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Enhancing Agricultural Productivity through Enhanced Water Use Efficiency

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ABSTRACT

In the background of shrinking water resources and competition from other sectors, the share of water allocated to irrigation is likely to decrease by 10 to 15 per cent in the next two decades. One of the ways of alleviating water scarcity is by enhancing its use efficiency or productivity. Water use efficiency (WUE) is a broad concept that can be defined in many ways. For farmers and farm managers, WUE is the yield of harvested crop produce achieved from the available water to the crop from rainfall, irrigation and soil water storage. A survey of literature shows that average WUE of major crops in India varies from 0.28 to 1.60 kg m^{-3} with wide differences among crop species. Improving WUE by 40% on rainfed and irrigated lands would be required to compensate the need for additional withdrawals of irrigation over next 25 years to meet additional demand for food. Improving WUE in agriculture will require an increase in crop water productivity (an increase in marketable crop yield per unit of water used by plant) and reduction in water losses from the crop root zone. For a comprehensive improvement of WUE, it is necessary to raise the following ratios to their maximum: stored soil water content/ water received through rainfall and irrigation, water consumption/ soil water storage, transpiration/ water consumption, biomass yield/ transpiration, and economic benefit/ biomass yield. In this paper, we have discussed various ways of enhancing use efficiency and productivity of water in agricultural production system. These include: better utilization of stored soil moisture by adjusting time and method of sowing, reducing evaporation loss of soil moisture by mulching, supplemental and deficit irrigation provided to crops at critical growth stages, practice of mixed cropping systems involving deep rooted crops during kharif season and shallow rooted crops during rabi season, removal of nutrient constraints by supplying optimum fertilizer inputs, crop diversification in lowlands, reducing water use in rice cultivation, improved irrigation methods like sprinkler and drip irrigation, improved planting patterns, integrated farming systems for flood-prone lowland areas, and multi-uses of water in agriculture by combining different farm enterprises like cropping, fishery and dairy. We have also discussed on the need of favorable public policies to create conducive socio-economic environments for enhancing WUE in the agriculture sector.

Key words: Water productivity, Minimum tillage, Supplemental irrigation, Raised and sunken bed system, Drip and furrow irrigation, Flood-prone lowland

Water is the most crucial input for agricultural production. Globally, agriculture accounts for more than 80% of all freshwater used by humans, most of that is for crop production (Morison *et al.*, 2008). Currently most of the water used to grow crops is derived from rainfed soil moisture, with non-irrigated agriculture accounting for about 60% of production in developing countries. Though irrigation provides only 10% of agricultural water use and covers just around 20% of the cropland, it can vastly increase crop yields, improve food

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security and contribute about 40% of total food production since productivity of irrigated land is almost three times higher than that of rainfed land. The Food and Agriculture Organization has predicted a net expansion of irrigated land of about 45 million hectares in 93 developing countries (for a total of 242 million hectares in 2030) and projected that water withdrawals by the agriculture sector will increase by about 14% during 2000 – 2030 to meet food demand (FAO, 2006).

Agriculture sector in India has been and is likely to remain the major consumer of water but the share of water allocated to irrigation is likely to decrease by 10 – 15 per cent in the next two decades. Current use efficiency or productivity of irrigation water is so low that most, if not all, of our future water needs could be met by increased productivity or efficiency alone, without development of additional water resources. Improving water use efficiency by 40% on rainfed and irrigated lands would be required to counter-balance the need for additional withdrawals for irrigation over the next 25 years to meet the additional demand for food. Growing more crop per drop of water use is the key to mitigating the water crisis, and this is a big challenge to many countries.

Vagaries of monsoon and declining water table due to over exploitation have resulted in shortage of fresh water supplies for agricultural use, which calls for an efficient use of this resource. Strategies for efficient management of water for agricultural use involves conservation of water, integrated water use, optimal allocation of water and enhancing water use efficiency by crops.

Water-use Efficiency/ Water Productivity

Productivity of irrigation water is defined broadly as the quantity or value of crop output per unit of water used. Definition of water productivity varies depending on how the denominator in this ratio is specified. When, at one extreme, water released from the system is used as the denominator, water productivity becomes all-inclusive subsuming water-use efficiency (WUE), that is, the ratio of consumptive use of water to the water released. At the other extreme, when the denominator consists of water lost as evapo-transpiration by plants in any particular season, and then improvement in water productivity can arise basically from the improvement in yields.

For farmers, WUE is the yield of harvested crop product achieved from the water available through rainfall, irrigation and soil water storage. Improving WUE in agriculture will require an increase in crop water productivity (an increase in marketable crop yield per unit of water removed by plant) and a reduction in water losses from the crop root zone. The amount of water required for food production depends on the quantity of agricultural commodities produced. For example, the production of 1 kg beef would require 14 times more water than for 1 kg of wheat grain. Hence, enhancing WUE in agriculture may also require some socio-economic adjustment to encourage and develop more water efficient enterprises. For comprehensive improvement of WUE in agriculture, it is necessary to raise the following ratios to their maximum: soil-stored water content/ water received through rainfall and irrigation, water consumption/ soil storage of water, transpiration/ water consumption, biomass yield/ transpiration, and economic benefit/ biomass yield. Upgradation of all these component parameters is the key issue for enhancing WUE.

Scope for Improving Water-use Efficiency in Agriculture

Considering the productivity of water in more than 40 irrigation systems worldwide, an International Water Management Institute study demonstrated a 10-fold difference in the gross value of output per unit of water consumed by crops. Some of these differences is due to environment, or the price of grain versus high-valued crops. But even among grain-producing areas, the differences are large. In many areas, potential productivity of water is not realized partly due to poor irrigation management. Improving performance of irrigated agricultural systems should be a high-priority action.

