Evaluating Irrigation Scheduling Efficiency of Paddy Rice and Berseem Fodder Crops in Sandy Loam Soil

Irrigation & Drainage Systems Engineering

Evaluating Irrigation Scheduling Efficiency of Paddy Rice and Berseem Fodder Crops in Sandy Loam Soil

Hatiye SD[1]*, Hari Prasad KS[1], Ojha CSP[1], Kaushika GS[1] and Adeloye AJ[2]

[1]Department of Civil Engineering, Indian Institute of Technology, Roorkee, India
[2]Institute for Infrastructure and Environment, Heriot-Watt University, Edinburgh, UK

Abstract

In this study, irrigation scheduling efficiency of two field crops; paddy rice and berseem fodder, grown in unpuddled sandy loam soil for a typical existing and imposed irrigations has been evaluated using the WINISAREG water balance and irrigation scheduling model that was calibrated and validated using data collected at field experimental plot in Roorkee, India. During the 1st season of each crop, typical irrigation schedules as practiced in the farmers' field was followed while in the 2nd crop season, a reduced irrigation schedule was imposed aiming for water saving. Water balance components were monitored daily during the crop growth periods. Deep percolation was measured using drainage type lysimeters. Soil moisture content in the root zone was observed using soil moisture profile probe (PR2/6). The crops were provided with all the necessary inputs including fertilizer, pesticide and weeding operations following agronomic practices of the area. The results show that nearly 82-87% of the input water goes to deep percolation during paddy season-1 (continuous irrigation period) while 64%-70% of input water was lost through deep percolation during berseem season-1. Due to the imposed irrigation, the deep percolation has been reduced to nearly 78-80% of input water during paddy season-2 and 42-52% of input water during berseem season-2 besides large input water saving in the crop seasons. The large input water saving was due to alternative irrigation scheduling strategy whose efficiency has been significantly improved. Irrigation scheduling efficiency has been increased from 9.65% to 30.5% for paddy and 23% to 92% for berseem. In particular, comparative irrigation water saving of 64-74% in paddy season and 82-88% in berseem season was achieved with nominal yield penalty. This study shows the possibility of large volume of water saving in water intensive crops such as paddy rice and berseem fields under un-puddled sandy loam soils by considering a reduced irrigation scheduling option.

Introduction

Rice (*Oryza Sativa L.*) is the most important staple food crop in Asia, providing 35-80% of the total calorie intake [1]. In Asia, irrigated agriculture accounts for about 90% of total diverted fresh water and more than 50% of this is used to irrigate rice [2]. Due to the inherent nature of water application, lowland rice is often seen as an inefficient water user [3]. This is due to the fact that large proportion of the applied water is lost through deep percolation and seepage [2,4-6]. Sizable efforts have been made to reduce deep percolation especially from rice fields including: alternate wetting and drying (AWD) [5,7-9]; aerobic rice [10]; delayed application of continuous flooding [11] and puddling [6,12]. Berseem fodder (*Trifolium alexandrinum L.*) is a forage crop widely cultivated in northern India and the other parts of the world [13]. Specifically, in India it grows in winter from October to June and offers a good rotation with other summer crops such as rice, cotton, barely and maize. The water requirement and irrigation scheduling of berseem fodder is almost similar to that of alfalfa forage crop. However, berseem is preferred to alfalfa since it provides the possibility of rotation with other crops, improves soil structure, relished by all kinds of stock and poultry, more succulent, supper in fattening stock and milk production [14].

Appropriate irrigation scheduling favours increase in crop yield, water saving, environmental protection as well as economic boost [15]. Accurate scheduling of irrigation water would limit over and/or under-irrigation situations, and thus, help to avoid deep percolation of water and stress to crops. Deep percolation phenomena, however, has become a major threat to proper irrigation scheduling particularly for surface methods of irrigation which are mostly practiced in developing countries. Most research studies considered presence of an impermeable layer (hard pan) below the bottom of rice paddy root zone to arrest deep percolating water. However, the efficiency of the

hard pan under farmer operated field conditions is not well proved to serve the purpose of impeding deep percolation. Incidences of large deep percolation under bunds and through cracks have been reported in puddled field conditions [3-5,16]. Another problem which has been documented against puddling practices in paddy fields is the interference of the puddled layer with the next crop [17]. Further, puddling operation is a costly task as it needs extra labour and cost. Therefore, nowadays farmers are escaping the puddling operation and grow both rice and berseem crops under unpuddled conditions. However, the quantity of deep percolation under such agronomic conditions is not well understood specifically applied to coarse textured soils. So far field measurement of deep percolation using drainage type lysimeters for water intensive crops was also limited probably due to large volumes of drainage below the root zone which is often difficult to monitor. Consequently, only limited studies are available with regard to deep percolation and irrigation scheduling evaluation of such water intensive crops on coarse textured unpuddled field conditions. Therefore, in this study, we carried out typical irrigation applications and timings as practiced in this particular region and imposed reduced irrigation applications for both crop periods under non-puddled coarse textured soil to study the extent of water saving

due to imposed irrigations, evaluate the irrigation scheduling efficiency of each crop seasons, test the applicability of the WINISAREG water balance model in simulating the water balance components and finally assess the efficiency of locally constructed lysimeters in metering deep percolation from the crop root zones.

Materials and Methods

Study site

The study site is located in the Uttrakhand state of India, an experimental plot situated at Department of Civil Engineering, Indian Institute of Technology, and Roorkee. Roorkee is located near the River Ganges in the geometric grid of 77°53′52″ East Longitude and 29°52′00″ North Latitude at an average altitude of 274 m above mean sea level. The climate of Roorkee is typical of north western India with hot humid summer and very cold dry winter [18]. The monthly average maximum temperature of the study area is recorded in the range of 19.33 (January) to 37.73°C (May) and monthly average minimum temperature in the range of 7.2 (January) to 25.6°C (July) according to the data from National Institute of Hydrology (NIH), at Roorkee. The average relative humidity runs from 52.2% (May) to 89.7% (January). The average annual daily sunshine duration is 7.7 hrs. The normal rainfall of Roorkee is 1060 mm per annum and out of which almost 80% is recorded during the monsoon season (June to September). The soil in the region can be classified as 'soils in old alluvial plains', which are well drained fine loamy soils on nearly level plain with sandy loam surface [18].

Field and laboratory experiments

The field experiment consisted of growing paddy rice (var. Supper

Figure 1: Field layout (a) and lysimeter setup details (b).

Basmati) in the 2013 and 2014 growing seasons with continuous saturation and intermittent application of irrigation respectively. The 1st paddy rice season hereafter called paddy season-1 was transplanted on July 23, 2013 and harvested on 02 November 2013 while the 2nd paddy rice (paddy season-2) was transplanted on 15 July, 2014 and harvested on 22 October, 2014. On the same field, berseem fodder (var. JB-1) crop was also grown in the winter seasons of 2013/14 and 2014/2015. The 1st season berseem (berseem season-1) was sown on 12 December, 2013 and finally harvested on 08 May, 2014 while the 2nd season berseem (berseem season-2) was sown on 17 November, 2014 and harvested on finally harvested on 16 April, 2015. Berseem was cut four times for green fodder in each of the seasons.

Lysimeter experiments were conducted at the experimental farm from July 2013 to April 2015 in both crop periods. The area of lysimeters is 1 m² having a depth of 1.35 m repacked soil monolith of the experimental field. A repacked soil column may take several years to duplicate the natural soil state for research with restricted irrigation (i.e., rain-fed or dry land applications) [19]. The construction of the lysimeters was took place in 2006 and hence they are considered to replicate the surrounding root zone soil environment. The lysimeters were constructed of steel metal sheets having a square shape. The soil monolith is a repacked soil material consisting of the upper 1.15 m filled with a sandy loam textured soil, moderately homogeneous throughout the profile, characterized by an organic content of 1.1 to 1.2%. The bottom 0.08 m was filled with a very coarse gravel of size more than 3 cm in diameter overlain by 0.12 m thick gravel of about 2 cm in diameter. This bottom arrangement allows drainage towards imbedded pipes which carry percolating water towards collecting buckets in the access hall (Figure 1). The lysimeters were located in the centre of the 1st compartment (plots A21 and A22) where plastic sheets were buried at field boundaries to a depth of 60 cm to impede lateral seepage out of the field. Each compartment has been further partitioned into smaller plots to manage the experimental run. The boundaries of the 2nd compartment (A11- A14) were left open to mimic actual field conditions elsewhere (Figure 1). The same experimental conditions have been maintained inside and outside the lysimeters in each of the growing periods of the crops.

