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PJBS

ISSN 1028-8880

Pakistan Journal of Biological Sciences

ANSInet
Asian Network for Scientific Information
308 Lasani Town, Sargodha Road, Faisalabad - Pakistan

Pakistan Journal of Biological Sciences 6 (18): 1600-1607, 2003
ISSN 1028-8880

Model for Efficient Use of Limited Water for Rice Production

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Abstract: In this model, firstly a simple conceptual model of water losses in rice field has been developed and quantified in spreadsheet form. Second, this model is used to simulate what would happen under three scenarios such as continuous ponding with soil management (filling and sealing of visual cracks by intercultural operation) "Case 1"; irrigation with intermittent drying and without soil management "Case 2"; and irrigation with intermittent drying and with soil management "Case 3". In Case 2 and Case 3 water is allowed to fall until water is no longer ponded at the surface and the soil dries and starts to crack. Third, conclusions have been drawn as to the consequences of not irrigating according to a schedule dictated by crack development. From this study it is observed that the total amount of water required for rice production is directly related to the nature of water and soil management practices to reduce crack during irrigation. The model reveals that irrigation in situations where cracks form should be applied before they reach the critical limit (3 mm wide), otherwise all the applied water may lost as bypass flow if the other conditions are favourable, so leading to crop failure. The study indicates the importance of soil management during irrigation to increase water use efficiency by reducing crack. Finally, it can be concluded that influence of cracking should be considered to develop an irrigation scheduling of this puddled soil.

Key words: Cracking puddle soil, limited water, rice production, simulation model

INTRODUCTION

Traditionally, rice (*Oryzae sative*) is grown under continuous ponded paddies and as a result a large amount of water (about 1500 mm, except land preparation) is required due to high seepage and percolation losses (Islam and Ghani, 1990) during the growing season. Rainfall is almost negligible in the dry winter season of Bangladesh and ground water levels normally remain at about 10 meter depth. Consequently, the irrigation system does not have enough water resource to irrigate the entire area. As a result, the cost of irrigation is higher, so the response of the water managers is to reduce the potential command area. Hence, a large area remains fallow due to shortage and appropriate management of water resources. Therefore, other water management practices instead of ponding are necessary for optimum and economic yield of rice. However, Kandia (1985) and Cooke (2000) reported that the water requirement for rice is not much different from other field crops. Under non-flooded conditions the cracks that form in paddy due to drying between irrigations may be connected with those of the subsoil and the water may drain through these cracks, thus increasing water losses significantly (Hatano and Booltink, 1992). Therefore, it is important to understand the proper management of water and to explore approaches that can help to bring about efficient utilization of water in cracking puddle soil. The main objective of this study is to increase the water use efficiency of limited water resources in cracking puddled soils.

MATERIALS AND METHODS

To investigate and quantify the cracking behaviours of puddled soils and to fit the findings in a simulation model, a series of field and laboratory studies such as (I) fundamental properties of puddled soil; (ii) cracking behaviour of puddled soils; (iii) infiltration and bypass flow of cracking puddled soils; (iv) management of cracking puddled soils; (v) determination of horizontal (K_h) and vertical conductivities (K_v) were conducted in a wet soil bin and laboratory of Silsoe College, UK with sandy loam, clay loam and clay soil. The 20 m x 1.5 m x 1.5 m bin of render bricks was used. The roof of the bin area was protected from the rain by a plastic sheet. The major findings of these studies were as follows- A 8-12% depletion of soil moisture from saturation level allows crack initiation on the above three puddled soils. Among the three soils, a higher number of cracks, surface area and volume of crack were recorded for clay loam soil. A maximum crack depth-width ratio of 10:1 was recorded for these study soils. The cracks of puddled soil became almost irreversible at 15 days of drying and nearly the whole volume of applied water was lost through the cracks without any swelling of the soils. However, the cracks on puddled soils became irreversible even after a short period of drying. Soil management even at crack initiation had a great influence on infiltration rate. Among the management practices, the hand hoe operation was better than trampling to reduce the cracks even at 10 mm crack width. The conclusion of the field and laboratory studies would be that if fields are allowed to crack between irrigations, large losses of water will occur on subsequent irrigations and such losses can only be minimized by filling and sealing of visual cracks. In order to quantify possible losses a simulation model has been developed. A description of the irrigated field and scheme layout is shown to identify the nature and magnitude of water management problems and to develop improved methods.

