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ICAR-National Rice Research Institute
Cuttack – 753006, Odisha, India
Phone: +91-671-2367757/67
EPBX: +91-671-2367768-783; Fax: +91-671-2367663
Email: director.nrri@icar.gov.in; https://icar-nrri.in

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IMPROVED WATER MANAGEMENT TECHNOLOGIES FOR RICE PRODUCTION SYSTEM

A.K. Nayak, Anjani Kumar, Rahul Tripathi, B.B. Panda, Sangita Mohanty, Md. Shahid, R. Raja, Rubina Khanam, Debarati Bhaduri, B.S. Satapathy, B. Lal, Priyanka Gautam, P.K. Nayak, S. Vijayakumar, P. Panneerselvam and P. Swain

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Dr. D. Maiti
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FOREWORD

For achieving the sustainable development goals, efficient management of irrigation water is crucial. Continuously depleting water table due to over exploitation of ground water for irrigation purpose has necessitated the need of efficient irrigation technologies for enhancing water use efficiency in agriculture sector in general and rice cultivation in particular. Adoption of innovative water management practices in rice cultivation has the potential to save significant amount of irrigation water. The emerging climatic vagaries further makes the water availability scenario more challenging. Judicious selection of efficient irrigation management practices for a particular agro-climatic zone is essential to enhance water productivity without having any adverse impact on climate.

This publication on "Improved Water Management Technologies for Rice Production System" thoroughly covers the information on different aspects of water management related issues for enhancing water productivity in rice cultivation. It also highlights impact analysis in terms of water footprint of rice production in different stats of India and eco-region based rice farming for enhancing water productivity.

I wholeheartedly appreciate the authors for bringing such an informative and valuable publication that would be helpful to all the stakeholders by disseminating knowledge on efficient irrigation management technologies for rice cultivation.

(D. Maiti)

PREFACE

Rice crop is known to have high water requirement, as it alone consumes more than 50% of the irrigation water available to agriculture sector. The amount of water applied to produce 1 kg of rice ranges from 800 to 5000 L, with an average value of about 2500 L. A major impact of climate will be visible in the form of water stress and rice cultivation being the major user of freshwater available is likely to be affected the most. In the next two decades, there is a need to produce around 25% more from 10-15% reduced share of water. Development of novel water saving technologies is an important step to help rice farmers cope with water scarcity.

ICAR-National Rice Research Institute has developed improved water management technologies for enhancing water use efficiency of the rice based cropping system. These technologies aims at identifying smart, innovative and scalable solutions and facilitating their co-implementation and scaling up. Innovative water saving technologies have the potential to save significant amount of irrigation water which is very crucial in achieving the sustainable development goals and cleaner production systems. Site-specific appropriate water management technology need to be advocated to optimize the water productivity and crop yield potential.

This bulletin is an attempt to provides a comprehensive information to different stakeholders about efficient irrigation management technologies. It also highlights water smart practices in rice farming for efficient irrigation management. These practices can be helpful in sustaining crop productivity even in water stress situations without associated ecological harm to the environment. Authors hope that farmers, researchers, extension workers, policy planners and other stakeholders will find this publication useful.

Authors

CONTENT

1. Introduction

Rice is staple food for about 800 million people of India. It plays a major role in diet, economy, employment, culture and history. It is the staple food for more than 65% of Indian population contributing approximately 40% to the total food grain production, thereby, occupying a pivotal role in the food and livelihood security of people. India grows rice in 43 Mha with production of 112 million tons (Mt) of milled rice and average productivity of 2.6 t ha^{-1} (Pathak *et al.,* 2020). The crop is grown in highly diverse conditions ranging from hills to coasts. Primarily a *kharif* crop, it is cultivated round the year in one or the other parts of the country. Area under rice has remained almost unchanged over the years, but production has increased more than five times. With this, India has not only achieved self-sufficiency in rice but also produces surplus to export. The leading rice producing states are West Bengal, Uttar Pradesh, Punjab, Odisha, Andhra Pradesh, Bihar and Chhattisgarh. About 40% of the rice area in India is rainfed and more than 70% of which is in eastern India. Out of the total rainfed area, 23% are rainfed upland and 77% are rainfed lowland. The entire rainfed upland and 52% rainfed lowlands are drought prone. About 17% of rainfed lowlands are flood prone (Pathak *et al.,* 2020). The climate change has further aggravated the water situations. There has been decrease in number of rainy days, increased dry spell, reduced wet spell; though there has not been much change in total precipitation but more rainfall is received in lesser time, resulting in increased frequency of both drought and flood. There is uneven spatial and temporal distribution of rainfall. Sustainable rice production is the key to achieving Sustainable Development Goals (SDGs), particularly for country like India. We need to enhance productivity, profitability, input use efficiency and climate resilience in rice systems to achieve the SDGs.

Rice is a water guzzling crop. In India, 52% of rice is irrigated and consumes around 40% of all irrigation water resources. Rice crop is regarded as most inefficient user of water, as 60-83% of total water applied to rice field is lost as deep percolation. Hence, assessing and reducing the water footprint of rice by employing irrigation water management, agronomic measures and other advanced tools and techniques has been a prioritized research area of National Rice Research Institute (previously known as Central Rice Research Institute)

2. Estimation of water footprint of rice production in different states of India

Indian agriculture contributes about 16% of India's total greenhouse gas (GHG) emissions, emitting 417.22 million tons of CO_2 equivalent each year, of which

74% is CH_4 and 26% is N_2O (MoEFCC, 2018). Water footprint (WF) refers to both direct and the indirect use of water by a consumer or a product (Haida *et al.,* 2018). WF has three components: blue, green and grey WF (Hoekstra *et al.,* 2011). The total rainfall or moisture available to plants held in the unsaturated soil is referred as green WF. The blue WF refers to the amount of fresh surface or groundwater consumed in producing goods and services. The grey WF, a measure of pollution, is the amount of water consumed for assimilating the pollutant load to meet ambient water quality standards (Haida *et al.,* 2018). Assessing WF is an important way of creating awareness about challenges of global water crisis (Chapagain and Tickner, 2012). Assessment of water footprints will help to innovate and adopt the possible approaches to reduce its footprint to combat the effects of climate change. ICAR-NRRI has done comprehensive water and carbon footprint profiling of different states of India and has come out with suitable recommendations.

Water footprint

There are three types of WF namely, **blue**, **green** and **grey WF,** which together indicates the direct and indirect application of freshwater resources used for crop production and are calculated for estimating the total water footprint of rice.

Green and Blue water footprint calculation using CROPWAT

Green and blue WFs for rice crop for Indian states were computed using FAO CROPWAT 8.0. Thirty-year average weather data during the crop seasons, soil data and crop details, which includes the crop growth period and crop coefficient (Kc) values, were used as inputs to the CROPWAT model for calculating the effective rainfall, crop evapotranspiration (ETc) and irrigation water requirements to fulfil the crop's evapotranspiration needs. The crop water requirement (CWR) module in CROPWAT was used to calculate the irrigation water requirement of the crop over the total crop growing season based on the difference between the crop evapotranspiration (ETc) and effective rainfall (ER). The USDA Soil Conservation Service (SCS) method (Smith, 1992; Pongpinyopap and Mungcharoen, 2012; Boer, 2014) was used for calculating the ER using CROPWAT.

We have used the CWR module in this study, which is based on the assumption that there was no water limitation during the crop growth period (Ortiz-Rodriguez et al. 2015). The soil moisture required for meeting the ETc needs is fulfilled by rainfall or/and irrigation. First, the water needs are fulfilled by the ER for the areas where rainfall occurs during the crop growth period and if there is excess water demand, it was fulfilled by irrigation. Hence it is assumed that crop does not suffer water stress.

The effective rainfall and the irrigation water requirement throughout the crop season for fulfilling the crop ET was considered as the green water and the blue water requirement of the crops, respectively (Lassche, 2013). In the present study, the volumetric approach for estimating the green, blue and grey water footprint (m^3 ha^{-1}) for different crops (Hoekstra, 2003; Chapagain and Hoekstra, 2008; Hoekstra *et al.,* 2009) was used (Equations 1-6).

