Research Article

Furrow Bed Irrigation System: Installation and Management

Ghani Akbar*, Muhammad Asif, Zafar Islam and Shahid Hameed

Climate, Energy and Water Research Institute (CEWRI), National Agricultural Research Centre (NARC), Park Road, Chak Shahzad, Islamabad.

Abstract | Furrow bed is the most efficient traditional surface irrigation method, but has been shown inefficient under actual farm condition in Pakistan. The main reasons being attributed to lack of knowledge of furrow bed design, installation and management. Therefore, this study is aimed to illustrate appropriate installation and management of furrow bed irrigation method for enhancing decision support on farms. Pakistan is a major irrigated agricultural country with more than 90% of crop production coming from irrigated areas. Irrigation water available at farm gates either from surface or groundwater resources are more precious, thus demands a more efficient use. However, unfortunately more than 50% of this water is lost due to poor irrigation management practices on farms. Flooding, flat basin and irregular and unlevelled border irrigation methods are the norms on majority of Pakistani farms, which is inherently inefficient. Sprinkler and drip irrigation are costly and require more technical knowledge, thus negligibly adopted and are generally considered as late time solutions. Although furrow bed irrigation, a relatively more efficient irrigation method, has been adopted, especially for row crops but decision support guidelines for their appropriate installation and management is very limited, thus potential benefits of furrow beds are yet to be achieved on Pakistani farms. Consequently, water productivity of major crops is below global average in general and neighbouring countries of Pakistan in particular. This study has illustrated some key guidelines for the appropriate installation and management of furrow bed irrigation method on farms, which may increase decision support and may lead to increased water productivity.

Received | April 18, 2018; **Accepted** | March 13, 2020; **Published** | June 23, 2020
***Correspondence** | Ghani Akbar, Climate, Energy and Water Research Institute (CEWRI), National Agricultural research Centre (NARC), Park Road, Chak Shahzad, Islamabad; **Email:** ghani_akbar@hotmail.com
Citation | Akbar, G., M. Asif, Z. Islam and S. Hameed. 2020. Furrow bed irrigation system: Installation and management. *Pakistan Journal of Agricultural Research,* 33(2): 406-413.
DOI | http://dx.doi.org/10.17582/journal.pjar/2020/33.2.406.413
Keywords | Raised beds, Water productivity, Irrigation efficiency, Soil management, Furrow irrigation

Introduction

Pakistan is a major irrigated agricultural country. The major portion of irrigation water in Pakistan comes from snow melt perennial river flows, underground water resources and seasonal rain water runoff (Ebrahim, 2020). All these water resources are negatively affected by frequent climate change perturbation, increasing demand for the competing sectors and their inefficient use, thus putting the country's economy at risk. To address these issues focus is needed to produce more with less water by increasing the existing crop water productivity on farms on sustainable basis. Crop water productivity (WP) is the grain yield or their economic value per unit of water used during the crop season. The existing crop water productivity of major crops in Pakistan are well below global average values (Zwart and Bastiaanssen, 2004). For instance, the current global average WP of maize, cotton and wheat crops are ~ 49%, 5% and 49% (Figure 1) larger than the average WP of Pakistan.

Links Researchers

Table 1: *Yield (ton/ha) gaps of major crops in Pakistan.*

Crop	Country	World Highest yield	Yield in research plots	Progressive farmer yield	National average	Yield gap from national average (%)		
						Progressive farmers	Research plots	World highest
Wheat	France	7.45	6.8	4.5	2.82	37	59	62
Cotton	China	3.98	4.3	2.89	1.87	35	56	53
Rice	USA	7.37	5.2	4.58	2.88	37	44	61
Maize	France	9.91	9.2	7.46	4.23	43	54	57
Sugarcane	Egypt	120	300	106.7	48.06	55	83	60

