Chapter 1

INTRODUCTION

Eastern India is bestowed with an annual rainfall ranging from 1200 to1700 mm, two-third of which is occurring during monsoon season spanning from June to September. About 50% of the annual rainfall occurs through a few intense storms. The spatial heterogeneity and temporal variability of rainfall leads to differential surface flooding, runoff, erosion and nutrient losses on one hand and water scarcity at the critical crop growth stages on the other (Panigrahi and Panda, 2003a; Kar and Verma, 2005; Cai and Sharma, 2010). Understanding of soil water dynamics under such monsoon climate is important for developing proper water management strategy for paddy production system.

In the rice field, rainwater is usefully conserved by erecting dykes around the crop fields. The major losses of water in these fields occured by surface runoff, lateral seepage through the dykes, vertical deep percolation and evapotranspiration (Walker and Rushton, 1984). All these processes affect nitrogen availability as nitrate-nitrogen (NO_3^- - N) that accumulates in aerobic either lost through leaching beyond root zone and contaminate the groundwater (Goswami et al., 1986; Zhang et al., 2009) or get diffused into the anaerobic (reduced) soil layer below and denitrified to the N_2 and N_2O gaseous forms, which are lost to the atmosphere contributing to global warming/climate change (Aulakh and Singh, 1997; Ayala, 2002; Dinnes et al., 2002). *In situ* conservation of rainwater in the cropped field, harvesting of excess rainwater in the OFRs and utilized for providing supplemental irrigation to rice followed by non-rice crops in dry winter season such as mustard with diversified cropping system are some of the rainwater management strategies for increasing the overall agricultural productivity of rainfed eco-system in a region (Biswas et al., 2006; Haefele and Konboon, 2009; Toure et al., 2009; Fusheng et al., 2010).

The major challenge of the rainfed agriculture is the sustainable management of rainwater and nitrogen so that a favourable environment is created for crop growth. Cultivation of non-rice winter crops following rice depends on the availability of residual soil water and water resources. In the absence of groundwater resources, the monsoon rains available in the crop field can be harvested in the OFR for supplying life saving irrigation to rice in the rainy season and the balance can be usefully utilized for cultivating non-rice crops in winter season. But no efforts has been done yet to investigate the effect of variable ponding depths in rice fields, which leads to different soil water regimes and also generates variable runoff that can be harvested and stored in the lined and unlined OFRs for future use. Much more studies are required on the effect of lining, as the availability of water in the OFR depends on it, for increasing the water use efficiency. Depending on the storage capacity of the OFRs, the crops will be differentially irrigated leading to seasonal variation in soil water regime, which in turn controls the availability and movement of water and NO_3^- - N.

In India fertilizer nitrogen is generally applied in the form of urea. When urea is applied in flooded rice fields, it is converted to ammonium-nitrogen (NH_4^+ - N) by the process of hydrolysis and finally to NO_3^- by nitrification. With the onset of monsoon and flooding of soil, NO_3^- - N which is soluble in water either moves with the percolating water and leaches down to groundwater or is lost through denitrification (Aulakh and Singh, 1997; Behera and Panda, 2009). This results in a net reduction of the mineral nitrogen pool at the beginning of the rice growing period (Shrestha and Ladha, 2000). The two major factors controlling leaching losses of nitrate are concentration of nitrate in the soil profile at the time of leaching and quantity of water leaving the root zone. Ammonium is generally considered immobile, as it gets adsorbed on the soil particles and absorbed by the plants, and is not transported by the percolating water (Wiklander, 1977) except when fertilizer is applied in very large quantities or soil is coarse textured and has low cation exchange capacity (Aulakh and Singh, 1997). Thus, it is required a much better understanding of the underlying processes of water extraction and nutrient uptake under the fluctuating conditions of the rainfed rice fields.

To meet the demands of accurate prediction of flow and transport processes for various environmental projects, development of more efficient and accurate measurement methods and more appropriate modeling approaches is imperative. Research on the measurement and modeling of water flow and solute transport and transformation processes under transient soil water regime has recently been recognized as an important area of research for paddy production system (Tournebize et al., 2006). Predicting water flow under different soil water regimes is a challenging task because of high variability of soil hydraulic properties with time and space, and the complex nature of underlying flow field. Computer models are becoming increasingly important tools for analyzing complex problems involving water flow and solute transport in the vadose zone (Belder et al., 2007). However, studies simultaneously estimating water flow and solute transport parameters for transient variably-saturated media are less common (e.g. Inoue et al., 2000), especially in a layered soil-profile and for field conditions. The two-dimensional HYDRUS-2D model is one such model that has been successfully used for simulating soil water transport by various workers (Šimůnek and Hopmans, 2002; Abbasi et al., 2004). More studies are to be required to evaluate suitability HYDRUS-2D model to simulate movement of soil water under variable soil water regimes in rice and mustard fields.

