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IRRIGATION MANAGEMENT FOR NON-MONSOON CROPS IN A MAJOR CANAL COMMAND IN EASTERN INDIA UNDER WATER LIMITING ENVIRONMENT

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Abstract: Acute irrigation water deficit during the non-monsoon (*rabi*) season in the Hirakud canal command in Eastern India demands efficient irrigation management strategies (*IMS*s) to sustain the irrigated agriculture. The study was undertaken to analyse the impact of different *IMS*s – namely full and deficit irrigation, on water use efficiency of different *rabi* crops and evolve the most efficient *IMS*s. Various water balance parameters were estimated on daily basis and stage wise crop production function was applied to compute the actual crop yields of five major *rabi* crops. The best *IMS*s for wheat, maize, rice, green gram and mustard were found to be 30% deficit irrigation at 14 days interval, 30% deficit irrigation at 7 days interval, 20% deficit irrigation at 4 days interval, 60 mm of irrigation per application at 21 days interval, and 20% deficit irrigation at 7 days interval, respectively. Realizing the scarce water resources and ever rising population, it is highly essential to implement the generated IMSs with a view to bring more area under cultivation and enhance the production potential of the command area.

Key words*: deficit irrigation, fixed depth application, soil moisture balance, water use efficiency*

INTRODUCTION

Rapid environmental alteration has adversely affected the agriculture sector [16] owing to limited water availability. Irrigated agriculture is the largest water user at global level, which consumes nearly 80% of the world's developed water resources [27]. On the other hand, ever-increasing urban and industrial sectors place greater pressures

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on agricultural water use. Hence, its effective management through improved irrigation management practices is of topmost importance to the agricultural scientists and researchers. It has been proven that almost 50% potential water saving can be resulted from better irrigation management practices [22].

Agricultural water management needs proper understanding of the crop irrigation scheduling. If water supply is adequate, irrigation can be given at times, to bring the root zone soil moisture to field capacity. However, deficit irrigation (DI) practices need to be followed under water limiting conditions, realizing the critical growth stages of crops. Deficit irrigation practices differ from traditional water supplying practices, on the way of scientifically under-irrigating crops in a controlled way [25,10]. Though under-irrigation results in stress and subsequent reduction in crop yield, still it has greater potential for increasing the water use efficiency (*WUE*) under water scarce environment [13] as the saved water can be diverted to irrigate other crops, for which amount of water would normally be insufficient under traditional irrigation practices. Deficit irrigation strategy in many crops has frequently proved to be an efficient tool to enhance *WUE* [20,12,9,24].

Similarly, in a field experiment with different levels of *DI* it was observed that 30% *DI* to sweet corn could be a water-saving treatment without a significant decrease in yield. In addition, highest protein content and sugar amount was also observed at the same *DI* level [11]. In another field experiment on two genotypes of maize it was found that the water deficit stress significantly increased glucose, fructose, and sucrose contents. The highest *WUE* was found at 50% *DI* [2]. Deficit irrigation can also be used as a cost-effective tool for attaining water for environmental purposes. Application of non-linear optimization model on *DI* involving crop production and profit functions achieved environmental flows and maximized net returns [18]. Simulation of an onion crop under optimized regulated *DI* conditions increased the crop yield by 3–7%, where as the gross margin raised up to 30% compared with an irrigation strategy, where the stress levels remain constant during the whole growth cycle [6]. Application of *DI* strategies on tomato crop allowed up to 48% of water saving and improved quality of fruits under a semi-arid climate in south Italy [19].

Previous studies have indicated that water-saving irrigation not only contributes to water saving but also to the reduction of greenhouse gas emissions, which can alleviate the negative impact of climate change on agricultural production [28,17]. Growing rice under *DI* in arsenic contaminated areas of West Bengal, India reduced the arsenic load. Crop water productivity was also reported to be increased by 11% under *DI* [21]. Now-a-days, use of saline water for irrigation and practicing DI are among the most frequently used methods for overcoming water shortages. However, since both salinity and drought reduce the availability of soil water for crops, yield reduction needs to be predicted accurately [5]. Therefore, before implementing a *DI* program it is imperative to know the crop yield response to water stress, either during defined growth stages or throughout the growing season.

