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Research Bulletin 43

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Ravender Singh, D. K. Kundu, K. Kannan, A. K. Thakur, R. K. Mohanty and Ashwani Kumar (2008) Technologies for Improving Farm-level Water Productivity in Canal Commands. Research Bulletin No. 43, Water Technology Centre for Eastern Region (Indian Council of Agricultural Research), Chandrasekharpur, Bhubaneswar 751023, India, 56p

Published by
Director
Water Technology Centre for Eastern Region
(Indian Council of Agricultural Research)
Bhubaneswar 751023, India
www.wtcer.ernet.in

Printed at
Capital Business Services & Consultancy
B-51, Saheed Nagar, Bhubaneswar 751007
Phone : 0674-2545484

Preface

Agriculture sector in India has been and is likely to remain the major user of water but 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 increasing its productivity. No doubt that water holds the key for enhancing and sustaining agricultural production. But the current water productivity and efficiency of water-use is so low, especially in irrigation, that most, if not all, of future water needs could be met by increased efficiency/ productivity alone, without development of additional water resources. Increasing the use efficiency and productivity of water in agriculture will play a vital role in easing competition for scarce resources, prevention of environmental degradation and provision of food security. In this publication we suggested some simple water management technologies for improving water productivity in canal commands of eastern India.

We sincerely hope information presented in this bulletin will be useful to the policy makers, scientists, scholars, developmental officials/agencies, farmers and others who are interested in enhancing use efficiency and productivity of available water in canal commands of eastern region of India.

The authors extend their sincere gratitude to the Director General, Deputy Director General (Natural Resource Management) and Assistant Director General (IWM), ICAR, Krishi Bhawan, New Delhi for their support, valuable suggestions and encouragement in carrying out this research work. Our sincere thanks are also due to all the colleagues and staff members of WTCER, Bhubaneswar for their help at times of need.

AUTHORS

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1. Introduction

With a rapidly growing population, pressure on land and limited fresh water resources is increasing. On 2.3 per cent of the world's land, India supports more than 17 per cent of world's population with only 4 per cent of the world's fresh water resources. Fresh water is a scarce resource and getting scarcer every passing day (Tuong and Bouman, 2003). Per capita water availability in our country is decreasing day-by-day. It was more than 5300 m^3 in 1951, but decreased to 1905 m^3 in 1999 and is likely to be less than 1500 m^3 by 2025. Per capita availability of water less than 1700 m^3 is considered as a stress level (Falkenmark et al., 1989). Agriculture sector in India has been and is likely to remain the major user of water but the share of water allocated to irrigation is likely to decrease by 10 to 15 per cent in the next two decades. India tops the world in irrigated area (with more than 59 million hectare of net irrigated area) but the average yield of irrigated areas at slightly more than 2.5 t/ha is pathetically low. Despite annual expansion in the created potential and capital investment in irrigation sector, the area irrigated by the major, medium and minor irrigation systems has been either stagnating or declining from mid-80s or mid-90s due to improper distribution of infrastructure. Official estimates reckon the loss of about 3 to 4 mha command area due to waterlogging and salinity (Selvarajan, 2001a). One of the ways of alleviating water scarcity is by increasing its productivity. No doubt that water holds the key for enhancing and sustaining agricultural production. But the current efficiency of water-use is so low, especially in irrigation, that most, if not all, of future water needs could be met by increased efficiency alone, without development of additional water supplies. Increasing the use efficiency of water in agriculture will play a vital role in easing competition for scarce resources, prevention of environmental degradation and provision of food security.

Productivity of irrigation water is defined broadly as the yield or value of crop output per unit of water used. Definition of water productivity varies in the literature 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, 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, then improvement in water productivity can arise basically from the improvement in yields (Molden and Sakthivadivel, 1999; Molden et al., 2001;

Droogers and Bastiaanssen, 2002; Kijne et al., 2003; Singh et al., 2006). Improvement in the use of water in crop production in the last few decades have accrued basically from the rise in crop yields and very little from improvement in water-use-efficiency.

Area situated between latitudes of 17^0 N and 29^0 N and longitudes of 80^0 E and 97^0 E constitutes the eastern India. Agricultural development is much below its potential in this region (Selvarajan, 2001b). The known potential from green revolution is yet to be fully realized in the eastern states where productivity of irrigation water can be raised significantly both on account of high precipitation which supplements irrigation water and the controlled nature of irrigation from ground water sources which are abundant in this region. The lack of dependability and reliability of irrigation water is one of the major constraints in realizing the production potential. In eastern states, majority of the canal command farmers do not get adequate and timely supply of irrigation. Tail-end farmers always get less water and some time they do not get any water during dry season. Baseline survey conducted in the selected projects in Orissa revealed that 30 to 60 % of the canal command farmers can not get adequate and timely water supplies. Use efficiency of applied irrigation water in canal command areas is very low often 30 per cent or less (Pande and Reddy, 1988). For achieving the stability in agricultural production under canal command area more attention to the on-farm management is required (Ghosh *et al.*, 2002, 2005).

2. Development of technologies for improving water productivity

The eastern region receives high rainfall during *kharif* season and sizeable area of this region comes under Canal Irrigation Command. Root zone soils of most agricultural farms in this region remain saturated or over-saturated through *kharif* as well as *rabi* season, and farmers can hardly grow any other crop than rice there. The productivity of rice in this region is very low (average 2 t ha^{-1}). Since rice farming is not remunerative, many farmers in this region do not like to grow two rice crops. Instead, they prefer to keep their land fallow during *rabi* season. Modification in field topography through construction of alternate raised and sunken beds improves the physical environment, particularly aeration status of the soil and creates proper condition for growth of crops other than rice (Siddiq and Kundu, 1993; Tomar *et al.*, 1996; Singh *et al.*, 2003a; Singh *et al.*, 2003b; Singh *et al.*, 2003c; Kannan *et al.*, 2003a; Kannan *et al.*, 2003b and Singh *et al.*, 2004). Field to field irrigation and low input use in rice cultivation are common in the canal command areas of eastern India. It often results in wastage of inputs applied, breaches in the bunds, unequal distribution and wastage of water, spread of pest and diseases and ultimately low yield. In dry season, farmers of this region can increase their yield by adopting proper time and method of sowing. Sowing time and methods hold the key of higher crop productivity during rabi and summers seasons. One to two-week's delay in sowing resulted in significant decrease in crop yield of test crops. Use of organic mulch helps in reducing evaporation by moderating temperature and conserving moisture in the soil. Application of rice straw mulch and growing of drought-tolerant crops like sweet potato or low-duty crops like horse gram, black gram, green gram and sesame, etc. may produce good yield in water deficit condition during dry season. Application of paddy straw mulch has been found to conserve soil moisture and maintain favourable thermal as well as moisture regime (Acharya and Sharma, 1994, Singh *et al.*, 2004 and 2007) mainly by reducing evaporation loss from soil. Paddy straw mulch is easily available, cheap during the month of November and December (after the harvest of wet season rice) and is an eco-friendly source of organic mulch. Proper time of irrigation and application of fertilizer also play crucial role in increasing crop yield and result in enhancing water productivity. We conducted a series of field studies towards development and standardization of technologies for improving farm-level water productivity in canal commands. Results of those studies are presented under following sections.

2.1. Land Modification

Experiments were carried out in the farmers' fields from 2002 to 2004 at village Barillo of Balipatna block in Khurda district, Orissa. The experimental sites were located in the command area of Nimapara Branch Canal under Puri Main Canal Irrigation System of Mahanadi Delta Irrigation Project. Average annual rainfall in this area was 1480 mm with nearly 80 per cent of it received during monsoon period spreading over 100 rainy days. Soils of the experimental plots were deep, poorly drained, fine, mixed loamy, hyperthermic, Aeric Tropaquepts of alluvial origin. The entire field was converted into alternate sunken and raised beds (50: 50) each of 30 m length and 5 m width. The top 30 cm soil was dug to make sunken beds and the dugout soil was used to prepare adjacent raised beds in the fields. The raised beds were thus 60-cm higher than the adjacent sunken beds (Fig. 1).

Seven cropping systems studied were: C1- conventional system (*rabi* rice followed by *kharif* rice with no land modification); C2- alternate raised and sunken bed system

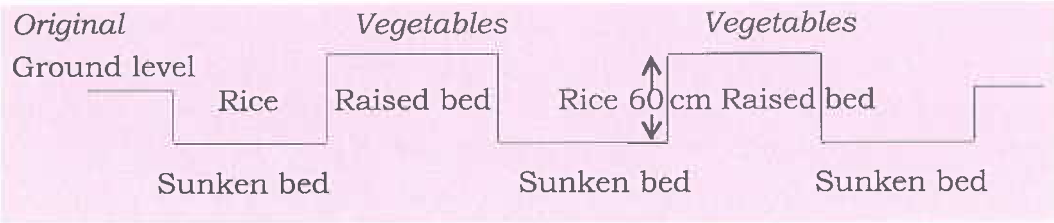

Fig.1 Schematic diagram of alternate sunken and raised bed system

(rice grown in sunken bed and cabbage – brinjal grown in raised bed); C3- alternate raised and sunken bed system (rice grown in sunken bed and pointed gourd grown in raised bed); C4- alternate raised and sunken bed system (rice grown in sunken bed and pointed gourd + bitter gourd grown in raised bed); C5- alternate raised and sunken bed system (rice grown in sunken bed and pointed gourd + papaya grown in raised bed); C6- alternate raised and sunken bed system (rice – rice+ fish grown in sunken bed and pointed gourd grown in raised bed); C7- alternate raised and sunken bed system (rice – fish seed grown in sunken bed and snake gourd + pointed gourd grown in raised bed, though snake gourd grown in sides of raised bed but they spread over open space of sunken bed). *Rabi* rice (*Oryza sativa* L.) variety "Lalat" was transplanted in the 2nd week of January and harvested in the last week of April. During *kharif* season rice variety "Durga" was transplanted in the 3rd week of July and harvested in the 3rd week of November. Cabbage (*Brassica oleracea*) variety "Capitata" was transplanted in the 1st week of January and harvested in the 2nd week of April. Pointed gourd (*Trichosanthes dioica*) variety "Swarna Rekha" and papaya (*Carica papaya)* variety "Pusa Nanha" were transplanted in the 1st week of February and harvested up to 2nd week of November. Brinjal (*Solanum melongena*) variety "Long green" was transplanted in the 2nd week of April and harvesting was completed in

Crop diversification by land modification the 2^{nd} week of October. Bitter gourd (*Momordica charantia*) variety "CO1" was sown in the 3^{rd} week of April and harvesting was completed by 1^{st} week of October. Snake gourd (*Trichosanthes cucumerina*) variety "APAU Swetha" was sown in the 3^{rd} week of April and harvesting was completed upto 1^{st} week of October. In order to ensure optimum soil moisture conditions, a pre-sowing irrigation (7 cm) was applied in raised beds, which was done manually in view of the plot size. No irrigation was required after the establishment of the crops since a lot of moisture was available 20 to 30 cm below the surface layer of these beds and in the adjacent sunken beds, which moved both in lateral and upward direction to meet crop water requirements. In two sunken beds, one with rice and another without rice crop, fish fry (< 1.2 g) of IMCs were stocked during last week of July and harvested during 3^{rd} week of November. Size of each of the raised and sunken beds were 5 m x 30 m and for fish plots in sunken bed 4 m area at one side deepened further up to 2 m depth leaving an area of 40 m^3 reserve for fish. Fish had open access to move all-round the field of 150 m^2 and finally come to the deeper portion (40 m^3).

Production potential in terms of rice-equivalent yield (REY) of different crops in the cropping system was calculated as:

$$REY = \frac{\text{Economic yield of a crop (kg) x price / kg of the same crop}}{\text{Price/ kg of rice}}$$

Water expense (mm/ha) was calculated by adding amount of water used for irrigation and effective rainfall during the crop-growing period. Effective rainfall (ER) is that portion of rainfall, which contributed towards the water requirement of growing crop in the field. The rainfall is only effective when it is stored and used by the growing crops. For raised and sunken bed system, where most of the rainwater stored in sunken beds for growing rice crop, the effective rainfall was determined by the drainage model of International Rice Research Institute (IRRI, 1997) as follows:

$$ER_j = \left[\frac{1 - DR_j}{RF_j + IR_j}\right] \times RF_j$$

Where RF_j is the rainfall during the period, cm; IR_j the irrigation applied during the period, cm; DR_j the drainage from the sunken bed, cm; ER_j the effective rainfall during the period, cm. Drainage was considered when standing water depth exceeded the maximum allowable water depth in the sunken bed.

The water expense efficiency (WEE) was calculated as follows:

$$WEE = \frac{\text{Total rice-equivalent yieldof a cropping system (kg/ha)}}{\text{Total water expenses for that cropping system (cm)}}$$

Gross water productivity (GWP) and net water productivity (NWP) was calculated as follows:

$$GWP = \frac{\text{Gross return from a cropping system (Rs)}}{\text{Total water expenses for that cropping system } (m^3)}$$

$$NWP = \frac{\text{Net return from a cropping system (Rs)}}{\text{Total water expenses for that cropping system } (m^3)}$$

Land use efficiency was calculated from total duration of crops (in individual cropping system) divided by 365 and production efficiency from total economic yield (total rice-equivalent yield, kg/ha/year and net return, Rs/ha/year) in a cropping system divided by total of crops in a system. Economic and byproduct yields, cost of cultivation and net returns were recorded separately for the component crops. Net returns (Rs/ha/year) were calculated for each cropping system every year. Benefit - cost ratio was calculated from gross return in a cropping system (Rs/ha/year) divided by total cost of cultivation of that cropping system (Rs/ha/year).

