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MONITORING AND QUANTIFICATION OF SOIL WATER CONTENT AND FLUXES IN DEEP LAYERS OF WHEAT CULTIVATED SOILS TO IMPROVE WATER USE EFFICIENCY

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Calculation of irrigation scheduling (IS) and improvement of irrigated water use efficiency (WUE) requires precise measurement of soil water content and fluxes in the soil layers. Deep irrigation fluxes in agricultural field of wheat crop at the Nuclear Institute of Agriculture & Biology (NIAB), Faisalabad, Pakistan were monitored and quantified using radio and stable isotope techniques. The time variant soil moisture content data were also used to determine the fluxes by water balance technique. The fluxes determined by isotope and water balance technique were compared and found in good agreement. On the basis of the flux data, suggestions were made to improve the irrigation plan in accordance with crop water consumption and to reduce the water loss through deep percolation.

Keywords : Water use efficiency, Deep irrigation fluxes, Isotopic techniques, Water balance technique

1. Introduction

Pakistan is an agricultural country and about 60% of its population is involved in agribusiness. Agriculture sector consumes almost 90% of the total fresh water available in the country. Like elsewhere in the world, competition for water among agriculture, industrial and urban sectors is increasing. The agriculture sector is most likely to be a loser in this competition because of lower economic productivity of water in agriculture (value per drop) than in the other sectors. With increasing population and depleting water resources, Pakistan is slowly but surely heading towards a situation of water shortage and a threat of famine. Per capita surface water availability for irrigation reduced from 5650 m^3 per year in 1951 to 1200 m^3 per year in 2006 and the minimum water requirement to avoid a water shortage in a country is 1000 m^3 per capita per year [1]. On the other hand, most of the water seems to be lost through deep percolation and evaporation due to poor irrigation techniques. In order to manage the water use efficiency, deep percolation and evaporation losses are needed to be controlled. These losses are of extreme importance in water balance studies in arid and semi-arid areas. Several attempts have been made to estimate the soil infiltration rates and losses to groundwater using analytical techniques [2,3]. The present study is an attempt to quantify the percolation (downward water flux) using isotopic and water balance techniques.

Tritium (^3H), a radio-isotope of hydrogen which decays by beta emission with a half life of 12.33 years [4], is used as a tracer for measurement of water fluxes in the soils. Tritium concentrations are expressed as absolute concentrations, using tritium units (TU). One TU corresponds to one ^3H atom per 10^{18} atoms of hydrogen ^1H [5] and is equal to 0.118 Bq Kg^{-1} or 3.19 pCi Kg^{-1} [6]. Tritium is commonly injected into the ground as an artificial tracer and its transport rate with irrigated water is determined to calculate water fluxes in the soil layers. The transport rates of atmospheric tritium, present in the atmosphere due to above ground nuclear testing in the early 1960 and injected into the soils naturally by its mixing with recharge waters, have also been used to calculate the water fluxes in the soils [7]. The isotopic concentrations of stable isotopes of hydrogen and oxygen (^2H & ^{18}O) present in irrigated water molecules are also used to estimate the downward fluxes of water in the soils. The fluxes are determined by the measurement of downward transport rate of cyclic variations in their isotopic ratios i.e., $RH={}^2H/{}^1H$ and $RO={}^{18}O/{}^{16}O$, caused by enrichment due to evaporation at the near surface soil. Isotopic ratios are normally represented in terms of isotopic delta values by the relation:

$$\delta = \frac{R_{sam} - R_{std}}{R_{std}} X1000$$

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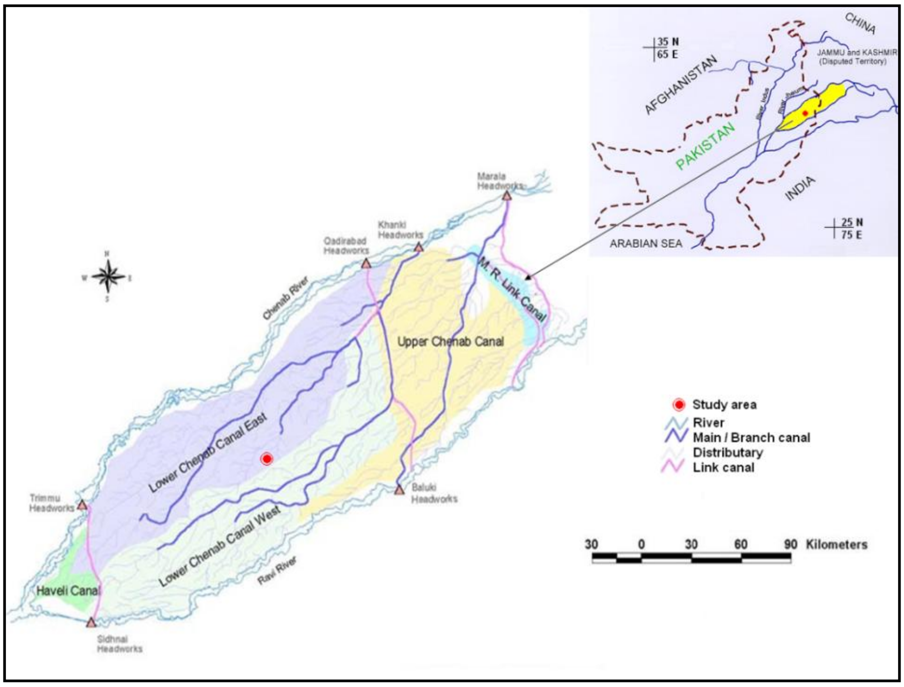

Figure 1. The map showing location of study area in Pakistan (Khan et. al., 2003).