During the paddy growing seasons, 21 days old seedlings were transplanted after thorough field preparation and flooding to saturate the soil. Prior saturation of the field by flooding before transplanting was made, which favoured initial conditions for the crop growth. A basal dose of Di-ammonium Phosphate (DAP) and Zinc Sulphate during transplanting and Urea after three weeks of transplanting were applied following agronomic practices of the area. Weeding was undertaken manually by hand removing all weeds from field three times during the growth periods of the crop. The crop was also protected from threatening insects by applying an insecticide commonly used in the area. The soil root zone in this particular experimental condition was left un-puddled. Similarly, in the winter season, berseem fodder crop was sown on prepared beds on the same plot. The field was soaked with water before sowing the seed to favour easy seed germination. Required does of DAP was applied for the fodder crop and weed control was undertaken in the similar way as that of the paddy rice. Irrigation was scheduled when nearly 40% of moisture depletion in the surface layer took place (mainly in berseem season-1). Additional irrigations were also provided during the winter season to ease the soil freezing effect on the crop.

The soil physical and hydraulic characteristics have been determined in the laboratory for three representative spots of the
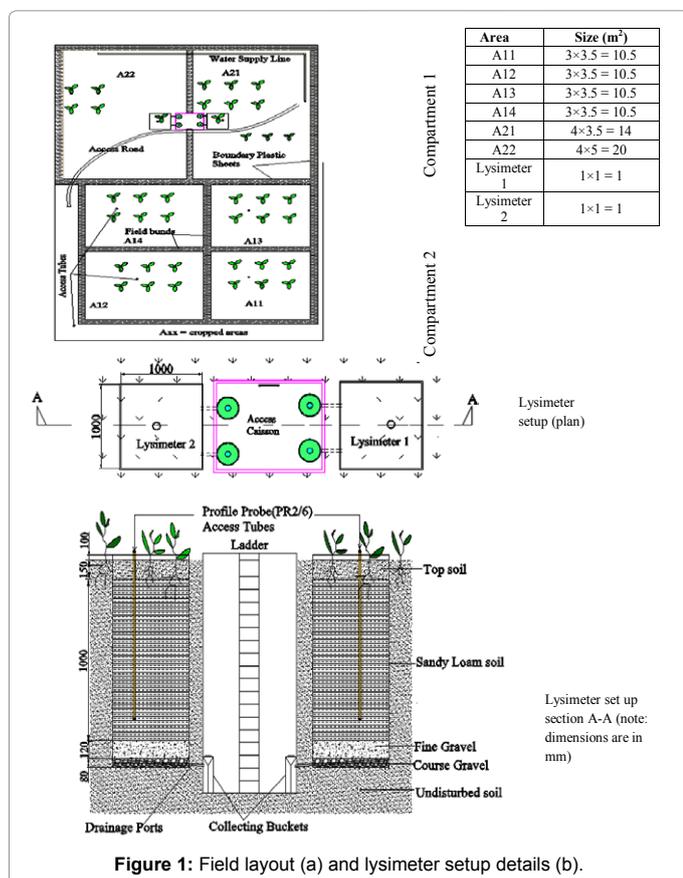
experimental plot and replicate depths from 0 to 140 cm. In this study, laboratory experimental works consisting soil physical properties such as grain size, bulk density, particle density and the soil characteristic curve of the experimental plot have been determined. The data from pressure plate apparatus (Ψ versus θ) enabled to furnish soil water characteristic curve of the experimental plot from which the wilting point and field capacity of the experimental plot have been determined. The soil bulk density was determined using the core cutter method as suggested by Trout et al. [20]. The soil particle density was obtained by conducting water Pycnometer test. The soil particle size was determined by employing mechanical sieve analysis (for coarser particles) and hydrometer (for the finer portion of the soil) methods as recommended by the American Society for Testing and Materials, ASTM. The soil properties determined are shown in the Table 1.

Irrigation water was applied for a specific area by knowing the supply line discharge and calculating time required to provide a predetermined depth of water for a given plot area. The depth of water required varies depending on pondage required (paddy rice season) or to fill up to field capacity after certain depletion of the available water has been occurred in the root zone (berseem fodder). The discharge of a permanent water supply line at a particular period was determined by measuring the time required (stop watch) to fill a known volume of container. After deciding irrigation depth, mainly based on local practices during paddy season (20-100 mm during continuous irrigation in paddy season-1), imposing reduced irrigation size (10-50 mm during paddy season-2) and based on certain deficit during the berseem season-1(30-60 mm) and berseem season-2 (4.8-18.5 cm), the time required to spend the flow in a particular plot of known area was calculated using the continuity equation. In similar fashion all the plots were irrigated. The variations of head and tail end ponding and consequently percolation are disregarded in this case since the areas of the plots and the border lengths are small (Figure 1) so that the water advances to the tail end in a very short time. Plastic hoses were used to deliver water to a particular plot from the water supply line.

During paddy season-1, the effort was to saturate the field every time to keep a saturated culture while in paddy season-2 the method similar to alternate wetting and drying (AWD) was practiced. Ponding for a long time in our case was impossible because the water quickly infiltrates.

The soil water status was monitored by using soil water probe (Profile Probe-PR2/6; Delta-T Devices, Cambridge) through access tubes installed both inside and outside the lysimeters. The probe consists of a sealed polycarbonate rod approximately 25 mm diameter, with electronic sensors arranged at fixed intervals along its length. Each of the sensors comprises a 100 MHz oscillator and transmits an electromagnetic field extending about 100 mm into the soil. The water content of the soil surrounding the rings dominates its permittivity, $\sqrt{\varepsilon}$. The permittivity of a material is a measure of its response to polarisation in an electromagnetic field. Water having a strong permittivity (≈ 81) than soil (≈ 4) and air (≈ 1) can easily be detected in an electromagnetic field. The detectors are sensitive to the different proportions of transmission and refection, and convert them into stable voltage output that acts as a simple, sensitive measure of soil moisture content. When installed in an access tube constructed from a composite material it can measure the dielectric constant at soil depths of 10, 20, 30, 40, 60 and 100 cm. The probe can either be logged in the access tube or it can be moved from one access tube to another to make spot readings. The output of the probe is in volts which can be converted into dielectric constant, ε which is useful for describing the microscopic interaction between electromagnetic radiation and matter [21]. The probe enables to measure the soil water content in volumetric bases for different types of soils ranging from clayey to sandy soils with accuracy between ± 0.04 (after soil specific calibration) and ± 0.06 (after generalized soil calibration in normal soils). However, it has been reported that the probe is very sensitive to air gaps which may be created due to soil cracking and installation operations [22]. Therefore, we have installed the access tubes with due care as suggested by the manufacturer of the instrument.

Deep percolation was measured twice in a day at the bottom of lysimeters early in the morning (07:00 a.m.) and evening (around 07:00 p.m.). The lysimeter rim was kept 10 cm above the ground to avoid run-on or runoff. Collecting buckets in access hall were used to collect the drainage water. The buckets were securely covered to avoid rainwater inflow. The caisson hall was also sheltered from rainfall to avoid any inflow from rain water to the buckets so that only drainage water should be collected. Drainage ports connected to the lysimeters were used to convey and discharge the percolating water to the buckets where the percolation measurement was being made. Further, data pertaining to crop specific parameters such as root depth, crop height and leaf area index were also monitored during the growth period of the crops.

Climatic data (temperature, relative humidity, pan evaporation, wind speed and rainfall) for the growth period of the crops was obtained from nearby metrological station, National Institute of Hydrology (NIH) India, located at a distance of 0.8 kilometres from the experimental station. These data were used to calculate the evapotranspiration component of the water balance.

Model description

Model inputs and the soil water balance: An irrigation scheduling and simulation model, WINISAREG, has been used to evaluate the imposed irrigation scheduling of the two crops. The model requires the soil, crop and climatic data (variables and parameters) and irrigation application options to carry out the root zone water balance computations. It also considers certain water supply restrictions which may encounter in practical field conditions. The detailed list of required inputs is documented in Fortes et al. [23].