For economic evaluation of the system, two dynamic economic indices, net present value (NPV) and internal rate of return (IRR), were used to compare each cropping system in raised and sunken beds for 3 year period, i.e. 2002, 2003 and 2004. A discount rate of 10% was used for NPV calculation. The selling price of rice was Rs 4/kg and the selling price of vegetable crops varied several time during sale of vegetable. Therefore, an average price of a season was used for calculation purpose. Selling price of brinjal, pointed gourd, papaya, cabbage, bitter gourd and snake gourd was Rs 10, 10, 4, 4, 12 and 7 per kg, respectively. The selling price of fish seed was Rs 40 per kg. Seasonal fluctuations were considered in calculating the labour cost. During transplanting season, the labour rate was Rs 50/day and during lean period it was Rs 40/day (for 6 working hours). During the analysis period (for raised and sunken bed system), profits and cost of raised and sunken bed construction were constant. Therefore, the present value of gross profit (GP) and total cost (TC) were calculated as follows:

$$GP = \sum_{t=1}^{n} \frac{P_t}{(1+i)^t}$$

$$TC = K_1 + K_2 + \sum_{t=1}^{n} \frac{C_t}{(1+I)^t}$$

Where P_t is the gross profit at the t^{th} year, C_t the cost of the t^{th} year, I is the discount rate, K_1 the investment on construction of raised and sunken bed system (Rs 36000/ ha required for construction), K_2 the investment on maintenance of the system in proper form (Rs 4000/ ha/ year required for maintenance from the second year onward) from the next year of construction; and n is the calculation period. Therefore, the net present value of profit is

$$NPV = GP - TC$$

If net present value (NPV) is 0, the system is accepted, if not the system is unfeasible. For calculating capital recovery period, when the net revenue compensates for the total investment, was considered three years in the present study.

We fixed three years.

The internal rate of return was calculated as follows:

$$\sum_{t=1}^{n} \frac{P_t}{(1+IRR)^t} - [K_1 + K_2 + \sum_{t=1}^{n} \frac{Ct}{(1+IRR)^t}] = 0$$

Where IRR is the internal rate of return. The IRR is acceptable if it is greater than minimum expected interest rate, i.e. more than 10% (Yuan *et al.*, 2003).

Rice equivalent yield of all the cropping systems in raised and sunken beds was higher than in original lowlands. The highest rice equivalent yield (38.80 t/ha) was recorded in C7 (rice- fish grown in sunken bed and snake gourd + pointed gourd grown in raised bed) cropping system followed by C2 (rice-rice grown in sunken bed and cabbage-brinjal grown in raised bed) and C6 (rice-rice+ fish grown in sunken bed and pointed gourd grown in raised bed) cropping systems. Rice equivalent yields of C2 and C6 cropping systems were statistically comparable. There was no significant difference between rice equivalent yields of C1 (conventional field) and C3 (rice-rice grown in sunken bed and pointed gourd grown in raised bed). This may be due to growing of only one crop of pointed gourd in raised bed (Table 1). Land utilization efficiency of all the cropping systems of modified land were significantly higher than that of original lowland (Table 1). The highest land utilization efficiency (77.26%) was recorded in C5 (rice-rice grown in sunken bed and pointed gourd + papaya grown in raised bed) cropping system, as this cropping system occupied field for the longer period (282 days) and land utilization efficiency was the lowest under original land condition.

Quantity of water used by C1, C2, C4, C5, C6 and C7 cropping systems were comparable. C3 cropping system used significantly lower amount of water in comparison to all other cropping systems. Water expense efficiency of all the cropping systems in raised and sunken bed system was significantly higher than water expense efficiency of original land. Among different cropping systems on raised and sunken beds, highest water expense efficiency was observed in C7 followed by C2 and C6 cropping systems. The lowest water-use efficiency in modified land use system was observed for C3 cropping system. Water-use efficiency of C2, C4 and C6 cropping systems were statistically comparable (Table 1). The economic index of net water productivity of all the cropping systems tested in raised and sunken bed was significantly higher than the net water productivity of rice-rice grown in original land. Among different cropping systems on raised and sunken beds, the highest net water productivity was achieved under C7 followed by C6 and C2 cropping systems. The lowest net water productivity was computed for C1 followed by C3 cropping system. C1 and C3 cropping systems were statistically comparable as far as the economic index of net water productivity was concerned. Thus, growing of rice-fish in sunken bed and snake gourd + pointed gourd on raised bed or growing of rice-rice+ fish in sunken bed and cabbage-brinjal on raised bed were the most productive way of using available water in lowlands.

All the cropping systems except C3 in modified raised and sunken bed, recorded significantly higher net return than the original fields. Net return of C3 cropping system was statistically comparable with conventional system of rice cropping. The highest net return (Rs 117152/ha/year) was recorded for C7 cropping system

Table 1: Rice equivalent yield, land utilization ratio, water productivity parameters and benefit-cost ratio of different cropping systems in original and modified lowland at Barillo (pooled data of 3 years)

Treatments	Efficiency parameters		Water productivity parameter			Economic parameters	
	Rice equivalent yield (t/ha)	Land utilization efficiency [% annum]	Water expense (mm/ha)	Water expense efficiency (kg/ha-cm)	Net water productivity (Rs/m³)	Net returns (Rs/ha/year)	B: C ratio
Original land							
C1-Rice alone (Ra) Rice alone (Kh)	7.68	59.73	22.86	33.59	0.51	11636	1.61
Modified land							
C2- Rice (Ra) Rice (Kh) Cabbage -Brinjal	26.70	69.59	2118	126.06	2.18	46047	1.76
C3- Rice (Ra) Rice (Kh) Pointed gourd	11.46	72.60	2076	55.20	0.92	19143	1.72
C4- Rice (Ra) Rice (Kh) Pointed gourd +Bitter gourd	22.16	72.60	2110	105.02	1.71	35988	1.68
C5- Rice (Ra) Rice (Kh) Pointed gourd + Papaya	15.46	77.26	2171	71.21	1.27	27465	1.80
C6- Rice (Ra) Rice (Kh) – Fish Pointed gourd	26.04	72.60	2273	114.56	3.23	74010	3.45
C7- Rice (Ra) Fish + Snake gourd Pointed gourd	38.80	72.60	2223	174.54	5.33	117152	4.08
$CD_{(0.05)}$	3.85	3.76	200	21.20	0.71	13426	0.36

Ra = rabi, Kh = kharif

followed by C6 and C2. Similarly, highest benefit cost ratio was recorded for C7 cropping system followed by C6 cropping system. The benefit cost ratio for other cropping systems (C1, C2, C3, C4 and C5) were statistically comparable (Table 1).

The net present values (NPV) for 6 cropping systems (C2, C3, C4, C5, C6, C7) tested in raised and sunken beds were computed, they are presented in Fig. 2. The NPV was highest for C7 followed by C6 cropping system. The lowest NPV was computed for C3 cropping system. The capital recovery period for C2, C6 and C7 system was 1 year, for C4 and C5 was > 1 year, and for C3 was > 2 year. The internal rates of return (IRR) for C6 and C7 cropping systems were higher than that of other cropping systems (Fig. 3). The lowest IRR (21.73%) was computed for C3 cropping system, which was also higher than the present interest rates of banks.

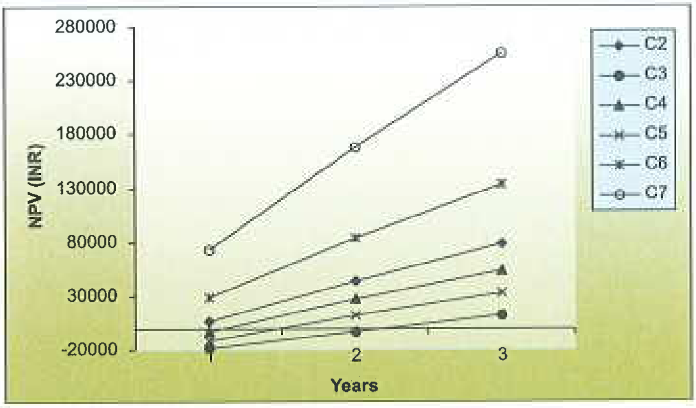

Fig. 2 Comparison of NPV for six cropping systems in raised and sunken beds at Barillo (interest rate 10%)

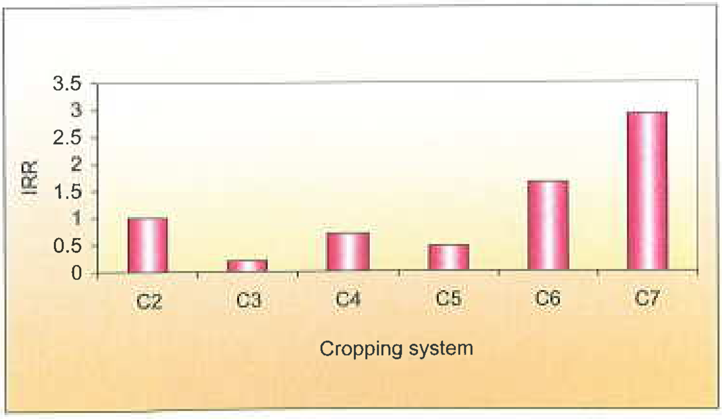

Fig. 3 Comparison of internal rate of retun at Barilo under different cropping systems of raised and sunken beds

Raised and sunken bed technique for improving water productivity in lowlands proved very effective than conventional system of rice cultivation. For modification of land into raised and sunken bed system, an investment of Rs 36000/ ha is required, which may be recovered within 1 to 2 years in most cases. Several small and marginal farmers at Balipatna block of Khurda district in Orissa have adopted this system. This system not only increased farm production and income but also generated more rural employment, livelihood options, provided food and nutritional security for poor rural masses. It enhanced productivity of fresh water resources used in agriculture.

2.2. *Controlled irrigation*

The effect of controlled irrigation and fertilizer management on yield and water-use of *kharif* rice was studied in coastal Orissa. The study was carried out under three land situations, viz. head; middle and tail reaches of the Gringo minor which comes under Nimapara branch canal of Puri main canal system of Mahanadi Delta Irrigation Project. The treatments tested were: controlled irrigation (field channel) with recommended dose of fertilizer, controlled irrigation with farmer's dose of fertilizer, field-to-field irrigation with recommended dose of fertilizer and field-to-field irrigation with farmer's dose of fertilizer. The treatments were randomized with three replications. Rice variety Gayatri (CR 1018) was transplanted at the spacing of 15 cm X 15 cm during the second week of July 2001. The recommended dose of fertilizer was 80:40:40 kg per ha of N: P_20_5:K_20. Farmer's dose of fertilizer was 40:20:20 kg per ha of N: P_20_5:K_20. The field experiment was laid in split –split plot design with land situation in main plot, irrigation treatments in sub-plot and fertilizer in sub-sub-plots. Irrigation was given to all the plots/treatments as and when required to maintain 5 cm standing water throughout the crop growing period.

Water expense (mm/ha) was calculated by adding amount of water used for irrigation and effective rainfall during the crop-growing period. The rainfall was considered effective only when it is stored in soil and used by the growing crops. For rice crop, the effective rainfall was determined by the drainage model of International Rice Research Institute (IRRI, 1997).

Pooled data on rice grain yield indicated that controlled irrigation (irrigation through field channels) with recommended (80:40:40 kg per ha of N: P_20_5:K_20) and farmer's (40:20:20 kg per ha of N: P_20_5:K_20) dose of fertilizer gave significantly

Field channels used for controlling irrigations

higher grain yield than uncontrolled irrigation (field-to-field irrigation) with same doses of fertilizer. The highest grain yield of 6.11 t/ha was observed in tail reach with controlled irrigation and recommended dose of fertilizer followed by that in tail reach with controlled irrigation and farmers' dose of fertilizer (5.49 t/ha); and the lowest grain yield of 3.77 t/ha was observed in head reach with uncontrolled irrigation and farmers' dose of fertilizer. In general, highest grain yield was observed in tail end situation followed by middle reach situation and the lowest in head reach situation (Table 2). Among different irrigation treatments, significantly higher grain yield was observed in controlled irrigation, irrigation through field channels in all the land situations with recommended dose of fertilizer. Controlled irrigation with farmers' dose of fertilizer showed significantly higher yields than in uncontrolled irrigation even with recommended dose of fertilizer. This indicated that method of irrigation is more important than dose of fertilizer. Similar trend was noticed for straw yield. Highest water-use efficiency of 152.75 kg/ ha cm was found in tail reach with controlled irrigation and recommended dose of fertilizers and the lowest of 53.86 kg/ ha cm was found in head reach with uncontrolled irrigation and farmers dose of fertilizers. Similar to grain and straw yield, higher water-use efficiency was observed under controlled irrigation treatments with recommended dose of fertilizer and lower under uncontrolled irrigation treatments with farmer's dose of fertilizer. Controlled supply of irrigation water enhanced use efficiency of water by 114 per cent in head, 99 percent in middle and 105 per cent in tail reach situation.