Grey water footprint calculation

The volume of water required for diluting the pollutant load to the normal adopted concentration standard which leaches and joins a receiving water-body depends on the concentration and the type of the pollutants. In the present study, nitrogen (N) was considered as the representative pollutant element for estimating grey water footprint, due to the importance on N as a pollutant in India and a lack of availability of information regarding other pollutants. The grey water footprint was calculated by considering the maximum allowable concentration of nitrate as 10 mg L^{-1} (measured as N) in drinking water as per the standard recommendation (EPA, 2005) and assuming that 10% of the applied N fertilizer on average is lost through leaching (Equation 7) i.e. considering a leaching factor of 0.10 (Chapagain *et al.,* 2006). The natural concentration (c_{nat}) of nitrate in the receiving water-body was assumed to be zero following Hoekstra *et al.,* 2011, due to lack of information on the nitrate concentration of the receiving water-body.

$$WF_{blue}(m^3ha^{-1}) = 10\ x \sum_{d=1}^{cgp} ET_{blue} \quad \text{Equation----- (1)}$$

$$WF_{green}(m^3ha^{-1}) = 10\ x \sum_{d=1}^{cgp} ET_{green} \quad \text{Equation---- (2)}$$

$$ET_{green}\left(mm\ day^{-1}\right) = \min(ET_c, P_{eff}) \quad \text{Equation---- (3)}$$

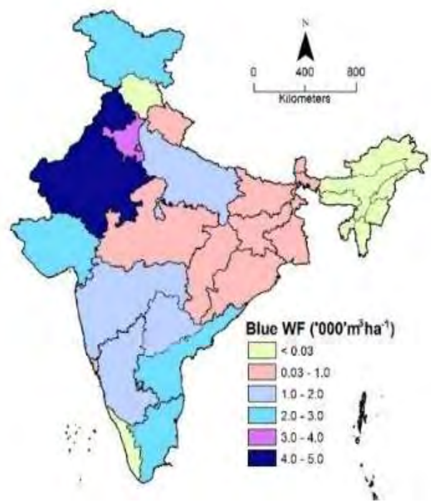
$$ET_{blue}\left(mm\ day^{-1}\right) = \max(0, ET_c - P_{eff}) \quad \text{Equation---- (4)}$$

$$WF_{grey}(m^3ha^{-1}) = \frac{f\ L_N(kgha^{-1})}{C_{N,max} - C_{N,nat}(mgL^{-1})} \times 10^3 \quad \text{Equation---- (5)}$$

$$TWF(m^3ha^{-1}) = WF_{blue}(m^3ha^{-1}) + WF_{green}(m^3ha^{-1}) + WF_{grey}(m^3ha^{-1}) \quad \text{Equation-- (6)}$$

Where, WF_{blue}, blue water footprint (m^3 ha^{-1}); WF_{green}, green water footprint (m^3 ha^{-1}); WF_{grey}, grey water footprint (m^3 ha^{-1}); ET_{blue}, blue water evapotranspiration (mm); ET_{green}, green water evapotranspiration (mm); factor 10 for converting water depths in mm into water volumes per land area (m^3 ha^{-1}); cgp, crop growing period (days); f, fraction of N which leaches or goes as runoff (kg ha^{-1}); L_N, N application rate (kg ha^{-1}); $C_{N,max}$, maximum acceptable N concentration to the receiving water body (g L^{-1}); $C_{N,nat}$, natural concentration of N in the receiving water-body (g L^{-1}); 103, factor for converting N concentration from mg L^{-1} to m^3 kg^{-1} and TWF, total water footprint of crop (m^3 ha^{-1}).

Rice is mainly cultivated during the wet season in India with an average rainfall of 300 to 650 mm. The average total water footprint of rice was estimated to be about 7.5×10^3 m^3 ha^{-1} whereas the green WF was 5.2 times higher than the blue WF. Average water footprint from the four states (Punjab, Haryana, Gujarat and Rajasthan) were around 18% higher than average rice water footprint of India (Fig 1a-c). In the north-western part of India (Punjab and Haryana) the irrigation water productivity (0.22 kg m^{-3}) is lower reflecting the inefficient kind of operating rice ecology irrigation method followed as compared to Chhattisgarh and Jharkhand where the irrigation water productivity (0.68 kg m^{-3}) is highest (Nayak *et al.,* 2021a).



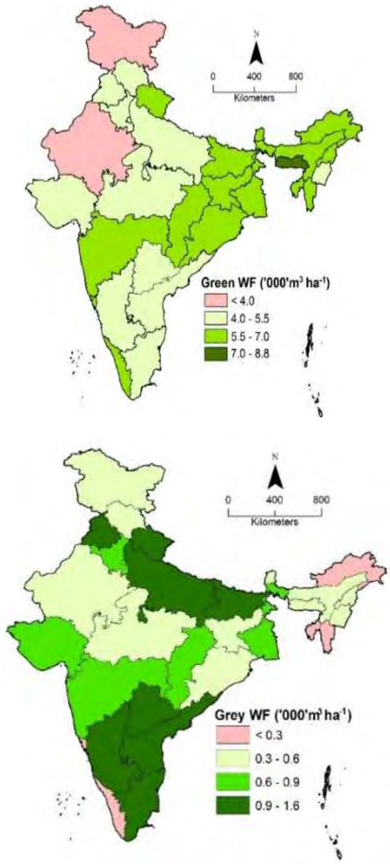


Fig. 1. Water footprint of rice in India (a) Blue water footprint (Blue WF), (b) Green water footprint (Green WF), (c) Grey water footprint (Grey WF).

It is suggested for shifting major chunk of rice productions to central and eastern states by diversifying rice grown area of Punjab and Haryana could help India to prevent an impending water crises.

3. Ecoregion-based rice farming for enhancing water productivity

Sustainable rice production is the key to achieving Sustainable Development Goals (SDGs), particularly for country like India. Growing rice in non-conventional and unsuitable ecoregions, however, has generated several environmental problems such as depletion of groundwater, pollution of air, degradation of soil and aggravation of climate change. All these degenerative factors are taking toll on the productivity, profitability and sustainability of rice farming. To achieve sustainable and environment-friendly rice farming, the crop should be cultivated in the region where its environmental footprint is the minimum. This can be accomplished with ecoregional approach of rice farming. Ecoregions are geographical regions with similar ecological, soil and climatic conditions. Rainfall, temperature and soil are the three most important biophysical factors determining ecoregions for growing rice.

ICAR-NRRI has come out with ecoregion based rice farming for enhancing productivity and reducing use of irrigation water (Pathak *et al.,* 2020). The

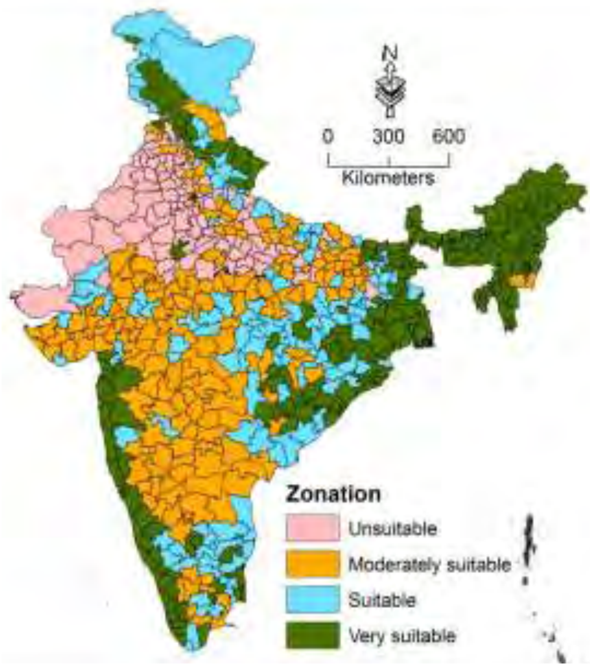


Fig. 2. Map depicting suitability of rice areas in India (Pathak *et al.*, 2020).

rice suitability index was developed using annual rainfall data, clay content and mean seasonal air temperature, and a map was developed using arcGIS 10.0 platform, which depicts suitability classes for different districts for rice production. As per the suitability classes north-eastern states and eastern states fall under suitable or very suitable categories (Fig. 2). Most of the central Indian states fall under moderately suitable zone and north western zone fall under unsuitable zone.

4. On - farm water saving technologies

Rabi rice is cultivated in Odisha, West Bengal, Assam and Andhra Pradesh under irrigated situation that consumes plenty of irrigation water. Some of the water saving technologies developed by conducting trials in different agro-ecologies has shown promising results under specific situation, if up scaled these technologies can save significant amount of irrigation water from rice production.

4.1. Agronomic practices for higher water use efficiency

Various agronomic practices like laser land leveling, field bund raising, furrow irrigated raised bed, and raised and sunken beds can increase irrigation water use efficiency and save significant quantity of irrigation water, with marginal or no reduction of grain yield.

