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Evaluation of hydraulic efficiency of lined irrigation channels – A case study from Punjab, Pakistan

Ghulam Zakir-Hassan[a,b,c], Muhammad Akram Kahlown[d], Jehangir F. Punthakey[c], Ghulam Shabir[a], Marjan Aziz[e], Muhammad Sultan[f], Hadeed Ashraf[f], Qurrat ul ain Nawaz[g] and Faizan Majeed[f,h,*]

[a] Irrigation Research Institute (IRI), Irrigation Department, Govt. of the Punjab, Lahore 54500, Pakistan
[b] School of Agricultural, Environmental and Veterinary Sciences, Charles Sturt University, Albury, NSW 2640, Australia
[c] Gulbali Institute, Charles Sturt University, Albury, NSW 2640, Australia
[d] Pakistan Council of Research in Water Resources (PCRWR), Khayaban-e-Johar Road, Islamabad 44000, Pakistan
[e] Barani Agricultural Research Institute (BARI), Talagang Road, Chakwal, Pakistan
[f] Department of Agricultural Engineering, Bahauddin Zakariya University, Bosan Road, Multan 60800, Pakistan
[g] Institute of Soil and Environmental Sciences, Faculty of Agriculture, University of Agriculture, Faisalabad 38040, Pakistan
[h] Department of Agricultural and Biosystems Engineering, University of Kassel, Witzenhausen 37213, Germany
*Corresponding author. E-mail: faizanmajeed@bzu.edu.pk

FM, 0000-0002-1965-4851

ABSTRACT

Indus Basin Irrigation System (IBIS) in Pakistan is the backbone of agriculture in the country. The IBIS provides irrigation support to agricultural lands across the country; however, hydraulic efficiency of the water conveyance system is impacted due to seepage losses. The lining of irrigation channels is considered a potential solution for improving hydraulic efficiency. Therefore, this study explores the impact of canal lining on the hydraulic efficiency of the canals in the Punjab province of Pakistan. Overall, 14 channels/distributaries/minors (total length 226 km) were monitored in terms of hydraulic performance in different irrigation zones. Hydraulic, geometrical, and socioeconomic parameters of channel/distributaries/minors including roughness coefficient, sediments, flow velocity, wetted parameter, breaches, theft cases, bed, side slope, water surface profile, hydraulic radius, crop yield, and vegetation growth area have been experimentally observed. Obtained results have been compared with the design and pre-lining data. Ten seepage tests using the inflow -outflow method and eight seepage tests using the ponding method were conducted to estimate seepage losses. Results indicate that almost all the parameters varied from the design values. A detailed comparison of the socioeconomic parameters has been carried out. Results from seepage tests show an approximately 78% reduction in losses.

Key words: canal lining, groundwater recharge, hydraulic performance, Pakistan, seepage, socioeconomic impact

HIGHLIGHTS

- Canal lining has reduced seepage losses by ~78%.
- Built cross-sections are ~5% bigger than design cross-sections.
- Concrete lining (1:2:4 P.C.C.) is more suitable for future canal lining.
- Froma socioeconomic view, canal lining improved equity and reliability of water distribution.
- The useful physical life of 1:2:4 P.C.C. lining is 30–50 years, brick lined ~20–25 years, and protected geosynthetics more than 50 years.

1. INTRODUCTION

The Indus Basin Irrigation System (IBIS) is a network of dams, canals, and other structures that were built in the early 20th century to irrigate agricultural land in the Indus River basin in Pakistan. It is one of the largest irrigation systems in the world, covering an area of about 16 million hectares. The IBIS is fed by the Indus River and its tributaries, and it provides water for crops such as wheat, rice, sugarcane, and cotton. The IBIS has played a major role in the development of agriculture in Pakistan, but it has also led to environmental and social problems, including water seepage losses, waterlogging in some cases, salinization of soil, and reduction in water table depth due to canal lining. Canal lining is a technique used to improve the efficiency of irrigation canals by preventing water loss due to seepage and evaporation.

