IRRIGATION EFFICIENCIES POTENTIAL UNDER SURFACE IRRIGATED FARMS IN PAKISTAN

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ABSTRACT

The conventional surface irrigation systems, border, level basin and furrow bed, are inherently inefficient in Pakistan, while the suboptimal field sizes (length and width) are considered as one of the main reasons of poor performance. Addressing these issues, the three surface irrigation systems were evaluated on thirteen fields under routine farmer management in Pakistan. Irrigation performance including application efficiency (AE), Potential Application Efficiency (PAE), Adequacy (AD) and distribution uniformity (DU), of 17 irrigation events were evaluated and further potential for improvement by optimising field sizes were identified using surface irrigation evaluation Model WinSRFR 4.1.3.

The study revealed poor irrigation efficiencies, AElq (41% to 82%), PAEmin (43% to 95%), ADlq (1.16 to 2.29) and DUlq (80% to 99%), on farms. The average AElq on farm was in the order of; level basin (58%) < border (65%) <furrow bed (68%). Simulation modelling indicated that there is further potential to increase average PAE up-to 94%, 87% and 96% for level basin, border and furrow bed irrigated fields respectively, by optimising field length and width. The analysis demonstrated increased understanding of the interactions of field sizes and irrigation efficiencies, which may support irrigators' decision making for enhancing irrigation performance at no significant cost to infrastructure, machinery or labour.

KEYWORDS: *Application efficiency; Adequacy; distribution uniformity; border; level basin; furrow bed*

INTRODUCTION

Agricultural production in Pakistan is heavily dependent on irrigation water, evidenced by the greater (>90%) share of irrigated lands in the total agricultural production of the country. It is worth mentioning that irrigated lands are around 80% of total cultivated lands in Pakistan. Thus the share of remaining 20% rain-fed cultivated lands is only 10% in total crop production[1]. Consequently, the 20-25% of annual GDP, 70% of export revenues, and 67% of the rural population[2], which depends on agriculture, rely on irrigation water. Importantly, additional 20 million acres land (50% of current cultivated land) has the potential to be brought under irrigated agriculture[3]. However, lack of water is the main impediment in bringing more cultivable lands under profitable production.

The irrigation water is currently facing several challenges, including climate change induced risks[4], population growth and increasing demand of various competing sectors. Notwithstanding all these challenges, we lose more than two third of our available water resources due to poor management. For instance, there is around 25-40%[5] water losses during irrigation application, which not only tends to exacerbate the waterlogging and salinity issues but has also significantly reduced the water productivity of major crops compared with the world average[6] in general and neighbouring countries in particular. Excessive deep drainage losses inherent to the conventional flooding or level basin irrigation system[7] is one of the main reasons of low water productivity. Adoption of border and furrow irrigation systems, relatively efficient irrigation methods, are low on Pakistani farms. Although furrow irrigation is practiced for few row crops and vegetables in Pakistan but their current management[8,9] have caused irrigation efficiencies down to 50%[10] on farms. Saving water losses on farms is not only essential for increasing crop water productivity, but it can also contribute in expanding the current irrigated lands. Therefore, irrigation performance of the conventional surface irrigation systems needs improvement.

There may be several causes but the suboptimal irrigation and field management are considered as one of the major reasons of poor irrigation efficiencies on Pakistani farms[7,10]. The irrigation water, generally sourced from snowmelt-fed perennial river flow, underground

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water resources or rainfall runoff, are available on farms of variable field sizes and in different inflow rates and irrigation periods. But there is lack of knowledge for efficiently fulfilling crop water demands on farms, which reduces the irrigation efficiencies of conventional surface irrigation systems[11-13]. Therefore, this study evaluated irrigation efficiencies of different surface irrigation systems on farms and identified strategies for their improvement using simulation modelling.