4.1.1. Laser land leveling

It is the process of leveling the land surface at an accuracy level of ± 2 cm from its mean elevation by using laser-equipped drag buckets (Fig. 3). Besides, this method creates a constant slope of 0-0.2% throughout the field, for which, irrigation water spreads uniformly in every part of the field with negligible loss from run-off or waterlogging. Large horsepower tractors and soil movers equipped with global positioning systems (GPS) and/or laser-guided instrumentation are used in this method. The soils are moved either by cutting or filling to make the land surface well leveled. Laser leveling increases water saving by approximately 20-25%, increases approximately 3 to 5% of cultivable land area, reduces GHG emission and increases the yield of crops (Nayak *et al.,* 2020a).

Fig. 3. Laser land leveler in action

4.1.2. Field bund raising

In lowland flooded paddy, water loss may occur mainly due to seepage, percolation loss and runoff. Water flow through and over bunds around rice fields are primarily responsible for higher water loss, thereby reducing water productivity. For this, about 50 cm high earthen bund along with mud plastering allows the water to retain within the field boundary (Fig. 4). These structures are easy to build, reduce runoff and conserve topsoil. However, further raising of field bund from 50 to 75 cm reduces the runoff of water in heavy rainfall events and provide additional water for groundwater recharge. Increasing peripheral field bund by 18-20 cm in rice paddy can store 90% of the total rainwater *in situ* and simultaneously improve rice productivity (Nayak *et al.,* 2020a).

Fig. 4. Field bund raising

4.1.3. Sunken and raised bed

Alternate sunken and raised bed is made by excavating soil of a strip of 5 m, a depth of 20-30 cm and placing the soil in the adjacent strip (5 m). The height of the raised bed is 40-60 cm higher than the adjacent sunken bed (Fig. 5). As the removal of top fertile soil from sunken bed creates poor fertility conditions, the application of FYM @ 10 t ha^{-1} is recommended for maintaining soil fertility. Vegetables like chillies, brinjal, okra, amaranthus, cucumber, bitter gourd can be grown on beds during monsoon season and long duration paddy cum fish (singhi/ magur) can be practiced in furrows. To prevent soil erosion from the raised bed, planting of papaya at a distance of 1.5 m is useful. A higher rice grain yield of about 13-15% is obtained in this system compared to unmodified

Fig. 5. Sunken and raised bed

and conventional rice cultivation. The water use efficiency as well as water productivity enhanced by about 3–4 times under sunken and raised bed as compared to farmers' practice of rice monocropping (Nayak *et al.,* 2020a).

4.2. Improved method of irrigation

Water is an essential input for crop growth. There are various ways (surface, pressurize, lift, and groundwater irrigations) in which the irrigation water can be applied to the fields. In surface irrigation, the soil is flooded with water, which is approximately followed in about 90% of the irrigated areas of the world. In pressurize irrigation, water is applied to the crop under pressure. About 5% of the areas are irrigated by this method. In lift irrigation, water loss during conveyance is avoided. Groundwater irrigation is applied through tubewells where groundwater quality is suitable for irrigating the crop. Choosing the right method of irrigation depends upon several factors like availability of water, topography, climate, soil type, crops to be grown, economics, local traditions, and skills (Nayak *et al.,* 2020a).

4.2.1. Surface irrigation

Surface irrigation is an age-old practice of providing irrigation water to the field and highly followed method of irrigation in the world. In this method water is applied through the action of gravity, sometimes the whole field is flooded (e.g. check basin) or the water is applied to small channels (e.g. channel to the field) or in strips (e.g. border strip). In these cases, irrigation application efficiency rarely exceeds over 45- 60% (Nayak *et al.,* 2020a).

Fig. 6. Check basins

4.2.2 Check basins

Check basins are necessarily rectangular or square areas measuring about 10-100 m^2 or even more with bunds surrounded by levees or checks, constructed around the area to control the irrigation water (Fig. 6). Construction of small irrigation channels in between two adjacent rows of beds helps the water to be conveyed to the field by the main irrigation channels and lateral field channels. This is a water-smart technology and scientifically designed check basins saves about 10-30% water compared to conventional flooding. Check basin irrigation is suitable for many field crops including rice and fodder crops that prefer flooded water. Heavy soil with low infiltration rate is preferred for check basin irrigation (Nayak *et al.,* 2020a).

4.2.3 Border strip irrigation

Fig. 7. Border strip irrigation

In border strip irrigation, borders are long, uniformly graded stripes of land separated by earth bunds. In contrast to basin irrigation, these bunds are not to contain the water for ponding, but to guide it as to flow down the field. In contrast to furrows, these bunds prevent lateral movement of water within the bunds, whereas furrows are provided for lateral percolation of water in the sub-soil directly (Fig. 7). The field to be irrigated is aligned into strips by parallel dikes or border ridges, and each strip is irrigated separately. Slopes of each unit should be uniform, with a minimum slope of 0.05% to facilitate suitable drainage and a maximum slope of 2% to limit the soil erosion. This water-smart technology saves about 10-30% of water as compared to the conventional flooding. Yield is also increased by 25-35% in the border strip method of irrigation over the conventional flooding. Deep homogenous loam or clay soils with medium infiltration rates are preferred for such irrigation. It is suitable for irrigating aerobic rice (Nayak *et al.,* 2020a).

4.2.4 Channel to field irrigation

Fig. 8. Channel to field irrigation

In eastern India, especially Odisha, canal irrigation is dominant in which water is flooded from field to field where farmers have less control over the flow of water. The water flows continuously through the fields, and the water distribution is quite irregular, with heavy percolation loss of applied irrigation water. The inclusion of field channels in existing flood irrigation system provides better control over water resulting in 15% saving of irrigation water (Fig. 8). However, channel to field method of irrigation during dry season at Badakushunpur could achieve a considerable increase in water use efficiency (17% higher) and grain yield (7-8% higher) of rice as comparable to farmer's traditional practice of field to field irrigation. Irrigation efficiency can further be increased by applying measured quantity of water using a parshall flume. The irrigation efficiency of this system is around 50% (Nayak *et al.,* 2020a).

4.3 Water-efficient rice production system

Rice consumes a large quantity of water. The share of irrigated rice is about 52% in India, while 43% in Odisha. Irrigated rice consumes 40% and 65% of all irrigation water resources in India and Odisha, respectively. In Odisha, rice is one of the dominant but the most inefficient user of water (3.7 kg ha mm^{-1}), approximately requires 1 cm water for each day duration. About 60-83% of total water applied to the rice field is lost as deep percolation. This scary situation is likely to be further aggravated in the context of climate change, some water-efficient rice production systems are available that involve growing of rice under less water than the conventional systems. Technologies like aerobic rice, system of rice intensification and dry direct-seeded rice need less water to the tune of 20-60% than the conventional method of cultivation (Nayak *et al.,* 2020a).

4.3.1 Aerobic rice

Aerobic rice production technology involves growing rice in non-puddled and non-flooded conditions (Fig. 9). The irrigation water is given intermittently when the soil moisture content reaches a lower threshold at tensiometer reading in between -20 and -30 kPa. However, a thin film of water (1-2 cm) should be maintained after panicle initiation. Being both water and energy-smart technology, this method could save about 37-60% of water as compared to the conventional flooded system. There could be a yield loss to the extent of 20-40%, which however could be minimized through improved crop management practices and selection of suitable short

Fig. 9. Aerobic rice

duration varieties like, Shabhagi Dhan, CR Dhan 200, CR Dhan 202, CR Dhan 203, CR Dhan 205, CR Dhan 206, CR Dhan 207, CR Dhan 209, Apo and MTU 1010. Aerobic rice production system reduces continuous seepage, percolation losses, enhances water productivity, reduces the labour requirement, energy requirement, and GHG emission (Kumar *et al.,* 2019a). However, aerobic rice is not suitable for high rainfall areas where water cannot be controlled. On station trial of rice (variety; Apo) grown under different soil water potential based irrigation management showed that there was a significant saving of irrigation water (38%) under soil water potential (SWP) of -40 kPa, without any significant decline in grain yield as compared to continuously flooded rice (Kumar *et al.,* 2017a; Ghosh and Singh 2010).

4.3.2 System of rice intensification

The system of rice intensification (SRI) is a package of improved practices for growing rice crop. It was first conceptualized in Madagascar by Father Henri Laulanie in 1983. It is essentially a water-smart technology saving up to 20-50% water. Irrigated medium and favorable bunded uplands in the wet season, rainfed shallow lowlands where water control is possible, irrigated boro/ *rabi* rice are suitable for SRI. It encompasses a set of five simple principles work synergistically to enhance yield:

Fig. 10. Transplanting of younger seedlings at wider spacing in SRI at vill – Badakushunpur, block – Tangi.

