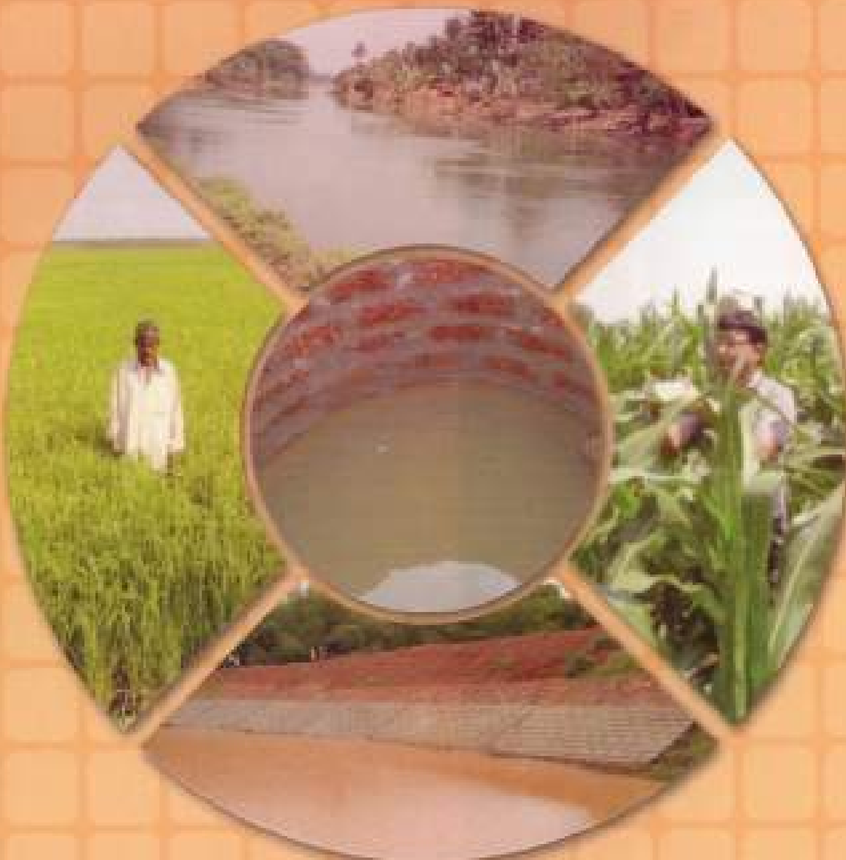
Research Bulletin 67

FARM LEVEL WATER FOOTPRINTS OF CROP PRODUCTION: CONCEPT AND ACCOUNTING



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PREFACE

With rapid population growth and rising expectation of better life, there will be ever increasing demand of water for various competing sectors like domestic, industrial and agricultural needs. Also more and more water will be required for environmental concerns such as aquatic life, wildlife refuges and recreation. With changing global climatic patterns coupled with declining per capita availability of surface and groundwater, sustainable water resources management is a great challenge in India. With increasing water demand from other sectors, agricultural water use in the country will face stiff competition for scarce water resource in future. Therefore, the available utilizable water resources would be inadequate to meet the future water needs of all sectors unless the utilizable quantity is increased by all possible means and water is used efficiently. Adoption of suitable agro-techniques for crop cultivation is need of the hour to produce more crops with less water so to check the decline of surface and ground water resources in India. Recognizing the importance of the above facts many water saving irrigation technologies like resource conservation technology including laser leveling improved irrigation methods including drip and sprinkler, rain water harvesting and ground water recharge techniques, diversification with low duty crops, waste water management, conjunctive and multiple use of water etc. have been developed to achieve 'more productivity per-drop'. But now the priority is the development of the indices which can be used to indicate appropriation of fresh water resources to produce a particular product or to complete one process requiring water from a particular management system. In this regard water footprints which are the ratio of volume of consumptive water use to quantity of produce of interest can be used to indicate direct and indirect appropriation of fresh water resources. The term fresh water appropriations include both consumptive water use (the green and blue water footprints) and the water required to assimilate pollution (the grey water footprint). Lower water footprints from a management system indicate its efficiency to produce more biological yield or product with less amount of water. The water footprint of a product can be used to provide information to consumers about the water-related impacts of products they use or to give policy makers an idea of how much water is being "traded" through imports and exports of the product.

A number of studies have been conducted to quantify the water footprint of rainfed and irrigated crops and crop products but still farm level water footprints information of crops production under actual water availability in the field are not available. In this research bulletin concept of farm level water footprints of crop production has been vividly discussed and water footprint accounting procedure has been standardized under different agro-management systems. We sincerely hope that the research bulletin will be helpful to researchers, extension workers, academicians and others those are engaged in agricultural water management research for computing water footprints at farm level.

Authors

CONTENTS

1.0 Introduction

The water resources potential of India which occurs as natural runoff in the rivers are estimated at about 186.9 M ha-m. Considering both uneven distribution of water resource over space and time about 112.2 M ha-m of the total potential can be put to beneficial use, 69 M ha-m through surface water resources and 43.2 M ha-m by groundwater (Kumar and Kar, 2013). India experiences high degree of spatial variability of annual rainfall, highest annual rainfall of 11,690 mm is recorded at Mousinram near Cherrapunji, Meghalaya, and lowest of 150 mm at Jaisalmer of Rajasthan. Average 75% precipitation of the country occurs during southwest monsoon season (June to September) only (Kumar and Kar, 2013). The country's vast cultivated area (82 M ha) is still rainfed. For adequate living standards as in western and industrialized countries, a renewable water supply of at least 2000 m^3 per person per year is necessary. If only 1000-2000 m^3 per person per year is available, the country is 'water stressed', while the value comes below 500 m^3 per person per year, the country is called 'water scarce' (Kumar and Kar, 2013). With rapid population growth and rising expectation of better life, there will be ever increasing demand of water for various competing sectors like domestic, industrial and agricultural needs. Also more and more water will be required for environmental concerns such as aquatic life, wildlife refuges and recreation. With changing global climatic patterns coupled with declining per capita availability of surface and ground water resources, sustainable water management in agriculture is a great challenge in India. With increasing water demand from other sectors, agricultural water use in India will face stiff competition for scarce water resource in future. Therefore, the available utilizable water resources would be inadequate to meet the future water needs of all sectors unless the utilizable quantity is increased by all possible means and water is used efficiently. Adoption of suitable agro-techniques for crop cultivation is need of the hour to produce more crops with less water so as to check the decline of surface and ground water resources in India. Recognizing the importance of the above fact, the country has developed water saving irrigation technologies like resource conservation technology including laser leveling, improved irrigation methods including drip and sprinkler, rainwater harvesting and groundwater recharge techniques, diversification with low duty crops, waste water management, conjunctive and multiple use of water etc. to achieve 'more productivity per drop'. But now the priority is the development of the indices those indicate appropriation of freshwater resources from a particular management system. In this regards water footprints which is the "ratio of the volume of consumptive water use to the quantity of produce of interest" can be used to indicate direct and indirect appropriation of freshwater resources (Hoekstra, 2003; Hoekstra and Chapagain, 2008). The term "freshwater appropriation" includes both consumptive water use (the green and blue water footprint) and the water required to assimilate pollution (the grey water footprint), (Postel et al., 1996 and Chapagain et al., 2006).

A number of studies have been conducted to quantify the water footprint of a large variety of different crop products and crops (Chapagain and Hoekstra, 2003, 2004, 2007; Oki and Kanae, 2004; Hoekstra and Hung, 2005; Chapagain, 2006; Chapagain et al., 2006; Chapagain and Hoekstra, 2007; Hoekstra and Chapagain, 2008; Gerbens-Leenes and Hoekstra, 2009; Chapagain and Orr, 2009, Hoekstra et al., 2011). These studies provided a broad-brush to the global picture since the primary focus of these studies was to establish a first estimate of global virtual water flows and/or national water footprints. More recently, though a few studies have separated global water consumption for crop production into green and blue water with a better spatial resolution (Rost et al., 2008; Siebert and Doll, 2008, 2010; Liu et al., 2009; Liu and Yang, 2010; Hanasaki et al., 2010; Fader et al., 2011), but still farm level water footprints information of crops and their accounting procedure under different management practices are not available. Keeping the importance of above points in view in this manual concept of farm level water footprints for crop production and their accounting procedure have been vividly discussed which can be used by researchers, extension workers, academicians and others those are engaged in agricultural water management research for computing water footprints at farm level.

2.0 Water productivity vs. Water footprints

Water productivity is the amount of crop production (kg) or money (Rs.) earned per unit amount of total water utilized (m^3) and usually expressed as kg m^{-3} or Rs. m^{-3}. But definition of water productivity changes with the background of the researcher or stakeholder involved. For example, obtaining more kilograms dry matter production per unit of transpiration is a key issue for plant breeders. At a basin scale, economists wish to maximize the economical value from water used. Water managers tend to be more concerned with the total water input. Rainfed farmers in arid areas are highly concerned with doing the most with the limited rainfall. Irrigation farmers and managers will evaluate their water productivity on the basis of canal water supplies in relation to crop yield.

Water footprints are the "ratio of the volume of consumptive water use (m^3) to the quantity (ton) of produce of interest" and can be used to indicate direct and indirect appropriation of freshwater resources (Hoekstra, 2003; Hoekstra and Chapagain, 2008). The water footprints of crops are expressed as volume of water consumed per unit quantity of produce (m^3 ton^{-1} or litre kg^{-1}) but units depend on what is being studied in the water footprint. Volumes of green, blue, and grey water are always in the numerator, but it may be time, mass, people, or units in the denominator depending upon the category of the product (e.g. liters/kg or m^3/ton for a crop, m^3 or liters/person/year for a consumer, m^3/ year for a land area, or liters/pair of cotton shirt for a product).

Water footprints (WF) indicate direct (the green and blue water footprint) and indirect (grey water footprint) appropriation of freshwater resources which (i) evaporates or evapo-transpires, (ii) is incorporated into a product, (iii) is contaminated, or (iv) is not returned to the same area where it was withdrawn. All four uses result in water being unavailable for local, short-term reuse and refer to water loss to the catchment only. Since the water outflows like seepage, percolation etc. are not a loss to the catchment, these types of water flows are not included for water footprint accounting. In water footprint accounting in addition to the water loss due to evaporation or evapo-transpiration, volume of freshwater that is required to assimilate the load of pollutants based on existing ambient water quality standards is also added. Evaporation or evapo-transpiration is often the most significant consumptive water use, and it will often be equated with total water use as the other components are negligibly small by comparison. Some amount of water is also needed for input production like fertilizers, pesticides to raise crops but that is insignificant as compared to evapo-transpiration. Since some amount of soil moisture is also lost during land preparation, puddling (in case of rice) to raise the crop, that water loss is also to be added to account water footprint.

3.0 Types of water footprints

Water footprint for any products or processes consists of three components: Blue, Green, and Grey.

3.1 Blue Water Footprint:

Blue Water refers to the amount of irrigation water applied from stored surface water or renewable groundwater sources other than effective rainfall (P_{eff}) and contribution from profile stored soil moisture (ΔSW) to grow a crop. Under unlimited irrigation water, entire deficit water is met through irrigation in order to fulfill potential crop evapotranspiration (PETc) or crop water requirements (CWR) and evaporation during land preparation / land soaking and hence crop water use (CWU) is equal to PETc or CWR. Thus, for fully irrigated crops, blue water (ET_{blue}) or the Irrigation Requirements (IR) is equal to the CWR minus P_{eff} and ΔSW. If P_{eff} and ΔSW are equal or more than that of CWR, blue water requirement is zero.

The **Blue Water Footprint** (WF_{blue}) refers to the ratio of volume of blue water consumed ($m^3\ ha^{-1}$) during the life cycle of a crop to the quantity of economic crop yield ($t\ ha^{-1}$) produced.

$$WF_{blue}\ (m^3\ t^{-1}) = \frac{Volume\ of\ Blue\ Water\ Use (m^3\ ha^{-1})}{Grain\ yield\ of\ the\ crop\ (t\ ha^{-1})} \quad \text{-----------------------} (1)$$

3.2 Green Water Footprint:

The **Green Water Footprint** (WF_{green}) refers to the ratio of loss of green water resources (profile stored soil moisture or rainwater in so far as it does not become runoff) due to evaporation or evapo-transpiration during the crop growth period to the quantity of economic crop yield ($t\ ha^{-1}$) produced. Thus,

$$WF_{green}\ (m^3\ t^{-1}) = \frac{Volume\ of\ Green\ Water\ Use (m^3\ ha^{-1})}{Grain\ yield\ of\ the\ crop\ (t\ ha^{-1})} \quad \text{-----------------} (2)$$

When no rainfall is received during crop growth period, effective rainfall component is zero but stored profile residual soil moisture of rainy season (PSMC) may serve as source of green water footprints.