Managing water in agriculture should not exclusively focus on improving the productivity of the 2,500 km^3 of water diverted to irrigation, but must also include improving the productivity of the 16,000 km^3 used in rainfed agriculture. Rainfed agriculture contributes to about 60% of cereal production on 70% of the area meant globally for cereal production. It is the primary means of food production in most countries, and the only means of production for many farmers. Consequently, a 1% increase in rainfed cereal production would have one and half times more effect than a similar productivity increase in irrigated cereal production. Improving the productivity of rainfed lands also has the potential to benefit some of the world's poorest people who currently struggle to farm marginal rainfed lands.

Enhancing WUE is a paramount objective, particularly in arid and semi-arid areas with erratic rainfall patterns. Under rainfed conditions, soil water may be lost from the soil surface through evaporation or through plant uptake and subsequently lost via stomata on plant leaves (transpiration). It can also be lost through runoff and deep percolation through soil. Improving WUE in arid and semi-arid areas depends on effective conservation of moisture and efficient use of limited water. When irrigation is considered, water losses also include the mismanagement of irrigation water from its source to the crop roots. Generally more than 50% of irrigation water is lost at the farm level. At the watershed level, however, it may be less due to possible recoveries from the subsoil and groundwater. Such off-site losses of water may result from either inappropriate land management practices to capture a substantial part of the rainfall within an agricultural landscape and retain in the crop root zone or excessive use of irrigation water. These losses not only cause wastage but also a potential hazard of soil salinity and water pollution resulting from the transport of nitrate, phosphate, sediments and agro-chemicals to the adjacent water bodies.

WUE of Major Crops in India

Range and average values of water-use efficiency of selected crops in India are presented in Table 1. Among the foodgrain crops, WUE of wheat, maize, sorghum and pearl millet are much higher than that of rice. Among the legume crops, chickpea, lentil and kidney bean were more efficient user of water than pigeonpea, greengram and blackgram. Among the oilseed crops, WUE of sesame is much lower than that of soybean, mustard, groundnut, sunflower and linseed. Of the two important cash crops, WUE of sugarcane is much higher than that of cotton. Among three important vegetable crops, cauliflower is more efficient user than tomato. The WUE of tomato is higher than that of brinjal. Deng *et al.* (2004) reported data on WUE of major crops grown in irrigated and dryland areas of north and northwest China. Values of average WUE of crops reported

Table 1. Water use efficiency of selected food grain crops grown in India

Crops	No. of sites/ observations	WUE range (kg m^{-3})	Average WUE (kg m^{-3})
Foodgrain crops			
Rice	6	0.30-0.54	0.45
Wheat	23	0.58-2.25	1.24
Maize (rabi)	10	0.49-1.63	0.91
Sorghum	7	0.56-1.43	0.88
Pearlmillet	4	0.41-0.70	0.54
Pulse crops			
Chickpea	8	0.40-4.02	1.60
Lentil	6	0.39-2.43	1.05
Green gram	4	0.37-0.50	0.44
Pigeon pea	3	0.27-0.72	0.46
Black gram	2	0.25-0.31	0.28
Kidney bean	2	0.55-0.79	0.67
Oilseed crops			
Groundnut	7	0.20-1.11	0.50
Mustard	3	0.41-0.98	0.67
Sunflower	8	0.16-0.93	0.59
Sesame	2	0.36-0.36	0.36
Linseed	4	0.15-0.93	0.53
Soybean	3	0.35-1.04	0.60
Vegetable and cash crops			
Sugarcane	9	3.25-7.83	4.68
Cotton	8	0.17-0.40	0.26
Cauliflower	7	13.8-114.9*	59.6*
Tomato	7	2.34-15.34*	6.80*
Brinjal	6	0.26-0.89*	0.50*

(*Source:* Yadav *et al.,* 2000)
*Efficiency of applied water only

from China were similar to that reported from India.

Strategies for Enhancing Water-use Efficiency in Agriculture

Water use efficiency by crops can be improved by (i) selection of crops and cropping systems based on available water supplies and (ii) increasing seasonal evapo-transpiration (ET) (Prihar *et al*., 2000). Seasonal evapo-transpiration is a measure of consumptive water use by the crops. Increasing the transpiration (T) component of evapo-transpiration (ET) results in higher utilization of water by the crops to increase the productivity. The rate of development of crop canopy and root system and the extent of soil wetting determine the relative fraction of ET lost as evaporation (E) or transpiration (T). Seasonal evapoinanspiration can be increased by selection of irrigation method, irrigation scheduling, tillage, mulching and fertilization. The strategies for increasing water use efficiency include appropriate integrated land and water management practices like (i) soil-water conservation measures through adequate land preparation for crop establishment, rainwater harvesting and crop residue incorporation, (ii) efficient recycling of agricultural wastewater, (iii) conservation tillage to increase water infiltration, reduce runoff and improve soil moisture storage, and (iv) adequate soil fertility to remove nutrient constraints for maximizing crop production for every drop of water available through either rainfall or irrigation. In addition, novel irrigation technologies such as supplementary irrigation (some irrigation inputs to supplement inadequate rainfall), deficit irrigation (omitting irrigation at times that have little impact on crop yield), drip irrigation (delivering irrigation water to plant rooting zones) and sprinkler irrigation can improve the water use efficiency of crops. In sandy soils of low fertility, nutrient deficiencies often override water shortage as the main factor limiting crop productivity. Crop growth may be so poor that it can utilize only 10 to 15% of total rainfall, the remaining being lost through evaporation, deep percolation and runoff. The resulting WUE may be very low as the amount of water required for food production would be higher than the average value of 2000–5000 kg water kg^{-1} food. Under such situations, increasing nutrient supply often leads to an increase in both crop production and WUE. Fertigation, which combines irrigation and fertilization, maximizes the synergy between these two farm inputs in increasing their efficiencies.