In the IBIS, lining canals can increase hydraulic efficiency by reducing the amount of water that is lost before it reaches the fields. This can lead to an increase in the amount of water available for irrigation and can also improve the quality of the water by reducing the amount of sediment and other contaminants that are carried in the canal. However, the effects of canal lining on hydraulic efficiency can vary depending on the type of lining used and the specific conditions of the canal. The concrete lining is often considered to be the most effective for reducing water losses, but it can also be costly and difficult to install and maintain. Alternative methods such as earthen, plastic, and polyvinyl chloride (PVC) lining can also be used, but they may not be as effective in reducing water losses. Overall, while canal lining is seen as a way to increase hydraulic efficiency in the IBIS, it is a complex issue and requires careful consideration of the technical and economic aspects, as well as the potential environmental and social impacts. Seepage from the canal network is one of the major sources of groundwater recharge and in the areas where surface water is not sufficient, this recharged water is reused for irrigation through pumping by tube wells (Kahlown *et al.* 2007; Shah 2019). When the IBIS was constructed by the British during their rule over the subcontinent during the 19th century, the water table started rising due to a significant amount of recharge contributed by seepage of canal water (Hassan & Bhutta 1996; Alam & Bhutta 2004). Sometimes this recharge to the aquifer has positive impacts while sometimes it poses adverse implications on the hydrogeological system. In urban localities, it has a positive environmental impact by improvising groundwater quality and replenishing the depleted aquifers, especially when groundwater quality is fresh (Zakir-Hassan *et al.* 2016, 2022). In other areas where groundwater quality is brackish, this water cannot be reused and such recharge is not recommended (Bhutta & Smedema 2007; IRI 2019). In IRB volume of recharge to the aquifer is linked with discharge in rivers and increases significantly during floods (Hassan & Hassan 2018). How much canal water is lost/recharged to the aquifer has remained a question for the planners and policy-makers for the management of water resources. Overall efficiency has been reported as low as 36% in some parts of the IRB (Hussain *et al.* 2011). By saving the canal seepage water, extra land can be brought under irrigation (Atmapoojya *et al.* 2001). Sometimes interceptor drains have been proposed and constructed for the seepage from canals (Izhar-ul-Haq 1996). While comparing seepage results by different methods, Zhang *et al.* (2017) found that if sufficient reliable data are available the empirical formula can yield results closer to the field experiment. What is the improvement in the hydraulic performance of irrigation canals after a huge investment in lining is a question still to be answered. Canal lining is adopted as one of the measures to control the hydraulic efficiency of the irrigation delivery system. To find out the answers to such questions, the government of the Punjab of Islamic Republic of Pakistan, through the Irrigation Department, implemented Punjab Irrigation System Improvement Project (PISIP) financed by Japan International Cooperation Agency (JICA) (IRI 2019). Under this project, a study titled 'Study on impact assessment of canal lining in Punjab' has been carried out by the Irrigation Research Institute (IRI) of Punjab Irrigation Department (PID) through field surveys, measurements, investigations, and performance of seepage tests (IRI 2019). Comparative hydraulic performance of lined and unlined canals in different parts of the Punjab Province of Pakistan has been carried out. This study was deemed imperative as the PID has lined more than 230 canals in the last 15 years (IRI 2019). Under PISIP alone, more than 1,000 km of irrigation channels have been lined. In addition to this, several channels have been lined under the Lower Chenab Canal (LCC) Projects, Command Water Management Project (CWMP), Fordwah Eastern Sadiqia South (FESS) Project, Public Sector Development Program (PSDP) projects by the federal government and Annual Development Programs (ADP) schemes by the provincial government (IRI 2019). Water saved through the lining of canals can ensure equitable and reliable water supply to farmers for increasing crop yields and cropping intensity, help control water logging, prevention of channel bank erosion and breaches, and reduction in operational and maintenance costs. The joint distribution of rainfall and tide level can have a significant impact on groundwater recharge and hydraulic efficiency in coastal areas where the IBIS is located. During high tide, the groundwater table can rise, allowing for more efficient recharge of aquifers through the percolation of surface water. Conversely, during low tide, the groundwater table can drop, reducing the efficiency of recharge. In addition, rainfall can also affect groundwater recharge and hydraulic efficiency. Heavy rainfall can cause flooding, leading to a rapid recharge of aquifers, but also potentially causing damage to irrigation infrastructure and reducing the efficiency of irrigation. On the other hand, low rainfall can lead to a decrease in recharge and an increase in water stress. A simulation and design study on the joint distribution of rainfall and tide levels in China shows that these parameters can be correlated with groundwater recharge and hydraulic efficiency of irrigation channels (Gao *et al.* 2021). Extreme value theory can be used to analyze the distribution of extreme nutrient concentrations in irrigation water and to estimate the probability of these concentrations exceeding certain thresholds. These thresholds can be used to establish nutrient criteria that are protective of aquatic life and human health. Grounding on the established nutrient criteria, managers can develop management strategies to mitigate negative impacts on groundwater recharge and hydraulic efficiency. For example, if high nutrient concentrations are found to be associated with reduced recharge and efficiency, management strategies could include reducing the use of fertilizers, implementing best management practices for nutrient application, or increasing monitoring and enforcement of water quality regulations. Similar studies have been conducted in China to establish the extreme value theory for nutrient criteria in bay waters (Fang *et al.* 2021). By using a runoff generation model, managers can identify areas where the irrigation system may be particularly vulnerable to changes in water availability, and develop targeted management strategies to protect these areas. For example, if the model predicts that irrigation efficiency is low in certain areas due to reduced recharge, management strategies could include increasing the use of water-saving technologies or implementing best management practices for irrigation. Furthermore, the correlation of the runoff model with groundwater recharge and hydraulic efficiency can also be used to identify areas where the irrigation system may be particularly vulnerable to changes in water availability and to develop targeted management strategies to protect these areas (Liu *et al.* 2020). Correlating root-zone soil moisture with groundwater recharge and hydraulic efficiency in the IBIS can help to understand the interactions between surface water and groundwater and inform management decisions. When the soil moisture in the root-zone is adequate, it can improve the efficiency of irrigation by reducing water stress on plants and allowing for more efficient use of water. However, when soil moisture is too high, it can lead to waterlogging and reduced oxygen to the roots, reducing plant growth and reducing the efficiency of irrigation (Zhang *et al.* 2019). Atmospheric parameters such as precipitation, temperature, humidity, and wind speed can affect the hydrological cycle, including the amount of water that is available for irrigation and the rate of evaporation from the canals. For example, high precipitation can lead to increased water in the canals, while high temperatures and low humidity can lead to increased evaporation. Furthermore, by correlating atmospheric parameters with the hydraulic efficiency of lined canals, managers can identify the specific conditions that are most likely to lead to reduced efficiency and develop targeted management strategies to address these issues (Zhao *et al.* 2020; Zhang *et al.* 2021; Quan *et al.* 2022). By using hydrological models, managers can identify conditions that are likely to lead to reduced hydraulic efficiency in the lined canals and develop management strategies to mitigate these effects. For example, if the model predicts that irrigation efficiency is low in certain areas due to reduced recharge, management strategies could include increasing the use of water-saving technologies or implementing best management practices for irrigation (Li & Zhang 2008; Huo *et al.* 2019). Correlating heterogeneous aquifer structures with the hydraulic efficiency of lined canals in the IBIS can help to understand how variations in the subsurface geology affect the performance of the canals and inform management decisions. A heterogeneous aquifer structure refers to variations in the subsurface geology, such as changes in rock type, porosity, or permeability, that can lead to variations in the amount of water that is available for recharge and the rate at which water can move through the subsurface. In general, a heterogeneous aquifer structure can lead to uneven distribution of water resources, with some areas having better recharge and storage capacity than others. This can affect the hydraulic efficiency of the lined canals, as some areas may have more water available for irrigation while others may have less (Zhan *et al.* 2022). Moreover, the construction of dams in the IBIS can have an impact on precipitation and ultimately on the hydraulic efficiency of lined canals. Dams can alter the local and regional weather patterns by changing the amount of water that is available for evaporation, which can affect precipitation. Dams can also alter the timing and distribution of precipitation by changing the flow patterns of rivers, which can affect the amount of water that is available for irrigation. The impact of dam construction on precipitation and hydraulic efficiency can vary depending on the location and design of the dam, as well as on the existing weather patterns and land use in the area. In general, dams can lead to a reduction in the amount of water available for irrigation, which can reduce the hydraulic efficiency of the lined canals (Zhu *et al.* 2022). Urbanization can lead to land use changes such as the conversion of agricultural land to urban or industrial areas, or the construction of buildings, roads, and other infrastructure. These changes can affect the hydraulic efficiency of lined channels by altering the amount of water that is available for irrigation, the rate of runoff, and the rate of evaporation. For example, urbanization can lead to increased runoff and reduced infiltration, which can reduce the amount of water that is available for irrigation. Urbanization can also lead to increased evaporation, which can reduce the amount of water that is available for irrigation. Additionally, urbanization can lead to changes in the timing and distribution of water, which can also affect the hydraulic efficiency of lined channels (Xu *et al.* 2022).