Where R_{sam} and R_{std} are isotopic ratios of sample and standard. Soil water balance technique uses water balance equation employing the soil moisture content, natural and irrigated water volumes and evapo-transpiration data to calculate the deep water fluxes in unsaturated zone. The soil moisture content is measured or estimated using soil moisture detection probes such as Neutron Moisture Meter (NMM) [7,8].

The overall objective of the study was to provide useful information for enhancement of WUE in the commonly used irrigation application technique i.e., floods irrigation. The specific objectives of the study were to quantify deep percolation fluxes in wheat crop (winter crop) fields under irrigated conditions using: i. ^{3}H as artificial tracer; ii. $\delta^{2}H$, $\delta^{18}O$ in water samples collected from soil cores and comparison of the fluxes calculated by isotopic data with the fluxes calculated by water balance technique.

2. Study Area

The study area, located in Nuclear Institute of Agriculture & Biology (NIAB), Faisalabad, Pakistan, is the part of Rechna doab which is the area between rivers Ravi and Chenab (Figure 1). The site (North 31^{o} 23', East 73^{o} 0', 184 m amsl) has semi-arid subtropical climate. Ten years (2000-2009) meteorological data collected from Agricultural Meteorology Cell, University of Agriculture, Faisalabad shows that during the month of January, the average maximum and minimum temperatures were 19.4°C and 6.9°C, while maximum and minimum temperatures during the month of June were 40.5°C and 27.8°C respectively. The average annual maximum and minimum temperatures are 31.66°C and 8.37°C, respectively.

Normally the May is the driest month of the year, with 29.9% average relative humidity (2000-2009). Due to the onset of monsoons in July and August, relative humidity increases perceptibly and rises near to 70%. In October and November, the weather becomes relatively dry and humidity decreases to some extent. Due to winter rains, the weather becomes more humid and the humidity may reach to the highest value. Summer rainfall occurs during July to September, mainly due to monsoons. The area also receives winter showers of lesser intensity during December to February. The average rainfall in monsoon period during 2000 to 2009 was about 157 mm and annual rainfall was about 287 mm. In 2009 monsoon was relatively dry except the month of August with 116 mm rain. Total monsoon showers were 180 mm. Total rainfall during 2009 was 285 mm with no rain during winter wheat crop.

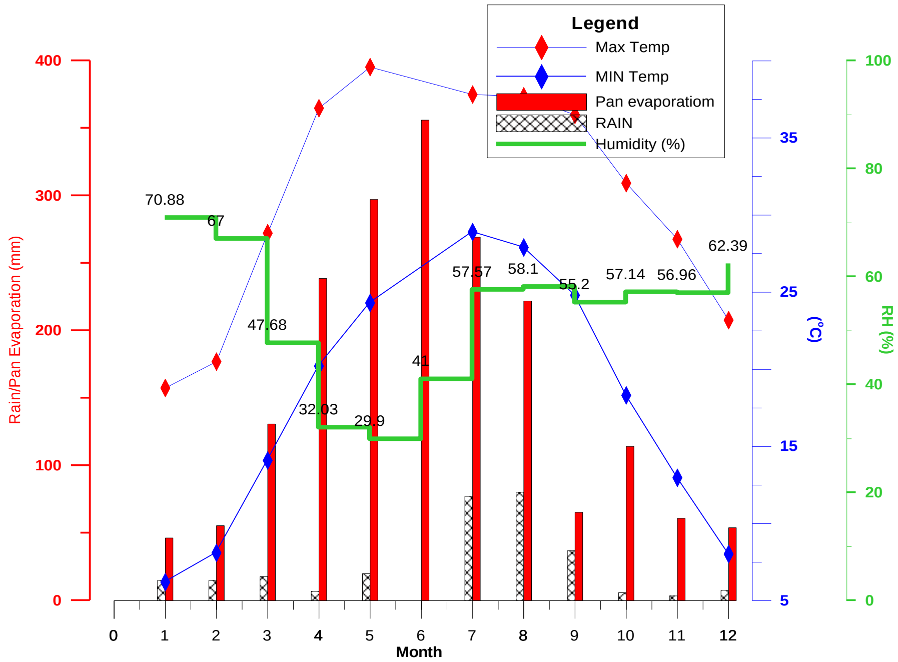

Figure 2. Average monthly meteorological data of Faisalabad (2000-2009).

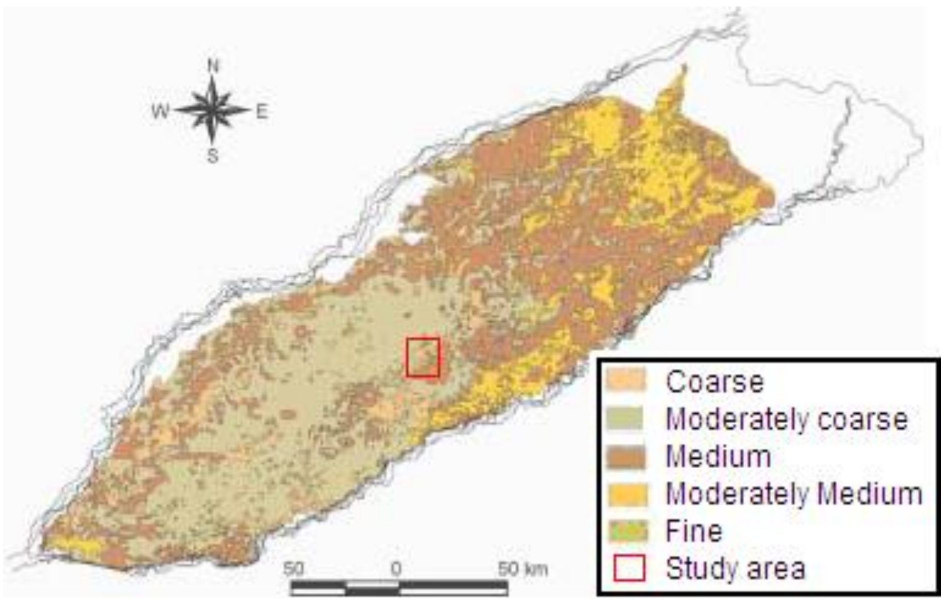

Figure 3. Soil textural map of the Rechna Doab (from Khan M. A., 1978).