The WINISAREG model which performs the soil water balance at field scale was developed and described by Teixeira and Pereira [24], Liu [25] and Pereira [26] The model is an integration of two different models, the EVAP56 (for computing reference evapotranspiration)

Depth below ground level (cm)	Bulk density (g/cm³)	Particle density (g/cm³)	Sand (%)	Silt (%)	Clay (%)	Soil Class (USDA)	θ_{fc} (%)	θ_{pwp} (%)	θ_{sat} (%)
0-30	1.58	2.55	73.40	22.70	2.96	Sandy loam	18.5	6.6	38
30-60	1.55	2.57	66.89	28.39	4.01	Sandy loam	24.5	6.6	40
60-80	1.54	2.56	68.57	26.54	4.33	Sandy loam	19.9	6.0	40
80-100	1.54	2.58	69.10	26.54	3.84	Sandy loam	20.2	6.3	40
100-140	1.59	2.62	68.01	27.38	4.58	Sandy loam	20.0	7.6	39

Table 1: Soil physical characteristics of the experimental plot.

and the ISAREG (to perform water balance computations) as described by Pereira [26]. WINISAREG has been tested and used in different parts of the world under varying soil, crop and irrigation management conditions [27-29]. The model specifically enables to compute deep percolation on seasonal bases which provides additional opportunity to compare model computed percolation with that of field measured percolation.

The governing equation in the WINISAREG water balance and scheduling model which can also be applied for the lysimeter water balance model is given as:

$$\theta_i = \theta_{i-1} + \frac{P_i + I_i - ET_{ci} - DP_i - R_i + GW_i}{1000Z_{ri}} \qquad (1)$$

where $\theta(m^3 m^{-3})$=soil water content in the root zone; P(mm)=precipitation; I(mm)=applied irrigation; ET_c(mm)=actual evapotranspiration; DP(mm)=deep percolation of water moving out of the root zone; R(mm) is surface runoff; GW is groundwater contribution or capillary rise into the crop root zone; Z_{ri}(m) is the rooting depth in day i; i and i-1 are, respectively, the current and previous time steps (days in this study).

Measured irrigation and precipitation from field observations were supplied as inputs. Actual evapotranspiration can be estimated by the model considering available soil water content in the root zone. The reference evapotranspiration can be estimated using the EVAP56 module from climate data or supplied directly into the modelling environment. In this particular study, the reference evapotranspiration estimated using Penman-Monteith approach has been used. The reference evapotranspiration, ET_o (mm/day), according to Penman-Monteith is:-

$$ET_o = \frac{0.408.\Delta(R_n - G) + \gamma \frac{900}{273+T} u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \qquad (2)$$

where R_n is net radiation at the crop surface (MJ/m²/day), G is soil heat flux density (MJ/m²/day), e_s is saturation vapour pressure (kPa), e_a is actual vapour pressure (kPa), T is air temperature at 2 m height (C°), u_2 is wind speed at 2 m height (m/s), Δ is slope of vapour pressure curve (kPa/C°), and γ is psychometric constant (kPa/C°).

The potential evapotranspiration is computed using FAO recommended procedures in the model by incorporating a crop coefficient, K_c, for a specified crop growth stage. The potential evapotranspiration for non water limiting conditions may be computed using:

$$ET_c = K_c \times ET_o \qquad (3)$$

where ET_c is the potential crop evapotranspiration and K_c is the crop coefficient. However, in actual field conditions, the actual evapotranspiration might be less than the potential evapotranspiration if the soil water is limiting [25]. In such conditions, the soil water stress coefficient, K_s, may be introduced in (3) to compute actual evapotranspiration.

$$ET_c = K_s \times K_c \times ET_o \qquad (4)$$

Further, the coefficient K_s may also be given by:

$$K_s = \frac{TAW - D_i}{TAW - RAW} \qquad (5)$$

where TAW (mm) =$1000Z_{ri}$ $(\theta_{fc} - \theta_{wp})$ is the total available water (mm); D_i (mm) is the soil moisture depletion on day i; RAW (mm) is readily

available water that can be obtained by multiplying TAW to a depletion coefficient, p, considering the crop water stress resistance. θ_{fc} is the soil moisture content at field capacity; θ_{wp} is the soil moisture content at permanent wilting point.

The crop coefficient for the respective crop development stages of each crop has been modified for Roorkee climatic condition and further calibrated using the model for the particular field and agronomic conditions. K_s describes the effect of water stress on crop transpiration and hence introduction of K_s in the computation of actual evapotranspiration is more valid for dual crop coefficient approach than the single crop coefficient approach. WINISAREG uses the single crop coefficient for water balance calculations. In fact, reasonable estimation of ET_c is also possible without the K_s coefficient when soil evaporation from soil is not a large component of ET_c [30]. A full detail of instructions to determine the coefficients for a particular crop season, climatic and agronomic conditions are available in FAO-56 paper [30].

Runoff component of the water balance has been neglected in this study since runoff from lysimeters is only possible when rainfall depth overtops lysimeter rim level. Whenever, such intense rainfall occurs, the depth of water which goes above the lysimeter rim level is deducted to obtain the effective rainfall. Groundwater contribution through capillary rise has also been ignored since the shallow groundwater table in the area is beyond 2 m below the ground surface.

Model outputs: The model outputs for a specified irrigation schedule (an option from a list of other irrigation simulation options) mainly consist of all seasonal water balance components such as total applied irrigation, total deep percolation from irrigation, seasonal potential and actual evapotranspiration, soil moisture storage, cumulative rainfall, unused rainfall and irrigation scheduling efficiency values. Deep percolation is computed as excess amount of water from irrigation application. The excess depth of water from rainfall is accounted as unused rainfall which may contribute to either deep percolation or runoff. The soil moisture content is determined based on the input water and the supplied soil hydrologic parameters (the wilting point and the field capacity). Thus it is possible to compare field observed and model simulated water content values as a model calibration step for specific field and crop conditions. The irrigation scheduling efficiency is determined based on the applied irrigation and deep percolation.

Irrigation scheduling efficiency

The scheduling efficiency of applied irrigation, as used in the water balance model, is given by:

$$SE = \left(1 - \frac{DP}{I}\right) \times 100 \qquad (6)$$

Where SE is the irrigation scheduling efficiency and other terms were defined earlier. The deep percolation is computed as excess water above the field capacity for an applied irrigation. The excess water due to rainfall is categorized as unused rainfall in the model although in actual field conditions deep percolation is contributed from both irrigation and rainfall. In principle, irrigation is scheduled when there is an occurrence of soil water deficit in the root zone, called management allowed depletion (MAD). However, 100% precision under agricultural field conditions cannot be achievable and hence water may be applied in excess of the field capacity or only satisfy some percentage of the soil moisture deficit (deficit irrigation). We are dealing here with the

excess irrigation under rice paddy and berseem fodder crops where water application is intensive compared with other crops. It is not possible to avoid deep percolation in such crop fields but opportunities do exist to reduce deep percolation. The reduction in deep percolation process can be achieved by adopting a certain irrigation schedule other than traditional approaches such as puddling. In this study, different applications of water were practiced for both crop seasons and the respective scheduling efficiency have been evaluated.

Model calibration and validation

Soil water content observations made in the lysimeters during the two crop seasons were used to calibrate the WINISAREG model for the experimental site conditions. Calibration of the model was undertaken in the 1st crop seasons of each crop period to determine crop parameters (K_c and depletion fraction for no stress, p) and soil hydrologic parameters (field capacity, θ_{fc}, and wilting point, θ_{wp}, soil moisture content values). The calibration process consisted of searching K_c and p for the crop development stages and soil hydrologic parameters for different soil layers in the root zone that allowed minimizing the differences between simulated and observed values of soil water content. In the first instance, k_c and p values as suggested by FAO were plugged as trial values to make water balance in the modelling environment. The initial entries for θ_{fc}, and θ_{wp} values were extracted from the soil moisture characteristic curve (SMCC) constructed from pressure plate test data. These values were tuned step by step, by varying a given parameter at a time and fixing the others in the model until a fitting between model simulated and field observed moisture content values is achieved. The model validation was carried out using the 2nd season of each crop. Figures 2 and 3 present the variation of model simulated and field observed soil moisture contents in the crop root zone during model calibration and validation. Observed cumulative deep percolation values were also used as additional criteria to test the sufficiency of model calibration and validation.

The soil water content values computed using the WINISAREG model represent the average soil water content variation in the entire crop root zone. Therefore, the measured average soil water content values were used to compare with the simulated values during model calibration and validation in each crop season.