3.3 Grey water footprint

The **Grey water footprint** (WF_{grey}) is defined as the volume of freshwater that is required to assimilate the load of pollutants based on existing ambient water quality standards

$$WF_{grey}\ (m^3\ t^{-1}) = \frac{Volume\ of\ Grey\ Water\ Use (m^3\ ha^{-1})}{Grain\ yield\ of\ the\ crop\ (t\ ha^{-1})} \quad \text{-----------------} (3)$$

The water footprint of a product is always expressed as volume of green, blue and grey water consumed per product unit. Examples:

- water volume per unit of mass (for products where weight is a good indicator of quantity)
- water volume per unit of money (for products where value tells more than weight)
- water volume per piece (for products that are counted per piece rather than weight)
- water volume per unit of energy (per kcal for food products, or per joule for electricity or fuels)

4.0 Applications of water footprint accounting

- The water footprints (WFs) of a product can be used to provide information to consumers about the water-related impacts of products they use or to give policy makers an idea of how much water is being "traded" through imports and exports of the product. As for example to produce one kilogram of rice approximately 3000 liters of water or for production of one kilogram of beef requires 15 thousand liters of water (Dourte and Fraisse, 2012). The actual water footprint of a product depends upon the type of production system, the composition and origin of the raw materials etc.

- WFs of a consumer will provide insight about his or her direct and indirect freshwater use. The direct water use is the water used at home, while the indirect water use relates to the total volume of freshwater that is used to produce the goods and services consumed. The water footprint of consumers can be expressed in terms of water volume per unit of time per capita. Example, The average resident in China and India has a water footprint of 1,071 and 1,089 m^3/person/year, respectively. (Dourte and Fraisse, 2012).

- WFs of a geographical or land area (county, watershed, or nation) provides information on water used to produce the goods and services consumed by the inhabitants of the nation. The internal water footprint is the appropriation of domestic water resources of that country; the external water footprint is the appropriation of water resources in other countries. The water footprint within a geographically delineated area is expressed as water volume per unit of time. For example, the United States has the highest per capita total water footprint of any nation 2,480 m^3 water /person /year compared to 700 m^3 water/ person/year for China. However, the U.S. is by far the leading exporter of water because of the large amount of agricultural exports. (Dourte and Fraisse, 2012).

- WFs of an agricultural crop can be used to compare consumptive water use among different agricultural systems in different regions, or it can be used at a farm level to compare water use among different management practices. The water footprints of crops are expressed as volume of water consumed per unit quantity of produce (m^3 ton^{-1} or litre kg^{-1}). Many products contain ingredients from agriculture or forestry. Crops are used for food, feed, fibre, fuel, oils, soaps, cosmetics, etc. Wood from trees and shrubs is used for timber, paper and fuel as well. Providing a water footprint label on agricultural based products could give consumers more information about the product's water footprint.

- WFs can be used for making comparisons of consumptive water use among different agricultural management systems: For example, converting a rainfed system to conservation agriculture may decrease the water footprint as there may be an increase in infiltration of rainfall and a reduction in non-beneficial soil evaporation.

- WFs in agriculture can be an important tool for reflecting water conservation impacts from various farm management options like changes in irrigation management, conservation, tillage, crop selection, and rotations can all have meaningful impacts on farm-level water footprints.

- When comparing different management strategies, a lower water footprint in a low-rainfall or a highly variable rainfall situation suggests higher water use efficiency.

- Regional comparisons of water footprints will suggest that production should be shifted to an area where production would have a lower water footprint by comparing management systems in different regions/ climates.

5.0 Accounting farm level crop water footprints

The water footprint of a crop is a special case of a process water footprint and has three components viz., green water footprint (soil evaporation or crop evapo-transpiration of water supplied from the rainfall or contribution from the stored soil moisture of the profile for crop production), blue water footprint (soil evaporation or crop evapo-transpiration of the irrigation water supplied from surface and renewable groundwater sources) and the grey water footprint (volume of water required to dilute pollutants to such an extent that concentrations are reduced to agreed maximum acceptable limits). (Hoekstra and Chapagain, 2008; Hoekstra et al., 2011). Thus, total water footprints (WF_{total})

$$WF_{total} = (WF_{green}) + (WF_{blue}) + (WF_{grey}) \left({}^{volume}/_{mass} \right) \quad \text{------------------} \ (4)$$

The unit of crop water footprints is thus volume per unit mass (often liters kg^{-1} or, equivalently, $m^3\ ton^{-1}$; 'ton' refers to a matric ton of 1000 kg). The yield in the denominator of the water footprint components is the yield at standard, marketable moisture content. Therefore, if a yield is measured in a field based on grains that were harvested above marketable moisture content, the yield value should be adjusted downward to account for the grain drying needed prior to marketing the crop (Hoekstra and Chapagain, 2008).

Thus, crop water footprints

$$\frac{WU_{green} + WU_{blue} + WU_{grey}\ (m^3\ ha^{-1})}{Economic\ yield\ of\ the\ crop\ (t\ ha^{-1})} \quad \text{...} \quad (5)$$

WU_{green} = 'green' crop water use, WU_{blue} = 'blue' crop water use and WR_{grey} = 'grey' crop water use

Crop Water Requirement is the total amount of water needed to compensate the evapo-transpiration (ET) loss from the crop field from planting to harvest for a given crop in a specific climatic region, when adequate soil water is maintained by rainfall and/or irrigation so that it does not limit plant growth and crop yield. The crop water requirements vary mainly with climate and crop factors like cultivar/species, growing stage, leaf area, leaf type, stomatal behavior, root characteristics etc.

Under unlimited water availability (either through rainfall or irrigation or both sources), the total blue and green crop water use (WU_{blue} + WU_{green}) are equal to potential crop evapo-transpiration (PET) or CWR. When limited water is available, WU_{blue} + WU_{green} would be equal or less than total crop water requirement (CWR) for the growing season and hence, CWU will be the actual crop evapo-transpiration (AET).

5.1 Step by step procedure for calculating farm level water footprints of crops with examples

Case-1: FOR IRRIGATED CROPS (FULL IRRIGATION)

Step-1: Identify the climatic zone and/or agro-ecological zone of the project area

Step-2: Select the appropriate crop/cropping pattern for the area

Step-3: Collect long-term climatic data and the soil information

Step-4: Estimation of ET_o following any emperical methods like FAO Penman-Monteith (Allen et al., 1998), Hargreaves and Samani (1985) (Annexure-1)

Step-5: Determine the crop coefficients, K_c at different growth stages

The determination of the K_c values for the various growth stages of the crops involves the following sub-steps:

(I) Determination of the total growing period of the crop

The total growing period (in days) is the period from sowing or transplanting to the last day of the harvest. It is mainly dependent on the type of crop and the variety, the climate, the planting date. As the growing period heavily depends on local conditions (e.g. local crop varieties) it is always best to obtain these data locally.

(ii) Determination of the various growth stages of the crop

Once the total growing period is known, the duration (in days) of the various growth stages has to be determined. The total growing period is divided into 4 growth stages.

- **The initial stage:** this is the period from sowing or transplanting until the crop covers about 10% of the ground.
- **The crop development stage:** this period starts at the end of the initial stage and lasts until the full ground cover has been reached (ground cover 70-80%); it does not necessarily mean that the crop is at its maximum height.
- The **mid - season stage:** this period starts at the end of the crop development stage and lasts until maturity; it includes flowering and grain-setting.
- The **late season stage:** this period starts at the end of the mid season stage and lasts until the last day of the harvest; it includes ripening.

Based on the outcome of some experiments at different locations of Odisha, the duration of these four stages of some crops have been given in Appendix-1. FAO Irrigation and Drainage Paper No-24 also provides general lengths for the four distinct growth stages and total growing period of some crops for various types of climate and locations.

(iii) Determine the K_c values for each crop for each of the growth stages

In absence of locally available Kc values, the Kc values given in Appendix-2 can be used (Allen et al., 1998)

Step-6: Determine the potential crop evapo-transpiration (PET_c) using the relationship $ET_c = ET_0 * Kc$

Under unlimited water supply, crop water use for a given crop, I (CWU_i) = crop water requirements for a given crop I (CWR_i), which is also equal to the potential crop evapo- transpiration for the crop, I($PETc_i$):

$$CWR_i(mm) = PET_{c_i}(mm) = \sum_{t=1}^{m} (ET_0 t \; X \; K_c t) \; mm \qquad \text{.................. (6)}$$

ET_0t is the reference crop evapo-transpiration (evapo-transpiration rate from a reference surface, not short of water) of the location for the day t, in mm, and is denoted as ET_0. K_c is the crop coefficient for the time t day, varies in time, as a function of the plant growth stage. The PETc is measured in units of depth (mm), but can be converted in units of volume/area, eg, $m^3 ha^{-1}$ by multiplying a factor 10.

Generally, the Kc is determined in four crop growth stages (initial, development, mid- and late stage). During the initial and mid-season stages, *Kc* is a constant and equals to $Kc_{,ini}$ and $Kc_{,mid}$ respectively. During the crop development stage, *Kc* is assumed to linearly increase from $Kc_{,ini}$ to $Kc_{,mid}$. In the late season stage, *Kc* is assumed to decrease linearly from $Kc_{,mid}$ to $Kc_{,end}$. The only factors affecting ET_0 are climatic parameters (Allen *et al.*, 1998).

Step-7: Determine the evaporation loss during land soaking for non-rice crops and for land preparation/puddling in case of rice

Water Requirement during Land preparation for non-rice crop

This is the water required to soak the land prior to the initial breaking of the soil, either by plowing or by any other means which can be estimated using the following relationship (Ali, 2010).

This is expressed as: $WR_{LS} = W_s + C \times ET_0 + P - Peff$ -------------------------------- (7)

where WR_{LS} is the depth of irrigation water required for land soaking (mm), W_s is the depth of water required to saturate the soil (mm), ET_0 is the reference evapo-transpiration during the time of soil saturation (mm), C is the evaporation coefficient equating reference evapo-transpiration to evaporation rate. The value of C is about 0.9.P is the deep percolation loss during the soil saturation (mm), P_{eff} is the effective rainfall during the period (mm).

Since for water footprints computation we are interested in evaporation loss (E_{LS}) during land preparation

$$E_{LS} = C \times ET_0 \quad \text{--} \quad (8)$$

ET_0 is the reference evapo-transpiration during the land preparation period

Water Requirement for Land Preparation for rice crop

This is the irrigation water required to maintain the saturation condition of the soil from the first breaking of the soil to seedling or transplanting. This water is required to replace evaporation, percolation, and application losses and includes the addition of water depth to suppress weeds or soften soil clods and is expressed by the equation below (Ali, 2010)

$$WR_{LP} = D_s + C \times ET_0 + P - P_{eff} \quad \text{------------------} (9)$$

Where, D_s water depth for submergence (mm).

P is the deep percolation loss during the soil saturation (mm), P_{eff} is the effective rainfall during the period (mm), since for water footprints computation only evaporation loss during land preparation is considered

$$E_{LP} = C \times ET_0 \quad \text{------------------} (10)$$

Et_0 is the reference evapo-transpiration during the land preparation.

Step-8: Compute the effective rainfall or contribution from profile stored soil moisture to determine green water contribution

Effective precipitation (P_{eff}) is the part of the total amount of precipitation that is retained by the soil so that it is potentially available for meeting the water requirement of the crop. It is often less than the total rainfall because not all rainfall can actually be appropriated by the crop due to surface runoff or percolation (Dastane, 1978).