- Transplanting at the early age, more preferably seedlings of 8-12 days are suitable, when the plant has only two small leaves, before the fourth phyllochron.
- Transplanting of a single seedling per hill and wider spacing in square fashioned is practiced. Seedling still attached with the seed, transplanted at 1-2 cm, keeping roots at horizontal position, planting at grid point demarcated by a marker.
- Mechanical weeding (rotary hoe/ conoweeder) for 2-3 times is recommended. The first series of weeding to be completed at 10 DAT (days after transplanting) and others in a frequency of 10-15 DAT.

- Maintenance of moist soil under non-saturated conditions during the vegetative phase, which results in the development of more tap and primary roots.
- Application of organic manures for optimum biological activity and continual release of nutrients.

The major benefits of this technology are lower seed requirement (5kg ha^{-1}), water-saving (20-50%), very high yields (35-40%), improved soil health, improved input use efficiency and lower methane emission (50-60%) (Lal *et al.,* 2016).

4.3.3 Direct seeded rice

Direct seeded rice (DSR) is an establishment technique for rice crop in which seeds are sown in the field directly in the main field rather than by transplanting seedlings from the nursery to the main field. Direct seeding is done by either sowing of pre-germinated seeds into a puddled soil (wet direct seeding) or well prepared non-puddled seedbed (dry direct seeding). Both the dry seeding and wet seeding are commonly practiced in Odisha. The main problem associated with DSR (more specifically in dry DSR) is the weed infestation. If proper weed management is not adopted the yield losses may go up to 85%. Seed priming using water and KCl is one of the promising approaches to overcome poor crop establishment. Short and medium duration rice varieties are preferred for DSR in upland and medium land. Water stress must be avoided during critical stages of seedling emergence, active tillering, panicle initiation, and flowering. The overall duration of the crop is reduced by approximately 10 days as compared to transplanted rice. The other benefits include reduced labour requirement that is required for nursery bed raising and transplanting and less methane emission (Kumar *et al.,* 2019a).

4.3.4 Dry direct-seeded rice

In dry direct-seeded rice (D-DSR), dry seeds are sown directly in the main field. Dry direct seeding is commonly practiced in rainfed uplands, medium low land, lowland and deepwater ecologies during the wet season. In D-DSR, land preparation is done by ploughing the soil twice by rotavator/ cultivator, followed by crop establishment using several methods, including (i) broadcasting of dry seeds on un-puddled soil after either zero tillage (ZT) or conventional tillage (CT) (ii) dibbled method in a well-prepared field and (iii) drilling of seeds in rows after CT, minimum tillage (MT) using a power tiller-tractor operated seeder. In the case of both CT and ZT, a seed-cum-fertilizer drill is used, which, after land preparation or in ZT conditions, places the fertilizer

Fig. 11. Sowing in dry direct seeding method using manual seeder

Fig. 12. Tractor drawn dry direct seeding for sowing

and drills the seeds (Figs. 11 & 12). In this method of establishment, weed is a major menace, which can be controlled by using post-emergence herbicide. The D-DSR saves water (up to 30%) over conventional transplanted rice. This method also helps in curbing CH_4 emissions ranging from 18-20% compared to conventional puddled transplanted rice (Kumar *et al.,* 2016). Additionally, this method reduces labour requirement, improves the emergence of seedlings, and reduces the chance of lodging.

Dry-DSR was demonstrated over an area of 0.73 acres in Badakusunpur village of Tangi where land preparation was done by using rotavator to make well pulverized soil followed by sowing by tractor drawn seed drill and weeding by herbicide application. Dry direct seeded rice (Dry-DSR) recorded 25% higher rice yield compared to random transplanted rice (Farmer's practice) Water productivity was 32% higher in dry DSR compared with transplanted rice followed in farmer's field (Annual progress report 2019-20) (Fig.13).

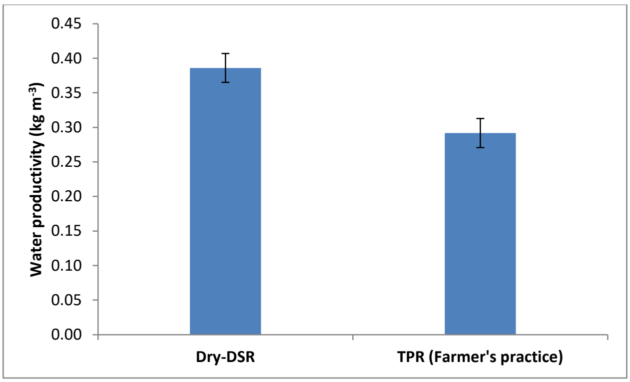


Fig. 13. Water productivity in Dry-DSR compared with random transplanted rice followed in farmer's field

4.3.5 Wet direct-seeded rice

Fig. 14. a. Broadcasting of sprouted seeds

Fig. 14. b. Power drawn drum seeder for sowing sprouted seed in WDSR

Although wet direct-seeded rice (W-DSR) does not save much water as compared to D-DSR, this practice is recommended when the late onset of monsoon rain does not allow farmers to sow the crop in time. Application of irrigation water and sprouted seeds can help to sow the crop through the direct seeding method on time and this method uses less water compared to the traditional transplanting. W-DSR involves sowing of pre-germinated seeds (radicle 1- 3 mm) on or into puddled soil through manual broadcasting or tractor-drawn drum seeder (Figs. 14 a & b). When pre-germinated seeds are sown on the surface of puddled soil, the seed environment is mostly aerobic and this is known as aerobic W-DSR. When pre-germinated seeds are sown/ drilled into puddled soil, the seed environment is mostly anaerobic and this is called anaerobic W-DSR. The W-DSR under aerobic and anaerobic, seeds can either be broadcasted or sown in-line using a drum seeder or an anaerobic seeder with a furrow opener and closer. The yield in W-DSR rice crop was found to be at par with that of transplanted rice when proper management practices are followed. It also increased water productivity by 0.3 to 0.4 kg rice m^{-3} water (Kumar *et al.,* 2017a; Nayak *et al.,* 2020a).

Wet-DSR was demonstrated over an area of 0.25 acres in Sundarda village of Niali block and Badakusunpur village of Tangi block where the field was prepared by puddling and followed by sowing the germinated seeds after 12-24 hours using a drum seeder.

W-DSR recorded 24.3% higher rice yield as compared to conventional random transplanted rice (TPR) (farmers' practice) (Fig 15 a) and there was a reduction of Rs 10500 in cost of cultivation per hectare as compared to TPR (farmers' practice) at Badakusunpur village, Whereas in Sundarda, there was 28.9% (Fig 15 b) higher rice yield in W-DSR as compared to conventional TPR and significant reduction in cost of cultivation per hectare as compared to TPR (farmers' practice). The water productivity at both the experimental sites were higher (24-28%) in W-DSR as compared to TPR (Annual progress report 2019-20).

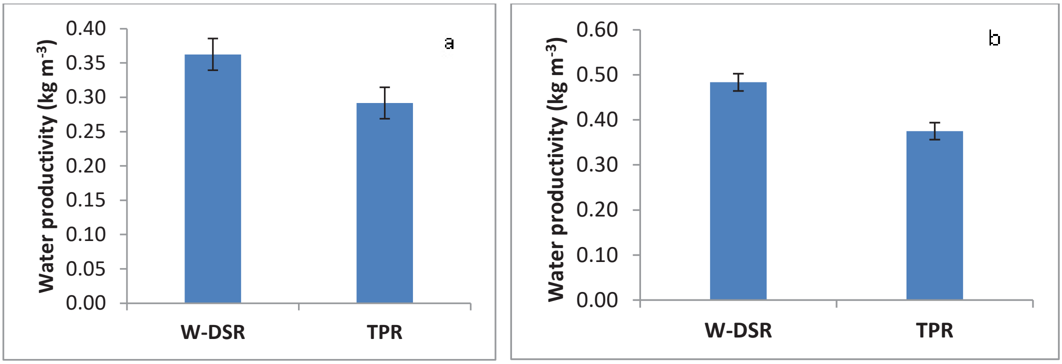


Fig. 15. Water productivity under W-DSR and TPR (Farmer's practice) at (a) village Badakusunpur and (b) village Sundara of block - Tangi block, Dist- Cuttack, Odisha.

4.4. Irrigation Scheduling

Application of irrigation water with respect to time and space based on the evaporative demand of the crops is referred as scheduling of irrigation. In water-scarce areas, irrigation scheduling in rice is done using saturated soil culture (SSC), alternate wetting and drying (AWD), tensiometer based irrigation, and critical stage based lifesaving irrigation.