Statistical parameters

Selected statistical parameters were employed to assess the significance of model calibration and validation efforts. We employed two statistical parameters, coefficient of determination (R^2) and root mean square error (RMSE) to test the performance of the model as used [31]. The respective equations for the parameters are given below.

$$R^2 = \left\{ \frac{\sum_{i=1}^{n}(x_i - \overline{x})(y_i - \overline{y})}{\left[\sum_{i=1}^{n}(x_i - \overline{x})^2\right]^{0.5}\left[\sum_{i=1}^{n}(y_i - \overline{y})^2\right]^{0.5}} \right\}^2 \qquad (7)$$

$$RMSE = \left[\frac{\sum_{i=1}^{n}(y_i - x_i)^2}{n}\right]^{0.5} \qquad (8)$$

Where x_i and y_i are, respectively, observed and model computed values of a given variable with the respective means $\overline{x}$ and $\overline{y}$; n refers to the number of sample data points. Statistical parameters for model calibration and validation are shown in Table 2.

Figure 2: Model predicted and observed soil moisture content during model calibration ((a) and (b)) for paddy season-1 and model validation for paddy season-2 ((c) and (d)). Figures (a) and (c) refer to lysimeter 1 while (b) and (d) refer to lysimeter 2 conditions.

Results and Discussions

Model parameterization

Through model calibration, the parameters crop coefficient, depletion fraction for no stress, the field capacity and wilting point soil moisture characteristics have been established (Tables 3 and 4). The crop coefficient and depletion fraction for no stress are specific to crop type and growth stages of each crop.

The crop coefficients so obtained were slightly different from the FAO tabulated values [30] owing to local climatic conditions, agronomic practices and specific experimental setup. The crop coefficient value
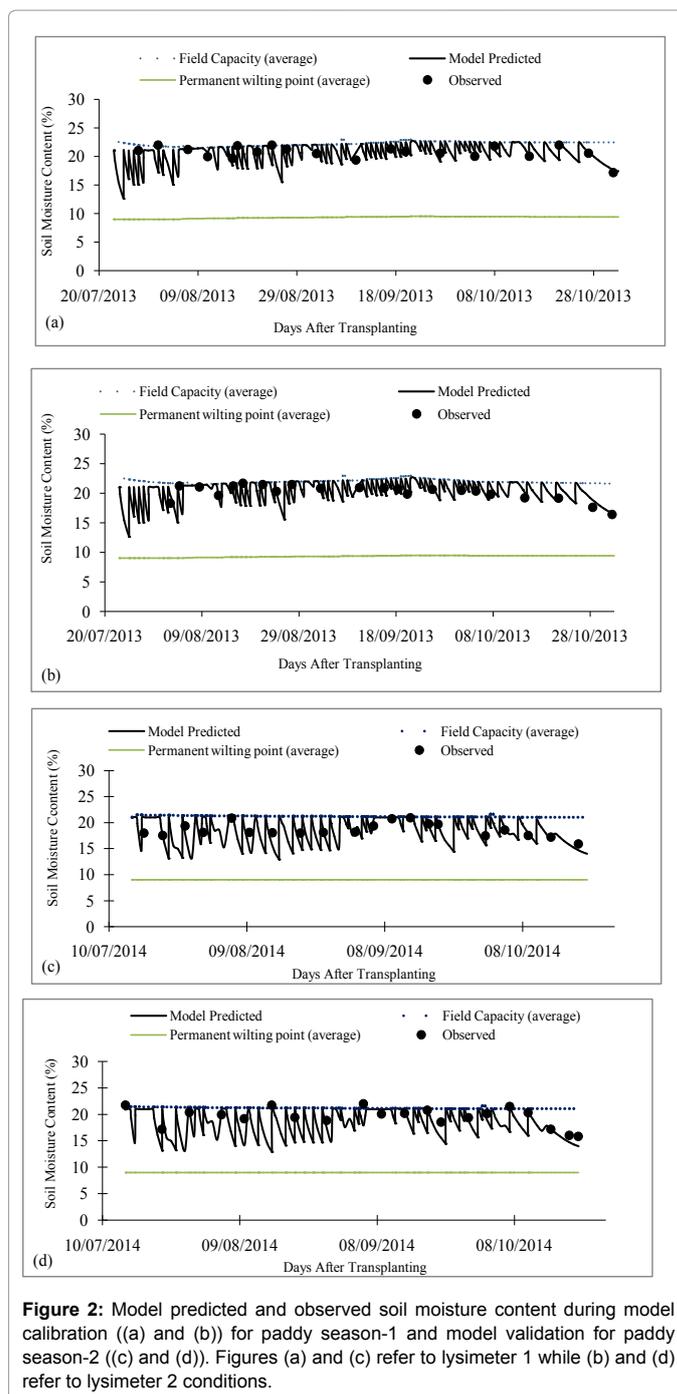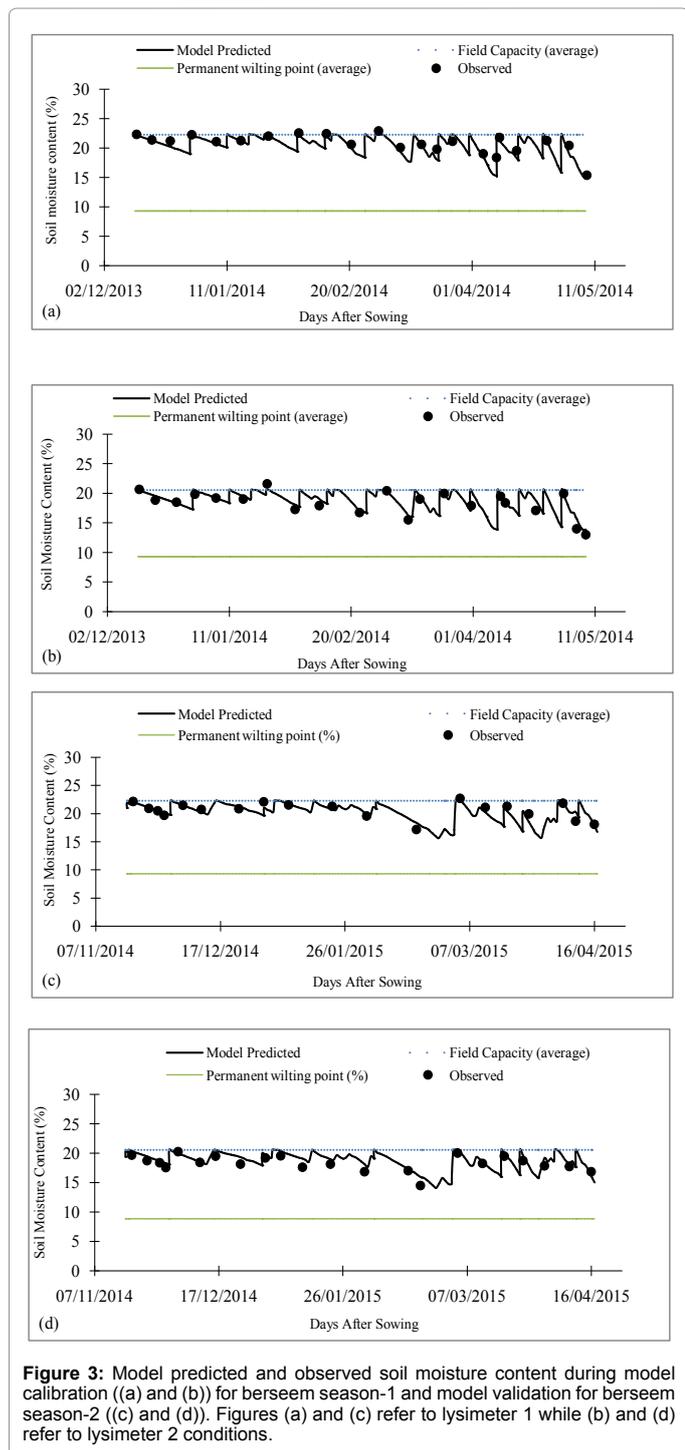
Figure 3: Model predicted and observed soil moisture content during model calibration ((a) and (b)) for berseem season-1 and model validation for berseem season-2 ((c) and (d)). Figures (a) and (c) refer to lysimeter 1 while (b) and (d) refer to lysimeter 2 conditions.

Table 2: Statistical parameters for model calibration and validation.

