

The potential of precision surface irrigation in the Indus Basin Irrigation System

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Received: 8 July 2015 / Accepted: 3 May 2016 / Published online: 14 May 2016
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Abstract In this research we explore the potential of precision surface irrigation to improve irrigation performance under the *warabandi* system prevalent in the Indus Basin Irrigation System. Data on field dimensions, field slopes along with characteristic soil infiltration properties and outlet discharge were collected through a survey of a sample tertiary unit of Maira Branch Canal, Khyber Pakhtunkhwa Province, Pakistan. The performance of all fields in the tertiary unit was analysed and reported in aggregate, with detailed results of one field presented for illustration. The objective is to determine the optimum field layout, defined as the number of border strips, for the observed field characteristics to maximize performance. The results indicate that performance improvement is relatively easily achievable through changes in field layout within current irrigation services. Estimated application efficiency is sensitive to the selected depth of application, and it is important that a practical depth of application is selected. We recommend a depth of application of 50 mm and show how this is achievable and leads to a low quarter distribution uniformity of 0.750 and an application efficiency of 80 %. We also

explore the feasibility of a 10-day *warabandi* rather than the 7-day *warabandi* and show that there is no significant change in the performance under a 10-day *warabandi*.

List of symbols

a_p	Proportion of total available area cultivated
D	Depth of water supplied to the root zone (mm)
ε_i	Efficiency
E	Total number of efficiency terms
N	Number of border strips in the field
q	Discharge per unit width
t	Irrigation interval (s)
t_{co}	Cut-off time for each border strip
V	Volume of water applied
w_N	Width of each border strip and
w_a	Water allowance ($L s^{-1} ha^{-1}$)

Introduction

Bautista et al. (2009a) report that the USDA-ARS has been involved in the development of numerical models to simulate and analyse surface irrigation since the 1970s. WinSRFR is reported by Bautista et al. (2009a) as the new generation of surface irrigation software following on from earlier softwares such as SRFR (Strelkoff et al. 1998), BORDER (Strelkoff et al. 1996) and BASIN (Clemmens et al. 1995), with an early objective of converting the earlier DOS-based software to a Windows operating system. Bautista et al. (2009a) present an overview of the functionality and organization of WinSRFR, and in the companion paper Bautista et al. (2009b) describe in detail the use of WinSRFR to field test CG/2-9-05 in the Yuma Mesa Irrigation and Drainage District described by Niblack (2005). A primary objective of surface irrigation analysis as described

Communicated by A. Kassam.

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by (Bautista et al. 2009b) is to evaluate application efficiency and distribution uniformity of an irrigation event.

Clemmens (1986) suggested that although plants may use water at the rate of 2–10 mm/day, surface irrigation systems are normally designed for a required depth of irrigation of 50–150 mm. In an application of WinSRFR Lecina et al. (2005) reported the average depth of application in Irrigation District V (IDV) of Bardenas, Spain, of 117 mm acknowledging that this is on the high side but not uncommon in the Ebro Valley of Spain. Chen et al. (2012) used WinSRFR to explore the optimum length of border irrigated fields in Panzhuang irrigation district along the lower Yellow River and set the required depth of irrigation at 100 mm. Gonzalez et al. (2011) also used WinSRFR to analyse basin irrigation design with longitudinal slope and also use a depth of irrigation of 100 mm. Gonzalez et al. (2011) undertake an extensive simulation of the effect on distribution uniformity of slope (and other parameters) on basin irrigation design using WinSRFR and a custom build program POZAL. Generally distribution uniformity increases as the slope increases from zero (level field) to a maximum and then starts to decrease. The optimum slope depends on other parameters such as the Kostiakov infiltration parameters, length and inflow. Further Gonzalez et al. (2011) show that at very low inflows the distribution uniformity is largely insensitive to slope.

Clemmens (1986) also suggested that water be applied over a period of 1–48 h (cut-off time). Clyma and Ali (1977) reported that in many countries including the USA the criterion for cut-off is when water reaches the lower end of the field. Wattenburger and Clyma (1989a, b) use the terminology completion of advance (CoA) for this criterion, and using mathematical simulation determined that for level basins this criterion is a practical and suitable technique. Reddy (2013) compared completion of advance (CoA) with the limiting length criterion and uses cut-off times of 3.75–5.50 h. Reddy (2013) concluded that the completion of advance (CoA) is more robust than the limiting length and particularly in a context of poor control of water—which is typical of developing countries.

Bishop and Long (1983) have suggested that for field channels in developing countries a discharge of 30–50 L s⁻¹ is appropriate as anything larger would be difficult to control and anything smaller and excessive seepage losses will occur. Discharge as reported by Lecina et al. (2005) in IDV ranges from 103 to 138 L s⁻¹. Gonzalez et al. (2011) use a discharge of 100 L s⁻¹ in their simulations with WinSRFR, whereas Chen et al. (2012) report discharges in the range of 30–40 L s⁻¹. Tyagi et al. (2012) in their study of the Bhakra Canal Project in India found field channel discharges to range from 20 to 100 L s⁻¹ and share the view of Bishop and Long (1983) that with flow rates in excess of 50–60 L s⁻¹ conveyance losses are excessive;

furthermore, with discharges less than 20 L s⁻¹ surface irrigation efficiency and uniformity are low. For developing countries discharges of 20–50 L s⁻¹ are advisable and a required depth of irrigation in the range of 50–150 mm, Clemmens (1986).

A range of indicators have been developed to assess the performance of irrigation systems, e.g. Bos et al. (2005), Burt et al. (1997), Clemmens and Dedrick (1994), Clemmens and Bos (1990). Bautista et al. (2012) summarized the performance indicators computed by WinSRFR specifically for surface irrigation. In the application of WinSRFR surface irrigation, application efficiency and distribution uniformity are the more commonly used performance indicators. Gonzalez et al. (2011) refer to both application efficiency and distribution uniformity, but use the distribution uniformity as a performance indicator of surface irrigation. Lecina et al. (2005) primarily use application efficiency as a performance indicator. Chen et al. (2012) uses three performance indicators to evaluate border irrigation, namely average depth applied to the field, application efficiency and distribution uniformity. Reddy (2013) primarily uses application efficiency, water requirement efficiency although also reports distribution uniformity. A criticism of application efficiency is that this indicator depends upon the required depth of application. In the literature this required depth of application is selected on user expert judgement, e.g. Chen et al. (2012) and Reddy (2013) use a value of 100 mm, Bautista et al. (2009a) use a value of 50 mm, whereas Lecina et al. (2005) use values of 65 mm for platform soils and 80 mm for alluvial soils. Hence application efficiency depends upon user-selected required depth of application. To paraphrase Burt et al. (1997) it is possible to obtain 100 % application efficiency by selecting a high required depth of application. On the other hand application efficiency is a commonly used performance indicator and furthermore informs large development investments, e.g. the World Bank funded project PK Punjab Irrigated Agricultural Productivity Improvement Program Phase I has the stated objective “It will also support provision of precision land levelling equipment for improving land levelling operations in the country, thus improving irrigation application efficiency”. World Bank (2016).

As with required depth of application, the range of roughness values used in this work are informed by the expert opinion and literature. Reddy (2013) uses values of 0.04, 0.10 and 0.25. Chen et al. (2012) estimates roughness values in the range of 0.07–0.14. Bautista et al. (2009a) recommend a range of 0.04–0.10.

This paper presents results from research examining the potential of the “precision surface irrigation” paradigm in the context of Pakistan’s Indus Basin Irrigation System. This paradigm describes engineered surface