Following any of the methods/empirical equations can be used to estimate effective rainfall (Peff) from rainfall (P)

i) *Fixed percentage:*

Peff= Fixed percentage* P, 0.7-0.9 is the recommended value ------------------(11)

ii) *Dependable rain (FAO/AGLW formula):*

Peff= 0.6*P-10 for $P_{monthly<=}$70mm ------------------(12)

Peff= 0.8*P-24 for $P_{monthly}$>70mm------------------(13)

iii) *USDA Soil Conservation Services method:*

Peff= P*(125 - 0.2*P)/125 for $P_{monthly}$ <=250mm ------------------(14)

Peff= 125+0.1* P for $P_{monthly}$>250mm------------------(15)

Similarly for daily or weekly water balance computation, daily or weekly effective rainfall can be computed

The above equations are available as in built in CROPWAT 8.0 model (**source: www.fao.org/water/infores-databases-cropwat.html**)

The effective rainfall can also be determined from measured soil water balance parameter

(i) Soil moisture depletion methods for crops other than rice

$(M_{AR}-M_{BR}) \times \rho_b \times D_e + ET_c$ --(16)

M_{AR}= soil moisture in (%) after rain, M_{BR}= soil moisture in (%) before rain, I_b = bulk density (Mg m^{-3}), ET_c= crop evapotranspiration during the interval between the cessation of rains and soil moisture sampling. P_b= Bulk density, D_e= depth of sampling (layer wise root zone depth may be considered)

(ii) For rice crop, effective rainfall P_{eff} can be measured using drum culture technique of Dastane, et. al(1966) with daily water balance parameters,

P_{eff}=P-R-D --(17)

P=Rain fall, R= Runoff, D= Deep percolation and seepage loss

Step-9: Estimation of irrigation or blue water requirement to meet the crop evapo-transpiration and soil evaporation loss by subtracting green water (effective rainfall and contribution from stored soil moisture of the profile).

Under unlimited water supply, blue water requirement is equal to the crop water requirements (evapotranspiration loss and evaporation loss during land preparation) minus effective rainfall (P_{eff} mm) and profile stored soil moisture contribution (ΔSW) if any. Under this condition it is assumed that entire deficit water is satisfied through irrigation.

$$\text{IR (mm)} = \left(\text{PETc} + E_{Ls/Lp} - P_{eff} - \Delta SW\right) \text{mm} \quad \text{------------------- (18)}$$

$E_{Ls/Lp}$= evaporation during land soaking or land preparation

When no rainfall is received or no irrigation is applied during crop growth period stored profile carry over residual soil moisture of rainy season (ΔSW) may serve as source of green water footprints during post rainy/ winter season.

$\Delta SW = SM_{1i}-SM_{2i}$ --(19)

Sm_{1i} = Soil moisture at the beginning of the growing period, mm for i^{th} layers

SM_{2i} =Soil moisture at the end of the growing period, mm for i^{th} layers

Soil moisture at any point of time (SM_t) can be determined by following relationship.

$$SM_t = \sum_{i=1}^{n} \frac{(V_{wi} \times \rho_{Si} \times Z_i)}{100} \quad \text{------------------- (20)}$$

Where V_{wi} is the percent moisture content in weight basis (w/w) for the layer *i*, ρ_{si} is the bulk density of soil of layer *i*, Z is the depth of soil layer i (m), and *n* is the total number of soil layers within the root zone (nos). Density of soil-water is considered as 1gm/cc or 1,000 kg/m^3.

Step-10: Computation of Grey water footprints

The grey water footprint is calculated by dividing the pollutant load (PL, in mass/time) by the difference between the ambient water quality standard for that pollutant (the maximum acceptable concentration C_{max} in mass/volume) and its natural concentration in the receiving water body (C_{nat}, in mass/volume) (Chapagain et al. 2006).

$$WF_{grey}(m^3 ton^{-1}) = \frac{PL\ (kg\ ha^{-1})}{(C_{max} - C_{nat})\ kg\ m^{-3}}\ X\ \frac{1}{t\ ha^{-1}} \quad \text{------------------------------} \quad (20)$$

As an of example of polluted water or grey water footprint, nitrogen (N) as a representative element for estimation of the grey water footprint has been explained here following Chapagain et al. (2006). Grey water footprint ($m^3\ ton^{-1}$) related to nitrogen pollution was calculated by multiplying the fraction of nitrogen that leaches or runoff by the nitrogen application rate ($kg\ ha^{-1}$) and dividing this by the difference between the maximum permissible concentration of nitrogen ($kg\ m^{-3}$) and the natural concentration of nitrogen in the receiving water body ($kg\ m^{-3}$) and by the actual crop yield ($ton\ ha^{-1}$). In this paper, we have taken a flat rate of nitrogen leaching equal to 10% of the nitrogen application rate and used the permissible limit of '10 mg nitrate-NO_3 per litre' as per the standard recommended by EPA (2005) for nitrate in drinking water to estimate the volume of water necessary to dilute leached nitrogen to the permissible limit. Natural concentration of nitrogen in the receiving water body was considered nil, for computing grey water foot prints in this study.

Step-11: Determine the water footprint ($m^3 t^{-1}$) using the ratio of volume of green, blue, grey water ($m^3 ha^{-1}$) to the total grain yield (tha^{-1}).

Step-12: Determine the total volume of water requirements using the ratio of water loss to the atmosphere (soil evaporation + crop **evapotranspiration**) + seepage + percolation +other losses of water (m^3) to the grain yield (ton).

Some examples of above case are given in Table-1, Table-2 and Table-3

Table-1: Computation of water footprints of rainy season rice with supplemental irrigation : Duration - 120 days, Sowing date: 1st July

Months	JAN	FAB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
ETo (mm/day)	4.5	4.7	5.9	6.6	8.7	5.4	5.1	4.9	5.1	4.8	4.6	4.3
Duration of growth stages	-	-	-	-	-	-	Initial Stage- 31 days	Crop dev. Stage- 31 days	Mid season stage- 30 days	Late season stage- 31 days	-	-
Kc values at growth stages	-	-	-	-	-	-	1.1	1.15	1.15	1		
Kc values for the month	-	-	-	-	-		1.1	1.15	1.15	1		
PETc (mm/day)	-	-	-	-	-	-	5.61	5.63	5.86	4.80		
PETc/month)	-	-	-	-	-	-	173.91	174.53	175.8	148.8		
Evaporation during land preparation (mm)		-	-	-	-	87	-	-	-	-	-	-
Percolation per month (mm)						119	145	154	135	88	-	-
Rainfall (mm/month)	0	0	12	20	16	268	345	309	295	134	0	0
Effective Rainfall (mm/month)	0	0	14.8	19.4	15.6	149	200	175	160	46	0	0
Irrigation requirements and applied (mm/month)						0	0	0	0	42		
AETc = PETc (mm)							173.91	174.53	175.8	148.8		
Water loss to the atmosphere (mm)	760											
Yield (t/ha)	4.5					-	-	-	-	-	-	-
Green and Blue Water footprint (m^3/ton)	1689					-	-	-	-	-	-	-
Grey Water footprint (m^3/ton)	1.8											
Total Water footprint (m^3/ton)	1690.8											
Total water needed (m^3/ton)	3113					-	-	-	-	-	-	-

Percolation loss was measured on daily basis using drum culture technique of Dastane (1966)

If duration of any stage falls at the middle or any dates of the month, Kc values have to be adjusted accordingly. If soil profile contributes some stored soil moisture towards crop growth, that has to be deducted from irrigation requirements and treated as 'Green Water Requirements'.

Based on available data it is revealed that 0.66 to 1.2 m^3 and 0.41 to 1.14 m^3 water are consumed during manufacturing process of one quintal of urea and P_2O_5, respectively (http://www.fertilizers.org, Swamminathan and Goswami, 2005). Therefore, based on the fertilizer used, quantity of water consumed can be computed and added to total water footprints.

Table-2: Computation of water footprints of irrigated rice during *rabi* season: Duration – 120 days, Sowing date: 1st February

Months	JAN	FAB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
ET_0 (mm/day)	4.5	4.7	5.9	6.6	8.7	5.4	5.1	4.9	5.1	4.8	4.6	4.3
Duration of growth stages		Initial stage	Crop dev. stage	Mid season stage	Late season stage	-	-	-	-	-	-	-
Kc values at growth stages		1.1	1.15	1.15	1	-	-	-	-	-	-	-
Kc values for the month		1.1	1.15	1.15	1	-	-	-	-	-	-	-
PETc (mm/day)		5.17	6.79	7.59	8.70	-	-	-	-	-	-	-
PETc/month)		144.7	270.4	227.7	269.7	-	-	-	-	-	-	-
Evaporation during land preparation (mm)	82					-	-	-	-	-	-	-
Deep percolation Per month (mm)	120	145	148	124	96	-	-	-	-	-	-	-
Rainfall mm/month)	0	0	12	20	16	223	345	309	295	120	0	0
Effective Rainfall (mm/month)	0	0	11.8	19.4	15.6	198	243	267	235	98	0	0
Irrigation requirements and given(mm/month)	202	289.7	346.6	332.3	350.1	-	-	-	-	-	-	-
AETc = PETc (mm)		144.7	210.4	227.7	269.7							
Water loss to the atmosphere (mm)	934.6											
Yield (t ha^{-1})	5											
Green and Blue Water footprint (m^3/ton)	1869											
Grey Water footprint (m^3/ton)	1.8											
Total Water footprint (m^3/ton)	1871											
Total water need (m^3 ton^{-1})	3135.3					-	-	-	-	-	-	-

Table-3: Computation of water footprint of fully irrigated maize during *rabi* season : Duration – 120 days, Sowing date: 1st February

Months	JAN	FAB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
ET_o (mm/day)	4.5	4.7	5.9	6.6	8.7	5.4	5.1	4.9	5.1	4.8	4.6	4.3
Duration of growth stages		Initial stage	Crop dev. stage	Mid season stage	Late season stage	-	-	-	-	-	-	-
Kc values at growth stages		0.35	0.75	1.05	0.35	-	-	-	-	-	-	-
Kc values for the month		0.35	0.75	1.05	0.35	-	-	-	-	-	-	-
PETc (mm/day)		1.645	4.425	6.93	3.05	-	-	-	-	-	-	-
PETc/month)		46.6	137.1	207.9	94.3	-	-	-	-	-	-	-
Evaporation during land soaking (mm)	40					-	-	-	-	-	-	-
Seepage or deep percolation per month (mm)	0	0	0	0	0	0	0	0	0	0	0	0
Rainfall (mm/month)	0	0	12	20	16	223	345	309	295	120	0	0
Effective Rainfall (mm/month)	0	0	11.8	19.4	15.6	198	243	267	235	98	0	0
Irrigation requirements and given (mm/month)	40	46.06	125.3	188.5	78.7							
AETc = PETc (mm)		46.1	137.71	207.9	94.3							
Total water loss to the atmosphere (mm)	525.5											
Yield (t/ha)	5.4											
Green and blue Water footprint (m^3/ton)	975.1											
Grey Water footprint (m^3/ton)	1.8											
Total Water footprint (m^3/ton)	976.9											

Case-2: FOR IRRIGATED CROPS WITH DEFICIT IRRIGATION

Step-1 to 6 (Same as case-1):Determine the potential crop evapo-transpiration (PET_c) using the relationship $PET_c = ET_o * Kc$

Step-7: Determine the evaporation loss during land preparation, puddling in case of rice and land soaking in case of non-rice crop

Step-8: Compute the effective rainfall or contribution from profile stored soil moisture to determine green water contribution.

Step-9: Determine the irrigation/blue water requirement to meet evaporation and evapo-transpiration loss (crop water requirements).

Step-10: Measuring actual crop evapotranspiartion (AETc) when crop is grown with different irrigation and applied irrigation water does not fulfill the PETc/CWR.

If rainfall, irrigation or profile stored soil moisture are insufficient to meet full crop water requirement, CWU will be AET_c which is equal to the rainfall received (P_t), applied net irrigation (I), contribution from stored soil moisture of the profile and upward flux from soil profile in case of shallow water table (G), minus deep percolation loss (D) and runoff (R). In case of water table of more than 1 m depth, G is negligible.

