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Deep-water rice production as influenced by time and depth of flooding on the east coast of India

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The saucer-shaped landform, high rainfall due to the south-west monsoon (June–September) and poor drainage conditions make certain parts of the east coast of India susceptible to waterlogging during the rainy season. There is no alternative other than to grow rice in the coastal lowlands, where surface water accumulation of 0.5–2.0 m occurs during the rainy season. In this study, the physical environments of a representative deep-water ecology were characterized and the performance of improved deep-water rice (DWR) varieties (Hangseswari, Saraswati, Ambika, Sabita) was compared with that of local varieties (Bankei, Dhalakartik) at three water depths (shallow flooded [0.6–0.8 m], medium flooded [0.8–1.2 m] and deep flooded [>1.2 m]). The rainfall–flooding depth relationship was also studied and the probability of successful crop production in relation to the time and depth of waterlogging was investigated, based on historical (34 years) flood data from the region. Among the varieties studied, 'Hangseswari' was found to have superior physiological traits for growth, development and production of grain yield and hence may be considered for inclusion in further DWR breeding programs. With the introduction of improved DWR varieties, productivity during the rainy season was enhanced and farmers received good yield (2.05–2.95 t ha^{-1}) and net return (4500 Rs ha^{-1}).

Keywords: deep water; east coast; flood; rice; waterlogging

Introduction

Soil water, either too much or too little, is recognized as the single most limiting factor for crop production on the east coast of India, where both excessive and deficient soil-water conditions are found in the same field in the same year. The saucer-shaped land form, high rainfall due to the south-west monsoon (June–September) and poor drainage conditions make the certain parts of the east coast of India susceptible to waterlogging during the rainy season (Kar et al. 2007). By contrast, after the floods recede, the land remains dry from December to May. Traditionally, local farmers plough agricultural fields two or three times before June with the help of pre-monsoon showers and broadcast dry seeds of local rice varieties of long duration (150 days) in the first week of June. But profitable crop production depends upon the time and depth of flooding/waterlogging. Prolonged waterlogging during the rainy season reduces tillering and growth of the normal rice crop at most growth stages. Sometimes a flash flood inundates the standing crop at any stage of

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growth for 8–10 days at a times, resulting in heavy mortality. The crop is damaged completely if this situation occurs in the early vegetative period. So, proper establishment of the crop before onset of flooding and the adoption of waterlogging-tolerant rice varieties are of paramount importance to realize net returns from the crop (Sahoo et al. 2005; Baruah et al. 2006). Early sowing (first week of June) allows the rice crop to grow to ~1.2–1.3 m height by the middle of the August and the crop can cope up if flooding occurs after this point.

Submergence caused by flooding ranks next only to drought as the most serious abiotic constraint on rice production (Datta 2002). However, there is no alternative other than to grow rice in coastal lowlands where surface water accumulation of 0.5–2.0 m occurs during the rainy season. Waterlogging-tolerant rice varieties (deep water rice [DWR] or floating rice) can be grown to make the waterlogged land productive during the rainy season (Rose-John and Kende 1984; Ambumozhi et al. 1998; Zeng et al. 2003; Khakwani et al. 2005; Sahoo et al. 2005; Roy Chowdhury et al. 2006; Kotera and Nawata 2007). Therefore, performance evaluation of improved varieties with better yield potential in deep-water areas is critical for sustainable rice production in the deep waterlogged ecology (Das and Uchimiya 2002; Baruah et al. 2006).

In this study, the physical environments of a representative deep-water ecology were characterized and the performance of improved DWR varieties (Hangseswari, Saraswati, Ambika, Sabita) was compared with that of local varieties (Bankei, Dhalakartik) at three water depths [shallow flooded (0.6–0.8 m), medium flooded (0.8–1.2 m) and deep flooded (>1.2 m)]. Although precise data on flooding patterns are of fundamental value for DWR cultivation, there is a surprising paucity of long-term water records on a daily basis from actual DWR fields. In this investigation, the rainfall–flooding depth relationship was also studied and the probability of successful crop production in relation to time and depth of waterlogging was investigated based on 34 years of historical flood data from the region.

Sometimes it is also necessary to assess the crop condition during the occurrence of flash floods, which may occur at any stage of crop growth. With the advent of remote sensing technology, the assessment becomes easier through computation of spectral indices. Hence, we also attempted to measure spectral reflectance of rice at different flooding depths (up to 0.45 m).

Materials and methods

General climate of study area

On average, the region receives 1500 mm annual rainfall, 65–80% of which occurs during the rainy season (June–September). The mean date of onset of effective monsoon (OEM) was found to be 16 June and the south-west monsoon generally ends on 29 September. Open pan evaporation values vary from 8.1 mm in May–June to 3.5-5 mm in December–January. Mean maximum temperature in the region ranges from 33 to 37°C during the pre-flood period (January–June). During the main flooding period (July–September), monsoon cloud cover lowers the maximum temperature to within a narrow range of 31–32°C. In November and December, maximum temperature decreases to 24–27°C and night-time temperature may go up to 9–10°C. In general, water accumulation or flooding starts from July after the onset of the fully fledged south-west monsoon in the region and the first rise in the depth of accumulated water in the region depends entirely on rainfall in the catchment areas. The flood recession phase is more consistent, occuring from November onwards, and the land remains dry from December to May. The flood, post-flood and pre-flood periods of the study site in general are given in Figure 1.

The first flood water spreading over the land at inundation is usually turbid with suspended alluvium brought down from the catchment area, plus material picked up as it spreads slowly over the land. After the initial spread of flood water throughout the region, the silt is mostly deposited before flushing out to sea. Thus, the greater part of the flooding is clear water, which probably originates largely from the accumulation of rainwater and can drain only very slowly because of the congested drainage channels and saucer-shaped topography (Kar et al. 2007). Water temperature near the surface varied from 29 to 32°C during July–October. Water pH was usually fairly close to neutral (5.9–6.3). Temperature, pH and O_2 were generally lowest near dawn and increased to a maximum in mid-afternoon or early evening.

Aquifer characteristics of the study area

The seasonal deep waterlogged areas of the delta and the coastal tracts of eastern India have a huge pile of unconsolidated sediments in which clays appear to predominate. The clays encountered in the deltaic tracts are sticky in nature. However, there is a sandy zone below 2 m and this extends up to a depth of 12–13 m in areas where the feasibility of shallow ground water can be explored. Lower aquifer below 195–300 m bears good quality ground water but it is expensive to use. The recharge rate varied from 1.18 to 4.7 $m^3\,h^{-1}$ in the sandy zone and 0.9 to 3.4 $m^3\,h^{-1}$ in clayey zone.