Data collected from Agricultural Meteorology Cell, University of Agriculture, Faisalabad reflects that the average maximum and minimum values of pan evaporation are 10.4 mm/day and 1.625mm/ day in the months of May and January, respectively. The maximum and minimum average values during year 2009 are 11.8 mm/day and 1.6 mm/day in the months of June and January respectively. Total pan evaporation during the year 2009 was 1881 mm. Summary of month-wise climatological data for 10 year average (2000-2009) are plotted in Figure 2.

The soil of the study site consists of grayish brown, fine to medium sand, silt and clay. The soil is a sandy clay loam developed in a mixed calcareous, medium-textured alluvium derived from Himalayas [3], as shown in Figure 3.

Table 1. Irrigation application dates, amount of water applied during each event in fields A and B, crop sowing and harvesting dates, and number of days after tritium injection (DAI) during wheat season 2009.

No.	Irrigation Date	Water Applied (mm)		Days after tritium injection (DAI)
		Field A	Field B	
Wheat crop sowing date: December 08, 2009				
1	Dec. 08, 2009	80	80	0
2	Dec. 19, 2009	32	16	11
3	Dec. 30, 2009	32	16	22
4	Jan. 14, 2010	32	16	37
5	Feb. 20, 2010	32	16	74
6	March 03, 2010	32	0	85
7	March 11, 2010	32	16	92
8	March 18, 2010	32	0	99
9	March 24, 2010	32	16	105
10	March 30, 2010	32	16	111
	Total water applied	368	192	
Wheat crop harvesting date: April 12, 2010				

The agricultural activity in Rechna Doab is supported by irrigation from main canals. The water from main canal is distributed to branch canals. The distributaries and their branches, called minors are the main arteries for releasing water through outlet to small irrigation areas. The layout of the canal system in Rechna Doab is shown in Figure 1.

Much of the present day irrigation in Rechna Doab is commanded by two major canals; Upper Chenab Canal (UCC) covers upper over one third of the system, whereas Lower Chenab Canal (LCC) covers the rest [9]. The canals have been routed out from Chenab river that flows about 30 km in the northwest of the Faisalabad city while the river Ravi meanders about 40 km off the city in the southeast. Due to enhanced cultivation in the area, the crop water requirements are increasing and the integrated irrigation capacity from surface and ground water supplies are decreasing. The data collected by International Irrigation Management Institute (IIMI), Lahore indicates that the annual crop water requirements has increased by 10% during the period between 1991 and 1995 whereas the annual total water supplies increased by 8% i.e., 2% less than the required increase [10]. A significant portion of the irrigated water is lost through deep percolation. These losses are required to be quantified to improve the irrigation techniques to overcome these losses and increase the water use efficiency in accordance with the quantity of irrigation water available.

3. Materials and Methods

3.1. Sowing of Wheat and Injection of Tritium in the Fields

Dry sowing of wheat was carried out on December 8, 2009 in two fields named Field-A and Field-B each measuring 25 m^2 (5m x 5m) in area. Tritium was injected in both experimental fields on the same date with activities of 7.08 mCi and 4.72 mCi in the Field-A and Field-B, respectively. The tritiated water was applied through a pipe irrigation system and depth of irrigation was kept 80 mm in both fields. The pipe irrigation system was designed to ensure full and uniform water distribution; hence no surface runoff occurred at any time during the growing season. For successive irrigations, measured quantities of plain irrigation water were applied. Field-B was irrigated in a normal course but the Field-A was irrigated almost with double the input of Field-B estimating the crop water requirements [11]. A rain gauge was also installed near the fields to record rain events and to collect rain samples for analysis. Irrigation, sowing and harvesting schedule is given in Table 1.

3.2. Measurement of Soil Moisture Content

Moisture content of the subsurface soil layers in the Field-A and Field-B was measured using Neutron Moisture Meter (NMM). In order to lower NMM probe, access tubes were installed upto the depth of 150 cm. Readings from the prefixed 15 cm depth intervals starting from 15 cm upto the whole depth of the tubes, i.e., 150 cm were taken periodically. Meter readings were converted to the moisture content using a calibration curve of NMM.

3.3. Estimation of Crop Evapotranspiration (ETc)

Evapo-transpiration for wheat crop (ETc) was calculated in separate lysimeter studies. Twelve cemented lysimeters were constructed in the year 2008. Each lysimeter had 3x3 m surface area and 2 m depth, and fine loam soil (bulk density = 1.43 g cm^{-3}). The ETc was calculated with Equation 1 [12].

$$I + P - D + ET_C = \pm \Delta S \qquad (1)$$

Where *I* and *P* represent irrigation and precipitation, respectively. Neutron moisture meter was used to estimate $\pm\Delta S$ representing change in soil water storage and *D* represent deep percolation to groundwater. Under applied conditions *D* was assumed to be zero as the experiment was made in lysimeters and no rainfall event occurred during the growing period of wheat.