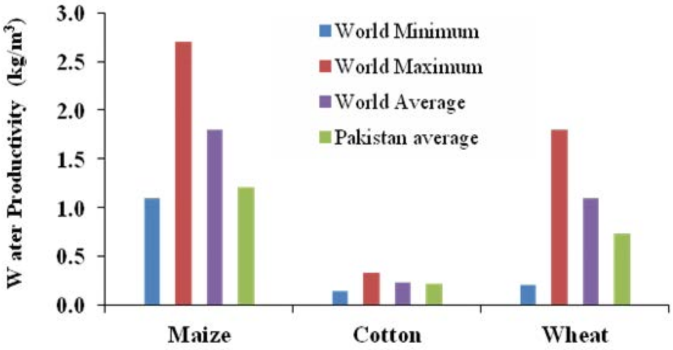

Figure 1: *Global water productivity comparisons with Pakistan (Zwart and Bastiaanssen, 2004).*

Similarly, the yield gaps of major crops ranges 35% to 83% (Aslam, 2016), when compared with world highest, progressive farmers and research results. The yield and yield gaps of different crops can be seen in Table 1.

One of the reasons for the low WP is the traditional flat basin irrigation system. Although, there are several options (sprinkler, trickle and furrow bed irrigation systems) for enhancing WP of crops in Pakistan but majority of these options may be late time solution due to their current cost, skills and adoption constraints, while the furrow bed system can provide immediate relief. Furrow bed irrigation system is one of the commonly used form of surface irrigation throughout the world and is generally considered a more water-efficient system compared with the flat basin and other traditional irrigation systems because of (i) the speed with which water is conveyed to the low end of a field (Gillies et al., 2008); and (ii) the relatively small proportion of the soil surface is in contact with the flowing water during irrigation than the basin (Walker, 1989). Furrow bed irrigation system has been shown effective in improving crop yield, reducing irrigation losses and enhancing water productivity.

Furrow beds have been shown effective in improving yield of wheat by 20%, cotton 19%, Maize 58%, rice 26% compared with flat basin or ridge irrigation systems (Gill et al., 2005; Ahmad et al., 2009). Crop yield per unit area increases by increasing the bed width. For instance, crop yield of maize showed up to 15% increase while wheat crop showed 26% increase on 180 cm bed size compared with flat basin (Akbar et al., 2009), which was the largest increase noted when compared with other bed sizes (Figure 2).

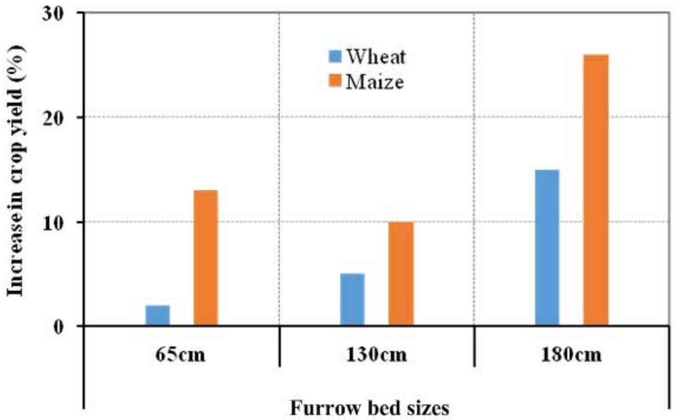

Figure 2: *Increase in crop yield on different bed sizes relative to flat basin.*

Efficient irrigation application is one of the major advantages in adopting furrow beds systems. Water saving up to 50% in wheat, 30% in maize, 40% in cotton, 29% in rice were reported by different researchers (Gill et al., 2005; Hassan et al., 2005; Ahmad et al., 2009; Akbar et al., 2017b). Increase in water saving by increasing bed width has been demonstrated in Figure 3 (Akbar et al., 2009), which shows 40% and 36% increase in water saving by adopting 180 cm bed size for maize and wheat crops respectively. However, lateral infiltration may negatively impact crop yield in the middle of bed if bed configurations are not properly designed according to site specific soil and cropping conditions.

Furrow bed increase crop yield and reduce irrigation application thus consequently the water productivity is increased. An increase in water productivity up to 70% in maize and up to 43% in wheat were reported by Hassan et al. (2005) and Akbar et al. (2010). Impact of bed width on water productivity is illustrated in Figure 4.