DWR crop management and experimental procedure

The experimental plots were located in a farmer's field of Alisha village, Puri district, Orissa, India. Seeds of six rice cultivars, viz. 'Hangseswari' (V_1), 'Saraswati' (V_2)

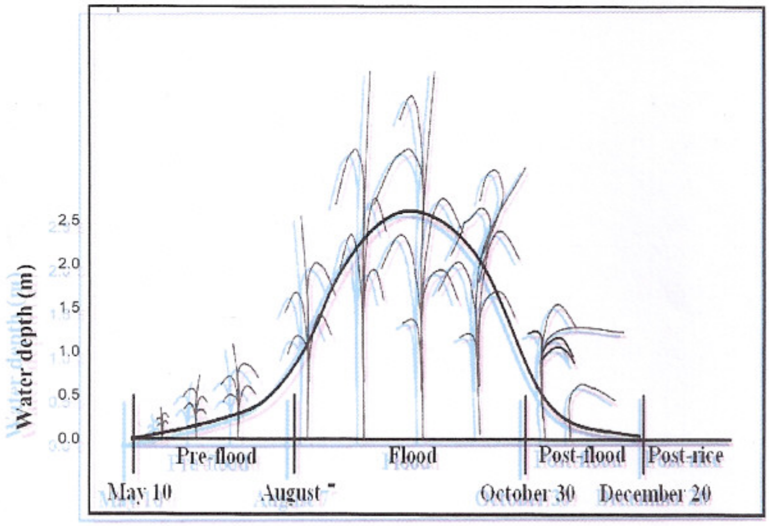

Figure 1. Water depth (m) scenario in general during pre-flood, flood and post-flood period in coastal Orissa.

'Sabita' (V_3) 'Ambika' (V_4), 'Bankei' (V_5) and 'Dhalakartik' (V_6), were sown in line (plant-to-plant distance 20 cm, row-to-row distance 25 cm) in three different land ecologies, viz. shallow (D1) (0.60–0.80 m), medium (D2) (0.80–1.2 m) and deep flooded (D3) (>1.2 m). Three farmers' fields were taken in any land ecology to replicate six cultivars three times. Similar fertilizer doses (N: 40 kg ha^{-1}, P: 20 kg ha^{-1}, K: 20 kg ha^{-1}) and management practices were applied for growing crops in all the land ecologies. All the fertilizers were applied as basal because after flooding it was very difficult to apply top dressing under on-farm conditions.

The different crop growth and yield attributes such as crop height, tillers m^{-2}, leaf area index, panicles m^{-2}, grain and straw yields of different DWR varieties were recorded. The results of average of five samples (five plants) at different water depths were presented. Throughout the rainy season, accumulated water depth was recorded and its inter-relationship with rainfall was also studied. The rainfall data during crop growth period were collected from Puri, Orissa meteorological observatory.

Total soluble sugar (TSS) and starch content in the rice grain were also determined using the Anthrone method (Chopra and Konwar 1976). These parameters were determined in brown rice on dry weight basis.

Analysis of long-term rainfall data

From the rainfall data of the past 34 years, monthly rainfall at 30, 50 and 70% probability levels were computed using normal, log normal, log Pearson and extreme value probability distribution methods. The estimated rainfall was compared with that of observed values, computed by using inverse Weibulls' formula,

$$P = \frac{m}{N+1} \times 100,$$

where, P = Probability of rainfall, m = rank number and N = total number of years.

The results (E) obtained using four probability distribution functions were compared with that of observed values (O) by chi-square test of goodness of fit to find out the best fit probability distribution for predicting monthly rainfall in the region.

$$\lambda^2 = \Sigma \frac{(O - E)^2}{E}$$

Initial and conditional probabilities of occurrence of weekly rainfall were determined using the following relationship.

Initial probability (probabilities of week considering being wet or dry):

(1) Probability of the week being considered being wet, $P(\mathrm{W}) = F(\mathrm{W})/N$, Where $F(\mathrm{W})$ is the frequency of wet weeks and N is the number of years of data used.

(2) Probability of the week considering being dry, $P(\mathrm{D}) = F(\mathrm{D})/N$, where $F(\mathrm{D})$ is the frequency of dry weeks and N the number of years of data used.

(3) Probability of the week being wet, provided the previous week was wet, P(W/W),

$$P(W/W) = \frac{F(W/W)}{F(W/W) + F(D/W)}$$

where F(W/W) is the frequency of wet week given that previous week was wet and F(D/W) the frequency of dry week given that the previous week was wet.

Spectral reflectance measurements

For crops grown in flooded environments, such as rice, alterations in the spectral response of canopies may happen due to the presence of surface water because liquid water, in particular, has strong absorption properties in the visible and the near infrared wavebands (400–1000 nm). However, the magnitude reflected in the red and the NIR spectral regions varies significantly according to water depth, turbidity, phytoplankton, suspended minerals, dissolved organic carbon, etc. (Casanova et al. 1998; Doxaran et al. 2002; Han and Rundquist 2003). In this study, we used UniSpec spectral analysis system (PP Systems, USA) to measure the spectral reflectance of rice under the submerged condition. Measurements were made in October after the peak flood had receded and when 30–60% of the crop was above flood water. Among the three study years (2005, 2006, 2007), reflectance was measured in 2005 and 2007, in 2006 no measurements were possible because the crop was damaged. Reflectance was measured up to the flooding depth of 0.45 m within the range 400–1100 nm and three measurements were performed at each flooding depth, which were taken at depths of 0.01, 0.05, 0.15, 0.25 and 0.45 m. Based on spectral reflectance data, the normalized difference vegetation index (NDVI) was derived and related to the percentage of emergence of the crop above flood water.

$$NDVI = \frac{IR - R}{IR + R},$$

where IR = infrared and R = red.

The intercepted photosynthetically active radiation (IPAR) was derived and related to the emerged crop above the flood. Dissolved oxygen was measured with the help of a DO probe of soil and water analysis kit (model – 131E, Electronics India).

The net returns from the produce were calculated by subtracting the operational cost (ploughing and land preparation, fertilizers, labours for sowing, harvesting, threshing etc.) from the gross return.

Results and discussion

Analysis of long-term rainfall data

Analysis of the seasonal distribution of rainfall is of paramount importance to study the flooding period, onset and recession of flood for sustainable agricultural development in deep waterlogged areas. The seasonal distribution of rainfall in representative waterlogged areas of the east coast of India was analysed and is presented in Table 1.

Analysis revealed that on an average, pre-monsoon (April to May) and south-west monsoon (June to September) showers contributed 7.8–12.3 and 61.8–73.3% of the total annual rainfall, respectively. The pre-monsoon showers were of special significance in the region for performing summer tillage (off-season tillage operation) and land preparation for rice cultivation. Summer tillage was also helpful to reduce weed, pest and disease infestation. Maximum rainfall occurred during the rainy season (June–September) due to the south-west monsoon and surface water accumulation started after the occurrence of heavy rainfall. During the winter season (December–January), 44.0–54.9 mm rainfall occurred, which could play a crucial role in sowing and the establishment of second crops after rice. During winter and summer, the land remained dry after the flood water had receded.

The analysis of coefficient of variation of monthly rainfall of the representative coastal areas revealed that among different months, rainfall variability was low (31.3–52%) in July and August. But the summer and winter rainfall was meager and highly variable (Table 2).