Rainfed area occupying about 63% (89 M ha) of the cultivated land in India accounts for only 40% of total food production, whereas irrigated area covering 37% (53 M ha) of the cultivated land contributes 60% to the national food basket. Supplemental irrigation combined with on-farm water-harvesting practices, such as mulching or bunding, reduces vulnerability to drought and helps farmers to get the most out of the scarce resources. Mitigating the effects of short-term drought is therefore a key step in achieving higher yields and water productivity in rainfed areas.

Discussed hereunder are various means of enhancing use-efficiency and productivity of water in agricultural production system.

A. Selection of crops and cropping system

Selection of crops and cropping systems for high water use efficiency should be done on the basis of availability of water under the following three categories viz., rainfed crops, limited irrigated crops and fully irrigated crops.

Rainfed crops: The amount of rainfall converted into plant-available soil water is determined by the amount and intensity of rainfall, topography, infiltrability and water retentivity of soil, depth of root zone and soil depth. Depth of soil due to its effect on the available water storage capacity decides the type of cropping system that can be followed in a locality. In the shallow vertisols of Indore region with 100 mm of available water, only monocropping of sorghum or corn can be practiced. On medium soil depth monocropping or intercropping can be practiced whereas in deep soil with 200 mm available soil moisture, double cropping can be practiced.

Limited irrigated crops: Selection of crops and cropping sequences under limited irrigation situation should be done in such a manner that there should be minimum water stress during the growing season although some water stress to the crops and associated yield reduction is inevitable. Therefore, along with selection of crops special care should be taken for irrigation scheduling of these crops.

Fully irrigated crops: Under this condition, selection of crops is not constrained by water availability but by adoptability of the crops to prevailing climatic and soil condition. In general, C4 plants have potential for greater water use efficiency than C3 plants, particularly under semiarid environment.

Mixed Cropping System

A new cropping system of corn mixed with grasses was proposed to make full and efficient use of water in grain and forage feed production practices (Lei *et al*., 2003). The results showed that WUEs in the mixed cropping fields of corn-grasses were much higher than those in the fields where only corn or grass was grown. Average WUE was 3.71 kg m^{-3} from the mixed fields of corn and rye, which is 30% higher than that from the plots where only corn or rye was grown. Average WUE was 4.55 kg m^{-3} from the alfalfa and corn mixture fields, 60% higher than that from the fields where only corn or alfalfa was grown. Under the same conditions of irrigation, yields from the rye and corn mixture plots could be increased by 33%, as compared with those from the fields where only corn or rye was grown. The yields from alfalfa and corn mixed fields were 61% higher than those from the fields where only corn or alfalfa was grown. The experimental results also indicated that corn and alfalfa mixed cropping is better than corn-rye mixed cropping.

Reducing Water Use in Rice Cultivation

Sustainability of rice production in India is threatened by declining availability of fresh water for irrigation. Irrigated agriculture accounts for about 84% of total diverted freshwater, and more than 50% of the same is used in irrigated rice. It is therefore imperative to reduce water use in rice cultivation and increase its use efficiency. It is important to understand various ways and means for reducing water use in rice cultivation without impairing yield.

Irrigated lowland is the dominant ecosystem for rice, the most productive in terms of yields and specific water use (the most water productive), but is the least efficient if one considers water use per cultivated area or the amount of water required for evapo-transpiration divided by the amount of water diverted into the system.

Early research focused on ways to improve water productivity in rice by developing improved varieties and improving agronomic management, then more recently on improving water use efficiency, and finally on improving water productivity (which considers yields or income per m^3 of water consumed) at all levels.

Reduction in seepage and percolation loss from rice field: Large reduction in water use in rice production can be achieved by reducing seepage and percolation loss during the crop growth as well as fallow periods. Therefore, most of the field-level water-saving strategies concentrate on the reduction of these losses, which can be achieved to some extent by increasing the resistance to water flow in the soil, and by decreasing the hydrostatic pressure of the ponded water. Generally farmers have a tendency to maintain a ponding depth of 10–15 cm which causes large percolation loss of water accompanied with leaching loss of mobile nutrients, especially in light-textured soils. Thus an optimal depth of ponding water needs to be worked out for different soil types and locations. While comparable rice yields are obtained with water ponding of 5 and 10 cm, irrigation water requirement is much higher in the latter treatment (Table 2). Increasing the ponding depth to 15 and 20 cm causes progressive reduction in rice yield, with a marked increase in irrigation water requirement.

Decreasing the floodwater depth in rice fields from 5–10 cm to zero reduces the hydrostatic pressure, thereby reduces water loss through percolation. Rice grown under saturated soil culture or alternate wetting and drying (intermittent flooding) treatments will have little water loss through seepage and percolation.