Normally, deep and shallow tubewells are widely used in dry season rice irrigation in Bangladesh. The command area of a deep tubewell (2 cusec) is about 20-40 ha depending on soil types, topography and management approaches. The water from the sources run through the secondary, tertiary and field channels to meet the demand of the individual plot. Generally, the bunds are 250 mm wide and 200 mm high. A typical mean plot size is 0.25 ha (50 x 50 m) and these measurement were used in the model. Cracks which form on the field surface, may extend through the bunds. Although the surface cracks are closed or removed by ploughing, but the cracks, which form through and under the bunds, are not completely removed by swelling. Ultimately these may cause significant lateral losses from the rice field. In the simulation model, seepage losses was determined by considering the worst case when the plot is situated at the corner of the scheme (Fig. 1).

Conceptual model: The conceptual model of water losses from an irrigated rice field is shown in Fig. 2. A similar model is used by Wickham (1978); Wopereis *et al.* (1994),

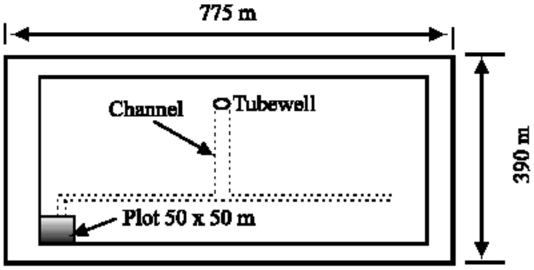


Fig. 1: Schematic diagram of irrigated scheme (30 ha)

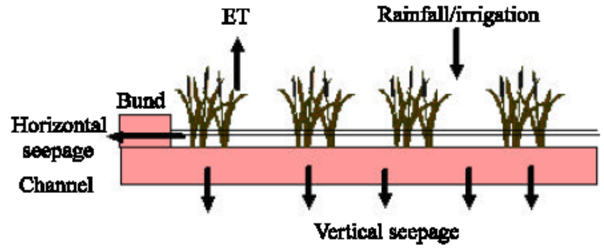
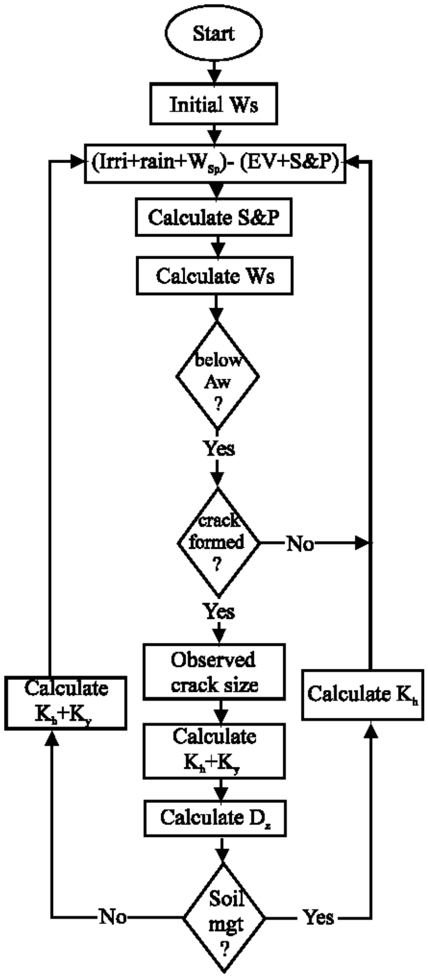