MATERIAL AND METHODS

This study comprised of field evaluation and analysis of irrigation efficiencies of farmer managed irrigation applications on farms. The experimental sites descriptions are as under:

Sites Description

The data collection was carried out on two locations including; (1) National Agricultural Research Centre (NARC) Islamabad farm and (2) District Mardan in Khyber Pakhtunkhwa (KPK) province. The distance between the two selected locations is around 150 km. The data collected on both locations were under actual farmers managed condition. The two location selected covered both dry land farming and irrigated agriculture. The general field conditions at both experimental sites are given below:

National Agricultural Research Centre Farm Islamabad

The National Agricultural Research Centre (NARC) farm is located at Chak Shahzad, Islamabad and is comprised of around 1400 acres of land with around 200 acres irrigated either from Rawal dam or ground water resources through tube wells. The soil type is medium textured with around six sub classes. Fodder, maize, wheat, oat and oil seed crops, vegetables and orchards are mainly grown at the farm. The farm has two water storage dams where canal water from Rawal dam or runoff from heavy rains is harvested. Majority of fields are under border or level basin irrigation systems during winter while few crops like canola, sunflower and maize are grown on furrow beds during summer season. Irrigation applications to oat, maize and sunflower crops were recorded on seven fields (with two level basins, two borders, and three furrow bed irrigation systems) at NARC farm.

District Mardan KPK Province

Mardan is one of the productive districts of KPK Province, situated in the north-west of Pakistan. It lies in the semi-arid zone, where mean seasonal rainfall of 250 mm occurs in summer (April-September) and around 300 mm during winter (October-March). The mean maximum temperature ranges from 27-30°C during June, while the mean minimum temperature ranges from 5-8°C during January. The soil at all these sites was sandy clay loam, that belongs to the Mardan soil series, which was classified as fine Usteric Camborthid, a greyish brown, non to slightly calcareous alluvial material of the Holocene age[14]. The soil at these sites has negligible shrink and swell qualities. The subsurface tile drainage system installed in this locality did not allow the water table to rise and generally remains at 350 to 500 cm depth. Irrigation application data was collected on six furrow bed farms with maize and tobacco crops during the summer (Kharif) season of 2014.

Field Topography and Configurations

Topographic survey of all fields was conducted prior to irrigation for determining the field slopes using levelling equipment, staff-rod and measuring tape of 100 m length. The field length and width were also recorded prior to irrigation. For furrow bed fields additional data including furrow top width, middle width, bottom width, furrow depth and furrow spacing readings were also measured at each furrow head, middle and tail sections.

Soil Moisture and Irrigation Measurement

The irrigation depth was calculated as the soil moisture deficit (SMD) in 0-60 cm root zone layer, prior to irrigation, by subtracting the existing volumetric soil moisture from field capacity moisture level, ~24% according to Shafiq and Hassan[14]. The soil moisture sampling of 60 cm root zone was conducted at 0-15 cm, 15-30 cm and 30-60 cm depth intervals using core sampler with ring size of 5cm x 5cm. These samples were collected from three locations covering field head, middle and tail sections. From furrow bed field the samples were collected from bed edge. Gravimetric method was used to calculate soil moisture and bulk density, which comprised oven drying of the soil samples for 48 hours at 105^0C. The gravimetric soil moisture was converted to volumetric soil moisture by multiplying with bulk density and depth of soil layer. The soil and water testing laboratory at Climate Change, Alternate Energy and Water Resources Institute (CAEWRI), NARC was used for soil moisture and bulk density evaluations.

The irrigation applications were closely monitored in all fields. The maximum inflow rate available at field inlet was delivered to the field, which was dependent on availability of water from tube well, canal or farm storage dam and the number of furrows irrigated simultaneously. The time to cut-off was based on farmer understanding to ensure wetting of the whole field and to avoid tail end overtopping. Irrigation data including inflow rate (*Q*), water advance time at multiple points along the field length and time to cut-off (*Tco*) were recorded during seventeen irrigation events (five on border, three on level basin and nine on furrow beds) on thirteen fields at NARC and Mardan KPK. The *Q* was measured using two methods including; time required for filling a bucket of known volume (125 litres) in case of tube wells and cut-throat flume water flow measurement in open channels. The water advance time to field middle and tail sections were recorded using stop watch. During each irrigation event the water advance data collection were replicated on six blocks of a border, level basin and furrow bed fields each.

Irrigation Efficiencies Evaluation

The following irrigation efficiencies were evaluated using simulation modelling as per definition given by Bautista et al.[15]

Application Efficiency (AE): It is the ratio of infiltrated depth contributing to irrigation target (Dz) to total irrigation depth applied (Dapp) or water received at the field inlet. When Dz is equal to minimum infiltration depth (Dmin) then it is called application efficiency of the minimum (AEmin) and when Dz is equal to low quarter infiltration depth (Dlq) then it is called application efficiency of the low quarter (AElq).