Table 2. Rice yield and irrigation water requirement in relation to depth of water ponding at selected locations

Location	Soil type	Ponding depth (cm)	Grain yield (t ha^{-1})	Irrigation requirement* (cm)
Kharagpur (WB)	Lateritic sandy loam	5	5.28	124 (–60%)
		10	5.27	183 (–38%)
		15	4.74	246 (–17%)
		20	4.53	297
Hyderabad (AP)	Sandy loam	5	4.59	167 (–54%)
		10	4.42	366
Chakuli (Orissa)	Sandy loam	5	4.55	49 (–29%)
		10	4.48	62

(Source: Chaudhari, 1997)
*Figures in parentheses indicate % decrease in irrigation requirement

Saturated soil culture and alternate wetting and drying: The 'water-saving irrigation techniques' for rice production aim at reducing seepage and percolation rates by (i) reducing the depth of floodwater in field, (ii) keeping the soil just saturated, or (iii) alternate wetting and drying, i.e. allowing the soil to dry out to a certain extent before re-applying irrigation water. Water-saving irrigation techniques, however, run the risk of reducing rice yield from possible drought-stress effects. Establishment of relationships between water input and rice yield is needed to know the extent of water input reduction without reducing yield and to optimize use of scarce water in rice production. Information on the optimum intermittent period for delaying irrigation and saving of irrigation water in kharif rice at selected locations is presented in Table 3. The optimum period is 2 days for locations with light-textuted soils, 3 days for locations with medium-textured soils and as high as 5 days for locations with silty loam soils. Intermittent flooding saved 21 – 66% water as compared to continuous flooded condition.

In saturated soil culture, soil is maintained as close to saturation as possible by providing shallow irrigation (to obtain about 1 cm floodwater depth) a day or so after the dissipation of standing water. In alternate wetting and drying treatments, irrigation water is applied to obtain 2–5 cm floodwater depth after certain days of dissipation of ponded water.

Table 3. Optimum intermittent period of delay in irrigation after the disappearance of floodwater and saving in irrigation water at selected locations

Location	Optimum intermittent period (days)	Saving in irrigation water (%)	Soil type
Pantnagar	3	25	Silty clay loam
Faizabad	5	66	Silty loam
Bikramganj	3	NA	Sandyclay loam
Chiplima	2	21	Sandy loam
Bilaspur	2	21	Clay loam
Jorhat	3	32	NA
Madurai	3	33	NA

(*Source:* Samra *et al.,* 2004)

Both saturated soil culture and alternate wetting & drying treatments resulted in decreased water input but at the expense of decreased rice yield. Saturated soil culture decreased water use by 5–50% (average 23%) but reduced rice yields by 0–12% (average 6%). However, cultivation of rice under saturated soil culture requires good water control and it is labour intensive. It has been found that construction of 120 cm wide raised beds separated by 30 cm wide and 15 cm deep furrows and near-continuous irrigation through the furrows keep the soils of raised beds saturated. Growing of rice on saturated raised beds saved 34% water but lost 16–34% yields compared to that grown under flooded field conditions.

Table 4. Grain yields of rice var. Lalat under different water management treatments at Biswanathpur in Balipatna block, Khurda district Orissa (Rabi season 2005–06)

Water management treatments	Irrigation water applied (cm)	Saving in irrigation water (%)	Rice grain yield (t ha^{-1})	Efficiency of applied water (kg grain cm^{-1} water)	WUE (kg grain m^{-3} water)
Continuous submergence	148		4.25	28.7	0.25
Irrigation 1 day after subsidence of standing water	122	17.6	4.20	34.4	0.29
Irrigation 2 days after subsidence of standing water	97	34.5	4.05	41.7	0.34
Irrigation 4 days after subsidence of standing water	81	45.3	3.85	47.5	0.37

Rainfall received during the season: 23 cm
(Source: Swarup *et al.,* 2008)

Alternate wetting and drying practices resulted in water savings but caused rice yield losses of 0–70% compared with the continuous flooding treatment, depending on the irrigation intervals and existing soil conditions. However, the yield losses are generally smaller than the reduction in water inputs and therefore water productivity is increased significantly. There is a trade-off between land productivity (yield) and water use efficiency. Data on grain yield of rice, saving of irrigation water and use efficiency of applied water under different water management practices (continuous submergence, irrigation supplied 1, 2 and 4 days after subsidence of standing water) from a field experiment conducted at Balipatna, Orissa during rabi season are presented in Table 4. Saving of irrigation water and enhancement of water use efficiency were highest when irrigation water was given 4 days after disappearance of standing water. The yield decrease due to intermittent flooding was not significant.

Aerobic rice: With the development of suitable varieties and improved management practices, there is increasing interest in aerobic rice cultivation. In a field study conducted in Deras Irrigation Command Area, grain yields of rice under aerobic condition were 2.57–3.95 t/ha with a yield reduction of 18.7– 47.1% compared to the flooded condition. Irrigation water input was 540-700 mm under aerobic and 1250 mm under flooded soil conditions. As reduction in water use was more pronounced than that in grain yield, water productivity under aerobic cultivation increased by 22.4 – 45.0% compared to flooded condition (Table 5).

Table 5. Grain yields of rice and water productivity under flooded and aerobic soil conditions at Deras Irrigation Command. Khurda district, Orissa during dry season 2007 (Swarup *et al.,* 2008)

Rice variety	Soil water regimes*			
	Flooded	Aerobic-I	Aerobic-II	Aerobic-III
Surendra				
Grain yield (t ha^{-1})	4.86	3.95	3.62	2.57
Water applied (mm)	1250	700	660	540
Water productivity (kg m^{-3})	0.39	0.56	0.55	0.48
Lalat				
Grain yield (t ha^{-1})	4.76	3.82	3.60	2.63
Water applied (mm)	1250	700	660	540
Water productivity (kg $m^{-}3$)	0.38	0.55	0.54	0.49

*Aerobic-I: soil moisture level maintained at 80-90% FC (field capacity) throughout growing season, Aerobic-II: soil moisture level maintained at 60-70% FC during vegetative and 80-90% FC during reproductive stage, Aerobic-III: soil moisture level maintained at 60-70% FC throughout growing season.