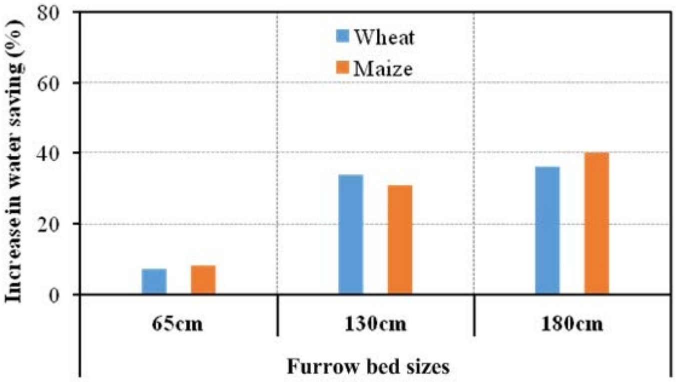

Figure 3: *Water saving in different bed sizes relative to flat basin.*

Furrow bed irrigation system has been widely adopted for row crops; maize, cotton, sugarcane, sugar beet, oil seed crops; sunflower and canola and majority of vegetables. Furrow beds adoption is limited for wheat crop due to machinery constraints. The cropping pattern of Pakistan indicating the potential for furrow bed irrigation system, as per above mentioned crops is shown in Figure 5.

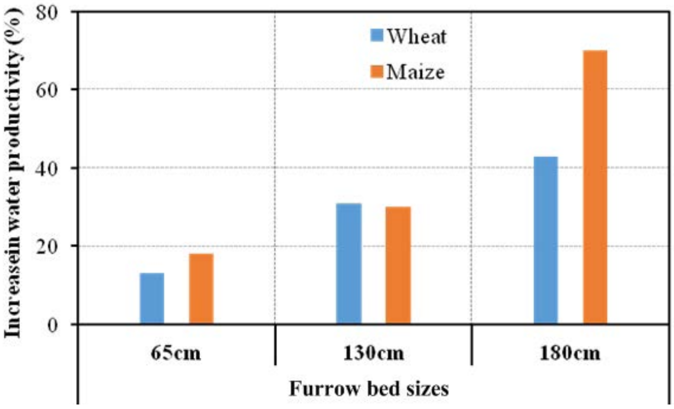

Figure 4: *Water productivity in different bed sizes relative to flat basin.*

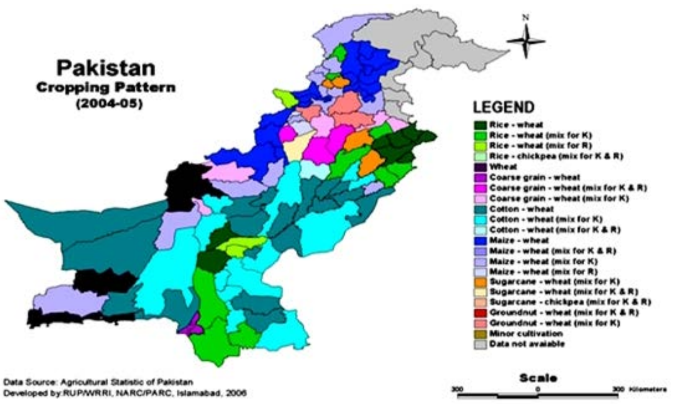

Figure 5: *Cropping pattern on Pakistan Map during 2004–05.*

Keeping in view the above constraints and limitations this study has been undertaken to formulate decision support system for the optimum design, installation and management of furrow bed under actual field conditions for improving water productivity on farm.

Materials and Methods

The study has been formulated by considering the key management practices that can be easily adopted by the farm managers at no significant cost to infrastructure or machinery. Majority of the recommendation are based on outcome of studies conducted in Pakistan. The furrow bed design and management details presented in the results and discussion section is based on field experience, literature review and outcome of multiple studies conducted in Pakistan.

Results and Discussion

The main principles and methods of improved installation and management of furrow beds has been presented in the following sections.

Design, layout and installation of furrow beds

Furrow bed management including; furrow bed design, installation, renovation, sowing, crop row spacing, irrigation, and planning for next crop can significantly influence on the overall performance of furrow bed irrigation system (Akbar et al., 2016a). Thus furrow beds needs careful installation and management depending on site specific conditions, as demonstrated by Wightman et al. (2005) for Australian soil conditions. An overview of the steps when establishing furrow bed systems under local Pakistani soil and farming conditions is provided in below section.