All in all, canal lining can improve the hydraulic efficiency of the irrigation water conveyance and delivery system, whereas it can also have an inverse impact on the groundwater level. Therefore, this paper encapsulates the evaluation and comparison of various hydraulic efficiency parameters of lined and unlined channels in the study area.

2. STUDY AREA AND METHODOLOGY

Different canals in Faisalabad, Sargodha, Dera Ghazi Khan, and Bahawalpur Irrigation Zones of the Punjab province in Pakistan have been selected for testing and evaluation. The location of these canals is shown in Figure 1. The scope of the study included hydraulic evaluation of canals lined, measurement of hydraulic and hydrological parameters including seepage rates; roughness coefficient; flow velocity; wetted perimeter; canal bed slope; side slope; water surface profile; hydraulic radius; and cross-sectional area of the channels. These parameters were observed in the field for the purpose of evaluating the hydraulic efficiency of the channels.

Keeping in view the problem statement in the previous section, different canals in Faisalabad, Sargodha, Dera Ghazi Khan and Bahawalpur Irrigation Zones were selected based on the criteria for selection, in line with published literature (IRI 2019), given below:

- Areal distribution-scattered across the whole province
- Location of the distributaries: head, middle, and tail of the main canal
- Discharge size of the distributaries: large, medium, small – more preference for small as same preferred for lining under PISIP
- Availability of pre-lining data on seepage and other hydraulic parameters
- Lining materials – efforts were made to select different lining materials like concrete, geosynthetics
- Lining age/life – some newly constructed and some old
- Representation of the channels lined – almost 5% of lined channels were selected for evaluation
- Groundwater quality zones: some channels from fresh and some from brackish zones were selected
- Soil strata – some from sandy and some from clay zones

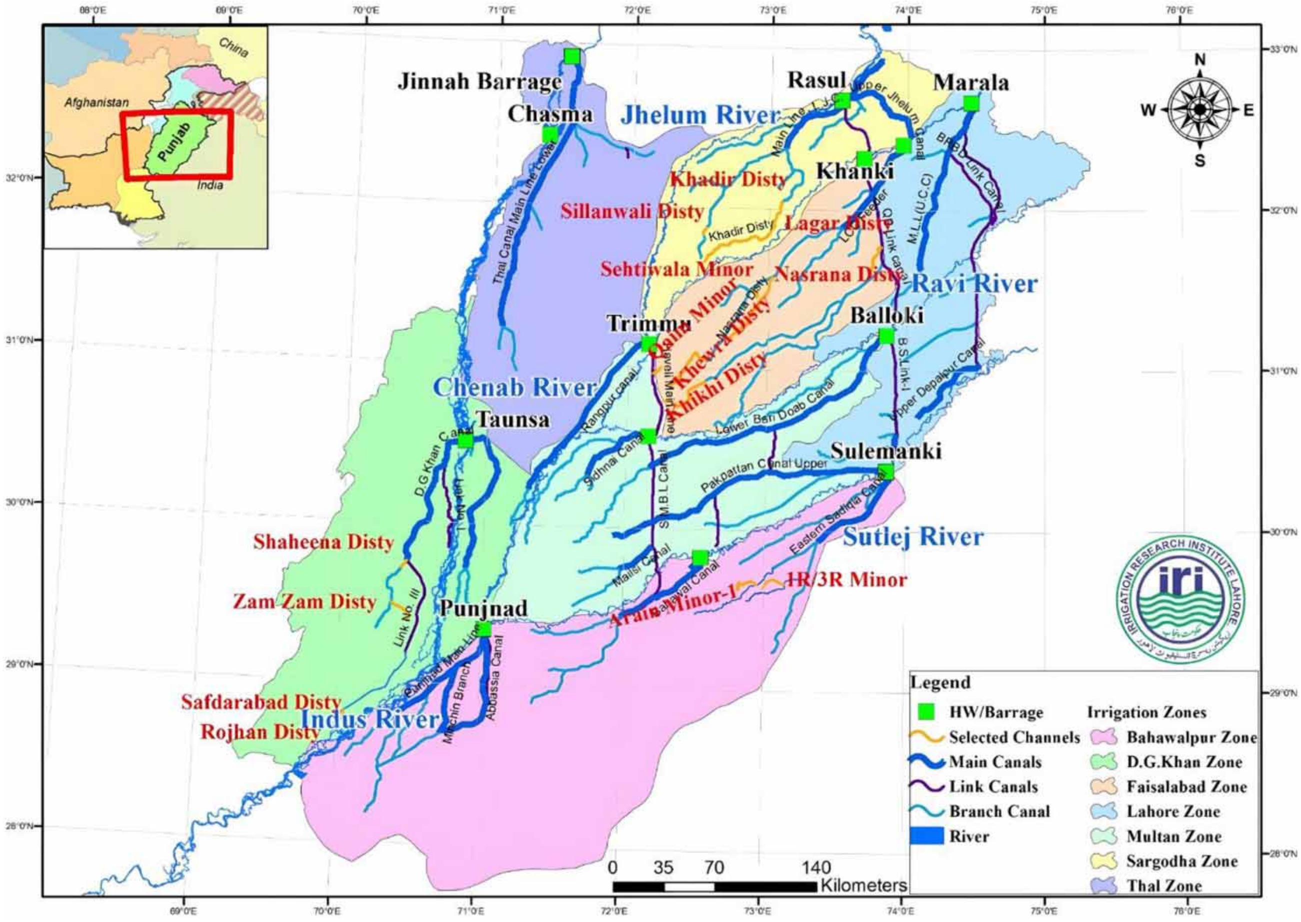


Figure 1 | Map of study area showing different irrigation zones in Punjab, Pakistan.

Efforts were made to select the channels to represent various geographical locations, different lining materials, old and new lining, and other factors as enlisted above. Based on these attributes, 14 channels were selected for the study of the impact assessment of lining on the hydraulic efficiency of irrigation channels. A number of channels selected in different zones under different categories of discharge is given in Table 1. About 5% sample of the total population of lined channels was selected for the study. Preference was given to small channels as the same was the criteria for the identification of channels for lining. The salient features of selected channels for the study are given in Table 2. Irrigation zones wise percentage of selected channels is shown in Figure 2. The location of selected channels in all irrigation zones are shown in Figure 3. Different steps taken to accomplish this research study are shown in Figure 4.

