ISSN (Print): 0974-6846 ISSN (Online): 0974-5645

Assessment of Water Application Losses through Irrigation Surveys: A Case Study of Mirpurkhas Subdivision, Jamrao Irrigation Scheme, Sindh, Pakistan

Irfan Ahmed Shaikh^{1*}, Aimrun Wayayok², Ahmad Fikri Bin Abdullah², Amin Bin Mohammad Soom² and Munir Mangrio¹

¹Department of Irrigation and Drainage, Faculty of Agricultural Engineering, Sindh Agriculture University, Tando Jam, Sindh, Pakistan; irfansir pk@yahoo.com

²Department of Biological and Agricultural Engineering, Faculty of Engineering, Universiti Putra Malaysia (UPM), 43400 UPM, Serdang, Selangor DE, Malaysia; aimrun@upm.edu.my, ahmadfikri@upm.edu.my, aminms@upm.edu.my, munirmangrio@yahoo.com

Abstract

A study was conducted to demonstrate the applicability and efficiency of an irrigation survey method for digging up reliable information to estimate application losses. A sample of 220 tertiary channels was drawn randomly to get information from the growers of the Mirpurkhas subdivision, Jamrao canal irrigation scheme. Pre and post soil moisture status based practical measurements of losses were also carried out at 20 different sites. The results showed that the irrigation methods and soil types have a pronounced effect on application losses whereas crop type has no effect on application efficiency. Drip, sprinkler and furrow irrigation methods showed better performance as compared to other methods (wild flooding, border and basin) used in the study area. The survey based losses results were validated against measured losses whilst values available in literature compared favorably. The overall application losses in the study area were calculated as 23%. The main assumption for the irrigation survey of knowing the irrigation depth (not target depth in accordance with crop actual demand) and cutoff time for a single irrigation event by farmers was almost fulfilled. Based on the encouraging results of this study, it is concluded that irrigation survey studies are useful in understanding the irrigation scheme losses pattern which in turn provide opportunities for improvement.

Keywords: Application Losses, Drip, Irrigation Survey, Mirpurkhas Subdivision, Sprinkler, Surface Irrigation Methods

1. Introduction

The full understanding of the water balance for irrigation fields is required for efficient and proper management of the irrigation system¹. Application efficiency (AE) is the ratio of stored + beneficially (Crop evapotranspiration-ET_c and Leaching Requirement-LR) used water or required in the root zone to the water applied to the field, expressed in percentage. The AE may reach up to the 100%, if the field is under-irrigated. It is less than 100% when a field is the over-irrigated. Leaching requirement is considered

as beneficially used water^{2,3} since beneficial use accounts for possible off-site needs⁴. As a practical measurement of efficiency requires at least one day for knowing post irrigation soil moisture status depending upon soil type, ET_c is considered while calculating application losses. The quantification of field losses is inevitable for identifying already achieved enhancements and the potential areas where the improvements are needed to be made⁵. Besides that, every planning, design, development and management activity in the irrigated agriculture require prior knowledge of water application losses (Losses = 1-AE)

^{*}Author for correspondence

to facilitate better understanding of water balance in an irrigation scheme. It is made only in special studies due to the high cost of this activity and the required time for an irrigation event to be evaluated for pre irrigation moisture measurement and post irrigation moisture content measurement (usually two to three days for soil to attain field capacity level)1. The lack of application losses knowledge has serious drawbacks such as a large safety margin being needed to be applied while the planning and design of irrigation systems. Investments are thus considerably higher than would otherwise be necessary. The limited water resources are not optimally distributed and used and as a consequence much water goes to waste and less land can be irrigated; and the low overall irrigation efficiency creates harmful side-effects such as rising groundwater tables and soil salinization6.

The quantitative and temporal governing physical characteristics of an irrigation operation are the crop evapotranspiration; the soil moisture retention between field capacity and the preselected depletion limit; irrigation methods and the soil type. There are other factors which can also effect irrigation operation efficiency, but these must be considered under all circumstances⁶.

Practical methods commonly employed to measure field losses either require irrigation advance data for the volume balance based and hydrodynamic models as demonstrated by Iqbal et al.7 and Walker8 or pre and post irrigation soil moisture measurements from different techniques^{9,10}. Besides that, irrigation surveys are also used to estimate application efficiencies⁵. The determination of the water application efficiency by soil moisture measurements require two components of water balance, i.e. volume of water applied; volume of water stored in the root zone plus beneficially used volume of water. The measurement of quantum of irrigation water delivered to a farm or plot fora particular irrigation can be made by measuring flow of irrigation stream and time for which the stream is applied. The stored volume is measured in terms of soil moisture status and can either be measured by taking soil samples before and after irrigation or by installing state-of-the-art equipment in the field to be tested and the soil moisture Readings can be directly obtained10. The beneficially used quantum of water includes crop consumptive use till the next moisture Reading and leaching requirement to remove salts from the vadoze zone. These beneficial usages can be calculated by suitable empirical relation available in the literature.

Having recognized the importance of application losses and understood its measurement process, it is also worth mentioning that its measurement of a large area is difficult through standard practical procedure as it require a huge financial investment for measuring volume balance components along with the time taken to evaluate individual irrigation events. It is evident from the published works that only selected irrigation events for small areas have been practically evaluated for measuring field losses in terms of application efficiency. Extensive review of literature revealed about a study pertaining to application losses on a large scale by conducting experiments i.e. Israelsen⁹ study for Utah. As similar study as reported by Khalic¹¹ was conducted throughout the Pakistan. No current study was conducted to measure field losses practically on a large scale to document losses pattern in a particular irrigation scheme. It does not imply that the countries do not have database with regard to such information, but in several countries such database is however maintained using irrigation surveys. In developed countries like America, such database is prepared and maintained through irrigation surveys. For example Sandoval-Solis et al.5 conducted a study to evaluate application efficiency based on survey of the different counties of California State. In his report he also mentioned about such several surveys previously conducted for his region of study. To cope with the constraints such as finance and time, developed countries adopted survey techniques to acquire and maintain the information on these losses for proper planning, better management and system improvement considering the understanding of grower with regard to agricultural practices. The developing countries which already are hampered by less monetary power can adopt such practices to understand the system losses occurring at irrigation fields related to farm practices. On the one hand, it will give affordability while on the other it will generate information with regard to potential losses area which will be helpful to the policy makers to formulate better management strategies. Besides that, it is easy to update the record by re-conducting surveys on sample growers.