Initial field survey

The first step is to visually inspect the field and collect soil samples for hydro-physical, chemical and biological analysis in 0-60 cm depth, if possible. This will assist in any soil remediation measure and guidance for future use. Engineering survey should be conducted for identifying the slope and direction of water flow; Prepare a detailed contour map showing all features in and around the field, which will accurately show all field slopes and will identify low field spots, where water may lie in furrows and waterlog the beds and other objects like roads, creeks etc. Furrow bed system may be a viable option if the slope ranges from 0.2% to 1.5%. Knowledge of furrow discharge point and runoff outlet provision is important consideration in designing a furrow bed field.

Direction of beds

Preferably the furrow beds should run north-south to evenly capture the winter sun. The direction of furrow beds also depends on slope of the field, soil susceptibility to erosion, field length and farmer preferences according to his farm infrastructure. For better runoff harvesting and recharge in sloppy lands, the furrow beds should be perpendicular to the slope direction. A typical furrow bed farm is shown in Figure 6.

Distribution channel and collector drains

The distribution channel must be on the higher end of the field and the longitudinal slope must be kept to a minimum to ascertain uniform distribution of water among individual furrows. The size and length of the distribution channel depends on available inflow rate, command area of field, soil infiltration properties and slope. The inclusion of collector drain in plan is helpful in avoiding seasonal waterlogging and crop damage due to lodging. The collector drains must be on the lower end of the field and should pick water from all furrows and then should discharge the excess water to a drainage outlet. These drains must be designed to cope with heavy monsoonal rains. The size of the collector drains depends on draining area, seasonal weather condition of the area, water table depth, slope and soil infiltration properties. The collector drains should have a safe disposal point either a farm storage dam or drainage channel.

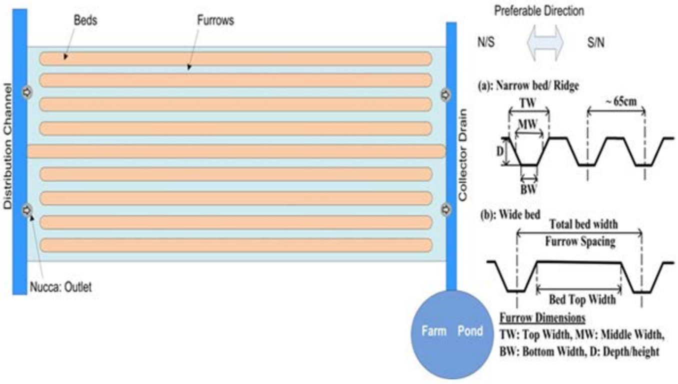

Figure 6: *Salient features of typical furrow bed field and furrow bed configurations.*

Field preparation

The field should be cleared from obstacles (rocks, tree trunks etc.) and should be sprayed with effective weedicide for breaking the life cycle of prominent weeds. The soil needs to be cultivated to a depth of 20cm to ensure 27cm loose soil depth before initial installation. Cultivation should be done when the soil is moderately moist not dry nor wet ideally at the Lower Plastic Limit[1] for ensuring best soil tilth and avoid compaction. The desired deeper cultivation in a single pass should be avoided and depth should be gained slowly. Clods formation and field surface disturbance should be avoided and fine tilth should be ensured. The contour survey and primary cultivation will determine whether field levelling is required, if so then the field should be levelled, preferably laser levelled, prior to the final cultivation. Based on laboratory results of soil analysis any recommended treatments (lime, gypsum etc) should be applied according to prescribed rates. The final cultivation should achieve around 20cm depth and should run perpendicular to the proposed direction of the beds for ensuring straight bed installation.

A simple test for the Lower Plastic Limit (LPL) is to roll a handful of soil taken from the base of the bed, (i.e. at ~27cm depth) between the palms of one's hands into a rod. If the soil will cohere and form a rod of about 1cm diameter before breaking up the soil moisture content is at the LPL. If it fails to cohere and form any sort of rod-like structure the soil is too dry. If the soil can be rolled into a rod with a diameter less than 1cm it is too wet.