2.1. Measurement of seepage losses

Seepage losses refer to the amount of water that is lost from a canal or reservoir due to percolation into the surrounding soil or rock. Measuring seepage losses can be important for understanding the performance of the irrigation system and for identifying areas where management actions may be needed to reduce losses. There are several methods that can be used to measure seepage losses, including (i) tracer methods which involve introducing a tracer, such as a dye or a radioactive substance, into the water and then measuring its concentration in the surrounding soil or rock, (ii) inflow–outflow method which is more commonly referred to as water balance method, which involves measuring the inflow, outflow, and storage of water in a canal or reservoir, and then calculating the seepage losses as the difference between inflow and outflow, (iii) seepage meters which involve installing a device, such as a standpipe or a seepage meter, in the canal or reservoir to directly measure the amount of seepage, and (iv) hydraulic gradient method which involves measuring the water pressure at different points along a canal or reservoir and then using the difference in pressure to calculate the seepage losses. The choice of method will depend on the specific conditions of the canal or reservoir and the information that is needed. Canal seepage primarily depends upon the soil permeability, water depth in the canal, wetted perimeter of the canal, geometry of channel, groundwater level, flow velocity in the channel, shear stress (force of moving water on bed), hydraulic gradient line, and other factors (Kraatz 1977; Shah 2019). Estimation of water loss in the canal is imperative for the design, operation, and maintenance of water distribution systems (Atmapoojya *et al.* 2001). Seepage losses can be determined by different methods including empirical equations, seepage meters, inflow–outflow method, ponding method, flow-nets, numerical models, tracer techniques (Scanlon *et al.* 2002; Alam & Bhutta 2004; Sepaskhah & Salemi 2004; Arshad *et al.* 2009a; Shah 2019). Numerical models are also being used globally to estimate the seepage/recharge to the aquifer (Punthakey *et al.* 1994). Kahlown & Kemper (2004) conducted a study to evaluate the impact of conditions and composition of channel banks on seepage rates from earthen canals. They found that about half of the water released in a canal is lost before it reaches the farm-gate. They also concluded that the seepage loss from the channels is more significantly dependent upon the formation of the bank of the channels as compared with soil strata. They also observed that 80% of seepage losses occur from the top 8 cm of the channels' bank. Akkuzu (2012) measured seepage losses by inflow–outflow methods and compared them with two empirical equations by Moritz and Davis-Wilson and concluded that estimates of seepage by empirical equations are on the much higher side. It was recommended that whenever empirical formulae are to be used; these must be calibrated with canal conditions before use. Electro-magnetic and numerical methods can also be used to analyze and measure the seepage

Table 1 | Zone-wise and discharge wise number of selected channels (1 cfs = 0.0283 cumecs)

	Discharge ranges (cfs)			
Name of irrigation zone	**< 50**	**51–200**	**> 200**	**No of channels selected**
Faisalabad	3	–	3	6
Sargodha	2	–	–	2
D.G. Khan	3	1	–	4
Bahawalpur	–	2	–	2
Total	8	3	3	14
	58%	21%	21%	

Table 2 | Salient features of the selected channels (1 cusec = 0.0283 cumecs; 1 ft = 0.3048 m)

Name of zone	Sr #	Name of channel	Discharge (Cusecs)	Lined length (ft.)	Year/month of lining Start date	Year/month of lining End date	Approximate age of lining (years)
Faisalabad Zone	1	Nasrana Disty	275	57,662	25 Feb 2011	29 Mar 2014	4
	2	Sehti Wala Minor	14	24,095	23 Sep 2011	31 Oct 2014	4
	3	Khewra Disty	372	76,100	30 Apr 2011	21 Oct 2014	4
	4	Qaim Minor	9.01	25,420	25 May 2011	21 Oct 2014	4
	5	Lagar Disty	38	62,215	2014	2015	3
	6	Khikhi Disty	321	131,635	2014	2015	3
Sargodha Zone	7	Sillanwali Disty	17	17,580	2006	2006	12
	8	Khadir Disty	235	Being lined	2018	2018	
DG Khan Zone	9	Shaheena Disty	9.7	11,500	18.05.2011	28 Mar 2014	4
	10	Zam Disty	133	24,974	13 May 2011	31 Mar 2014	4
	11	Safdar Abad Disty	21.71	21,200	15 Apr 2011	05 May 2014	4
	12	Rojhan Minor	47	35,000	15 Apr 2011	05 May 2014	4
Bahawalpur Zone	13	Arain Minor	58	65,547	22 Aug 2011	18 Sep 2014	4
	14	1R/3R minor	80	60,375	1998	1999	19

losses from canals (Rushton & Redshaw 1979; Pognant *et al.* 2013) There are uncertainties associated with each method depending upon many factors like channels geometry, discharge of canal, soil strata, equipment errors, human errors, fluctuations in discharge (IRI 1996; 1998; Scanlon *et al.* 2002; Alam & Bhutta 2004; Sepaskhah & Salemi 2004). Among all these methods, ponding and inflow–outflow are the most adopted methods for physical and site-specific measurements in the field and further; ponding methods are comparatively more accurate and reliable if permitted by site conditions (IRI 1996; Alam & Bhutta 2004; Zhang *et al.* 2017). The aquifer underlying the IBIS is mostly unconfined where seepage from the irrigation system is a major source of recharge to groundwater (Arshad *et al.* 2009a; Shah 2019).

The selection of a method for estimation of seepage losses from the irrigation canals generally depends upon the purpose of the study, availability of time, accuracy required, rate of seepage, finances available, technical, and human resources (Martin

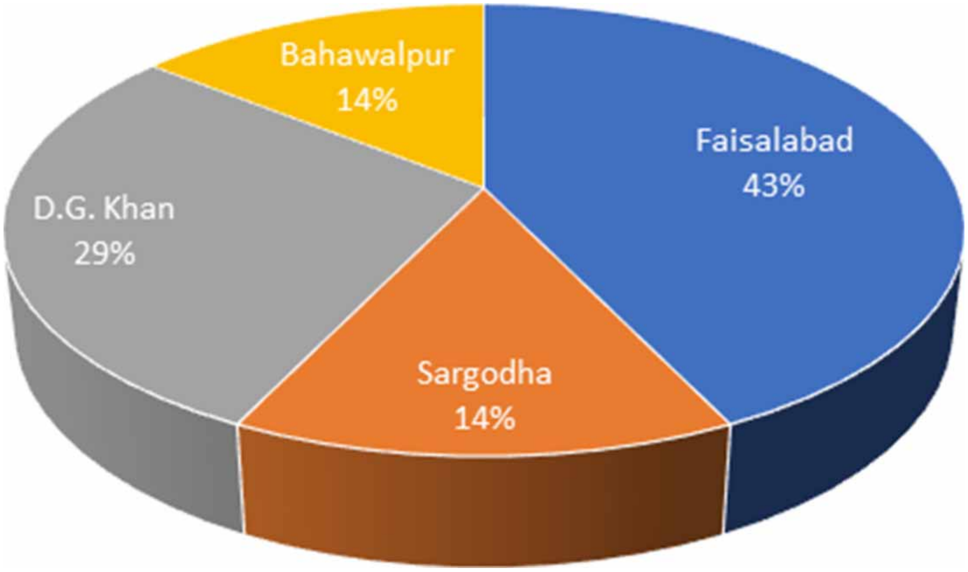


Figure 2 | Irrigation zones wise percentage of selected channels.