According to the Pakistan Bureau of Statistics¹², the total cropped area of the country is about 23 million hectares for the last ten years, out of which approximately 80% is irrigated. The available water resources, surface and ground, are insufficient to support irrigated agriculture due to the increasing population and food requirements¹³. Apart from the fact that a vast area is

available for agricultural extension in the country, the limited water resources become a major constraint. Therefore, it is prudent to use available water resources with the utmost care to get maximum production by avoiding losses in the irrigation network and on the field¹⁴. A lot of work pertaining to the transmission losses has been conducted in the country and relevant database is maintained, which is manifested from the plethora of literature available in the form of periodic reports. But, little attention has been given to field losses quantification at a grower's farm as the literature found to have minimum space for this issue. While the field losses are equally important and almost of the same magnitude as conveyance losses.

The above discussion sheds light on such research studies limitations and constraints in terms of resources (time, money, access, etc.). Likewise, it was not possible to conduct physical experiments all over the area of this presentstudy due to several constraints, thus the present study was carried out by a mixed approach. The mixed approach implies that the potential and accessible areas were identified for practical measurement of application losses for selected irrigation events and the questionnaire used by Orang et al.¹⁵ was modified technically, translated into local language and distributed among the grower's randomly over the whole study areato get the information regarding irrigation method, depth of application, hours of application, cropping pattern and soil type from farmers of sample tertiary channels. This information was used to assess field losses in conjunction with the actual water requirement information for different crops of the study region obtained by the research department. Furthermore, attainable values of the application efficiencies were also sourced from nationally and internationally available literature for comparison purposes. The irrigation survey conducted in this study differs from previously conducted surveys regarding information required and practically adoptable. The work is novel as far as the mechanism of estimating losses through questionnaire is concerned.

This study was carried out in the irrigation scheme specifically the Mirpurkhas sub-division, Jamrao, Sindh, Pakistan through the survey method. The aim is to identify the potential areas for improvement can be identified and database of these losses can be prepared which will be beneficial for the planners of this region for future agriculture planning and management endeavors. The results were validated against practically measured losses and literature values. The present study evaluated the effect of crop, soil and irrigation methods on application losses.

2. Materials and Methods

2.1 Study Area

The study was carried out in the jurisdiction of Mirpurkhas sub-division, Jamrao, Pakistan, which lies between latitudes 25° 25'14.22" to 25° 44' 08.96" North and between longitudes 68° 53'11.58" to 69° 09'34.79" East. Questionnaires were distributed among farmers through the Farmer Organizations (FOs) chairmen to acquire complete information regarding their current cultivation practices on the farm (irrigation method, crop, depth of application, soil type, the cultivation area under the method used etc.) to estimate application losses. Aggregated sample size of 220 watercourses command areas based on Rea and Parker¹⁶ method was taken at the 95 % confidence level followed by questionnaire distribution to the farmers selected at random from the head, middle and tail reaches watercourses of the main canal. The soils in this study were categorized as coarse (sandy), medium (loamy) and fine (clayey). Additionally, the twenty (20) fields for five irrigation methods (4 fields for each irrigation method) were randomly selected for evaluating application losses practically under conventional practices taking into account the irrigation methods (basin, border, furrow, sprinkler, drip) used having different soil types and crops. For identification purposes in the experiment, fields were designated with the capital letters A, B, C and D for all methods.

2.2 Application Losses Determination

The application losses were determined in terms of application efficiency (Losses = 1-AE). In the present study, the losses were measured practically 17-19 and as well as estimated through questionnaire for the study area. Both approaches had a different mechanism for determining the application losses keeping in view the fundamental definition of application efficiency and are subsequently explained under these headings. Losses determined practically and Losses estimated through questionnaire information.

2.2.1 Losses Determined Practically

The relations used to determine application losses are expressed as:

$$AE = \frac{Volume \ stored + beneficially \ consumed}{Volume \ applied}$$

$$= \frac{\left(A \times BD \times IMC \times RZD\right) + \left(\left(ET_c \times NOD\right) + LR\right)}{O \times t} \tag{1}$$

$$Application losses = 1 - AE \tag{2}$$

Where, AE is the application efficiency; A is the area in m². BD is the bulk density in kg m⁻³; IMC is the increase in moisture content in fraction; ETc is the crop water requirement in m d⁻¹; NOD is the number of days after which the post irrigation Reading of moisture content was taken; LR is the leaching requirement in meters. The selected areas for experiments were not affected by the salinity problem, hence this parameter was zero in above equation; Q is the stream size in m³ h⁻¹; t is the time of irrigation in hours.

Based on above relation, the practical measurement of two components of water balance (Volume applied and Volume stored + beneficially consumed) requires measurement of area under trial; pre and post irrigation soil moisture status of trial area; root zone depth of the crop grown in the trial area, soil bulk density of the root zone; crop water requirement (ET_c) of the crop grown in the trial area; Leaching requirement; stream size applied to the trial area and time of irrigation. To get the data under the conventional practices of farmer regime, it was carefully taken into account that the farmer's activities should not be meddled with while taking above-stated measurements.

2.2.2 Volume Stored and Beneficially Consumed 2.2.2.1 Measurement of Area

The tract of the selected field was measured with the help of measuring tape. At first, several wooden pegs were fixed along the length and width of the area for avoiding inaccuracies in the measurements and then, distances from corner to corner were measured. Finally, the area was calculated by multiplying measured lengths and widths of the trial area. The shape of all the trial areas was rectangular with exception of three sites which were of irregular shape. The area of those sites was determined by subdividing the area into regular shape sections and then, aggregated the sub-section areas to get the total area.

2.2.2.2 Measurement of Soil Moisture

The electrical resistance blocks were installed in the trial tract to measure the soil moisture^{20,21} in the separate auger holes at the depth of 10, 20, 30, 40, 60, 90 and 100 cm (this is the maximum root zone depth encountered in the field, while at some place the total depth was less than this) with the horizontal span of 10 cm. The setup was replicated randomly and installed at six places in the trial area. A resistance block meter was used to take readings (Eijkelamp Agric-research Giesbeek, the Netherlands). The resistance blocks readings were converted to soil moisture content by calibration. Then, a gravimetric soil moisture percentage was changed to volumetric soil moisture percentage by multiplying with the bulk density. The results from the resistance blocks were validated against the results obtained from the soil moisture measurement by the gravimetric method which showed the reliability of the results obtained from resistance blocks. Besides that moisture content of large area was also determined by gravimetric method for randomly collected soil samples. To find the increase in moisture content, readings were taken before the irrigation and again one or two or three days after, depending on the soil.