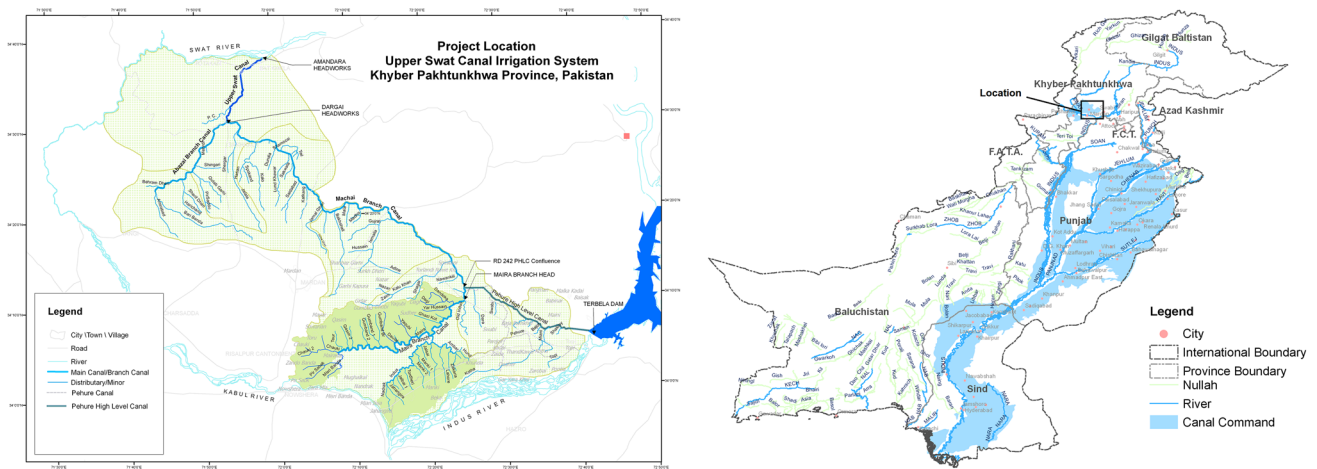


Fig. 1 Location map of the Upper Swat Canal Irrigation System, Pakistan

irrigation whereby fields are accurately (laser) graded, and border strip widths, flow rates, cut-off times are optimized to the field dimensions and infiltration characteristics within the context of the *warabandi*. From a research perspective distribution uniformity is a preferred performance indicator as it is independent of the required depth of application. However, from a development investment perspective, such investments are guided by improvements in application efficiency. Therefore, this research evaluates precision surface irrigation using both distribution uniformity and application efficiency as performance indicators. Distribution uniformity is the ratio of the average smallest depth of application over a user-selected fraction of the area to the average depth over the entire area (Burt et al. 1997). Hence distribution uniformity is augmented with a term to indicate the user-selected fractional area over which the average smallest depth of application is estimated. Burt et al. (1997) reports that for some theoretical studies the absolute minimum value of depth of application has been used leading to the term minimum distribution uniformity. Burt et al. (1997) reports that minimum distribution uniformity is often impractical for field use and further reports that USDA and NRCS have extensively used the lowest $\frac{1}{4}$ as the fractional area which has proved to be practical and useful in irrigated agriculture. This leads to the term low quarter distribution uniformity. Hence in this research we use the low quarter distribution uniformity as a performance indicator rather than the minimum distribution uniformity.

This evaluation of precision surface irrigation is limited to an assessment of the potential performance of field application of water. We do not report on or compare our results in detail with existing field practice.

Materials and methods

The study area

The vast Indus Basin Irrigation System (IBIS) is managed under a system known as *warabandi*—a literal translation is fixed turns—which refers to the fixed weekly schedule of deliveries characteristic of this irrigation system. Anwar and Ul Haq (2013) have reasoned that *warabandi* is actually a comprehensive management system for Pakistan's rather unique deficit-by-design irrigation system. The study area is located in the north-western Khyber Pakhtunkhwa Province of Pakistan, as shown in Fig. 1, described in detail by Ghuman et al. (2010) and Latif and Tariq (2009). The Maira Branch Canal is part of the Upper Swat Canal and was rehabilitated as part of the Pehur High-Level Canal Project supported by the Asian Development Bank (ADB 2005). ADB (2005) provides a thorough insight into the rehabilitation of this irrigation system. Through this rehabilitation the capacity of canals was increased to $0.6\text{--}0.7\text{ L s}^{-1}\text{ ha}^{-1}$. The canal capacity normalized by irrigated area is termed water allowance in the Pakistan/India irrigation terminology (Ghuman et al. 2010). Latif and Tariq (2009) report the water allowance after rehabilitation as $0.77\text{ L s}^{-1}\text{ ha}^{-1}$. Figure 2 shows that by Pakistan's standards this canal is comparatively well resourced with water. The majority of canal systems have a water allowance of the order of $0.2\text{--}0.3\text{ L s}^{-1}\text{ ha}^{-1}$. The Upper Swat Canal water allowance $0.77\text{ L s}^{-1}\text{ ha}^{-1}$ corresponds to a gross depth of 6.6 mm/day, whereas reference crop evapotranspiration typically exceeds this, e.g. during June 2012 reference crop evapotranspiration exceeded 8 mm/day (authors data). Therefore, during the hot months (June–August) the capacity of even this comparatively well-resourced irrigation system remains inadequate. The

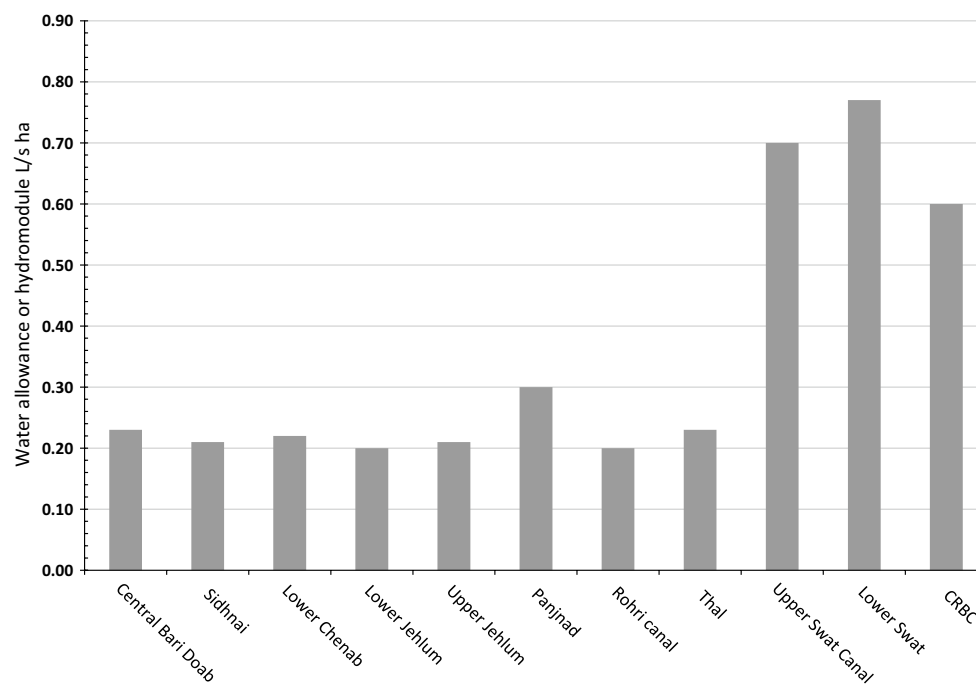


Fig. 2 Water allowance or hydromodule of a selection of irrigation systems of the Indus Basin Irrigation System

deficit-by-design of the Indus Basin Irrigation System is widely reported, e.g. Bandaragoda and Rehman (1995), Seckler et al. (1998), Hussain et al. (2011), and is one of the reasons that substantial areas of land remain fallow in the irrigated areas. Latif and Tariq (2009) sampled six of the sixteen tertiary canals supplied from the Maira Branch Canal and reported the cropping intensity (cropped area over both summer and winter crop seasons) had increased from 145 to 170 % following the rehabilitation and modernization, i.e. 85 % of the land area is now cultivated and 15 % of the land remains fallow. Latif and Tariq (2009) present these data disaggregated by crop season with 20 % land remaining fallow in the summer season (April–October) and 10 % land remaining fallow in the winter season (November–March). ADB (2005) presents cropping intensities in the range 152–181 % in their Project Completion Report to reflect different future scenarios. The primary crops grown in the area are wheat (50 %), sugar cane (15 %), tobacco (12 %) and Maize (35 %) Latif and Tariq (2009).

In the context of this irrigation system Laycock et al. (2005) describe one facet of *warabandi* system whereby water flows continuously in a field channel and is diverted sequentially to individual fields with the duration (maximum cut-off time) for each field proportional to the area of the field. The principle of the *warabandi* is to provide a constant volume of water per unit of area each week. The *warabandi* works on a weekly rotation, i.e. each field is provided the opportunity to irrigate once a week. Laycock

et al. (2005) further observe that ... “Farmers often trade their *warabandi* turns and routinely waste excess water into the drainage system, especially if their turn comes during the night” and citing a study by the International Water Management Institute suggest that efficiency is as low as 40 %. Ghuman et al. (2010) also note that no night-time irrigation was observed particularly in the monsoon months of July–August and winter months of November–December, and that ... “water users either closed the outlets of their watercourses or they simply let water flow to nearby drains at the downstream end of the watercourse”. The authors conducted a weekly survey of a random sample of 100 farmers over an entire year. Figure 3a, b shows the proportion of farmers that irrigated or abstained from irrigation each week for the summer 2012 and winter 2012–2013 crop seasons and reference evapotranspiration. The rational behaviour of farmers is self-evident from Fig. 3. In the peak evapotranspiration weeks—June—almost 100 % of farmers irrigate each week. The proportion of farmers irrigating drops to 8 % in September which coincides with the lowest evapotranspiration rates. Ghuman et al. (2010) make a similar observation. During the winter season on average only 14 % of farmers irrigate with 86 % abstaining. Given this high proportion of farmers not irrigating it is easy to understand why there is trading of turns and wasting excess water into the drainage system as reported by Laycock et al. (2005). Figure 3b shows that towards the end of December the entire sample of farmers abstain from irrigation; January is the annual canal maintenance period—a