Furrow bed installation

The first step is to design an appropriate bed width and bed height. This depends on soil type, crop type, available machinery and farmer preferences. Fields with little slope, impermeable top soil and short length require higher beds, because of greater susceptibility to waterlogging than lands with good slope. Generally new bed height of 15-25 cm is very effective in controlling waterlogging. Wider beds increase land use efficiency by increasing the bed area for growing crops and by reducing the unplanted furrow area (Jin et al., 2007). However, wider beds can reduce crop yield due to poor lateral infiltration into the bed mid if crop is grown on the whole bed surface (Akbar et al., 2010; Akbar et al., 2017a). For instance, the available 50hp tractor has a wheel gap of ~130cm thus can form two ridges of 65 cm width or a single wide bed. The 130cm wide bed has been shown effective in increasing yield and saving up to 40% of irrigation water than flat basin (Akbar et al., 2016a). The 130 cm bed size accommodates two rows of maize and five rows of wheat crop. Speed of operation exerts a great influence on the size and shape of beds and their furrows. Best results can be achieved by ensuring the bed-former operates at < 5kph.

Soil management for furrow beds

The soil disturbance with intensive cultivation should be avoided and the track should be kept permanent. The use of good quality bed former/ridger and seeder machines should be pursued while machines performing bed forming and seeding in a single operation should be preferred. Most bed formers/ ridgers have a tool frame carrying furrowers only, while the planter work separately and comprised of two seed boxes; one for seed and second for fertiliser, and a seed and fertiliser metering devices. Several bed forming and seeding machinery types are available in the market and adopted by the farmers. Majority of these machines comprised of a separate bed former and a seeder thus require multiple operations for crop sowing. Machines with both bed forming and seeding also available in market for certain crops like wheat and maize as shown in Figure 7. However, these machines work well for wheat but did not ensure precision planting (spacing and depth) of precious seeds for high value crops and are not versatile. Machines with improper furrower design compact furrow sides/ bed shoulders tend to reduce lateral infiltration thus further work is needed to refine the machines.

Figure 7: *Bed former cum seeder developed by (a) CEWRI-NARC Islamabad and (b) Water Management Research center, UAF Faisalabad.*

The CEWRI-NARC and Australian Centre for International Agricultural Research (ACIAR) pursued advanced machines for ensuring low cost, versatile in operation and capable of precision planting. The bed forming should loosen the soil in a controlled manner. The machine should be capable of renovating the existing beds with minimal soil disturbance. The stubbles and root matter should be conserved in beds. The bed former should enhance the lateral movement of water into wider beds and the machine should be capable of planting multiple crops.

Figure 8: *View of the bed former imported from Australia constructing narrow beds.*

To achieve the above mentioned features a separate bed former (Figure 8) and seed planter (Figure 9) was initially developed in Australia according to local Pakistani requirement and was imported and then indigenously produced with local manufacturers. These machines are commercially available with leading farm machinery manufacturers in Pakistan for adoption. However, currently we are pursuing to make both machines a single one and to make it low cost, less weight and versatile as shown in Figure 7a.

Figure 9: *Seeder sowing two rows of wheat on narrow bed with row spacing of 20 cm. Insert shows diagram of the press wheel and seed placement component.*

Irrigation management for furrow beds

Irrigation performance is generally determined by the following indicator:

Irrigation application efficiency (*Ea*): is the ratio of irrigation water available to the crop in the root zone and water received at field inlet (Purcell and Associates, 1999).

Requirement efficiency (*Er*): It is the ratio of the volume of water stored in the root zone immediately after irrigation to the pre-irrigation root zone soil moisture deficit (Raine and Bakker, 1996).

Links Researchers

Distribution uniformity (*DU*): The average infiltrated depth of water in the lower one quarter of the field, divided by the average infiltrated depth over the whole field (Michael, 1999).

The irrigation performance is largely affected by irrigation management factors including inflow rate (*Q*), time to cut-off (*Tco*) and soil moisture deficit (*SMD*) before irrigation.

Inflow rate (*Q*): Furrow inflow rate is generally controlled by the number of furrows served concurrently, as the total *Q* available at farm outlet is mostly fixed that vary in the range of 1-2 cusecs. Generally the inflow rate is not optimised for the variable field conditions as given in Figure 10 and 11.

Time to cut-off (*Tco*): The time to cut-off often depends on the water arrival time to the furrow tail end or furrow filling. Time to cut-off is inadvertently selected which generally cause excessive water losses as illustrated in Figure 10 and 11 (Akbar et al., 2016b; Akbar et al., 2017b).