Crop season	Model process	Parameter		Lysimeter/ Locations of data
		R²	RMSE (%)	
Paddy rice -1	Calibration	0.69	0.64	L1
		0.80	0.68	L2
Paddy rice -2	Validation	0.75	0.77	L1
		0.86	0.98	L2
Berseem-1	Calibration	0.79	0.93	L1
		0.88	0.94	L2
Berseem-2	Validation	0.77	0.66	L1
		0.83	0.88	L2

Table 3: Calibrated crop characteristics used in the model.

Crop name/ parameters	Crop growth stages			
	Initial	Development	Mid season	Late season
Paddy season -1	23/07/13-06/08/13	07/08/13-05/09/13	06/09/13-03/10/13	04/10/13 - 02/11/13
Paddy season -2	15/07/14-05/08/14	06/08/14-30/08/14	31/08/14-30/09/14	01/10/14 - 22/10/14
K_c	1.10	1.10-1.20	1.20	0.67
p	0.1	0.1	0.1	0.1
Berseem fodder	Individual Cutting Dates			
Berseem season-1	21/02/14	19/03/14	09/04/14	06/05/14
Berseem season-2	05/02/15	09/03/15	27/03/15	16/04/15
K_c	K_c initial 0.34	K_c before cut 0.85	K_c after cut 0.4	K_c end 0.95
p	0.40	0.40	0.40	0.40

Table 4: Calibrated field soil characteristics used in the model.

Lysimeter (Location)	Layer (10 cm interval)	θ_{fc} (%)	θ_{wp} (%)	TAW (mm)
L1	1	21	9	120
	2	24	10	140
	3	22	9	130
	4	22	9	130
	5	22	9	130
L2	1	21	9	120
	2	24	10	140
	3	18	9	90
	4	18	9	90
	5	18	9	90

is directly dictating the evapotranspiration component of the water balance and hence altering the deep percolation. Various studies on the crop coefficients of rice based systems were undertaken so far in the region [32,33]. Choudhury et al. [32] have reported that the Kc values of dry-seeded irrigated bed planted rice ranged from 0.62(initial) to 1.16(mid season) while for dry seeded conventional flat land it varied from 0.61(initial) to 1.42(mid-season) in the Indo-Gangetic plains of India, Karnal. Tyagi [33] have computed K_c values of 1.15, 1.23, 1.14 and 1.02, respectively for initial, crop development, reproductive and last stages using Penman-Monteith method in the same region grown under submerged conditions. These results at mid stage growth period are fairly at par with the calibrated values of K_c in this study although there are differences in the initial and late stages owing to differences in the agronomic practices and experimental conditions. Investigation for berseem K_c was also made in the same region earlier employing weighing type lysimeters [13]. The results reported are significantly different (0.62 -1.27) when compared with the calibrated results obtained here. This would be probably due to the differences in agronomic practices, crop variety and sowing time which are different from the current condition. In this study, berseem crop coefficients were considered for individual cutting periods.

The depletion fraction for no stress for rice is 0.1 according to FAO [30]. The average value of p equal to 0.1 has also been adopted in this study. In fact, p is more preferably applied for deficit irrigation conditions than the near saturated field conditions as in the case of rice fields. The parameter basically modifies the potential

evapotranspiration based on the soil available water. However, in paddy fields, soil moisture limitation is not a critical consideration as irrigation was applied frequently. In berseem season p has modified the evapotranspiration and hence the soil water balance since irrigation was intermittently applied during the berseem season besides reduced size of rainfall. Evapotranspiration was taking place almost at potential rate and it has a weak effect on deep percolation during the paddy season-1. However, the effect of evapotranspiration on deep percolation during paddy season-2 and berseem periods was reduced since more water was demanded by evapotranspiration from lower layers. The depletion fraction for no stress equal to 0.4 for berseem has been adopted in this study.

The soil water characteristics for the experimental field were determined for each 10 cm depth of the crop root zone (Table 4). Field observation of root growth besides observed soil moisture regime in the root zone enabled to determine the rooting depth of each crop. Accordingly, the root depths of paddy and berseem were 27 cm and 45 cm, respectively, making nearly three and five layers. The general behaviour of observed soil water content showed that the 2nd layer (10-20 cm below ground level) exhibit more water content value than the adjoining layers. Therefore, this layer was assigned with larger values of field capacity and wilting points than the other layers. Soil compaction during field preparations and cultivation of earlier crops would be responsible for the formation of a plough layer at such depths which exhibit higher water retention property than the other layers [34]. The field capacity water content is very sensitive to deep percolation. When field capacity is higher, deep percolation would be smaller and vice versa.

Climatic data and evapotranspiration

The total seasonal rainfall that fell during both crop seasons is presented in Table 5 along with other water balance components. The total numbers of growing days were almost similar for each season of both crops. Fortunately, the rainfall amount was reduced in the 2nd season of both crops during which time irrigation applications were also reduced for the purpose this study. However, rainfall was not spread over the entire growing season but concentrated in a small interval of a season in which more water goes away by runoff and/ or deep percolation losses. For example, almost half (509 mm) of the annual average rainfall in the year 2013 fell in just 15 days in the month of August in the paddy season; five of these 15 days events recorded 365.4 mm. Obviously, the rainfall which occurs during the time when the soil is near field capacity or above could not be utilized by the crops. The model computes the rainfall balance which does not take part in either soil water storage or evapotranspiration as non-used rainfall. In our field experimental plot where either run-on or run-off was controlled, the excess rainfall balance goes for augmenting deep percolation. Accordingly, more percentage of rainfall was left unused during the paddy seasons than the berseem seasons. In paddy season-1,

for example, nearly 80% of the rainfall was returned as deep percolation. During berseem season 2 and lysimeter 1 irrigation schedule, only 44% of the rainfall occurred was lost. This shows that by appropriately reducing irrigation frequency and depth, it is possible to utilize more amount rainfall for crop production.

In the paddy growing seasons, intense and continuous downpours for two to three days were not considerably contributed for crop water utilizations. Such rains have more of basin water resources importance than field scale water use as they quickly contribute to runoff or deep percolation and thus for surface water storage or groundwater aquifers. During berseem seasons, rainfall was intermittent and two to three major storms occurred in both years of growing. As these heavy storms occur after long intervals of time, most of these were returned as percolation losses due to formation of cracks and macropores in the root zone in the season [3,35]. Runoff was considered only for a heavy rainfall event occurred on August 6, 2013 in paddy season -1 when the rainfall depth overtopped the lysimeter rim level. This particular excess depth was deducted before adding the rainfall value into the modelling environment. Thus, the total rainfall recorded was taken as effective rainfall for model simulation.

In general, temperature, relative humidity and wind speed play a greater role in shaping the evapotranspiration in the area, although wind speed has comparatively less impact as it seldom appears to be more than 1 m/sec. During the growth periods, Maximum temperatures were observed in April and May (late seasons for berseem crop) and the minimum temperature values were in December (in seedling stages of berseem seasons). The average relative humidity has ranged between 100% and 29%. Therefore, larger values of evapotranspiration during periods of April through August for both crop periods were attributable to high temperature, comparatively less humidity and proportionately windy weather conditions.

The seasonal potential evapotranspiration computed in paddy season-1 and paddy season-2 were 403.80 mm and 433.3 mm respectively. During berseem season-1 the potential evapotranspiration was 260.3 mm while it was 198 mm in berseem season-2. This shows that in all the seasons, the seasonal potential evapotranspiration was higher than the actual evapotranspiration showing there was certain limitation in soil moisture in the root zone, although there was heavy irrigation and rainfall during paddy season-1, for example. Comparatively, large root zone soil moisture stress was occurred during paddy season-2 due to reduced irrigation application and high evaporative demand in the particular crop season. The seasonal actual evapotranspiration values computed were shown in Table 5.