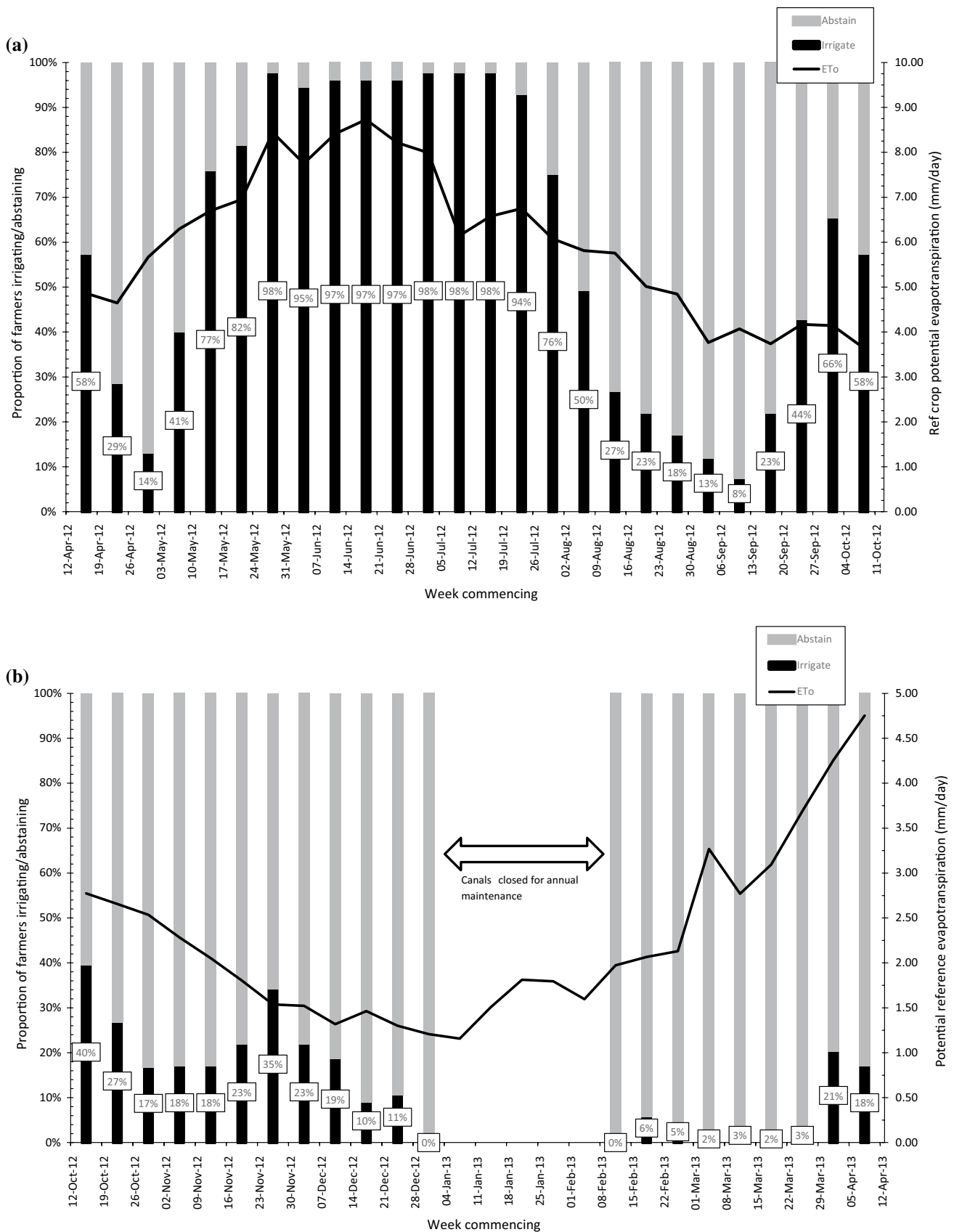


Fig. 3 Farmer irrigation and abstaining from irrigation behaviour. **a** Crop season *Kharif* 2012 (16 April 2012–14 October 2012). **b** Crop season *Rabi* 2012-13 (15 October 2012–14 April 2013)

practice institutionalized during the British colonial era. In the rigid *warabandi* system the choice whether to irrigate or to abstain is about the only choice that farmers have, cut-off time, discharge are fixed by the system agency. Typically a farmer will use their judgement to decide whether the soil is moist and taking the weather/season into account decide to irrigate or abstain, thereby to a degree adjusting irrigation to the water requirements.

This subject of an irrigation system responding to farmer demand is a separate body of research, e.g. Clemmens (1987), Salvador et al. (2011) McCornick (1993) and described by De Vries, and Anwar (2004) as an operations research problem. This paper is limited to infield irrigation operations and does not address irrigation operations.

The data for the modelling undertaken in this research are obtained from a tertiary unit located on the canal turnout at RD160 + 00R (running distance 160 + 00 ft on the right bank) of the Maira Branch Canal. The Maira Branch Canal and subsidiary/child canals have a total of 295 canal turnouts (population size 295). From data collected for a random sample of 54 canal turnouts the average size of a tertiary unit is 88.80 ha (max. size 391.58 ha, min size 2.42 ha). The average number of fields per tertiary units is 152 (max. 614, min. 6), and the average field size is approximately 0.6 ha. Each tertiary unit is serviced by one turnout, and the turnout is sized to release a discharge proportional to the area serviced. Turnouts are typically open flume or orifice structures.

All fields are irrigated using surface irrigation—typically border strip irrigation with blocked downstream ends, i.e. no field drains. Currently there is very limited use of laser levelling in this area, but the use of such equipment is growing. Humphreys et al. (2010) report that the most rapid expansion of laser levelling is happening in the adjacent province of Punjab, Pakistan. Jat et al. (2006) predicted that approximately 1.8 M ha of land in Punjab, Pakistan, will be laser levelled by 2016. The technology is beginning to spill over into the neighbouring Khyber Pakhtunkhwa Province where this study area is located—hence this research is timely.

Turnout discharge

The records of the irrigation agency show that canal turnout at running distance (RD)160 + 00R serves an area of 27.67 ha. In the Indus Basin Irrigation System turnouts are sized based on the water allowance ($0.7 \text{ L s}^{-1} \text{ ha}^{-1}$) and area served by a turnout (27.67 ha). The discharge for turnout RD160 + 00R is 19.37 L s^{-1} and is herein referred to as the rated discharge. This is slightly below the range of $30\text{--}50 \text{ L s}^{-1}$ recommended by Bishop and Long (1983).

A field survey undertaken during June–July 2012 revealed that the actual area irrigated by turnout RD160 + 00R is currently 20.70 ha, i.e. 25 % is fallow/not irrigated which is slightly higher than the 20 % reported by Latif and Tariq (2009). The average discharge, between June and December 2013 measured by a USDA long throat flume, was 29.17 L s^{-1} (+50 % of rated discharge) albeit ranging from 1.20 to 72.79 L s^{-1} which certainly makes this a management challenge for farmers. The observed turnout discharge agrees with values reported by Tyagi et al. (2012). The duration (cut-off time) a farmer is entitled to receive water remains constant irrespective of actual turnout discharge. For the purposes of this paper we start our analysis using the rated discharge as this would be of primary interest to agencies making development investments. However, we also explore the sensitivity of the solutions to turnout discharge given the large variation in turnout discharge.

For the rated discharge (19.37 L s^{-1}) and given that water flows continuously the volume of water per unit service area (27.67 ha) is 43 mm/week.

To use application efficiency as a performance indicator it is necessary to first define the depth of application. We use two techniques to determine the required depth of application:

1. Depth of application guided by expert opinion cited in the literature;
2. Depth of application as function of water allowance, irrigation interval, efficiencies and fractional area cultivated.

The literature reports a depth of application based on expert opinion in the range of 50–150 mm. We use a depth of application of 50 mm and report the application efficiency estimated with this depth of application as AE_{50} .

Given that the Indus Basin Irrigation System (IBIS) is deficit-by-design we also estimate the depth of application considering the water allowance and adjusting for efficiencies and cropping intensity. Kahlow and Kemper (2005) report 25–30 % of water is lost in conveyance (turnout to field boundary). Zeb et al. (2000) estimate conveyance losses at 26 %, whereas Sarki et al. (2008) put this value at 28 %. In this paper for the purpose of estimating depth of application we assume a conveyance loss of 25 %. Guided by the results from others, e.g. Chen et al. (2012), Reddy (2013), Hussain et al. (2011) again for the purposes of estimating the depth of application, we assume a field application efficiency of 80 %. We will revisit these assumptions for conveyance losses and field application efficiency after obtaining results from our modelling. Donaldson et al.

(2003) report using an overall efficiency of 60 % which corresponds well with our figures. From a volume balance, we can estimate the depth of water supplied to the root zone from

$$D = \frac{w_a t \prod_{i=1}^E \varepsilon_i}{10^4 a_p} \quad (1)$$

where D = depth of water supplied to the root zone (mm); w_a = water allowance ($\text{L s}^{-1} \text{ha}^{-1}$); t = irrigation interval (s); ε_i = efficiency; a_p = proportion of total available area cultivated; i = index representing the efficiency terms; and, E = total number of efficiency terms.

From (1) for a water allowance of 0.7 L s^{-1} , a weekly irrigation interval, conveyance and application efficiencies of 75 and 80 %, respectively, and if the entire area were cultivated (proportion of total available area cultivated = 100 %), we obtain a depth of 25.4 mm/week. Considering the potential reference evapotranspiration of 56 mm/week (8 mm/day from Fig. 3a) this depth of 25.4 mm/week is sufficient for non-deficit irrigation for only 45 % of the total available area. Field observations and the literature report that the farmers apply the available water to 75 % of the area rather than 45 %, suggesting that crop evapotranspiration may be less than reference evapotranspiration and/or farmers accept a degree of deficit irrigation. From (1) for 75 % proportion of total area cultivated we obtain a depth of application of 34 mm/week. We report the application efficiency estimated using depth of water supplied to the root zone as AE_{34} .