2.2.2.3 Root Zone Depth

The root zone is either assumed or estimated as the precise measurement of root zone depth is impossible due to several varying conditions²⁰. For the present study, the root zone depth data for crops grown in the area were procured from the Research department, which is used by them for designing and scheduling of the irrigation plan. The values from literature including FAO were also taken for some crops considering depth to ground water, soil type and the crop. Based on the facilities available, root zone of some full grown crops (wheat, cotton, vegetables) was measured practically in the experimental field by slicing out the randomly selected plants taking into account the expected depth and radius. The plant taken out with the roots followed careful washing with water and measurement of root length.

2.2.2.4 Soil Bulk Density of Crop Root Zone

Samples for determining bulk densities at the experimental site were made with the help of core sampler having cylinder volume of 50 cm³ and representative undisturbed soil samples were collected for the cultivated crop for 15 cm vertical segments up to the root zone from randomly

selected places of trial tract sand packed in polyethylene bags separately. The samples were brought to the laboratory of the Department of Irrigation and Drainage, Faculty of Agricultural Engineering, Sindh Agriculture University Tandojam for analysis and soil texture, bulk densities and soil moisture content were determined.

2.2.2.5 Crop Water Requirement

The pertinent data with regard to reference evapotranspiration (ET) computed from the Penman-Monteith equation using weather data and well established crop coefficients (K_c) values for the crops grown by study area farmers were acquired from the research department and ET was computed by multiplying ET and K values for different for different growth stages.

$$ET_{c} = ET_{o} \times K_{c}$$
 (3)

2.2.3 Volume Applied

2.2.3.1 Measurement of Stream Size and Time of *Irrigation*

A cutthroat flume (8" x 3' or 12" x 3') was installed at the inlet of the field to measure stream size. Before using, flumes were calibrated as per guidelines of Skogerboe et al.²² and relevant equation given in the literature was invoked to compute the stream size depending on flow conditions (free or submerged) for surface irrigation methods. Flow rate Readings for sprinkler and drip irrigation methods were recorded directly from the flowmeters installed in the system during the irrigation event. The time of irrigation was noted as soon as the waterstarted flowing in the field or emitting from the emitters/nozzles till cutoff. The volume applied was, thus, calculated by multiplying the measured streamsize with irrigation time.

2.2.3.2 Losses Estimated through Questionnaire Information

The approach to estimate losses through questionnaire was adopted all over the area due to the high cost of experiment with the assumptions that: 1. The farmers know well about their practices such as irrigation application depth, time of irrigation, soil types etc., and 2. The guidelines for the required depth of irrigations for different crops used by the research department in the study area is applicable to the whole study area and irrigation surveys are representative samples of the population. The

basis of application losses calculations was kept considering the definition of application efficiency given by Bos and Nugteren⁶ which is quantitatively expressed as:

$$AE = \frac{Depth \text{ Re quired}}{Depth \text{ Furnished}} = \frac{D_m}{D_f}$$
 (4)

Where, D_m is the depth of irrigation water required (m); D_i is the depth of irrigation water applied.

The application efficiency was determined on the basis of total required and applied depths. The total applied depth was estimated by multiplying the depth of one irrigation event with the number of irrigations for surface irrigation methods. For sprinkler and drip, discharge and operational time in conjunction with wetted area were used to compute applied depth. 10% leaching requirement recommended by the irrigation department for saline area was considered to compute the required depthof thosetracts of study area which are saline. While interviewing the farmers of the study region, it was appraised by the farmers that they irrigate their fields, even if there is rainfall since the rainfall in the region is erratic and insufficient to support the agriculture. This is also shown in the meteorological records that the rainfall is highly variable in the study area and mostly falls in the months of June to September. Considering the farmers practice, rainfall was not considered in calculating the losses.

2.3 Application Losses in the Study Area

Considering irrigation methods and corresponding area under them, overall water application losses occurred in Mirpurkhas subdivisions fields were computed by following relation.

$$\sum_{i}^{MU} A_{Li} \times \frac{a_i}{A_t} \tag{5}$$

Where, A_L is the application losses in fraction; 'a' is area under particular irrigation method; and A, is the total area; subscript i indicates particular irrigation method.

3. Results and Discussions

3.1 Crops Grown and Irrigation Methods in the Study Area

Originally, the questionnaire used in the study comprised 20 possible crops in the study area, but after completing the survey, it was revealed that the cropping pattern of the study area consists of 11 crops shown in Table 1. While surveying, it was also told by almost all of the farmers that the cropping pattern was the same for the last ten years but however with variation in cropping intensities. It can also be seen from the Table 1 that the main crops of the region are wheat, cotton and sugarcane occupying 35, 23 and 12 % area respectively.

In the questionnaire, the farmers were to choose among subsurface irrigation method, surface irrigation methods, sprinkler and drip irrigation methods or a combination of these as per their practices. The responses of farmers are summarized in Tables 1 to 3. For the sake of summarizing the results, irrigation methods were categorized as gravity (subsurface + surface methods) and pressurized irrigation methods (sprinkler +drip) on the basis of flow principal and results were portrayed in Table 2. The results were also categorized by summing the crops into fields, vegetable and orchard (Table 3.) categories. From the farmers' responses, it is clear that the subsurface irrigation method is not used in the study area whilst surface and pressurized irrigation methods are practiced by the farmers to irrigate their lands.

All types of gravity methods (surface methods) are in practice in the study region as shown in Table 1 viz; wild flooding, border, basin and furrow. On the basis of the area under surface irrigation methods, the most preferable surface method is furrow irrigation method used on 59% (73475 acres) irrigated area by the farmer followed by basin and border which are practiced on 16 and 13 % area respectively. The wild flooding method has its existence only in head Reaches of the channels for 3 % area. The farmers of the study area informed during survey that they used to practice wild flooding on most of the area more than ten years ago for irrigating their lands, but with the introduction of farm machinery and government awareness programs, they have changed their practices to other methods. Among the seven types of sprinkler irrigation methods, only the permanent installed sprinklers were observed to be used in the study region for irrigation purposes on 3926 acres. Even farmers of the region were not aware of the other types of sprinkler methods. Only buried drip irrigation method was seen and reported by the farmers for 7067 acres which is 45 % more than the sprinkler area. According to the farmers of the study area,

 Table 1.
 Irrigated area (acres) of study area by crop and irrigation method

						Irri	gation N	Aethod						
Crop	Subsurface Surface					S	prinkle	r			Drip			
•	DP/DD	WF	BR	BN	F	PS	НМ	LM	SR	MM	HP	CP	AG	В
Cotton	0	529	1763	4323	22101	66	0	0	0	0	0	0	0	0
Maize	0	88	452	1455	1887	0	0	0	0	0	0	0	0	0
Wheat	0	2414	9234	5264	24911	0	0	0	0	0	0	0	0	0
Oilseeds	0	7	302	805	382	0	0	0	0	0	0	0	0	0
Sugar cane	0	308	3841	2473	7647	0	0	0	0	0	0	0	0	0
Pulses	0	106	86	2037	330	0	0	0	0	0	0	0	0	0
Chilies	0	0	0	491	6341	0	0	0	0	0	0	0	0	0
Pasture	0	398	467	589	5479	0	0	0	0	0	0	0	0	0
Onion & vegetables	0	34	0	339	2120	1716	0	0	0	0	0	0	0	2594
Tomato	0	0	0	533	1904	2143	0	0	0	0	0	0	0	1376
Orchard	0	0	0	1389	373	0	0	0	0	0	0	0	0	3096