Irrigation was applied using locally fabricated irrigation system to ensure the equal distribution of irrigation water and high irrigation efficiency [13]. To assess ΔS using neutron moisture meter, PVC access tubes were installed down to the bottom of lysimeters. The soil moisture pre-commencement of the experiment and post-harvest was estimated on the basis of readings recorded with NMM taken at prefixed six 15 cm depths starting from 15 to 95 cm at ~10 days interval specially one day prior to irrigation events.

3.4. Measurement of Tritium and Stable Isotope Concentrations

Soil cores were collected from the experimental fields at different depths and times for the analysis of tritium and water stable isotopes (^{2}H and ^{18}O concentrations) in the pore water. First core was collected on December 8, 2009 before irrigation for initial soil moisture content. After irrigation with tritiated water, the remaining cores were collected on December 15, 2009 (7 days after irrigation or DAI), January 26, 2010 (49 DAI) and March 2, 2010 (84 DAI).

For the analysis of tritium and stable isotope concentrations, the soil water from the core samples was extracted by vacuum distillation at/about a temperature of 80^{o}C. Quantitative recovery of water from the sample is critical for the isotope analyses, as it has been shown that yields of <98% of the total water in a sample can lead to significant shifts in the isotopic composition of the water [14,15].

Tritium was measured by counting β-decay events in a liquid scintillation counter (LSC). Liquid scintillation counter (PACKARD, Tri Carb-4530) was employed for this purpose.

The isotopic ratios ^{2}H/^{1}H or D/H and ^{18}O/^{16}O of the water samples were measured on Varian MAT GD-150 mass spectrometers. The isotopic ratios were converted into isotopic delta values, (δ^2H and δ^{18}O), relative to Vienna Standard Mean Ocean Water (VSMOW) using the relation: $\delta = \frac{R_{sam} - R_{std}}{R_{std}} X1000$, Where R_{sam} and R_{std} are isotopic ratios of sample and standard [16-18].

4. Results and Discussion

4.1. Soil Moisture Content

The time variant depth profiles of moisture content are plotted in the Figures 4a and 4b. Data indicate that soil moisture content in Block-A remains above field capacity at all the depths while in the Block-B it falls below field capacity in the upper 15 cm of soil layer between February 8 and March 16, 2010. The moisture content in the root zone should be above field capacity to meet the crop requirement. Therefore, a change in the irrigation schedule to bring the moisture content above field capacity represents a mandatory requirement.

4.2. Calculation of Fluxes by Tritium Transport

The depth profiles of tritium in the Fields A and B at different dates are shown in Figures 5a and 5b, respectively. The water velocity or fluxes were determined from the transport rates of tritium in the soil. Tritium is transported in the soil by the processes of advection and dispersion. Advection of tritium is preceded with the rate equal to the percolation rate of water carrying it. Dispersion of tritium occurs due to change in water velocity in the soil pores and molecular diffusion; therefore the rate measured from the tritium profiles would include dispersion and would be higher than the water percolation velocity. Tritium profile of 7 DAI indicates that 99% of the total added tritium was transported to the distance of 33 cm in both fields

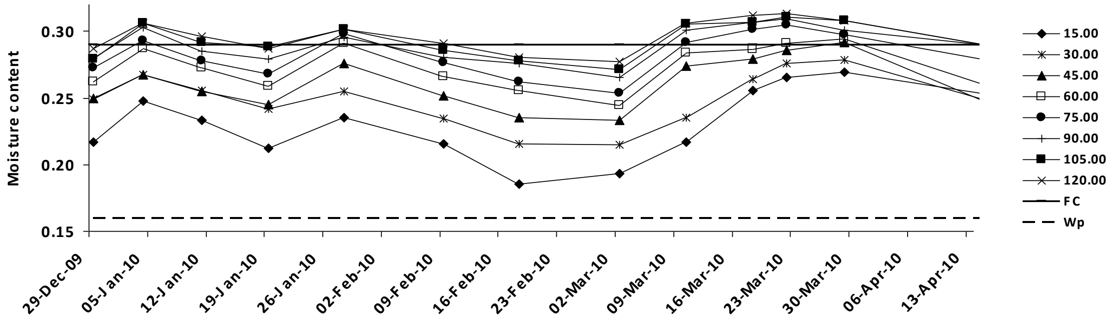

Figure 4a. Fluctuations in the soil moisture at different soil depths in Field-A under surplus irrigation practice during the wheat crop growth period.

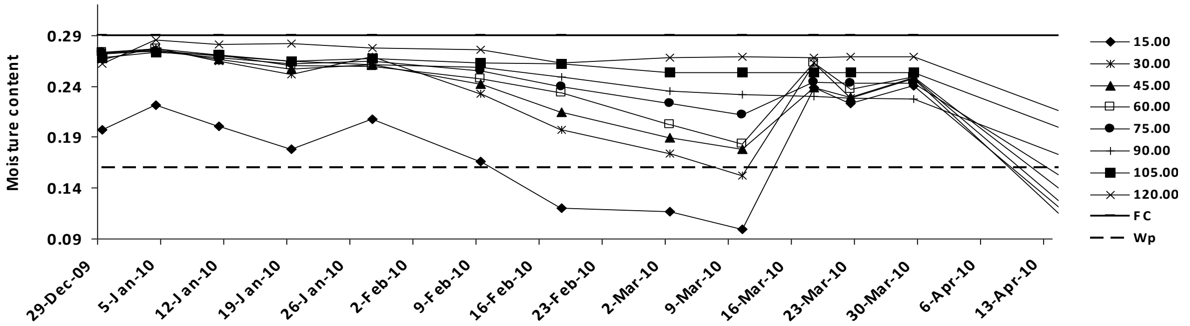

Figure 4b. Fluctuations in the soil moisture at different soil depths in Field-B under normal irrigation practice during the wheat crop growth period.

resulting into an average percolation velocity of 4.7 cm/day. The higher tritium transport rate is because of the reason that the plots were ploughed before irrigation to the depth of 20 cm that expedited water percolation. Tritium transported to a depth of 80 cm on 49 DAI and to a depth of 130 cm on 84 DAI, resulting in percolation velocities of 1.12 and1.43 cm/day respectively in the field A below 40 cm. The average percolation velocity from first irrigation on December 8, 2009 to March 02, 2010 (84 DAI) in the Field A is calculated as 1.53 cm/day.