Under this case, seasonal $CWU = AET_c < PET_c = (SM_{1i} - SM_{2i}) + P + I + G - D - SR$ ------------(22)

$= (SM_{1i} - SM_{2i}) + P_{eff} + I + G_c$ ---------------------(23)

SM_{1i} = Soil Moisture available at the beginning of the growing season, mm for i^{th} layer

SM_{2i} = Soil moisture available at the end of crop growing season, mm for i^{th} layer

P_{eff} = Effective rainfall

Total soil moisture within the root zone at a particular time (SMt) may be calculated as per the equation (20)

For better accuracy of water footprint accounting estimation of AETc using the soil water deplation approach should be done at short interval like, 7 days, 10 days and 15 days etc.

In that case seasonal $CWU/AET_c = \sum_{i=1}^{n} CWU_p = \sum_{i=1}^{n} [(SM1_p - SM_{2p}) + P_{effp} + I_p + G_p]$ ---------- (24)

SM_{1p} = Soil moisture at the timing of first sampling at the beginning of cycle

SM_{2p} = Soil moisture at the time of second sampling at end of the cycle

CWU_p = crop water used during that cycle

P_{effp}, I_p, G_p are the effective rainfall, irrigation and ground water copntribution (if any) for that cycle, respectively. n is the numbers of measurement cycle.

SR, Surface run-off (mm) which can be estimated through SCS curve number (CN) method as per the equations below.

$R = (P - 0.2S)^2 / (P + 0.8S)$ if $(P - 0.2S) > 0$ else $R = 0$ ....(25)

CN values for different land uses are given in Appendix-3.

Deep Drainage or Percolation is the water moving out of the root zone is negligible in case of limited or deficit water supply.

Upward flux (U) or downward flux / deep drainage are computed based on the Darcy's law (Landsberg, 1986) as:

$$F = -K(\varphi)\frac{\Delta\varphi}{\Delta Z} \text{ ------------------------ } (26)$$

Where F is the volume flux of water through a unit cross-sectional area per unit time in the direction of lower potential and Z is the distance, $K(\varphi)$ is the unsaturated hydraulic conductivity.

The hydraulic pressure potential ($\Delta\varphi/\Delta Z$) is the difference between the gravitational potential, φ_g and the matric potential, φm. As long as φ_g is greater than φm, water will flow downward, when φ_g is exactly balanced by the φm, water flow equals to zero. But when φm gradient is greater than φg the water flow direction will be upward.

The soil hydraulic conductivity falls rapidly as θ decreases; the unsaturated hydraulic conductivity depends on soil texture and poor size distribution Campbell (1974) gave the following relationship to compute the hydraulic conductivity when soil water falls below saturation as a function of the water potential ($\varphi = f(\theta)$).

$$\frac{K(\varphi)}{K_S} = \left(\frac{\theta}{\theta_s}\right)^{2b+1} \text{ ------------------------ } (27)$$

K_s = Saturated hydraulic conductivity can be determined by constant head method of Klut(1965).

θ= water content at particular time, θs= saturated water content.

For clay to sand textured classes b value varies from 4 to 11. (Clap and Hornberger, 1978)

In case of non-availability on saturated hydraulic conductivity and matric potential data, the following equations can be used to determine the ground water table contribution under shallow water table (<1 m)

For heavy textured soils : G_c (mm/day) = -2.850 (WTD) + 3.117, R^2 = 0.898 ------------ (28)

For medium textured soils : G_c (mm/day) = -2.298 (WTD) + 2.646, R^2 = 0.750 -------- (29)

For light textured soils : G_c (mm/day) = -2.252(WTD) + 2.525, R^2 = 0.802 ------------- (30)

Where, WTD = Water Table Depth in meter

Step-11: Estimation of grey water footprint (m^3t^{-1})

Step-12: Compute the Green and Blue water footprints using the ratio of total volume of green and blue water (AETc) to total grain yield (t ha^{-1}) and add the grey water footprints (m^3 ha^{-1}) to compute total water footprints.

An illustration of above case is given in Table-4.

Table-4: Computation of water footprints of maize during *rabi* season with limited irrigation: Duration – 120 days, Sowing date: 1st February

Months	JAN	FAB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
ET_0 (mm/day)	4.5	4.7	5.9	6.6	8.7	5.4	5.1	4.9	5.1	4.8	4.6	4.3
Duration of growth stages		Initial Stage	Crop dev. stage	Mid season stage	Late season stage	-	-	-	-	-	-	-
K_c values at growth stages		0.35	0.75	1.05	0.35	-	-	-	-	-	-	-
K_c values for the month		0.35	0.75	1.05	0.35	-	-	-	-	-	-	-
PET_c (mm/day)		1.58	3.52	6.19	2.31	-	-	-	-	-	-	-
PET_c/month)		44.2	109.1	185.7	71.6	-	-	-	-	-	-	-
Evaporation (E) during land preparation (mm)	40					-	-	-	-	-	-	-
Deep Percolation per month (mm)	0	0	0	0	0							
Rainfall (mm/month)	0	0	12	20	16							
Effective Rainfall (mm/month)	0	0	11.8	19.4	15.6							
ΔSW (mm)	45	15	21	38	35							
Irrigation requirements (mm/month)	0	29.24	76.3	128.3	21.1							
Irrigation applied (mm)	0	60	60	120	0	-	-	-	-	-	-	-
AET_c < =PET_c (mm)	-	44.2	92.8	177.4	50.6							
Total water loss to the atmosphere (mm) (E+AET_c)	405.4											
Yield (t/ha)	3.5											
Water footprint (m^3/ton)	1157											

ΔSW – Contribution of stored soil moisture from profile

G_c= Ground water contribution

Case-3: FOR PURE RAINEFD CROPS (WHEN EFFECTIVE RAINFALL IS MORE THAN THAT OF PET_c/CWR)

Step-1 to 6 of method 1: Determine the potential crop evapo-transpiration (PET_c) using the relationship $PET_c = ET_0 * Kc$

Step-7: Determine the evaporation loss during land soaking/preparation

Step-8: Compute the effective rainfall as per the methodology mentioned in section 5.1.

Step-9: Determine the irrigation or blue water requirement. Since effective rainfall is more than that of PETc/CWR, irrigation or blue water requirement is zero.

Step-10: Determine the Green water footprint ($m^3 t^{-1}$) using the ratio of volume of green water use ($m^3 ha^{-1}$) to meet the PET_c and evaporation loss during land preparation to the total grain yield (tha^{-1}).

Step-11: Computation of grey water footprints

Step-12: Add the green water and grey water footprints to determine total water footprints

An example of above case is give in Table-5.

Example-5: Computation of water footprints of rainfed maize during *kharif* season: Duration – 120 days, Sowing date: 1st July

Months	JAN	FAB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
ET0 (mm/day)	4.5	4.7	5.9	6.6	8.7	5.4	5.1	4.9	5.1	4.8	4.6	4.3
Duration of growth stages	-	-	-	-	-	-	Initial stage- 31 days	Crop dev. Stage- 31 days	Mid season stage- 30 days	Late season stage- 31 days	-	-
K_C values at growth stages	-	-	-	-	-	-	0.35	0.75	1.05	0.35	-	-
K_C values for the month	-	-	-	-	-		0.35	0.75	1.05	0.35	-	--
PET_C (mm/day)							1.785	3.675	5.355	1.68	-	-
PET_C/month)	-	-	-	-	-	-	55.3	113.9	160.6	52.08	-	-
Evaporation (E) during land preparation (mm)	-	-	-	-	-	40	-	-	-	-	-	-
Rainfall (mm/month)	0	0	12	20	16	223	345	309	295	120	0	0
Effective Rainfall (mm/month)	0	0	11.8	19.4	15.6	143.4	159.5	155.9	154.5	97.0	0	0
Irrigation requirements and applied (mm/month)						0	0	0	0	0	-	-
AET_C = PET_C (mm)							55.3	113.9	160.6	52.08		
Water loss to the atmosphere (mm)(E+PET_c)	421.9											
Yield (t/ha)	3.9					-	-	-	-	-	-	-
Green Water footprint (m^3/ton)	1081.7					-	-	-	-	-	-	-
Grey Water footprint (m^3/ton)	1.8											
Total Water footprint (m^3/ton)	1083.5											

Case-4: FOR PURE RAINEFD CROPS (WHEN EFFECTIVE RAINFALL IS LESS THAN THAT OF PET_c/CWR)

Step-1 to 6 (same as case-1): Determine the potential crop evapo-transpiration (PET_c) using the relationship $PET_c = ET_0 * Kc$

Step-7: Determine the evaporation loss during land preparation, puddling in case of rice and land soaking in case of non-rice crop

Step-8: Compute the effective rainfall

Step-9: Determine the irrigation or blue water requirement to meet the crop evapo-transpiration and soil evaporation loss by subtracting effective rainfall and soil water contribution if any (green water).

Step-10: Determine the green water footprints ($m^3 t^{-1}$) using the ratio of volume of green water use actually or actual evapo transpiration($m^3 ha^{-1}$) to the total grain yield ($t\,ha^{-1}$).

Step-11: Computation of grey water footprints

Step-12: Computation of total water footprints by adding green and grey water footprints ($t\,ha^{-1}$).

To illustrate the above case, an example has been given in Table-6.

Table-6: Computation of water footprints of irrigated rice during *kharif* season: Duration – 120 days, Sowing date: 1st July

Months	JAN	FAB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
ET_0 (mm/day)	4.5	4.7	5.9	6.6	8.7	5.4	5.1	4.9	5.1	4.8	4.6	4.3
Duration of growth stages							Initial Stage-31 days	Crop dev. Stage-31 days	Mid season stage-30 days	Late season stage-31 days		
K_C values at growth stages	-	-	-	-	-	-	1.1	1.15	1.15	1	-	-
K_C values for the month							1.1	1.15	1.15	1		
PET_C (mm/day)	-	-	-	-	-	-	5.61	5.63	5.86	4.8		
PET_C/month)	-	-	-	-	-		173.9	174.6	175.9	148.8		
Evaporation (E) during land preparation (mm)						85						
Rainfall (mm/month)	0	0	23	25	28	210	304	234	202	98	0	0
Effective Rainfall (mm/month)	0	0	22.2	24	26.7	139.4	155.4	146.4	136.7	82.6	0	0

Months	JAN	FAB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
ΔSW (mm)						0	0	0	0	43		
Irrigation requirements but not applied (mm/month)						0	0	29.6	29.6	40.8		
$AET_C = <PET_C$ (mm)							173.9	145	149	108		
Water loss to the atmosphere (mm), E + PET_C	660.9											
Yield (t/ha)	3.8					0	0	0	0	0		
Green and Blue Water footprint (m^3/ton)	1739											
Grey Water footprint (m^3/ton)	1.8											
Total Water footprint (m^3/ton)	1741											

6.0 Computation of Water Footprints from Some Case Studies

Some case studies of field level crop water footprint accounting have been given below under different agro-management and experiments conducted in different previous projects at different places of Odisha.

6.1 Computation of farm level water footprints of irrigated rice under different water and nitrogen management based on measured crop evapo-transpiration and deep percolation

Rice (cv. Lalat of 120 days duration) crop was grown Puri district, Odisha during rainy seasons of 2008-2009 with 3 water regimes in main plots (W_1 = continuous flooding of 5 cm, W_2= irrigation after 2 days of water disappearance, W_3 = irrigation after 5 days of water disappearance) and 5 nitrogen levels in subplots (N_1 = 0 kg N ha^{-1}, N_2= 60 kg N ha^{-1}, N_3=90 kg N ha^{-1}, N_4=120 kg N ha^{-1}, N_5=150 kg N ha^{-1}) and water footprints of the crop was computed under different treatments.

Crop evapo-transpiration (ETc) along with the percolation loss of water during crop growth period were measured in the field daily using Drum technique of Dastane (1966). In each plot, 3 plastic drums (D_1, D_2 and D_3) each of 125 cm hight and 50 cm in diameter were inserted into the field leaving about a quarter of their height above ground level. The bottoms of drum D_2 and D_3 were removed. The drums were filled up with soil and rice was grown inside along with the adjoining field crop. The water levels in the drums awere maintained at the same level as outside. The difference in the values on two successive days caused by the daily loss of water in drum D_1 represents evapo-transpiration, while in drum D_2, it indicates daily total needs of water. The daily difference between water levels in drum D_1 and D_2 was percolation loss. The drum D_3 was intended to assess ineffective rainfall or over bund flow for which the water level was set at the desired height. Water footprint refers to a real loss to the catchment, while the percolation is actually not a loss to the catchment, therefore, percolation water was not included in water foot print calculation, only the amount of water evaporated or evapo-transpired or polluted was considered to compute water footprint (Hoekstra, 2003; Chapagain et al. 2006; Hoekstra and Chapagain, 2008).