Net irrigation water productivity also followed the similar trend. Significantly highest net irrigation water productivity of 3.72 Rs/m^3 was observed in tail reach with controlled irrigation and recommended dose of fertilizer followed by the tail

Table 2: Effect of irrigation method and fertilizer treatments on grain yield, straw yield, use efficiency of irrigation water and net water productivity of applied irrigation water of kharif rice at Balipatna, Khurda district, Orissa, 2002

Irrigation treatments	Grain yield (t/ha)			Straw yield (t/ha)			Irrigation water use efficiency (kg/ha-cm)			Net irrigation water productivity (Rs/m³)		
	Fertilizer treatments			Fertilizer treatments			Fertilizer treatments			Fertilizer treatments		
	RDF	FDF	Mean	RDF	FDF	Mean	RDF	FDF	Mean	RDF	FDF	Mean
Head reach (S1)												
Controlled irrigation	4.89	4.44	4.67	5.87	5.46	5.67	122.25	111.00	116.63	2.50	2.40	2.45
Field to field irrigation	3.86	3.77	3.82	5.01	4.90	4.96	55.14	53.86	54.50	0.99	0.84	0.92
Mean	4.38	4.11		5.44	5.18		88.70	77.43		1.67	1.70	
Middle reach (S2)												
Controlled irrigation	5.07	4.45	4.76	6.14	5.97	6.06	126.75	111.25	119.00	2.68	2.41	2.55
Field to field irrigation	4.24	4.11	4.18	5.51	5.34	5.43	60.57	58.71	59.64	1.06	1.18	1.12
Mean	4.66	4.28		5.83	5.66		93.66	84.98		1.87	1.80	
Tail reach (S3)												
Controlled irrigation	6.11	5.49	5.80	7.94	7.10	7.52	152.75	137.25	145.00	3.72	3.45	3.59
Field to field irrigation	5.06	4.83	4.95	6.58	6.30	6.44	72.29	69.00	70.65	1.53	1.59	1.56
Mean	5.59	5.16		7.26	6.70		112.52	103.13		2.63	2.52	
CD (0.05) For I		0.042			0.082			1.565			0.37	
CD (0.05) For F		0.047			0.040			0.292			0.17	

RDF: Recommended dose of fertilizer, FDF: Farmer's dose of fertilizer reach with controlled irrigation and farmer dose of fertilizers (3.45 Rs/m^3); and the lowest net irrigation water productivity of 0.84 Rs/m^3 was observed in head reach with uncontrolled irrigation and farmer dose of fertilizers. In general, highest net irrigation water productivity was observed in tail end situation followed by middle reach situation and the lowest in head reach situation. Among different irrigation treatments, highest net irrigation water productivity was observed in I_1 treatments in all the land situations with recommended dose of fertilizer. Controlled irrigation with farmer's dose of fertilizer showed significantly higher net irrigation water productivity than in uncontrolled irrigation even with recommended dose of fertilizer. Higher grain yield, straw yield, yield attributes and water-use efficiency were observed in tail reach situation followed by middle reach and the lowest in head reach situation. This may be due to relatively higher water-use in head reach than the middle and tail reach situations. Washing out of applied nutrients in uncontrolled irrigation treatments and high water-table in head reach situation also create unfavourable condition (Singh *et al.*, 2002a). For getting more benefit per unit of water and each gram of fertilizer, irrigation water must be applied in required quantity and in controlled manner (Singh *et al.*, 2002a).

2.3. *Optimum time and method of sowing*

A study was conducted during dry season of 2002 and 2003 at Balipatna block of Khurda district under Nimapara Branch Canal Command with the main objective to find out the effect of time and method of sowing seeds on water-use efficiency of *rabi* horsegram under shallow water-table conditions. The experiment was conducted in a randomized block design with four replications. The treatments included two dates and methods of sowing, viz. broadcasting horsegram 'Mukta' seed @30kg/ha on 15th October, after minimum tillage (one ploughing with country plough), broadcasting seed @30kg/ha on 1st November, after minimum tillage, and broadcasting seed @ 40 kg/ha on 15th October, as relay crop, 10 days before rice harvest (*pyra* cropping). Evapotranspiration of the crops was computed using general water balance equation.

Rainfall during the study period was nil, run off was also nil and no irrigation was given to the crops. Change in soil-water content ($\Delta\theta$) and depletion of water in the soil profile was monitored weekly for each crop. Soil-water matric potential and unsaturated hydraulic conductivity data as a function of the volumetric soil-water content were determined in the laboratory in undisturbed soil cores by using methods described by Black (1965). These data were utilized to calculate moisture flow at the boundary of the root zone. Data on open pan evaporation was collected daily by using a screened USWB class A pan at the meteorological observatory of Central Institute for Freshwater Aquaculture, Bhubaneswar, 8-10 km away from the experimental site. Rainfall data were collected from Balipatna Block Development Office, 1-2 km away from the study site. Capillary contribution, i.e. upward flux of water at the root zone boundary at 90- cm depth was estimated by using numerical solution given by Hanks *et al.* (1969) and evapotranspiration (ET, mm d^{-1}) by roots was estimated following the procedure outlined by Stibbe (1975). During the month of October, groundwater table was at 55 cm and it started receding after November and was at 121 cm depth in January and 140 cm depth in February.

At the time of crop sowing, moisture content under 15th October sowing crop, after minimum tillage, and in *pyra* cropping of the same day was higher than that under 1st November sowing crop, after minimum tillage. At the time of harvesting, moisture content was highest under *pyra* cropping followed by 1st November sowing crop and the least moisture content was observed under 15th October sowing crop. This indicated that profile water was used more under 15th October sowing crop and least under *pyra* cropping treatment. The estimates of profile water use were made by calculating changes in soil water contents on a weekly basis at 30 cm intervals and pooled data for 0-90 cm soil layer for all the three treatments. Profile water contribution from the 0-30 cm soil depth amounted to 46 – 49 % of the total profile water use. The use of profile water decreased as the soil depth increased and it was 13-19 % of the total from the 60-90 cm soil layer.

Use of residual soil moisture to grow pulses

Similar type of observations were also reported by Minhas *et al.* (1990). In the present study, total depletion of water from the soil profile was found to be 196.7, 164.2 and 171.8 mm under 15th October sowing crop, 1st November sowing crop and *pyra* cropping, respectively. Water flux under all the treatments was found upward. Under 15th October sowing crop treatment, total upward flux during the entire growth period (starting from 15 October, 2002 to 11 February, 2003) was 17.6 mm with the maximum rate of 0.26 mm/day observed in October and the minimum rate of 0.01 mm/day in February. Total 18.7 mm of upward flux was observed under T2 treatment (during 1 November, 2002 to 11 February, 2003) with maximum rate of 0.54 mm/day in December and the minimum rate of 0.01 mm/day in February. Whereas under *pyra* cropping treatment (during 15 October 2002 to 11 February 2003), total upward flux was 16.8 mm with the maximum rate of 0.25 mm/day observed in October and the minimum rate of 0.01 mm/day in February. Observed differences in upward flux may be due to different cropping time, method of cropping and particularly fluctuation in water-table depth and atmospheric demand. In case of 15th October sowing crop, 8.2 per cent of total water-use was contributed by the upward flux. The contribution of upward flux under 1st November sowing crop and *pyra* cropping were 10.3 and 8.9 per cent, respectively. Since crop under 15th October sowing crop and *pyra* cropping was sown earlier than under 1st November sowing crop, when higher profile water content was available, it could draw relatively less water from the water-table. Though the water-table was closer to the root zone under 15th October sowing crop and *pyra* cropping treatments as compared with the other treatments. Total ET was found to be 214.3 mm under 15th October sowing crop, 182.8 mm under 1st November sowing crop and 188.6 mm under *pyra* cropping (Table 3).

The highest grain yield of 1290 kg/ha was obtained with 15th October sowing crop treatment, while grain yield of 1060 and 750 kg/ha was obtained with 1st November sowing crop and *pyra* cropping treatments, respectively. Similarly highest straw yield was found with 15th October sowing crop treatment and the lowest with *pyra* cropping treatment. Mean evapotranspiration was the highest under 15th October sowing crop followed by *pyra* cropping and 1st November sowing crop treatments. Highest water-use efficiency (60.2 kg/ha cm) and net water productivity (4.85 Rs/m^3) was observed under 15th October sowing treatment and the lowest (39.8 kg/ha cm and 2.93 Rs/ m^3) under *pyra* treatment, respectively (Table 3). It may be due to variation in their sowing times and sowing methods. The crop with minimum tillage was sown earlier under 15th October sowing crop than under 1st November sowing crop treatment. Under *pyra*

Table 3: Growth, yield, water use and N uptake of horse gram as influenced by treatments

Treatments	Grain yield (t/ha)	Straw yield (t/ha)	Total ET (mm)	Water use efficiency (kg/ha-cm)	Net used water productivity (Rs/m^3)
Early sowing with minimum tillage	1.29	3.16	214.3	60.2	4.85
Late sowing with minimum tillage	1.06	2.50	182.8	58.0	4.30
Pyra cropping, no tillage	0.75	2.11	188.6	39.8	2.93
CD (P=0.05)	0.13	0.27	21.4	6.1	0.37

croppingtreatment, the crop was sown early but without tillage. An advancement of sowing time by 15 days and minimum tillage, (just one ploughing) increased the evapotranspiration, water-use efficiency and yield of unirrigated crops. For better utilization of residual soil moisture and efficient tapping of water from shallow water-table in dry season, early sowing of dry season crops was thus necessary. One ploughing or minimum tillage treatment given to field before sowing of seeds further increased the water-use efficiency, net water productivity and crop yield of dry season crops. In terms of yield, water-use efficiency and net water productivity, 15th October sowing crop treatment (early sowing with minimum tillage) was the best and it was followed by 1st November sowing crop treatment (late sowing with minimum tillage). Hence, during dry season when water is not available, particularly in tail reach, early sowing of crops with minimum tillage can increase the water productivity.

2.4. *Use of mulch and optimum planting geometry*

To evaluate the effect of paddy straw mulch and irrigation on water-use and water-use efficiency (WUE) of sweet potato (cv. Shankar), a study was conducted during winter (*rabi*) season of 2001-02 and 2002-03 at Balipatna block of Khurda district. Experiment was laid-out in randomized block design with three replications. Treatments consist of one irrigation of 30 mm was applied 30 days after planting in one treatment, as early irrigation and 60 days after planting in another treatment, as late irrigation. The rest two treatments did not receive any irrigation. However in one treatment mulching with paddy straw @ 5 t/ha was applied 30 days after planting. The crop was planted on 28th November in 2001 and 20th November in 2002. Initially up to 60 days after planting (DAP), vines were turned around periodically to avoid unwanted root development from vine nodes. The crop was harvested after 120 days. N, P_2O_5 and K_2O was applied @ 75: 50: 75 kg ha^{-1} with N and K_2O applied in two equal split doses. Half of the N and K_2O with full quantity of P_2O_5 were applied during land preparation along with farmyard manure at 5 t ha^{-1}. Remaining half of the N and K_2O were applied 30 days after planting. Periodical monitoring of soil moisture in field under different treatments started 30 days after planting with establishment of the crop and continued till harvest. The soil moisture content was determined by gravimetric method and was expressed on volume basis (Miller and Donahue, 1992). Evapotranspiration, ET, of the crops were computed by general water balance equation. Flux of water at different depth in the root zone and at the root zone boundary at 90 cm depth was estimated by numerical solution of Hanks *et al.* (1969) and soil-water extraction by roots (ET in mm d^{-1}) was estimated following the procedure outlined by Stibbe (1975).

The no-mulch and no-irrigation plot showed the lowest levels of soil moisture at all the stages of the crop growth, due to fastest depletion of soil moisture in contrast with mulch plot. Soil moisture under the two irrigation plots was found intermediate between no-mulch and no-irrigation plot and mulch plot. Total water depletion from 0-90 cm soil profile was the highest (291 and 298 mm) under early irrigation treatment followed by the late irrigation (285 and 288 mm) and no-irrigation and no-mulch (272 and 274 mm) treatments. The lowest soil water depletion was observed under mulch treatment plot (241 and 248 mm) in both the years. Although evapotranspiration is equated with water depletion from soil profile in many investigations, discrepancy between water depletion and evapotranspiration can be enormous at times (Aydin, 1994).

The flux at 90 cm was always upward. During 120 days of crop growing period, maximum upward fluxes of 64 and 62 mm were recorded under late irrigation treatment and the lowest upward fluxes of 47 and 45 mm were observed under no-mulch and no-irrigation treatment at 30 cm soil depth. This indicated that most of the water got lost through evaporation processes and less water was used by the crop under late irrigation treatment. In 90 cm soil profile, maximum upward fluxes of 118.1 and 114 mm were observed under mulch plot and the lowest fluxes of 83.5 and 94 mm were observed under late irrigation treatment in both the years. This indicated that mulching increased the upward flux under shallow water-table condition. Similar observations were also recorded by Das *et al.*, 1990, Singh *et al.*, 2002b and Singh *et al.*, 2003c. Upward flux at higher rate was maintained under the mulch treatment. Rate of profile water-use and evapotranspiration after 100 days of crop planting decreased very fast under no-mulch and no-irrigation treatment, early irrigation and late irrigation treatments, while it increased steadily up to crop harvest under mulching treatment. These results indicated that mulching increased the profile water-use, upward flux under shallow water-table condition and evapotranspiration rate for a longer period. The upward flux contributed significantly to evapotranspiration under all the treatments. Out of cumulative evapotranspiration of 366.2, 375.5, 381.0 and 359.1 mm, the upward flux contributed 21.7, 22.5, 23.7 and 32.9 % during 2001-02. Similarly, out of cumulative evaporation of 366.6, 378.4, 382.6, and 362.4 mm, the upward flux contributed 26.1, 21.3, 24.9 and 31.5% under no-mulch and no-irrigation plot, early irrigation, late irrigation and mulching treatments, respectively, during 2002-03 (Table 4). Similar observations were also made by Minhas *et al.* (1990) for mungbean and by Aydin (1994) for cotton crop.