However, growing irrigated rice under aerobic condition faces several constraints, such as (i) higher inputs for weed control, (ii) increased susceptibility to diseases, (iii) imbalance of soil nutrients, (iv) difficulty in on-farm water management, (v) increased investment and maintenance costs, and (vi) ingrained traditions and general practices based on flood irrigation management.

Crop Diversification in Lowlands

Root-zone soils of most agricultural farms of lowlands in canal irrigation commands remain saturated to over-saturated through *kharif* as well as *rabi* seasons. Farmers in such areas can hardly grow any other crop than rice. Use efficiency of water in rice cultivation is very low and rice farming is not very remunerative. Modification of field topography by construction of alternate raised and sunken beds improves soil aeration status in half of the farm area and makes cultivation of more profitable crops than rice possible there. WTCER has developed alternate raised and sunken bed system for crop diversification and thereby enhancing water use efficiency for such lowland areas. Singh *et al.* (2005) reported a 600% enhancement in the use-efficiency of water by practicing this technology at small and marginal farms of Khurda district, Orissa (0.36 kgm^{-3} for rice cropping, and 2.62 kgm^{-3} for diversified cropping) (Table 6).

Integrated Farming System for Lowland Areas Prone to Waterlogging

In wetland ecosystem, water productivity can be improved by introducing fishery. With the same quantity of water used in rice cultivation, it is possible to increase the water productivity by several times if it is used for fish production (Table 7).

Conversion of 50% of lowland area prone to waterlogging into pond by digging to 100 cm depth and construction of 2.5 m high peripheral dykes with the excavated soil offer scope for development of a profitable, integrated agri-horti-aquacultural production system. In such production system, deepwater rice and fish are grown in waterlogged area and ponds, horticultural crops like coconut, papaya, banana,

Table 6. Water-use efficiency and net water productivity in original and modified lowland at Balipatna block of Khurda district, Orissa

Land treatment and cropping systems	Crop yield ($t\ ha^{-1}$)	Rice equivalent yield ($t\ ha^{-1}$)	Water expense ($mm\ ha^{-1}$)	Water expense efficiency ($kg\ m^{-3}$)	Gross water productivity ($Rs\ m^{-3}$)	Net water productivity ($Rs\ m^{-3}$)
Original lowland						
Rice (Ra) +	4.40	8.18	2,262	0.36	1.45	0.56
rice (Kh)	3.78					
Modified lowland						
Rice (Ra) +	5.40	24.59	2,150	1.14	4.58	2.64
rice (Kh) +	4.85					
pointed gourd +	12.37					
papaya	4.00					
Rice (Ra) +	5.40	35.75	2,435	1.46	5.87	3.49
rice (Kh) +	4.11					
cabbage +	26.87					
snake gourd	20.07					
Colocasia +	42.27	51.16	1,949	2.62	10.50	7.88
pointed gourd +	12.37					
papaya	4.00					

(*Source:* Singh *et al.,* 2005)

Table 7. Comparison of water productivity of rice and fish at farm level in Bhavani Basin, Tamilnadu (Source: Palanisami and Ramesh, 2009)

Particulars	Water productivity ($kg\ m^{-3}$)	($Rs\ m^{-3}$)
Rice	0.46	2.75
Fish	3.08	77.13

brinjal, okra, etc. are grown on the peripheral dykes, and a low-duty second crop like black gram is grown in lowland during dry season after harvesting of kharif rice. In a farmer's field at Khentalo in Cuttack district, performance of several treatments on water productivity in lowland prone to waterlogging was studied by WTCER. While net productivity of water in traditional deepwater rice cultivation was only Rs 0.46 m^{-3}, it increased to Rs 7.30 m^{-3} for newly developed agri-horti-aquacultural and Rs 8.17 m^{-3} for aquacultural production system (Table 8).

Multiple Uses of Water in Agriculture

Comparing the different combination of farm enterprises, crop + fishery system gives more profit per unit of water followed by crop + dairy combination. The water productivity has increased considerably where allied enterprises involved along with crops. Among the allied enterprises, dairy component requires minimum water which in turn produced maximum water productivity per unit of water (Table 9).

B. Increasing seasonal evapo-transpiration

Seasonal evapo-transpiration can be improved by following better irrigation method, irrigation scheduling, tillage, mulching and fertilization.

Table 8. Productivity of water in deepwater ecosystem under different uses

Treatment	Gross water productivity ($Rs\ m^{-3}$)	Net water productivity ($Rs\ m^{-3}$)
Rice-fish (with cull harvesting) + black gram + on dyke horticulture	12.52	7.30
Rice-fish (without cull harvesting) + black gram + on dyke horticulture	11.32	6.90
Rice only	0.96	0.46
Fish and prawn culture only (without cull harvesting)	16.83	8.17

(*Source:* Mohanty *et al.,* 2008)

Table 9. Water productivity of different agriculture enterprises at field level in Bhavani Basin, Tamilnadu