The highest total water footprint (TWF) was observed under W3 with the value being 1643 $m^3 t^{-1}$ whereas, $WFPs_{Total}$ of 1569 and 1561 $m^3 t^{-1}$ were computed under W_1 and W_2 treatments, respectively (Table-7). Among nitrogen treatments, highest WFP_{Total} was observed when no N was applied with the values being 2465, 2165, 2308 $m^3 t^{-1}$ in W_1, W_2 and W_3 treatments, respectively. On the other hand, the lowest WFP_{Total} of 1299, 1276 and 1324 $m^3 t^{-1}$ were achieved under 150 kg N ha^{-1} in three respective water regimes. It is to be informed that WFP_{Total} achieved under 150 kg N ha^{-1} was statistically at par with the values obtained at 120 kg N ha^{-1}. The TWF of the crop was higher when no or lower doses of N were applied which might be attributed to low grain yield obtained in N stress plots. The WFP reduced significantly with increased dose of N from 0 to 120 kg ha^{-1} due to significant yield enhancement under all water regimes. On the other hand TWF were significantly lower under W_1 and W_2 than that of W_3 because of production of more yield under the treatments W_1 and W_2.

Table 7: Grain yield and water footprints of rice under different water and nitrogen management practices

Treatments	GY (kg ha^{-1})	ETC (mm)	PER_C (mm)	E_LP (mm)	PER_LP (mm)	TOT_LP (mm)	Runoff (mm)	Peff (mm)	TWD (mm)	IRRI (mm)	$WF_{Blue+Green}$ (m^3 t^{-1})	WFgr (m^3 t^{-1})	TWF (m^3 t^{-1})	PERC_V (m^3 t^{-1})	TWU_V (m^3 t^{-1})
W1															
N1	2880	623	413	87	105	192	65	438	1420	185	2465.	0.0	2465	1799	4264
N2	3920	623	413	87	105	192	65	438	1420	185	1811	1.5	1813	1321	3134
N3	4955	623	413	87	105	192	65	438	1420	185	1432	1.8	1434	1045	2480
N4	5404	623	413	87	105	192	65	438	1420	185	1313	2.2	1316	959	2274
N5	5465	623	413	87	105	192	65	438	1420	185	1299	2.7	1301	948	2250
Mean	4524.8	623	413	87	105	192	65	438	1420	185	1569.1	1.64	1570	1145	2716
W2															
N1	2789	604	337	87	105	192	65	514	1325	90	2165	0.0	2165	1585	3750
N2	3825	604	337	87	105	192	65	514	1325	90	1806	1.3	1807	1156	2963
N3	4755	604	337	87	105	192	65	514	1325	90	1453	1.9	1455	930	2385
N4	5345	604	337	87	105	192	65	514	1325	90	1292	2.2	1295	827	2122
N5	5415	604	337	87	105	192	65	514	1325	90	1276	2.8	1278	816	2095
Mean	4425.8	604	337	87	105	192	65	514	1325	90	1561	1.64	1562	999	2562
W3															
N1	2517	581	253	87	105	192	65	598	1218	0	2308	0.0	2308	1422	3731
N2	3465	581	253	87	105	192	65	598	1218	0	1927	1.4	1929	1033	2962
N3	4267	581	253	87	105	192	65	598	1218	0	1565	2.1	1567	839	2407
N4	5032	581	253	87	105	192	65	598	1218	0	1327	2.4	1329	711	2041
N5	5042	581	253	87	105	192	65	598	1218	0	1324	3.0	1327	710	2038
Mean	4064.6	581	253	87	105	192	65	598	1218	0	1643	1.64	1645	889	2526

GY = Grain yield, PET_c = Potential Crop evapotranspiration, E_LP = Evaporation during land preparation, PER_LP = Measured percolation during land preparation, PER_C = Measured percolation during cropping season, TOT_LP = Total water required during land preparation, Peff= Effective rainfall, TWD = Total irrigation water demand, IRRI = Irrigation requirements and applied, $WF_{Green+Blue}$= Green and Blue water footprint, WF_{grey} = Grey water footprint t /ha area, TWF = Total water footprint, PERC_V = Volume of percolation water TWU_V = Volume of total water use

6.2 Field based water footprints of maize under different irrigation levels

In an on-farm experimental trial maize was sown during November, 2008 under different levels of phenology based irrigation. The Water footprints of maize were computed under different levels of irrigation viz. (I_1 = 180 mm at stage 2, stage 4, stage 8; I_2 = 180 mm at stage 2, stage 5, stage 8 , I_3 = 240 mm at stage 2, stage 6, stage 6, stage 8; I_4 = 240 mm at stage 2, stage 4, stage 5, stage 8; I_5 = 300 mm at stage 2, stage 4, stage 6, stage 7, stage 8; I_6 = 300 mm at stage 2, stage 4, stage 5, stage 7, stage 8; I_7 = 360 mm at stage 2, stage 4, stage 5, stage 6, stage 7, stage 8). The average water footprint differs significantly among irrigation treatments. Treatments with a high yield or large fraction of crop biomass and higher water productivity have a smaller water footprint (m^3 ton^{-1}) than the treatments with a low yield or small fraction of crop biomass harvested. Accordingly, average water footprint of the crop was lower in I_6 (831 m^3t^{-1}) and I_7 (766 m^3t^{-1}) treatments (Table-8). The highest water footprint of 1389 m^3t^{-1} was obtained in I_1 treatment where yield and water productivity were the lowest. Due to meager winter rainfall, green water footprints due to direct rainfall was negligible (2.89-5.75%), but 20.3-38.7% water footprints were contributed from stored profile soil moisture of rainy season and thus 23-41% water footprints have been contributed from green water. On the other hand, 59-77% water footprints were contributed from blue water in different treatments.

Table 8: Water footprints of maize grown with different irrigation levels during 2008-09

Irrigation treatments	Grain Yield (kg ha^{-1})	IWA (mm)	PET_c (mm)	ΔSW (mm)	AET_c <=PET_c (mm)	Green and blue water footprints (m^3t^{-1})
I_1	2080	180	342	109	289	1389
I_2	2355	180	342	111	291	1236
I_3	2580	240	342	105	342	1326
I_4	2855	240	342	103	342	1198
I_5	3702	300	342	104	342	924
I_6	4115	300	342	102	342	831
I_7	4465	360	342	94	342	766

*ΔSW was measured based on weekly soil moisture depletion

PET_c= Potential crop evapo-transpiration (mm); AET_c= Actual crop evapo-transpiration (mm); WF_{green}= Green water footprint, ΔSW = Stored Soil water Contribution from profile ; Assuming there was no runoff and deep percolation loss. Groundwater table depth is more than 1 m, soil upward flux was nil.

Stage 2 = Stem elongation(1), Stage 3 = Stem elongation(2), Stage 4 = Stem elongation(3), Stage 5 = Flowering, Stage 6 = Water ripe stage, Stage 7 = Milk ripe stage, Stage 8 = Dry ripe stage, Stage 9 = Ripeness

6.3 Water footprints of rice and non-rice crops under rainfed condition during *kharif season in Odisha*

Water footprints(WF) of non-rice crops *viz.*, maize, (cv. Navjyot), pigeonpea (cv. UPAS-120), groundnut (cv. Smriti), blackgram(cv. T_9) and cowpea(cv. Pusa Kamal) were compared with that of sole rice (cv. Vandana) to explore possibility of crop diversification in rainfed upland rice area (Table-9). The crops were grown under rainfed condition following recommended agronomic practices during 2000-2002 at Dhenkanal, Odisha. Among the various crops, WF was lower (701 to 888 m^3 ton^{-1}) in case of maize crop because of higher productivity. Since effective rainfall for all the study years was more than that of crop water requirements, the blue water requirement was nil and entire footprints were contributed by 'green water'.

Table 9: Water footprints of rice and non-rice crops under rainfed condition

Treatments (Crops)	Yield (kg ha^{-1}) of individual crops			Effective rainfall (mm)			PET_c = AET_c (mm)			WF_{green} (m^3 t^{-1})		
	2000	2001	2002	2000	2001	2002	2000	2001	2002	2000	2001	2002
Maize	5450	4400	4300	651	1099	639	375	382	307	688	868	900
Pigeonpea	1480	1355	1405	945	1458	886	567	552	590	383	4074	4132
Groundnut	1410	1560	1370	889	1159	780	470	494	480	3333	3167	3504
Blackgram	1050	1225	1010	614	955	601	405	416	434	3857	3396	4119
Cowpea	1400	1800	1200	635	1100	639	409	407	424	2921	2261	3533

PET_c= Potential crop evapo-transpiration (mm); AET_c= Actual crop evapo-transpiration (mm);
WF_{green}= Green water footprints

6.4 Computation of water footprints of some winter crops (maize, groundnut, sunflower, wheat, potato) grown in rice fallow with limited irrigation at Dhenkanal, Odisha during 1999-2000 and 2000-01.

Study revealed that supplemental irrigation had a significant effect ($P < 0.01$) on grain yield and water footprints of winter crops (Table-10) and with two supplemental irrigation, mean yield of 1845, 785, 905,1420, 8050 kg ha^{-1} was obtained in maize, groundnut, sunflower, wheat and potato (tuber) respectively. The 59 %, 29 %, 33 %, 58 %, and 19 % higher yield was obtained in respective crops when three irrigation was applied. With increase of irrigation i.e. with four supplemental irrigation 214 %, 89 %, 78 %, 81 % and 54 % yield was enhanced in maize, groundnut, sunflower, wheat and potato respectively over two irrigation. Water footprints of the crops were also decreased with the increasing the crop yield at higher irrigation levels (Table-10).

Table-10: Yield and water footprint (pooled data of two years) of different crops with limited irrigation scheduling during 1999-00 and 2000-01

Crop	Grain yield (kg ha^{-1})			CWR/ PET_c (mm)	AET_c (mm)			$WF_{Green+Blue}$ (m^3 ton^{-1})		
	I_2	I_3	I_4		I_2	I_3	I_4	I_2	I_3	I_4
Maize	1845	2950	4805	342	243	308	342	1317	1044	712
Groundnut	785	1020	1590	469	249	302	450	3172	2961	2830
Sunflower	905	1205	1715	429	253	310	429	2796	2573	2501
Wheat	1420	2250	2780	484	256	305	451	1803	1356	1622
Potato (tuber)	8050	9650	12400	450	260	325	404	323	337	326

AET_c was measured at 7-10 days interval

PET_c= Potential crop evapo-transpiration (mm); AET_c= Actual crop evapo-transpiration (mm); $WF_{Green+Blue}$= Blue and Green water footprints, CWR = Crop water requirements

I_2= Two supplemental irrigation (120 mm), I_3= Three supplemental irrigation (180 mm), I_4= Four supplemental irrigation (240 mm);

Assuming all the irrigation was efficiently utilized and there was no runoff and deep percolation loss. Groundwater table depth is more than 2 m, Soil upward flux was nil.

6.5 Computation of water footprints of some low water requiring winter crops ((linseed, safflower, mustard, chickpea and pea) grown during 2001-02 at Dhenkanal Odisha

Water footprints of different crop ranged from 4636-7158 $m^3 t^{-1}$ and 3283-4444 $m^3 t^{-1}$ under I_2 and I_3 respectively (Table-11). With higher amount of irrigation, WF of all the crops was reduced because of higher yield.