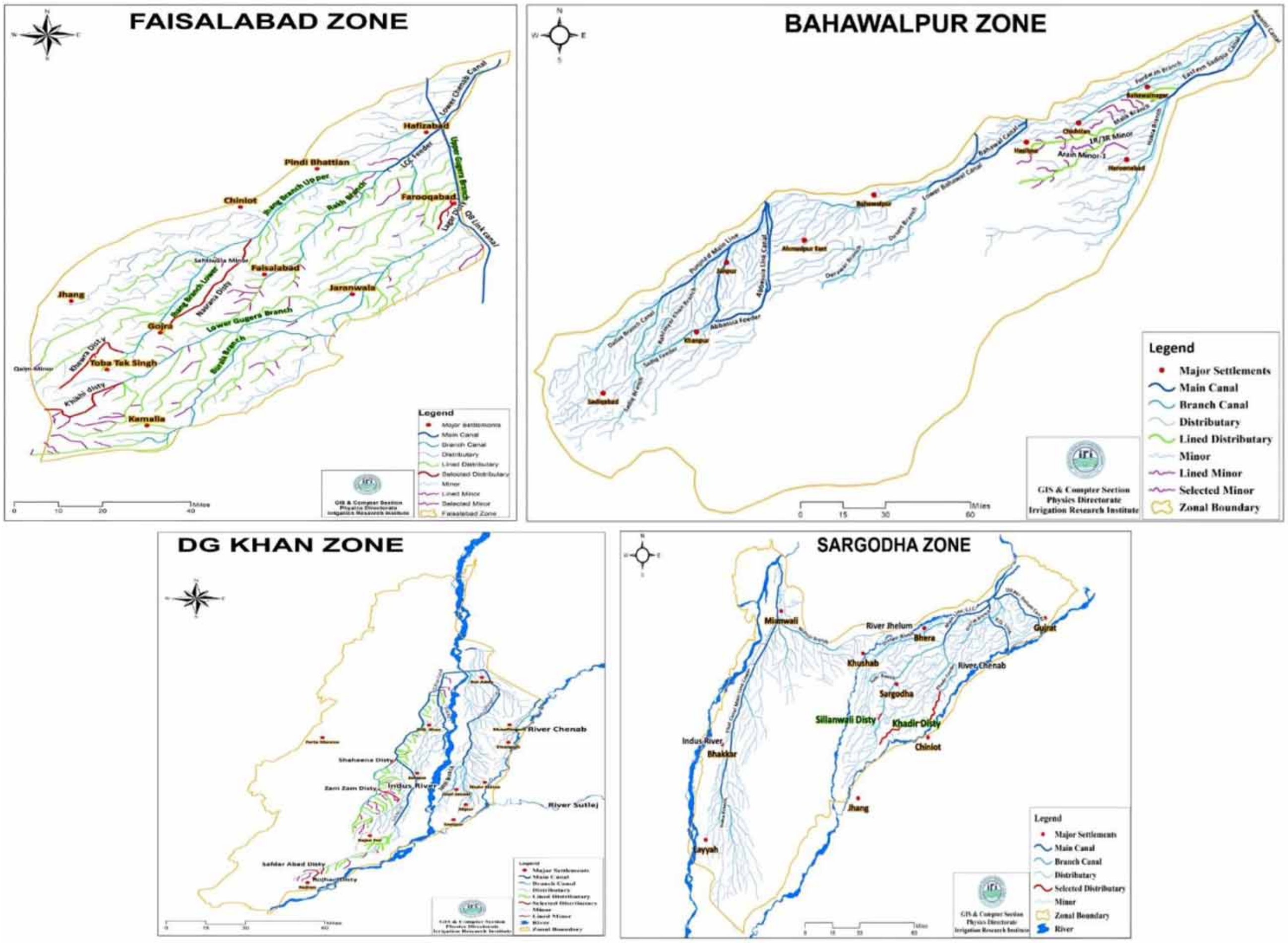


Figure 3 | Locations of channels selected in different irrigation zones.

& Gates 2014). They have further reported that the inflow-flow (water balance) method is most extensively used in flowing canals. While carrying uncertainty and sensitivity analysis they concluded that besides the discharge measurements at both ends, the fluctuations in discharge in the channel also have a significant impact on the accuracy of results. In the present study, inflow–outflow and ponding methods were used in the field for measurements of seepage losses from selected channels (IRI 2019). The ponding method is rarely used for large canals (Zhang *et al.* 2017).

2.1.1. Inflow–outflow method

The water balance method is a common approach for measuring seepage losses in canals and reservoirs. The method involves measuring the inflow, outflow, and storage of water in a canal or reservoir, and then calculating the seepage losses as the difference between inflow and outflow. Inflow can be measured by measuring the flow rate at the upstream end of the canal or reservoir, while outflow can be measured by measuring the flow rate at the downstream end. Storage can be measured by measuring the water level in the canal or reservoir. By measuring these variables over a period, the seepage losses can be calculated as the difference between inflow and outflow, minus any changes in storage. It is important to note that, for accurate results, the measurements should be taken over a period that is long enough to capture changes in water availability due to precipitation and evaporation, but not so long that the measurements are affected by long-term changes in the canal or reservoir, such as sedimentation. Additionally, the water balance method may not account for all the losses, such as losses due to evapotranspiration, infiltration, or other causes. Therefore, it is important to