Irrigation schedules

The total amount of applied irrigation during the crop seasons is shown in Table 5. Figures 4 and 5 also present irrigation schedules conducted in the crop seasons. In each of the crop seasons, the 1st season

Crop season	Lysimeter	Irrigation (mm)	Rainfall (mm)	Measured DP (mm)	Irrigation water saving (%)	Input water (I + P) saving (mm)	Percentage reduction in DP (%)
Paddy season-1	L1	2388.80	659.30	2668.83	Control	Control	Control
	L2	2388.80	659.30	2525.86	Control	Control	Control
Paddy season-2	L1	630.00	532.90	937.19	73.60	61.80	7.0
	L2	851.00	532.90	1069.16	64.40	54.60	5.6
Berseem season-1	L1	520.00	225.8	522.79	Control	Control	Control
	L2	520.00	225.80	478.49	Control	Control	Control
Berseem season-2	L1	63.10	220.8	148.15	88.00	61.90	17.8
	L2	91.90	220.8	132.27	82.30	58.10	21.9

Table 5: Water balance components during the crop seasons for each of the lysimeters.
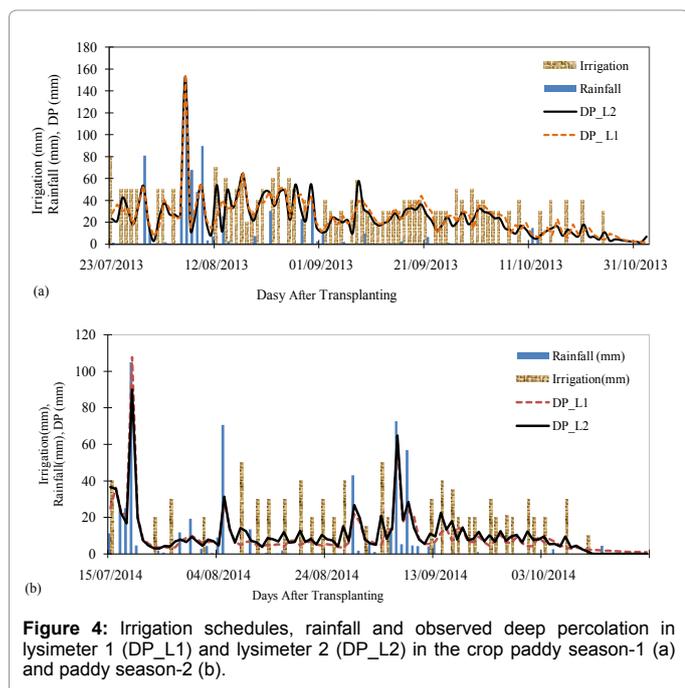
Figure 4: Irrigation schedules, rainfall and observed deep percolation in lysimeter 1 (DP_L1) and lysimeter 2 (DP_L2) in the crop paddy season-1 (a) and paddy season-2 (b).
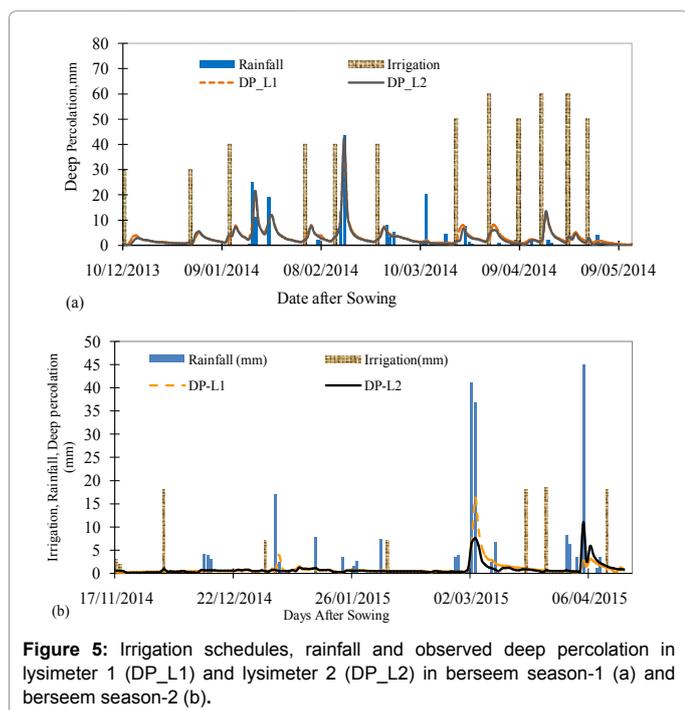

Figure 5: Irrigation schedules, rainfall and observed deep percolation in lysimeter 1 (DP_L1) and lysimeter 2 (DP_L2) in berseem season-1 (a) and berseem season-2 (b).

was used as control and resembles typical irrigation applications in the region at farmers' field while the 2nd season was presenting scenario of reduced water application. Table 6 presents the seasonal irrigation depth, percentage water saving, deep percolation and percentage reduction in deep percolation.

Average depth of applied irrigation for paddy season-1 was 41 mm (±13 mm). In this season, irrigation was applied every day, except the rainy days, in the development and mid-season growth stages while in the late season stage 2-3 days irrigation interval was imposed. During the initial growth stage, more frequent rainfalls also supplied the water demand of the crop besides irrigation. The schedule in this crop season yielded large volume of irrigation input. Such types of seasonal irrigation input for paddy rice fields were also reported in literature [4,5], although mainly concerned with puddled field conditions. During paddy season-2 average irrigation depths ranging 20 and 27 mm (±7.2 and 10 mm) were imposed in lysimeters 1 and 2 respectively. The number of irrigations was halved besides reducing the depth of irrigation events in the 2nd season of both crop periods. Overall, 59 irrigations during paddy season-1 and 31 irrigations events in paddy season-2 have been applied. An average irrigation interval of nearly 2 days was practiced in paddy season-2 period. Kukal et al. [2] reported that an interval of 2 days after complete infiltration of ponded water is a recommended procedure in North-western Indian condition irrespective of soil type and irrigation depth under puddled paddy fields.

Berseem, on the other hand, needs frequent irrigation throughout its growing season because of its shallow root zone that dries quickly [13]. Average depth of irrigation equal to 47.3 mm (±10 mm) was applied during berseem season- 1 with average irrigation interval of nearly 9 days. In berseem season-2, the average depth of application was ranging between 8-11.5 mm (±4.6-7.3 mm) with an average irrigation interval of nearly 12 days for each of the lysimeters. In berseem season-1 a total of 11 irrigations were applied and only 6 irrigation events were made in berseem season-2. More frequent irrigations were applied near the end of the crop season (April-May) owing to the increased evaporative demand as responded in the crop root zone soil moisture content variation. It has been shown that large saving in irrigation as well as overall input water was achieved by imposing reduced irrigation in both crop seasons. Further, percentage reduction in percolation has also been achieved; i.e., for example the during paddy season-1 in lysimeter 1, 87.60% of input water has been turned as deep percolation. In paddy season-2, for the same lysimeter, deep percolation was 80.60%; showing a percentage reduction of 7% due to the imposed irrigation schedule.

Deep percolation

The measured and model computed deep percolation results are summarized in Table 5 and their temporal patterns during the growth

Crop season	Lysimeter	Irrigation (mm)	Rainfall (mm)	DP Irrigation (mm)	Unused Rainfall (mm)	Total DP (mm)	Measured DP (mm)	Actual ETa (mm)	Soil moisture Storage (mm)	Irrigation Scheduling Efficiency (%)
Paddy season-1	L1	2388.80	659.30	2157.90	524.10	2682.00	2668.83	378.5	-12.40	9.65
	L2	2388.80	659.30	2158.20	524.10	2682.30	2525.86	378.0	-12.20	9.67
Paddy season-2	L1	630.00	532.90	438.00	380.10	818.10	937.19	360.9	-16.10	30.48
	L2	851.00	532.90	659.00	380.10	1039.10	1069.16	360.9	-16.10	22.56
Berseem season-1	L1	520.00	225.8	364.10	145.80	509.86	522.79	260.3	-24.4	29.98
	L2	520.00	225.80	365.80	145.80	511.60	478.49	257.7	-23.50	29.65
Berseem season-2	L1	63.10	220.8	4.81	97.70	102.51	148.15	196.3	-14.91	92.38
	L2	91.90	220.8	24.62	107.30	131.92	132.27	196.0	-15.22	73.21

Table 6: Seasonal irrigation depth, percentage water saving and reduction in deep percolation in the crop seasons.

periods are shown in Figures 4 and 5. During the continuous irrigation season of paddy rice, nearly 82-87% of input water has been returned as deep percolation while in the intermittent irrigation season, the percolation loss amounted approximately 77-80% of the overall input water. For coarse textured soils, nearly same depth of percolation has been reported [4,5]. In fact, in unpuddled paddy field conditions, the percentage reduction in percolation due to reduced irrigation size is not significantly differing. This may be attributable to preferential flow through cracks and macropores during the intermittent irrigation season when such soil phenomena are prevalent (3). However, the overall water saving together with percentage reduction in percolation loss is encouraging.

In berseem season, comparatively less amount of water has been percolated as expected. Respectively, 64.2% and 70% of input water was lost through deep percolation during berseem season-1 in lysimeter 1 and 2. Due to the imposed irrigation schedule, deep percolation was limited to 52.2% and 42.3% of input water in lysimeter 1 and 2 respectively.