Table-11: Yield and water footprints (pooled data of two years) of different crops with limited irrigation scheduling during 2001-02 and 2002-03

Crop	Grain yield (kg ha^{-1})		CWR/PET_C (mm)	AET_C (mm)		WF_{Blue} ($m^3 ton^{-1}$)		$WF_{Blue+Green}$ ($m^3 ton^{-1}$)	
	I_2	I_3		I_2	I_3	I_2	I_3	I_2	I_3
Linseed	701	845	325	235	289	1712	2138	3352	3420
Safflower	762	1258	413	245	303	1575	1429	3215	2406
Chickpea	475	765	340	236	298	2526	2353	4968	3895
Pea	787	1168	394	243	301	1525	1541	3087	2577
Mustard	547	938	381	259	297	2194	1919	4734	3166

AET_c was measured at 7-10 days interval

PET_c= Potential crop evapo-transpiration (mm); AET_c= Actual crop evapo-transpiration (mm); $WF_{Green+Blue}$= Blue and Green water footprints, WF_{Blue}= Blue water footprints, CWR = Crop water requirements,

I_2 = Two supplemental irrigation (120 mm), I_3 = Three supplemental irrigation (180 mm)

6.6 Water footprints of winter crops grown in rice fallow with shallow water table utilizing soil upward flux and supplemental irrigation at Dhenkanal, Odisha

Owing to higher soil upward flux and moderate available water capacity, reasonable yield was obtained even under rainfed condition with the mean values being 940, 716, 720 and 510 kg ha^{-1}, in groundnut, blackgram, greengram and chickpea, respectively. Study also revealed that 57.4 %, 51.6 %, 38.1 % and 42.0% yield was enhanced in groundnut, blackgram, greengram and chickpea, respectively when one irrigation was applied at pod formation stage as compared to no irrigation. With one irrigation 1480, 1086, 995 and 725 kg ha^{-1} yield, was obtained in groundnut, blackgram, greengram and chickpea, respectively. Whereas, with two irrigation, very less yield was enhanced (only 2-3 %) over one irrigation for all the crops. It might be due to the fact that one irrigation of 60 mm at pod formation stage was sufficient to meet the total crop water requirements of all the crops which was sown in the second week of November when sufficient amount of carry-over residual soil moisture was available in the field (Table-12). WF values of 1933-3926, 2590-4735, 2952-4708 and 3124-6667 $m^3 t^{-1}$ were obtained under different irrigation treatments in groundnut, black gram, green gram and chickpea, respectively.

Table-12: Water footprints of winter crops grown in rice fallow with shallow water table utilizing soil upward flux and supplemental irrigation.

Crop and irrigation treatment	Capillary contribution (soil upward flux), mm	CWR/PET$_c$ (mm)	Grain yield (kg ha^{-1})	AET$_c$ (mm)	WF$_{Blue}$ (m^3 ton^{-1})	WF$_{Blue+Green}$ (m^3 ton^{-1})
Groundnut						
I_0	217	369	940	284	0	3361
I_1	189	369	1480	316	405	2135
I_2	164	369	1520	351	789	2309
Blackgram						
I_0	187	339	716	246	0	2808
I_1	166	339	1086	286	552	2633
I_2	156	339	1111	336	1080	3024
Greengram						
I_0	171	339	720	228	0	2425
I_1	149	339	995	266	603	1797
I_2	141	339	1023	318	1173	2092
Chickpea						
I_0	204	340	510	261	0	5117
I_1	185	340	725	302	828	4165
I_2	171	340	980	340	1224	3551

AET$_c$ was measured at 7-10 days interval

I_0 = No irrigation, I_1 = One irrigation, I_2 = Two irrigation

ET$_c$= Crop evapo-transpiration, TWFP=Total water footprint, BWFP= Blue water footprint.
Assuming no runoff and deep percolation losses from applied irrigation water

6.7 Water footprints of winter crops grown in rice fallow grown utilizing residual soil moisture under different seeding/tilling methods

Four crops *viz.,* Lathyrus, blackgram, chickpea and pea were grown after rice in main plots and different tillage/seeding methods are in sub-plots at Dhenkanal during 2001-2003. Study revealed that tillage and seeding methods had a significant effect ($P < 0.01$) on grain yield and green water footprints of winter crops (Table 13). The highest, mean grain yield of 590, 620, 670, 490 kg ha^{-1} and the lowest water footprints of 5136,6210,5881, and 6939 $m^3 t^{-1}$ obtained in lathyrus, blackgarm, pea and chickpea, respectively when two ploughings were applied in different days and seeding was done after second ploughing. With farmer's traditional relay cropping system, only 350, 300, 400 and 220 kg ha^{-1} grain yield was obtained in lathyrus, blackgram, pea and chickpea, respectively. With two ploughings 68.5 %, 106.6 %, 67.5 % and 122.7 % higher yield was obtained in lathyrus, blackgram, pea and chickpea, respectively over traditional relay cropping system. On the other hand with conventional tillage only 430,490,510 and 270 kg ha^{-1} yield was obtained in four respective crops. It might be due to fast depletion of soil moisture by evaporation from the field due to repeated ploughing. As a result, less moisture was available in the field throughout the growing period in the conventional tillage treatment than that of other treatments. Since yield of all crops under relay cropping system was lower, less water foot prints of all the crops were recorded under this treatment.

Table-13: Yield (pooled data of three years) and water footprints of different crops with different seeding/tilling methods in rainfed lowland rice fallow

Treatments	Crop yield (kg ha^{-1})				CWR/PET_c (mm)				AETc<PET_c				WF_{Green} ($m^3 t^{-1}$)			
	Lathyrus	Black gram	Pea	Chick pea	Lathyrus	Black gram	Pea	Chick pea	Lathyrus	Black gram	Pea	Chick pea	Lathyrus	Black gram	Pea	Chick pea
R	350	300	400	220	303	385	394	340	285	290	289	298	8657	12833	9850	15455
T_1	510	570	590	400	303	385	394	340	275	295	280	280	5941	6754	6678	8500
T_2	590	620	670	490	303	385	394	340	270	280	276	289	5136	6210	5881	6939
Z	390	420	430	330	303	385	394	340	258	250	256	265	7769	9167	9163	10303
C	430	490	510	270	303	385	394	340	235	245	240	247	7047	7857	7725	12593

AET_c was measured at 7-10 days interval

R =Relay (farmers' practice), T1 = One ploughing and sowing on same day, T2 = Two ploughing in different days and sowing after second ploughing, Z = Zero tillage, C = Conventional tillage GWFP= Green water footprints

7.0 Strategies to reduce water footprints in crop production

Strategies to reduce water footprints revolve around the central themes of reducing blue water requirements by reducing the losses out of the system (ie. evaporation, deep drainage, runoff), reducing crop evapo-transpiration during non-critical periods, and increasing the effectiveness of stored soil moisture and rainfall during the season.

Water savings at the field scale may be achieved by:

- maximizing the pre-season soil moisture storage;
- minimizing evaporation losses;
- minimizing crop transpiration while maintaining agronomic and economic goals;
- maximizing net effective precipitation during the growing season;
- improving the application efficiency of the irrigation application system; and
- reducing deep percolation

Reduction measures of blue water footprints should include improved irrigation system management to provide more reliable water supply to farmers through storage and improved operation of reservoirs, better distribution of water with improved control structures as well as more responsive management. More reliable water supply allows farmers to invest in better on-farm water management such as better land leveling, zero tillage, or pressurized irrigation.

7.1.1 Irrigation scheduling based on scientific approach

Irrigation scheduling is a systematic method of deciding the quantity and timing of irrigation. It helps the irrigator to decide on when and how much water to apply for minimizing crop yields and efficiency of water use. The basic objective of Irrigation scheduling is to make available the correct amount of water for the biological processes of plants at appropriate time by applying the exact amount of water needed to replenish the soil moisture to the desired level. Irrigation scheduling becomes particularly sensitive under scarce water supplies where water shortage requires a refined timing of water application in order to minimize yield restrictions, thus water footprints of crop production will be reduced.

7.1.2 Pressurized irrigation system

The crop yield and water use efficiency under conventional flood method of irrigation, which is predominantly practiced in Indian agriculture, are very low due to substantial conveyance and distribution losses. Pressurized irrigation system is proved to be an efficient method in saving water and increasing water use efficiency and crop yield as compared to the conventional surface method of irrigation, where use efficiency is only about 35-40 %. (Table-14).

Table-14: Irrigation efficiency under different methods of irrigation (%)

Irrigation efficiency	Methods of irrigation		
	Surface	Sprinkler	Drip
Conveyance efficiency	40-50 (canal) 60-70 (well)	100	100
Application efficiency	60-70	70-80	90
Surface moisture evaporation	30-40	30-40	20-25
Overall efficiency	30-35	50-60	80-90

Source: ***Sivanappan, (1987)***

7.1.3 Irrigation layout

It has been observed that farmers don't adopt the suitable layout as per the crop requirements. Generally restricted flooding is followed. But irrigation layout of appropriate sizes are very much essential for proper distribution of irrigation water which also encourages uniform crop growth, reduces water losses.

7.1.4 Improving water use efficiency of canal command

Considerable amount of water is lost in canal command through evaporation, seepage and percolation. In no irrigation project in India the total losses in the canal distribution system & field has been less than 50% of the head discharge. A review of 90 irrigation projects of the world indicated generally low irrigation efficiencies, with only 20-40 % of water diverted from the reservoir being effectively used by the crop, while in India, the irrigation efficiency is around 10-20%. The losses of irrigation water are unlined canal distributor system in north India is given in Table-20. The method to reduce conveyance losses are by lining the bed and sides of the canal, eradication of weeds, reduction of wastage from escapes and tail ends. The use of plastic films as lining material has offered tremendous scope in India.

Table-20: Losses of irrigation water in unlined canal distribution systems and in the field

Source of loss	% of supplies at canal head		
	Seepage	Evaporation	Total
Main canals and branches	13.6	3.4	17.0
Distributaries (10% of supply at 6.4 1.6 8.0 distributary	6.4	1.6	8.0
Field water courses (27% of supply at outlet head)	16.0	4.0	20.0
Losses from field during application (30% of supply reaching the head)	13.2	3.3	16.5
Total	49.2	12.3	61.5

Source: Kumar and Kar, 2013

7.1.5 Conservation agriculture

Conservation agriculture along with some prominent water saving technological interventions like alternate raised and sunken bed technique in low lands, system of rice intensification (SRI) technique of rice cultivation and mulching etc. can be adopted to increase crop yield, to reduce evapo-transpiration and water footprints. Precision land leveling enables efficient water utilization of scarce water resources through elimination of unnecessary depression and elevated contours. Laser leveling is laser guided precision leveling technique used for achieving very fine leveling with desired grade on agriculture field . Rotational irrigation is often recommended to irrigate a large area with a limited water supply which also ensures more effective use of rainfall.

7.1.6 Reduction of grey water footprints

To reduce the grey water footprint, the option is to have optimal application of fertilizer so that the application exactly matches the plant uptake. The grey component of the water footprint can only be reduced with a reduction in the leaching of fertilisers and pesticides from the field, e.g., by increasing water use efficiency, using slow-release fertilisers and nitrification inhibitors, puddling the rice fields, planting catch and cover crops and using crop residues in situ (Choudhury and Kennedy, 2005). The fate of nitrogen in soil is mainly governed by different processes: plant uptake, ammonia volatilization, denitrification and losses to surface (runoff) or groundwater bodies (leaching). All these three processes are inter-linked and it is hard to study them in isolation. A systematic analysis of fate of nitrogen should be carried out at field level to reveal any specific impacts on the system. Otherwise, the loss of nitrogen may cause environmental and health problems.

8.0 Conclusion

Water forms the backbone for all the future endeavors to achieve the vision of food security. In the present data context, up-scaling agricultural economic growth to more than 4% annually is the main challenge. Taking water technologies for better water management from lab to land is a formidable task to be addressed. Modernization / automation of irrigation system, precision irrigation, land reforms, corporate farming, cooperative farming, water and energy pricing, crop insurance, institutional mechanism for better governance, water rights are some of the key issues for better water management in agriculture and . The projected food requirement demands a pronounced role for research, development and training in the water and agriculture sector.

It is evident that the water availability for agriculture is declining and to enhance agricultural production more water is needed. Therefore concerted and holistic efforts are required in increasing the overall water use efficiency at system level which would be achieved through various measures like timely execution of projects, minimizing the losses, better operational efficiency through stake holders participation, implementation of on – farm water management technologies, conjunctive use of water and changes in irrigation policy. Simultaneously, the effort of R & D institutions are required in development of water management technologies, suitable database development, economic studies of various irrigation systems, policy guidelines for on farm water management and adoption of participatory irrigation management. The serious efforts of developmental agencies as well as research institute are required to develop a suitable water perspective plan for various regions in the country for its implementation.