Modelling with WinSRFR

We use WinSRFR (Bautista et al. 2012) to model each of the 95 fields on turnout RD160 + 00R of Maira Branch Canal. As the downstream end of the fields is blocked, we use the zero-inertia model (Bautista et al. 2015). Chen et al. (2012) reported it is possible to improve application efficiency by optimizing the length of the field; however, in the context of the Upper Swat Canal, there are practical barriers to this approach particularly the difficulty of merging small fields into large fields due to land ownership. In this paper we consider the following alternatives:

- Dividing field widths into an integer number of border strips, with each border irrigated sequentially.
- Increasing the discharge at the turnout (and hence field channel) and correspondingly decrease the cut-off times such that the total volume of water per unit area remains constant.
- Changing the *warabandi* to a 10-day rotation and consider a range of discharges in the field channel (up to

50 L s^{-1}) and corresponding cut-off time such that the total volume of water per unit area remains constant.

- Sensitivity analysis: the performance of surface irrigation is a function of a number of variables including discharge, roughness, slope and infiltration. In this paper we limit our sensitivity analysis to discharge and roughness. This paper examines the sensitivity of performance to discharge because the discharge from turnouts can vary significantly from the rated discharge. In practice turnout discharge is rarely measured; rather, turnouts are sized based on hydraulic equations and rarely checked/calibrated. Roughness is determined by expert opinion and inherently subjective and may vary over the crop season. It would be preferable for the performance to insensitive to variations in turnout discharge and/or roughness and hence robust. We examine the solution with a ± 50 % change in discharge (the difference between the rated turnout discharge and average turnout discharge observed over the period June to December 2013).

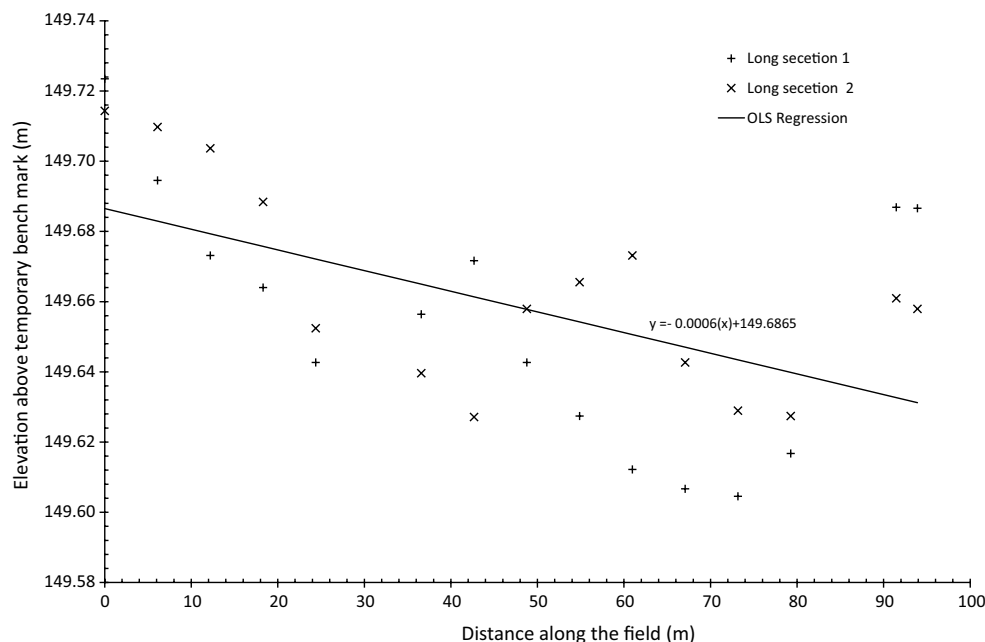
Bautista et al. (2009a) described solutions where the cut-off ratio is less than 1.00 as *risky* in the sense that firstly such problems are poorly posed mathematically, i.e. small changes in the inputs can cause large variations in the outputs and secondly such problems are more vulnerable to field slope and infiltration non-uniformities. For level basins Clemmens and Dedrick (1982) suggested the cut-off ratio should exceed 0.85 although as reported by Bautista et al. (2009a) such criteria have not been developed for graded basins. Similarly Reddy (2013) concluded that setting the cut-off ratio to 1.00 led to robust design of level basins. For the purpose of this work we consider an optimum solution as the one that maximizes low quarter distribution uniformity subject to the constraint that the cut-off ratio is equal to or greater than 1.00. In the event that for any given field under all configurations the cut-off ratio is less than 1.00, we select the configuration that maximizes the cut-off ratio. Hereinafter, we describe configurations where the cut-off ratio is less than 1.00 as “incomplete advance”.

Table 1 shows measured dimensions for the fields and the average, maximum, minimum and coefficient of variation in geometric properties of all 95 fields to expose the physical heterogeneity of fields within the tertiary unit. Table 1 also shows the observed number of border strips in each field. 63 % of the fields are irrigated as a single border strip, whereas 15 and 16 % of the fields are irrigated as two and three border strips, respectively, and the remaining 6 % as fields with four or more border strips. For the sake of brevity data for only 6 of the 95 fields are presented in Table 1. Lengths and widths were measured using a laser distance meter and slopes using an automatic level. For

Table 1 Field geometric properties and summary statistics

#	Field ID	Length (m)	Width (m)	Area (ha)	Slope (m m ⁻¹)	Border strips	Condition	End
1	G1	93.9	24.4	0.23	0.0006	1	Bare soil	Blocked
2	G2	81.4	24.4	0.2	0.0024	1	Bare soil	Blocked
3	G3	175.3	7.6	0.13	0.00007	1	Wheat	Blocked
4	WD115	181.7	15.5	0.28	0.0004	2	Wheat	Blocked
5	SA5	73.2	17.4	0.13	0.0083	1	Wheat	Blocked
...
...
95	LB	86.3	61	0.53	0.0027	1	Wheat	Blocked
Sum			20.7					
Average		76.66	27.85	0.22	0.00273			
Max.		193.90	88.72	1.1	0.0173			
Min.		1.52	3.66	0.005	0.00001			
CV		55.04 %	59.78 %	94.32 %	111.31 %			

Fig. 4 Longitudinal slope of field G1



field G1 we show the measured field elevations for two longitudinal sections and the ordinary least squares regression in Fig. 4. The coefficient of the ordinary least squares regression equation is reported as the slope of the field in Table 1. All 95 fields slope in the downstream direction although the minimum slope of 0.00001 indicates some fields are almost horizontal. If laser grading were to be introduced in this location, this does provide an opportunity to change in the slope of the field; however, the scope of this paper is limited to examining the irrigation performance using the existing slope (as determined by a regression of longitudinal survey) of fields.

The coefficient of variation shows that the variation in length and widths are comparable, whereas the variation in slope is considerably higher. The NRCS infiltration

families are not in widespread use in Pakistan. Hence Kostiakov infiltration parameters were estimated from a regression analysis of field data obtained from three double ring infiltrometer tests, summarized in Fig. 5. The average 6-h infiltration is 84.44 mm (14.07 mm/h) which corresponds to an NRCS soil intake family 0.50–0.60—clay loam to sandy clay loam (US Department of Agriculture, Natural Resources and Conservation Service 2012). The soil texture defined by the NRCS soil intake family is in agreement with the observed soil texture. The average cumulative infiltration curve represented by a Kostiakov function shows reasonable agreement with the data and is implemented in WinSRFR.

For the purposes of modelling, informed by the literature, we use Manning roughness coefficient of 0.10 and

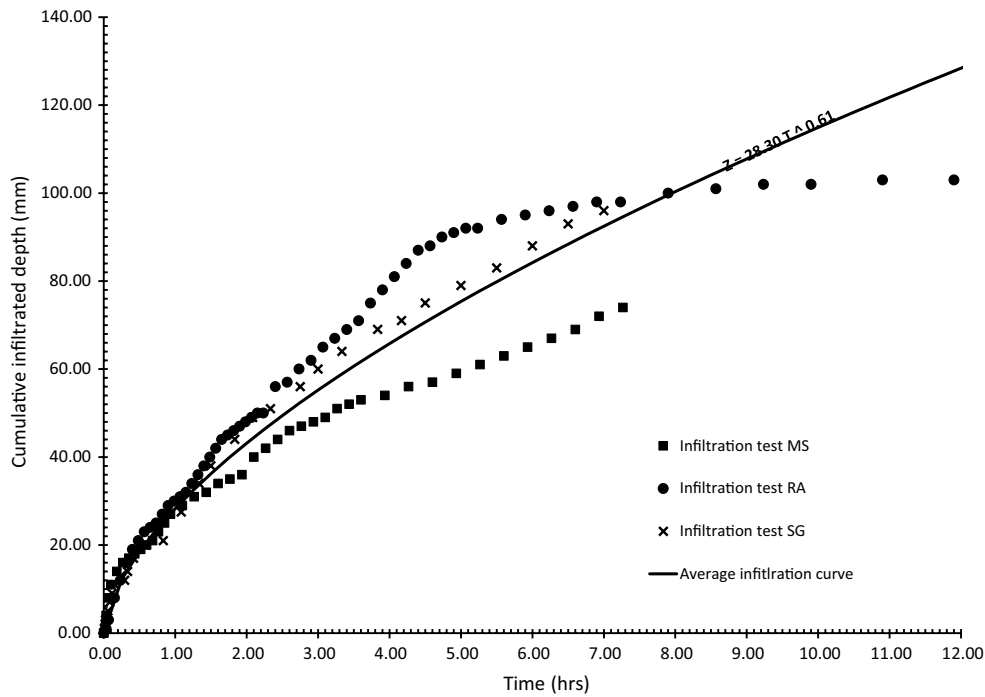


Fig. 5 Infiltration data and average Kostiakov infiltration function

Table 2 Unit discharge for various number of border strips for field G1

Number of border strips	Unit discharge ($L s^{-1} m^{-1}$)	Cut-off time per border strip (h)	Width of border strips (m)	Volume of water (m^3)
1	0.79	1.860	24.40	129.07
2	1.58	0.930	12.20	129.07
3	2.37	0.620	8.13	129.07
4	3.16	0.465	6.10	129.07
5	3.95	0.372	4.88	129.07