Weekly rainfall probability analysis revealed that initial probability, $P(W)$ of receiving 20 mm or more rainfall exceeded 50% towards end of May and reached the most dependable limit (70% probability) in 24–33 and 36–43 standard meteorological weeks after onset of the south-west monsoon (Fig 2a). Therefore, in most years, sowing in the standard week 24 (11–17 June) was likely to produce successful establishment of crops in the region. The conditional probability [wet week followed by wet week, $P(W/W)$] of 20 mm or more rainfall occurring followed almost same trend, exceeding 70% probability level from standard weeks 23–28 and 36–42 (Fig 2b). Based on weekly rainfall probability, it could be said that standard weeks 24–42 were prone to flooding. Flooding usually had one or two peaks during the season, but the number might vary depending upon the rainfall pattern. The water typically rose fairly gradually after heavy rainfall and the flood level remained virtually unchanged for a few weeks after onset because of slow drainage. In the pre-flood or pre-monsoon period (standard weeks 1–13), rainfall was meager and uncertain because the probability of receiving rainfall at a dependable limit was very much less when cropping was not possible without irrigation.

Predicted and observed monthly rainfall in the study area (Puri, Orissa) was also computed and is presented in Table 3. The monthly rainfall was predicted using four probability distributions, viz. normal, log normal, log Pearson and extreme value methods, and computed with the values obtained by Weibulls' formula using λ^2 test. Log Pearson probability distribution was found to be best for predicting monthly rainfall in the region based on the chi-square test.

Table 1. Season-wise distribution of rainfall (mm) in different undivided districts of Orissa.

Districts	Monsoon		Post-monsoon		Winter		Pre-monsoon	
Puri	1062.8	(73.3)	224.9	(15.5)	47.7	(3.3)	113.7	(7.8)
Balasore	1107.7	(70.6)	213.3	(13.6)	54.9	(3.5)	192.5	(12.3)
Ganjam	862.8	(61.8)	248.4	(17.8)	44.0	(3.2)	140.4	(10.1)

Note: Fgures in parentheses indicate the percentage of total annual rainfall.

Table 2. Coefficient of variation (%) of monthly rainfall in different coastal districts of Orissa.

	Month											
Districts	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Puri	193.36	144.09	125.60	102.60	167.30	52.00	39.60	35.78	38.24	99.32	144.38	261.72
Cuttack	193.79	126.40	135.18	92.66	99.85	41.69	38.98	29.74	36.88	85.26	164.47	258.77
Balasore	144.69	120.54	114.61	81.11	78.84	44.73	31.35	33.85	41.29	78.62	163.85	282.92
Ganjam	152.70	129.13	102.17	65.21	117.09	49.36	36.64	37.25	40.93	70.03	137.91	331.50

Table 3. Predicted and observed monthly rainfall (mm) at Puri district.

	Normal			Log normal			Log Pearson			Extreme Values			Weibulls		
Months	30%	50%	70%	30%	50%	70%	30%	50%	70%	30%	50%	70%	30%	50%	70%
Jan	25.8	12.9	–	–	–	–	–	–	–	21.7	8.8	–	9.8	2.6	0.0
Feb	29.0	16.6	3.9	–	–	–	–	–	–	25.1	12.7	2.4	20.1	8.0	0.7
Mar	34.6	20.9	7.0	–	–	–	–	–	–	30.2	16.6	5.4	30.3	8.1	0.8
Apr	36.7	23.9	10.9	–	–	–	–	–	–	32.6	19.9	9.3	31.7	16.6	7.5
May	105.9	56.7	6.6	–	–	–	–	–	–	90.2	41.2	0.5	60.7	32.0	22.4
Jun	204.7	161.1	116.7	185.2	142.0	108.4	184.8	141.6	108.1	190.7	147.3	111.3	186.5	150.8	105.2
Jul	342.3	283.9	224.5	321.4	265.3	218.2	317.7	261.3	216.0	323.6	265.5	217.3	334.9	261.2	216.0
Aug	375.2	318.7	261.0	362.8	299.6	246.4	370.8	309.9	253.3	357.1	300.8	254.0	366.8	328.8	274.5
Sep	261.4	217.7	173.2	255.3	198.9	154.3	269.5	226.1	176.0	247.4	203.9	167.8	255.7	222.3	174.0
Oct	201.7	133.0	63.0	146.3	84.2	48.0	156.3	93.6	52.3	179.7	111.3	54.4	134.6	106.3	62.0
Nov	73.4	41.9	9.8	–	–	–	–	–	–	63.3	32.0	5.9	43.5	15.8	2.0
Dec	10.0	4.3	–	–	–	–	–	–	–	8.2	2.5	–	0.8	0.0	0.0

Basic soil properties of the experimental site

Before initiating the experimental trials, soils of the representative seasonal deepwater field were tested in respect of different chemical and physical properties. The results of analysis of an average of six profiles are presented in Table 4.

Taxonomically, the soil belongs to the very fine, mixed, iso-hyperthermic, Vertic Endoaquepts soil series. Soils were clay textured, poorly drained, with very low saturated hydraulic conductivity (0.11–0.24 cm h^{-1}). The soil reaction was moderately acidic and no soil problem was detected in the soil profile. The highest electrical conductivity of 1 dS m^{-1} was observed at 0.15–0.30 m soil depth. The organic carbon status of the soils was high, and ranged between 1.1 and 2.0%. The soil texture varied from clay to heavy clay with high bulk density (1.59–1.65 Mg m^{-3}). The available nitrogen (average of six profiles) varied from 110 to 254 kg ha^{-1}, and the available phosphorus ranged between 8.2 and 15.3 kg ha^{-1}. The available potassium ranged between 113.9 and 148.7 kg ha^{-1}. The fertility status of the soil was found to be low to moderate and integrated nutrient management is required to obtain optimum crop productivity.

Flooding–rainfall relationship

The dominant factors determining the success or failure of rice in deep-water ecology are the rate of rise and maximum depth of flood water. A consistent record of water level is necessary to properly interpret the performance of DWR varieties and the reasons for the success, or lack of success of crop production. Our study revealed that the first rise of accumulated depth of water levels in the region depends entirely on rainfall in the catchment areas and the onset of flooding can vary greatly between

Table 4. Major soil physical and physical properties of the experimental site.

Depth (cm)	Sand (2.0–0.05 mm) (%)	Silt (0.05–0.002 mm) (%)	Clay (<0.002 mm) (%)	Texture	Bulk density (Mg m^{-3})	Saturated hydraulic conductivity (cm h^{-1})
0–15	24.5	19.6	55.9	c	1.59	0.17
15–38	20.4	17.6	62.6	c	1.60	0.20
38–62	12.5	21.7	65.8	c	1.63	0.24
62–95	22.3	15.4	62.3	c	1.65	0.23
95–150	25.6	15.9	58.5	c	1.65	0.11

Sample	pH	EC (dSm^{-1})	Organic carbon (%)	Avail. N (kg ha^{-1})	Avail. P (kg ha^{-1})	Avail. K (kg ha^{-1})	Ca + Mg (meq 100 g^{-1})
0–15	5.6	0.3	1.8	249.5	13.2	113.9	0.45
15–30	4.9	1.0	1.1	180.0	15.3	128.9	0.48
30–60	5.4	0.0	1.7	254.0	14.9	143.5	0.49
60–90	4.9	0.9	1.6	234.5	10.3	148.7	0.45
90–120	5.3	0.4	2.0	255.5	08.4	122.0	0.32
120–150	5.1	0.9	1.5	110.7	09.9	121.3	0.35

Note: c, clay.

years depending upon the rainfall. The floodwater depth in relation to rainfall during the monsoon season (June–October) at three experimental land ecologies (D_1, D_2 and D_3) are given in Figure 3(a–c) for 2005, 2006 and 2007, respectively.