Rice has five critical stages (tillering, panicle initiation, booting, heading, and flowering/anthesis). Moisture stress at active tillering phase and reproductive phase reduces yield by 30% and 50-60%, respectively. Application of water in AWD or SSC upto tillering followed by maintenance of 5-8 cm standing water saves about 50% of water as compared to continuous submergence without any yield loss. During *kharif*, the application of water could be delayed up to 3-4 days of disappearance of ponded water in vegetative stage, while in *rabi*, the application of water could be delayed up to 1-2 day of complete disappearance of ponded water. This method saves about 10-25% of irrigation water.

4.4.1 Saturated soil culture

In saturated soil culture (SSC), the soil is kept as near to saturation as possible and it requires regular shallow irrigation (standing water depth 1 cm) on daily basis or once in every two days (Fig. 16). The best way of using SSC is in raised beds in which the soil can be kept around saturation effectively. The raised beds are used for growing rice and shallow irrigation is applied in furrows. About 5-50% water can be saved if SSC is used scientifically. However, the saving of water varies with soil type and groundwater table depth. On an average, SSC can decrease water input by 23% from the continuously flooded condition. This technology is a good alternative to flooded rice production in semi-arid tropical environment (Nayak *et al.,* 2020a).

Fig. 16. Saturated soil culture

4.4.2 Alternate wetting and drying

Alternate wetting and drying (AWD) is a method of controlled and intermittent irrigation. It is a water-saving technology that saves up to 15-30% water with no/little yield loss (up to 5%). In this process, irrigation water is applied from 10 DAT or 20 DAS only after the disappearance of ponded water from the soil surface. The most efficient and accurate way to implement AWD is through the use of a 'field water tube' or 'pani pipe' of 30 cm length and 7-10 cm diameter to keep vigil the water depth. After a few days of application of irrigation, when the water level drops below 15 cm from soil surface, the field should be re-irrigated (Figs 17 a & b). However, during the sensitive stages (flowering) a thin layer of water of about 5 cm is always advocated. AWD improves water use efficiency and reduces greenhouse gas emissions by 30-50% (Annual progress report 2019-20).

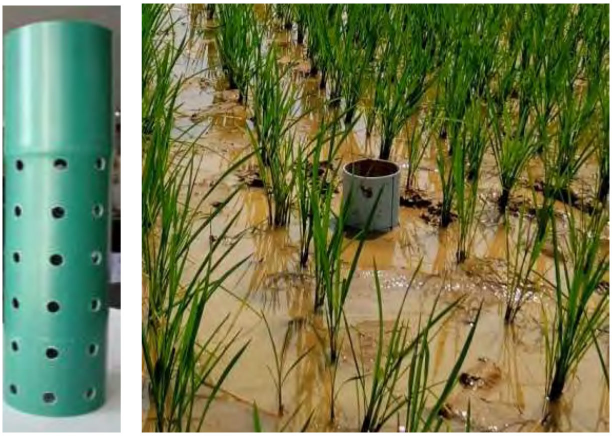


Fig. 17. (a). pani pipe (b) alternate wetting and drying method in rice field

4.4.3 Tensiometer based irrigation management

In AWD method of irrigation in rice, effective irrigation scheduling can also be done based on soil water potential as measured by tensiometer. ICAR –

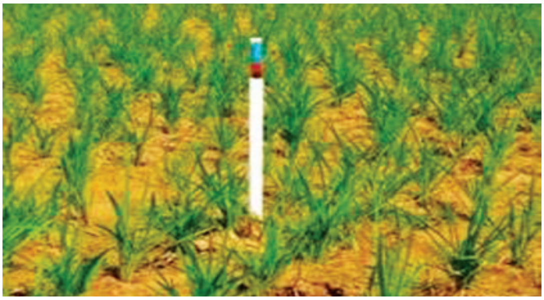


Fig. 18. Color coded tensiometer based irrigation management

Fig. 19. Color coded tensiometer showing different color bands

NRRI has developed a simplified and farmer-friendly version of tensiometer tube for irrigation scheduling based on real-time measurement of soil water potential (Kumar *et al.,* 2021b; Tripathi *et al.,* 2021). In this tensiometer tube, the usual measuring gauge has been replaced by the stripes of light blue, deep blue, orange and brown colour (Figs 18 & 19). The water level in tensiometer tube up to light blue stripe signifies no need for irrigation, there is a need to irrigate when the water level enters the deep blue stripe. The entry into the orange and brown stripe may adversely affect the crop yield and hence should be avoided. Irrigation scheduling based on tensiometer is reported to save around 30% of irrigation water (Kumar *et al.,* 2017a, 2021c) as compared to continuously flooded method.

Water productivity and other benefits of improved methods (AWD, SRI and Tensiometer based irrigation) practiced at Tangi block, Cuttack is presented in Table 1. The water productivity of flooded irrigation treatment was lowest (0.25 kg m^{-3}) as compared to all the climate smart water management methods implemented (Annual progress report 2019-20).

Table. 1 Water productivity of rice under different irrigation regimes

Treatments	Grain yield (t/ha)	Water used (mm)	Water productivity (kg/m^3)	% of water saved over flooding
Flooded	4.14	1610	0.25	-
AWD	4.63	1099	0.42	31.73
Tensiometer based	4.14	1140	0.36	29.19
SRI	5.35	1119	0.47	30.49

AWD = Alternate wet and drying; SRI = System of rice intensification

5. Monitoring of Meteorological drought and rice productivity

Mapping and monitoring meteorological drought will help effective crop and water planning that helps in enhancing crop and water productivity. ICAR – NRRI has mapped the meteorological drought and its relationship with block level rice productivity of Odisha using the 1-, 2- and 3- month standardized precipitation index (SPI) using rainfall data (1983–2008) from 168 rain gauge stations. SPI, calculated at different time scales, e.g. 1- or 3-month SPI of a particular month, represents the deviation in total precipitation amounts for the same month and current plus previous 2 months, respectively (Fig. 20). The 1- and 3-month SPI data were computed for 168 rain gauge stations using monthly rainfall data of the wet season for the period 1983–2008 by the following equation:

$$SPI_{ij} = (X_{ij} - \mu_{ij})/\sigma_{ij}$$

where SPI_{ij} is the SPI of *i*th month at *j*th time scale, X_{ij} is precipitation total for *i*th month at *j*th time scale, μ_{ij} and σ_{ij} are long-term mean and standard deviation, respectively, associated with *i*th month at *j*th time scale. Standardized precipitation index (SPI) is another tool used to detect drought over different periods at multiple time scales. The applicability of SPI is time scale-dependent, 1-month SPI reflects short-term soil moisture stress, 3-month SPI reflects seasonal while medium-term precipitation trend is indicated by 6 & 9-month SPI (Ji and Peters 2003). Temporal and spatial drought monitoring for rice in Odisha can be better done by using 1-month SPI tool. Based on 1-month SPI, August showed a higher risk for severe drought as compared to other months.

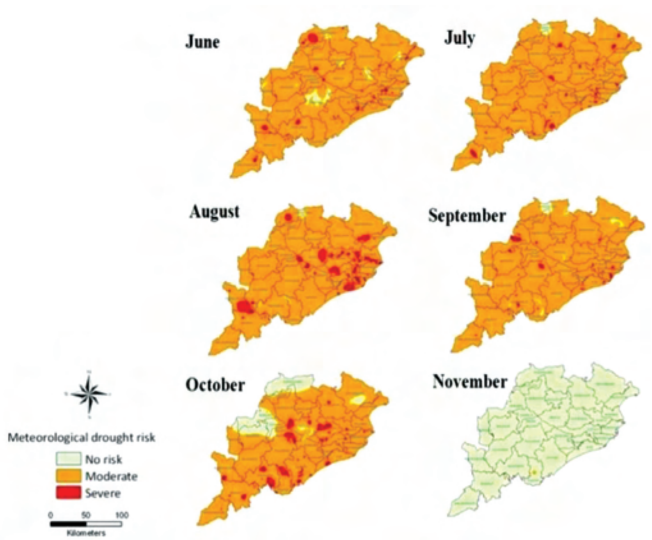


Fig. 20. Drought risk maps of Odisha based on 1-month standardized precipitation index.

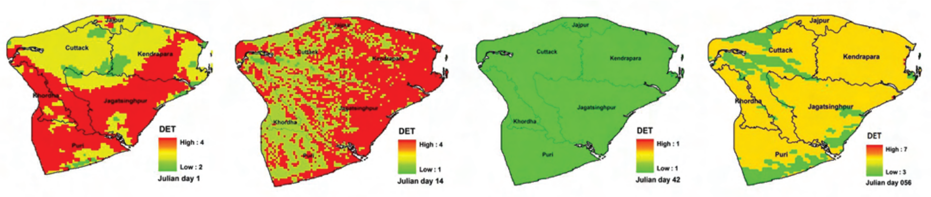
Drought risk map developed using 1- month SPI was having higher correlation with rice productivity index (RPI) and explained 27% yield variability. The

3-month SPI-based drought risk map could better explain the severity. The map showing the area with moderate and severe drought risk in *kharif* season can be effectively managed and be made drought proof by ensuring 1-2 and 2-3 supplemental irrigations (Raja *et al.,* 2014a).