explore the sensitivity of the solution to roughness and turnout discharge. We report the performance of the tertiary unit with cut-off times limited by the *warabandi*. This paper does set out to validate WinSRFR as that can be found in work of others, e.g. Bautista et al. (2009b), etc.

Results and discussion

Dividing the field width into an integer number of border strips

In the interest of brevity the analysis is reported for one field (Field ID G1) only although this analysis was repeated for each of the 95 fields within this tertiary unit. Field ID G1 has an area of 0.23 ha. The area of Field ID G1 is 1.11 % of the total irrigated area of 20.70 ha serviced by the outlet at RD160 + 00R. The *warabandi* dictates this

field is entitled to receive 1.11 % of the water each week (168 h)—a duration of 1.86 h ($1.11 \% \times 168$). This is the upper bound on the cut-off time. As Chen et al. (2012) point out, it would be difficult for a farmer to change the length of the field; however, a farmer can at the beginning of a cropping season decide to divide the width of the field into a number of border strips irrigated sequentially. For the purpose of this analysis it is assumed that the field can be divided in any integer number of equal width border strips up to a minimum border strip width of 5 m. The volume of water applied to the field is given by

$$V = qt_{co}Nw_N \tag{2}$$

where V is volume of water applied; q discharge per unit width; t_{co} cut-off time for each border strips; N number of border strips in the field; and w_N width of each border strip. Table 2 shows the various unit discharges and cut-off times if a farmer chooses to divide his/her field G1 in 1, 2, 3, 4

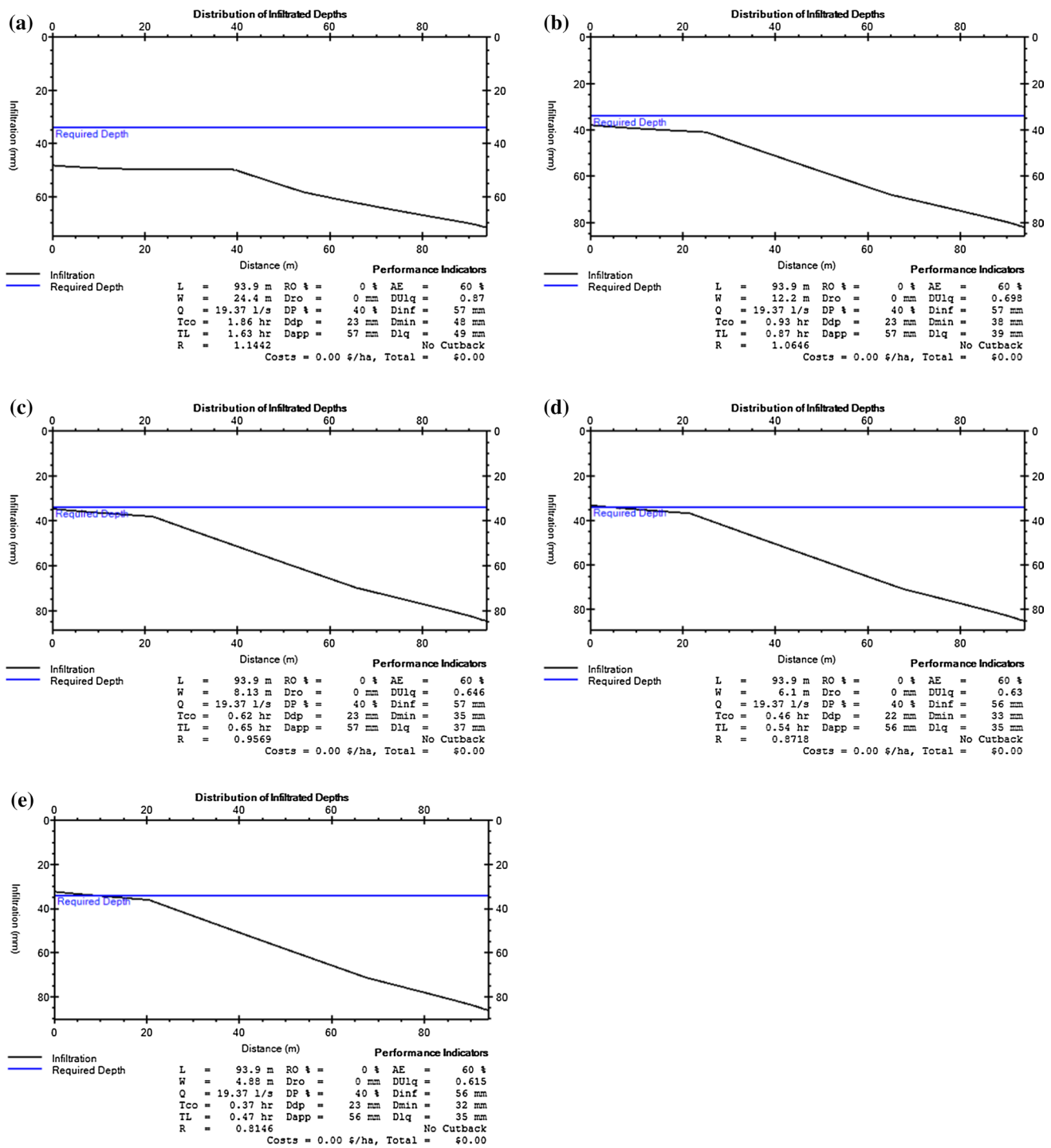


Fig. 6 Analysis of Field G1 with a turnout discharge of 19.37 L s⁻¹, n = 0.10. **a** Number of border strips = 1. **b** Number of border strips = 2. **c** Number of border strips = 3. **d** Number of border strips = 4. **e** Number of border strips = 5

and 5 border strips. With five border strips the width of a border strip is approximately 5.00 m which is the lower bound for the width of border strip. A similar check was made for each of the 95 fields modelled. The total volume of water given by (1) remains constant, confirming that the

water resource remains constant and only the management of water is changed. Table 2 summarizes the input data used in the WinSRFR simulations.

Figure 6 shows the results of the analysis of the surface irrigation event for field G1 under existing *warabandi*

conditions, i.e. rated discharge 19.37 L s^{-1} and roughness 0.10. In Fig. 6a the field is modelled with a single border. The cut-off ratio (R) is greater than one indicating that water advances to the end of the field before cut-off. A relatively high–low quarter distribution uniformity of 0.870 is achieved. Figure 6a shows that the lack of uniformity is due to greater infiltration at the downstream end of the field. It is intuitive that if the unit discharge is increased and cut-off time decreased, the non-uniformity will increase; however, for the purposes of expounding this point we will present the results obtained by varying the number of border strips. Figure 6b displays the results from WinSRFR for the field irrigated with two border strips. The performance as indicated by the low quarter distribution uniformity deteriorates to 0.698, and the cut-off ratio (R) remains above 1.00. Figure 6c shows that if the field is divided into three borders, the cut-off ratio (R) < 1.00 as is the case when the field divided into four or five border strips as shown in Fig. 6d, e, respectively. From this we can conclude that for the rated discharge of 19.37 L s^{-1} the optimum configuration is to irrigate the field as a single border strip which for this field confirms what was observed in practice and is reported in Table 1.

Heterogeneity of fields

The previous section presented the results and performance analysis for a single field G1. The scripting function of WinSRFR was used to analyse the performance of all 95 fields within the tertiary unit and extract the key performance indicators namely low quarter distribution uniformity, application efficiency for 34 and 50 mm depth of application, cut-off ratio and low quarter average infiltrated depth. Table 3 summarizes the results for field G1. Table 3 reports application efficiency for a depth of application of 34 mm and 50 mm. The italicized values represent those configurations where the cut-off ratio < 1.00 . In the last row of Table 3 we report the maximum low quarter distribution uniformity and the corresponding application efficiencies for configurations where the cut-off time exceeds 1.00. In the event that for a given discharge all configurations report a cut-off ratio < 1.00 the reported low quarter distribution uniformity and application efficiencies are for the configuration with the maximum cut-off time. In Table 3 for the rated turnout discharge of 19.37 L s^{-1} the optimum configuration is a single border strip and this achieves a maximum low quarter distribution uniformity of 0.880. In this instance the same optimum configuration is obtained if application efficiency is used as the determining performance indicator, i.e. maximizing application efficiency rather than the low quarter distribution uniformity. Typically low quarter distribution uniformity and application efficiency are highly correlated. For fields with blocked

ends potential application efficiency and distribution uniformity are identical and under such circumstances application efficiency will be closely correlated with distribution uniformity.