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ANNEXURE-1

1. FAO Penman–Monteith Equation (Allen et al, 1998)

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34 U_2}$$

Where, ET_0 = reference evapo-transpiration, mm day^{-1}
R_n = net radiation at the crop surface, $MJ m^{-2} day^{-1}$ G=soil heat flux density ($MJ m^{-2} day^{-1}$)
T= Mean daily air temperature at 2m height (O_c), U_2 = wind speed at 2m height ($m s^{-1}$)
e_s = saturation vapour pressure (kP_a), e_a = actual vapour pressure (kP_a)
e_s-e_a = saturation vapour pressure deficit (kP_a), Δ= Slope of the vapour pressure deficit (kP_a)
Γ= psychrometric constant ((kP_a) O_c^{-1})

2. Blaney–Criddle Method

The recommended relationship is expressed as:

$$ET_0 = C[p(0.46T + 8)]$$

Where ET_0 is the reference crop evapo-transpiration (mm day^{-1}), T is the mean daily temperature (°C), p is the daily percentage of total annual daytime hours, and C is the adjustment factor. For calculation of monthly ET_0 value, monthly percentage of total annual daytime hours should be used instead of daily percentage. The daily day-time hours can be obtained from solar equations. The monthly p values for different latitudes are given in Appendix-6.

3. FAO Radiation Method

The relationship recommended is expressed as:

$$ET_0 = C(WR_s)$$

Where ET_0 is the reference crop evapo-transpiration (mm day^{-1}), R_s is the solar radiation in equivalent evaporation (mm/day), W is the weighing factor that depends on temperature and altitude, and c is the adjustment factor. In areas where the measured value of R_s is not available, it can be obtained from measured sunshine duration record with the following equation:

$$R_s = (0.25 + 0.50 * n_{/N})R_a$$

Where n/N is the ratio between actual measured bright sunshine hours and maximum possible sunshine hours, and Ra is the extra-terrestrial radiation, which is the amount of radiation, received at the top of the atmosphere. (Appendix-7). The mean daily duration of maximum possible sunshine hours for different months and latitude are given in Appendix-8. To convert the units from MJ m^{-2} d^{-1} to mm day^{-1}, multiply by 0.408.

The weight factor W depends (Appendix-9) on daily average temperature and altitude and ranges from 0.5 (low temperature and zero altitude) to 0.9 (high temperature and high altitude) [Doorenbos and Pruitt (1977)]. The adjustment factor *C* depends greatly on mean relative humidity and daytime wind at 2-m height above the soil surface. Its value generally ranges from 0.75 (high RH and low wind speed) to 1.25 (low RH and high wind speed).

4. Hargreaves and Samani Method

Hargreaves and Samani (1985) suggested a method involving only temperature and radiation data. Their equation is given by:

$$ET_0 = (0.0023R_a)(T_{mean} + 17.8)TD^{0.5}$$

Where, R_a is extra-terrestrial radiation in equivalent mm of water evaporation for the period, T_{mean} is the mean temperature in °C, and TD is the difference between maximum and minimum temperatures.

5. Pan evaporation Method:

Reference crop evapo-transpiration (ET_0) can be obtained from:

$$Et_0 = K_p . E_{pan}$$

Where E_{pan} is the pan evaporation in mm day^{-1} and K_p is the adjustment factor. The pan coefficients for class A pan for different ground cover, relative humidity and wind are mentioned in Appendix-10.

Appendix-1

Lengths of development stages for various crops based on different experiments grown at Dhenkanal, Balasore, Khurda districts

Crop	Initial stage	Development stage	Mid season stage	Late season stage	Total	Planting dates
a. Cereals						
Rice (short duration)	20	30	30	30	110	July
Rice (medium duration)	30	35	30	25	125	July/August
Rice (long duration)	30	40	40	40	150	July/August
Summer rice	25	30	35	30	120	December
Maize (*kharif*)	20	35	40	30	125	June
Maize (*rabi*)	20	35	40	15	110	October
Wheat	20	25	45	30	120	November
b. Vegetables						
Brinjal	30 30	40 45	40 40	20 25	130 140	June October/November
Tomato	30 35	40 40	40 50	25 30	135 155	June October/November
Cucumber	20 25	30 35	40 50	15 20	105 130	June November, February
Pumpkin	20	30	30	20	100	March /April
Spinach	20	30	40	10	100	November
Radish	10	15	35	20	80	November/December
Cabbage	20	25	30	20	95	October/November
Carrots	20	30	30	20	100	November/December
Cauliflower	25	25	25	20	95	October/November
Onion (dry)	20	35	110	45	210	October
Onion (green)	25	30	10	5	70	October
Water melons	20	25	25	20	90	February
Sugarbeets	25	30	25	10	90	November/December
Potato	25	30	35	30	120	November
Sweet potato	20 15	30 30	60 50	40 30	150 125	June December, January

b. Legumes ***(Leguminosae)***						
Beans (green)	20 15	30 25	30 25	10 10	90 75	February/March August/September
Beans (dry)	20 15 25	30 25 25	40 35 30	20 20 20	110 95 100	May/June June June
Faba bean Broad bean	15 20	25 30	35 35	15 15	90 100	November November
Green gram	20	25	25	20	90	March
Groundnut	25 25	35 35	45 35	25 25	130 120	November May/June
Black gram	20	25	40	25	110	October/November
Peas	35	25	30	20	110	October
Cowpeas	20	30	30	20	110	November
c. Fibre Crops						
Jute	25	35	50	40	150	April
d. Oil Crops						
Mustard						
Safflower	20	35	45	25	125	October/November
Sesame	20	30	40	20	100	June
Sunflower	25	35	45	25	130	April/May
Linseed	22	28	35	15	100	November
e. Sugarcane						
Sugarcane	35	60	140	130	375	November
f. Short duration fruits						
Banana, 1st yr	120	90	120	60	390	June
Pineapple	60	120	600	10	790	February

Appendix-2

Crop coefficients (Kc) of different crops to calculate crop evapo-transpiration (Source: Allen etal., 1998)

Crops	Crop Coefficient (Kc)			
	Initial stage	Crop development stage	Mid season stage	Late season stage
Field Crops				
Alfalfa	0.9	0.9	0.9	0.9
Barley	0.4	0.8	1.2	0.75
Beans Dry	0.4	0.8	1.2	0.3
Beans Green	0.4	0.75	1.05	0.95
Grains	0.4	0.73	1.15	0.6
Ground Nut	0.5	0.8	1.1	0.55
HYV Sorghum	0.5	0.8	1.15	0.6
Maize Grain	0.5	0.85	1.2	0.95
Maize Sweet	0.5	0.9	1.2	1.15
Potato	0.5	0.8	1.2	0.7
Pulses	0.45	0.75	1.15	0.6
Rabi Groundnut	0.4	0.7	1	0.7
Rice	1.15	1.5	1.3	1.05
Safflower	0.4	0.8	1.2	0.25
Sorghum	0.4	0.75	1.15	0.5
Soyabeans	0.4	0.8	1.15	0.45
Sugarbeet	0.5	0.85	1.2	0.7
Sugarcane	0.5	1	1.3	0.6
Sunflower	0.4	0.8	1.2	0.4
Tobacco	0.4	0.8	1.2	0.8
Winter Wheat	0.4	0.8	1.2	0.75
Horticulture crops				
Banana Sub Tropical	0.65	0.9	1.2	0.85
Banana Tropical	0.5	0.85	1.1	0.85
Citrus	0.75	0.7	0.65	0.75
Datepalm	0.9	0.9	0.9	0.9
Grape	0.55	0.8	0.9	0.4
Mango	0.9	0.9	0.9	0.9
Watermelon	0.5	0.8	1.05	0.9
Grass	1	1	1	1
Pasture	1	1	1	1
Cabbage	0.5	0.8	1.1	0.85
Onion Dry	0.6	0.8	1.1	0.75
Onion Green	0.6	0.75	1.05	0.75
Peas	0.5	0.85	1.2	1.1
Tomato	0.5	0.8	1.25	0.6
Vegetable	0.75	0.92	1.1	0.95
Peppers	0.4	0.75	1.1	0.9

Appendix-3

CN values for different types of land use

Land use or cover	Treatment or practice	State	Hydrological soil class			
			A	B	C	D
Fellow Row crops	Straight row	Poor	77	86	91	94
	Straight row	Poor	72	81	88	91
	Straight row	Good	67	78	85	89
	Contoured	Poor	70	79	84	88
	Contoured	Good	65	75	82	86
	Contoured and terraced	Poor	66	74	80	82
	Contoured and terraced	Good	62	71	78	81
Small grains	Straight row	Poor	65	76	84	88
	Straight row	Good	63	75	83	87
	Contoured	Poor	63	74	82	85
	Contoured	Good	61	73	81	84
	Contoured and terraced	Poor	61	72	79	82
	Contoured and terraced	Good	59	70	78	81
Closed-seeded legumes or rotation meadow	Straight row	Poor	66	77	85	89
	Straight row	Good	58	72	81	85
	Contoured	Poor	64	75	83	85
	Contoured	Good	55	69	78	83
	Contoured and terraced	Poor	63	73	80	83
	Contoured and terraced	Good	51	67	76	80
Pasture or range		Poor	68	79	86	89
		Fair	49	69	79	84
		Good	39	61	74	80
	Contoured	Poor	47	67	81	88
	Contoured	Fair	25	59	75	83
	Contoured	Good	6	35	70	79
Meadow (Permanent) woodland (Farm woodlots)		Good	30	58	71	78
		Poor	45	66	77	83
		Fair	36	60	73	79
		Good	25	55	70	77

Source: FAO Irrigation and Drainage Paper NO. 24

Appendix-4

Weighed Average Specific Water Consumption and Waste Water Discharge of Indian Ammonia Urea Plants

Year	Water Consumption (m^3/MT Urea)	Waste Water Discharge (m^3/MT Urea)
1990-91	12	2.3
1991-92	11.7	2.2
1992-93	11.5	1.8
1993-94	11.1	1.9
1994-95	10.5	1.7
1995-96	9.9	1.5
1996-97	9.5	1.4
1997-98	8.5	1.2
1998-99	8.5	1.2
1999-00	8	1.1
2000-01	7.8	0.9
2001-02	7.4	0.8
2002-03	7.3	0.6
2003-04	6.6	0.4

Source: http://www.fertlizer.org (Swaminathan and Goswami, 2005)

Appendix-5

Weighted Average Specific Water Consumption and Waste Discharge of NP/NPK Fertiliser Plant

Year	Water Consumption (m^3/MT P_2O_5)	Waste Water Discharge (m^3/MT P_2O_5)
1990-91	11.4	3.9
1991-92	9.2	4
1992-93	9.3	3.4
1993-94	7.9	3.1
1994-95	7.9	2.7
1995-96	7.9	2.8
1996-97	7.8	2.7
1997-98	6.5	1.8
1998-99	6.9	2.3
1999-00	5.7	1.3
2000-01	5.3	1
2001-02	4.1	0.4
2002-03	4.1	0.3
2003-04	4.1	0.4

Source: http://www.fertlizer.org (Swaminathan and Goswami, 2005)