Note: $DP/DD = drain\ pipe\ or\ ditch;\ WF = wild\ flooding;\ BR = border;\ BN = basin;\ F = furrow;\ PS = permanent\ sprinkler;\ HM = hand\ move;\ LM = linear\ move;\ SR = side\ roll;\ MM = micro\ mini;\ HP = hose\ pull;\ CP = center\ pivot;\ AG = above\ ground;\ B = buried\ and\ Vegetable\ (cucumber,\ cauli\ flower,\ Radish\ etc.)$

Table 2. Irrigated area (%) by crop and two irrigation methods categories (Rounded %age)

Crop	Gravity	Pressurized
Cotton	99.8	0.23
Maize	100	0
Wheat	100	0
Oilseeds	100	0
Sugar cane	100	0
Pulses	100	0
Chilies	100	0
Pasture	100	0
Onion & Vegetables	37	63
Tomato	41	59
Orchard	36	64
Total	91	9

Table 3. Percentage of irrigated area by irrigation methods and crop categories (Rounded %age)

Crop					
Field	Vegetable	Orchard	All		
100	60	36	91		
0	20	0	3		
0	20	64	6		
100	100	100	100		
	100 0 0	Field Vegetable 100 60 0 20 0 20	Field Vegetable Orchard 100 60 36 0 20 0 0 20 64		

they were recommended by the designers to install buried system due to the high temperatures in the summer season which reduces the life of the system.

The gravity methods are mostly used for irrigating the fields as shown in the Table 2. All crops are grown by irrigating through gravity methods except vegetables, orchard areas and small area of cotton which are also irrigated by the pressurized irrigation methods. 91% of the total area is irrigated by gravity methods and remaining 9 % of the total area is under pressurized irrigation methods. Fields crops are entirely irrigated by surface methods (99.8%). The 60 % vegetable and 36 % orchard crops are surface irrigated. The sprinkler and drip irrigation methods are practiced for 20 and 20 % of the vegetable area respectively. It was also observed that the 64 % orchard area is irrigated by the drip irrigation method and the sprinkler system is not used to irrigate the orchard. Overall, 91 % area is irrigated by surface methods, 3 % is sprinkler irrigated and the remaining 6 % is irrigated by the drip irrigation method. In spite of the high efficiency of pressurized irrigation methods (discussed in subsequent paragraphs), the major portion of the area 91 % is surface irrigated because there are several constraints due to which farmers are not adopting the modern low volume methods. Some of them are political and some are technical. Only technical Reasons are discussed here. While conducting the survey, the Reasons for not changing the practices from conventional surface irrigation method to low volume irrigation methods were that only a few companies install the system due to its complicated design requiring design experts and skilled technicians and plumbers to install the system. It was also discovered that these companies import the fabricated material from abroad, which incur huge investment on the installation of the system. Moreover, the system requires frequent maintenance to work efficiently and which also require skill. Hence, they have to pay to companies for its maintenance as well, thus making it a non-favorable choice.

3.2 Application Losses Estimated through Questionnaire Information

The information collected through the questionnaire was summarized according to the crop, irrigation methods and soil type in Tables 4 through 8 and Figure 1. From Table 4, it can be noted from the results that the time to irrigate one acre ranges from 1.5 to 7 hours for surface irrigation methods and 4 to 12 hours for sprinkler and drip irrigation methods. The time to irrigate is a function of stream size. Considering the time and area, it was roughly estimated that the stream size for the study area

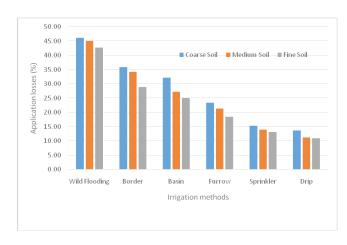


Figure 1. Application losses by soil type and irrigation method.

Table 4. Ranges of data collected through questionnaire

Data		Method							
Data	WF	BR	BN	F	S	D			
Time to irrigate one acre (hrs)	2.0-7.0	2.0-7.0	2.0-4.0	1.5-3.0	8.0-12.0	4.0-8.0			
Require Depth (mm)	276–1216	276–1216	276–1217	276–1218	330-1130	330-1130			
Applied Depth (mm)	513-2222	384–1925	355–1892	332–1601	384-772	368-1340			
AE (%)	52-61	63-72	66-77	74-84	84-87	84-92			

Note: Additionally, S = sprinkler; D = drip

ranges from 0.5 to 3 cusecs for surface irrigation methods and less than 0.5 cusec for pressurized irrigation methods. For the crops grown in the study region, the required depth of irrigation ranges from 276 to 1216 mm.

The total applied depths were observed as less than or equal to 2222 mm for surface irrigation methods and less than 1400mm for pressurized irrigation methods. The application efficiency varied from 52 to 84% for surface methods and 84 to 91 % for the sprinkler and drip irrigation methods. The magnitude of application losses in terms of influencing factors for the study area are discussed hereafter.

3.3 Crop Effect

Several crops were grown by farmers and each crop type has different water demands. Taking into the account this fact, the effect of different crops on application losses was assessed. The coefficient of variation (a statistical measure of the dispersion) for the same soil category and each irrigation method used for different crops was calculated to observe the variation in the losses (Table 5-7).