The deep percolation in the model was estimated as cumulative value for the whole growing season. The model predicted deep percolation well, although it separately computed percolation loss from applied irrigation and rainfall. The rainfall amount not contributing to crop growth is reported as the non-used rainfall in the model. Since runoff was controlled in our experimental field, the non used rainfall again goes on the account of deep percolation. Hence, the total seasonal percolation is the sum of the non-used rainfall and percolation amount from irrigation as computed in the model. In both crop seasons, large volume of deep percolation was attributable to rainy days and weeks in which rainstorms are intense and continuous for longer hours. With regard to growth stages of the crops, the initial stages of the crops share larger losses due to deep percolation. Therefore, irrigation schedules which consider the onset of rainy days or seasons are suggested to be implemented to limit deep percolation losses and enhance water productivity.

Percolation from an irrigated field would depend on many factors such as depth of applied water, soil and plant characteristics, groundwater depth etc. However, the depth of input water and frequency of its occurrence and/or application in sand dominated soils play a major role in transferring input water to deep percolation outflow. During both crop periods, large depths of input water due to event storms contributed to maximum daily deep percolation losses (Figures 4 and 5). Apparently, the antecedent soil moisture condition before the rainfall incident favoured more percolation during paddy crop season which was frequently irrigated compared to the berseem season. Crops during development and mid-season growth periods exhibited to withdraw more water than the other periods. It can be shown that during both crop periods that deep percolation was reduced during the development and mid-season growth stages.

The performance of the two lysimeters in metering deep percolation has also been investigated. It has been seen that the amount of deep percolation observed in both lysimeters was fairly similar showing the repacked soil monolith exhibit the same property in both lysimeters particularly during the non-storm periods. During storm periods, however, the lysimeters were observed to demonstrate variations in allowing percolation. This may be due to the fact that the lysimeters depict differences in preferential flow which is significant during rainy days. Thus we deduce from these results that locally constructed drainage type lysimeters could owe better understanding of deep percolation phenomena in an irrigated farm. Figure 6 presents
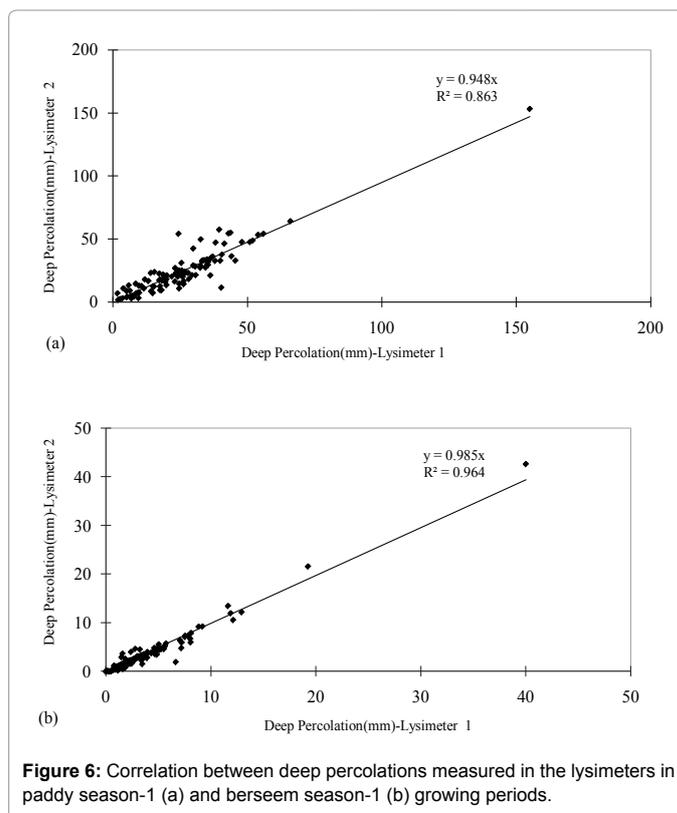

Figure 6: Correlation between deep percolations measured in the lysimeters in paddy season-1 (a) and berseem season-1 (b) growing periods.

the correlation between the measured deep percolations in the two lysimeters for paddy season-1 and berseem season-1.

Irrigation scheduling efficiency

The calculated irrigation scheduling efficiency values based on equation (4) are summarized in Table 4 above. The irrigation scheduling efficiency of the paddy season-1 was very low due to continuous flooding of the field. Again large loss of deep percolation in berseem season-1 shows that such irrigation schedules are not recommended. Due to an alternative irrigation schedule, the scheduling efficiency has been significantly improved in both paddy season-2 and berseem season-2 crop periods.

The scheduling efficiency depends mainly on applied irrigation depth and amount of deep percolation loss from irrigation. Refereeing to equation (4), it is evident that if deep percolation is zero, then the efficiency value becomes infinity. However, note that we are referring to water intensive crops growing on coarse textured soils. In fact, deep percolation can occur in even heavy soils or puddled paddy field conditions and hence negligible amount of deep percolation from surface irrigation is unlikely. For example, in berseem season irrigation was reduced eightfold and still there was deep percolation from irrigation as computed using the model. Further, the scheduling efficiency index is mainly applicable to irrigated fields than rainfed agriculture. In general, deep percolation process is the key component of water balance in sandy loam soils reducing irrigation scheduling efficiency and hence it calls for proper irrigation schedules containing less water depth and longer irrigation intervals depending on respective irrigation requirements and the nature of water consumption of a given crop under unpuddled field conditions.

Crop season	Location	Yield (tones/ha)	Water use efficiency (=Yield/input water) (Kg/m³)	Comparative yield reduction (%)	Remarks
Paddy season-1	L1	3.54	0.12	Control	Dry grain yield
	L2	3.25	0.11	Control	
Paddy Season-2	L1	2.69	0.23	24.0	
	L2	2.70	0.20	16.9	
Berseem season-1	L1	37.2	4.98	Control	Green fodder harvest (four cuts in each season)
	L2	41.2	5.52	Control	
Berseem season-2	L1	21.3	7.50	42.7	
	L2	27.9	8.90	32.3	

Table 7: Crop yield, water use efficiency and comparative yield reduction in crop seasons.

Water use efficiency and crop yield

Table 7 shows measured crop yield values for both crop periods in the lysimeters. Yield response of paddy rice can vary widely depending on rice variety, environmental factors, climatic conditions, soil characteristics and agronomic practices applied in an area. Yields ranging from 2-3.5 tonnes/ha are common as reported by Ladha et al. [36]. de Vries et al. [8] also investigated rice yield responses ranging 2-11.8 tonnes/ha in their water saving and continuous flooded rice field in the Sahelian environment. Due to reduced input water, there was yield penalty in both crop seasons. However, compared to such significant amount of water saving, the yield reduction is nominal since water use efficiency has been increased. Additionally, crop yield can be improved by employing improved agronomic practices, shifting of sowing/planting dates and adoption of appropriate technologies [37]. In fact yield reduction could have been occurred due to other reasons, but we made an effort to maintain similar crop growing and agronomic conditions except irrigation scheduling. Therefore, reductions in yield were mostly attributed to the reduced input water application in the crop seasons.

Conclusion

Two major crops, rice paddy and berseem, were grown in four seasons (two experimental runs for each crop) in an experimental field under different regimes of water application. For each crop, typical irrigation schedules as practiced in the farmers' field have been selected and conducted in the 1st growing season. Again a reduced depth and frequency of irrigation was applied in the 2nd growing period of each crop aiming for input water saving in unpuddled sandy loam field conditions. For the purpose of computing the water balance components, the WINISREG water balance and irrigation scheduling model has been employed which has been calibrated and validated for field soil and crop parameters. The field observed average root zone soil moisture content was used to calibrate and validate the model. The model was found to be adequately simulating the water balance components (deep percolation) and average root zone soil moisture content.

It has been observed that continuous application of irrigation water under non puddled paddy field of sandy loam soil resulted in quite large volume of percolation loss. Continuous irrigation in the case of paddy fields is having poor irrigation scheduling efficiency indicating very low irrigation efficiencies. On the other hand, intermittent irrigation based on soil water status would greatly reduce deep percolation and improve scheduling efficiency. Large saving in input water was achieved due to reduced irrigation applications with nominal yield penalty. In general, irrigation depths under 5 cm with 2-3 days interval for paddy irrigation and irrigation applications below 2 cm with irrigation interval of 8-12 days for berseem fodder crop resulted in percentage reduction of deep percolation in unpuddled fields besides large input water saving.