Potential Application Efficiency (PAE): Attainable *AE* when inflow rate and time to cut-off are such that *Dlq* = *Dreq* (required irrigation depth) then it is called potential application efficiency of the low quarter *(PAElq)* and when *Dmin* = *Dreq* then it is called potential application efficiency of the minimum (PAEmin).

Adequacy (AD): It is the ratio of Dlq to Dreq for adequacy based on low quarter (ADlq) and the ratio of Dmin to Dreq for adequacy based on minimum infiltration depth (Admin).

Distribution Uniformity (DU): It is the ratio of Dlq to Dinf (average depth of infiltrated water, infiltrated volume/area) for DUlq and the ratio of Dmin to Dinf for DUmin.

Simulation Modelling of Surface Irrigation Systems

The surface irrigation systems were evaluated using the WinSRFR 4.1.3[15]. The WinSRFR integrates tools for irrigation system evaluation, irrigation system design and operational analysis. The WinSRFR model has been extensively used[16-20] for evaluation and optimization of surface irrigation performance throughout the world. The WinSRFR is coded into four colours worlds[21] with the names Event Analysis World (Irrigation event analysis and parameter estimation functions), Physical Design World (Design functions for optimizing the physical layout of a field), Operations Analysis World (Operations functions for optimizing irrigations) and Simulation World (simulation functions for testing and sensitivity analysis).

Field irrigation data and infrastructure details were entered into the model using the Event Analysis World for model as described by *Bautista et al.*[22]. The model calibration was based on a fair compatibility of the observed advance and recession curves with the simulated ones. The soil infiltration functions i.e. a, b, c and k parameters of the *Philp*[23] equation were determined using the calibrated model for each irrigation event. The average calibrated infiltration functions of modified Kostiakov-Lewis infiltration equation are given in Table 1.

In the later stage, the calibrated infiltration functions were used for optimizing and developing different design alternatives using the Design World of the model. In the optimization stage, the model was set to develop performance contours as a function of length and border width for a given inflow rate. The performance contours

Table 1. Manning roughness coefficient n and infiltration functions a, b and k

Treatment	n	a	b	k
Border	0.06 (0.02)*	0.44 (0.05)	6.87 (0.65)	82.02 (29)
Level Basin	0.04 (0.01)	0.45 (0.02)	5.08 (0.51)	127.07 (25)
Furrow Bed	0.12 (0.09)	0.44 (0.01)	5.30 (1.09)	96.54(26)

Values in parenthesis are standard deviations

were used for identifying impact of three strategies; 1) optimizing field length only, 2) optimizing field width only and 3) optimizing field length and width together simultaneously, as compared to current farmer practice.

Sample Calculations using WinSRFR

Border Irrigation Event: In the event analysis world basin/border was selected, required depth (40mm) was entered while Meriam and killer post irrigation volume balance analysis was selected. In the system geometry field length L (122m), width W (3.41m), maximum depth Y (300mm) and field slope S_0 (0.001771) was entered. Roughness method based on Manning's n (0.1) was selected. In the inflow/runoff tab inflow rate Q (21.5 l/s), cut-off time (0.51 hrs) with no cut-back and blocked end was selected. In the field measurement tab the advance table was filled by entering 0.36 and 0.7 hrs advance time next to field middle and tail ends, respectively. In the recession table 0.7, 1.27 and 1.8 hrs were entered next to field head, middle and tail reaches, respectively. The opportunity time table was calculated automatically by the model based on entered data. In the execution tab the infiltration function was selected using the modified kostiakov k (95.56 mm/hr^a) estimated for user entered a (0.44), b (6 mm/hr) & c (0) while using zero inertia model and then execution was performed by clicking the verify and summarize button. The results tab presented the performance summary and parameters & goodness of fit. The application efficiency, *DU* minimum and *DU* low quarter were identified as 41%, 0.89 and 0.95 respectively in the results outputs.

RESULTS

Field Topography and Configurations

The measured field configuration and slopes details are given in Table 2. Results showed that the level basin and furrow bed fields were shorter in length and wider than the border irrigation fields. Similarly, the slopes of level basin and furrow bed irrigation system fields were flatter than the border irrigation fields. Majority of beds were narrow (65-76cm furrow spacing) and a single row of crop was planted in the middle of the bed. However, only one field at Mardan KPK was on wide beds (100 cm furrow spacing) and crop was sown on bed edges at ~ 60 cm row to row spacing.