In 2005, flood water depth at D3 ranged between 0.41 and 1.89 m. The highest flood water exceeded 1 m depth on 16 August when the crop height was 1.1 m. From 17 to 22 August water depth varied from 1.70 to 1.76 m and the crop was submerged for 9 days. The crop was at active tillering stage (75 DAS) and the height of the crop was reached 1.25–1.4 m during that time. After 30 August, the crop was visible when

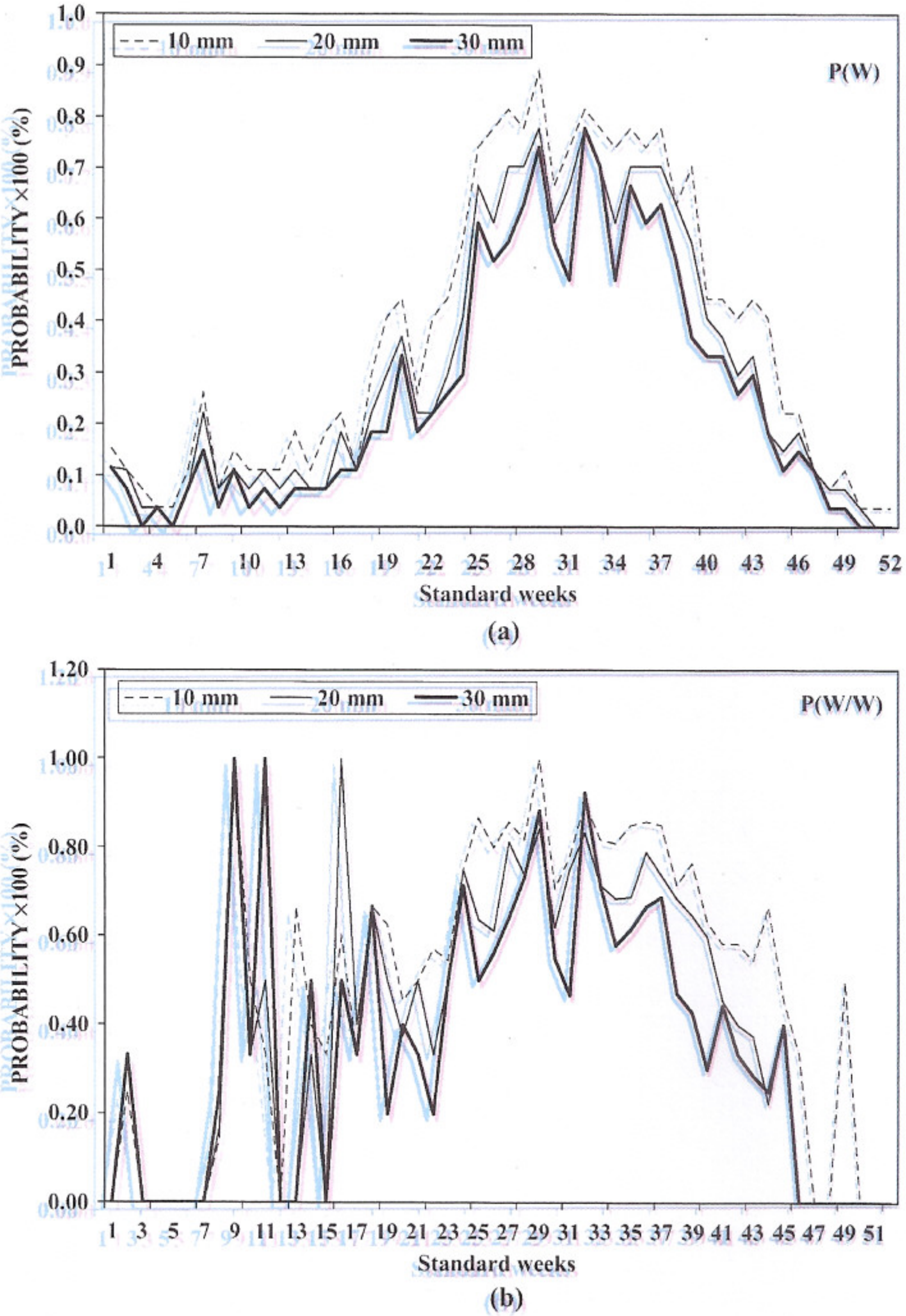

Figure 2. (a) Initial probability of obtaining wet–dry spells analysis in study area. (b) Conditional probability of obtaining wet–dry spells analysis in study area.