Fig. 2 Water flow paths for bunded paddy

Panigrahi and Bohera (1999). But they do not take into account the cracking of puddle soils. The water losses from paddy as percolation may be reduced or minimized by applying measure volume of water at certain sensitive (critical) stages to water stress instead of continuous ponding (Islam and Ghani, 1990; Guerra *et al.*, 1998). In this model, the primary control on deep percolation was assumed to be the degree and depth of cracking. Seepage loss is concerned with the ponding depth but it is more severe when there are cracks on paddy and bund (Walker and Rushton, 1984; Asokaraja, 1998). In the present model, the influence of cracking on seepage losses was assumed to be critical. EV will be reduced with decreases in soil moisture content but increase with surface area. In this model crack surface area was also considered to calculate EV. The daily rate of evaporation is closely related to the daily potential evapotranspiration requirement of a rice crop (IRRI, 1983). Therefore, the EV rate of winter season (Boro) of Bangladesh was considered in this model.

The spreadsheet model: The objective of the spreadsheet model was to quantify water losses from rice fields under a small number of identified scenarios involving soil cracking or non-cracking. The water requirement on a daily basis was determined by considering the weather and soil water balance. The field experimental findings of this study especially cracking behaviour and local weather data were used whenever it was available. But some assumptions were made which was normally applicable to modern rice varieties such as field duration of winter modern varieties, length of different growth stages, sensitive stages to water stress, rooting depth etc. (Table 1). In this model, the simulation was run (irrigation was scheduled) to avoid water stress.

Flow chart for a water loss simulation model for puddled soils: A flow chart (Fig. 3) for the water management model approach has been developed on the basis of the cracking behaviour/moisture status relationship, by using the recorded soil bin experimental data to predict the



Ws = Water status, depth of water (mm)
Irri = Irrigation (mm)
Rain = Rainfall (mm)
W_{sp} = Water status of previous day (mm)
EV = Evaporation (mm)
S&P = Seepage and percolation (mm)
Aw = Allowable water (mm) below which the crop will suffer from water stress
K_h = Horizontal conductivity (mm)
K_v = Vertical conductivity (mm)
D_z = Thickness of uncracked puddled layer+compact layer (mm)

Fig. 3: Flow chart of water management approach in simulation model

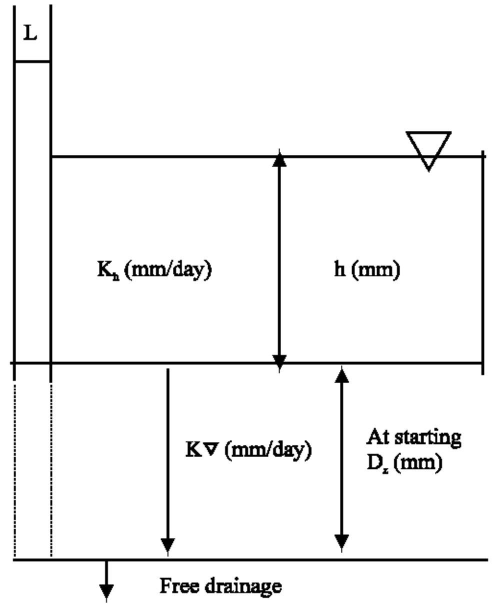


Fig. 4a: Illustration of combine horizontal and vertical seepage

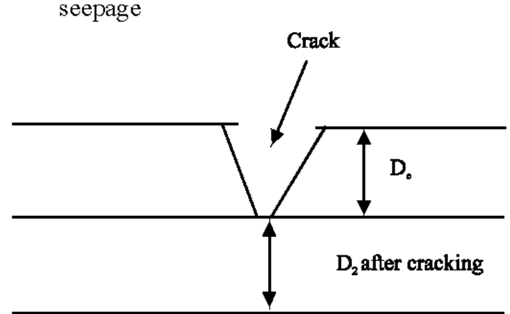


Fig. 4b: Illustration of vertical seepage
K∇ = Vertical conductivity
K_h = Horizontal conductivity
L = Width of the bunds
h = Depth of water
D_e = Depth of crack
D_z = Compact+uncracked puddled layer

magnitude of cracking under different conditions. In the flow chart, the paddy soil was assumed to be saturated immediately prior to day zero (Initial). A water balance model (eq.2) was used to determine the subsequent water status (Ws) on a daily basis. Water status in this study is defined as the depth of water (mm) on a given day and it is shown relative to soil saturation. Moisture depth above saturation (ponding) was represented as a positive and below saturation by a negative value. Then daily crop water requirement according to rooting depth for different growth stages was estimated on the basis of calculated seepage and percolation and the necessary water status to avoid crop stress. Horizontal (K_h) and vertical (K_v) conductivities were determined on the basis of crack size based on the soil bin experimental findings of this study. The depth of the uncracked puddled layer + compact