Farm type	Enterprises	Unit (acres)	Water (m^3)	Yield (kg)	Income (Rs)	$WP_{(IP)}$ ($kg\ m^{-3}$)	$WP_{(IP)}$ ($Rs\ m^{-3}$)
Crops alone	Banana-surface irrigated	1.5	8122	10,500	1,26,000	1.29	15.5
	Banana-drip irrigated	0.5	2525	5,000	60,000	1.98	23.8
	Leaf vegetable	0.25	1080	500	4,000	0.46	3.7
	Total farm	2.25	11727		1,90,000		16.2
Crops + dairy	Rose-surface irrigated	1.0	6220	3,06,000 No.	76,500		12.3
	Rose-drip irrigated	1.0	2264	3,40,000 No.	85,000		37.5
	Maize	0.5	778	800	4,800	1.02	6.2
	Dairy	1 No.	25	3,300 lit/ lac tonne	26,400	132.96 l	1063.7
	Total farm	2.5	9287		1,92,700		20.7
Crops + fishery	Grape-drip	1.0	922	2,500	25,000	2.71	27.1
	Banana-drip	1.0	6336	14,400	1,72,800	2.27	27.3
	Fishery	1.0	8645	26,670	6,66,750	77.13	77.1
	Total farm	3.0	15903		8,64,550		54.4

$WP_{(IP)}$= Water productivity for total water used (irrigation water + precipitation)
(*Source:* Palanisami and Ramesh, 2009)

(i) Irrigation Method

Efficient micro irrigation methods and technologies i.e. sprinkler and drip irrigation for utilization of available water in scarce areas developed for irrigation of horticultural and plantation crops have been reported to result in 30-50% saving of water and 20-40% increase in crop yields. Bandyopadhyay et al. (2010) reported that when 20 cm irrigation was supplied up to flowering stage or 14 cm irrigation was supplied up to tillering stage, through sprinkler method in 4 and 3 splits, respectively at critical growth stages, it resulted in higher grain yield and WUE of wheat in a Vertisol than that in flood irrigation method.

Water management studies in sugarcane conducted at Rahuri showed that the drip method saved more than 60% water compared to furrow method and produced 12–15% more cane yield. In an effort to lower operational cost of drip system, planting pattern has been changed to cut down initial investment on laterals and drippers. Three distinct patterns of planting, viz. normal, paired row and pit method were evaluated. The yield in paired row planting in drip irrigation method was better than all surface irrigation treatments, indicating that the cost of drip system could be reduced by adopting paired row planting (Table 10).

The performance of drip and conventional surface (check basin) irrigation methods in banana was evaluated in clay soils at Rahuri. Normal planting pattern had an edge over paired planting pattern. Nevertheless, the fruit yield and WUE of banana were higher under drip than that obtained under check basin method of irrigation (Table 11).

Table 10. Effect of drip and furrow irrigation methods on water-use efficiency in sugarcane crop at Rahuri, Maharashtra

Irrigation method	Cane yield ($t\ ha^{-1}$)	Water applied (cm)	WUE ($kg\ m^{-3}$)
Drip, paired row	130.7	91	14.3
Drip, pit method	138.6	68	20.3
Irrigation in each furrow	114.7	216	5.31
Irrigation in paired furrow	111.4	160	6.96
Irrigation in alternate furrow	92.1	143	6.44

(Data source: Yadav *et al.,* 2000)

Table 11. Effect of planting pattern and irrigation method on fruit yield and water use efficiency of banana at Rahuri, Maharashtra

Planting pattern and irrigation method	Fruit yield ($t\ ha^{-1}$)	Water applied (cm)	WUE ($kg\ m^{-3}$)
Drip irrigation			
Normal planting	82.86	154	5.38
Paired planting	75.75	154	4.92
Surface irrigation	72.61	311	2.33

(Data source: Yadav *et al.,* 2000)

Among the irrigation methods, drip irrigation has recorded the maximum water productivity compared to surface irrigation in Bhavani Basin, Tamilnadu. Water productivity is expressed both in terms of product or profit per unit of evapotranspiration, or irrigation water or total water used (IW+P). Maximum water productivity was observed for rose flower cultivation followed by grapes and banana. In general, fruit crops produced higher water productivity that grain crops (Table 12).

(ii) Irrigation Scheduling

This can be discussed under following two conditions

(a) *Adequate irrigation*: Under adequate water supply condition the objective of irrigation is to secure potential yield of crops without wasting water.

(b) *Limited irrigation*: Irrigation should be supplied at critical crop growth stages to achieve maximum water use efficiency. The first step in this effect is to generate quantitative information relating to yield reductions with water deficit during various periods of growth that can be used to optimize the dated inputs of limited water for maximum water use efficiency. There are different methods of irrigation scheduling viz., critical crop growth stage approach, soil moisture depletion approach, irrigation water at different cumulative pan evaporation (IW/CPE) approach etc., that may be adopted for optimizing the timing of irrigation.

Table 12. Water productivity (Rs m^{-3} of water) in respect of evapotranspiration (WP_{ET}), irrigation (WP_{I}) and total water productivity (WP_{IP}) for different crops at farmers' situation. Bhavani Basin, Tamilnadu

Crop	Unit (acre)	Total ET (m^3)	Total IW (m^3)	Total water: IW+P (m^3)	Income (Rs)	$WP_{(ET)}$	$WP_{(I)}$	$WP_{(IP)}$
Banana- surface	1.5	9960	7299.6	8121.6	126000	12.65	17.26	15.51
Banana- drip	0.5	3320	1962.5	2524.5	60000	18.07	30.57	23.76
Rose- surface	1.0	3805.9	5096.8	6220.0	76500	20.10	15.01	12.30
Rose- drip	1.0	3805.9	1140.4	2264.4	85000	22.33	74.53	37.50
Maize- surface	0.5	500	499.6	777.6	4800	9.60	9.60	6.17
Leaf veg.- surface	0.25	106.8	941.0	1080.0	4000	36.83	4.25	3.70
Grape- drip	1.0	1421.4	357.6	921.6	25000	17.59	69.9	27.13

(*Source:* Palanisami and Ramesh, 2009)