Table 2. Average configurations of surface irrigated fields

Irrigation systems Fields	Field/ furrow length (m)	Field width (m)	Furrow bed configurations (cm)					Field/ furrow slope (m/m)
			Top width	Middle width	Bottom width	Furrow Depth	Bed width	
Border	122	4.53	--	--	--	--	--	0.003
	(1)*	(0.7)						(0.0029)
Level basin	112	9.0	--	--	--	--	--	0.00145
	(3)	(0.8)						(0.000714)
Furrow bed	50	9.4	44	32	20	16	75	0.00181
	(20)	(2.5)	(4)	(3)	(2)	(2)	(11)	(0.00019)

*Values in brackets show standard deviation (SD)

Soil Moisture and Irrigations Application

The bulk density of 60 cm layer for border and level basin fields were comparable but around 10% higher than level basin fields (Table 3). Irrigation scheduling was according to farmer's preference with no specific criteria, thus showed variable *SMD* before irrigation that ranged 36 mm to 50 mm for border, 75 mm to 79 mm for level basin and 41 mm to 75 mm for furrow bed irrigation systems.

Different key irrigation management parameters measured are summarised in Table 3. The results showed excessive irrigation application of 49% to furrow bed, 63% to border and 79% to furrow bed fields. The excess irrigation applications were lost as deep drainage because all fields were blocked at the tail ends and there was no tail drain runoff.

Table 3. Average bulk density (BD) and soil moisture deficit (SMD) of 0- 60cm root zone layer and irrigation applications with Q = inflow rate, Tco = time to cut-off and ID = irrigation depth for different surface irrigation systems fields

Irrigation System Fields	BD (gm/cm^3)	SMD (mm)	Q (l/s)	Tco (minutes)	ID (mm)
Border	1.51 (0.07)*	43 (5)	31.40 (10)	22.40 (6)	70.00 (9)
Level basin	1.52 (0.09)	77 (3)	23.55 (1)	97.50 (13)	137.50 (30)
Furrow Bed	1.36 (0.12)	57 (12)	01.92 (1)	27.70 (10)	85.1 0(15)

*Values in brackets show standard deviation (SD)

Water Advance Rate

Water advance rate in different fields were variable depending on irrigation method, inflow rate, field length and soil conditions (Figure 1). According to field observations, irrigation inflow to field was cut-off when the water advance crossed more than 80% of the field length before reaching the tail end in level basin and border irrigation fields. However, in furrow bed fields, due to quicker advance time, irrigation cut-off times exceeded the water advance time to furrow tail end. The reason for longer time to cut-off according to farmer was to ensure wetting of bed middle. Other factors also affected water advance along furrow including field slope, cultivation method, weeds infestation and number of furrows irrigated simultaneously.

Irrigation Efficiencies

The AElq ranged 41% to 82% for border, 42% to 71% for level basin and 60% to 73% for furrow bed irrigation systems (Table 4). The PAEmin ranged 48% to 90% for border, 43% to 73% for level basin and 60% to 95% for furrow bed irrigation system. Average potential application efficiency of the low quarter were 74%, 58% and 73% for border, level basin and furrow bed respectively. Excessive irrigations were applied compared to SMD thus ADlq ranged 1.16 to 2.29 for border, 1.26 to 2.14 for level basin and 1.18 to 1.65 for furrow bed. The average *DUlq* ranged 86% to 100% for border irrigation, 88% to 93% for level basin and 80% to 99% for furrow bed irrigation systems. The *ADlq* > 1 for all measured irrigation events indicated that the applied irrigation fulfilled 100% of the crop water demand. However, this was achieved with significant deep drainage loss that ranged 79% in level basin, 63% in border and 49% in furrow bed irrigation systems. The deep drainage losses identified for different irrigation systems were in the order of level basin > border > furrow bed irrigation systems.

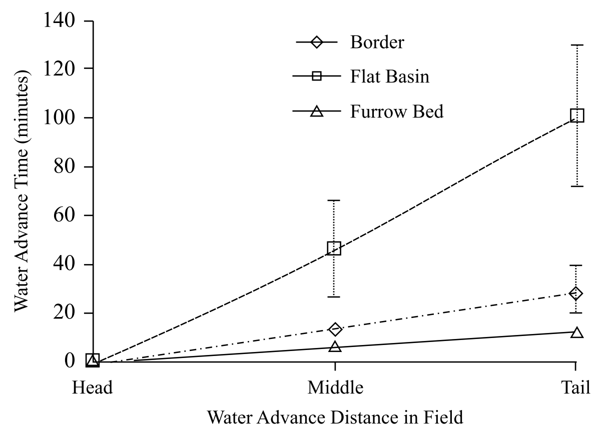

Figure 1. Average water advance time along field length under three different irrigation systems (Vertical bars show SD)