The field experiments and model results show that deep percolation is the most important component of irrigated field water balance lowering scheduling efficiency. Deep percolation was observed to mainly depend on the depth of input water and its frequency. Wetter antecedent soil moisture conditions due to irrigation favoured large deep percolation records from consecutive intense storms; in which more rainfall was observed to go unused.

Therefore, critical consideration of irrigation scheduling is suggested to reduce deep percolation to enhance irrigation scheduling efficiency and thereby increase overall irrigation efficiency for such water intensive crops. Our investigation shows that the existing irrigation schedule practiced in typical farmers' fields is by no means saving water and needs to be altered. The alternative irrigation schedule indicated in this study may be beneficial and better scheduling strategy can also be applied.

The locally constructed lysimeters were robust enough to monitor percolation loss beyond the crop root zone and can be implemented in various water management or research programs. These are affordable, can be easily constructed, maintained and provide reliable field monitoring which could be utilized in research and monitoring programs elsewhere.

References

1. Timsina J, Connor DJ (2001) Productivity and management of rice-wheat cropping systems: issues and challenges. Field Crops Res 69: 93-132.

2. Kukal SS, Hira GS, Sidhu AS (2005) Soil matric potential-based irrigation scheduling to rice (Oryza Sativa). Irrigation Sci 23: 153-159.

3. Garg KK, Das BS, Safeeq M, Bhadoria PBS (2009) Measurement and modelling of soil water regime in a lowland paddy field showing preferential transport. Agr Water Manage 96: 1705-1714.

4. Yadav S, Li T, Humphreys E, Gilla G, Kukal SS (2011) Evaluation and application of ORYZA2000 for irrigation scheduling of puddled transplanted rice in North West India. Field Crops Res 122: 104-117.

5. Bouman, Lampayan, RM, Tuong TP (2007) Water Management in Irrigated Rice: Coping with Water Scarcity. International Rice Research Institute, Los Banos.

6. Kukal SS, Aggarwal GC (2002) Percolation losses of water in relation to puddling intensity and depth in a sandy loam rice (Oryza sativa) field. Agr Water Manage 57: 49-59.

7. Belder P, Bouman BAM, Cabangon R, Lu G, Quilang EJP, et al. (2004) Effect of water-saving irrigation on rice yield and water use in typical lowland conditions in Asia. Agr Water Manage 65: 193-210.

8. de Vries ME, Rodenburg J, Bado BV, Sow A, Leffelaar PA, et al. (2010) Rice production with less irrigation water is possible in a Sahelian environment. Field Crops Res 116: 154-164.

9. Tan X, Shao D, Liu H (2014) Simulating soil water regime in lowland paddy fields under different water managements using HYDRUS-1D. Agr Water Manage 132: 69-78.

10. Nie L, Peng S, Chen M, Shah F, Huang J, et al. (2012) Aerobic rice for water-saving agriculture. A review. Agron Sustain Dev 32: 411-418.

11. Dunn W, Gaydon DS (2011) Rice growth, yield and water productivity responses to irrigation scheduling prior to the delayed application of continuous flooding in south-east Australia. Agr Water Manage 98: 1799-1807.

12. Kukal SS, Sidhu AS (2004) Percolation losses of water in relation to pre-puddling tillage and puddling intensity in a puddled sandy loam rice (Oryza sativa L.). Field Soil and Tillage Res 78: 1-8.

13. Tyagi NK, Sharma DK, Luthra SK (2003) Determination of evapotranspiration for maize and berseem clover. Irrigation Sci 21: 173-181.

14. Kennedy PB, Mackie WW (1925) Berseem or Egyptian clover (*Trifolium alexanderinum):* A preliminary report. University of California Printing Office, Berkley.

15. Mintesinot B, Verplancke H, Ranst EV, Mitiku H (2004) Examining traditional irrigation methods, irrigation scheduling and alternate furrows irrigation on vertisols in Northern Ethiopia. Agr Water Manage 64: 17-27.

16. Janssen M, Lennartz B (2009) Water losses through paddy bunds: Methods, experimental data, and simulation studies. J Hydrol 369: 142-153.

17. Mitchell J, Cheth K, Seng V, Lor B, Ouk M, et al. (2013) Wet cultivation in lowland rice causing excess water problems for the subsequent non-rice crops in the Mekong region. Field Crops Res 152: 57-64.

18. Shankar V, Hari Prasad KS, Ojha CSP, Govindaraju RS (2012) Model for Nonlinear Root Water uptake Parameter. J Irrig Drain Eng 138: 905-917.

19. Hillel D (2004) Introduction to Environmental Soil Physics. Elsevier Academic Press, Heidelberg.

20. Trout TJ, Garcia-Castillas IG, Hart WE (1982) Soil Water Engineering Field and Laboratory Manual. Academic Publishers, Jaipur, India.

21. Bohren CF, Huffman DR (1983) Absorption and scattering of light by small particles. John Wiley, New York.

22. Whalley WR, Cope RE, Nicholl, CJ, Whitmore AP (2004) In-field calibration of a dielectric soil moisture meter designed for use in an access tube. Soil Use Manage 20: 203-206.

23. Fortes PS, Platonov AE, Pereira LS (2005) GWINISAREG-A GIS based irrigation scheduling simulation model to support improved water use. Agr Water Manage 77: 159-179.

24. Teixeira JL, Pereira LS (1992) WINISAREG, an irrigation scheduling simulation model. ICID Bull 41: 29-48.

25. Liu Y, Teixeira JL, Zhang HJ, Pereira LS (1998) Model validation and crop coefficients for irrigation scheduling in the North China Plain. Agr Water Manage 36: 233-246.

26. Pereira LS, Teodoro PR, Rodrigues PN, Teixeira JL (2003) Irrigation scheduling simulation: the model WINISAREG. Kluwer Academic Publishers 161-180.

27. Popova Z, Pereira LS (2011) Modelling for maize irrigation scheduling using long term experimental data from Plovdiv region, Bulgaria. Agr Water Manage 98: 675-683.

28. Pereira LS, Paredes P, Eholpankulov ED, Inchenkova OP, Teodoro PR, et al. (2009) Irrigation scheduling strategies for cotton to cope with water scarcity in the Fergana Valley, Central Asia. Agr Water Manage 96: 723-73.

29. Liu Y, Pereira LS, Fernando RM (2006) Fluxes through the bottom boundary of the root zone in silty soils: Parametric approaches to estimate groundwater contribution and percolation. Agr Water Manage 84: 27-40.

30. Allen RG, Pereira LS, Raes D, Smith M (1998) Crop evapotranspiration: Guidelines for computing crop requirements. Irrigation and Drainage, FAO, Rome.

31. Cholpankulov ED, Inchenkova OP, Paredes P, Pereira LS (2008) Cotton irrigation scheduling in Central Asia: Model calibration and validation with consideration of groundwater contribution. Irrigation and Drainage 57: 516-532.

32. Choudhury BU, Singh AK, Pradhan S (2013) Estimation of crop coefficients of dry-seeded irrigated rice-wheat rotation on raised beds by field water balance method in the Indo-Gangetic plains, India. Agr Water Manage 123: 20-31.

33. Tyagi NK, Sharma DK, Luthra, SK (2000) Determination of evapotranspiration and crop coefficients of rice and sunflower with lysimeter. Agr Water Manage 45: 41-54.

34. Bertolino AVFA, Fernandes NF, Miranda JPL, Souza AP, Lopes MRS, et al. (2010) Effects of plough pan development on surface hydrology and on soil physical properties in south-eastern Brazilian plateau. J Hydrol 393: 94-104.

35. Tournebize J, Watanabe H, Takagi K, Nishimura T (2006) The development of a coupled model (PCPF–SWMS) to simulate water flow and pollutant transport in Japanese paddy fields. Paddy Water Environ. 4: 39-51.

36. Ladha JK, Fischer KS, Hossain M, Hobbs PR, Hardy B (2000) Improving the productivity and sustainability of rice-wheat systems of the Indo-Gangetic Plains: a synthesis of NARS-IRRI partnership research. Inst Rice Research Institute, Los Banõs, Philippines.

37. Balwinder-Singh, Humphreys E, Gaydon DS, Yadav S (2015) Options for increasing the productivity of the rice-wheat system of north-west India while reducing groundwater depletion. Part 2. Is conservation agriculture the answer? Field Crops Res 173: 81-94.