Figure 5b shows the tritium profiles in the Field-B. The percolation velocity remained 4.7 cm/day on 7 DAI similar to Field-A because the same amount of water was applied in both the fields in the first irrigation. Figure shows that the leading front transported from 33 cm to 60 cm on 49 DAI (January 26, 2010) resulting in the infiltration velocity of 0.64 cm/day. The leading front did not show any shift from 49 DAI to 84 DAI (January 26, 2010 to March 02, 2010) showing negligible infiltration below 60 cm that may be due to single irrigation event after 26 Jan. 2010 (Table 1). The average percolation velocity from first irrigation to 84 DAI (December 08, 2009 to March 02, 2010) is calculated to be 0.7 cm/day.

Table 2. Evapotranspiration from wheat crop.

Date	Days after sowing	ET_C (mm/day)
18 Dec. 2009	10	0.63
28 Dec. 2009	20	0.68
07 Jan. 2010	30	0.8
17 Jan. 2010	40	0.8
27 Jan. 2010	50	1.1
06 Feb. 2010	60	0.9
16 Feb. 2010	70	1.65
26 Feb. 2010	80	2.3
08 March 2010	90	2.45
18 March 2010	100	2.5
28 March 2010	110	1.7
07 Apr. 2010	120	2.35
17 Apr. 2010	130	2.5

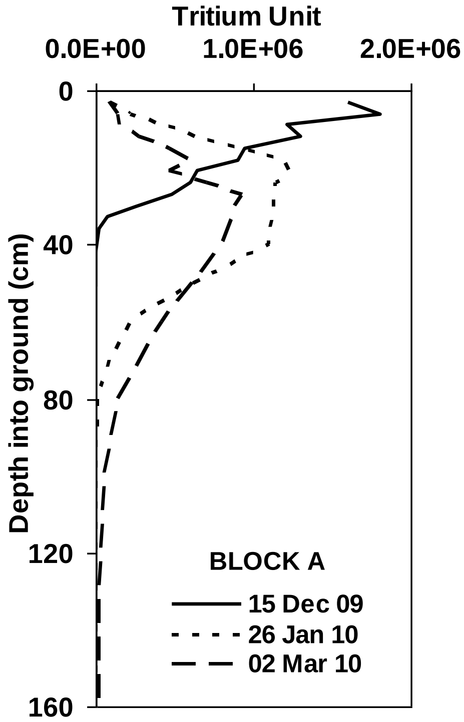

Figure 5a. Temporal variation in depth profiles of tritium in field A.

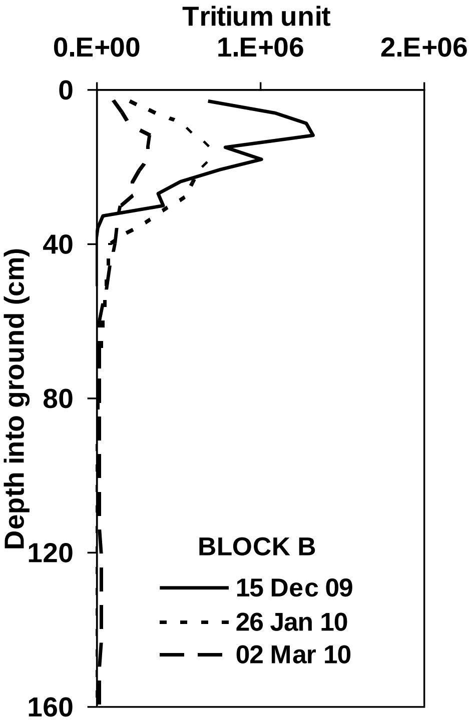

Figure 5b. Temporal variation in depth profiles of tritium in field B.

The profiles in both the fields show that tritium in very small amount also transported below 130 and 60 cm in the Field-A and Field-B, respectively. This tritium transport may be attributed to molecular diffusion which takes place even when there is no infiltration. Due to this reason, the profiles below 130 and 60 cm are not included in the calculation of fluxes.

4.3. Calculation of Fluxes by Stable Isotopes (Deuterium and Oxygen-18)

Figures 6a and 6b show depth profiles of $\delta^{18}O$ and $\delta^{2}H$ in Fields. The fields were irrigated with canal water having $\delta^{18}O$ value ranging between -6.43 and -8.48 ‰ and $\delta^{2}H$ value between -38.46 and -56.4‰.

Both the figures show depth wise cyclic variations in $\delta^{18}O$ and $\delta^{2}H$ signatures. The variations are smaller on 7 DAI (December 15, 2009) that becomes intense on 84 DAI (2 March, 2010). Also the cyclic variations are intense in the first 40 cm depth of soil and become less intense with depth. The profiles on December 15, 2009 represent the isotopic signatures that was preserved before first irrigation on December 8,2009 due to recharge and evaporation on earlier dates. The cyclic effect in the isotopic signatures is due to the enrichment caused by evaporation in near surface layer of soil. This phenomenon was explained by Clark and Fritz [5] by evaporating a soil column surface. Due to evaporation, enrichment takes place in the surface layer and the evaporating front moves down having enriched isotopic signatures with passage of time.