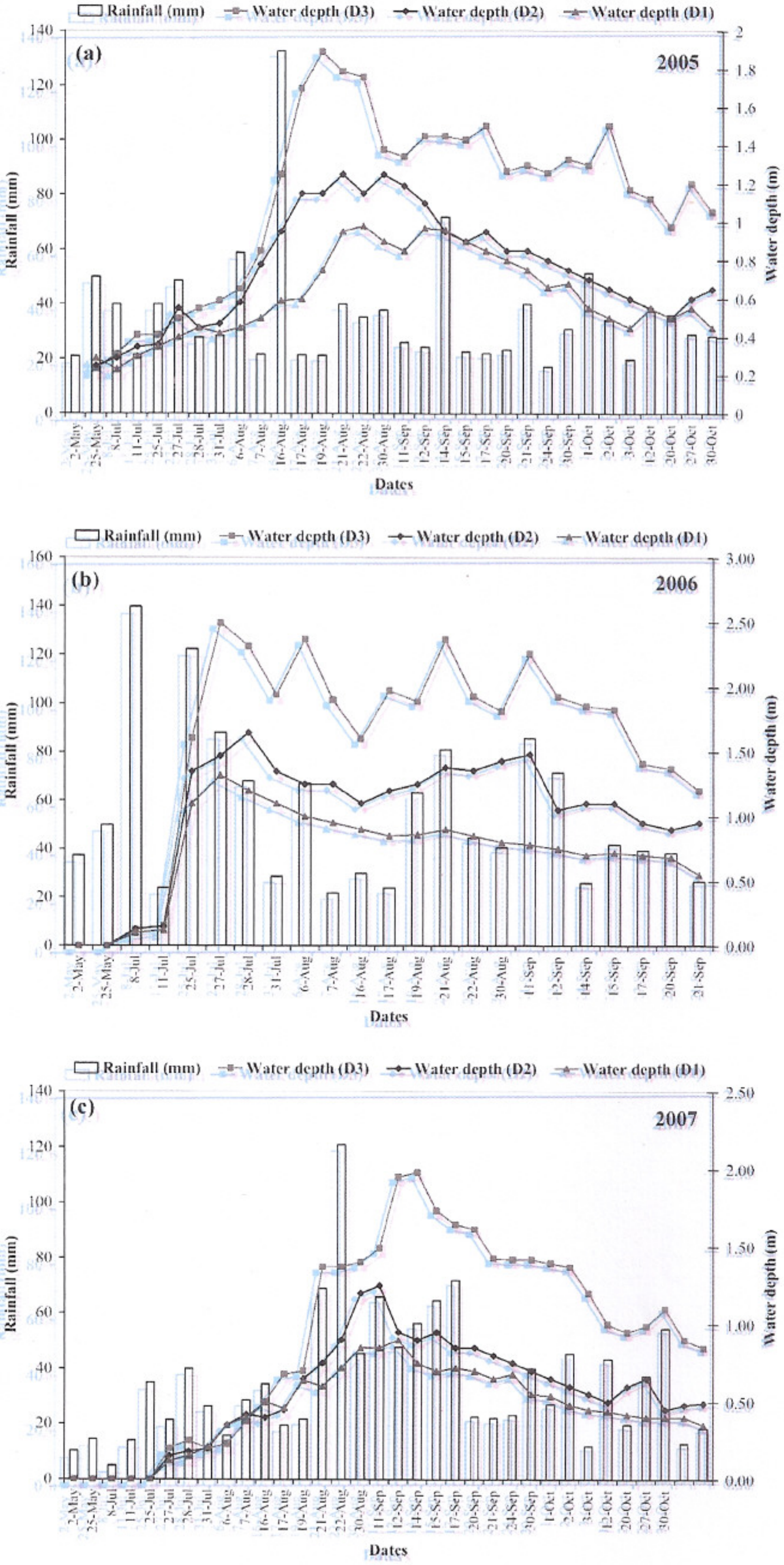

Figure 3. Rainfall and accumulated water depth during *kharif* (rainy) season (a) 2005, (b) 2006, (c) 2007.

the water level deacreased to 1.38 m. In D2, the highest flood level (1.25 m) was found on 21 August after onset of the fully fledged south-west monsoon. By contrast, in D1, the highest flood water depth of 0.97 m was observed on 12 September.

In 2006, heavy rainfall occurred in the first week of June itself and surface water accumulation started early (from first week of July itself). At that time, the crop was at the early vegetative stage with the crop height being only 0.10–0.20 m. In this year, the highest flood water depths were 1.32, 1.48 and 2.49 m at D_1, D_2 and D_3, respectively. Early heavy rainfall and flood caused extensive damage to the rice crop in 2006 in all the ecologies because the crop height was very much lower during that time.

In 2007, flood water depth exceeded 1 m (1.37 m) on 21 August, when the crop height was 1.4–1.5 m. Following a further increase in the water level, the crop was under water for 5–7 days in D3 and after only after the flood water receded did the crop revives. The crop condition was almost similar in 2005 and 2007 because heavy rainfall occurred during the later part of the crop growth and flooding occurred when the crop had attained sufficient height to tolerate it. However, due to the occurrence of early flooding and early heavy rainfall, the crop was damaged in 2006.

Because the success or failure of the rice crop in deep-water ecology depends upon the time of monsoon onset, rainfall distribution and time of flood water receding, we also investigated the rainfall patterns in different years based on last 34 years' flood and rainfall data. Based on rainfall occurrence and distribution, different situations occurred, for example: (1) dry summer followed by early monsoon rains; (2) good summer rains followed by early monsoon; (3) good summer rains followed by a weak monsoon; (4) heavy rainfall in July–August or later; and (5) well-distributed rains until August or September, followed by torrential October rains. Based on experience, it was revealed that the best condition for obtaining a successful rice crop in a deep-water ecology was summer rains and well-distributed monsoons, and a crop height of >1 m before flooding. The date of the beginning of waterlogging was also found to be quite variable. Flooding might occur as early as 10 June, i.e. just after the onset of south-west monsoon in the region, but in exceptional years it might be delayed until July–August. We analysed the probability of receiving floods in different months based on data from the past 34 years. Our study revealed that the probability of receiving floods after 15 August was 52% (when the crop height was >1 m). It was also revealed that in 4 of 10 years, flooding was likely to commence by mid-July (Figure 4) when the crop was <2–2.5 months old and crop height was <1 m. Based on this study, it could be said that the probability of obtaining a successful crop in a deep-water ecology was 52%. Therefore, farmers had to depend on other options such as integrated pond-based farming for the security of their food and livelihood.

Performance of rice in a deep-water ecology in three study years

The rainfall–flood relationship revealed that the flooding pattern is completely dependent on rainfall in the catchment area and the performance of the rice crop is highly influenced by flooding time. Among the three study years (2005, 2006, 2007), crop growth and yield attributes were recorded for two successful crop years (2005 and 2007) at three water depths and mean results are presented in Figures 5–10.

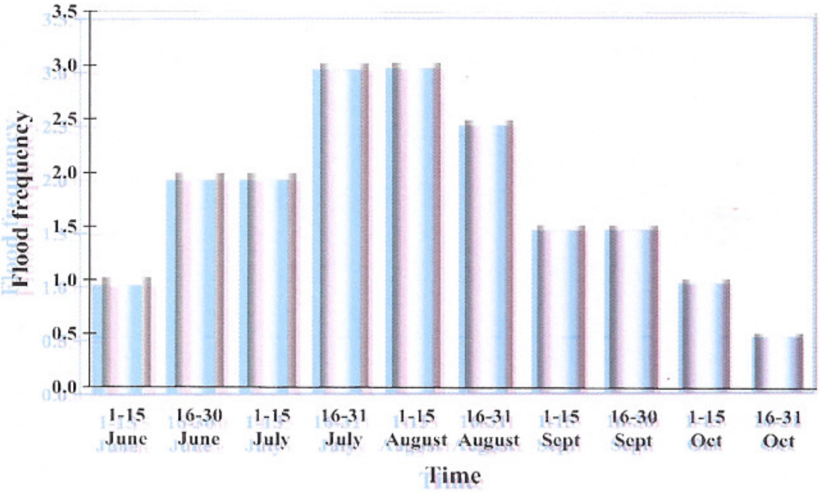

Figure 4. Frequency analysis of timing of flood (>1 m water depth).

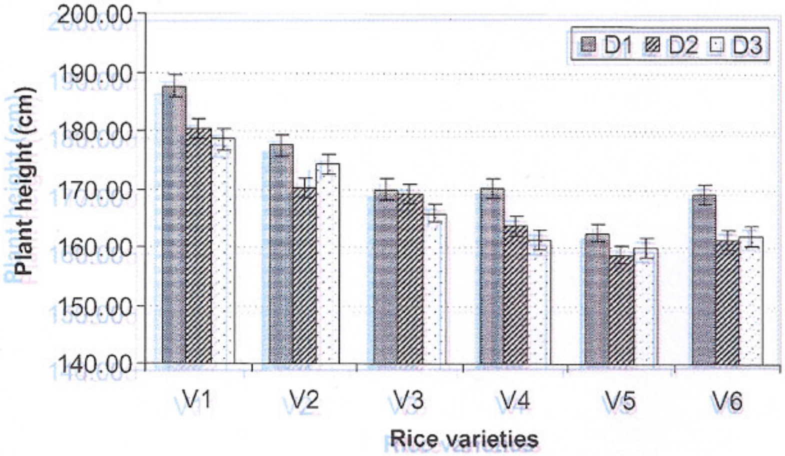

Figure 5. Maximum plant height of different deep water rice varieties at three water depths.

It has already been mentioned that in 2006 the study site experienced high floods during the early growth phase (35 DAS), and as a result the crop was damaged.