The canal command of the Hirakud irrigation project, Odisha (eastern India) is one of the major surface irrigation projects and is highly heterogeneous in nature. Hence, irrigation management in such a case is a very complex process. Spatio-temporal variation in water supply has resulted in much lower crop yield as compared to the national average. Rice being the major crop in all the seasons, its diversification to non-rice crops (vz. wheat, maize, pulses, oilseeds, vegetables etc.), specifically during *rabi* season has, therefore, become necessary for optimal utilization of land and water resources of the command area. It is also inevitable to adopt alternate irrigation management strategies. In this study, a regional daily soil moisture balance model was developed for estimation of crop yield and water requirement with a view to evaluate the net benefit per unit area of each crop under different irrigation management strategies.

MATERIAL AND METHODS

Area description. The Hirakud canal command area lies between latitude 20°53' to 21°36' N and longitude 83°25' to 84°10' E covering an area of about 2,540 km^2 (Fig. 1). Topography of the area varies from plain to undulating and comprises mostly terrace lands with average slopes between 1 to 6%. The elevation of the land surface varies from 120 to 180 m above the mean sea level. The soils of the study area have been developed mostly from granite rocks. The command area is characterized by sub-humid climate with extremely hot summer, cold winter and uneven distribution of rainfall. During summer (March-May), day temperature varies from 35 to 45°C and May is the hottest month of the year. In winter (November-February), temperature varies from 10 to 20°C and December is the coldest month of the year. The relative humidity is high (more than 75%) during monsoon (mid June-mid October) and it is rather low (30 to 40%) in summer. The average annual rainfall of the command is around 1200 mm, out of which about 90% is received during monsoon. The southwest monsoon is the principal source of rainfall.

The study region prevails two principal crop seasons, viz. *kharif* (June to October) and *rabi* (November to May). Rice is the major crop in both the seasons. It is cultivated in more than 90% of the culturable command area (*CCA*) during monsoon and during non-monsoon season rice area exceeds 40% of *CCA* (1,590 km^2). Other crops like wheat, sugarcane, pulses, millets, oilseeds, vegetables, and condiments etc. are also cultivated in the command area in both the crop seasons.

Irrigation strategies. The applied depth of irrigation may vary between different crops grown on different types of soils and climatic zones. However, this heterogeneity is often not considered and allocation plans are based on a fixed depth of water. When water is scarce, using *DI* may be beneficial compared to full irrigation [14]. As the degree of deficit for different crops during different growing periods are different, DI results in variable depth of irrigation. Based on these findings, the following three *IMS*s were considered for obtaining the irrigation management plans. The heterogeneity in the irrigation scheme in terms of soil, crop, system efficiency, irrigation interval and other parameters influencing the water demand is not considered in this strategy.

(1) Full irrigation strategy: Full irrigation is the depth of application needed at the time of irrigation to bring the root zone soil moisture to field capacity. When the irrigation interval is large, full irrigation may still cause stress to the crop and reduce the crop yield. Crop yields were estimated for different irrigation intervals with full irrigation at each event.

(2) Fixed depth irrigation strategy: Fixed depth irrigation is the application of a fixed quantity of water to a crop per irrigation. In this strategy, three different fixed depths (6, 8 and 10 cm) for non-rice crops and three different fixed depths (9, 12 and 15 cm) for rice crop were considered. The effects of those different fixed depths along with different irrigation intervals (7, 14, 21 and 28 days for non-rice crops and 4, 8 and 12 days for rice) on crop yield and *WUE* were studied by using the concept of daily soil

moisture balance. *WUE* has been defined as crop yields per unit amount of irrigation water applied (kg·ha^{-1}-mm).