Table 1: Different phases and stages of 150-days variety and its irrigation stages

Growth phases and duration 30 (day) →	← Vegetative → 85			← Reproductive → 35	← Ripening → 30	
Growth stages →	Seeding ↑ Seedling	Transplanting ↑ Tillering		Panicle initiation ↑ Booting/heading/lowering	Milking stage ↑ Dought mature	
Duration (day) →	40	45		35	30	
It is sensitive stage? →	no	yes	no	Most	Less	No
Name of the stage →	Seeding stage	seedling establish-ment period	Tillering stage	Reproductive stage	Ripening stage	
Duration of the stage	40	10	35	30	25	10
Irrigation stages		1st	2nd	3rd	4th	5th
Period (day)		40-49	50-84	85-114	115-139	140
Irrigation advice		100 mm to saturation	Up to -16.5 mm	100 mm to saturation	Up to -27.5 mm	
Location	Seedbed	Paddy				

layer (D_z) through which infiltration took place was determined on the basis of crack size using the finding of crack depth-width ratio of this study and the illustration shown in Fig. 4. Finally, a soil management practice has been included to increase the water retention capacity by reducing bypass flow. The model was re-iterated on a daily basis for the whole crop season to determine the water usage under the given water and soil management scenario.

Use of field data and assumptions: Allowable water status for different irrigation stages was determined on the basis of root depth and soil moisture content. Allowable water status means the moisture content below which the crop will suffer from stress. During the critical stages (seedling establishment and reproductive) soil moisture was not allowed to go below saturation level (Table 1). According to Doorenbos and Kassam (1986) rice yield begins to decline when the moisture content of the soil decreases to 70-80% of saturation value. In the spreadsheet, the 80% of saturation value was taken as the limiting soil moisture content for rice production especially during the second (tillering) and fourth (ripening) stages of 150 days rice variety which is a favourable cultivars in Bangladesh (Table 1). But during the critical stages, 100 mm water was applied in each irrigation and then the soil was allowed to reach saturation before the next irrigation.

Average evaporation rate and rainfall for a 10 years period for Dhaka, Bangladesh was used in the spreadsheet. The date of irrigation was determined by considering the allowable water status, evaporation and rainfall. At each irrigation, not more than 100 mm of water was applied in order to limit the seepage and percolation losses. Darcy's law together with experimental data of this study was used to determine seepage and percolation. The following formula was used considering based of the boundary conditions (Fig. 4) to determine seepage and percolation losses.

$$S = (K_h h^2/2L*P/A*1/1000)+(K_v h/D_z+K_v) \quad (1)$$

Where,
- S = Total seepage and percolation (mm/day)
- K_v = Vertical conductivity (mm/day)
- K_h = Horizontal conductivity (mm/day)
- L = Width of bund (mm)
- P = Perimeter (m, converted to mm)
- A = Area (m^2, converted to mm)
- h = Depth of water (mm)
- D_z = Thickness of uncracked puddled layer+compact layer (mm)

It was assumed that there was no runoff losses in this study period, because the rainfall was very low during the dry season and the levee height was about 200 mm and well managed. Horizontal and vertical conductivities (K_h+K_v) were determined by considering the conductivities of cracks and the puddled soil matrix of soil bin studies. Accordingly, these parameters were used to calculate total soil water losses when there was crack in the field. Horizontal conductivity (K_h) was calculated on the basis of the crack dimension that was derived from the experimental data (eq.5) to determine lateral seepage losses from cracks in the bund. Under non-cracking conditions, K_h was assumed equal to the base infiltration rate. The base infiltration rate was derived using the field data of this study.