The results for the *warabandi* default discharge (19.37 L s^{-1}) from Table 3 and similar results obtained for each of the 93 fields are partially (in the interest of brevity) reported in Table 4. For 10 of the 95 fields it is not possible to complete the advance phase of irrigation, i.e. the cut-off time is less than the advance time irrespective of the number of border strips selected. To aggregate the results over the tertiary unit we use a weighted average rather than an arithmetic average to account for the variation in field area. The weighted low quarter distribution uniformity for the tertiary unit is 0.77 which is a reasonably high uniformity. In Table 4 we report a weighted application efficiency of 85 % for a required depth of 50 mm and 60 % for a required depth of 34 mm can be achieved. This again emphasizes in quantitative terms the sensitivity of application efficiency to depth of application. Table 4 also reports the coefficient of variation in the low quarter distribution uniformity and application efficiency. It is more instructive to examine the coefficient of variation in the “unweighted” low quarter distribution uniformity as the variation in the area accounts for most of the variation in the weighted low quarter distribution uniformity and the weighted application efficiency. Table 3 reports a coefficient of variation of 25.4 % for the low quarter distribution uniformity (max.) and a coefficient of variation of 11.4 and 6.3 % for AE_{50} and AE_{34} , respectively. This indicates that despite the significant variation in the physical properties (length, width and slope) of the fields the variation in performance is comparatively less.

In Fig. 7 we present a histogram of the number of border strips both observed and optimized. We observed 64 % of the fields were irrigated using a single border strip; however, to optimize the low quarter distribution uniformity, 85 % of fields would need to be irrigated using a single border strip. Similarly 3 % of the fields were observed to be irrigated using five border strips, whereas to optimize the low quarter distribution uniformity only 1 % of the fields within the tertiary unit would need to have five border strips. This research shows that in general fewer border strips should be used to optimize the low quarter distribution uniformity. Table 5 provides some additional insight. Under optimized conditions (maximizing low quarter distribution uniformity), the optimum average border strip width is in the range of 20 m–25 m (with the exception of two field where the optimum configuration is for four border strips and five border strips each of 14 m width and 16 m width, respectively). In contrast observed average border strip width ranges between 11 and 25 m. Configuring fields with fewer border strips could potentially have

Table 3 Performance evaluation of field G1 (7-day *warabandi*, Manning roughness = 0.10)

No. of border strips	Border strip width (m)	Turnout discharge ($L s^{-1}$)	19.37	25	30	35	40	45	50
		Duration turnout remains open (h/week)	168	130	108	93	81	72	65
1	24.4	Cut-off time (h)	1.86	1.44	1.2	1.03	0.9	0.8	0.72
		Distribution uniformity low qtr.	0.88	0.8	0.75	0.73	0.71	0.7	0.7
		Application efficiency (AE ₃₄)	60 %	60 %	60 %	60 %	60 %	60 %	60 %
		Application efficiency (AE ₅₀)	88 %	86 %	85 %	84 %	84 %	83 %	83 %
		Cut-off ratio ^a	1.14	1.15	1.12	1.09	1.06	1.02	0.99
		Low qtr. avg. infiltrated depth (mm)	50	45	43	41	40	40	39
2	12.2	Cut-off time (hr)	0.93	0.72	0.6	0.51	0.45	0.4	0.36
		Distribution uniformity low qtr.	0.72	0.7	0.69	0.68	0.68	0.67	0.67
		Application efficiency (AE ₃₄)	60 %	60 %	60 %	60 %	60 %	60 %	60 %
		Application efficiency (AE ₅₀)	84 %	83 %	83 %	83 %	83 %	82 %	82 %
		Cut-off ratio ^a	1.06	0.99	0.94	0.89	0.85	0.81	0.78
		Low qtr. avg. infiltrated depth (mm)	41	39	39	39	38	38	38
3	8.13	Cut-off time (hr)	0.62	0.48	0.4	0.34	0.3	0.27	0.24
		Distribution uniformity low qtr.	0.69	0.68	0.67	0.67	0.67	0.66	0.66
		Application efficiency (AE ₃₄)	60 %	60 %	60 %	60 %	60 %	60 %	60 %
		Application efficiency (AE ₅₀)	83 %	83 %	82 %	82 %	82 %	82 %	82 %
		Cut-off ratio ^a	0.94	0.87	0.81	0.76	0.72	0.68	0.65
		Low qtr. avg. infiltrated depth (mm)	39	38	38	38	38	37	37
4	6.1	Cut-off time (hr)	0.46	0.36	0.3	0.26	0.23	0.2	0.18
		Distribution uniformity low qtr.	0.68	0.67	0.67	0.66	0.66	0.66	0.66
		Application efficiency (AE ₃₄)	60 %	60 %	60 %	60 %	60 %	60 %	60 %
		Application efficiency (AE ₅₀)	83 %	82 %	82 %	82 %	82 %	82 %	82 %
		Cut-off ratio ^a	0.85	0.77	0.72	0.67	0.62	0.59	0.55
		Low qtr. avg. infiltrated depth (mm)	38	38	38	37	37	37	37
5	4.88	Cut-off time (hr)	0.37	0.29	0.24	0.21	0.18	0.16	0.14
		Distribution uniformity low qtr.	0.67	0.67	0.66	0.66	0.66	0.65	0.65
		Application efficiency (AE ₃₄)	60 %	60 %	60 %	60 %	60 %	60 %	60 %
		Application efficiency (AE ₅₀)	83 %	82 %	82 %	82 %	82 %	82 %	82 %
		Cut-off ratio ^a	0.78	0.7	0.64	0.59	0.55	0.51	0.48
		Low qtr. avg. infiltrated depth (mm)	38	38	38	37	37	37	37
Results for max. low qtr. distribution uniformity		Cut-off time (h)	1.86	1.44	1.2	1.03	0.9	0.8	0.72
		Distribution uniformity low qtr. max.	0.88	0.8	0.75	0.73	0.71	0.7	0.7
		Application efficiency (AE ₃₄)	60 %	60 %	60 %	60 %	60 %	60 %	60 %
		Application efficiency (AE ₅₀)	88 %	86 %	85 %	84 %	84 %	83 %	83 %
		Cut-off ratio ^a	1.14	1.15	1.12	1.09	1.06	1.02	0.99
		Low qtr. avg. infiltrated depth (mm)	50	45	43	41	40	40	39

^a For cut-off ratio ≥ 1 (min/min), for cut-off ratio < 1 (m/m)

the additional benefit of reducing labour inputs/costs associated with field preparation in addition to improving the low quarter distribution uniformity.

Hence a simple recommendation to optimize the number of border strips would be to use border strips in the range of 20–25 m, adjusting as appropriate to divide the field into an integer number of border strips and simply use the *warabandi* time divided by the number of border strips as the cut-off time for each border strip. This would maximize

weighted low quarter distribution uniformity achieving a value in the range of 0.770 and an application efficiency of 85 or 60 % for a depth of application of 50 or 34 mm, respectively.

Turnout discharge

In this section we examine the impact of changing the turnout discharge and the duration the turnout remains open

Table 4 Aggregated results for the tertiary unit (7-day *warabandi*, roughness = 0.10)

Field ID	Area (ha)	Area prop. (%)	Performance indicators					
			DU _{lq} max.	Wtd. DU _{lq}	AE ₅₀ (%)	Wtd. AE ₅₀	AE ₃₄ (%)	Wtd. AE ₃₄
G1	0.23	1.11	0.88	0.010	88	0.974	60	0.664
G2	0.2	0.96	0.72	0.007	79	0.758	60	0.575
G3	0.13	0.65	0.89	0.006	88	0.568	60	0.387
WD115	0.28	1.36	0.91	0.012	88	1.201	60	0.819
SA5	0.13	0.61	0.54	0.003	64	0.393	57	0.350
...	...							
LB	0.13	2.54	0.81	0.021	85	2.160	60	1.525
Sum	20.7	100		0.771		83 %		59 %
Average	0.22	1.05	0.72		80		59	
Max	1.1	5.08	1.00		88		60	
Min	0.005	0.02	0.26		45		37	
CV	94.3 %	94.3	25.4 %		11.4		6.3	

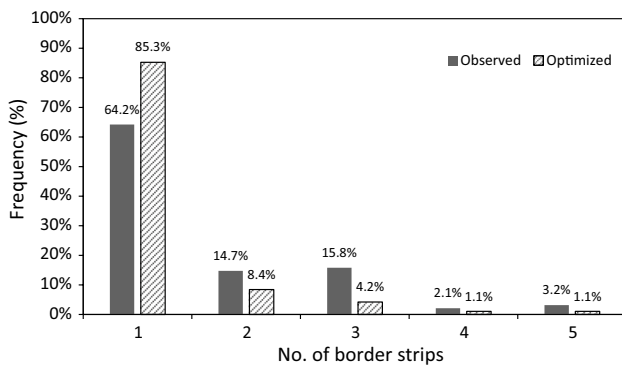


Fig. 7 Histogram of the number of border strips

Table 5 Border strip width (m)

	No. of border strips				
	1	2	3	4	5
Optimized					
Frequency (%)	85.3	8.40	4.2	1.1	1.1
Min. (m)	4	14	11	14	16
Max. (m)	71	36	30	14	16
Avg. (m)	23	24	20	14	16
Observed					
Frequency (%)	64.2	14.7	15.8	2.1	3.2
Min. (m)	4	5	2	6	7
Max. (m)	61	18	24	20	18
Avg. (m)	25	12	11	13	14

for irrigation We examine turnout discharges in the range 19.37 L s⁻¹ (the authorized flow) to 50 L s⁻¹, the recommended upper limit of stream size manageable by an

individual operator, Bishop and Long (1983), with corresponding irrigation durations from 7 days (168) h to 65 h (2.7 days) to maintain a constant total volume water allocation of 129.07 m³ s⁻¹ as summarized in Table 6.