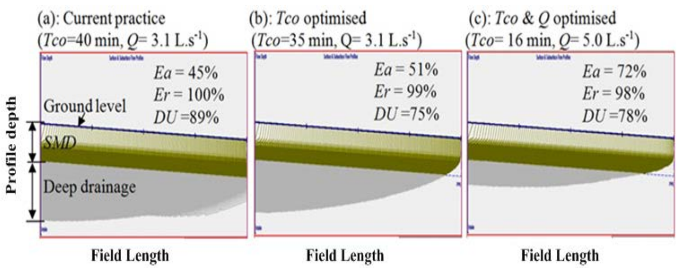

Figure 10: *Impact of inflow rate and time to cut-off on irrigation performance under high infiltration soil.*

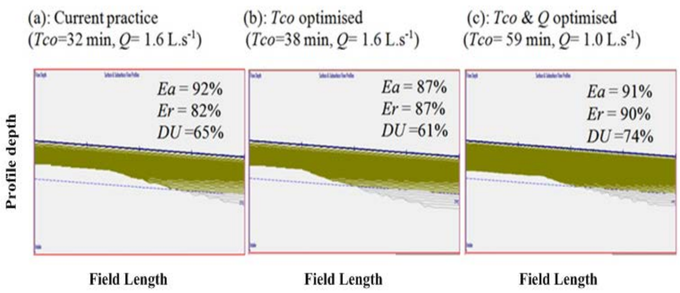

Figure 11: *Impact of inflow rate and time to cut-off on irrigation performance under low infiltration soil.*

Soil Moisture Deficit (*SMD*): Soil moisture deficit is the volume of water required to fill the root zone to field capacity. When to irrigate is an important decision in the irrigation scheduling process which not only affect the crop performance but change soil properties which affects the irrigation performance. Therefore, irrigation management needs to be optimised for the changed soil and field conditions as illustrated in Figures 10 and 11.

Bed width management

Wider beds are more beneficial because it increase the crop area of beds and reduce the unplanted furrow area (Jin et al., 2007). The soil infiltration is two dimensional under furrow beds comprising vertical and lateral components as illustrated in Figure 12. If the bed width is not optimised for the field and irrigation conditions on farm then the dry bed middle of wide beds can reduce crop yield in the centre (Akbar et al., 2015). Similarly, applying excess water into narrow beds can exacerbate deep drainage losses thus making irrigation inefficient. So, the bed width should be optimised according to the lateral infiltration properties of soil to avoid reduction in crop yield. Alternate furrow irrigation can also be helpful in narrow beds in reducing water losses and managing salinity.

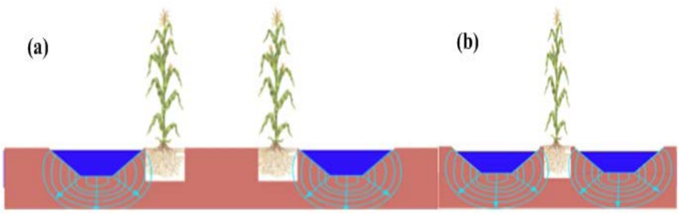

Figure 12: *Crop rows and wetting pattern under (a) wide bed and (b) narrow bed.*

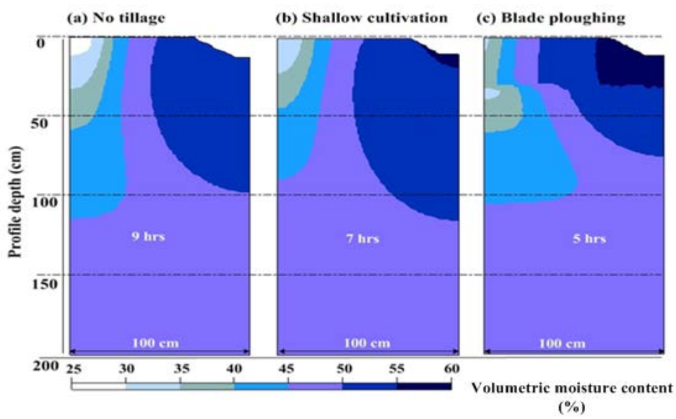

Figure 13: *Wetting front movement across half bed width when renovated with three different tillage treatments under Vertisol soil (Akbar et al., 2015).*