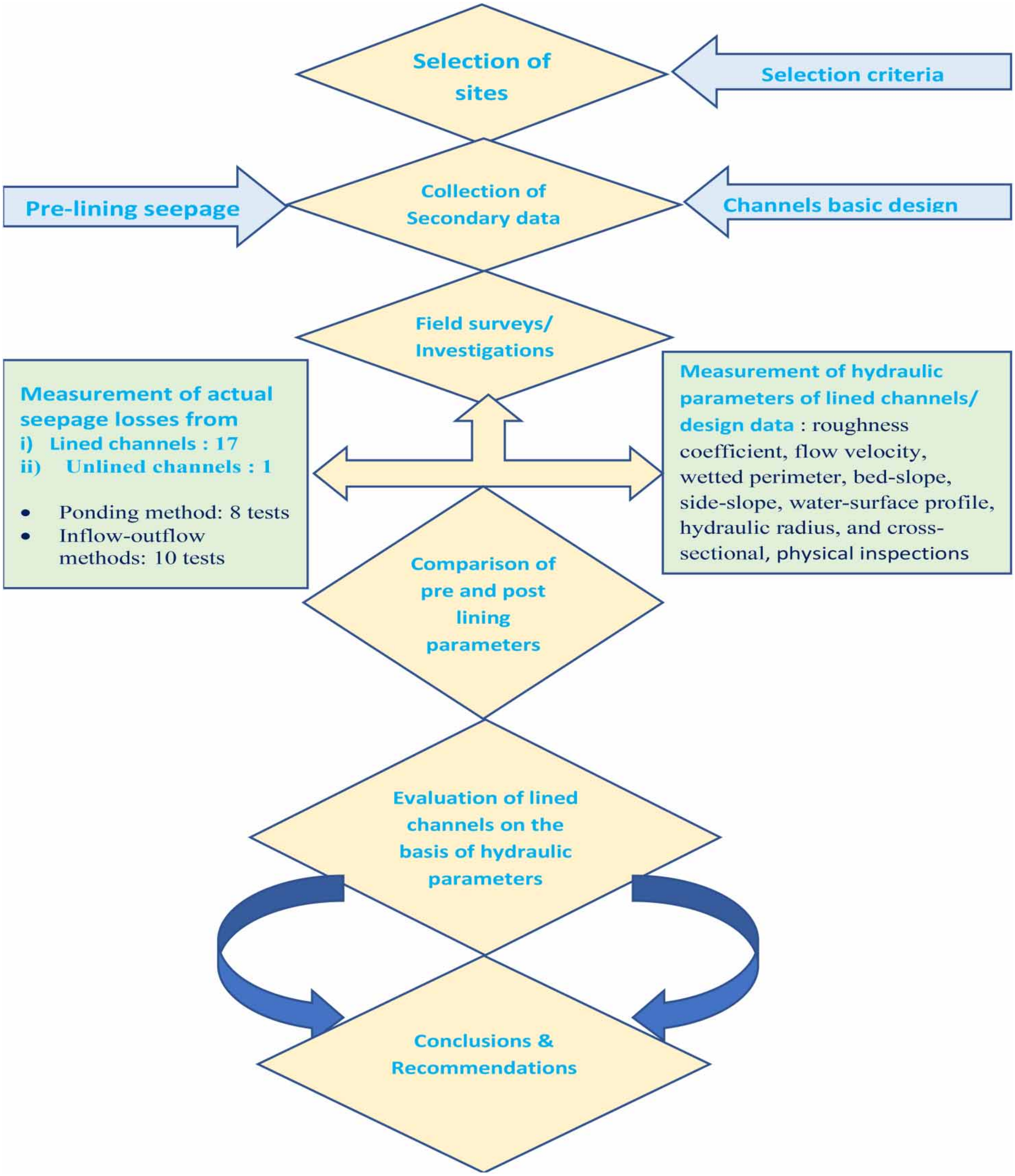


Figure 4 | Selected research methodology for the study.

consider these factors when interpreting the results. Overall, the water balance method is a simple and effective way to measure seepage losses in canals and reservoirs, but it should be used in conjunction with other methods to provide a more comprehensive understanding of the system's losses. The major advantage of this method is that it can be used in flowing water (IRI 1998; Arshad *et al.* 2009b). The basic equation used for the inflow–outflow method is given as the following equation:

$$S = \frac{Q_a - \sum_{i=1}^{n} Q_i - Q_b - E + R}{PL} \tag{1}$$

where S is the seepage loss (cfs/ft^2) (1 cfs/ft^2 = 0.3048 cumecs/m^2); Q^a is discharge of canal at the inflow section (cfs) (1 cfs = 0.0283 cumecs), Q_b is the discharge of canal at outflow section (cfs) (1 cfs = 0.0283 cumecs); Q_i is the discharge of its off -takings/outlets within the test reach (cfs) (1 cfs = 0.0283 cumecs); n is the total number of off -takings in test reach; E is the evaporation loss (cfs) (1 cfs = 0.0283 cumecs); R is rainfall (cfs) (1 cfs = 0.0283 cumecs); P is the average wetted perimeter (ft) (1 ft = 0.3048 m); and L is the length of test reach (ft) (1 ft = 0.3048 m).

All the efforts were made to minimize the errors in measurements due to equipment, humans, flow-fluctuations. Evaporation losses were measured at the site using class-A evaporation pan (IRI 2019). If seepage losses are small, evaporation and rainfall must also be considered even though these factors generally have no significant effect on seepage loss (Kraatz 1977). In the present study, rainfall was observed/measured by installing standard rain gauges at the test sites. Well-calibrated current meters were used to measure the discharge. The two-point and six-tenths depth methods are two recommended methods for the observation of velocities in channels (IRI 2019). The two-point method is recommended for large canals, where the depth of water is more than 0.75 m. It consists of measuring the velocities at 0.2 and then at 0.8 of the depth of water from the water surface. Then the average of these two observations is adopted as the mean velocity in a vertical. The accuracy obtained with this method is high. In situations where the two-point method is not applicable or where the depth of water is less than 0.75 m, the six-tenths method is used. This method consists of measuring the velocity at 0.6 of the depth from the water surface and adopting this velocity as the mean velocity in that vertical. This procedure gives satisfactory results (Kraatz 1977). The water gauge in the channel was kept constant to minimize the fluctuations in the discharge of the channel during test duration. Discharges of all outlets were measured with similar accuracy to keep minimum errors. All measurements were repeated three times to get an average value to be used in the further calculation for seepage measurements (IRI 2019). A summary of inflow–outflow tests performed is given in Table 3. As evident from Table 3, a total of 10 tests were performed on eight channels. The total length of these eight channels is 692,709 ft (211 km) out of which 224,200 ft (68 km) length has been tested which becomes 32% of the total length. One test was performed on the unlined channel (Khadir Disty), which was being lined at the time of field testing. The range of test reaches is 4–9 km with an average value of 7 km of test reach. It is a significant length of test reach and is generally not available in the literature (Shah 2019). Each test was repeated to get an average and more accurate results.