6. Water balance study: A case study of Mahanadi delta

The knowledge on spatial water availability or water balance of a region is very important for formulation of plans for evaluating actual land use for sustainable utilization of water resources. Information on water availability and requirement in a region helps in determining the surplus or deficit water which is required in effective land and water utilization. The sharing of Mahanadi river water between Odisha and Chhattisgarh, interlinking of Mahandi and Godavari river necessitate the accurate assessment of water balance in the respective river basis for proper management of water more so in agriculture. ICAR-NRRI has come out with energy balance and potential evaporation demand of Mahanadi delta in the year 2019, one of the agriculturally important productive area in

a.



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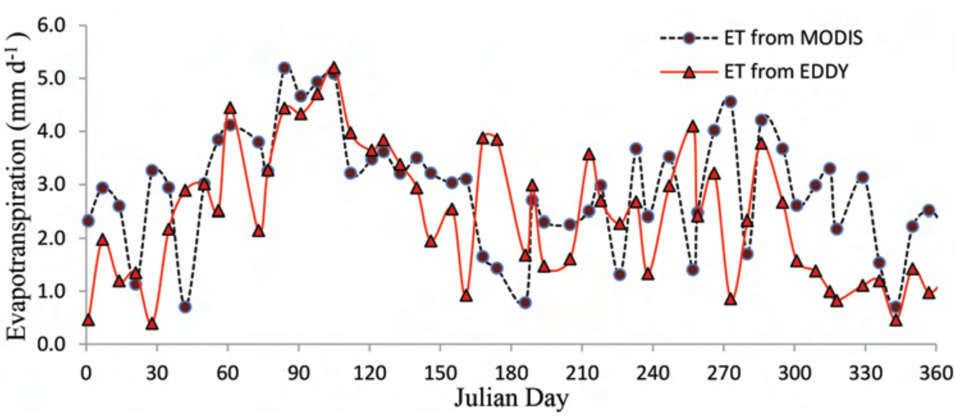

Fig. 21. a. Spatial map of evapo-transpiration at 1,14,42 and 56 julian days; b. Temporal variation of the evapo-transpiration in the Mahanadi delta (Tripathi *et al.*, 2019).

the state of Odisha. The ET over these majorly rice area was estimated to be 6602 million m^3 including *kharif* and *rabi* seasons whereas the ET from whole Mahanadi delta for the year was 10446.36 million m^3 having 3601 million m^3 evapo-transpirative water demand during *rabi* season and 6844 million m^3 during *kharif* season (Tripathi *et al.,* 2019). The ET from rice field estimated using eddy covariance system in NRRI has been used to validate the satellite derived ET having similar pattern with RMSE value 1.4 (Fig. 21).

7. Exploitation of residual soil moisture in *rabi* crops

Proper selection of crops, crop varieties, appropriate sowing, crop establishment methods and length of growing period (LGP) are key function that influences better utilization of natural resources particularly soil moisture (Nayak *et al.,* 2021b). Based on the above parameters, crop calendars for different agro-climatic zones of Odisha was prepared (Nayak *et al.,* 2021b). On the basis of which the crop plannings were recommended to accommodate suitable *rabi* crops in the region. The success of *rabi* crops in the rainfed areas of eastern India depends on how early the *kharif* crop was harvested making the land free for sowing of *rabi* crop and water holding capacity. It was found from the experiment that if 75-80% water requirement of *rabi* crop is fulfilled from residual moisture, application of 0-1 supplemental irrigation can increase the productivity under rice-fallow system by growing crops like: green gram, blackgram, lentil, lathyrus and toria as a succession crop to rice. In such situations pyra crop can also be taken if making the land free for sowing of succession crop is delayed. Blackgram is a suitable option for pyra crop. Similarly, if 55-60% water requirement of *rabi* crop is fulfilled from residual moisture, then application of 2-3 supplemental irrigations is sufficient to

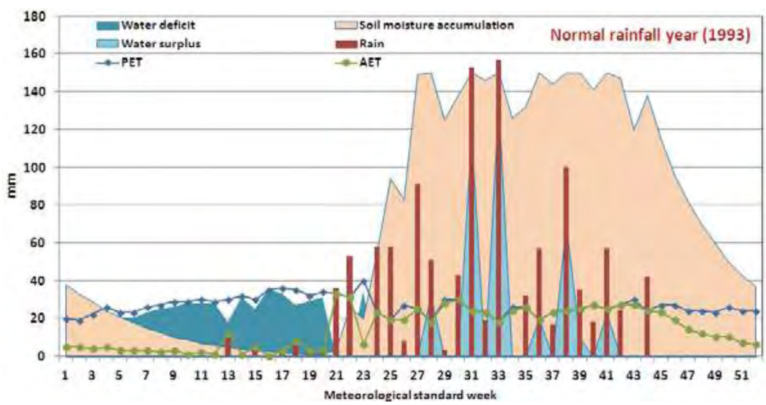

Fig. 22. Typical water balance at Khalikote, Ganjam district, Odisha during normal rainfall year (Raja *et al.*, 2014b)

successfully take groundnut, sunflower, maize and vegetables in the *rabi* seasons (Raja *et al.,* 2014b).

Table2: Variability at the beginning and end of growing period in Purusottampur and Khalikote block of Ganjam district, Odisha (Raja *et al.,* 2014b)

Particulars	Purusottampur	Khalikote
Beginning of season		
Normal	23 MSW	24 MSW
Assured	25 MSW	25 MSW
Standard Deviation (Days)	17	16
End of season		
Normal	4 MSW	2 MSW
Assured	52 MSW	52 MSW
Standard Deviation (Days)	33	38

**** For soils having 150 mm water holding capacity***

8. Management of rice in Arsenic contaminated areas

Arsenic contamination is one of the growing water quality problem in India. Starting from West Bengal in 1978, the problem of arsenic contamination has reached in the state of Bihar, Jharkhand and Uttar Pradesh in India. In arsenic contaminated area, the groundwater is often used for irrigating rice crop, thus increasing the chances of contamination of food chain through rice, over and above the drinking water. Arsenic contaminated groundwater is used not only for drinking purpose but also for crop irrigation, particularly for the *rabi* rice. A scientist of ICAR-NRRI in her Ph. D work (Khanam, 2021), assessed the magnitude of arsenic contamination in irrigation in temporal and spatial scale (Figs. 23 and 24). Crop management options for excluding accumulation of arsenic in plant parts include growing of relatively arsenic tolerant rice varieties, growing non-edible and leguminous crops during dry season and agroforestry interventions. In the areas with moderate to higher arsenic contamination, other crops such as groundnut, mustard etc. are also suggested. Increased use of FYM, vermicompost and green manure crops, and application of amendments like, calcium silicate and iron sulphate are recommended for amelioration of arsenic contamination. Water management strategies for arsenic mitigation includes conjunctive use of ground and surface water, storing of arsenic contaminated groundwater in ponds and subsequent dilution with rainwater, and sowing of direct seeded rice using drum seeder and seed drill.