Use of rice-straw mulch in sweet potato

No significant difference in tuber yields was noticed between no-mulch and no-irrigation and late irrigation treatments in both the years (Table 4). The yields

Table 4: Tuber yield and water-use efficiency (WUE) of sweet potato grown with different treatments. Balipatna, Khurda district, Orissa

Treatments	Rabi season 2001-02				Rabi season 2002-03			
	Tuber yield (t ha^{-1})	Total ET (mm)	WUE (kg ha^{-} mm^{-1})	Water productivity (Rs/m^3)	Tuber yield (t ha^{-1})*	Total ET (mm)	WUE (kg ha^{-} mm^{-1})	Water productivity (Rs/m^3)
No irrigation and no mulch	8.15	366.2	22.26	2.56	10.22	366.8	27.86	5.39
One irrigation of 30 mm at 30 DAP*	12.91	375.5	34.38	8.24	14.22	378.8	37.54	9.99
One irrigation of 30 mm at 60 DAP*	7.84	381.0	20.58	1.47	12.40	382.6	32.41	7.42
No irrigation and straw mulch @ 5 tha^{-1}	16.35	359.1	45.53	11.54	19.74	362.2	54.50	16.12
$CD_{(0.05)}$	2.45				2.38			

*DAP = Days after planting

measured under mulch treatment and early irrigation treatments were significantly more than that under no-mulch and no-irrigation plot. The straw mulch treatment, gave the highest tuber yield of 16.35 and 19.74 t ha^{-1}, respectively during 2001-02 and 2002-03. Data revealed that crop under treatment no-mulch and no-irrigation plot and late irrigation treatments was subjected to water stress conditions at critical stage of tuber development. Water-use efficiency was found to be the highest (45.53 and 54.50 kg $ha\text{-}mm^{-1}$) under mulch treatment and the lowest (20.58 and 222.26 kg $ha\text{-}mm^{-1}$) under the late irrigation treatment and no-mulch and no-irrigation treatment, respectively (Table 4). Similar observations were also recorded by Ossom *et al.* (2001). Highest net water productivity (11.54 Rs/m^3 and 16.12 Rs/m^3) was also observed under treatment mulch treatment and the lowest (1.47 and 2.56 Rs/m^3) under the late irrigation treatment and no-mulch and no-irrigation treatment, respectively. Use of mulch can increase the water productivity many folds during dry season when no irrigation water is available.

Another field experiment was also conducted on mulching during the main season (January-December) of 2001 at the experimental farm of Sakthi Sugars Ltd., Dhenkanal, Orissa to tackle the problem of formative stage moisture stress in sugarcane crop. The soil was loamy with pH 7.3 having 182, 23.3 and 220 kg/ha of available N, P and K. The field capacity, permanent wilting point and bulk density of soil are 18.5%, 11% and 1.23 g/cc respectively for the depth up to 60 cm. The treatments comprised of three plant spacing viz., normal row spacing 90 cm, paired row spacing of 60/90 and wide row spacing 150 cm as main plots treatments and four water management practices during the formative phase viz., irrigation once in 5 days, equal to 25% depletion of available soil moisture, designated as full irrigation with mulch; full irrigation with out mulch; irrigation once in 8 days, equal to 50 % depletion of available soil moisture, designated as deficit irrigation with mulch; deficit irrigation without mulch as sup plot treatments. The experiment was laid out in split-plot design and replicated thrice. Sugarcane seedling (variety: CO 86032) was planted in the month of December with the spacing of 30 cm between the plants. Common irrigation was given up to the February. Thereafter, irrigation was given according to the treatments up to June I week. The plot size was 9.0 m x 6.0 m. Sugarcane trash was applied @ 7.5 t/ha for the mulch treatments. Recommended dose of fertilizer were applied as pocket application near the root zone.

Growth characters of sugarcane were significantly influenced by spacing and water management practices (Table 5). Among the planting methods, the highest plant height was recorded under wide row spacing followed by paired row planting. But the difference between normal row spacing and paired row spacing was not significant. The highest average plant girth was also recorded under wide row spacing. This might be due the availability of more space and other resources per tiller in wide row spacing. But the leaf area index, the measure of spread of leaves over unit area was lesser in the case of wide row spacing. This might be due to the lesser tiller number in wide row spacing under water deficit condition. Number of internodes were not influenced by the treatments significantly.

Table 5: Effect of planting and water management practices on growth characters

Treatments	Plant height, m	Leaf area index	Plant girth, cm	Number of inter nodes
Spacing				
Normal row spacing (90 cm)	3.35	3.82	8.75	34.33
Paired row spacing (60/90 cm)	3.47	3.78	8.56	33.62
Wide row spacing (150cm)	3.66	3.65	9.18	33.90
CD (P=0.05)	0.27	0.07	0.22	NS
Water management				
Irrigation once in 5 days + mulch	3.76	3.88	9.72	35.86
Irrigation once in 5 days	3.61	3.82	9.18	34.63
Irrigation once in 8 days + mulch	3.47	3.72	8.51	33.57
Irrigation once in 8 days	3.14	3.58	7.77	31.73
CD (P=0.05)	0.12	0.11	0.42	1.03

Among water management practices, full irrigation with mulch significantly increased all the growth characters viz., plant height, leaf area index, cane girth and number of internodes followed by normal irrigation with out mulch. Crop growth characters recorded under deficit irrigation with mulch was comparable with normal irrigation with out mulch. The least crop growth characters were recorded under deficit irrigation without mulch. The rate of decrease in plant growth character in deficit irrigation was the highest under wide row spacing compared to other two planting methods. The yield attributes such as number of tillers/ha and average cane weight were significantly influenced by planting method and water management (Table 6) and Fig. 4. The average highest tiller number of 1, 40090 per hectare was recorded under paired row planting which was followed by normal row spacing. The least was recorded under wide row spacing. Among water management practices, the highest average tiller number per hectare was recorded under the treatment full irrigation with mulch followed by normal irrigation without mulch and deficit irrigation with mulch. The least was recorded under deficit irrigation under mulch.

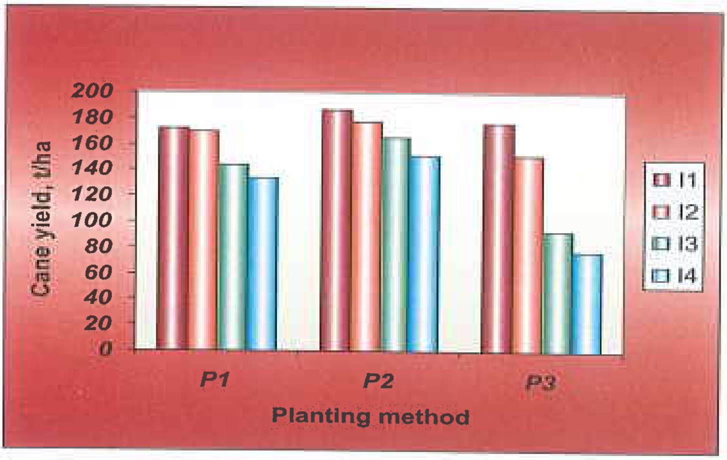

Fig. 4 Interaction effect of planting and water management on cane yield

Interaction effect of planting and water management shows that though average tiller number was the least under wide row spacing, the tiller number under this planting method was comparable with other two planting methods under full irrigation condition. The rate of decrease in tiller number from the highest moisture availability to lower moisture availability (from I_1 to I_4) was the highest under wide row spacing compared to other planting methods. This might be due to the fact that under moisture stress condition, crop could not use the available space and nutrients to produce more tillers in wider row spacing. Wider row spacing significantly increased average single cane weight over other planting methods. The average single cane weight was recorded (1.52 kg) under this planting method. There was no significant difference in average single cane weight between normal row and paired row planting. Among water management practices, the highest average single cane weight (1.58 kg) was recorded under full irrigation with mulch followed by full irrigation with out mulch and deficit irrigation with mulch The least average cane weight was recorded under deficit irrigation with out mulch. This might be due to higher evaporation under no mulch combined with less water availability under deficit irrigation.

Table 6: Interaction effect of planting method and water management practices on yield attributes

Treatments	Number of tillers('000)/ha				Average cane weight, kg			
	NRS	PRS	WRS	Average	NRS	PRS	WRS	Average
Irrigation once in 5 days + mulch	146.66	160.66	113.66	140.32	1.49	1.45	1.82	1.58
Irrigation once in 5 days	130.68	148.50	95.99	124.90	1.44	1.40	1.52	1.45
Irrigation once in 8 days + mulch	118.51	131.55	80.66	110.24	1.36	1.33	1.40	1.36
Irrigation once in 8 days	115.55	119.66	75.68	103.63	1.31	1.28	1.33	1.30
Average	127.85	140.09	91.49		1.40	1.36	1.52	

NRS= Normal row spacing (90 cm), PRS= Paired row spacing (60/90 cm), WRS= Wide row spacing (150cm)

Interaction effect of planting methods and water management shows that the highest average single cane yield (1.82 kg) was recorded in wider row spacing under full irrigation with mulch. This might be due to the lesser competition between tillers under the availability of wider space. Though the least single cane weight was recorded under paired row spacing in deficit irrigation, it did not affect the final cane yield as the cane numbers compensated the average cane weight.

The highest average cane yield (170.5 t/ha) was recorded in paired row planting followed by normal row spacing (155 t/ha). The least average cane yield (124 t/ha) over all the water management was recorded under wide row spacing. Among water management practices, the highest cane yield of 178 t/ha was recorded under full irrigation followed by I_2 and I_3. The least cane yield was observed under deficit irrigation without mulch. Interaction effect of planting methods and water management shows that the highest cane yield (187 t/ha) was observed in paired row planting under full irrigation with mulch followed by wide row spacing and normal row spacing. Even though the second highest cane yield was recorded under wide row spacing, the least cane yield was observed in this planting method under deficit irrigation. This might be due to lesser tiller production under deficit irrigation compared to other planting method. The rate of decrease in cane yield under deficit irrigation in wide row planting was more (47%) compared to other planting methods.

There was no significant difference in brix reading among planting methods. Among water management practices, the highest brix reading was observed under deficit irrigation condition. This might be due the highest total solids present in the juice under moisture stress condition. But the commercial cane sugar per cent was more under full irrigation. No significant difference in cane sugar content was observed among planting methods. Among planting methods, the highest water expense efficiency was achieved with paired row planting (90 kg cane/ ha mm water use) followed by normal row spacing and the least was observed in wide row spacing. This might be due to drastic reduction in yield in wide row planting under deficit condition. The highest water expense efficiency was achieved under full irrigation with trash mulch. The difference between full irrigation with out mulch and deficit irrigation with mulch was not significant (Table 7).

Table 7: Effect of treatments on cane quality and water use

Treatments	Brix (%)	CCS (%)	Irrigation water use, mm	Water Expense Efficiency (WEE) kg/ha-mm
Planting				
Normal row spacing (90 cm)	19.48	12.05	1880	82.44
Paired row spacing (60/90 cm)	19.46	11.01	1880	90.69
Wide row spacing (150cm)	19.50	12.00	1880	66.30
CD (P=0.05)	NS	NS		5.03
Water Management				
Irrigation once in 5 days + mulch	19.28	12.27	2090	85.30
Irrigation once in 5 days	19.37	11.56	2090	79.74
Irrigation once in 8 days + mulch	19.27	11.37	1670	80.23
Irrigation once in 8 days	20.03	11.19	1670	72.65
CD (P=0.05)	0.82	0.52	-	6.22

2.5. *Cultivation of low-duty crops*

To study the possibility of growing low duty crops like horse gram, green gram and sesamum, a field experiment was conducted under shallow water-table condition in tail reach of Nimapara branch canal command area of Puri main canal system (Balipatna block of Khurda district in Orissa). Horse gram (*Dolichos biflorus*, var. Mukta) was sown on 15th December 2000, green gram (*Vigna radiata* L.Wilczek, var. K-851) on 10th January 2001 and sesamum (*Sesamum indicum* L., var. Vinayak) was sown on 31st January 2001 in separate plots measuring 20 m x 10 m. The seed rate was 40 kg ha^{-1} for horse gram, 20 kg ha^{-1} for green gram and 5 kg ha^{-1} for sesamum. Evapotranspiration, ET, of the crops were computed by general water balance equation. Capillary contribution, i.e. upward flux of water at the root zone boundary (90 cm depth) was estimated by numerical solution given by Hanks *et al.* (1969) and soil-water extraction by roots (ET in mm d^{-1}) was estimated following the procedure outlined by Stibbe (1975).

Total depletion of water from soil profile was found to be 118.72 mm under horse gram (97 days crop), 138.53 mm under green gram (105 days crop) and 138.18 mm under sesamum (91 days crop). Total upward flux of soil water at 90-cm depth through the crop growing season was about 85 mm under horse gram and green gram, while 68.74 mm under sesamum. The upward flux of water contributed 41.7% of total water use in horse gram, 38.2% in green gram and 33.2% in sesamum. Highest grain yield of 6.25 q ha^{-1} was obtained in horse gram (Table 8), while both green gram and sesamum yielded 4.6 q ha^{-1} grain per ha. Highest water-use efficiency 3.07 kg/ha-mm was found in horse gram followed by sesamum and lowest in green gram. But the highest net water productivity of 4.05 Rs/m^3 was observed in sesamum followed by horsegram and lowest in green gram. In terms of yield and WUE, horse gram was the best option but in case of water productivity sesamum was the best option. Vast areas of land adjacent to the canal command are commonly kept fallow by the farmers in dry season due to lack of irrigation water. Result of the present study reveal that there is a lot of scope for growing unirrigated crops during dry season.

Cultivation of low-duty crop horsegram

Table 8: Yield, evapotranspiration and water-use efficiency of three crops grown at Balipatna block in Khurda district, Orissa. Dry season 1999 - 2000

Name of the crop	Grain yield (t ha^{-1})	Straw yield (t ha^{-1})	Grain/ Straw ratio	Total ET (mm)	WUE (kg ha^{-1} mm^{-1})	Net water productivity (Rs/m^3)
Horse gram	0.62	1.66	0.38	203.75	3.07	3.03
Green gram	0.41	1.33	0.31	224.06	1.81	2.97
Sesamum	0.41	1.25	0.33	206.92	1.96	4.05

2.6. *Optimum time of irrigation*

To workout the optimum time for irrigating crops during dry season a study was carried out at Balipatna block of Khurda district, Orissa under Nimapara Branch Canal Command during summer season of 2004 with sesame crop. Six treatments viz. early sowing (15-1-2004) without irrigation and fertilizer; late sowing (30-1-2004) without irrigation and fertilizer; late sowing with one irrigation and no fertilizer; late sowing with one irrigation and fertilizer (recommended dose); late sowing with two irrigations and no fertilizer; and late sowing with two irrigations and fertilizer (recommended dose) were imposed in a randomized block design with four replications. Irrigation of 50 mm each was given applied 25-1-2004 and 15-2-2004 to the irrigated treatments and recommended fertilizer dose (30 kg N, 15 kg P_2O_5 and 15 kg K_2O/ha) was applied according to the treatments. The sesame variety V*inayak* was sown on 15-1-2004 and 30-1-2004, respectively, for early and late sown conditions. Crop was harvested on 30-4-2004 and 15-05-2004, respectively. Evapotranspiration of the crop was computed by general water balance equation. Capillary contribution, i.e upward flux of water at the root zone boundary (90-cm depth) was estimated by numerical solution given by Hanks *et al*. (1969) and evapotranspiration (ET, mm d^{-1}) by roots was estimated following the procedure outlined by Stibbe (1975).