Although the number of border strips can vary between fields, the discharge at a tertiary unit level must remain identical for all fields. It is not possible to have one discharge for one field and a different discharge for another field as the turnout discharge is fixed.

In Table 6 we see that the global optimum is under the default *warabandi* discharge of 19.37 L s⁻¹ where the turnout is operated for 7 days per week (168 h per week). The weighted maximum low quarter distribution uniformity decreases as turnout discharge increases and irrigation duration decreases. Furthermore the application efficiency for both 50 mm and 34 mm depths of application also decreases. As turnout duration decreases, the cut-off time in each field also decreases leading to an increasing number of solutions where the advance phase of irrigation remains incomplete (cut-off ratio < 1.00). Table 6 shows that for a turnout discharge of 50 L s⁻¹ the cut-off time is less than the time required for the water to advance to the downstream end of the field for 21 fields. The results indicate that, given the *warabandi* constraints of a fixed volumetric allocation whereby turnout discharge can only be increased by decreasing the irrigation duration, there is no advantage in seeking to increase the turnout discharge.

Changing the *warabandi* to 10-day rotation

In this section we explore the impact of increasing the *warabandi* irrigation interval from a 7-day interval to a 10-day interval over a range of turnout flowrates and irrigation durations. This would entail each farmer receiving an opportunity to irrigate three times per month rather

Table 6 Performance indicators for varying turnout discharge (7-day *warabandi*)

	Turnout discharge ($L s^{-1}$)						
	19.37	25	30	35	40	45	50
Turnout duration (h/week)	168	130	108	93	81	72	65
Volume (m^3)	129.07	129.07	129.07	129.07	129.07	129.07	129.07
Wtd. DU_{lq} max.	0.77	0.77	0.75	0.73	0.72	0.71	0.70
Wtd. AE_{50} (%)	83	82	81	80	79	79	79
Wtd. AE_{34} (%)	59	59	59	59	58	58	58
No. of solutions with incomplete advance	10	11	11	13	16	20	21

Table 7 Performance Indicators for varying turnout discharge (10-day *warabandi*)

Performance indicator	Turnout discharge ($L s^{-1}$)						
	19.37	25	30	35	40	45	50
Turnout duration (hrs/10-day interval)	240	186	155	133	116	103	93
Wtd. DU_{lq} max.	0.79	0.76	0.73	0.71	0.70	0.69	0.67
Wtd. AE_{48} (%)	59	59	58	58	58	57	57
No. of solutions with incomplete advance	2	2	2	2	4	4	6

than four times per month. Hence the total volume per month remains constant—i.e. the implications on the water resource remain identical.

From (1) for a 10-day interval the depth of application is 48 mm. Table 7 summarizes the results of the analysis reporting the weighted low quarter distribution uniformity (DU_{lq}) and application efficiency for a 48-mm application (AE_{48}) over flow rates of 19.37–50 $L s^{-1}$ for irrigation durations in the range 240–93 h, to maintain the volumetric allocation.

The results indicate no substantial change in weighted low quarter distribution uniformity or application efficiency as compared to the 7-day *warabandi*. The global optimum is obtained under the *warabandi* default discharge of the turnout of 19.37 $L s^{-1}$ with continuous flow for the 10-day interval. Comparing Table 7 with Table 6, we observe that maximizing the low quarter distribution uniformity (DU_{lq}) yields similar performance levels for the 7-day *warabandi*. As observed under the 7-day interval performance decreases as turnout discharge increases and irrigation duration decreases; however, there are fewer fields where the cut-off time is less than the time required for the water to advance to the downstream end of the field. This is intuitive as the turnout duration has increased (by 43 %) from 168 h in the 7-day *warabandi* to 240 h in the 10-day *warabandi*, and hence the cut-off time for each field increases by the same proportion (43 %).

In summary there is no significant advantage to be gained in performance by increasing irrigation period to 240 h with a 10-day *warabandi*. There may be some advantage in terms of lower labour costs under a 10-day *warabandi*, i.e. three irrigations per month rather than four irrigations per month. There are likely to be fewer fields where

the water is cut-off before it advances to the downstream end of the field. A 10-day *warabandi* would certainly synchronize better with 10-day cycle of water releases from the major reservoirs of the Indus Basin Irrigation System. However, there would be significant costs associated with changing the vast Indus Basin Irrigation System to a 10-day *warabandi*.

Sensitivity analysis

The sensitivity of the solution to discharge and Mannings roughness is summarized in Table 8. We use the weighted low quarter distribution uniformity and the weighted application efficiency as performance indicators. The sensitivity of the model solutions was tested over a range of discharge (19.37 $L s^{-1}$, ± 60 %) without any adjustment to cut-off times. This is the range of measured discharge relative to the rated discharge. Similarly the sensitivity of the model solutions was tested over a range of roughness coefficients (Mannings roughness 0.10 ± 60 %). Table 8 reports the absolute values of the performance indicators and also the percentage change in these performance indicators (δ). The weighted low quarter distribution uniformity varies non-linearly with discharge. For modest changes in discharge ± 20 % the weighted low quarter distribution uniformity is not very sensitive. For larger decreases in discharge (-60 %) the weighted low quarter distribution decreases significantly; however, for larger increases in discharge ($+60$ %) the weighted low quarter distribution uniformity is less sensitive. The tertiary unit displays similar behaviour whether configured for the 7-day and 10-day *warabandi*. The weighted application efficiency displays a rather different behaviour as compared to the weighted

Table 8 Sensitivity to discharge and Mannings roughness

	Parameter	7-day Warabandi		10-day Warabandi	
		Wtd. DU_{1q}	Wtd. AE_{34} (%)	Wtd. DU_{1q}	Wtd. AE_{48} (%)
Sensitivity to discharge (Mannings Roughness $n = 0.10$)	$Q - 60\%$	0.093 ($\Delta = -88\%$)	84.40 ($\Delta = 42\%$)	0.182 ($\Delta = -77\%$)	85.52 ($\Delta = 44\%$)
	$Q - 40\%$	0.386 ($\Delta = -50\%$)	81.32 ($\Delta = 37\%$)	0.424 ($\Delta = -46\%$)	81.70 ($\Delta = 38\%$)
	$Q - 20\%$	0.717 ($\Delta = -7\%$)	72.07 ($\Delta = 21\%$)	0.718 ($\Delta = -9\%$)	71.94 ($\Delta = 21\%$)
	$Q - 10\%$	0.770 ($\Delta = 0\%$)	65.78 ($\Delta = 11\%$)	0.785 ($\Delta = -1\%$)	65.02 ($\Delta = 10\%$)
	$Q = 19.37$	0.770	59.34	0.792	59.26
	$Q + 10\%$	0.750 ($\Delta = -3\%$)	54.56 ($\Delta = -8\%$)	0.766 ($\Delta = -3\%$)	53.50 ($\Delta = -10\%$)
	$Q + 20\%$	0.725 ($\Delta = -6\%$)	49.77 ($\Delta = -16\%$)	0.736 ($\Delta = -7\%$)	49.52 ($\Delta = -16\%$)
	$Q + 40\%$	0.676 ($\Delta = -12\%$)	42.82 ($\Delta = -28\%$)	0.693 ($\Delta = -13\%$)	42.65 ($\Delta = -28\%$)
	$Q + 60\%$	0.640 ($\Delta = -17\%$)	37.82 ($\Delta = -36\%$)	0.666 ($\Delta = -16\%$)	36.61 ($\Delta = -38\%$)
Sensitivity to Mannings Roughness (discharge = 19.37 L s^{-1})	$n - 60\%$	0.758	59.36	0.777	59.12
	$n - 40\%$	0.763	59.39	0.783	59.16
	$n - 20\%$	0.767	59.37	0.788	59.19
	$n - 10\%$	0.769	59.36	0.790	59.23
	$n = 0.1$	0.770	59.34	0.792	59.26
	$n + 10\%$	0.772	59.37	0.793	59.27
	$n + 20\%$	0.773	59.34	0.795	59.28
	$n + 40\%$	0.774	59.32	0.798	59.32
	$n + 60\%$	0.775	59.30	0.801	59.34

low quarter distribution. For decreases in discharge the weighted application efficiency increases, and for increases in discharge the weighted application efficiency decreases. This is because application efficiency is calculated as a ratio with a constant denominator—required depth of application. With smaller discharges smaller volumes of water are added to the field, and inevitably there is less deep percolation or surface runoff relative to this fixed required depth of application. Hence application efficiency increases. The converse is also true, and this again emphasizes the difficulty in using application efficiency as a performance indicator. This analysis suggests that surface irrigation performance is particularly sensitive to the available discharge, and thus, discharge needs to be managed particularly well.