Lateral infiltration management

Lateral infiltration under a furrow bed depends on soil type, field conditions and hydraulic gradient. The loam soil under Pakistani field conditions has reduced infiltration (vertical and lateral) properties, which did not support adoption of wide beds (Akbar et al., 2015). Additional tillage and irrigation management measures are generally needed for enhancing lateral infiltration. Lateral wetting can be altered by increasing the furrow water head or soil management technique as illustrated in Figure 13 (Akbar et al., 2015). Reducing tillage and increasing crop residue retention can increase organic matter, which can also leads to soil structure stability and increased lateral infiltration.

Farm pond

Farm pond should be developed on a furrow bed farm, if possible, for collecting water from collector drains, excess irrigation application and monsoonal floods. The pond capacity should be according to farm size, weather and farmer resources. Generally, pond embankments built with a compacted mixture of mud, gravel and stone will meet the requirement of majority of Pakistani farmers. Precautions to avoid seasonal failure during peak rainy period are required. The pond base should be well compacted or lined for controlling deep percolation. The water stored in pond can be used during peak water demand period in summer. The pond should collect water from the draining area preferably through gravity. Provision for a tractor PTO/engine driven pumping unit at the pond can be beneficial in avoiding crop damage due to seasonal flooding and reuse during dry spell period.

Additional measures and precautions

A range of potential problems can occur on crops grown on furrow beds, especially when not properly managed. Symptoms of rising pests, diseases, rodents, insects etc should be monitored. Effective prevention measures should be timely undertaken to avoid damage to crop. Intensive tillage should be avoided and minimum tillage should be encouraged.

The furrow spacing should match the tractor track width to avoid bed compaction and perform mid season operations conveniently mechanically. Crop rotation should be followed to break the life cycle of weeds, insects and diseases. Stubble retention should be encouraged for better soil quality. The beds should not be reconstructed each time and only minor renovation operation may be sufficient before each crop sowing for reducing operation cost.

Conclusions and Recommendations

- Furrow bed irrigation is one of the efficient surface irrigation methods but needs appropriate land, water and irrigation management for harvesting the full potential productivity and water saving benefits;
- The furrow bed design should be site specific depending on soil type, slope, field length, water source, inflow rate, crop type and available machinery;
- Initial field investigation should be conducted for determining soil physical and hydro-chemical characteristics. The land levelling and input requirements should be fulfilled as per site specific needs before and after installation of furrow beds;
- The soil management should involve minimum soil disturbance by avoiding intensive tillage and compaction while enhancing crop residue retention and soil cover or mulching;
- The irrigation management should reduce advance time to field tail end and tail water collection and to ensure lateral infiltration to meet water needs of crop in bed middle;
- Additional measures of constructing farm pond, insect, pest and weeds management needs to be undertaken. The furrow spacing should match the tractor track width and crop rotation should be followed.

Author's Contribution

Ghani Akbar: Conceived the idea, conducted literature review, synthesize the data, wrote the paper and presented the results, discussions and conclusions while utilzing his field experience and research background.
Muhammad Asif: Supported in literature review and data analysis.
Zafar Islam: Supported in data collection, data compilation and analysis.
Shahid Hameed: Supported in data collection, data entry and graphical presentation.

Conflict of interest

The authors have declared no conflict of interest.

References

Ahmad, N., M. Arshad and M.A. Shahid. 2009.

Bed-furrow system to replace conventional flood irrigation in Pakistan. 60th Int. Exec. Counc. Meet. 5th Asian Reg. Conf. New Delhi, India.

Akbar, G., M.M. Ahmad, M. Asif, I. Hassan, Q. Hussain and G. Hamilton. 2016a. Improved soil physical properties, yield and water productivity under controlled traffic, raised-bed farming. Sarhad J. Agric. 32: 325-333. https://doi.org/10.17582/journal.sja/2016.32.4.325.333

Akbar, G., M.M. Ahmad, A. Ghafoor, M. Khan and Z. Islam. 2016b. Irrigation efficiencies potential under surface irrigated farms in Pakistan. J. Eng. Appl. Sci. (JEAS), Peshawar. 35: 15-23.