Table 13. Critical growth stages of selected crops in respect of water demand

Crop	Critical growth stage(s)
Rice*	Transplanting to tiller initiation, panicle initiation to flowering
Wheat	Crown root initiation, booting, milking, grain formation
Maize (kharif)	Silking
Maize (rabi)	4-5 leaves, knee-high, taselling, silking, grain formation
Sorghum (kharif)	Booting
Sorghum (rabi)	Vegetative, booting
Pearlmillet	Flowering
Pigeonpea	Flower initiation, pod development
Chickpea	Branching, pod development
Kidney bean	Vegetative, flowering, pod development
Greengram (summer)	Vegetative, flowering, pod development
Soybean	Flowering
Sesame	Flowering
Mustard	Branching, siliqua development
Groundnut (kharif)	Pegging, pod development
Groundnut (rabi)	Vegetative, branching, flowering, pegging, pod development
Sunflower	Vegetative, disc formation, flowering

* for maintenance of submerged soil condition
(*Source:* Yadav *et al.,* 2000)

Deficit irrigation, a strategy which maximizes the productivity of water by allowing crops to sustain some degree of water deficit and yield reduction, holds promise for severely water deficit areas. ICARDA studies in Syria have shown that applying 50% of the supplemental irrigation requirement only reduces yields by 15%. For deficit irrigation to function as a realistic strategy, we need to better understand the relationship between yield and water deficit and we need to identify the types of support and incentives that farmers need to adopt the practice.

Increased WUE of field crops in the dry season may be achieved through proper irrigation scheduling at critical growth stages. Extensive experimentation conducted over years has identified critical growth stages of various crops in respect of their water demand (Table 13). Irrigation needs to be applied at critical growth stages of the crops to realize maximum water-use efficiency.

Results of field experiments conducted by DWM in Dhenkanal district, Orissa showed that with two supplemental irrigations, WUE of maize, groundnut, sunflower, wheat and potato was 0.55, 0.22, 0.23, 0.41 and 2.27 kg m^{-3} respectively (Table 14). It increased by 40, 14, 22, 38 and 7% when three irrigations were applied. With four

Table 14. Yield and WUE of selected crops grown with limited irrigation at Arnapurnapur village, Dhenkanal, Orissa

Crop	Grain yield (kg ha^{-1})			Water use (mm)			WUE (k gm^{-3})		
	I_2	I_3	I_4	I_2	I_3	I_4	I_2	I_3	I_4
Maize (grain)	1,845	2,950	5,805	334	385	438	0.55	0.77	1.32
Groundnut	785	1,020	1,590	348	395	444	0.22	0.26	0.36
Sunflower	905	1,205	1,715	395	429	476	0.23	0.28	0.36
Wheat	1,420	2,250	2,780	348	390	440	0.41	0.58	0.63
Potato (tuber)	8,050	9,650	12,400	355	394	432	2.27	2.45	2.87

I_2= two irrigations, I_3= three irrigations, I_4= four irrigations by recycling of harvested rainwater in village pond.
(*Source:* Kar *et al.,* 2004)

Table 15. Grain yield, evapotranspiration, WUE and net water productivity of horsegram under different methods of crop establishment

Method of crop establishment	Grain yield (kg ha^{-1})	Total ET (mm)	Water Use Efficiency (kg m^{-3})	Net productivity of used water (Rs m^{-3})
Early[1] sowing with minimum tillage	1290	214.3	0.60	4.85
Late[2] sowing with minimum tillage	1060	182.8	0.58	4.30
Pyra[3] cropping without tillage	750	188.6	0.40	2.93
CD (P=0.05)	130	21.4	0.06	0.37

[1]on 15th October, [2]on 1st November, [3]on 15th October, 10 days before rice harvest
(*Source:* Singh *et al.,* 2008)

supplemental irrigations, WUE of 1.32, 0.36, 0.36, 0.63 and 2.87 kg m^{-3} was obtained in the respective crops. Among all the five crops, the highest water use was observed in sunflower crop, probably due to its deeper root system.

(iii) Tillage

Tillage affects water use efficiency by modifying the hydrological properties of soil and influencing root growth and canopy development of crops. Tillage methods influence wettability, water extraction pattern and transport of water and solutes through the soil profile through its effect on soil structure, aggregation, total porosity and pore size distribution. Tillage system suitable for a soil depends upon soil type, climate and cropping system practiced. Shallow inter-row tillage into growing crops has been reported to reduce short term direct evaporation loss from soil even under weed-free condition by breaking the continuity of capillary pores and closing the cracks.

In a field study on the effect of sowing time and method on WUE of *rabi* horsegram conducted at Balipatna in Khurda district, WUE and net water productivity were higher under minimum tillage than under no tillage. Then within the minimum tillage treatment, early sown crops recorded higher yield, WUE and net water productivity obviously due to better utilization of residual soil moisture and/or efficient tapping of water from shallow water table (Table 15). Thus when irrigation water is not available for raising dry-season crops, early sowing of seeds using minimum tillage enhances water-use efficiency.

Deep tillage to a depth of 30 - 45 cm at 60-120 cm intervals helps in breaking subsoil hard pans in Alfisols facilitating growth and extension of roots and improving grain yield of crops as well as increase in the residual soil moisture. However, the benefit is absent in subnormal rainfall years and restricted to only deep-rooted crops in high rainfall years.

Conservation tillage practice normally stores more plant available moisture than the conventional inversion tillage practices when other factors are same. The high soil moisture content under conservation tillage is due to both improved soil structure and decrease in the evaporation loss due to crop residue mulch cover. Increase in the available water content under conservation tillage, particularly in the surface horizon, increases the consumptive use of water by crops and hence improves the water use efficiency.