9. Enhancing water productivity through multiple use of water

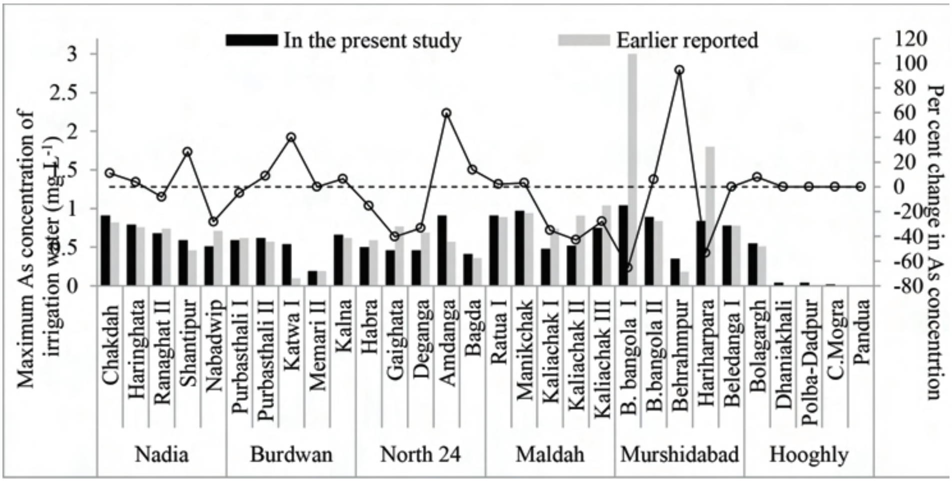

Fig. 23. Block wise comparison of maximum As concentration (mg L^{-1}) in irrigation water

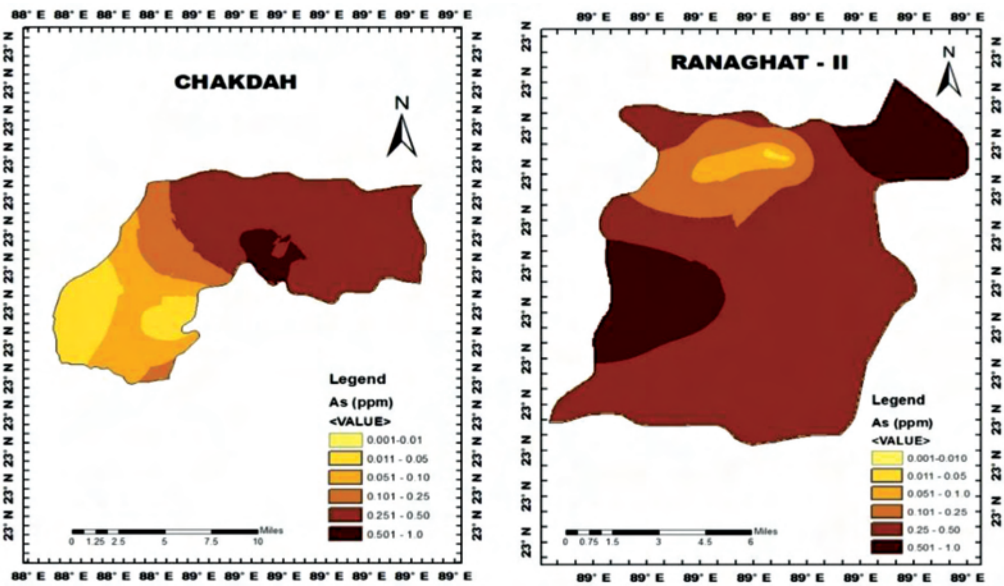

Fig. 24. Spatial distribution maps showing As in irrigation water (mg L^{-1}) in different blocks of Nadia district

Rainwater harvesting, conservation and judicious use of existing available water resources can improve the water productivity. The rice-fish based integrated farming system models developed at ICAR - NRRI provides a provision of rainwater harvesting, storage and conservation of water that ensures higher water productivity (WP), gross water productivity (GWP) and net water productivity (NWP) as compared to conventional system (Table 3; Fig. 25). The IFS ensure, multiple use of water, water applied to one enterprise is partly utilized by other neighboring enterprises through lateral seepage thus ensuring higher water productivity (Nayak *et al.*, 2020b).

Table 3. Water productivity of conventional rice farming and Integrated Farming System

Treatment	WP (kg m^{-3})	GWP (Rs m^{-3})	NWP (Rs m^{-3})
Conventional farming	0.390	5.854	1.235
Integrated Farming System	0.872 (2.3)	13.310 (2.2)	7.272 (5.8)

Values in bracket indicates times higher in water productivity in Rice-fish- livestock agro forestry based integrated farming as compared to the rice-mono cropping. WP = Water productivity, GWP = Gross water productivity, NWP = Net water productivity

10. Maximizing rice grain yield under submergence stress affected areas

Fig. 25. Crop-livestock-agroforestry based farming system for lowland rice ecologies

Transient complete submergence reduces survival and yield of more than 22 million ha of rice in rainfed lowlands and flood prone areas in Asia (Samal and Kumar, 2017). ICAR-NRRI has tested and validated several agronomic and nutrient management approaches for managing excess water and come out with suitable recommendations.

Agronomic approaches such as using tolerant varieties (Swarna *Sub-1*, Samba Mansuri *Sub-1*,Savitri *Sub-1*, IR 64 *Sub-1*), higher seed rates and better seeding methods (Lal et al., 2018), age of seedlings (Gautam et al., 2017), skipping basal N application (Gautam et al., 2014a), post submergence application of N (both foliar and soil application) (Gautam et al., 2015), basal P and K application (Gautam et al., 2014b; Gautam et al., 2016) and application of silica (Gautam et al., 2016) have been found to increase the productivity of both sub 1 introgressed and non introgressed HYV subjected to submergence of 14 days duration (Table 4). The technology was evaluated in the famers field and it revealed that the cost of production was lower when farmers field practices (FFP) was followed but the net return and B: C ratio were higher when basal P, K and post-flood N management options were adopted because of higher grain yield under the treatment. Net return were around 355 USD higher in basal P, K and post-flood N management over FFP, irrespective of the cultivar and locations. Further, net returns were increased by 4.4% and 2.9% in Swarna and Swarna *Sub-1* when urea foliar spray was applied over N supply through urea broadcasting as post-flood.

Rainfed shallow and semi-deep water lowland rice suffer from flash floods and waterlogging. Flash floods occur due to the overflow of rivers and canals because of heavy and intense rainfall events and sometimes due to tidal movements in coastal areas. Rice varieties with 140-155 day duration are usually cultivated in these flood-prone areas. Due to complete submergence aerobic respiration and gas exchange is restricted and chlorophyll senescence takes place consequently. Flood tolerant local rice landraces are cultivated in eastern India for the last seven decades. ICAR-National Rice Research Institute, Cuttack, India released pure line selections such as FR13A from Dhalaputia in the early 1950s. Three genes SUB1A, SUB1B, and SUB1C were identified within the Sub1 (QTL) region of which SUB1A was subsequently identified as the major determinant of submergence tolerance. The new varieties with SUB1A retain the entire genome of the original varieties having a small segment of the donor genome containing Sub1 (QTL) gene (Kumar *et al.,* 2021a). These varieties possess all characteristics of original parental lines except for the added trait of submergence tolerance. The new Sub1 introgressed lines exhibited tolerance to complete submergence for up to 2-3 weeks (Nayak *et al.,* 2017), depending on the floodwater conditions, whereas the original varieties cannot withstand submergence beyond 4-5 days (except for IR 64, which has moderate tolerance to submergence). The wide adaptability of Sub1 varieties is important because flood incidences are becoming more erratic in recent years. The list of rice varieties tolerant to stagnant flood is given in Table 5.

11. Maximizing rice grain yield under deficit water stress

11.1. Proper nutrient management strategies

The nutrient availability to rice plants in fields under water deficit stress condition is decreased as compared to the fields having continuous standing water, which results in reduction of grain yield. There is ample scope to increase rice productivity under limited water situation. One of the options could be the identification of proper nutrient management strategy for rice crop under water deficit stress condition. Apart from efficient water management technologies, ICAR-NRRI has come out with suitable nutrient management technologies for mitigating the effect of water deficit stress on rice.

Application of P (75 kg ha^{-1} as P_2O_5), Fe (30 kg ha^{-1} as $FeSO_4$), and Si (200 kg ha^{-1} as SiO_2) under water deficit stress (-60 kPa) condition reduced relative water content and increased activity of osmolyte (proline) and antioxidant metabolites (catalase and peroxidase) which enhanced the water deficit stress tolerance in rice, and resulted in higher grain yield. Due to absence of significant interaction between P, Fe, and Si on grain yield, there was no significant advantage of application of more than one of these nutrients together (Fig. 26; Table 4). The results indicate that, application of P, Fe, and Si alone can increase rice grain yield under water deficit stress condition (Kumar *et al.,* 2019b). However, evaluation needs to be done to explore the potential interaction, if any, in other rice ecology.

Common abiotic stresses in rain-fed rice areas like drought can occur at any phase of crop growth and may occur periodically. Besides the tolerant cultivar, application of nutrients @ 80, 40, 40, 70, 25, 25 kg N, P, K, Ca, Zn, Fe ha^{-1} respectively also helped the rice plants to overcome the drought stress and its after-effects. The combined application of nutrients resulted in higher proline accumulation, chlorophyll and carbohydrate concentrations, and photosynthesis and antioxidant enzymes, ultimately better tolerance to drought. The combined application of P, K, Ca, Zn, and Fe resulted in 52.9, 53.3, 48.9% higher yield over P or K application. Rice drought tolerance can be managed by combining breeding of drought-tolerant high yielding varieties with the proper application of suitable fertilizer nutrients. As possible technological alternatives, the use of drought-tolerant cultivars associated with extraneous supply of nutrients, which are not available due to water deficit, may help cope with or at least ameliorate this problem. (Lal *et al.,* 2019).