In the case of Lagar Disty and Nasrana Disty, two tests were performed for each and the ponding method was preferred where possible, i.e., rotational canal-closure was available. All tests were performed with greater accuracy and care to minimize the element of human and equipment error.

Table 3 | Summary of the inflow-outflow tests performed (1 ft = 0.3048 m)

Test No.	Name of channels	Test reach (ft)	Total length of channel	Percentage of length tested
1	Lagar Disty-1	23,000	62,215	85
2	Lagar Disty-2	29,850		
3	Nasrana Disty-1	16,560	57,662	83
4	Nasrana Disty-2	17,400		
5	Sehtiwala Minor	19,880	24,095	59
6	Khikhi Disty.	23,310	131,635	18
7	Arain minor-1	28,600	65,547	44
8	1R/3R Disty.	23,650	60,375	39
9	Sillanwali Disty.	13,450	17,580	77
10	Khadir Disty (unlined)	28,500	273,600	10
	Total	224,200	692,709	32

2.1.2. Ponding method

The ponding method is a technique used to determine seepage losses in canals and reservoirs by measuring the water level changes in a ponded area. The basic principle of this method is that the water level in a ponded area will change in response to seepage losses or gains. The steps to determine seepage losses using the ponding method are:

(a) Create a ponded area by constructing a small embankment or dam across the canal or reservoir.
(b) Measure the water level in the ponded area at regular intervals over a period of time.
(c) Compare the initial water level in the ponded area to the final water level after a specific time interval.
(d) The difference between the initial and final water levels is an estimate of the seepage losses over that time interval.

This method can be used to estimate seepage losses for a specific time period, such as 1 day, 1 week, or one month. The ponding method can also be used to estimate the seepage losses over a longer period by repeating the measurements over several time intervals and then averaging the results. It consists of the ponding water in a selected reach of a channel and observing the rate of drop in the pond with respect to time (IRI 1996; Arshad *et al.* 2009b; IRI 2019). This method is the most reliable method, with the only objection that the seepage rate may be different for flowing and standing water due to the settlement of sediments. Also, it cannot be performed in flowing channels. Equation (2) shows the seepage rate in the ponding method:

$$S = \frac{(G1 - G2)*W*L}{(P*L)} \tag{2}$$

where S is the seepage rate in ft^3/ft^2 per day (1 ft^3/ft^2 per day = 0.3048 m^3/m^2 per day); W is the average water surface width (ft) (1 ft = 0.3048 m); $G1$ is the gauge in a pond at beginning of the test (ft) (1 ft = 0.3048 m); $G2$ is the gauge in a pond after 24 h (ft) (1 ft = 0.3048 m); L is the length of the pond (ft) (1 ft = 0.3048 m); and P is the average wetted perimeter (ft) (1 ft = 0.3048 m).

A summary of tests performed in the field by ponding methods is given in Table 4. A total of eight ponding tests were performed on eight channels with an average pod size of 697 ft (1 ft = 0.3048 m). Tests were repeated to obtain more accurate estimates. Tests on Lagar Disty. and Arian Minor-1 were repeated using ponding methods as well, to obtain better and more accurate estimates of seepage rates.

2.2. Field tests and data collection

Data on seepage rates before lining of canals was obtained from previous studies carried out by IRI and some other secondary sources (IWASRI 1995; IRI 1996, 1998) while field tests using inflow–outflow and ponding methods were conducted to obtain the seepage rates after lining (IRI 2019). Design data of different hydraulic parameters were obtained from the concerned field formations of the PID and actual measurements of various parameters were conducted in the field. Some pictorial views of field testing and surveys are given in Figure 5. The hydraulic and geometrical parameters investigated for the study are flow velocity, roughness coefficient, wetted perimeter, bed and side slopes, water surface slope, hydraulic radius, length of the channel, bed width, water surface width, depth of the channel, and cross-sectional area.

In addition, the physical observations made during the experimental investigation of the inflow–outflow method and ponding method are expansion joints, vegetation growth, erosion of channel bed and sides, settling of lining, condition of

Table 4 | Summary of the ponding tests performed (1 ft = 0.3048 m)

Test No	Name of channels	Length of pond/test reach (ft)	Total length of channel
1	Qaim Minor	595	25,420
2	Khewra Disty	740	76,100
3	Shaheena Disty	500	11,500
4	Zam Disty	535	24,974
5	Safdarabad Disty	500	21,200
6	Rojhan Minor	635	35,000
7	Lagar Disty.	600	62,215
8	Arain Minor-1	670	65,547

Figure 5 | Pictorial views of field testing and surveys at different study sites.

canal berms, channel crossings, M&R requirements, stability of slopes, sedimentation, cracks, lining material, and life of the lining.

3. RESULTS

3.1. Pre-lining and post-lining seepage losses

Analysis of the collected and measured data of seepage losses from the selected channels before and after lining has been carried out which revealed that seepage loss rates in the unlined canals varied from 3.5 to 9.87 cfs/msf (1 cfs/msf = 0.3048 cumecs/million m^2) with an average loss rate of 6.92 cfs/msf. Before lining, the Sillanwali Distributary was carrying 17 cfs and losing the maximum quantity of water whereas the Safdar Abad Distributary was carrying 20 cfs and losing a minimum amount of water (IRI 2019). After lining the loss rate in the selected channels varied from 0.20 to 2.03 cfs/msf with an average loss rate of 1.24 cfs/msf. On average, there was a 78% reduction in seepage loss rates after lining channels. A comparison between pre-lining and post-lining seepage loss rates suggests that the lined canals are quite effective in reducing seepage losses. Figure 6 shows the variation in the actual vs. designed seepage losses calculated using Moritz, Molesworth, and Punmia models.