As the evaporating front has higher $\delta^{18}O$ and $\delta^{2}H$ signatures than the layer of water beneath it, the concentration gradient causes diffusion of isotopes in the underneath soil. Above the front, water exists in the form of vapors having depleted isotopic values. This results in the formation of a horizontal peak which is shifted down by infiltrating water during irrigation. Prior to irrigation, the moisture content of soil is smaller at the ground surface due to evaporation and increases with depth. Under unsaturated conditions the application of water does not result in purely piston flow but results in mixing of irrigation water with the pore water. During irrigation, water infiltrates rapidly into the unsaturated surface soil of lower moisture content resulting in the formation of a mixing layer which has isotopic composition between the irrigation and evaporated pore water. In this mixing layer, the cyclic variation caused by evaporation is retained; however, broadening of

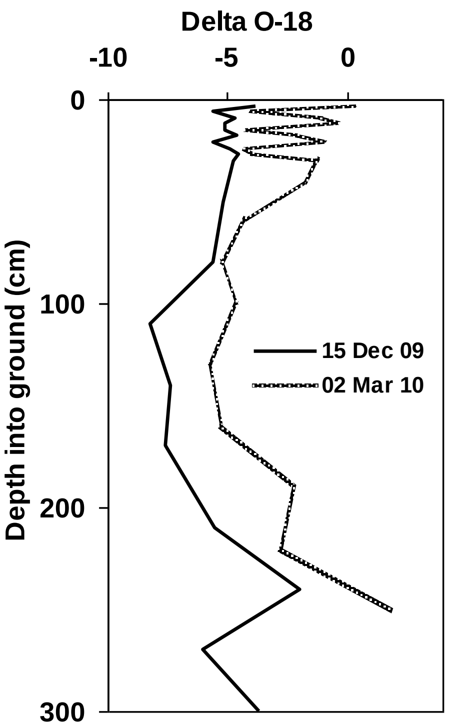

Figure 6a. Depth profiles of $\delta^{18}O$ of soil moisture in the cores of Field A

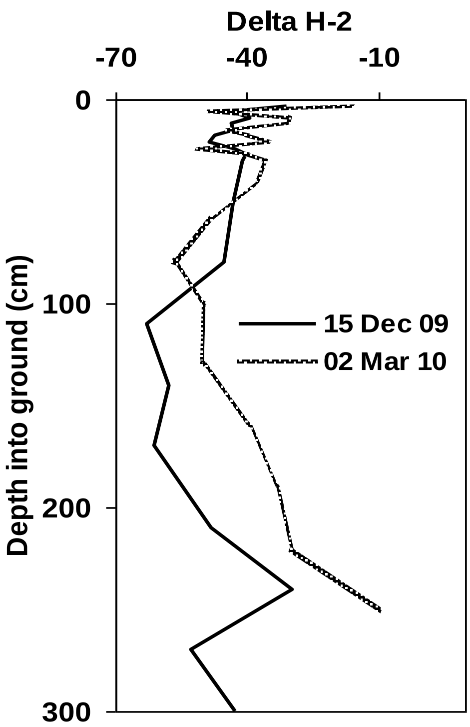

Figure 6b. Depth profiles of $\delta^{18}O$ of soil moisture in the cores of Field B

peak may occur as shown in the profiles in Figure 6. Below this layer the water still exists less than saturation and water infilters at smaller rate than in the surface layer. This causes the differential mixing that is larger at the surface and decreasing with increasing moisture content of soil. When the top soil becomes saturated, the mixing process stops in saturated portion and water infilters purely as piston flow. The mixing layer moves downwards preserving the isotopic compositions of water in the form of cyclic variation. After, all the irrigated water enters into the soil, the moisture content of surface layer starts decreasing again due to combined effect of evaporation and infiltration of water into the deeper layers causing another cyclic variation in isotopic signature.

Figures 6a and 6b also indicate that the cyclic variations are dampening at depth beyond 40 cm. This is because of the reason that the layer of water that existed in near surface soil on 7 DAI (December 15, 2009) had moved down on later dates. This layer also had cyclic variation preserved before first irrigation which broadened after moving down in the deeper layers. As evaporation does not occur in deeper parts of soil causing the cyclic variations, the diffusion causes dampening of the peaks.

Figure 7 shows plots of δ^2H versus $\delta^{18}O$ values of the pore water extracted from soil cores taken from field A at two different dates between 0 and 170 cm. The trends obtained from plotted data of the cores show that the slope of line decreased from 6.6 to 4.5 in the period between 15 December, 2009 and 2 March, 2010. The decrease in slope is due to the effect of evaporation that took place on the top layers. Figure 7 also shows that the isotopic values became enriched with time through the entire length of core which is due to the downward movement of enriched water from surface layers to the deeper layers.

From Figure 6, it is clear that the variations that existed in the surface layers on 7 DAI (December15, 2009) shifted below 80 cm on 84 DAI (March 02, 2010) in 77 days giving an average fluxes of 1.04 cm/day, respectively. The variations also have broadened. This indicates that downward movement of variations and broadening has occurred due to diffusion.