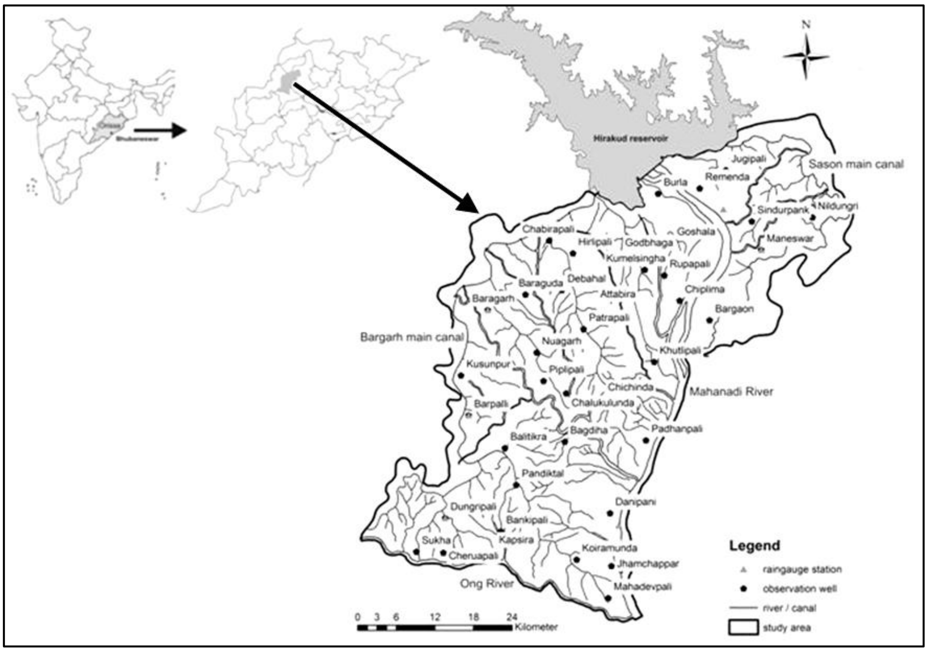

Figure 1. Location map of the study area

(3) Deficit irrigation strategy: In a water-limiting situation, it may be beneficial to apply less amount of water per application than the full irrigation, which is termed as deficit irrigation that helps in spreading the water to a larger area. The deficit ratio is used to represent the degree of deficit that ranges from zero (applying no irrigation water or skipping this irrigation) to one (full irrigation). The intermediate values of deficit ratios (0.1 to 0.9 with an increment of 0.1) indicate the irrigation depth as a fraction of the full irrigation. Effect of those different deficit ratios along with different irrigation intervals on the crop yield and *WUE* irrigation was studied by the help of daily soil moisture balance model.

Soil moisture balance model. A soil moisture balance model was formulated in order to estimate the yield and water requirement of different *rabi* crops grown in the canal command under different *IMS*s. Various model components were estimated on daily basis and actual crop yields were estimated by using the dated crop production function that consider the water stress and yield sensitivity factors during each crop growth stage. Java language was used to formulate the soil moisture balance model. Considering the effective root zone of crops as single layer and neglecting the capillary contribution from groundwater, the generalized soil moisture balance model for crops can be written as:

$$SMC_{t+1}Z_{t+1} = SMC_tZ_t - ETa_t - SP_t + Da_t + ER_t + SS_t + PS \quad (1)$$

where:

SMC [cm·m^{-1}] - soil moisture content,

Eta [cm] - actual evapotranspiration on t^{th} day,
Da [cm] - depth of irrigation applied,
SP [cm] - seepage and deep percolation,
ER [cm] - effective rainfall,
Z [m] - root zone depth,
SS [cm] - surface storage or ponding depth,
PS [cm] - pre-sowing irrigation,
t [days] - time index.

During *rabi* season, the water requirement for nursery raising and transplanting of rice was taken as 250 mm and for non-rice crops, a pre-sowing irrigation of 40 mm was considered for land preparation [23].

In the soil moisture balance model, the effective root zone of rice (45 cm) and the ponding depth was together considered as a single layered reservoir. A ponding depth of 5 cm was allowed throughout the growing period, except last 15 days before harvesting [26]. Seepage and percolation loss components were together considered as 6 mm/day [4]. For non-rice crops, seepage and percolation loss and surface storage components are zero. Details of the different model components are described below.

Estimation of Model Parameters. Various methods are available to estimate the reference crop evapotranspiration (ET_0) [8,1]. However, based on the availability of meteorological data of the study area, the Hargreaves method [15] of estimating ET_0 was selected, which is as given below:

$$ET_0 = 0.0023 \times (T_{mean} + 17.8) \times (T_{max} - T_{min})^{0.5} \times R_a \tag{2}$$

where:
ET_0 [mm·day^{-1}] - reference evapotranspiration,
R_a [mm·day^{-1}] - extraterrestrial radiation,
T_{max} [°C] - maximum air temperature for a given day,
T_{min} [°C] - minimum air temperature for a given day,
T_{mean} [°C] - mean air temperature for a given day.