The results reveal that the crop type has no effect on seepage losses for the study region as indicated by the negligible CVs values varying from 1 to 4 % for coarse soils; 1 to 3% for medium type soils and 0 to 5% for fine soils for different irrigation methods. The farmers were observed to irrigate their land with excess water considering soil type (i.e. quick water ponding on heavy soil than light soils) and crop period (frequency of irrigation is more for long period crops such as sugar cane which in turn increases the total applied depth). Farmers do not consider the crop type and soil characteristics (such

Table 5. Application losses (%) by crop and irrigation method for coarse soils

C		Method					
Crop	Wild Flooding	Border	Basin	Furrow	Sprinkler	Drip	
Cotton	46.5	36.2	31.6	23.6	16.0	0.0	
Maize	0.0	35.4	32.4	24.0	0.0	0.0	
Wheat	45.9	36.1	31.3	23.0	0.0	0.0	
Oilseeds	0.0	36.4	32.2	22.0	0.0	0.0	
Sugar cane	0.0	35.8	32.1	23.9	0.0	0.0	
Pulses	0.0	0.0	32.0	23.5	0.0	0.0	
Chilies	0.0	0.0	32.2	23.7	0.0	0.0	
Pasture	0.0	35.7	33.0	23.7	0.0	0.0	
Onion	46.1	0.0	0.0	23.8	15.0	13.4	
Tomato	0.0	0.0	32.6	23.6	15.0	13.9	
Orchard	0.0	0.0	32.2	23.0	0.0	13.8	
CV (%)	1	1	1	2	4	2	

Table 6. Application losses (%) by crop and irrigation method for medium soils

Cuan		Method						
Crop	Wild Flooding	Border	Basin	Furrow	Sprinkler	Drip		
Cotton	45.8	33.8	27.6	21.5	0.0	0.0		
Maize	43.9	34.9	27.5	22.1	0.0	0.0		
Wheat	43.7	33.9	27.7	21.3	0.0	0.0		
Oilseeds	46.2	33.9	26.2	21.7	0.0	0.0		
Sugar cane	44.6	34.2	27.3	21.4	0.0	0.0		
Pulses	46.5	34.9	27.7	21.5	0.0	0.0		
Chilies	44.9	0.0	25.9	20.3	0.0	0.0		
Pasture	45.4	34.2	27.7	22.3	0.0	0.0		
Onion	45.0	0.0	27.8	21.5	14.8	11.5		
Tomato	0.0	0.0	27.8	21.5	14.9	10.9		
Orchard	0.0	0.0	27.4	21.5	0.0	11.4		
CV (%)	2	1	2	3	1	3		

Table 7. Application losses (%) by crop and irrigation method for fine soils

C			Method	d		
Crop	Wild Flooding	Border	Basin	Furrow	Sprinkler	Drip
Cotton	42.7	28.1	24.9	18.6	14.9	0.0
Maize	42.7	29.0	25.7	18.3	0.0	0.0
Wheat	0.0	28.7	25.3	19.9	0.0	0.0
Oilseeds	0.0	28.9	24.7	18.3	0.0	0.0
Sugar cane	0.0	29.5	25.2	18.4	0.0	0.0
Pulses	0.0	29.5	25.0	18.3	0.0	0.0
Chilies	0.0	0.0	24.9	19.2	0.0	0.0
Pasture	0.0	0.0	25.0	18.2	0.0	0.0
Onion	0.0	0.0	24.8	18.5	13.5	11.3
Tomato	0.0	0.0	24.5	18.1	14.1	10.9
Orchard	0.0	0.0	25.3	18.3	0.0	10.7
CV (%)	0	2	1	3	5	3

as field capacity) while irrigating their fields, but would rather wait to pond the pre-specified depth on the land knowing the time to cutoff.

3.4 Consequences of Irrigation methods

Irrigation methods effect on application losses was seen by analyzing the variance among methods using irrigation methods mean values shown in Tables 5-7 for application losses under different soils. The results are tabulated in Table 8 and this show that there is a significant difference

at the significance level of 5% among irrigation methods under study with regard to application losses. The methods differed for all soil types (p<0.05). Among five surface irrigation methods furrow (Losses Mean = 18 to 23 %) was observed to be more efficient, followed by basin (Losses Mean = 25 to 32 %) and border (Losses Mean = 29 to 36 %).

The worst method was wild flooding in which almost half of the applied water found to be wasted. Among the pressurized irrigation methods, the drip irrigation

Table 8. Variance analysis results of irrigation methods

Method	Means					
Method	Coarse Soil	Medium Soil	Fine Soil			
Wild Flooding	46.16	45.12	42.72			
Border	35.94	34.25	28.94			
Basin	32.16	27.32	25.04			
Furrow	23.40	21.39	18.49			
Sprinkler	15.33	14.01	13.21			
Drip	13.72	11.28	10.98			
F value	2480.8	2079.1	1750.58			
P value	< 0.05	< 0.05	< 0.05			

method has less losses compared to the sprinkler method. On the whole, the pressurized irrigation system efficiency was higher than the surface irrigation methods. The difference in the losses among surface methods are due to different design which affect the wetted area and applied depth. For example, in the furrow irrigation method about half of the area or less is in touch with water which is ponded up to pre-specified depth and also allow lateral movement of water in the ridges and reduce the vertical movement and percolation losses while in wild flooding or border irrigation methods the water is allowed to flow until it gets ponded all over the surface to the desired depth which result in huge losses. The pressurized irrigation methods are designed and installed by the engineers thus, these methods incur less losses as compared to surface irrigation methods since the farmers operate these systems in accordance with the guidelines given by the engineers which are based on the scientific and required amount of water for specific crops. The losses in the pressurized irrigation systems are attributed to the improper maintenance, friction carelessness on the farmer's part regarding timely cutoff and wind drift losses in case of sprinkler system which is evident from the sprinkler losses which is 2 to 3% more than a drip method.

3.5 Soil Effect

Figure 1 demonstrates the application losses with respect to soil types under different irrigation methods. As already stated, the soils of the study area were categorized as coarse, medium and fine soils. The dropping trend in losses (from course to fine soils) is visible from Figure 1 which shows that the losses are influenced by the soil type. It is noteworthy that the apart from the different irrigation method the maximum losses occurred in the coarse soil and the minimum losses were observed in the fine soil type. However, the farmers do not consider soil characteristics at the time of irrigation yet they have a simple understanding that on which soil, water will pond soon and take time to infiltrate therefore, the losses difference are not in tens but the trend provide sufficient information regarding effect of soil texture on application losses. Oil seeds needs 276 mm to be grown which is a minimum requirement among all crops. If simply 1 % losses are taken of this demand for one acre it will be 2.76 acre-mm or 11 m³. It means, if losses differed by 1 % due to different soil types, it will be at least 13 m3 losses from each acre of the study area.

3.6 Application Losses Determined **Practically under Conventional Practices**

Losses were also practically measured at selected fields to check and validate the questionnaire results. The results for all evaluated methods are summarized in the Tables 9 through 10. Table 9 presents the ranges of data practically collected at the trial fields for tested irrigation methods. The collected data included crop type, area, pre and post irrigation Moisture Content (MC), bulk density of soil, ET and soil type. The crops growing at experimental sites were cotton, wheat, vegetables, and oilseeds. The table results show that the area under trial ranged from 0.8 to 3 acres. The pre irrigation moisture content determined on a weight basis varied from 5.64 to 15.74 % depending upon soil type. 14 to 25.8 % moisture content was recorded for post irrigation soil moisture content. The bulk density values ranged from 1.33 g cm⁻³ for silty clay loam to 1.59 for sandy clay. Root zone depth determined and used in the calculations were varied from 300 to 900mm according to the crop grown. ET values were in the range of 0.93 to 6.24 mm d⁻¹ depending on the crop growth stage and time of experiment.