In three waterlogging ecologies (D_1, D_2 and D_3), the maximum crop height of six rice varieties was measured. Mean results from 2005 and 2007 revealed that maximum crop heights of 1.78–1.87 m were achieved by 'Hangseswari' (V_1) in three different land ecologies. Maximum crop heights of 1.62 and 1.69 m were recorded in the case of two local DWR cultivars, viz. Bankei (V_5) and Dhalakartik (V_6), respectively. The difference in maximum height of different rice varieties was not statistically significant in different land ecologies (Figure 5). Our study also revealed that the average number of productive tillers m^{-2} was 179–215 in four improved DWR varieties in D_1 land ecology. With increasing water depth, the number of productive tillers decreased. In D_2 land ecology, the reduction was not significant, but at D3 productive tillers m^{-2} were reduced by 19.2–25.7%. In all the land ecologies, introduced DWR varieties like 'Hangseswari' (V_1), 'Saraswati' (V_2), Sabita

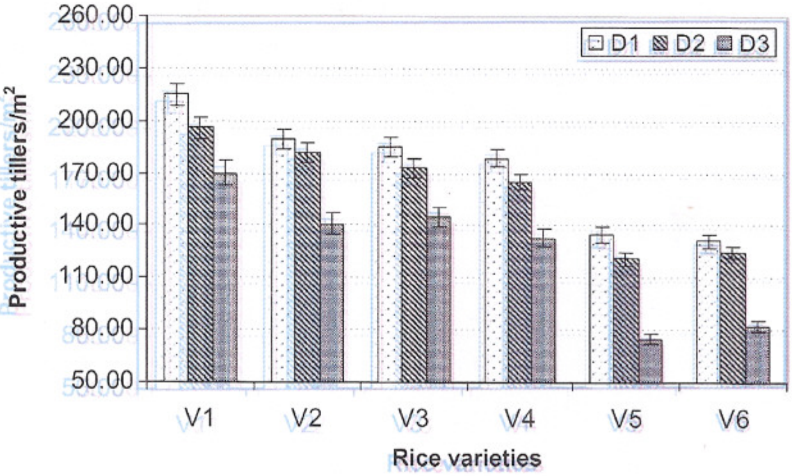

Figure 6. Productive tillers of different deepwater rice varieties at three water depths.

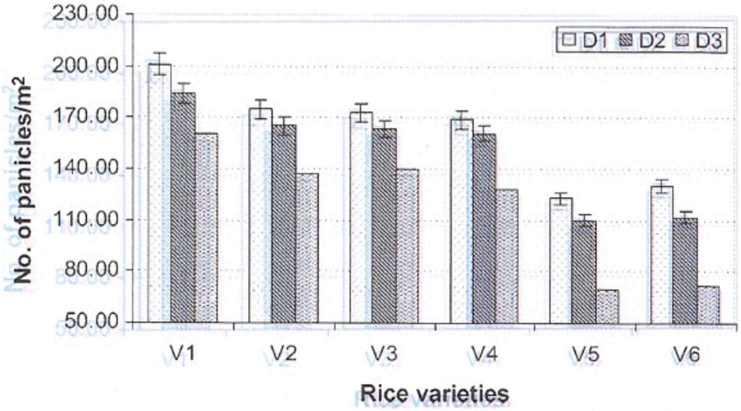

Figure 7. Number of panicles m^{-2} in different rice varieties as influenced by water depth.

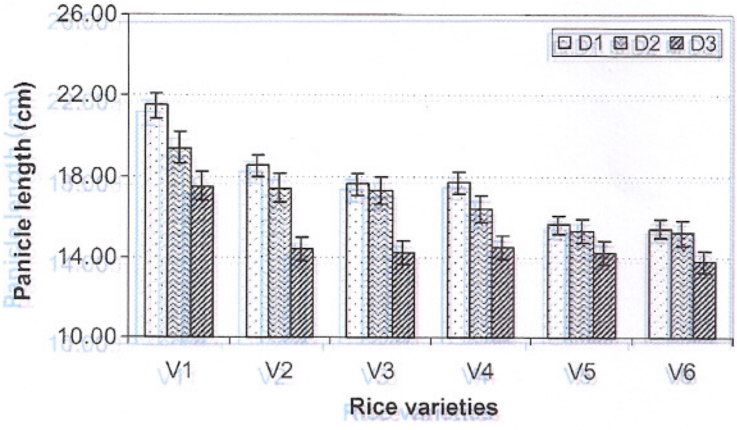

Figure 8. Panicle length of three deepwater rice varieties at three water depths.

(V_3) and Ambika (V_4) performed better than local varieties (V_5 and V_6). Prolonged waterlogging of 0.5–2.5m depths caused a reduction in productive tillers by 37.8–48%, but the DWR variety thrived very well. A similar trend was also observed in the case of production of effective panicles m^{-2}. The highest numbers of panicles m^{-2} of 201, 184 and 161 were observed for the Hangseswari variety in D_1, D_2 and D_3, respectively. With the cultivation of improved DWR varieties like 'Hangseswari' and 'Saraswati', productivity during the rainy season was enhanced and farmers received good yield (2.05–2.95 t ha^{-1}) and net return (4000–5000 Rs ha^{-1}), in different improved varieties (Figure 10). The productivity of all the varieties was decreased with increasing water depth. In D3 (>1.2 m depth), the grain yield was reduced by 31.5–56.1% for different varieties. However, in D_2 ecologies the yield reduction was not very significant in the case of the improved rice varieties, although the two local cultivars recorded significantly lower yields. Yield was reduced by 21.2–25.1% in the case of two local cultivars, viz. Bankei and Dhalakartik, respectively.

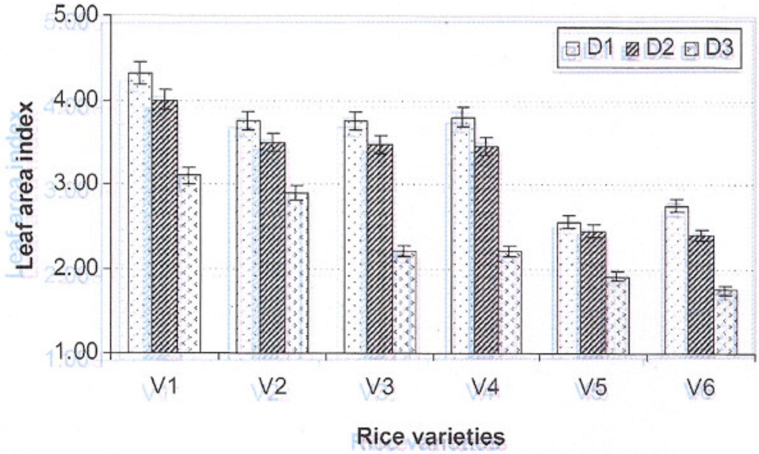

Figure 9. Leaf area index of different deepwater rice varieties at various water depths.