Appendix-6

Mean Daily Percentage (p) of annual Daytime Hours for different latitudes

Latitude North	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Latitude South	**July**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**June**
60°	.15	.20	.26	.32	.38	.41	.40	.34	.28	.22	.17	.13
58	.16	.21	.26	.23	.37	.40	.39	.34	.28	.23	.18	.15
56	.17	.21	.26	.32	.36	.39	.38	.33	.28	.23	.18	.16
54	.18	.22	.26	.31	.36	.38	.37	.33	.28	.23	.19	.17
52	.19	.22	.27	.31	.35	.37	.36	.33	.28	.24	.20	.17
50	.19	.23	.27	.31	.34	.36	.35	.32	.28	.24	.20	.18
48	.20	.23	.27	.31	.34	.36	.35	.32	.28	.24	.21	.19
46	.20	.23	.27	.30	.34	.35	.34	.32	.28	.24	.21	.20
44	.21	.24	.27	.30	.33	.35	.34	.31	.28	.25	.22	.20
42	.21	.24	.27	.30	.33	.34	.33	.31	.28	.25	.22	.21
40	.22	.24	.27	.30	.32	.34	.33	.31	.28	.25	.22	.21
35	.23	.25	.27	.29	.31	.32	.32	.30	.28	.25	.23	.22
30	.24	.25	.27	.29	.31	.32	.31	.30	.28	.26	.24	.23
25	.24	.26	.27	.29	.30	.31	.31	.29	.28	.26	.25	.24
20	.25	.26	.27	.28	.29	.30	.30	.29	.28	.26	.25	.25
15	.26	.26	.27	.28	.29	.29	.29	.28	.28	.27	.26	.25
10	.26	.27	.27	.28	.28	.29	.29	.28	.28	.27	.26	.26
5	.27	.27	.27	.28	.28	.28	.28	.28	.28	.27	.27	.27
0	.27	.27	.27	.27	.27	.27	.27	.27	.27	.27	.27	.27

Appendix-7

Extra Terrestrial Radiation (Ra) expressed in equivalent evaporation in mm/day

Northern Hemisphere													Southern Hemisphere											
Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	LAT	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
3.8	6.1	9.4	12.7	15.8	17.1	16.4	14.1	10.9	7.4	4.5	3.2	50°	17.5	14.7	10.9	7.0	4.2	3.1	3.5	5.5	8.9	12.9	16.5	18.2
4.3	6.6	9.8	13.0	15.9	17.2	16.5	14.3	11.2	7.8	5.0	3.7	48	17.6	14.9	11.2	7.5	4.7	3.5	4.0	6.0	9.3	13.2	16.6	18.2
4.9	7.1	10.2	13.3	16.0	17.2	16.6	14.5	11.5	8.3	5.5	4.3	46	17.7	15.1	11.5	7.9	5.2	4.0	4.4	6.5	9.2	13.4	16.7	18.3
5.3	7.6	10.6	13.7	16.1	17.2	16.6	14.7	11.9	8.7	6.0	4.7	44	17.8	15.3	11.9	8.4	5.7	4.4	4.9	6.9	10.2	13.6	16.7	18.3
5.9	8.1	11.0	14.0	16.2	17.3	16.7	15.0	12.2	9.1	6.5	5.2	42	17.8	15.5	12.2	8.8	6.1	4.9	5.4	7.4	10.6	14.0	16.8	18.3
6.4	8.6	11.4	14.3	16.4	17.3	16.7	15.2	12.5	9.6	7.0	5.7	40	17.9	15.7	12.5	9.2	6.6	5.3	5.9	7.9	11.0	14.2	16.9	18.3
6.9	9.0	11.8	14.5	16.4	17.2	16.7	15.3	12.8	10.0	7.5	6.1	38	17.9	15.8	12.8	9.6	7.1	5.8	6.3	8.3	11.4	14.5	17.0	18.3
7.4	9.4	12.1	14.7	16.4	17.2	16.7	15.4	13.1	10.6	8.0	6.6	36	17.9	16.0	13.2	10.2	7.5	6.3	6.8	8.8	11.7	14.6	17.0	18.2
7.9	9.8	12.4	14.8	16.5	17.1	16.8	15.5	13.4	10.8	8.5	7.2	34	17.8	16.1	13.5	10.5	8.0	6.8	7.2	9.2	12.0	14.9	17.1	18.2
8.3	10.2	12.8	15.0	16.5	17.0	16.8	15.6	13.6	11.2	8.0	7.8	32	17.8	16.2	13.8	10.9	8.5	7.3	7.7	9.6	12.4	15.1	17.2	18.1
8.8	10.7	13.1	15.2	16.5	17.0	16.8	15.7	13.9	11.6	9.0	8.3	30	17.8	16.4	14.0	11.3	8.9	7.8	8.1	10.1	12.7	15.3	17.3	18.1
9.3	11.1	13.4	15.3	16.5	16.8	16.7	15.7	14.1	12.0	9.5	8.8	28	17.7	16.4	14.3	11.6	9.3	8.2	8.6	10.4	13.0	15.4	17.2	17.9
9.8	11.5	13.7	15.3	16.4	16.7	16.6	15.7	14.3	12.3	9.9	9.3	26	17.6	16.4	14.4	12.0	9.7	8.7	9.1	10.9	13.2	15.5	17.2	17.9
10.2	11.9	13.9	15.4	16.4	16.6	16.5	15.8	14.5	12.6	10.3	9.7	24	17.5	16.5	14.6	12.3	10.2	9.0	9.5	11.2	13.4	15.6	17.2	17.7
10.7	12.3	14.2	15.5	16.3	16.4	16.4	15.8	14.6	13.0	11.1	10.2	22	17.4	16.5	14.8	12.6	10.6	9.6	10.0	11.6	13.7	15.7	17.1	17.5
11.2	12.7	14.4	15.6	16.3	16.3	16.3	15.9	14.8	13.3	11.6	10.7	20	17.3	16.5	15.0	13.0	11.0	10.0	10.4	12.0	13.9	15.8	17.0	17.4
11.6	13.0	14.6	15.6	16.1	16.1	16.1	15.8	14.9	13.6	12.0	11.1	18	17.1	16.5	15.1	13.2	11.2	10.4	10.8	12.3	14.1	15.8	17.0	17.1
12.0	13.3	14.7	15.6	16.2	15.9	15.9	15.7	15.0	13.9	12.4	11.6	16	16.9	16.4	15.2	13.5	11.7	10.8	11.2	12.6	14.3	15.8	16.8	16.8
12.4	13.6	14.9	15.7	15.8	15.7	15.7	15.7	15.1	14.1	12.8	12.0	14	16.7	16.4	15.3	13.7	12.1	11.2	11.6	12.9	14.5	15.8	16.7	16.6
12.8	13.9	15.1	15.7	15.7	15.5	15.5	15.6	15.2	14.4	13.3	12.5	12	16.6	16.3	15.4	14.0	12.5	11.6	12.0	13.2	14.7	15.8	16.5	16.5
13.2	14.2	15.3	15.7	15.5	15.3	15.3	15.5	15.3	14.7	13.6	12.9	10	16.4	16.3	15.5	14.2	12.8	12.0	12.4	13.5	14.8	15.9	16.4	16.2
13.6	14.5	15.3	15.6	15.3	15.1	15.1	15.4	15.5	14.8	13.9	13.3	8	16.1	16.1	15.5	14.4	13.1	12.4	12.7	13.6	14.9	15.8	16.2	16.0
13.9	14.8	15.4	15.4	15.1	14.9	14.9	15.2	15.3	15.0	14.2	13.7	6	15.8	16.0	15.6	14.7	13.4	12.8	13.1	14.2	15.0	15.7	16.0	15.7
14.3	15.0	15.5	15.5	14.9	14.6	14.6	15.1	153.	15.1	14.5	14.1	4	15.5	15.8	15.6	14.9	13.8	13.4	13.4	14.3	15.1	15.6	15.3	15.4
14.7	15.3	15.6	15.3	14.6	14.3	14.3	14.9	15.3	15.3	14.8	14.4	2	15.3	15.7	15.6	14.1	14.1	13.5	13.7	14.5	15.2	15.5	15.35	15.1
15.0	15.5	15.7	15.3	14.4	14.1	14.1	14.8	15.3	15.4	15.1	14.8	0	15.0	15.5	15.7	15.3	14.4	13.9	14.1	14.8	15.3	15.4	15.4	14.8

Source: FAO Irrigation and Drainage Paper No. 24 (Doorenbos and Pruitt, 1975)

Appendix-8

Mean Daily duration of Maximum Possible Sunshine hours(N) for Different months and latitudes

Northern lats	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Southern lats	July	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June
50	18.5	10.1	11.8	13.8	15.4	16.3	15.9	14.5	12.7	10.8	9.1	8.1
48	18.8	10.2	11.8	13.6	15.2	16.0	15.6	14.3	12.6	10.9	9.3	8.2
46	9.1	10.4	11.9	13.5	14.9	15.7	15.5	14.2	12.6	10.9	9.5	8.7
44	9.3	10.5	11.9	13.4	14.7	15.4	15.2	14.0	12.6	11.0	9.7	8.9
42	9.4	10.6	11.9	13.4	14.6	15.2	14.9	13.9	12.6	11.0	9.8	9.1
40	9.6	10.7	11.9	13.3	14.4	15.0	14.7	13.7	12.5	11.2	10.0	9.3
35	10.1	11.0	11.9	13.1	14.0	14.5	14.3	13.5	12.4	11.3	10.3	9.8
30	10.4	11.1	12.0	12.9	13.6	14.0	13.9	13.2	12.4	11.5	10.6	10.2
25	10.7	11.3	12.0	12.7	13.3	13.7	13.5	13.0	12.3	11.6	10.9	10.6
20	11.0	11.5	12.0	12.6	13.1	13.3	13.2	12.8	12.3	11.7	11.2	10.9
15	11.3	11.6	12.0	12.5	12.8	13.0	12.9	12.6	12.2	11.8	11.2	11.2
10	11.6	11.8	12.0	12.3	12.6	12.7	12.6	12.4	12.1	11.8	11.6	11.5
5	11.8	11.9	12.0	12.2	12.3	12.4	12.3	12.3	12.1	12.0	11.9	11.8
0	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1

Source: FAO Irrigation and Drainage Paper No. 24 (Doorenbos and Pruitt, 1975)

Appendix-9

Weighting factor (W) for the effect of radiation on ET0 at different temperatures and altitude

Temperature °C	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40
W at altitude m 0	0.43	.46	.49	.52	.55	.58	.61	.64	.66	.68	.71	.73	.75	.77	.78	.80	.82	.83	.82	.85
500	.45	.48	.51	.54	.57	.60	.62	.65	.67	.70	.72	.74	.76	.78	.79	.81	.82	.84	.85	.86
1000	.46	.49	.52	.55	.58	.61	.64	.64	.69	.71	.73	.75	.77	.79	.80	.82	.83	.85	.86	.87
2000	.49	.52	.55	.55	.61	.64	.66	.69	.71	.73	.74	.75	.79	.81	.82	.84	.85	.86	.87	.88
3000	.52	.55	.58	.61	.64	.66	.69	.71	.73	.75	.77	.79	.81	.81	.82	.84	8.5	.86	.88	.89
4000	.55	.58	.61	.64	.66	.69	.71	.73	.76	.78	.79	.81	.83	.84	.85	.86	.88	.89	.90	.90

Source: FAO Irrigation and Drainage Paper No. 24 (Doorenbos and Pruitt, 1975)

Appendix-10

Pan coefficient (Kp) for class A pan for different ground cover and levels of mean relative humidity and 24hour wind

Class A Pan	Case A : Pan placed in short green cropped area				Case B : Pan placed in dry fellow area			
RH mean %		Low <40	Medium 40-70	High >70		Low <40	Medium 40-70	High >70
Wind Km/day	Wind ward side distance of green crop , m				Wind ward side distance of dry fellow, m			
Light <175	1	.55	.65	.75	1	.7	.8	.85
	10	.65	.75	.85	10	.6	.7	.8
	100	.7	.8	.85	100	.55	.65	.75
	1000	.75	.85	.85	1000	.5	.6	.7
Moderate 175-425	1	.5	.6	.65	1	.65	.75	.8
	10	.6	.7	.75	10	.55	.65	.7
	100	.65	.75	.8	100	.5	.6	.65
	1000	.7	.8	.8	1000	.45	.55	.6
Strong 425-700	1	.45	.5	.6	1	.6	.65	.7
	10	.55	.6	.65	10	.5	.55	.65
	100	.6	.65	.7	100	.45	.5	.6
	1000	.65	.7	.75	1000	.4	.45	.55
Very strong >700	1	.4	.45	.5	1	.5	.6	.65
	10	.45	.55	.6	10	.45	.5	.55
	100	.5	.6	.65	100	.4	.45	.5
	1000	.55	.6	.65	1000	.35	.4	.45

Source: FAO Irrigation and Drainage Paper No. 24 (Doorenbos and Pruitt, 1975)