Crop Evapotranspiration. The crop evapotranspiration (*ETc*) was calculated using the following equation.

$$ETc = ET_0 \times K_c \tag{3}$$

where:
ETc [mm·day^{-1}] - crop evapotranspiration,
K_c [-] - crop coefficient.

K_c values of different field crops at the different growing stages were taken from [1], [7] and [8].

Root Zone Depth. Root depth was modelled using the algorithm developed by [3]. This model describes root depth by a sigmoid development of the roots from planting date until maturity. The empirical model is given by:

$$Z_t = Z_{max} \times [0.5 + 0.5 \times \sin\{3.03 \times (t/t_m) - 1.47\}] \tag{4}$$

where:
Z_t [cm] - root depth on t^{th} day after sowing,
Z_{max} [cm] - maximum possible root depth,
t [days] - day after planting,
t_m [days] - time for the full development of the root zone.

Maximum root depth of different field crops has been reported by [8].

Soil Water Depletion Factor. The soil water depletion factor (p_t) was computed by the numerical approximation of adjusting p for maximum Etc [1], which is as given below.

$$p_t = p_{table} + 0.04 \times (5 - ETc) \tag{5}$$

where:
p_{table} [-] - table value of soil water depletion factor of crops.

Effective Rainfall. Several methods of estimating effective rainfall for irrigation scheduling are widely used. Those are based on long experiences and have been found to work quite satisfactorily in specific conditions under which they were developed [1]. For the study area, the effective rainfall for crops other than rice was considered as 70% of the average seasonal rainfall. For rice crop, 50 to 80% of total rainfall was assumed effective [1].

Actual Evapotranspiration. The actual evapotranspiration was estimated by using the linear model as developed by [7].

$$ETa_t = ETc_t, if\ (SMC_t - SMC_w) \times Z_t \geq (1 - p_t)(SMC_{fc} - SMC_w) \times Z_t \tag{6}$$

Otherwise,

$$ETa_t = \frac{(SMC_t - SMC_w) \times Z_t \times ETc_t}{(1 - p_t)(SMC_{fc} - SMC_w) \times Z_t} \tag{7}$$

where:
ETa_t [cm·day^{-1}] - actual evapotranspiration,
SMC_{fc} [cm·m^{-1}] - soil moisture content at field capacity,
SMC_w [cm·m^{-1}] - soil moisture content at wilting point.

The SMC_{fc} component in Eqs. 6 and 7 has to be replaced by SMC_{sat} (saturated SMC) and the component ETc_t in both the equations has to be replaced by ETm_t (maximum evapotranspiration) for rice crop.

Soil Moisture Depth. Soil moisture depth was calculated as below.

$$Da_t = \left[\left(SMC_{fc} - SMC_t\right) \times Z_t + SS_t\right]\emptyset \tag{8}$$

where:
ϕ [-] - deficit ratio (fraction).

For rice crop, the term SMC_{fc} in Eq. 8 should be replaced by SMC_{sat} and for non-rice crops, surface storage (SS) equals zero.

Depth of Irrigation and Water Delivery Depth. Further, the depth of irrigation (ID) and the water delivery depth (WD) were calculated by using the equations as given below.

$$ID_t = D_a / E_a \tag{9}$$

$$WD_t = E_c \times E_d \times ID_t \tag{10}$$

where:
E_a [-] - application efficiency (fraction),
E_c [-] - conveyance efficiency (fraction),
E_d [-] - distribution efficiency (fraction).

The conveyance, distribution, and application efficiency were assumed to be 70, 70 and 80%, respectively [8].

Actual Crop Yield. The actual crop yield (Y_a) was calculated by using the additive approach of the dated water-production function [7].

$$\frac{Y_a}{Y_m} = \sum_{r=1}^{r} \left[1 - Ky_r \left(1 - \frac{ETa_r}{ETc_r}\right)\right] \quad (11)$$

where:
Y_m [kg·ha^{-1}] - potential crop yield,
r [-] - no. of yield stages,
Ky_r [-] - yield response factor.