Table 4. Average irrigation efficiencies with AElq = application efficiency of low quarter, PAElq Potential Application Efficiency of low quarter, ADlq = Adequacy of low quarter and DUlq = Distribution Uniformity of low quarter under different surface irrigated fields

Irrigation Systems	AElq (%)	PAElq (%)	ADlq	DUlq (%)
Border	65 (11)	74 (13)	1.518 (0.3)	95 (3)
Level basin	58 (10)	58 (10)	1.617 (0.3)	90 (3)
Furrow bed	68 (4)	73 (9)	1.401 (0.1)	94 (5)

(Values in brackets show standard deviation SD)

Potential for Improving on Farm Irrigation Efficiencies

In majority of the cases fields were over irrigated, thus the water was lost as deep drainage, because the fields were blocked at tail end and no tail drain runoff system was installed. Therefore, irrigation field design optimisation using simulation modelling indicated significant improvement. When three strategies including; 1) optimising field length alone and 2) optimising field width alone and 3) optimizing field length and width together were applied using WinSRFR, the results (Table 5) illustrated potential for further improvement in irrigation efficiencies. The results clearly indicated that there is further potential for increasing the *PAElq* by reducing field length and width.

Histograms showing the distribution of *PAElq* for farmer managed irrigation and for strategy 3 are presented in in Figure 2 and Figure 3 respectively.

DISCUSSION

Surface Irrigation Systems Efficiencies on Farm

The existing irrigation efficiencies on farm under actual field conditions are poor. Majority of irrigation events are over-irrigated, as shown in the current study with *ADlq* values above 1 in majority of cases. The excess irrigation applications were lost as deep drainage because all the fields were not equipped with tail drainage system. The reduced irrigation performance under actual farm conditions in this study closely conform to the findings reported by *Kalwij*[7] and *Akbar et al*.[10]. The greater *ADlq* than unity in majority of measured irrigation events indicated that the *SMD* was met throughout the field. However, the lower *AElq* indicates that the existing variable *SMD* was fulfilled with significant deep drainage losses. Thus, the irrigation was not optimally managed for the variable field conditions and to meet the *SMDs*. There were clear differences in irrigation efficiencies (*PAElq* and *DUlq*) among all the three irrigation systems evaluated on farms.

Table 5. Potential for improving potential application efficiency of low quarter (PAElq) under three irrigation systems using two strategies; 1) optimizing field length (L), 2) optimizing field width (W) and 3) optimizing both length and width compared with existing Farmer Practice (FP)

Irrigation Systems	FP	Strategy 1	Strategy 2	Strategy 3
Border	74(122, 4.7)#	85(54, 4.7)	82(122, 3.2)	87(79, 5.2)
Level basin	58(110, 9.1)	90(40, 9.1)	87(110, 3.2)	94(34, 9.6)
Furrow Bed	73(28, 29.6)	92(11, 29.6)	93(28, 7.7)	96(19,8.5)

Values in parenthesis are (L, W in meters)

Field Size and Irrigation Efficiencies Interactions

The field length and width largely influenced the irrigation efficiencies of all the three surface irrigation systems. This study has confirmed that the irrigation efficiencies of small farms under level basin, border and furrow bed systems is very sensitive to the field management factors. Field length and width are the key elements in irrigation management as indicated by many authors[24-26]. When the field length and width were optimised using WinSRFR model, further improvement