(iv) Mulching

Mulching is known to influence water use efficiency of crops by affecting the hydrothermal regime of soil, which may enhance root and shoot growth, besides helping in reducing the evaporation (E) component of the ET. Under moisture stress conditions, when moisture can be carried over for a short time or can be conserved for a subsequent crop, mulching can be beneficial in realizing better crop yield.

Comparative effects of using single 30 mm irrigation and paddy-straw mulch @ 5 t ha^{-1} on field surface on WUE of sweet potato during rabi season were studied at Balipatna in Khurda district. Water use efficiency as well as productivity of the crop was the highest under straw-mulch treatment. While early application of the irrigation water produced moderate benefits, late application of irrigation had no significant effect on tuber yield and WUE of the crop (Table 16). Use of mulch thus can enhance water productivity several folds during dry season when no irrigation water is available.

(v) Improved Planting Geometry

A study on the effect of planting geometry on yield and water use efficiency of sugarcane at Rahuri, Maharashtra revealed that paired row or four row planting were superior to normal planting in drip irrigated crop (Table 17).

Table 17. Effect of planting pattern on yield and water-use efficiency of sugarcane at Rahuri, Maharashtra

Planting pattern	Cane yield (t ha^{-1})	Water applied (cm)	WUE (kg m^{-3})
Paired row planting (0.75 m)	158.8	91.4	17.37
Four row planting (0.90 m)	161.4	106.4	15.16
Normal planting (1.00 m)	136.8	193.0	7.08

(*Source:* Yadav *et al.,* 2000)

Water use efficiency in different planting methods of cotton was evaluated at three locations in cotton zone of Punjab, Pakistan (Ali and Ehsanullah, 2007). Six planting methods, viz. flat planting and no earthing-up (P1), flat planting and earthing-up after 1st irrigation (P2), flat planting and alternate row earthing up after 1st irrigation (P3), flat planting in 112.5/37.5 cm apart paired rows and earthing up after 1st irrigation (P4), ridge planting (P5) and bed planting (P6). Cotton obtained maximum benefit from available water at all three locations in P3 (flat planting with alternate row earthing-up) resulting in maximum water use efficiency (6.79 kg ha^{-1}mm^{-1}) with higher seed cotton yield (3,432 kg ha^{-1}).

(vi) Fertilization

There is strong interaction between fertilizer rates and irrigation levels for crop yield and water

Table 16. Tuber yield, WUE and water productivity of sweet potato as influenced by irrigation and mulching treatment. Balipatna, Khurda district. *Rabi* season 2002-03

Irrigation and mulching treatment	Tuber yield (t ha^{-1})	Total ET (mm)	WUE (kg m^{-3})	Water productivity (Rs m^{-3})
No irrigation, no mulch	10.22	366.8	2.79	5.39
One irrigation of 30 mm at 30 DAP, no mulch	14.22	378.8	3.75	9.99
One irrigation of 30 mm at 60 DAP, no mulch	12.40	382.6	3.24	7.42
No irrigation, straw mulch @ 5 t ha^{-1}	19.74	362.2	5.45	16.12

(*Source:* Singh *et al.,* 2008)

Table 18. Water use efficiency of groundnut (kg m^{-3}) as influenced by levels of irrigation and nutrient application. Rabi season 2004. Balipatna

Irrigation levels	Nutrient levels				
	No nutrient	40 kg N ha^{-1}	60 kg P_2O_5 ha^{-1}	40 kg N + 60 kg P_2O_5 ha^{-1}	Mean
No irrigation	0.262	0.414	0.445	0.695	0.454
One irrigation of 5 cm	0.381	0.512	0.550	0.740	0.546
Mean	0.322	0.463	0.498	0.718	

CD (P=0.05) Irrigation: 0.016, nutrient: 0.021, Irrigation x nutrient: 0.014
(*Source:* Singh *et al.,* 2008)

use efficiency. Application of nutrients facilitates root growth, which can extract soil moisture from deeper layers. Furthermore, application of fertilizers facilitates early development of canopy that covers the soil and intercepts more solar radiation and thereby reduces the evaporation component of the evapo-transpiration.

Effects of nutrient-water interaction on WUE of groundnut crop were studied in *rabi* season. Mean water use efficiency in irrigated plots was significantly higher than that of unirrigated plots. Both N and P significantly increased WUE over that of no-nutrient control. Application of N and P together was more beneficial than the application of either of the two or no nutrients. Interaction between irrigation and nutrients had positive effect of WUE (Table 18). In another field trial conducted in Khurda district, water use efficiency in summer sesame significantly increased with use of recommended dose of fertilizers (Singh *et al.* 2008).

Conclusions

Increased water scarcity conditions in this century will result in reduced availability of irrigated land available for food production than in the past. The main challenge confronting both rainfed and irrigated agriculture is to improve productivity or use efficiency of water and sustainable water use for agriculture. This can be achieved through (i) an increase in crop water productivity (an increased marketable crop yield per unit of water taken up by crop), (ii) a decrease in water outflows from the crop root zone other than that required by plants, (iii) an increase in soil water storage within the crop root zone through better soil and water management practices at farm and catchment scales, and (iv) reallocating water from low to high priority uses. Adoption of novel irrigation technologies for crop production and multi-uses of water with introduction of fishery, dairy and other enterprises in the farming can further enhance productivity and use efficiency of water in agriculture. Besides technological advancement, favorable public policy to create conducive socio-economic environment is required for enhancing water productivity in the agricultural sector of our country.

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