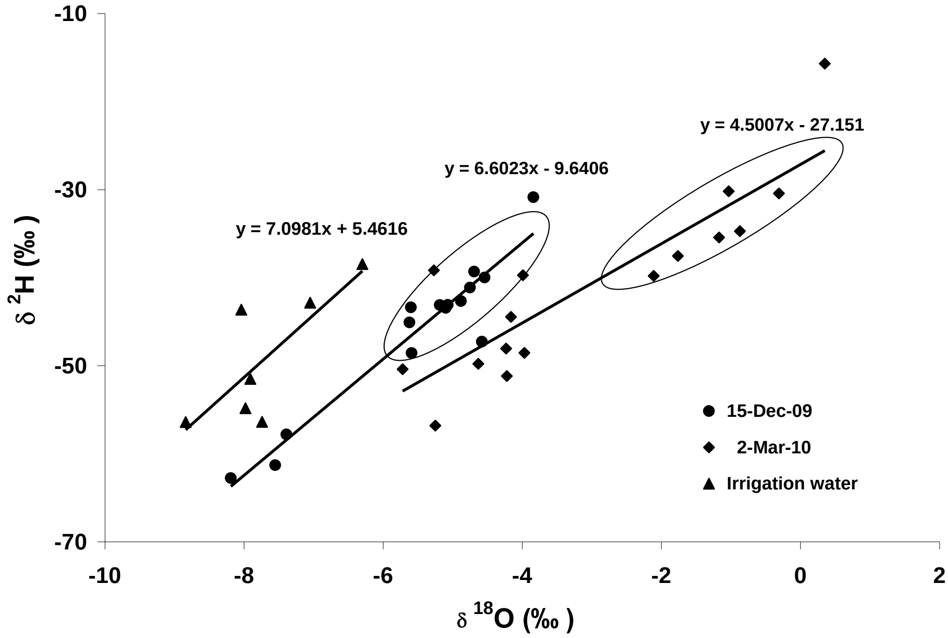

Figure 7. Plots of $\delta^{18}O$ versus δ^2H for irrigation water and pore water samples collected from soil cores of field-A on different dates.

4.4. Determination of Fluxes by Water Balance Approach

The rate of water draining out or water flux from a layer of soil can be calculated if the net rate of water entering into that layer at the input boundary and change in moisture in the layer are known. The water balance in the soil layer is represented as:

$$V_{in} = \Delta\theta + V_{out} + V_{ET} \quad (2)$$

Where "V_{in}" and "V_{out}" are the volumetric inflow and outflow from the top and bottom of soil layer respectively, $\Delta\theta$ represents change in soil moisture, and "V_{ET}" is the water lost due to evapotranspiration. If the soil is considered as combination of horizontal layers, the water outflow "V_{out}" from the bottom of one layer becomes equal to the water inflow "V_{in}" into the next adjacent layer due to the continuity of porous medium. The rate of volumetric outflow "V_{out}" from bottom of any soil layer represents discharge from that layer and can be represented as:

$$Q = V_{out} / t = (V_{in} - \Delta\theta - V_{ET}) / t \quad (3)$$

Where "Q" and "t" represent discharge and time respectively. The velocity or flux of water in the layer can be determined from discharge by using area of layer and porosity of soil as:

$$v = Q / (A * n) = (V_{in} - \Delta\theta - V_{ET}) / (A * n)t \quad (4)$$

Where "A" and "n" are area of layer and porosity respectively.

Table 3 shows the amount of irrigated water applied to both the fields and evapotranspiration between the two consecutive irrigation events. It is clear from the table that total water applied to the Field-A between 8 December 2009 and April 15, 2010 is almost double the amount of evapotranspiration during the same period while the amount of water applied to Field-B is nearly equal to the amount of evapotranspiration. However, negative values of the difference in water applied and evapotranspiration in the Fields shows that irrigation schedule be revised to make water applied equal to the evapotranspiration.

Figures 8a & 8b show the fluxes calculated from the soil moisture content data in the two Fields at different depths and dates by using equation 4. The soil was assumed as a combination of 15 cm thick layers. The fluxes from the layers were calculated from the amount of water drained from the bottom of each layer which is equal to the difference of water entered from the top of each layer and change in moisture content.

Table 3. Table showing difference of amount of irrigated water applied and evapotranspiration.

Irrigation date	Field-A			Field-B		
	Water applied (mm)	Evapo-transpiration until next irrigation (mm)	Difference	Water applied (mm)	Evapo-transpiration until next irrigation (mm)	Difference
Dec. 08, 2009	80	6.93	73.07	80	6.93	73.07
Dec. 19, 2009	32	7.6	24.4	16	7.6	8.4
Dec. 30, 2009	32	12	20	16	12	4
Jan. 14, 2010	32	46.6	-14.6	16	46.6	-30.6
Feb. 20, 2010	32	25.9	6.1	16	45.6	-29.6
March 03, 2010	32	19.7	12.3	-	-	-
March 11, 2010	32	17.5	14.5	16	28.5	-12.5
March 18, 2010	32	11	21	-	-	-
March 24, 2010	32	10.85	21.15	16	10.85	5.15
March 30, 2010	32	41.15	-9.15	16	41.15	-25.15
Total water	368	199.23		192	199.23	

Both the Figures 8a & 8b show positive and negative values for the time variant fluxes. Positive values are for downward movement of water while negative values are for movement in the reverse direction due to capillary action or due to the reversal of hydraulic gradient. Figure 8a shows the higher value of flux upto 0.97 cm/day at 15 cm depth and 0.17 cm/day at 120 cm depth on December 29, 2009 as water did not percolate to this depth on this date. The flux then decreases and increases to the highest value of 1.2 cm/day between March18 and 30, 2010 at all depths in field A. By looking into the irrigation dates, it is clear that two irrigations were made on March18 and 24, 2010. Due to these irrigations, fluxes at all the depths increased which could be lowered if only single irrigation would have been applied between March11 and 30, 2010. The rate remained 0.6 cm/day even after March 30, 2010 in the deeper soil layers. Similarly, the flux could be lowered in the beginning by reducing the amount of first irrigation which is 80 mm. Figure 8a shows that the flux became reversed between January 17, 2010 and February 20, 2010 upto the depth of 45 cm due to the loss of moisture by evapo-transpiration as shown in the Table 3 where the difference value is negative. Therefore, irrigation is required in this period. Figure 8a also shows that the flux became negative between 21 February, 2010 and 13 March, 2010 in the deeper layers below 45 cm showing decrease in moisture while it remained positive in the upper layers which is according to the requirement.