Application efficiency and losses results according to the field and method of irrigationare shown in the Table 10. Average application losses determined for the border irrigation method were 32 to 35% while losses in basin irrigation methods were measured in the range of 23 to 26 % for the applied depths of 77 to 154 mm and stored depths of 58 to 117 mm. 18 to 22 % losses were measured under the furrow irrigation method while irrigating with a minimum stream size of 30.58 LS⁻¹. Under sprinkler and drip irrigation methods 11 to 15 % irrigation water was measured as wasted.

Table 9. Data ranges by irrigation methods collected at selected sites

Data Collected	Tested Irrigation Methods							
Data Conected	Border	Basin	Furrow	Sprinkler	Drip			
Field -A								
Crop	Wheat	Maize	Cauli Flower	Canola	Turnip			
Area (acres)	1.6	1.2	0.8	1.3	1.2			
Pre Irrigation M.C	11.6–15.1	14.37-15.74	9.31-11	13.21-13.79	10.2-11.7			
Post Irrigation M.C	25-25.8	22.11-24.22	18-19.23	21.12-22	14.15.1			
Bulk density (g cm ⁻¹)	1.46	1.42	1.59	1.41	1.57			
Root zone depth (mm)	900	900	400	800	500			
ET_{c} (mm d^{-1})	1.71-2.73	3.38-5.38	1.04-1.43	0.93-1.092	1.04-1.43			
Soil type	Clay loam	Silt loam	Sandy clay	Sandy loam	Sandy loam			
Field -B								
Стор	Wheat	Wheat	Sun flower	Cucumber	Cotton			
Area (acres)	2.2	1	1.6	1	1			
Pre Irrigation M.C	10.84-14.5	5.64-8.2	14.66-15	11.26-14.21	10.2-11.57			
Post Irrigation M.C	24.11-26.1	14.14.7	22.56-23.1	20.12-21.23	14-15.26			
Bulk density (g cm ⁻¹)	1.35	1.56	1.38	1.39	1.55			
Root zone depth (mm)	900	900	850	600	850			
ET_{c} (mm d^{-1})	1.71-2.34	0.93-1.48	3.25-6.24	2.62	3.22			
Soil type	Silt loam	Sandy loam	Clay loam	Silt loam	Sandy loam			
Field-C								
Стор	Maize	Carrot	Cotton	Cotton	Spinach			
Area (acres)	3	1.1	1.4	1	1			
Pre Irrigation M.C	11.09-16	13.8-1.57	15.18-15.75	7.2-8.26	11.84-13.08			
Post Irrigation M.C	24–25	22.22-23	23-24	14-14.23	16-16.78			
Bulk density (g cm ⁻¹)	1.4	1.4	1.51	1.53	1.48			
Root zone depth (mm)	900	500	950	950	300			
ET_{c} (mm d^{-1})	3.8-4.94	1.04-1.4	4.9-5.7	51.4-5.7	1.04-1.43			
Soil type	Silt loam	Silty clay loam	Clay loam	Loam	Loam			
Field-D								
Стор	Cotton	Cotton	Cotton	Onion	Radish			
Area (acres)	1.5	1	1	1.5	1			
Pre Irrigation M.C	13.64-16.21	13.4-15.1	8.5-12.4	8.1-13.12	14.11-15.8			
Post Irrigation M.C	22.22-23.52	22.85-23	19-19.43	18-18.43	19.23-20			
Bulk density (g cm ⁻¹)	1.39	1.33	1.41	1.41	1.4			
Root zone depth (mm)	950	950	950	300	300			
ET_{c} (mm d^{-1})	3.6-5.4	3.27-5.7	5.17-5.72	1.43-2.06	1.04-1.41			
Soil type	Clay loam	Silt clay loam	Silt loam	Sandy Loam	Silt loam			

Table 10. Percentage of application losses by irrigation methods and experimental fields (all values are mean of three different irrigation events)

Irrigation Method	Stream size (LS ⁻¹)	Depth Stored +ET (mm)	Depth Applied (mm)	Application Efficiency (%)	Application losses (%)
		Field-	A		
Border	50.97	171.72	264.18	65.00	35.00
Basin	29.07	113.08	150.78	75.00	25.00
Furrow	30.58	56.07	72.11	77.75	22.25
Sprinkler	3.99	31.20	36.57	85.33	14.67
Drip	10.99	91.31	105.89	86.23	13.77
		Field-	В		
Border	66.07	154.55	241.49	64.00	36.00
Basin	31.43	109.96	149.95	73.33	26.67
Furrow	61.35	107.66	135.84	79.25	20.75
Sprinkler	5.00	52.64	60.28	87.33	12.67
Drip	7.99	71.76	81.45	88.11	11.89
		Field-	С		
Border	72.68	153.01	242.07	63.21	36.79
Basin	32.28	58.40	77.18	75.67	24.33
Furrow	57.58	133.99	164.99	81.21	18.79
Sprinkler	3.99	18.80	22.18	84.74	15.26
Drip	10.99	97.60	114.72	85.08	14.92
		Field-	D		
Border	35.40	124.02	183.59	67.55	32.45
Basin	36.62	117.26	154.09	76.10	23.90
Furrow	44.36	131.38	166.68	78.82	21.18
Sprinkler	3.99	20.87	24.78	84.24	15.76
Drip	7.99	36.42	41.54	87.67	12.33

3.7 Comparison between Estimated **Application Losses through Questionnaire and Practically** Measured Losses

For comparison purposes, the overall means of application losses by averaging the categorized values of questionnaire (coarse, medium and fine soil type wise) and all fields values (A, B, C, and D) were computed. The results are depicted in Table 11 which is self-explanatory and shows that more or less losses estimated through questionnaire compared favorably with the measured losses as the mean values for each tested method are in close match with each other. The practically measured losses strengthen the accuracy of estimated losses and also indicate that the assumption regarding depth of application and applicability of required depth obtained from research departments have met. It is noteworthy here that experiment for wild flooding was not carried out hence, no mean value is reported. It is also pertinent to mention here that the pressurized systems evaluated in this study were 2 to 3 years old since the very old system do not perform efficiently as reported by Wolf et al²³. Overall application losses were calculated using equation 5 for the study area as 23%.