All the yield attributes and yield of sesame were significantly influenced by the treatments. The least yield attributes were recorded under late sowing without irrigation and fertilizer treatment. Increased yield attributes due to increased moisture availability was also reported by Duraisamy *et al*. (1999). The highest seed yield was recorded under late sowing with two irrigations and fertilizer treatment followed by

Cultivation of sesamum

early sowing without irrigation and fertilizer treatment. This might be due to higher yield attributes recorded under these treatments. Under late sown condition, there was 51.24%, 91.74%, 84.25% and 129.74% increase in seed yield due to one irrigation, one irrigation with fertilizer, two irrigation and two irrigation with fertilizer, respectively compared to no-irrigation, no-fertilizer (Table 9). Kannan and Wahab (1995), Subrahmaniyan and Arulmozhi (1999) and Balasubramaniyan (1996) also reported increase in sesame seed yield with application of fertilizer.

Total depletion of water from the soil profile was found to be 195.7, 173.5, 216.1, 221.6, 260.1 and 271.0 mm under early sowing without irrigation and fertilizer; late sowing without irrigation and fertilizer; late sowing with one irrigation and no fertilizer; late sowing with one irrigation and fertilizer; late sowing with two irrigations and no fertilizer; and late sowing with two irrigations and fertilizer treatments, respectively. Soil water flux under all the treatments was found to be in upward direction but very low. Total water-use or evapotranspiration was 207.7, 185.0, 227.6, 233.2, 271.8 and 282.7 mm, respectively under early sowing without irrigation and fertilizer; late sowing without irrigation and fertilizer; late sowing with one irrigation and no fertilizer; late sowing with one irrigation and fertilizer; late sowing with two irrigations and no fertilizer; and late sowing with two irrigations and fertilizer treatments (Table 8). The highest water-use efficiency and net water productivity was observed under early sowing without irrigation and fertilizer treatment (Table 9). Better seed yield, effective utilization of soil moisture and reduction in the irrigation requirement may be the reason for higher water efficiency and net water productivity under the early sowing without irrigation and fertilizer treatment. It was followed by late sowing with one irrigation and fertilizer and late sowing with two irrigations and fertilizer treatments, respectively. Even though the treatments late sowing with one irrigation and no fertilizer and late sowing with two irrigations and no fertilizer received one and two irrigations, respectively, however, water-use efficiency and net water productivity under these treatments were low due to poor seed yield resulted from nutrient deficiency. The least water-use efficiency and net water productivity were recorded in the late sowing without irrigation and fertilizer treatment. This

Table 9: Effect of irrigation and fertilizer on growth, yield and water-use of summer sesame at Balipatna block in Khurda district, Orissa

Treatments	Plant height (cm)	No. of branches	Dry mater production (g/m²)	Yield, (t/ha)	Water use (mm)	Water use efficiency (kg/ha mm)	Net Water use productivity (Rs/m³)
Early sowing without irrigation and fertilizer	93.87	4.11	302.67	0.59	207.7	2.82	6.91
Late sowing without irrigation and fertilizer	68.20	3.11	180.00	0.31	185.0	1.61	3.14
Late sowing with one irrigation and no fertilizer	84.60	4.11	230.67	0.46	227.6	1.99	4.41
Late sowing with one irrigation and recommended dose of fertilizer	87.93	4.55	284.00	0.59	233.2	2.51	5.55
Late sowing with two irrigation and no fertilizer	85.87	4.44	265.33	0.56	271.8	2.06	4.63
Late sowing with two irrigation and recommended dose of fertilizer	98.07	4.89	364.90	0.70	282.7	2.48	5.64
CD (P=0.05)	6.20	0.43	17.07	0.07	13.02	0.19	0.47

might be due to the poor seed yield as the crop was not able to utilize the soil moisture. It is concluded from the result that early sowing of sesame with residual soil moisture produced better seed yield with higher water productivity compared to late sowing without irrigation and was comparable with irrigated condition under late sowing. Under late sown condition, two irrigations with recommended fertilizer produced more yield with higher water productivity. One irrigation with fertilizer produced more yield with higher water productivity than two irrigations without fertilizer.

2.7. *Intermittent flood irrigation in rice*

Large reduction in water use in rice production can be achieved by reducing seepage and percolation loss during crop growth and idle periods. Therefore most of the field-level water-saving strategies concentrate on the reduction of seepage and percolation loss. These losses can be reduced by: (i) increasing the resistance to water flow in the soil, and (ii) 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. Thorough puddling results in compacted plough soil which impedes vertical flow of water from ricefields. Thorough puddling decreased percolation rate of water from 9 to 4 mm per day in sandy loam soil under Deras Irrigation Command, Khurda district, Orissa (Kundu *et al.*, 2007). Placement of physical barriers like bitumen layers and plastic sheets underneath rice soils also drastically cut percolation loss, but they are expensive and will not be economically attractive to farmers. 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 & drying (intermittent flooding) treatments will have little water loss through seepage and percolation.

Alternate wetting & drying practices resulted in both water savings and rice yield losses of 0-70% compared with the continuous flooding treatment, depending on the irrigation intervals and existing soil conditions. It has been found that rice yield losses are generally smaller than the reduction in water inputs and therefore water productivities are increased. There is a trade-off between land productivity and water productivity. Field experiments on grain yields of rice var. Lalat under four different water management treatments (continuous submergence, irrigation supplied 1, 2 and 4 days after subsidence of standing water) were conducted at Balipatna block in Khurda district, Orissa during rabi season 2005-06. Saving of irrigation water under intermittent submergence treatments was worked out. Use efficiency of water under different irrigation management treatments was computed. Mean use efficiency of applied irrigation water increased from 28.7 kg grain/cm water under continuous submergence to 47.5 kg grain/cm water under the treatment where irrigation applied 4 days after subsidence of standing floodwater (Table 10). It was found that irrigation applied 4 days after subsidence of standing floodwater in fields saved 42 to 45 % water without significant reduction in rice grain yields.

Table 10: 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)	Efficiency of applied water (kg grain/cm water)	WUE (kg grain/cm water)
Continuous submergence	148	——	4.25	28.7	24.8
Irrigation 1 day after subsidence of standing water	122	17.6	4.20	34.4	29.0
Irrigation 2 days after subsidence of standing water	97	34.5	4.05	41.7	33.8
Irrigation 4 days after subsidence of standing water	81	45.3	3.85	47.5	37.0

Rainfall received during the season: 23 cm: *CD (0.05) for comparing mean grain yields: 0.43

2.8. *Wet-seeding in rice*

Transplanting of rice is widely practiced in irrigated environment. Main advantage of transplanting is the ease in crop care like weeding and fertilizer application. However transplanting is labour-intensive and requires too much water. In transplanting system, about 5,000 liters of water is required to produce 1 kg of rice (Puttana, 1983). Because of decreasing water resources (falling ground water, silting of reservoirs), decreasing quality (pollution) and increasing industrial and urban users, the water availability for irrigation is increasingly getting scarce day by day. On the other hand, demand for rice is still on rise because of continuous population growth. So, there is a need to "*grow more rice with less water*" (Guerra *et al.*, 1998). Expansion of irrigated areas, increasing transplanting cost, unavailability of labour, and declining profitability of rice production have forced many farmers to shift from transplanting to wet seeding (De Datta, 1986). In wet seeded rice (WSR), farmers generally broadcast pre-germinated seeds directly on the puddled and levelled field, which are free from standing water (Moody and Cornova, 1985).

Weed competition is greater in WSR (Wet seeded rice) than in TPR (Transplanted rice) because the weed and rice grow at the same time (Moody, 1983). The similarities in age and morphological features of young grassy weeds and rice seedlings make hand weeding in broadcasted wet seeded rice more difficult than that in TPR (De Datta and Bernasor, 1973). However, such operational problem of weeding in WSR can be minimized through 'line' or 'spot' seeding of pre-germinated seeds in puddled field.

Field experiments were conducted at the Deras Farm, Mendhasal in Khurda district, Orissa, India (20° 30′ N, 87° 48′ 10″E) during 2001-2004. Rice crop (*Oryza sativa* L.) was established by following six different methods, viz. transplanting of 3 week old seedlings (TPR), dry seeding by broadcast (DSB), wet-seeding by broadcast (WSB), wet-seeding by broadcast followed by beushening (WSBB), wet-seeding in line (WSL), and wet-seeding in spot (WSS). The seed rates were 35 kg ha^{-1} for transplanting and 80 kg ha^{-1} for all the direct seeding methods.

Tillering efficiency was found better in WSS as compared to other methods of crop establishment (Table 11). Thus among all the treatments involving sowing of pre-germinated seeds (wet seeding), the spot seeding was found superior. Wet-seeding in spot facilitated better tillering and grain yield compared to the WSL or WSB methods. Tiller number under WSS increased by about 9% and finally reflecting in approx. 12% yield increase compared to TPR.

Panicle number and length was found significantly higher in transplanted and WSS treatment compared to other methods (Table 11). The number of grains per application. However transplanting is labour-intensive and requires too much water. In transplanting system, about 5,000 liters of water is required to produce 1 kg of rice (Puttana, 1983). Because of decreasing water resources (falling ground water, silting of reservoirs), decreasing quality (pollution) and increasing industrial and urban users, the water availability for irrigation is increasingly getting scarce day by day. On the other hand, demand for rice is still on rise because of continuous population growth. So, there is a need to *"grow more rice with less water"* (Guerra *et al.*, 1998). Expansion of irrigated areas, increasing transplanting cost, unavailability of labour, and declining profitability of rice production have forced many farmers to shift from transplanting to wet seeding (De Datta, 1986). In wet seeded rice (WSR), farmers generally broadcast pre-germinated seeds directly on the puddled and levelled field, which are free from standing water (Moody and Cornova, 1985).

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Table 11: Yield components of rice under different crop establishment methods

Crop establishment methods	Tiller number m^{-2}	Panicle number m^{-2}	Panicle length (cm)	Grains number/ panicle	Filled grains/ panicle	Yield ($t\ ha^{-1}$)
TPR	378.0b	329.7b	23.57ab	109.2a	90.0b	3.26b
DSB	293.7d	205.8e	20.57c	87.0c	71.7d	2.28e
WSB	310.2d	261.3d	21.38bc	91.7bc	76.0cd	2.65d
WSBB	330.8c	266.0d	20.25c	91.8bc	77.2c	3.05c
WSL	345.3c	308.8c	22.25abc	94.2b	79.7c	3.22b
WSS	413.0a	392.8a	24.60a	108.8a	95.3a	3.64a

*Each value is mean of two year data. In a column, means having a common letter are not significantly different at 5% level by DMRT.

panicle and grain filling percent were also found higher in these two methods. In fact main factor affecting the rice yield, i.e. panicle number is directly proportional to tiller number, which is function of the number of seedlings per unit area.

Water requirements for different operations in rice cultivation under three crop establishment systems are presented in Table 12. Total water required for growing rice crop by transplanting, wet seeding and dry seeding methods were 1041.15, 941.53 and 915.03 ha-mm, respectively (Thakur *et al.*, 2004). Evapotranspiration values were 3.7-7.2 mm day^{-1} during the crop growth period from last week of January to first week of May. A seepage and percolation loss combined (SP) was 4 mm day^{-1} in transplanted and wet seeded plots. But in dry seeded plots, SP was as high as 6 mm day^{-1}. Higher SP under dry seeding was due to unpuddled field. Maximum water consuming system was transplanting and the least water was required in dry seeding system. Water saving in wet seeding was 10% compared to the traditional transplanting system. It was found that water saving in wet seeding compared to TPR was mainly in the land preparation. Water requirement for land preparation in wet seeding was less by about 30% compared to transplanting system, as it took just 7 days to complete all land preparation activities, like land soaking, ploughing and leveling while in transplanting system these operations took 21-25 days. The reason is that in transplanting, traditionally farmers start using water in the main field for land soaking at the same time or soon after they start to prepare nursery for the raising seedlings. They continue to use water in the main field until the seedlings are ready for the transplanting.

Table 12: Water requirements (ha-mm) under different methods of rice crop establishment on sandy clay-loam soil during 2002 and 2003 at Bhubaneswar, India

Items	Transplanting		Wet-seeding		Dry seeding	
	2002	2003	2002	2003	2002	2003
Nursery preparation	19.9	19.9	–	–	–	–
Crop demand for nursery (20 days)	13.8	14.86	–	–	–	–
Land soaking (Tillage)	150	150	150	150	20	20
Land preparation	140.0	148.6	40.0	49.0		
Crop demand						
Evapo-transpiration	405	430.25	396	428.05	396	428.05
Seepage & Percolation	270	320.0	310	360.0	468	498
TOTAL	**998.7**	**1083.6**	**896.0**	**987.05**	**884.0**	**946.05**
Mean	**1041.15**		**941.53**		**915.03**	
Relative (%)	**100**		**90.4**		**87.9**	

Thus, large amount of water is lost from the main field through evaporation, seepage and percolation, and surface runoff. Contrary to this, wet seeding required only 3-4 days of land soaking and incubation of seeds before seeding into main field. More demand of water in transplanting was also due to requirement of nursery preparation and more crop duration (7 days).