Akbar, G., M.M. Ahmad, M. Khan and M. Asif. 2017a. Furrow lateral wetting potential for optimizing bed width in silty clay. Irrig. Drain. 66: 218-226. https://doi.org/10.1002/ird.2092

Akbar, G., G. Hamilton and Z. Hussain. 2009. Permanent raised bed cropping system improves water use efficiencies of wheat and maize crops, Mardan/Pakistan experience. Pak. J. Water Resour. 13: 17-24.

Akbar, G., G. Hamilton and S. Raine. 2010. Permanent raised beds configurations and renovation methods affect crop performance 19th world congress of soil science, soil solutions for a changing world. Aust. Soc. Soil Sci. Brisbane, Australia. pp. 171-174.

Akbar, G., S. Raine, A.D. McHugh and G. Hamilton. 2015. Managing lateral infiltration on wide beds in clay and sandy clay loam using Hydrus 2D. Irrig. Sci., 33: 177-190. https://doi.org/10.1007/s00271-014-0458-9

Akbar, G., S. Raine, A.D. McHugh, G. Hamilton and Q. Hussain. 2017b. Strategies to improve the irrigation efficiency of raised beds on small farms. Sarhad J. Agric. 33: 615-623. https://doi.org/10.17582/journal.sja/2017/33.4.615.623

Aslam, M., 2016. Agricultural productivity current scenario, constraints and future prospects in Pakistan. Sarhad J. Agric. 32: 289-303. https://doi.org/10.17582/journal.sja/2016.32.4.289.303

Ebrahim, Z.T., 2020. Is Pakistan running dry? Water Issues in Himalayan South Asia. Springer. pp. 153-181. https://doi.org/10.1007/978-981-32-9614-5_7

Gill, M.A., M. Ahmad and N.A. Awan. 2005. Evaluation and performance of growing crops on permanent raised beds in Pakistan's Punjab. In: C. Roth, R. Fischer and C. Meisner eds. Evaluation and performance of permanent raised bed cropping systems in Asia, Australia and Mexico. ACIAR, Griffith, NSW, Australia. pp. 66-71.

Gillies, M., R. Smith and S. Raine. 2008. Measurement and management of furrow irrigation at the field scale irrigation Australia conference, share the water, share the benefits. Melbourne, Australia.

Hassan, I., Z. Hussain and G. Akbar. 2005. Effect of permanent raised beds on water productivity for irrigated maize-wheat cropping system. In: C. Roth, R. Fischer and C. Meisner eds. Evaluation and performance of permanent raised bed cropping systems in Asia, Australia and Mexico. ACIAR Proc. No. 121, Griffith, NSW, Australia. pp. 59-65.

Jin, H., L. Hongwen, N. Kuhn, Z. Xuemin and L. Wenying. 2007. Soil loosening on permanent raised-beds in arid northwest China. Soil Tillage Res. 97: 172-183. https://doi.org/10.1016/j.still.2007.09.016

Michael, A.M., 1999. Irrigation: Theory and practice. Vikas Publ. House Pvt. Ltd. Jangapura, New Delhi, India.

Purcell, B. and Associates. 1999. Determining a framework, terms and definitions for water use efficiency in irrigation. Land and Water Resour. Res. Dev. Corp., Narrabri, NSW. pp. 26.

Raine, S. and D. Bakker. 1996. Increased furrow irrigation efficiency through better design and management of cane fields. Aust. Soc. Sugar Cane Technol. Mackay. pp. 114-124.

Walker, W.R., 1989. Guidelines for designing and evaluating surface irrigation systems. FAO, Irrig. Drain.

Wightman, B., R. Peries, C. Bluett and T. Johnston. 2005. Permanent rasied bed cropping in southern Australia: practical guidelines for implementation. In: C.H. Roth, R.A. Fischer and C.A. Meisner eds. Evaluation of performance of permanent rasied bed cropping systems in Asia, Australia and Mexico. ACIAR Proc. No. 121, Griffith, NSW, Australia. pp. 173-190.

Zwart, S.J. and W.G.M. Bastiaanssen. 2004. Review of measured crop water productivity values for irrigated wheat, rice, cotton and maize. Agric. Water Manage., 69: 115-133. https://doi.org/10.1016/j.agwat.2004.04.007