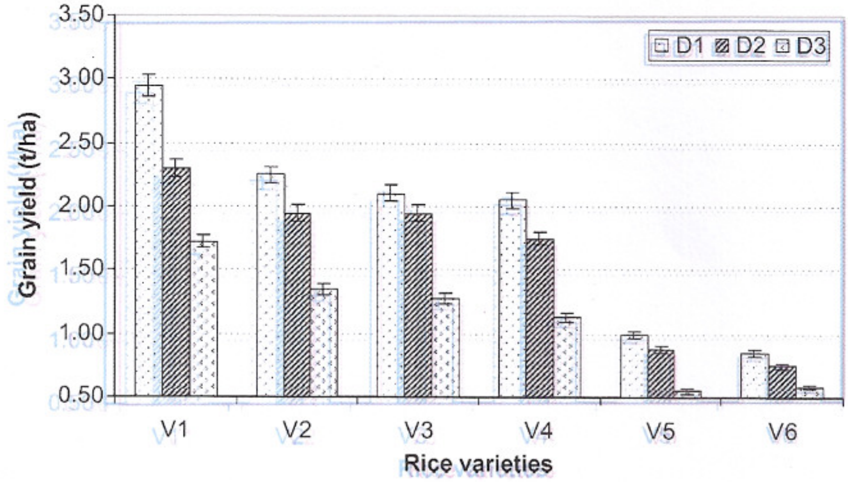

Figure 10. Grain yield of different deepwater rice varieties as influenced by water depths.

In 2006, surface water accumulation occurred early and a surface water depth of 1.5 m was recorded on 4 July after early heavy rainfall on 2 and 3 July. The crop was at the early vegetative stage and crop height was only 0.25–0.35 m during that time (35 DAS). The water depth increased to 2.0 m in 10 days and damaged improved and local varieties of rice crop.

In 2007, the start date for waterlogging was found to be 5 August after heavy rainfall on 4 August. The crop was at the active tillering stage and had attained a height of >1.0 m during that period. As a result, successful cropping was possible during that year.

The starch and total soluble sugar (TSS) contents of grains of different rice varieties were analysed and correlated with their submergence-tolerant ability. The study revealed that varieties differed in their grain quality in terms of starch and total soluble sugar contents (Figure 11 and 12).

The highest amounts of grain soluble sugar and starch were recorded in 'Hangseswari' variety, which has the highest level of submergence tolerance. The mobilization of carbohydrates to provide energy to maintain basic metabolic processes under submerged conditions has been implicated as one of the major metabolic adaptations of rice plants (Baruah et al. 2006). Therefore, it is rational to suggest that the amount of carbohydrates in plant parts may be correlated with the level of submergence tolerance. This information may also be judiciously considered for varietal improvement for adaptation in deep-water ecology (Mallik et al. 1982). Panicle length varied from 13.8 to 21.5 cm in different rice varieties in D1 ecologies. Among the varieties highest panicle weight, filled grain percentage and yield were obtained in 'Hangseswari'. Low yield of rice in D3 ecology might be attributed to fewer ear-bearing tillers per hill.

'Hangseswari' (V1) exhibited higher yield under flooded conditions, which might be due to its superior sink capacity in terms of higher panicle length, panicle weight, grains per panicle and filled grain percentage (Table 5).

Proper agrotechnology needs to be developed for the cultivation of this variety in flood-prone areas. Poor grain yield of rice might be due to limited supply of

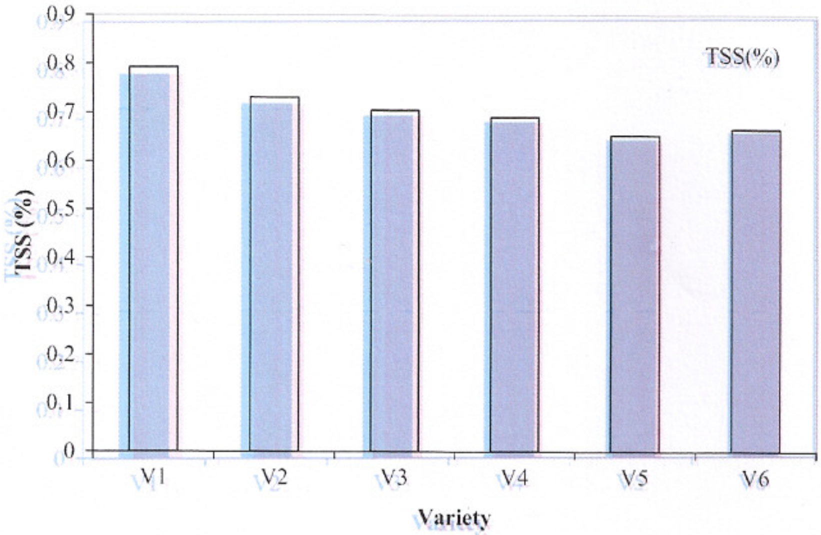

Figure 11. Total soluble sugar (%) in different rice varieties.

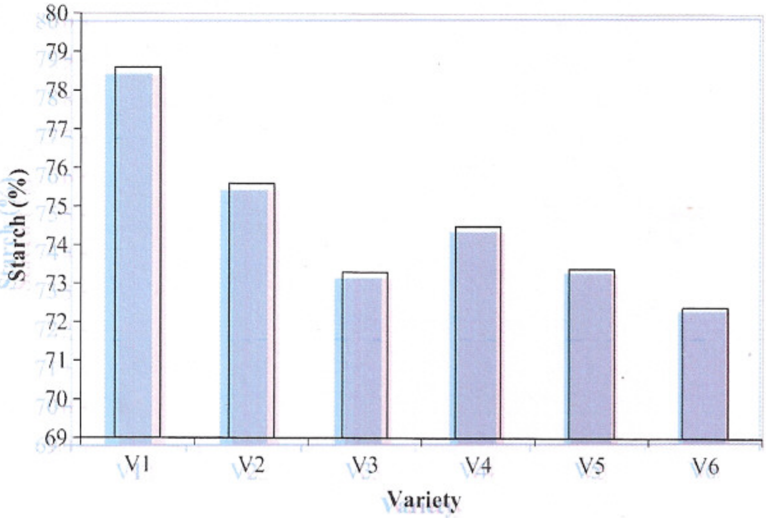

Figure 12. Starch (%) content of different rice varieties.

Table 5. Yield and yield attributing characters of different DWR (average of 2005 and 2007 in D1 ecology).

Variety	Days to 50% flowering	Panicle weight (g)	No of grain per panicle	Filled grain (%)	1000-grain weight (g)
V1	109	4.80	236	90	24.5
V2	108	3.22	214	81	23.8
V3	105	3.40	210	81	25.8
V4	105	2.85	209	80	22.8
V5	100	2.20	194	74	23.8
V6	100	2.05	198	72	24.8
LSD (0.05)		0.675	18.4		NS

NS, not significant.

assimilates to the developing grains (source limitation) or because of a limited capacity of the reproductive organs to accept assimilates (sink capacity).

Further, yields of all the varieties were reduced with increasing flood water depth. The complexity of the aquatic environment necessitates quantitative information about the factors that may limit growth during flooding. Several factors might be responsible for restricting growth like low light intensity, mechanical damage due to turbulence and limited gas diffusion.

The study revealed that oxygen concentrations in flood water in the morning were low (Figure 13). During the daytime, the O_2 concentration at the water surface increased rapidly and reached ~ 0.34 mol m^{-3} around mid afternoon. At depths of 0.5 m or more, O_2 concentration was 0.8 mol m^{-3} throughout the day. The carbon dioxide concentration at the flood water surface contrasted with those of O_2 over the day, levels were usually high in the morning and low in the evening. The carbon dioxide concentration was much higher (1.4–1.8 mol m$^{-3)}$ at lower depths, which might be responsible for restricted growth in deep-water ecology.