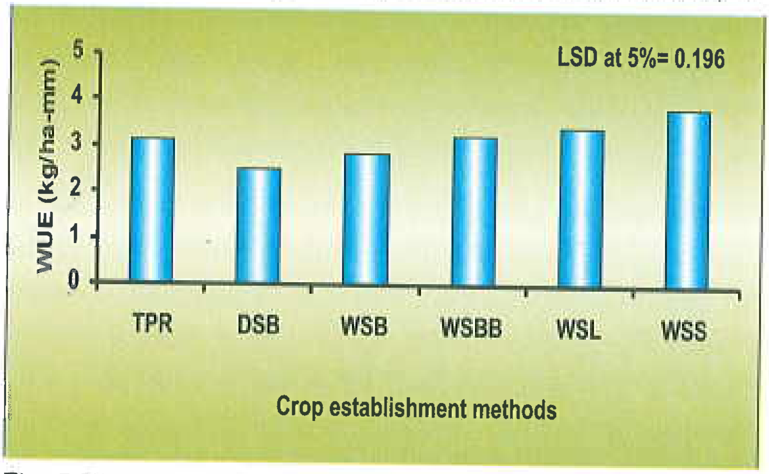

Fig. 5 Water use efficiency (kg/ha-mm) under different crop establishment methods during dry season (each value is mean of two-year data)

Bhuiyan *et al.* (1995) reported that the amount of water needed to complete land preparation and crop irrigation for TPR is 40% and 10% more as compared to WSR and total water consumed is 21% more for TPR compared with WSR. With continuous standing water, wet-seeded rice requires 19% less water during the crop growth period (Tabbal *et al.*, 2002).

Comparison of water use efficiency (WUE) for different methods of rice crop establishment showed lowest WUE for dry seeding and highest for wet seeding in spots (Fig. 5). Wet seeding in lines (WSL) and spots (WSS) showed 9.7 and 24.0% higher WUE, respectively, over the traditional TPR method.

2.9. *System of Rice Intensification (SRI)*

Currently, several emerging technologies intended to boost paddy yield per hectare require less water. Some of these technologies offer other economic and environmental benefits as well. The existing system of paddy production, particularly green revolution technology is input intensive and favours cash rich farmers. Increasing prices of agricultural inputs prevent poor farmers from completely adopting modern production technologies. Excessive use of agrochemicals (chemical fertilizers and pesticides/insecticides) damages soil biota. There are negative social and environmental externalities. At a time when rice farmers in many countries must begin finding ways to achieve their production goals with less use of water, because of growing water shortages and competing demands, an innovation in rice farming methods has become available known as the system of rice intensification (SRI). It can (a) increase yields and production so that economic and food-security goals are met at the same time that it can (b) reduce farmers' costs of production, enhancing profitability, and (c) decrease the amounts of irrigation water required (Stoop *et al.*, 2002; Uphoff, 2003)

SRI changes the management of rice plants, and of the soil, water and nutrients that support them, in simple but specific ways to create optimal growing environments for rice plants so that their genetic potentials are better expressed. The basic principles of SRI practice are preparing high-quality land, developing nutrient-rich and un-flooded nurseries, using young seedlings for early transplantation, transplanting the seedlings singly, ensuring wider spacing between seedlings, preferring compost or farmyard manure to synthetic fertilizers, managing water carefully so that the plants' root zones moisten, but are not continuously saturated, and weeding frequently (Satyanarayana *et al.*, 2007).

The System of Rice Intensification improves yields with less water, less seed, and less chemical inputs than most conventional methods of rice cultivation. This means that the returns on inputs are higher, making the method potentially more profitable than most of the traditional methods. Initially it does require significantly more labour – mainly for preparing land and weeding. Most SRI farmers have found that as they get to know the methods better and gain confidence in them, their pace of work speeds up, and SRI actually becomes labour-saving. SRI could contribute to job creation in rural areas. It is a different matter that SRI is becoming popular more for the obvious overall productivity gains in land, labour, water and capital. SRI improves the productivity of land, labour, water and capital used in rice cultivation. Implementation of SRI has helped to improve the yield of local varieties by between 6 and 8 tonnes per hectare. With improved management, hybrid varieties have yielded between 10 and 12 tonnes per hectare under SRI. Often a 20 to 40% increase in yield compared to that under conventional methods is observed in SRI (Satyanarayana *et al.*, 2007). However, the actual yield increases depend on how well farmers practice SRI.

SRI method of rice cultivation

During *rabi*, 2006 and 2007, an experiment was conducted at Deras Research Farm, Mendhasal, Khurda dist. with three levels of irrigation, viz (continuous flooding (CF), 3 days after disappearance of ponded water (DAD), and 5 DAD under SRI and compared with transplanted rice (TP). In SRI, fields were flooded after 7-10 days interval and kept for disappearance of ponded water for 3 or 5 days during vegetative stage. After panicle initiation, 2-4 cm of water was kept on the field up to 15 days before harvest. This method of alternate wetting and drying (AWD) was found labour saving compared to the conventional system where field was kept 4-5 cm depth water throughout the growth period. About

22-35% of saving in water was attained mainly due to reduction in seepage and percolation loss, reduced nursery demand and lesser need for land preparation. Grain yield, water requirements and water-use efficiency (WUE) under different treatments are presented in Table 13.

Table 13: Grain yield, water requirement and water-use efficiency under different treatment of SRI and TP (var: Surendra) during *rabi* at Deras Farm, Bhubaneswar

Treatments	Grain yield (t/ha)	Water requirement (ha-mm)	Water-use efficiency (kg/ha-mm)
TP-CF	4.19	1242.96	3.37
TP-3DAD	4.13	1074.03	3.85
TP-5DAD	3.76	920.73	4.08
SRI-CF	6.16	1132.05	5.44
SRI-3DAD	6.30	963.12	6.54
SRI-5DAD	6.27	809.82	7.74

*Each value is mean of rabi, 2006 and 2007. CF- Continuous flooding, DAD- Days after disappearance of ponded water

SRI had significantly higher grain yield in all the treatments compared to TP. In the transplanted rice, as water stress increases, the grain yield reduced. However, in SRI it was found that the there was no significant reduction in grain yield with water stress. The highest water use efficiency was found in SRI with 5 DAD (i.e. 7.74 kg/ha-mm) mainly due to high grain yield and less water requirement. Similar to grain yield, all the treatments in SRI had higher WUE than TP.

2.10. *Aerobic rice*

The cultivation of rice is increasingly threatened by irrigation water scarcity. In the eastern region of India, farmers show much interest in summer rice as the productivity is higher compared to wet season rice. But availability of irrigation water is limited during this season. Aerobic rice is a fundamentally different approach to reduce water requirement of rice. Rice is grown in nonflooded and nonsaturated soils under supplemental irrigation. Rice grain yield as high as 5.7

t/ha during dry season has been recorded under aerobic soil conditions in Philippines. Identification of suitable varieties, optimum irrigation regimes, and management practices hold the key for success of aerobic rice.

With the development of new varieties and the improvement of agro-technical methods and practices, rice yield obtained under aerobic conditions reach the level of production as under flood irrigation. A field experiment on aerobic rice was initiated at Deras Farm, Mendhasal in Khurda district, Orissa during summer season of 2007. Objectives of this study were to study the rice growth and yield under irrigated aerobic condition and workout irrigation schedule for aerobic rice. Under aerobic condition, several rice varieties including *Surendra* and *Lalat* were sown directly on the main field without puddling on 12th January 2007. All these rice varieties were also sown on the same day in nursery and transplanted later on 7th February 2007 for comparison. Irrigation treatment consisted of I_1- keeping soil moisture at 80-90% FC (Field Capacity) throughout the crop season; I_2- keeping soil moisture at 60-70% FC during vegetative and 80-90% FC during reproductive stage; and I_3-keeping soil moisture at 60-70% FC throughout the crop growing season. Butachlor @ 1.5 lit/ha was sprayed at 3 days after sowing of rice to control weeds. The crop was harvested in 2nd week of May 2007. Grain yields of these two rice varieties under aerobic conditions were 2.57-3.95 t/ha and they were 18.7-47.1% lower than under flooded conditions. Irrigation water input was 540-700 mm under aerobic and 1250 mm under flooded soil conditions. As water use decreased relatively more than yield, water productivity under aerobic cultivation increased by 22.4-45.0% over that under flooded conditions (Table 14).

However, growing irrigated rice under aerobic conditions still faces severe constraints:

- Higher inputs for weed control
- Increased susceptibility to diseases
- Imbalance of soil nutrients
- More know-how required in on-farm water management
- Increase of investment and maintenance costs
- Deep ingrained traditions and social customs based on flood irrigation management

Table 14: Grain yield and irrigation water productivity of two rice varieties at Deras Irrigation Command under flooded and aerobic soil conditions. Khurda district, Orissa. Dry season 2007

Rice Variety	Soil water regimes*			
	Flooded	Aerobic-I	Aerobic-II	Aerobic-III
Surendra				
Grain yield (t/ha)	4.86	3.95	3.62	2.57
Water applied (mm)	1250	700	660	540
Water productivity (kg/mm)	3.89	5.64	5.48	4.76
Lalat				
Grain yield (t/ha)	4.76	3.82	3.60	2.63
Water applied (mm)	1250	700	660	540
Water productivity (kg/mm)	3.81	5.46	5.45	4.87

*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.

2.11. *Nutrient-water interaction*

To study the nutrient–water interaction, an investigation was carried-out during *rabi* 2004 at Balipatna block, Khurda district of Orissa, which comes under Nimapara Branch Canal of Mahanadi delta. The experiment was laid out in a split-plot design with three replications. Treatments comprised of two irrigation levels (no irrigation and one irrigation of 5 cm depth scheduled 35 days after sowing) as main plot and four nutrient levels (no nutrient, application of only N @ 40 kg/ha, application of only P_2O_5 @ 60 kg/ha and application of both N and P_2O_5 @ 40 and 60 kg/ha) as sub-plots. N was supplied through urea and P_2O_5 supplied through single super phosphate. The crop groundnut (cv. AK-12-24) was sown on 1st January 2004 and harvested on 29th April 2004.

Capillary contribution, i.e. upward flux of water at the root zone boundary (90-cm depth) was estimated using numerical solution given by Hanks *et al.* (1969). Evapotranspiration (ET, mm d^{-1}) was estimated following the procedure outlined by Stibbe (1975). In the beginning of the study, water-table was 149 cm below ground level (bgl) and receded to 157 cm bgl at the end of January. During February, March and April water-table fluctuated between 157 and 90 cm bgl.

Nutrient-irrigation interaction in groundnut crop

Irrigation and occurrence of rainfall influenced total water content in unirrigated and irrigated plots of groundnut. With advancement of crop growth, stored profile moisture depleted continuously from irrigated and unirrigated plots except during rainfall and irrigation events. Different nutrition levels did not vary considerably up to 60 days after sowing in terms of profile moisture depletion in unirrigated plots. However, this consistency was observed only upto 40 days after sowing in irrigated plots. Total profile moisture depletion through unirrigated and irrigated plots was 260.7, 266.8, 272.5, 275.3 mm and 296.9, 302.2, 308.2, 310.8 mm, at no N and P, only 40 kg N/ha, only 60 kg P_2O_5/ha and 40 kg N/ha + 60 kg P_2O_5/ha treatments, respectively. Application of 40 kg N/ha + 60 kg P_2O_5/ha to *rabi* groundnut could deplete maximum profile moisture under both irrigated and unirrigated conditions. This may be due to sound canopy foliage and proliferated root system. Application of only P_2O_5 @ 60 kg/ha could deplete more water than the application of only N @ 40 kg/ha, showing relatively better response of *rabi* groundnut to the applied phosphorus.

Water flux in unirrigated treatments was upward throughout the growing season. However, in irrigated treatments it was downward between 35 and 42 days after sowing. This was mainly due to 5 cm irrigation applied to these treatments. Total upward soil-water flux throughout the crop-growing season under unirrigated and irrigated plots was about 45.1, 47.1, 53.6, 67.1 and 18.2, 20.4, 30.3, 40.6 mm in no-N and P, only 40 kg N/ha, only 60 kg P_2O_5/ha and 40 kg N/ha + 60 kg P_2O_5/ha levels, respectively. Maximum upward flux of 67.07 mm during the entire growth period was observed in the plots where 40 kg N/ha + 60 kg P_2O_5/ha were applied under unirrigated conditions and minimum upward flux of 18.20 mm was observed in the plots where no-nutrients were applied under irrigated conditions. Percent contribution of upward flux towards ET under unirrigated and irrigated conditions was 14.75, 15.00, 16.44, 19.59 and 5.78, 6.31, 8.95, 11.49 per cent in no-N&P, only 40 kg N/ha, only 60 kg P_2O_5/ha and 40 kg N/ha + 60 kg P_2O_5/ha, respectively. The crop evapo-transpiration increased steadily from germination stage onward in all the treatments, reaching its peak between 60–110 days in unirrigated treatments and between 40–110 days in irrigated treatments. Irrigation showed considerable influence on crop evapo-transpiration (Table 15). Higher rate of evapo-transpiration for longer duration was maintained in irrigated treatments than in unirrigated treatments. In both the irrigation levels evapo-transpiration values were high in the fertilized plots than in the unfertilized plots throughout the growing season. Nutrient levels also influenced crop ET throughout the growing period. Nutrients stimulate root and shoot biomass that utilize intercepting solar radiations efficiently resulting into enhanced evapo-transpiration (Anderson, 1992). Root proliferation also plays an important role in enhancing evapo-transpiration (Corbeels *et al.*, 1998).