Ky values of different field crops were taken from [8]. While the *Ky* values for rice were considered as 1.1 in initial stage, 1.1 in crop development stage, 2.4 in flowering stage, 2.4 in grain formation stage, and 0.33 in ripening stage [23].

RESULTS AND DISCUSSION

In the present study, five major *rabi* crops, such as rice, wheat, maize, greengram and mustard, are considered for the development of their corresponding *IMS*s. Water use efficiency was used as an indicator to compare the performances of different *IMS*s under consideration.

Deficit Irrigation Strategy. Under the *DI* strategy, the deficit ratios were considered to range from 0.1 to 1.0 with an increment of 0.1. Deficit ratio of 1.0 indicates that the irrigation is applied to bring the moisture in the root zone to field capacity, whereas deficit ratio of 0.1 indicates 90% reduction in irrigation or the degree of deficit as 90%. The developed ISM was run for the irrigation intervals of 7, 14, 21 and 28 days for non-rice crops and 4, 8 and 12 days for rice crop. The *WUE* of wheat was found to increase with increase in deficit ratio up to 0.7 for both 7 and 14 days irrigation intervals (Fig. 3a). Beyond this level the *WUE* was reduced for both the irrigation intervals. There was always increasing trend in *WUE* for 21 and 28 days irrigation intervals. Maximum *WUE* was attained at the deficit ratio of 0.7 (30% deficit) and irrigation interval of 14 days. Hence, 30% *DI* to wheat at an interval of 14 days can be the best *IMS* under *DI* strategy.

For maize, the *WUE* was found to increase with increase in deficit ratio up to 0.7 and 7 days irrigation interval, which then reduced with further increase in deficit ratios (Fig. 3b). At 14 days irrigation interval the *WUE* was found to increase up to deficit ratio of 0.8 and then reduced. But the *WUE* of maize at both 21 and 28 days irrigation intervals went on increasing up to the deficit ratio of 0.9. Comparison of *WUE*s for all the irrigation intervals and deficit ratios showed that 30% DI to maize at an interval of 7 days may be the best *IMS* under *DI* strategy. The trend of *WUE* in case of rice was increasing up to the deficit ratio of 0.8 and 4 days irrigation interval, which was then altered, whereas the trend of *WUE* was found increasing up to the deficit ratio of 0.9 at both 8 and 12 days irrigation intervals (Fig. 3c). Among all the deficit ratios and irrigation intervals considered, the *WUE* was highest for 20% *DI* at 4 days interval that could be taken as the best *IMS* for rice under *DI* strategy.

The *WUE* of greengram was found to increase with increase in deficit ratio up to 0.7 and at 7 days irrigation interval, which then decreased with increase in deficit ratios (Fig. 3d). At 14 days irrigation interval the *WUE* of greengram was found to increase up to deficit ratio of 0.8 and then reduced. But at both 21 and 28 days irrigation intervals, the *WUE* followed the increasing trend up to the deficit ratio of 0.9 and then decreased. Comparison of *WUE*s at various deficit ratios and irrigation intervals revealed highest *WUE* for 20% *DI* at 14 days interval. Hence, it may be considered as the best *IMS* for greengram under *DI* strategy. The *WUE* of mustard was found to increase with increase in deficit ratio up to 0.8 at 7 days irrigation interval, and then decreased with further increase in deficit ratios (Fig. 3e). At 14 days and 28 days irrigation intervals, the *WUE* of maize was found to increase up to the deficit ratio of 0.9 and then decreased. The *WUE* of mustard showed a decreasing trend at 21 days irrigation interval, after achieving the highest value at the deficit ratio of 0.7. Among all the irrigation intervals and deficit ratios considered, the *WUE* of mustard was found to be highest for 20% *DI* at 7 days interval, which may be considered as the best *IMS* under *DI* strategy.

Fixed Depth Irrigation Strategy. In this strategy, three different fixed depths (6, 8 and 10 cm for non-rice crops and 9, 12 and 15 cm for rice crop) were considered. The effects of those fixed depths and irrigation intervals on the yield and *WUE* of crops was studied. The *WUE* of wheat was found to decrease with increase in depth of irrigation per application for all the irrigation intervals except 28 days (Fig. 4a), where the *WUE* showed a reverse trend up to 80 mm irrigation per application. The *WUE* was found to be the highest for 60 mm irrigation per application at 21 days irrigation interval. Thus, it can be taken as the best *IMS* in case of fixed depth irrigation strategy. Similar to wheat, the *WUE* for maize was also found to decrease with increase in depth of irrigation per application at all irrigation intervals (Fig. 4b). Comparing *WUE* of maize at all irrigation intervals, the *WUE* was found to be the highest at 28 days irrigation interval with 60 mm irrigation per application that may be considered as the best *IMS* for maize in case of fixed depth irrigation strategy.