Neither of the performance indicators is particularly sensitive to variations in roughness whether the tertiary unit is configured for the 7-day or 10-day *warabandi*. Therefore, changes in roughness due to crop growth or agronomic practices should not affect the performance significantly—stated alternatively the system performance is robust over a range roughness values.

Application efficiency and discharge

In “Materials and methods” section guided by the literature we assumed an application efficiency of 80 %. We have shown in Table 4 that the weighted application efficiency (for a depth of application of 50 mm) is indeed of this

order. However, when we use this application efficiency in a volume balance (1) we obtained a depth of application of only 34 mm for which the weighted application efficiency is only 60 %. Figure 8 shows the relationship between weighted application efficiency and the depth of application. Using (1) for a depth of application of 50 mm and application efficiency of 80 % the water allowance would need to be increased from 0.7 to $1.03 \text{ L s}^{-1} \text{ ha}^{-1}$. This corresponds to a turnout discharge of 28.60 L s^{-1} rather than 19.37 L s^{-1} operated continuously, i.e. 168 h per week. Coincidentally this is close to the average observed discharge of 29.17 L s^{-1} . At this discharge the weighted low quarter distribution uniformity is 0.75 and the application efficiency 81.13 %.

Hence for this tertiary unit the turnout discharge should be set based on delivering a 50 mm depth of application using (1) rather than based on the *warabandi* water allowance. Alternatively if the turnout discharge cannot be increased, then the area irrigated would need to be reduced from the current value of 75 % to approximately 51 % which would be socially difficult if not impossible to implement. Turnout discharges in the Indus Basin Irrigation System are reset at regular intervals and during major rehabilitation/development projects. Although changing the turnout discharge is entirely feasible. However, setting the discharge of a turnout such that it can deliver a minimum of 50 mm at an application efficiency of 80 % would have implications on the infrastructure, i.e. canal capacities and

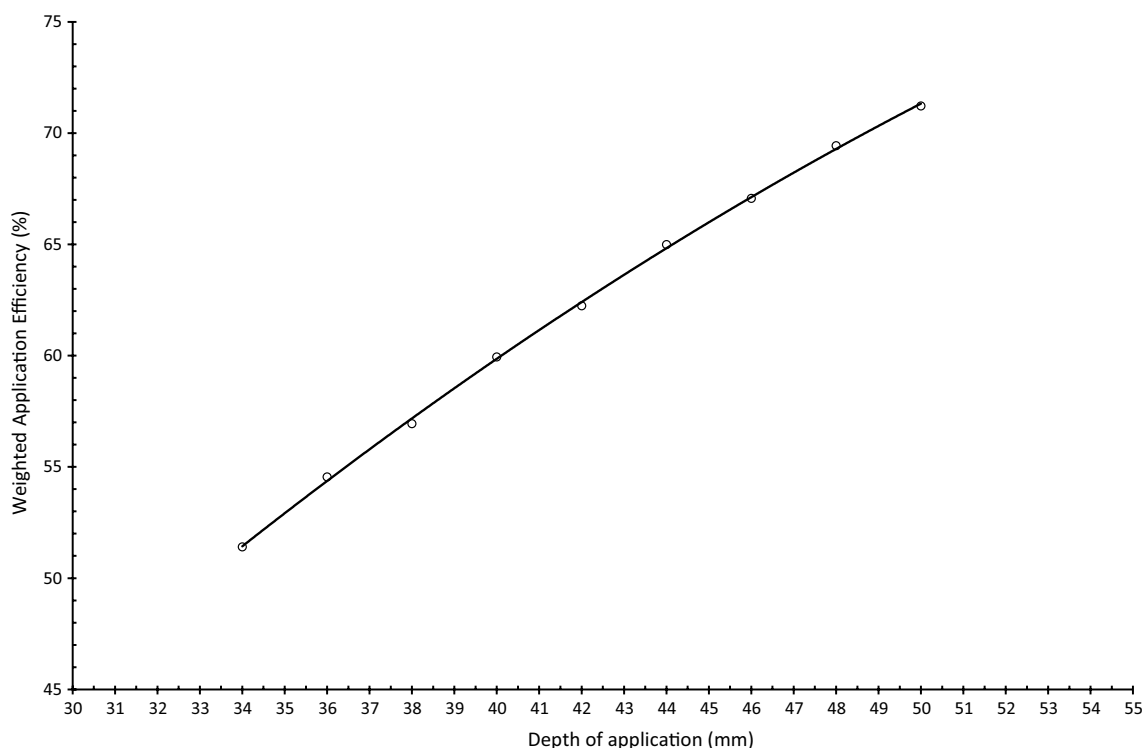


Fig. 8 Weighted application efficiency as a function of depth of application

the water resource. In the context of the Pehur High-Level Canal the system may have the ability to deliver the higher flows and the province of Khyber Pakhtunkhwa has never used its full water entitlement, i.e. the water resource may be available to exploit. Increasing turnout discharges would probably be more challenging and indeed infeasible in the Punjab Province where water is distributed over a much larger area and hence scarcer. However, in the Punjab the area irrigated as a proportion of total area is considerably less than that in the Khyber Pakhtunkhwa Province, and hence this merits further investigation.

Conclusions and recommendations

In this paper we present an analysis of irrigation performance for a tertiary unit with 95 heterogeneous fields that are irrigated under the *warabandi* system of management prevalent in the Indus Basin Irrigation System. We have shown that it is possible to achieve a high application efficiency of the order of 80 % for realistic required depths of application. Guided by the literature we recommend a value of 50 mm and show it is possible to obtain an application efficiency of 80 %. We have presented and recommend a simple volume balance equation (Eq. 1) that enables turnout discharge to be estimated for given irrigation design parameters. This is a fundamentally different approach to

the current practice of setting turnout discharge based on a *warabandi* water allowance.

We show that there is no substantial performance improvement to be obtained by increasing turnout discharge if the total volume of water delivered remains constant. We also show that there is no substantial change in performance if the *warabandi* interval is increased from 7 days to 10 days. This makes the case to maintain the status quo of the 7-day *warabandi* interval and a cut-off time based on the *warabandi* principles.

Our research indicates that an application efficiency of 80 % is achievable provided the depth of application is set at the recommended value of 50 mm. This in turn has implications for turnout discharge and a fundamental divergence from how turnout discharge is typically estimated in *warabandi* managed irrigation systems. From a farmers perspective the turnout discharge would increase; however, the cut-off times dictated by the *warabandi* would remain unchanged—hence we assert this would be socially acceptable. For the fields to behave as predicted by the model presented fields would need to be accurately (laser) graded and turnout flow rates maintained at a constant optimum value and border strips set to the range recommended. From this research we conclude that the precision surface irrigation paradigm in the context of the Indus Basin Irrigation System has the potential to deliver irrigation efficiently. We would recommend intervention in one tertiary unit

and detailed field measurements undertaken to determine whether the observed performance indicators correspond to those obtained through such a modelling exercise.

This work is limited in scope to one relatively small tertiary unit. The work presented herein does not consider changing the slope of fields to optimize performance and nor does it examine the sensitivity of the performance to variability in slope or infiltration which could be the subject of further research. Further research needs to be undertaken to determine whether these findings are valid in the context of larger tertiary units and in the context of a whole canal system. Furthermore, this work has been applied to only one irrigation canal within the 14.87 M ha (Frenken 2012), Indus Basin Irrigation System with a relatively generous water allowance. This research needs to be extended to other irrigation canals which have considerably smaller water allowances and more prevalent within the Indus Basin Irrigation System to assess whether such high application efficiencies are achievable in these field units. This work is limited to in-field irrigation operations, i.e. it only addresses the issue if/when a farmer chooses to irrigate. However, the data show that farmers regularly abstain from irrigation. Hence the system needs to respond to the demand for water. This is an entire body of research in its own right.

Acknowledgments The International Water Management Institute (IWMI) is in receipt of financial support from the Embassy of the Kingdom of Netherlands, Islamabad, Pakistan, through Grant #22294, the United Nations University, Institute of Sustainability and Peace Grant# 600UU 848 and the CGIAR Research Program on Water, Land and Ecosystems (WLE) which were used in part to support this study. The authors would like to acknowledge the contribution of research interns, Shamoil Bin Akram and Khan Abdul Hannan. The study design, data collection, analysis and interpretation of the results are exclusively those of the authors.

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