According to the conceptual model (Fig. 2), illustration of the horizontal and vertical seepage losses from a rice paddy is shown below.

$$Ws = (Irri+Rain+Ws_p) - (EV+SandP) \quad (2)$$

Where,
- Ws = Water status (mm)
- Irri = Irrigation (mm)
- Rain = Rainfall (mm)
- Ws_p = Water status of previous day (mm)
- EV = Daily evaporation (mm)
- S and P = Daily seepage and percolation (mm)

Considering data of soil bin and laboratory experiments of this study, the relationships of crack width and soil moisture content was determined. On the basis of those relationships two equations were developed to determine crack width from water status. Depth of soil water (mm) varies according to root depth under the same moisture content (Θv%). Therefore, equation (3) and (4) which are shown below were developed for the second and fourth irrigation stage respectively by considering their root zone depth.

$$C_w = (-13.09)+(-1.02*Ws) \quad (3)$$
$$C_w = (-12.46)+(-0.60*Ws) \quad (4)$$

Where,
- C_w = Crack width (mm)
- Ws = Water status (mm)

Childs' (1969) model was used with the experimental data of soil bin to determine K_h. The following equation was used to determine the horizontal conductivity of the cracking field.

$$K_h = g\rho f C_w^2/12\mu \quad (5)$$

Where,
- K_h = Horizontal conductivity (mm/d)
- g = Acceleration due to gravity (m/s^2)
- ρ = Density of water (Kg/m^3)
- μ = Viscosity of water (Kg/ms)
- C_w = Width of crack (mm)
- *f* = Area of conducting channel per unit area of cross section ≈ porosity,

Here the area = 1 m x 1 m of individual plot and the values of *f* are derived from the experimental data of this study. For example--Porosity for 1.8 mm crack width (when average no. of cracks-20 and average length of cracks-132 mm

$$f = \frac{132mm \times 1.8mm \times 20}{1000mm \times 1000mm} = 0.00475$$

Finally, the values of K_h and corresponding crack widths (C_w mm) of experimental data of soil bin were used to develop a model equation. The following model equation was used in the spreadsheet to determine K_h.

$$K_h = 0.0013\ C_w^{3.7998} \quad (eq.6)$$

Where,
- K_h = Horizontal conductivity (m/s)
- C_w = Width of crack (mm)

Using data derived from the experimental findings of soil bin, the relationship between reduction of bypass flow and elapsed time had been found. It was assumed that the resulting decreasing trend of bypass flow might be due to closure of the crack tip by swelling or by sealing as slaking. This phenomenon was included in the simulation model to determine D_z. Finally, the crop response to water status was calculated on the basis of allowable water status at different growth stages. Between 80% of saturation value to 75% of saturation was considered as "stress". Below this range was considered as severer stress.

Irrigation scenarios (cases)

Case 1: (Water management for continuous ponding): Is an irrigation schedule with continuous ponding. A measured amount of water was applied in each irrigation to return the water height to its maximum level (100 mm). This is the most common and usual water management practice in rice farming of Bangladesh.

Case 2: (Water management allowing cracking with irrigation based on crop water stress): Is an irrigation schedule where the water is applied according to an allowable deficit at different growth stages but avoiding stress. In this case, soil management was not included with irrigation whether there was cracks or not.

Case 3: (Water management based on cracking and soil management): Is an irrigation schedule where the water was applied according to allowable water status of growth stages and soil management was included with irrigation to remove cracks.

RESULTS

Case 1 (Continuous ponding): It is observed that a total amount of 920 mm of water with 12 irrigations is required if the continuous ponding height of 50-100 mm is maintained throughout the growing season. In this case there was no crack on the field due to continuous ponding water. Consequently, there was no change of D_z. Water status versus growing season is presented in Fig. 5. It is observed from this figure that the irrigation applications are almost equally distributed throughout the growing season and the range of water status varied from 50 mm to 100 mm.