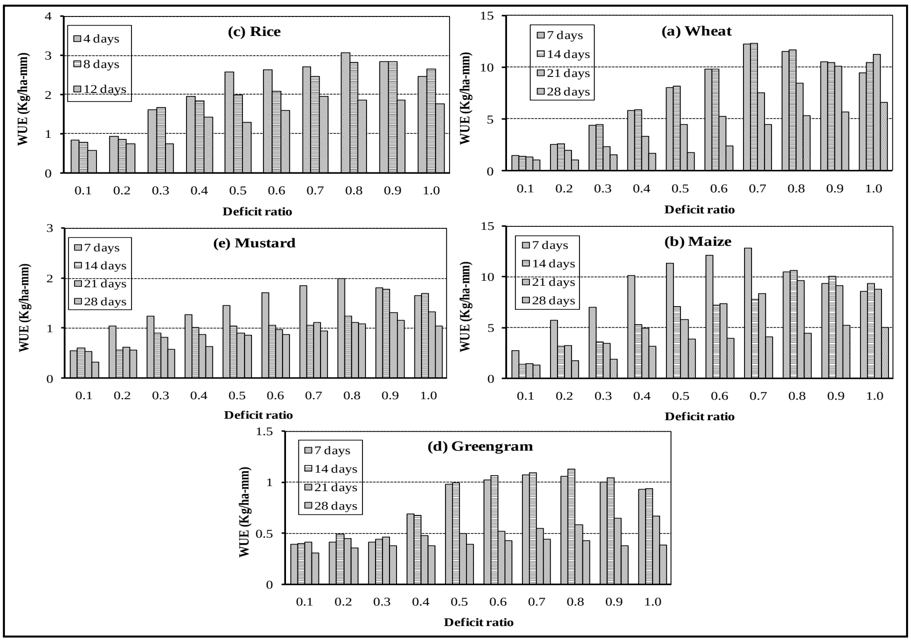

Figure 3. WUE of different rabi crops under DI strategy at various irrigation intervals

The WUE of rice showed a decreasing trend with increase in depth of irrigation per application at all irrigation intervals considered (Fig. 4c). The *WUE* was found to be the highest for irrigation depth of 90 mm at an interval of 8 days. Hence, 90 mm irrigation per application to rice at an interval of 8 days can be followed as the best *IMS* for rice under the fixed depth irrigation strategy. The *WUE* for greengram decreased with increase in depth of irrigation per application at all irrigation intervals except 28 days (Fig. 4d), where the *WUE* first increased and then decreased. Comparing *WUE* of greengram at all irrigation intervals, it was found that the *WUE* was highest for 60 mm irrigation per application at 21 days interval. Thus, 60 mm irrigation per application at 21 days interval can be the best *IMS* for greengram in case of fixed depth irrigation strategy. At all irrigation intervals, the *WUE* of mustard was found to decrease with increase in depth of irrigation per application (Fig. 4e). However, the *WUE* was highest under 60 mm irrigation per application at 28 days interval, which may be taken as the best *IMS* for mustard in case of fixed depth irrigation strategy.