Spectral properties of rice in deep-water ecology

Vegetation, in general, showed a spectral response typical of green tissues, with higher energy absorption in visible and higher reflection in NIR bands. But when rice is grown in flood water, spectral reflectance typical of green tissue may not occur. We studied the spectral reflectance pattern of 'Hangseswari' rice at five depths, 0.1, 0.5, 0.15, 0.25 and 0.45 m. Our study revealed that, as water level increased by 5 cm, the difference between visible and NIR reflectance was reduced because of absorption in the visible range and low reflectance in NIR bands (Figure 14).

On average, reflectance in the visible increased from 8 to 32% as water reached above 0.15 m. The highest flooding level (0.25 m) showed a decrease in reflectance at 800 nm from 54 to 29%. In the same way, a higher flood level (0.45 m water depth)

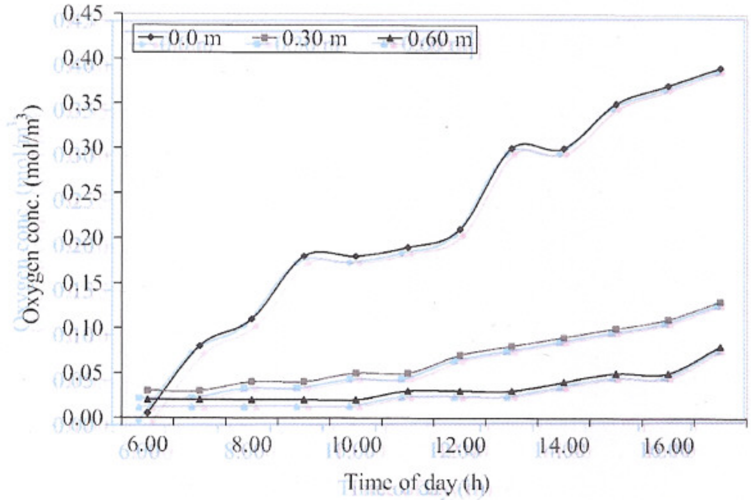

Figure 13. Concentration of O_2 at different depths of flood water.

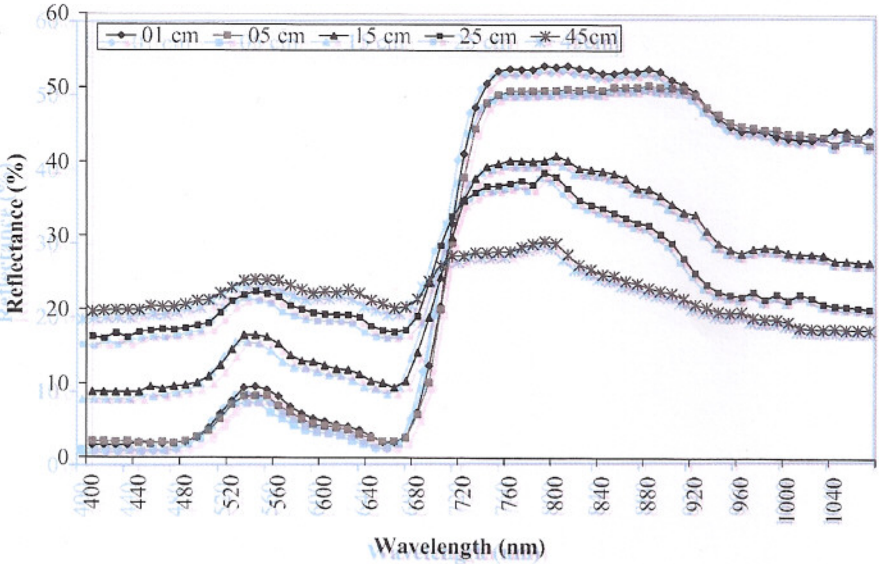

Figure 14. Spectral reflectance pattern of rice under waterlogged condition.

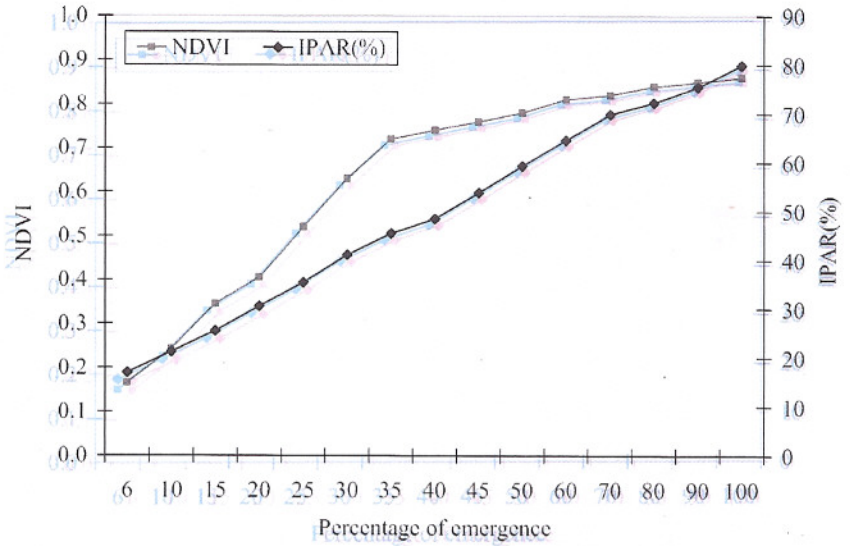

Figure 15. Relationship between normalized difference vegetation index (NDVI) and intercepted photosynthetically active radiation (IPAR) with percentage of emerged biomass.

did not show significant differences between visible and NIR reflectance throughout the range of 430–1000 nm. In the red edge spectral region, which covers ~710–750 nm and was related to vegetation features, reflectance increased with increasing flooding levels. As flooding level increased, absorption in red wavelengths decreased and reflectance in the near infrared decreased. For flooded soils (5–20 cm depth of surface water), a similar pattern of rice reflectance was observed by Casanova et al. (1998). From reflectance values, normalized difference vegetation index was derived and related to the percentage of emergence of the crop. NDVI did not show differences between flooding levels <10 cm, where $>60\%$ of biomass was above water. From 5 cm, NDVI decreased with decreasing proportion of emerged biomass. These results evidence not only the alterations in spectral response data under flooded situations, but also the conditions limiting vegetation index as a reliable estimator of plant biophysical characteristics. The intercepted photosynthetically active radiation (IPAR) was also found to be well correlated with the percentage of emergence of the crop (Figure 15).

Conclusion

Our study revealed that with the introduction of improved DWR varieties, productivity during the rainy season was enhanced and farmers received good yield (2.05–2.95 t ha^{-1}) and net returns (4500 Rs ha^{-1}). Our study also revealed that success and failure of the rainy season rice crop depends upon the onset time of the monsoon, rainfall distribution, and time and depth of waterlogging. Knowledge of flood characteristics such as the nature, duration and frequency of flooding, data on turbidity, water quality and water regimes in shallow, intermediate and deepwater were helpful for adopting DWR. Important crop traits like elongation capacity for particular situations, tolerance for complete submergence for a minimum of seven days, photo-period sensitivity, good tillering ability, kneeing ability, and a strong rooting system with nonshattering grains are very desirable for the successful adoption of rice varieties in deep-water ecology.

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