Thus, in order to maximize the water and nitrogen use efficiency of rainfed upland rice under different ponding depths, an in-depth knowledge is required on water and nitrogen dynamics as affected by variability of rainfall and the OFR irrigation induced soil water regimes. The present investigation has, therefore, been undertaken to assess the influence of runoff and supplemental irrigation from the OFR on soil water and NO_3^- - N dynamics under rainfed upland rice (*Oryza sativa* L.) and irrigated mustard (*Brassica campestris* L.).

1.1 Objectives and scope

The specific objectives of the present investigation are:

1. To simulate soil water under rice-mustard cropping system using HYDRUS-2D.
2. To evaluate the effect of runoff induced soil water regimes on water and nitrate-nitrogen dynamics under rainfed upland rice.
3. To study the effect of soil water regimes, as induced by frequency of irrigation from the lined and unlined on-farm reservoirs, on water and nitrate-nitrogen dynamics under rainfed mustard.
4. To asses the effect of runoff and the OFR irrigation induced soil water regimes on root growth, nutrient uptake, yields, and economics of rice-mustard cropping system.

Although the impact of soil water regimes on the productivity of rice based cropping system is well conceived, its variation under changing conditions of rainfall distribution, runoff and irrigation from the OFR as well as their impact on the dynamics of water and NO_3^- - N are scarcely understood. No attempts have been made till-date to know the complex dynamics of the lateritic (*Oxyaquic haplustalf)* tract of eastern India where rice is traditionally adopted as a rainfed crop during monsoon season and a low duty crop like mustard during the post-monsoon dry winter season. Moreover the impact of lined and unlined OFRs on volume of storage, water losses and frequency of supplemental irrigation on yields of crop has been requiring more attention.

1.2 Organization of the thesis

The present research includes both modeling followed by experimental study for quantification of daily water balance parameters under cropped field condition with different weir heights. Physically based dynamic modeling will be made to determine the water losses through seepage and deep percolation. The results of the model study will be validated with experimental findings. In addition, the economic analysis will be carried out to establish the feasibility of the farming system. A brief overview of the thesis are given below.

Calibration and validation of HYDRUS-2D model

Owing to large-scale variation in climate during monsoon and post-monsoon seasons, physical measurement of soil water becomes difficult and in such situation modeling studies are often adopted to simulate soil water. HYDRUS-2D (Šimůnek et al., 1999) has been used for simulating soil water in the rice and mustard fields under variable runoff generated due to various weir heights and supplemental irrigation from the OFR. Model can be used to determine water losses through seepage and deep percolation in the field soil. The model was calibrated and validated after defining the domain geometry with finite element mesh (FEM), observation nodes, initial and boundary conditions of the rice and mustard field cross sections. Maximum root-zone depth of crops (45 cm for rice and

105 cm for mustard) was considered as the model domain. Soil profile of the rice and mustard fields was divided into 3 and 7 layers of 15 cm intervals, respectively. Soil water contents measured at different layers on the first day of simulation was specified as initial boundary conditions. Daily rainfall/supplemental irrigation and potential evapo-transpiration for the entire simulation period of 120 days for monsoon rice including 15 days of turn-in period (period between harvest of rice to sowing of mustard) and 75 days for winter mustard were used as a time-variable boundary at the soil surface. The soil surface was assumed to have atmospheric boundary condition for the model domain. The bottom boundary at the root-zone depth was assigned to have free drainage boundary condition for vertical percolation. The vertical boundaries were assigned as no-flow boundary conditions. The measured values of hydraulic parameters for different soil layers of the cropped fields were input to different layers of the model domain.

Using inverse modeling approach, HYDRUS-2D model was calibrated for the simulation of daily soil water content and to get optimized calibrating parameters at 95% confidence intervals. The calibrated parameters such as coefficient (α) and exponent (n) in soil water retention function for each soil layer were estimated using neural network prediction and van Genuchten and Mualem (VGM) hydraulic model. The optimized calibrated parameters of HYDRUS-2D can be further used for the simulation of soil water content in different soil layers and vertical percolation for rice and mustard fields under variably saturated condition. The model performance was evaluated using regression analysis (coefficient of determination), scattered diagram and error statistics (root mean square error and prediction efficiency) of simulated and observed daily data.