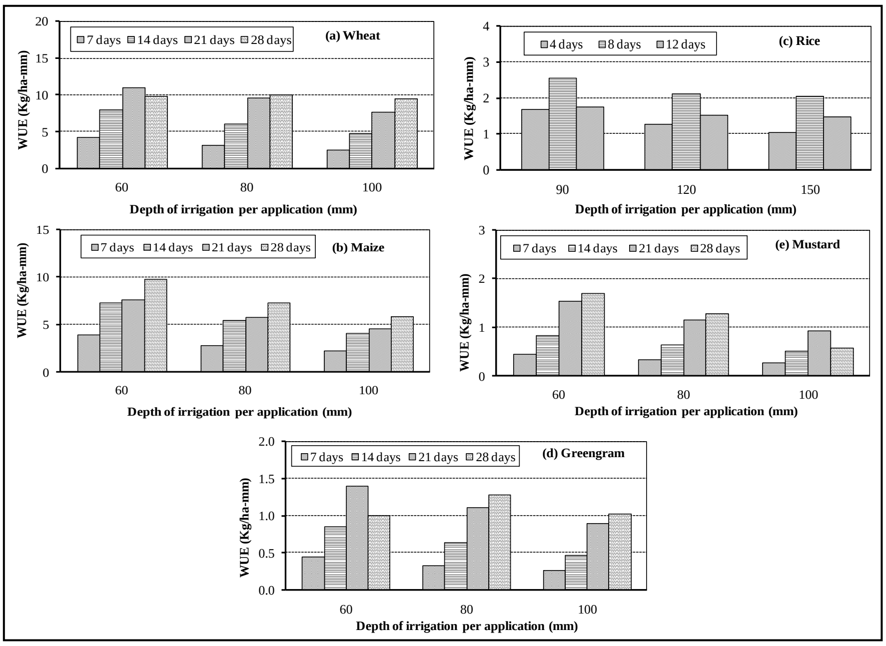

Figure 4. WUE of different rabi crops under fixed depth IMS at various irrigation intervals

CONCLUSIONS

In the above section, best *IMS*s of various crops separately under fixed depth application and deficit irrigation at different intervals are presented. However, it is essential to compare the crop-wise *IMS*s for both *DI* and fixed depth application strategy so as to evolve the best IMSs of crops giving highest *WUE*. Optimum *IMS* of each crop was found out by comparing the best *IMS*s under full irrigation, deficit irrigation and fixed depth application. It was found that 30% *DI* to wheat at an interval of 14 days is the most efficient *IMS* and the best IMS for maize is to irrigate with 30% *DI* at an interval of 7 days. Irrigating rice with 20% *DI* at an interval of 4 days is the efficient *IMS* and the most effective *IMS* for greengram is to apply 60 mm of water per irrigation at an interval of 21 days. Mustard gives maximum *WUE* when it is irrigated with 20% *DI* at an interval of 7 days.

Since agricultural area is diminishing day by day due to ever increasing population and rapid industrialization, hence, it is inevitable to grow more to earn more from the limited land and water resources. It can be seen from the above results that deficit irrigation practice can be a viable option to achieve better *WUE* under water limiting environments. Hence, the crop-wise irrigation management strategies as presented above may be adopted by the beneficiaries of the selected canal command area during rabi season so as to bring more area under crops, which in turn will enhance the production potential of the command area.

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UPRAVLJANJE NAVODNJAVANJEM NE-MONSUNSKIH USEVA U OBLASTI GLAVNOG KANALA U ISTOČNOJ INDIJI, U USLOVIMA OGRANIČENOG SNABDEVANJA VODOM

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Sažetak: Izražen nedostatak vode u ne-monsunskom periodu (*rabi*) u oblasti Hirakud kanala i istočnoj Indiji zahteva efikasne strategije upravljanja navodnjavanjem (*IMS*s). Ovo istraživanje je sprovedeno radi analize uticaja različitih *IMS* – punog i defcictarnog navodnjavanja i različitih *rabi* useva na efikasnost upotrebe vode i razvoja najefikasnije *IMS*. Različiti parametri bilansa vode su ocenjivani na dnevnoj bazi i izračunati su stvarni prinosi za pet glavnih *rabi* useva. Najbolje *IMS* za pšenicu, kukuruz, pirinač, zlatni pasulj i slačica imale su 30% deficita navodnjavanja u periodima od 14 dana, 30% deficita navodnjavanja u periodima od 7 dana, 20% deficita navodnjavanja u periodima od 4 dana, 60 mm vode po aplikaciji i u periodima od 21 dan i 20% deficita navodnjavanja u periodima od 7 dana, redom. Imajući u vidu siromašne izvore vode i stalno rastuću populaciju, veoma je neophodno primeniti ove strategije sa ciljem dobijanja veće obradive površine i unapređenja proizvodnog potencijala ove oblasti.

Ključne reči: *deficit navodnjavanja, primena na stalnu dubinu, balans zemljišne vlage, efikasnost upotrebe vode*

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