Differential irrigation and nutrient levels influenced evapo-transpiration, water-use efficiency and net water productivity (based on pod yield), pod yield and haulm yield, significantly . Interactions between irrigation and nutrient levels for the above parameters were observed to be positive. Mean maximum evapo-transpiration (331.81 mm), water-use efficiency and net water productivity (5.46 kg/ha-mm and 6.17 Rs/m^3) were observed in irrigated plots, significantly higher over unirrigated plots. Among the nutrient levels, application of both N and P resulted in highest mean evapo-transpiration (346.74 mm) and could achieve mean maximum water-use efficiency and net water productivity (7.18 kg/ha-mm and 9.75 Rs/m^3), significantly superior to all other nutrient levels. Application of N along with P under irrigated conditions showed sound interactive effects and resulted in evapo-transpiration, water-use efficiency and net water productivity values of 351.14 mm, 7.40 kg/ha-mm and, 10.11 Rs/m^3, respectively. Zhang *et al.* (1998) also reported the similar results under fertilized conditions (Table 15).

Table 15: Evapo-transpiration, water-use efficiency, pod and haulm yield of groundnut as influenced by irrigation and nutrient levels

Irrigation levels	Nutrient levels				Mean
	No nutrient	N@40 kg/ha	P_2O_5@60 kg/ha	N@40kg/ha + P_2O_5@60kg/ha	
Evapo-transpiration (mm)					
No irrigation	305.83	313.90	326.12	342.34	322.05
One irrigation	315.04	322.57	338.48	351.14	331.81
Mean	310.44	318.24	332.30	346.74	
CD (P=0.05)	Irrigation = 3.70, Nutrient = 2.86 and Irrigation x Nutrient = 5.74				
Water-use efficiency (kg/ha-mm)					
No irrigation	2.62	4.14	4.45	6.95	4.54
One irrigation	3.81	5.12	5.50	7.40	5.46
Mean	3.22	4.63	4.98	7.18	
CD (P=0.05)	Irrigation = 0.16, Nutrient = 0.21 and Irrigation x Nutrient = 0.14				
Net water use productivity(Rs/m^3)					
No irrigation	0.56	3.73	4.33	9.38	4.50
One irrigation	2.77	5.49	6.30	10.11	6.17
Mean	1.67	4.61	5.32	9.75	
CD (P=0.05)	Irrigation = 0.19, Nutrient = 0.24 and Irrigation x Nutrient = 0.17				
Pod yield (kg/ha)					
No irrigation	800	1300	1450	2380	1483
One irrigation	1200	1650	1860	2600	1828
Mean	1000	1475	1655	2490	
CD (P=0.05)	Irrigation = 37, Nutrient = 21 and Irrigation x Nutrient = 120				
Haulm yield (kg/ha)					
No irrigation	1280	2023	2266	3601	2292
One irrigation	2036	2496	2670	3744	2737
Mean	1658	2260	2468	3673	
CD (P=0.05)	Irrigation = 53, Nutrient = 31 and Irrigation x Nutrient = 186				

Lone irrigation of 5 cm depth scheduled after 35 days of sowing could raise mean pod and haulm mean yield levels to 1828 and 2737 kg/ha, respectively, which were 23.26 and 19.42 per cent higher over unirrigated control. Application of 40 kg N/ha + 60 kg P_2O_5/ha could obtain mean maximum pod and haulm yield of 2490 and 3673 kg/ha, respectively and out-yielded all other nutrient levels. Under irrigated conditions, application of N alongwith P achieved maximum interactive pod and haulm yields of 2600 and 3744 kg/ha, respectively. Yadkari *et al.* (1992) and Kumar *et al.* (2000) also reported the similar effects of irrigation and fertilizers on groundnut. Influence of irrigation and nutrient levels on evapo-transpiration, water-use efficiency, pod and haulm yield was statistically significant and their interactions were positive. Application of N and P together was more beneficial than the application of either of the two or no nutrients under shallow water-table conditions.

2.12. *Productivity maximization through short-duration aquaculture*

Alternate raised and sunken bed technology through topographic modification in canal command provides various options of crop diversification and short-duration fish culture. In sunken beds of 45-60 cm deep (70-75% land) followed by 1.0 m deep at one end (25-30% land) or rice field with dyke height of 50 cm, infield refuge (1.2-1.5m depths) of 15-25% area of rice field, peripheral tren-ch of 0.5 m depth and 1.0 m width with a moderate slope of 0.5% towards the refuge is most prefer-red, for adoption of fry/fingerling production and rice-fish culture respec-tively using surface and ground water. Water and soil quality variables generally determine the production potentiality of this system, as several *biotic* and *abiotic* factors play a key role in the enhancement of productivity. Therefore, intensive hydro-biological studies prior to site selection are essential.

Fish farming for enhancing water productivity

Texture and properties of soil, its water retentivity capacity and suitability as a constructional material to build up the surrounding dykes should be determined. Generally soil with higher percentage of clay and pH ranging from 6.5 to 7.5 is considered suitable. The lands having higher water table and with suitable drainage system may be selected.

2.12.1. *Species suitability*

Fish species should be adaptable, compatible, resistant to environmental changes, high-yielding and be able to tolerate heavy doses of fertilizer. Since the water column in the sunken beds/ refuge, and the paddy field in the renovated system is suitable for rearing of carps, three Indian major carps, i.e., *Catla catla, Labeo rohita and Cirrhinus mrigala,* prawn (*Macrobrachium rosenbergii* and *M. malcolmsonii*) and exotic carps like common carp may be stocked for culture. Improved high-yielding, tall, long-duration, submergence and pest resistance variety of rice with in-built characteristics of photoperiod-sensivity, strong seedling vigor can be tried.

2.12.2. *Application of fertilizer and chemicals*

The growth and development of paddy and the fish is greatly influenced by the kind and quantity of fertilizers applied and the method of application. Nitrogen, phosphorous and potassium needed by the paddy are also nutrients required by the planktonic and benthic organisms, which are in turn, the natural food of fish. But too much inorganic fertilizer is also toxic to fish. The improved technique of fertilization is to use nutrient rich organic manures as much as possible and inorganic fertilizer as little as possible. Organic manure should be applied after fermentation. Seventy percent of the total manure should be applied as basal and rest as supplementary manure, which should be applied in small amounts frequently.

Although fish in rice fields can eat some of the pests and play a role in the biological control, they cannot totally replace insecticides, so chemical control is needed. However, chemical plant protection should be avoided to prevent fish/prawn mortality. But in emergency, chemicals that have low toxicity, low residue, high effectiveness and a broad spectrum can be applied. Chemicals in powder form should be applied in the early morning hours, while there is still dew around, and application of sprays should be delayed until after the due fades. Nowadays, the splashing method is adopted with good results especially when the rice grows tall. It is always economical and advisable to reduce the water level before application of fertilizer and chemicals.

2.12.3. *Fish culture and yield*

After proper field/refuge preparation, liming @ 500-750 kg ha^{-1}, manuring with raw cattle dung @ 5000-7000 kg ha^{-1} as basal dose should be carried out at the onset of monsoon during June. Before fingerlings are released, it is essential to clear it from aquatic vegetation and predatory fishes (*Channa punctatus, C. orientalis, Glossogobius giuris, Puntius ticto, Esomus danricus, Ambasis* spp. and *Barilius* spp.) if any. During the month of July-August, when the rainwater starts accumulating, early fingerlings of Catla, Rohu, Mrigal, Silver carp, Common carp and prawn juveniles may be stocked with a composition of 30:25:45 (surface feeder: column feeder: bottom feeder). *Labeo bata* can also form a stocking component in this system. As the culture duration is short, fingerlings (>15g size) should be stocked at a higher density of 15,000 – 20,000 per ha for continuous rearing for a duration of 4-5 months or advanced fry (<1.5g size) at a higher density of 75,000-1,00,000 per ha for advanced fingerling production, based on the principle of phased harvesting. An optional stocking density of fish/prawn species is critical in attaining high cumulative fish yields and in reaching the upper carrying capacity of the system. Ways to intensify fish production from integrated rice-fish farming system therefore, involve management strategies like high-density stocking (stocking with a higher initial fish biomass) followed by phased harvesting, when the growth curve of stocked fish/prawn starts to slow down. This will help in reducing the population pressure and enhance the growth of remaining stock. To augment growth, supplementary feed comprising mustard oil cake/ground nut oil cake and rice bran in 1:1 ratio may be given to fishes daily @ 3% in the initial two months and then 2.5% rate of mean body weight of stocked fish/prawn. In this culture system the fish/prawn will grow for a period of 3-4 months in the entire area and then 2-3 months in the confined area of infield refuge/ perimeter canal. Under this system, production range between 1400-1800 kg ha^{-1} (if stocking size <1.5g) or 2800-3200 kg ha^{-1} (if stocking size >15g) per crop with a survival rate of about 65-90 percent. In an experiment on 'rice-fish co-production system' conducted by WTCER at Balipatna Block of Khurda district, Orissa; fish yield increased by 29.8% against that of mono-culture system, while net return from another experiment on 'short-duration culture for fingerling production' was Rs.1,00,300/ ha/120 days .

2.12.4. *Water quality monitoring and management for fish culture*

Since scientific water quality management and maintenance of tolerance limit of hydrological parameters cannot be expected at farmers end, the minimum adoptable techniques for water quality monitoring at farmers end should be encouraged. This includes periodic liming @ 100-150 kg/ha, phased manuring with raw cattle dung @ 2000-3000 kg/ha to maintain plankton bloom, which in turn regulates dissolved oxygen and pH of the eco-system. As these two parameters are too much critical for fish growth and survival, utmost care must be taken for bloom management. As the optimum ratio of phyto and zoo plankton is 10:1, periodic estimation of plankton is essential. In case of plankton crash, re-inoculation should be carried out followed by fertilization with Urea + SSP (1:1) @ 3-4 ppm or systematic water replenishment in case of excessive bloom build up. Further to maintain a clear aquatic environment, meal to meal feed management is essential in reducing the organic load in the system that affects water quality. Suggested water quality criteria for fish rearing are given in Table16.

Table 16: Suggested water quality criteria for fish rearing

Chemical parameters	Tolerance ranges
Ammonia (NH_3)	<0.125 ppm (un-ionized form)
Calcium	10.0-160.00 ppm
Carbon dioxide	0.00 to 10 ppm
Chlorine	0.03 ppm
Hydrogen sulphide	0.002 ppm
Iron (total)	0.0 to 0.15 ppm
Nitrate (NO_3)	0.0 to 3.0 ppm
Nitrite (NO_2)	0.1 ppm in soft water,0.2 ppm in hard water
Dissolved oxygen	5.0 -9.0 ppm
pH	7.5 to 8.5
Phosphorous	0.01 to 3.0 ppm
Total suspended solids	80.0 ppm or less
Total Alkalinity	90-170 ppm
Water colour	Green to brown
Temperature	26-32^0 C

2.12.5. *On-dyke horticulture*

The dykes to be constructed for preventing escape of fish from the integrated system may be used for growing vegetables and other fruit trees like papaya and banana to make the system more economically viable. Vegetables such as gourd, radish, brinjal, leafy vegetables during *pre-kharif* and *kharif* season and vegetables such as tomato, french beans, radish, bitter gourd, cucumber, cauliflower, cabbage, brinjal, pumpkin and leafy vegetables (coriander, amaranthus and Indian spinach) can be grown during winter. Vegetables such as snakegourd, bittergourd, ridgegourd, bottlegourd or ashgourd can be grown throughout the year on raised platforms.

3. Conclusions

We have developed and standardized several simple water management technologies for enhancing crop production, use efficiency and productivity of available water in canal commands of eastern India. Land modification through raised and sunken bed system modifies the soil physical environment and improves aeration status of the soil. Improved aeration status of soils allowed growing of several vegetable crops. Rice-rice, rice-fish and rice-rice+ fish were grown in the sunken beds and different vegetable crop sequences, viz. cabbage-brinjal, pointed gourd, pointed gourd+ bitter gourd, pointed gourd+ papaya, pointed gourd + snake gourd were grown on the raised beds. The highest rice equivalent yield (38.80 t/ha), water-use efficiency (174.54 kg/ha-cm) and net water productivity (Rs 5.33/m^3) was achieved in alternate raised and sunken bed system with rice – fish in sunken bed and pointed gourd + snake gourd in raised bed. Conventional rice-rice cultivation on unmodified land produced the least yield (7.68 rice t/ha) with lowest water expense efficiency (33.59 kg/ha-cm) and water productivity (Rs 0.51/m^3, net) values. Irrigation through field channels enhanced the use efficiency of nutrient and water.

In another study, highest grain and straw yields were observed in controlled irrigation (irrigation through field channels) treatments under all the land situations with recommended dose of fertilizer. Controlled irrigation with farmer's dose of fertilizer produced significantly higher yields than uncontrolled irrigation (irrigation through field-to-field) even with recommended dose of fertilizer. Highest water-use efficiency (152.75 kg/ ha-cm) and net irrigation water productivity (Rs 3.72/m^3) were observed in control irrigation with recommended dose of fertilizer and the lowest was observed in uncontrolled irrigation with farmers' dose of fertilizer.

Optimum time and method of sowing are the simple methods those help in enhanced crop yields without adding any input particularly during dry season. Study revealed that early sowing of dry season crops was helpful for better utilization of residual soil moisture and efficient tapping of water from shallow water table. One ploughing or minimum tillage operation before sowing of seeds increased the yield, water-use efficiency and net water productivity of dry season crops. In terms of yield, water use efficiency and net water productivity, early sowing with minimum tillage was the best followed by late sowing with minimum tillage.

Application of paddy straw mulch @ 5 t/ha enhanced the sweet potato yield from 8.15 and 10.22 to 16.35 and 19.74 t/ha, water-use efficiency from 22.26 and 27.86 to 45.53 and 54.50 kg ha/mm and water productivity from 2.56 and 5.39 to 11.54 and 16.12 Rs/m^3.