Figure 8b shows the fluxes in the field B at different depths and time. Figure shows that the flux increased in the 45 cm surface soil layers upto a value of 0.44 cm/day on December 29, 2010 then it decreased to negative value in the whole crop period indicating decrease in moisture in the surface layers due to evapo-transpiration. The decrease remained highest during the period between 3 and 24 March, 2010. The reason is maybe that field B was not irrigated on March 3 and 18, 2010. Therefore, the irrigation on March 3, 2010 is a necessary requirement. Figure 8b also shows that flux in the deeper layer of 75 and 120 cm increased to 1 cm/day after March 29, 2010. Therefore, irrigation on March 30, 2010 could be reduced. Comparison of figures 8a and 8b shows that quantity of water applied to Field-B is sufficient to the crop requirement, However, the irrigation schedule is slightly changed by including irrigation event of March 3, 2012 increasing the amount of irrigation on January 14, 2010 and 20 Feb., 2010 and reducing the amount of irrigation on 30 March, 2010.

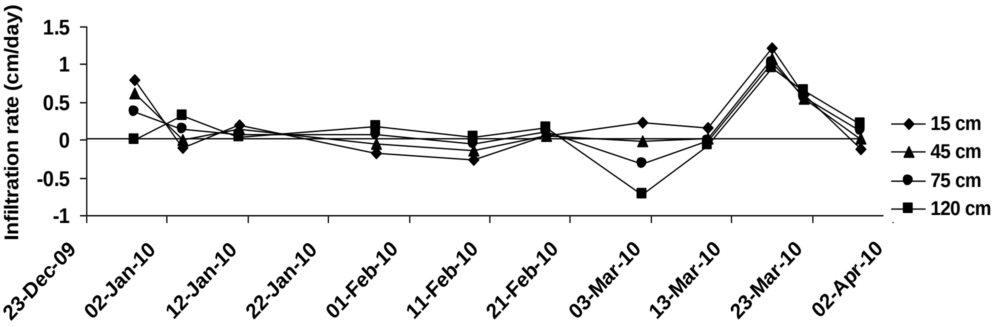

Figure 8a. Depth profiles of fluxes in Field-A calculated by Eq. (4).

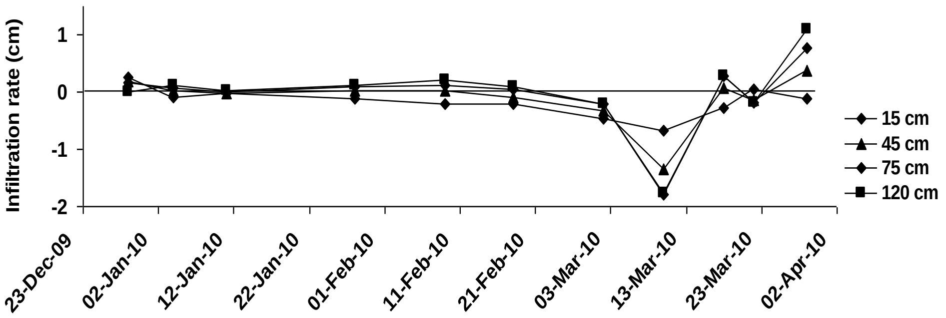

Figure 8b. Depth profiles of fluxes in Field-B calculated by Eq. (4).

5. Conclusions

The deep water fluxes from the field of a wheat crop at NIAB were calculated by the application of isotope and moisture balance techniques. The isotope techniques provided the values of water fluxes in the soil by calculating the transport rates of tritium and stable isotopes (hydrogen-2 and oxygen-18) in the soil. On the other hand, moisture balance technique used moisture content data and gave the depth wise fluxes in the soil at 15 cm increment showing an advantage over the isotope techniques.

The average values of water fluxes calculated by tritium were 1.53 and 0.7 cm/day in the field A and field B, respectively, between December 8, 2009 and March 2, 2010. On the other hand, the average value of flux calculated by stable isotope technique in the field A was 1.04 cm/day. The fluxes calculated from the water balance approach using soil moisture content data showed that the fluxes vary with depth and time and depend upon the irrigation events and soil moisture content. The positive values represent downward fluxes and negative values represent in the upward direction. The flux values were higher after irrigations and decreased with decrease in soil moisture content when water drained from the soil layer. The flux values as higher as 0.97 and 0.44 cm/day were calculated in the field A and field B, respectively, between first irrigation and March 2, 2010 compared to the values of 1.53 and 0.7 cm/day by tritium in the two blocks respectively and 1.02 cm/day in Block-A by stable isotope. Therefore, the values calculated by stable isotope and water balance technique are in good agreement in Block-A while the value calculated by tritium is higher.

The comparison of the flux values calculated by the three techniques shows that tritium tracer technique gives higher values than stable isotope and water balance techniques. It is due to the effect of hydrodynamic dispersion which is not subtracted from the flux value obtained by tritium tracer technique. Hence, more reliable estimations can only be made if the corrections due to dispersion and diffusion are made to the tritium transport rates.

The water fluxes and crop evapotranspiration data showed that the amount of irrigation applied to Field-B is sufficient for wheat crop requirement and water applied to Field-A is in excess. However, the irrigation schedule is required to be revised to reduce the deep fluxes and make water available to the surface layers for crop growth.

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