Case 2 (Cracking / no soil management): From this study it is observed that the seepage and percolation losses varied according to ponding height as expected and remained above 1 mm day^{-1} when there is ponded water on the field. Percolation rate is less than 1 mm/day while the moisture remains below saturation. The low rate of percolation is due to the structureless nature of the puddled soil. Initially there are no cracks so the rates of seepage and percolation were low. The study reveals that the apparent recovery of D_z (closure of the crack tip) due to consecutive irrigations had no impact on the total seepage losses. Which means that the cracks in paddy are inter connected and most of the water is loss through bunds. The study indicates that soil management together with bunds management (repairing and compact) is very important to reduce seepage losses.

Under this circumstance, irrigation water would have to be applied almost every day to maintain saturation level during the reproductive stage to prevent crop stress. Water requirement was lower in the first stage (seedling establishment) than the third stage. Total water requirement for the 10 days of the first stage was about 50 mm whereas the 30 days of the third stage needs about 2800 mm of water. The high requirement of water during the third (reproductive) stage was mainly due to the

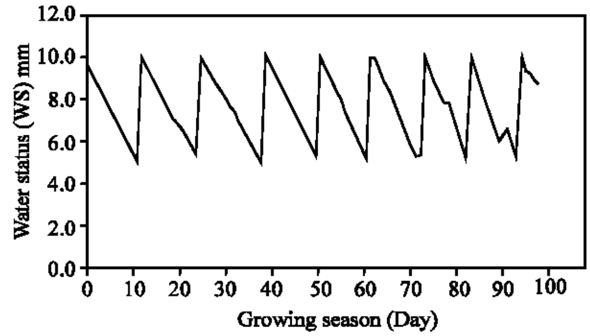


Fig. 5: Water status throughout the growing season with continuous pondig

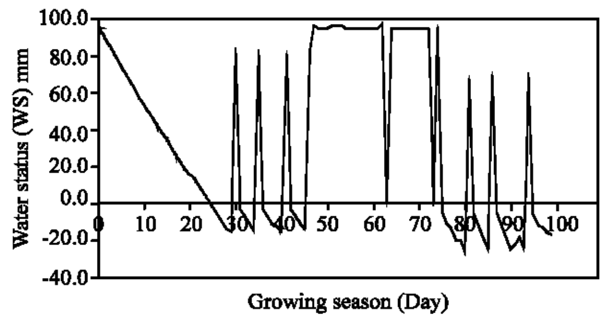


Fig. 6: Water status during the growing season without soil management

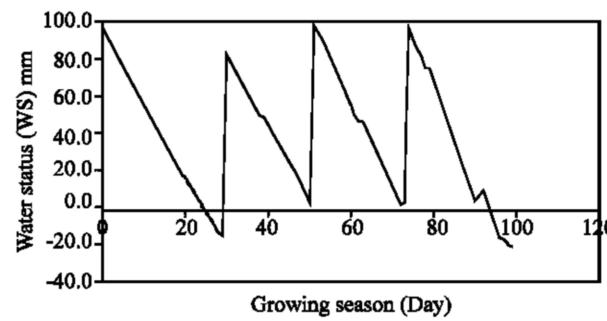


Fig. 7: Water status throughout the growing season with soil management

influence of soil cracks. In this stage, almost all the applied water passed through the cracks. Water status versus growing season is shown in Fig. 6.

Therefore, without soil management the total irrigation water requirement for a crop season is very high especially when there are cracks on the field. As a result, it needs a total amount of 3500 mm water with 35 irrigations, which is neither economically viable nor practicable with limited water resources. Consequently, this approach to water management is not acceptable.

Case 3 (Cracking / soil management): It is found that a total of only 780 mm irrigation water is required for the whole crop season which is a significant saving in comparison to usual practice (Case 2). There was negligible horizontal seepage loss in the soil management plot as there was no crack. Therefore, only vertical seepage was considered as the main water loss. Consequently, only 8 irrigations were required for the whole growth season without the crop suffering. As a result, total irrigation water requirement for the season was very low compared to the without soil management practices. The experimental work indicates that it needs extra time and labor to perform soil management with irrigation. But water is more valuable than time to the farmer especially in the dry season. However, synchronizing it with weeding and other intercultural operations can reduce the cost of soil management.