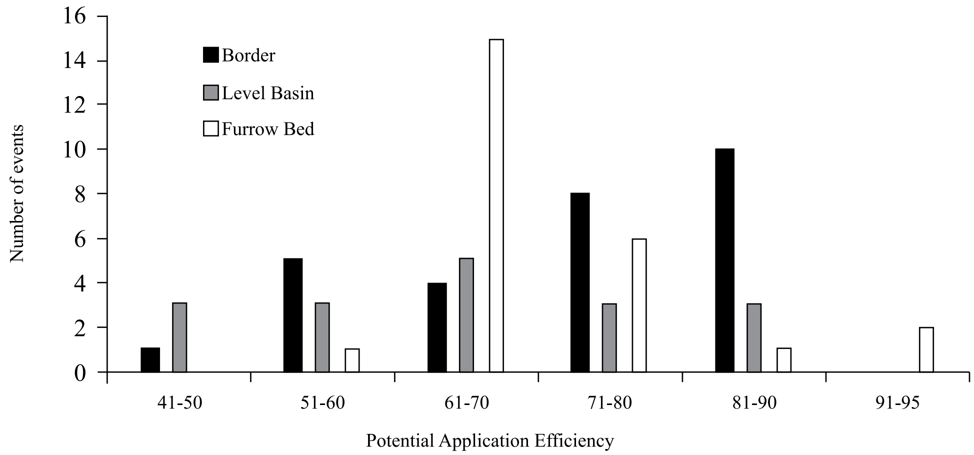

Figure 2. Distribution of Potential Application Efficiency of low quarter (PAElq) for farmer managed irrigations under three irrigation systems

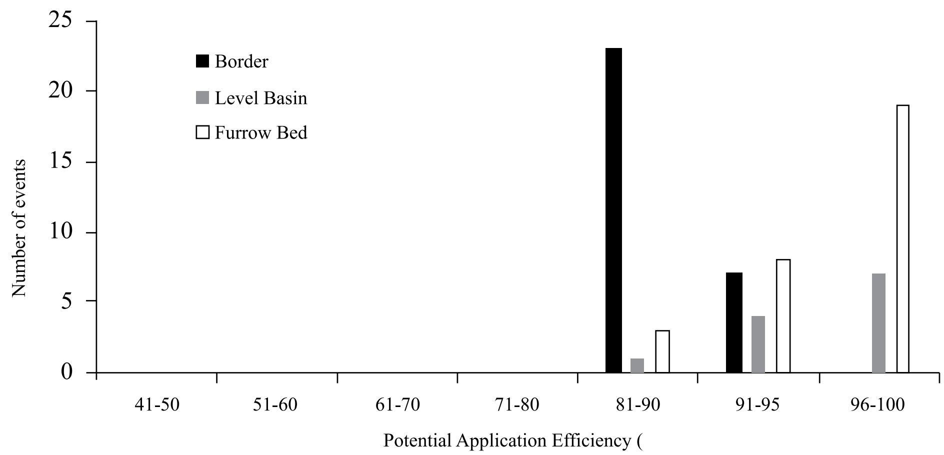

Figure 3. Distribution of Potential Application Efficiency of low quarter (PAElq) for strategy 3 under three irrigation systems

in irrigation efficiencies were explored.

The three strategies of optimizing 1) field length alone and 2) field width alone and 3) field length and width together using WinSRFR, demonstrated that there is further potential for increasing the irrigation efficiencies on surface irrigated farms in Pakistan. Therefore, irrigation performance can be improved by optimizing the existing field sizes for the available inflow rate and cut-off time, evidenced by maximum achievable potential application efficiency of 97% for furrow bed followed by 94% for level basin and 87% for border irrigation systems when strategy 3 was applied. Similarly, if field sizes are difficult to change then irrigation performance improvement is also possible by optimizing inflow rate and time to cut-off as reported by *Akbar et al.*[10] and *Gillies et al.*[27] . The improved irrigation performance can be instrumental in saving the limited available water at NARC farm and district Mardan, especially during the summer season when demand for water is on peak. Interestingly majority of these improvements can be achieved without significant increase in machinery, labour and infrastructure cost.

CONCLUSIONS

- The existing irrigation application efficiencies of surface irrigated fields at NARC farm and Mardan district of KPK are poor and are in the order of level basin (AElq = 58%) < border (AElq = 65%) < furrow bed (AElq = 68%).

- Majority of irrigation applications on farms are in excess of 49%, 63% and 79% of crop water demand under flat basin, border and level basin respectively, thus leading to greater deep drainage losses.

- Simulation modelling using WinSRFR 4.1.3 indicated potential of achieving irrigation potential application efficiency up-to 87%, 94% and 96% for border, level basin and furrow bed irrigated fields by optimising field length and width.

- Optimising field length and width together, if possible, is more beneficial in improving the potential application efficiencies, up to 3% and 7% increase in PAElq, than optimizing field length and width alone.

- The evaluation procedure, simulation modelling (WinSRFR) and analysis successfully quantified the soil infiltration and irrigation application, thus can be instrumental in improving understanding of field size and efficiencies interaction, which may lead to improved irrigation efficiencies at no significant cost to infrastructure, machinery or labour.

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