Table 11. Overall means of application losses by irrigation method (questionnaire and experiment)

Method	Questionnaire	Experiment
Wild Flooding	44.67	
Border	33.05	35.06
Basin	28.17	24.98
Furrow	21.09	20.74
Sprinkler	14.18	14.59
Drip	12.00	13.23
Overall losses compute by equation (5)	23 %	

3.8 Comparison of Results with Previous **Studies**

National and international literature available pertain to application efficiency is either reported as a single method or comparison of some methods according to study site conditions. Particularly in Pakistan, limited literature is available with regard to field water losses measurement and its effect. However, most of the literature revealed that the researcher use assumed losses even of different regions considering some similar characteristics. Because water application losses measurement is labor intensive and expensive activity for individual irrigation events and fields. Some relevant literature is reproduced and discussed subsequently. Sandoval-Solis et al.5 estimated application efficiency for crops grown in hydrological regions of California State considering irrigation methods and stated that application losses depends on irrigation method and not on the type of crop. On the contrary, Oster et al.²⁴ study showed that the crop type effect greatly application losses than other factors. But, in the current study, variation in losses for different crops under same irrigation method was not significant (Tables 5-7).

The reason being of crop type not effecting the losses in the area is likely farmer's practice of the study area, they reported while interviewing and practically observed during experiment that the irrigation water is applied considering soil texture and crop period and not taking into account the soil characteristics that how much will it hold and actual crop demand that how much water crop require. The study area farmer's perception was, the more water the more production. A study was conducted by Khalic¹¹ the then chief engineer of Water and Power Development Authority(WAPDA), all over Pakistan including study area to assess irrigation losses. The application losses in the study were reported for three soil texture categories namely coarse, medium and fine in the range of 36 to 52 %, while losses determined in the current study have reduced by almost 10% in the study area since the modern farm machinery for preparing the land and carrying out other farms operation was not available at that time which helped to increase application efficiency. Besides that beneficially used water (ET_c) was not considered in the calculations by Khalic¹¹. The same study showed the same trend as in the current study with regard to soil type effect on losses i.e. losses reported in the report varied with change in soil type by 5 to 6 %. Despite this fact that the losses have reduced, still huge quantity is wasted through injudicious and excess application of water on the fields as manifested from the results. Similarly, Awan and Ali25 determined losses at farmer's fields and reported losses up to 66%.

Waheed-u-Zaman et al.26 evaluated application efficiencies under furrow, border, sprinkler and drip irrigation methods in the Punjab province of Pakistan and reported 34 to 42% and 27 to 34% losses when experimental areas were irrigated by border and furrow irrigation methods respectively. Sprinkler irrigation method had 16 to 22 % losses. Under Drip irrigation method 13 to 7% losses were computed by Waheed-u-Zaman et al.26 The results of the present study compared well with that of Waheed-u-Zaman et al²⁶. Kumari et al.²⁷ stated that the drip irrigation method is highly efficient in saving water. Iqbal et al.7 determined basin method efficiency to test volume base and hydrodynamic models and reported that the basin irrigation system can attain about 72% efficiency by losing 28% water as losses which is also evident from the present study results for basin irrigation method (Table 11). Tariq and Usman²⁸ conducted a research study on Maize crop scheduling in Pakistan, he irrigated the crop by border irrigation method and also evaluated the application efficiency. In his study apart from maize scheduling he concluded that the application efficiency for the border method can be achieved up to 80%. Wolters and Berisavljevic²⁹ stated that application losses are a function of soil type and irrigation methods. Some average application losses (Losses = 1-AE) were calculated from attainable application efficiencies ranges available in literature and compared with the results of the present study in tabular form shown in Table 12. The application efficiency values used in computing means were adopted from the Sandoval-Solis et al.5; Canessa et al.30, Tanji and Hanson³¹, Morris and Lynne³², Roger et al.³³, Howell²; Hanson et al.34 and Irmak et al10. From the table, it can

Table 12. Comparison between literature and present study application losses (%)

Method	Means				
Metnoa	Literature	Present Study			
Wild Flooding	32.00	44.67			
Border	27.00	33.05			
Basin	27.00	28.17			
Furrow	21.00	21.09			
Sprinkler	17.00	14.18			
Drip	14.00	12.00			

be seen that except wild flooding and border irrigation method, the losses values determined for the study area are in agreement with the mean values available in the literature.

4. Conclusion

A study to test the applicability of survey studies in estimating losses occurred at irrigation fields was conducted with the assumption that the farmers are well aware of their irrigation practices. The sampling was done to select respondents at random from head, middle and tail reaches of the main canal. The database pertain to irrigation methods used and cropping pattern of the area was also prepared. The effect of different crops and irrigation methods taking into account the soil types was assessed. Losses estimated through survey information were compared against practically measured losses and literature values. The assumptions made as the conduct of the survey were observed to be met.

Based on the survey results, surface and pressurized irrigation methods in use account for 91 and 9% of the area respectively. The cropping pattern of study area comprised 11 crops mainly wheat, cotton, and sugarcane. Among the surface irrigation methods used in the study region, the furrow was found to be dominated, followed by the basin and the border irrigation methods. The buried drip irrigation method is used on a larger area than the sprinkler mainly for the orchard. On the whole, surface irrigation methods are extensively used by the farmers in the study area as compared to pressurized irrigation methods. Amongst sample respondents, no one uses subsurface irrigation method.

The irrigation methods and soil types influenced the losses significantly while crop type was not affecting the losses in the study region. Under the furrow irrigation method, losses were about 10 % less as compared to other surface irrigation methods. Drip performance was found to be better with 2 to 3% more efficiency than the sprinkler method. Overall performance of pressurized irrigation methods with measured and estimated losses less than 20 % in all cases was better than the surface irrigation methods which are contributing to field losses in the range of 20 to 40%. Comparison of current losses in the area with that of 30 years ago show that the overall application efficiency in the study region has enhanced by almost 10%. The overall losses for the study area was computed as 23%. It is inferred on the basis on study results that the lack of knowledge of their target depth provokes farmers to use excess water than demands. However, farmers were observed to know the depths they apply/pond over their lands which was one of the assumptions of the present study. This study presents a novel idea to estimate water application losses using applied and required irrigation depths. Knowing the farmer practices of a particular region, the irrigation survey method evolved in this study can be applied for field losses estimation.

5. Acknowledgements

The authors are highly indebted to the Farmer Organization Chairmen with regard to distribution of questionnaire. We also would like to thank to the farmer community for providing pertinent information, particularly to those farmers who allow carrying out field experiments on their lands. Cooperation extended by Sindh Agriculture University Tandojam staff is highly appreciated.