Water status versus growing season for the soil management practice is shown in Fig. 7. From this figure it is observed that the irrigation intervals are almost equally distributed, as there is no influence of cracks on percolation due to the impact of soil management. From this study it is found that the cracks could be closed after the irrigation if there is soil management with irrigation. As a result, seepage and percolation rates following irrigation are similar to those of the non cracking field. The study indicates that soil management during irrigation can help to reduce the total irrigation water requirement without the crop suffering. Therefore, soil management during irrigation is very important to reduce irrigation water losses from the cracking field. Consequently, this management practice can be recommended to prevent loss of valuable water in the dry season, especially in limited water resource areas.

DISCUSSION

Soil management during irrigation on a cracking field is a promising approach for saving irrigation water in rice growing areas where water is limited, especially in the dry season. Soil management should be carried at the beginning of irrigation with a portion of water depending on soil dryness or hardness. It may also be accomplished with irrigation by considering the soil moisture and crack dimensions. The most commonly used secondary hand tillage implements (i.e hand hoe, spade and weeder), which are normally used, for weeding and mixing of top dressing fertilizers with irrigated soil may be used for this purpose. A simple flow chart (Fig.8) has been developed on the basis of the simulation model findings for the better management of puddled soils to increase irrigation application efficiency.

Continuous monitoring of puddled fields is important to determine the daily water status. If the water status is below saturation then cracks should be observed and checked whether they reach critical limit (3 mm wide). Therefore, irrigation water should be applied before critical limit or as soon as crack appear on the paddy to reduce the water losses. If the crack width is 3 mm or above then soil management must be included to increase the application efficiency by sealing cracks. The above procedure should be continued for the whole crop season to save the valuable irrigation water resources.

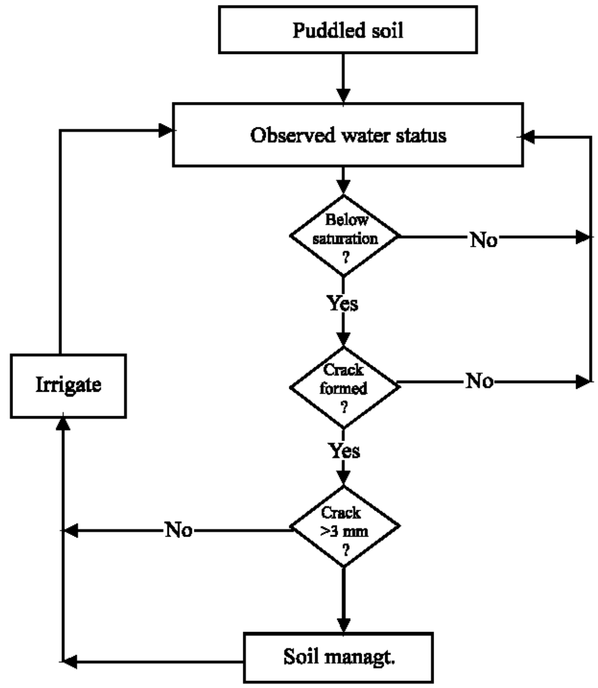


Fig. 8: Water management approach for puddled soils

From this simulation model it is observed that the total amount of water required for rice production is directly related to the nature of water and soil management practices during irrigation. Irrigation requirement without soil management was about 4.5 times greater than irrigation with soil management practice. Similarly, irrigation without soil management required 4.0 times more water than continuous ponding. This extra volume of water is mainly needed for high horizontal (seepage) loss. However, the study indicates the importance of soil management during irrigation to increase water application efficiency. Moreover, the study reveals that a significant amount of irrigation water can be saved from the discontinuous ponded paddies by reducing seepage with bunds management.

The model reveals that irrigation in cracking soils must be applied before the cracks reach the critical limit (3 mm wide), otherwise the whole amount of water may lost as bypass flow. The study also indicates that irrigation with soil management is the most effective and increase water use efficiency by reducing cracks. With this technology a large volume of irrigation water can be saved without crop suffering. As a result, this irrigation management practice (Case 3) may be recommended especially for limited water resource areas. Therefore, this recommended irrigation practice would help to increase total yield by bringing more area under irrigation practices with limited water resources.

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