In sugarcane crop, the highest average cane yield (170.5 t/ha) was recorded in paired row planting (60 cm/90 cm, spacing) followed by normal row spacing (90 cm) (155 t/ha). The least average cane yield (124 t/ha) over all the water management was recorded under wide row spacing. Among water management practices, the highest cane yield of 178 t/ha was recorded under full irrigation followed by full irrigation without mulch and irrigation once in 8 days (equal to 50 % depletion of available soil moisture, designated as deficit irrigation). The least cane yield was observed under deficit irrigation without mulch. Interaction effect of planting methods and water management shows that the highest cane yield (187 t/ha) was observed in paired row planting under full irrigation with mulch followed by wide row spacing and normal row spacing.

Under shallow water-table condition lowduty crops like horse gram, green gram and sesame grown on residual soil moisture showed good performance without any irrigation. The upward flux of water contributed 41.7 per cent towards total water- use in horse gram, 38.2 per cent in green gram and 33.2 per cent in sesame. Highest grain yield of 625 kg ha^{-1} was obtained in horse gram, while both green gram and sesame yielded 460 kg ha^{-1} grain. In terms of yield and water-use efficiency, horse gram was the best followed by sesame and green gram, but in terms of the net water productivity sesamum was the best followed by horse gram. Early sowing of sesame with residual soil moisture produced better seed yield compared to late sowing without irrigation and was comparable to irrigated condition under late sowing. Under late sown condition, two irrigations with recommended fertilizer produced more yield with higher water productivity. One irrigation with fertilizer produced more yield and net water productivity than two irrigation without fertilizer.

During a study it was observed that influence of irrigation and nutrient levels on evapo-transpiration, water-use efficiency, pod and haulm yield of groundnut was statistically significant and their interactions were positive. Application of N and P together was more beneficial than the application of either of the two or no nutrients under shallow water-table conditions for getting higher water productivity. Addition of short-term fish culture in agriculture system further enhanced production and productivity of available water in different commands.

4. References

Acharya C L and Sharma P D. 1994. Tillage and mulch effects on soil physical environment, root growth, nutrient uptake and yield of maize and wheat on an Alfisol in north- west India. *Soil Tillage Research* **32**: 291-302.

Anderson W K.1992. Increasing grain yield and water use of wheat in a rainfed Mediterranean type environment. *Australian Journal of Agricultural Research* **43**: 1-17.

Aydin Mehmed. 1994. Hydraulic properties and water balance of a clay soil cropped with cotton. *Irrigation Science* **15**:17-23.

Balasubramaniyan P. 1996. Effect of time of nitrogen application on irrigated Sesame (*Sesamum indicum*). *Indian Journal of Agronomy* **41**(1): 108-110.

Bhuiyan, S I, Sattar, M A and Tabbal, D F. 1995. Wet seeded rice: water use efficiency, productivity, and constraints to wider adoption. In: K. Moody (ed), *Constraints, Opportunities and Innovations for Wet Seeded Rice*, IRRI, Los Banos, Philippines, pp. 143-155.

Black C A (Ed). 1965. *Methods of Soil Analysis, Part 1*, Monograph No **9**, Agronomy Series, Madison, Wisconsin, USA. pp 770.

Corbeels M, Hofman G and Van Cleemput O. 1998. Analysis of water use by wheat grown on a cracking clay soil in a semiarid Mediterranean environment: Weather and nitrogen effects. *Agricultural Water Management* **38**: 147 –167.

Das D K, Singh, Ravender and Singh A K. 1990. Root water extraction and evapotranspiration by young Leucaena and Eucalyptus plantations under semi-arid climate. *Annals of Agricultural Research* **11**:1-13.

De Datta, S K. 1986. Technology development and the spread of direct seeded rice in Southeast Asia. *Exp. Agric.*, 22: 417-426.

De Datta, S K and Bernasor, P. 1973. Chemical weed control in broadcast-seeded flooded tropical rice. *Weed Res.*, 13: 351-354.

Droogers P and Bastiaanssen W G M. 2002. Irrigation performance using hydrological and remote sensing modeling. *Journal of Irrigation and Drainage Engineering* **128**:11-18.

Duraisamy K, Kathiresan G and Balasubramaniyan P. 1999. Effect of irrigation frequency and coir pith application in sesame (*Sesamum indicum*). *Indian Journal of Agronomy* **44**(2): 416-418.

Falkenmark M, Lundquist J and Widstrand C. 1989. Macro-scale water scarcity requires micro-scale approaches: aspect of vulnerability in semi-arid development. *Natural Resource Forum* **13**:258-267.

Ghosh S, Kannan K, Singh Ravender and Kundu D K. 2002. Socio-economic profile and cropping pattern in canal command area in Khurda district of Orissa. *Indian Journal of Extension Education* **38**: 99-103.

Ghosh S, Singh Ravender and Kundu D K. 2005. Evaluation of irrigation-service utility from the perspective of farmers. *Water Resources Management* **19**: 467-482.

Guerra, L C, Bhuiyan, S I, Tuong, T P and Barker, R. 1998. Producing more rice with less water from irrigated systems. *SWIM Paper 5*. IWMI/IRRI, Colombo, Sri Lanka, 24 p.

Hanks R J, Klute A and Bresler E. 1969. Numerical method for estimating infiltration, redistribution, drainage and evaporation of water from soil. *Water Resources Research* **5**: 1064 –1069.

International Rice Research Institute, IRRI. 1977. *Annual Report for 1977*. Los Banos, Philippines.

Kannan K, Singh Ravender and Kundu D K. 2003a. Raised and sunken bed system for crop diversificationin high rain fall areas. *Indian Journal of Agricultural Sciences* **73**: 453 –455.

Kannan K, Singh Ravender, Kundu D K and Reddy G P. 2003b. Fitting Malabar Spinach in rice based cropping system by modifying microenvironment in canal command of eastern region. *Environment & Ecology* **21**: 1 – 3.

Kannan K and Wahab K. 1995. Economics of nitrogen and weed management in sesamum. *Madras Agricultural Journal* **82**(2): 154-55.

Kijine J, Barker R and Molden D. (Eds.). 2003. Water productivity in agriculture: Limits and opportunities for improvement. *Comprehensive Assessment of Water Management in Agriculture.* Series No.**1**. CABI press, Wallinford, UK, 352 p.

Kumar V, Ghosh B C, Bhat R and Karmakar S. 2000. Effect of irrigation and fertilizer on yield, water-use efficiency and nutrient uptake of summer groundnut (*Arachis hypogaea*). *Indian Journal of Agronomy* **45**: 756- 760.

Kundu DK, Chaudhari SK and Singh R 2007. Effect of soil puddling and potassium application on rice in a canal irrigation command of Orissa. *J. Indian Soc. Soil Sci.* 55: 84-86.

Miller R W and Donahue R L. 1992. *Soils: An Introduction to Soils and Plant Growth.* Prentice Hall of India Pvt. Ltd., New Delhi, p.786.

Minhans P S, Sharma D R and Khosla B K. 1990. Mungnbean response to irrigation with waters of different salinities. *Irrigation Science* **11**: 57-62.

Molden D, Murry-Rust H, Sakthivadivel R and Makin I. 2001. A water productivity framework for understanding and action. Workshop on Water productivity. Wadduwa, Sri Lanka, November 12 and 13, 2001.

Molden D and Sakthivadivel R. 1999. Water accounting to assesses and productivity of water. *Journal of Water Resources Development* **15** (1/2): 55-72.

Moody, K. 1983. The status of weed control in rice in Asia. *FAO Plant Prot. Bull.*, 30(3/4):119-124.

Moody, K and Cornova, V G. 1985. Wet-seeded rice. *In: Women in Rice Farming*, International Rice Research Institute, Philippines, pp. 467-480.

Ossom E M, Pace P F, Rhykerd R L and Rhykerd, C. L. 2001. Effect of mulch on weed infestation, soil temperature, nutrient concentration, and tuber yield in Ipomoea batatas in Papua New Guinea. *Tropical Agriculturist* **78**: 144-151.

Pande H K and Reddy M D. 1988. Improving efficiency of irrigation water-use in rice-based cropping system. *In Proceeding of National Seminar on Water Management: The Key to Developing Agriculture.* (Ed. J. S. Kanwar). Agricole Publishing Academy, New Delhi, pp 652 – 82.

Puttana L.1983. Water management in rice in India: A review of research. *WAMANA*, **3:** 1-22.

Satyanarayana A, Thiyagarajan T M and Uphoff N. 2007. Opportunities for water saving with higher yield from the system of rice intensification. *Irrig. Sci.* **25**: 99–115.

Selvarajan S. 2001a. Sustaining India's irrigation infrastructure. *Policy Brief Paper* **15**. National Centre for Agricultural Economics and Policy Research, Pusa, New Delhi.

Selvarajan S. 2001b. Irrigation Equity: Impacts, Sources and Strategies. *Policy Brief Paper* **19**. National Centre for Agricultural Economics and Policy Research, Pusa, New Delhi.

Siddiq E A and Kundu D K. 1993. Production strategies for Rice-based Cropping Systems in the Humid Tropics, pp. 155-162. *International Crop Science 1.* Crop Science Society of America, WI 53711, USA

Singh Ravender, Kundu D K, Kannan K, Ghosh S, Roy Chowdhury S, Thakur A K, Reddy G P, Mishra A, Nanda P and Sahoo N. 2002a. Developing optimum irrigation schedules in canal command. Water Technology Centre for Eastern Region, Bhubaneswar, Orissa-751023, India. Annual Report-2001-2002: 24-25.

Singh Ravender, Kundu D K and Kannan K. 2002b. Water use by horse gram, green gram and sesamum under shallow water table condition. *Annual Report* 2001-02 WTCER, Bhubaneswar, Orissa, India. p 23-24.

Singh Ravender and Kundu D K. 2003. Water use by horsegram (*Macrotyloma uniflorum*), greengram (*Phaseolus radiatus*) and sesame (*Sesamum indicum*) under shallow water-table condition in Orissa. *Indian Journal of Agricultural Sciences* **73** (2): 89- 93.

Singh Ravender, Kundu D K and Kannan K. 2003a. Crop diversification through land modification in canal irrigation command of Eastern India. *SAARC Journal of Agriculture* **1**: 99 – 104.

Singh Ravender, Kundu D K, Kannan K and Verma H N. 2003b. Modification of soil environment for crop diversification in high rainfall area. Paper presented during the *National Symposium on Emerging Trends in Agricultural Physics*, held at the Division of Agricultural Physics, IARI, New Delhi from April 22-24, 2003.

Singh Ravender, Kundu D K, Mohanty R K and Ghosh S. 2004. Crop diversification in canal irrigation commands of high rainfall areas through land configuration. Page 105 *in Abs. Proc. National Symposium on Recent Advances in Rice-based Farming Systems*, held at CRRI, Cuttack on 17 – 19 Nov 2004. Central Rice Research Institute, Cuttack, Orissa 753006, India.

Singh Ravender, Roychowdhury S, Kundu, D K and Kannan K. 2004. Effect of paddy straw mulch on hydrothermal state, nutrient availability, growth and tuber yield of sweet potato (*Ipomoea batatas* L.). *Adv. Hort. Sci.* **18 (1)**: 15-20

Singh Ravender, Kundu D K, Roychowdhury S and Kannan K. 2007. Mulch and irrigation effects on water use by sweet potato (*Ipomoea batatas* L.) under shallow water conditions. *Journal of Water Management*. **15(1)**: 40-49

Singh R, Van Dam J C and Feddes R A. 2006. Water productivity analysis of irrigated crops in Sirsa district, India. *Agricultural Water Management* **82**: 253-278.

Stibbe E. 1975. Soil moisture depletion in summer by an Eucalyptus grove in a desert area. *Agro-Ecosystems* **2**:117-126.

Stoop W A, Uphoff N and Kassam A. 2002. A review of agricultural research issues raised by the system of rice intensification (SRI) from Madagascar: opportunities for improving farming systems for resource-poor farmers. *Agric. Syst.* **71**: 249–274.

Subrahmaniyan K and Arulmozhi N. 1999. Response of sesame *(Sesamum indicum)* lto plant population and nitrogen under irrigated condition. *Indian Journal of Agronomy* **44**(2): 413-415.

Tabbal D F, Bouman B A M, Bhuiyan S I, Sibayan E B and Sattar M A. 2002. On-farm strategies for reducing water input in irrigated rice; case studies in the Philippines. *Agricultural Water Management*, **56:** 93-112.

Thakur AK, Roychowdhury S, Kundu DK and Singh Ravender. 2004. Evaluation of planting methods in irrigated rice. *Archives Agron and Soil Sci.* 50: 631-640.

Tomar S S, Terbe G P, Sharma S K and Tomar V S. 1996. Studies on some land management practices for increasing agricultural production in vertisols of Central India. *Agricultural WaterManagement* **30**: 91-106.

Tuong T P and Bouman B A M. 2003. Rice production in water-scarce environments. Proceedings of the Water Productivity Workshop,12-14 November 2001, IWMI, Sri Lanka.

Uphoff, N. 2003. Higher yields with fewer external inputs? The system of rice intensification and potential contributions to agricultural sustainability. *Int. J. Agric. Sustain.* 1:38–50

Yadkari M, Hussain M N M and Satyanarayana V. 1992. Response of rainfed groundnut (*Arachis hypogaea*) to potassium with varying levels of nitrogen and phosphorus. *Indian Journal of Agronomy* **37**: 202 –203.

Yuan Tian, Fengmin Li and Puhai Liu. 2003. Economic analysis of rainwater harvesting and irrigation methods, with an example from China. *Agricultural Water Management* **60**: 217-226.

Zhang H, Oweis T, Garabet S and Pala M. 1998. Water use efficiency and transpiration efficiency of wheat under rainfed conditions and supplemental irrigation in a Mediterranean-type environment. *Plant and Soil* **201**: 295- 305.