Water dynamics in the crop field

The water balance simulation model was developed for rainfed monsoon rice and winter mustard field with different weir heights (0, 5 and 10 cm) and discussed in this section. The field water balance parameters considered are rainfall, runoff generated at different weir heights, actual evapotranspiration, supplemental irrigation at critical growth stage, vertical percolation, and lateral seepage through the dyke. Maximum root depth considered for rice and mustard was 45 and 105 cm, respectively, as the soil reservoir. Vertical percolation losses in the rice field with 0 cm weir height were simulated using HYDRUS-2D model under variably saturated condition, whereas in case of 5 and 10 cm weir heights (ponding condition) Darcy's approach was used.

Water balance in the OFR

This section explains about all the inflow and outflow components of the lined and unlined OFR. The inflow components are the direct rainfall received on the OFR and surface runoff contribution to the OFR from the crop field through different weir heights; and the outflow components are supplemental irrigation supplied to crop, evaporation from open water surface, and seepage losses. The water balance model for the lined and unlined OFR with different weir heights for rice-mustard cropping system with the provision of supplemental and pre-sowing irrigation is presented in this section.

Root growth and Nitrogen dynamics in the field

This section deals with the root growth and root distribution of rice and mustard crop under variably saturated soil. Root distribution in soil used to correlate the total amount of water and nutrients uptake and yield of crops. For nutrient-use efficiency in rainfed ecosystems, the special challenge is the dynamic of the water regime. If water is available but nutrients are limiting, the crop may not be able to utilize the water efficiently. The root growth and nitrate concentration were monitored in rice field at three depths (15, 30 and 45 cm) and up to 105 cm depth at an interval of 15 cm in mustard fields. Soil water samplers were installed in each plot at 15, 30 and 45 cm depths in rice field while soil core samples were used in mustard field up to 105 cm depth at an interval of 15 cm for first three layers and at 30 cm interval for lower two layers, for monitoring NO_3^--N transport. The leaching loss of NO_3^- -N in the rice field was affected by distribution and amount of rainfall occurred during growing period.

Crop yields and economic analysis

This section explains about the effect of variably saturated soil on crop yields and economics of the system. Different moisture levels affect the total amount of water and nutrients uptake and yield of rice and mustard crops. The nitrogen uptake in rice field was influenced by variation in crop yields obtained as a result of distribution pattern of rainfall. While in mustard field, it was affected to a great extent by different yields as influenced by various weir heights.

A present worth analysis is used to evaluate the economics of the OFR system. The factors considered for the economic evaluation were initial investment, the OFR maintenance cost, land lease cost, irrigation cost, and annual returns from the OFR system. Considering 12% interest rate and 25 years life span of the lined and unlined OFR, present worth value of total annual cost for the lined and unlined OFR was calculated. From the increased production of rice and mustard against the traditional rainfed condition (without the OFR), present worth value of the total return was estimated and net profit (NP), benefit cost ratio (BCR) and pay back period (PBP) was calculated.

Field experiments

In order to verify the simulation results of water balance parameters and justify the investment in the OFRs, three years (2002, 2003 and 2004) of field experiments were carried out in the experimental farms of the Agricultural and Food Engineering Department, Indian Institute of Technology, Kharagpur, West Bengal State in eastern India. The field experimental set-up consists of the lined and unlined OFRs with three weir heights (0, 5, 10 cm) replicated thrice in split-plot design. In addition, three plots without the OFR were cultivated for economic evaluation of the OFR system over traditional method. Each plot is 40 m × 20 m size with 30 cm dike height around. Initially square shaped pyramidal 9 lined and 9 unlined OFRs were constructed at one corner of each plot. During the monsoon season, rice (cv. MW 10) of 101 days duration and in winter season, mustard (cv. B 54) of 70 days duration was grown in the experimental field.

When the soil water content in the effective root zone of rice depletes 40% below saturation soil water content during critical growth stage, supplemental irrigation has been provided from the OFR. Irrigation was provided to mustard when the soil moisture content in the effective root zone depleted 25% below the available soil moisture during the critical growth stages.

1.3 Contributions of the thesis

- The impact of the on-farm reservoir with different weir heights on the dynamics of water and NO_3^- - nitrogen under variable soil water regime has been studied for the first time for rainfed upland rice based cropping system.

- Present study of testing the lined and unlined OFR systems in rainfed upland rice based cropping system suggests for the adoption of the unlined OFR system without allowing any ponding depth in the field. But, one can go for the lined OFR system without any ponding in the field so as to check contaminant transport to groundwater and hence protect the environment.

- This study will be helpful for conservation of natural resources and sustainable production of rice-mustard with variable quantity of rainwater harvested in the OFR in rainfed ecosystem.