6. References

- 1. Jensen ME. Beyond irrigation efficiency. Irrigation Sci. 2007; 25:233-45.
- 2. Howell TA. Irrigation efficiency. Encyclopedia of water science. New York: Marcel Dekker; 2003. p. 467-72.
- 3. Tanji KK, Kielen NC. Agricultural drainage water management in arid and semi-arid areas. Food and Agriculture Organization of the United Nations. Irrig and Drain Paper
- 4. Burt CM, Clemmens AJ, Strelkoff TS, Solomon KH, Bliesner RD, Hardy LA, Howell TA, Eisenhauer DE. Irrigation performance measures: efficiency and uniformity. J Irrig Drain E-ASCE. 1997; 123:423-42.
- 5. Sandoval-Solis S, Orang M, Richard LS, Steve Orloff, Williams KE, Jenna M. Rodriguez MS. Spatial analysis of application efficiencies in irrigation for the state of

- California, University of California, Davis, Research report. 2013. Available from: http://watermanagement.ucdavis.edu/ e-library/
- 6. Bos MG, Nugteren J. On irrigation efficiencies. 4th ed. Wageningen: International Institute for Land Reclamation and Improvement; 1990. p. 19.
- 7. Iqbal M, Khaliq A, Choudhry MR. Comparison of volume balance and hydrodynamic models for level basin irrigation systems. Pakistan J Agric Sci. 1994; 31:37-40.
- 8. Walker WR. Guidelines for designing and evaluating surface irrigation systems. Food and Agriculture Organization of the United Nations, Rome, Italy; 1989.
- 9. Israelsen OW, Criddle WD, Fuhriman DK, Hansen VE. Water-application Efficiencies in Irrigation Bulletin No. 311; 1944.
- 10. Irmak S, Odhiambo LO, Kranz WL, Eisenhauer DE. Irrigation efficiency and uniformity, and crop water use efficiency. Agriculture and Natural Resources, University of Nebraska, Lincoln and U.S. Department of Agriculture. Lincoln, NE; 2011.
- 11. Khalic IA. Irrigation system in Pakistan, measures to improve. Irrigation efficiency at the farm level. Pakistan engineering congress, Proceedings of 57th annual session paper.No. 445, Lahore, Pakistan; 1980.
- 12. Pakistan Bureau of Statistics. Agricultural statistics of Pakistan: agriculture statistics tables; 2013. Available from: http://www.pbs.gov.pk/agri-stat-tables
- 13. Akram AA. Is a surface-water market physically feasible in Pakistan's Indus Basin Irrigation System? Water Int. 2013; 38:552-70. DOI:10.1080/02508060.2013.832099
- 14. Ringler C, Anwar A. Water for food security: challenges for Pakistan. Water International. 2013; 38:505-14. DOI:10.10 80/02508060.2013.832122
- 15. Orang MN, Scott Matyac J, Snyder RL. Survey of irrigation methods in California in 2001. J Irrig Drain E-ASCE. 2008; 134:96-100.
- 16. Rea LM, Parker RA. Designing and conducting survey research: A comprehensive guide. John Wiley and Sons; 2012.
- 17. NSWAD. Introduction to irrigation management: Evaluating your surface irrigation system. A training manual. 2002; Available from: http://www.dpi.nsw.gov.au/_data/assets/ pdf_file/0006/176694/surface-irrigation-notes.pdf18.Anyoji H, Wu IP. Normal distribution water application for drip irrigation schedules. Trans. of the ASAE. 1994; 37:159-64.
- 19. Soccol OJ, Ullmann MN, Frizzone JA. Performance analysis of a trickle irrigation subunit installed in an apple orchard. Brazilian Archives of Biology and Technology. 2002; 4:525-30.
- 20. Laghari KQ, Lashari BK, Memon HM. Perceptive research on wheat evapotranspiration in Pakistan. Irrig and Drain. 2008; 57:571-84.

- 21. Dela BF. Measurement of soil moisture using gypsum blocks. By og Byg; 2001.
- 22. Skogerboe GV, Hyatt ML, Anderson RK, Eggleston KO. Design and calibration of submerged open channel flow measurement structures. Part 3, Cutthroat flumes. In: Report WG31-4, Utah Water Research Laboratory, College of Engineering, Utah State University, Logan, Utah; 1967.
- 23. Wolf G, Gleason JE, Hagan RE. Conversion to drip irrigation: Water savings, facts or fallacy, lessons from the Jordan Valley. Proceedings of the 1995 Water Management Seminar, Irrigation Conservation Opportunities and Limitations US Committee on Irrigation and Drainage, Sacramento, CA. 5-7 Oct 1995.
- 24. Oster JD, Meyer JL, Hermsmeier L, Kaddah M. Field studies of irrigation efficiency in the Imperial valley. Hilgardia-California Agricultural Experiment Station (USA). 1986; 54:1–15.
- 25. Awan QA, Ali A. Irrigation efficiencies in the farm irrigation system: Water as a constraint. University of Agriculture Faisalabad; 1988.
- 26. Waheed-u-Zaman, Arshad M, Rana A, Sabir MS. Water saving and crop yield potential of modern irrigation methods in semi-arid area. Pakistan J Agric Sci. 2000; 37:181-82.
- 27. Kumari R, Kaushal A, Singh KG. Water use efficiency of drip fertigated sweet pepper under the influence of different kinds and levels of fertilizers. Indian Journal of Science and Technology. 2014; 7(10):1538-43.
- 28. Tariq J, Usman K. Regulated deficit irrigation scheduling of maize crop. Sarhad J Agric. 2009; 25:441-47.
- 29. Wolters W, Berisavljevic GK. Patterns and trends in field application efficiency. Int'l Commission on Irrig and Drain Bull. 1991; 40:11-26.
- 30. Canessa P, Green S, Zoldoske D. Agricultural water use in California: A 2011 Update. In: Norum K, editor. Center for Irrigation Technology, California State University, Fresno; Fresno. CA; 2011.
- 31. Tanji KK, Hanson BR. Drainage and return flows in relation to irrigation management irrigation of agricultural crops. In: Stewart BA, Nielsen DN, editors. Agronomy Monograph No. 30. American Soci Agro, Madison, WI; 1990.
- 32. Morris M, Lynne V. Measuring and conserving irrigation water. National Center for Appropriate Technology. Butte, MT; 2006.
- 33. Rogers DH, Lamm FR, Alam M, Trooien TP, Clark GA, Barnes PL et al. Efficiencies and water losses of irrigation systems. Irrigation Management Series, Research and Extension Engineers, Kansas State University; 1997.
- 34. Hanson B, Schwankl L, Fulton A. Scheduling irrigations: when and how much water to apply. Publication 3396. Division of Agriculture and Natural Resources, University of California, Davis; 1999.