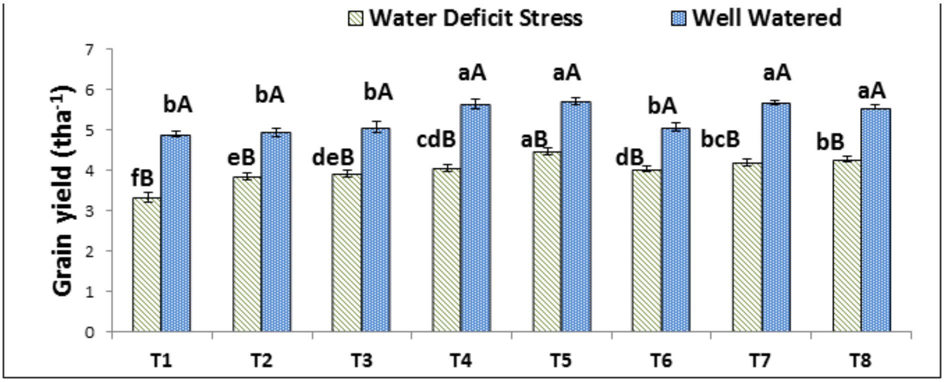

Fig. 26. Grain yield under different nutrient management practices. T1 = RDF, T2 = RDF + P, T3 = RDF + Fe, T4 = RDF + Si, T5 = RDF + P + Fe + Si, T6 = RDF + P + Fe, T7 = RDF + P + Si, T8 = RDF + Fe + Si. *Different lower case letters indicate significant difference among nutrient management treatments under a particular water regime, whereas different upper case letters indicate significant difference among different water regimes under a particular nutrient treatment by DMRT*

High-temperature stress is a constraint to rice production and the most detrimental effect is on spikelet sterility. It increases cell damage and thus affects water, ion, and organic solute movement across plant membranes. Spikelets that are exposed to temperatures above 35°C during anthesis for about 5 days during the flowering period remained sterile and set no seed. External application of boron helps to mitigate the negative effects of high temperature during both vegetative and reproductive crop growth stages. Boron application at 1 and 2 kg ha^{-1} and 0.2% foliar spray enhanced the rice grain yield by 8-20%, respectively over no boron application (Shahid *et al.,* 2018).

Table 4. Role of agronomic and nutrient management practices in enhancing grain yield under stress conditions

Nature of stress	Management Intervention	Details of management	Response	Reference
Submergence	Nutrient management	Post-flood nitrogen application as foliar spray (2.0% (w/v) urea)	• Spraying removes adhered silt particles from leaf surface • Maintains chlorophyll stability and assimilate partitioning	Gautam *et al.,* 2014.
		Basal potassium application (150% of recommended dose of potassium)	• Maintains good growth and metabolism • Helps in activation of several enzymes • Enhances photosynthetic pigments and photosynthetic capacity • Helps in stomatal movement and turgor regulation • Increases plant nutrient uptake	Gautam *et al.,* 2016.
		Basal silica application	• Prevents crop lodging and imparts erectness to leaves • Enhances N responsiveness of rice • Reduces stem elongation, leaf senescence, lodging, chlorosis and depletion of NSC	Gautam *et al.,* 2016.

	Spacing	Spacing (cm) 20 × 20 cm vs 15 × 15 cm	• Higher penetration of underwater radiation • Higher initial non-structural carbohydrate (NSC) content • Slower NSC depletion rate	Bhaduri *et al.*, 2020.
	Age of seedling	Older seedlings (35-45 days)	• Taller, sturdier, and healthier seedlings • More mature tissues, greater dry biomass • Higher carbohydrate storage • Higher tolerance level	Gautam *et al.,* 2017.
Water deficit stress	Nutrient management	Basal application of 50% higher dose of phosphorus (75 kg/ha), Fe @ 30 kg/ha and Si @ 200 kg/ha.	• Reduced relative water content and increased activity of osmolyte (proline) and antioxidant metabolites (catalase and peroxidase) due to application of P, Fe, and Si contributed to tolerate the WDS, which resulted in higher grain yield.	Kumar *et al.,* 2019b.
High temperature stress	Nutrient management	Soil application of boron @2.0 kg/ha	• Exogenous application of boron had asubstantial effect on cell membrane stability, sugar mobilization, pollen viability, and spikelet fertility and hence the grain yield increased.	Shahid *et al.,* 2018.

11.2 Optimum irrigation management strategies

Apart from efficient nutrient management technologies, ICAR-NRRI has come out with optimum scheduling of irrigation management based real time soil water potential as measured by tensiometer for maximisation of water productivity for rice varieties introgressed with drought QTLs. Water productivity (Wp) of varieties introgressed with drought QTLs like DRR Dhan 44, Swarna Shreya, CR Dhan 801 and CR Dhan 802 was higher under different levels of stress as compared to susceptible varieties. For drought tolerant varieties, even at moderate level of water deficit stress (- 40 kPa) there was an increase in Wp by 52% for DRR Dhan 44, 60% for Swarna Shreya and 40% for CR Dhan 802, whereas the increase in Wp at severe water deficit stress (-60 kPa) was 28% for DRR Dhan 44, 25% for Swarna Shreya and 35% for CR Dhan 802 as compared to continuously flooded condition.

11.3 Low water requiring drought tolerant varieties

Drought is widespread climatic stress and can occur at any time and for any duration during the cropping season affecting crop physiological, biochemical, and molecular processes drastically reducing rice yield. The extent of loss due to drought varies depending on the timing, intensity, and duration of drought. To avoid drought, farmers quite often rely on early maturing varieties. These varieties are not tolerant of drought, but they escape late-season drought due to earliness. If a drought occurs early in the season, these short-duration varieties can be sown late. Rice plant overcomes drought stress through two mechanisms viz. drought escape and drought avoidance. Drought escape is an adaptive mechanism in which rapid plant development occurs to enable plants to complete the full life-cycle before the drought event. Whereas in drought avoidance, the plant maintains relatively higher tissue water content even when there is less water content in the soil. The higher relative tissue water content is maintained either through a prolific root system or increasing root growth, reducing transpiration, limiting vegetative growth or osmatic adjustment, etc. The development of drought-tolerant varieties will greatly enhance and stabilize rice productivity in drought-prone areas. Eight QTLs (DTY 1.1, DTY 2.12, DTY 2.23, DTY 3.1, DTY 3.2, DTY 4.1, DTY 6.1, and DTY 12.1) with large effects on grain yield under drought stress have been identified (Nayak *et al.,* 2017). These QTLs show effect against two or more genetic backgrounds and across both lowland and upland ecosystems. Efforts to transfer this drought tolerance QTLs into mega varieties such as IR 64, Swarna-Sub1, and IR 64-Sub1 using MABC breeding approach are ongoing. The first genuine drought-tolerant rice variety, Sahbhagidhan, developed through conventional breeding was released in India in 2010. Depending upon the severity of drought, this short duration (105-110 days) variety offers a yield advantage of 0.8-1.0 t ha-1 both under upland and lowland conditions. The list of drought-tolerant rice varieties is given in Table 5.

Table 5. Rice varieties tolerant to different abiotic stresses

Abiotic stress	Varieties
Submergence	Bina Dhan 11, Sambha-Mahsuri Sub 1, CR Dhan 802, Swarna Sub 1, Ranjit Sub 1, CR Dhan 801, CR 1009 Sub 1, Bahadur Sub 1, CR Dhan 505, CR Dhan 401, Reeta, Sumit, Chakaakhi
Drought	Kalinga III, Rudra, Shankar, Vanaprava, Anjali, Vandana, Virender, Sahabhagidhan, CR Dhan 100 (Satyabhama), CR Dhan 101(Ankit), Ananda, CR Dhan 202, CR Dhan 206, BRRI Dhan 71, DRR 42, DRR 44, Swarna Sreya, Brahman Nakhi, Sal Kain, Khandagiri

12. Conclusions

Rice is one of the most inefficient user of water. About 60-83% of total water applied to rice field is lost as deep percolation. This scary situation is likely to be further aggravated in the context of climate change. Water management technologies like agronomic practices for higher water use efficiency, improved method of irrigation, water-efficient rice production system and proper scheduling of irrigation alongwith low water requiring aerobic rice varieties can increase water use efficiency, and save a significant amount of irrigation water, with marginal or no reduction of grain yield. Among these highly preferred technologies, some technologies have co-benefits that fulfill the criteria for climate-smart technology.

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