3.2. Hydraulic parameter

The design values of hydraulic parameters of selected channels were taken from the longitudinal sections of the channels provided by the PISIP office. For post-lining data, actual measurements of the hydraulic parameters were made in the field. A channel's cross-section is most economical or most efficient when it passes a maximum discharge for a given cross-section area, resistance coefficient, and bottom slope. The cross-sectional area has a direct relationship with construction cost. Therefore, an optimum cross-section area needs to be designed keeping in view all other factors. The comparison of design and measured values of the cross-sectional areas conclude that the under-design values of the channel cross-sectional area ranged from 0.51 to 15% while the over-design values ranged from 0.46 to 10%. The overall average of the over-designed cross-sectional area was 5% and under-designed was 7%. This analysis suggests that the variation in design and measured values of the cross-section is reasonably close. The over-design variation in the wetted perimeter ranged from 3 to 33% with an overall average of 15% and average under-design values ranged from 3 to 19% with an overall average of 11%. The comparison of design and measured values of wetted perimeter suggests that under-design values ranged from 3 to

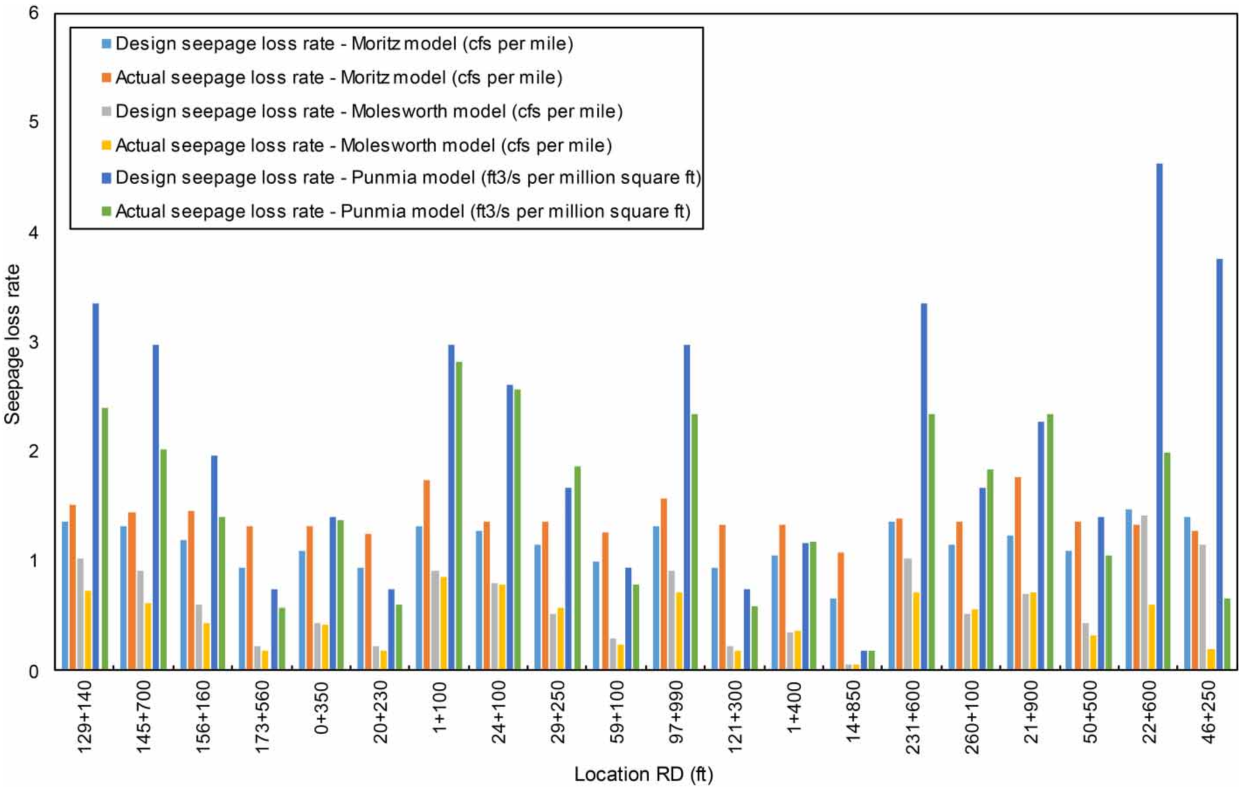


Figure 6 | Variation in the actual vs. designed seepage losses calculated using Moritz, Molesworth, and Punmia models (1 cfs per mile = 0.0175 cumecs/km. 1 ft^3/s per million square ft = 0.3048 cumecs/million m^2).

19% and over-design values ranged from 2.50 to 19% with an average of 11%. These results are tabulated in Table 5 and their statistics are depicted in Figures 7 and 8. The overall summary of physically measured hydraulic parameters is shown in Figure 9, which indicates that 51% of sites are overdesigned, 46 are under-designed, while only 3% are as per design. The greatest variations have been observed in the water surface slope in the channels and the least variation in the wetted perimeter as shown in Figure 10.

Considering the field conditions and technical quality of the workforce involved in the lining of canals, this variation appears to be reasonable. The optimum value of the perimeter leads to an efficient and economical channel section. Channels can have the same cross-sectional area, gradient, and roughness, but still have different velocities of flow according to their shape. The reason is that water close to the sides and bottom of a stream channel is slowed by the friction effect, so a channel shape which provides the least area of contact with the water will have the least frictional resistance and so a greater velocity.

The shape of the lined section which provides the least area of contact, reducing the friction to the flow, plays an important role in the design of the channel. Channels can have the same cross-sectional area, gradient and roughness but still have different velocities of flow according to their shape. The values of hydraulic radius more than the design values ranged from 1 to 13% with an overall average of 15%. The under-designed variation in the designed and measured hydraulic radius values ranged from –5 to 13% with an average of 9%. The comparison of the design and actual values of hydraulic radius indicates that 14 values are less than the design and six are more than the design. Hydraulic radius less than design affects the reduction in velocity. The channel sides slope is finalized considering the stability of the channel and cross-section area and thus the cost. The designed side slopes and actual values of the side slopes of 14 selected channels have been collected and measured. The variation between the design and measured values was small and negligible. The variations in the designed vs. measured discharge, x-section area, wetted perimeter, velocity, hydraulic radius, water surface slope, and Manning's n are shown in Figures 11–17, respectively.

Table 5 | Comparison of design and measured hydraulic parameters (1 cfs = 0.0283 cumecs. 1 ft^2 = 0.093 m^2. 1 ft = 0.3048 m. 1 ft/s = 0.3048 m/s)

		Discharge (cfs) *Q*			**X-sectional (ft^2) *A***			**Wetted perimeter (ft) P**			**Velocity (ft/s) *V***			**Hydraulic radius *R***			**Water surface slope *S***			**Manning's *n* (Design *n* = 0.016)**	
Name of channel	**Location RD (ft)**	**Design**	**measured**	**% variation**	**Design**	**measured**	**% variation**	**Design**	**measured**	**% variation**	**Design**	**measured**	**% variation**	**Design**	**measured**	**% variation**	**Design**	**measured**	**% variation**	**Measured**	**% variation**
Nasrana Disty	129 + 140	43	44.7	4	21.2	19.77	−7	12.7	13.7	8	2	2.26	11	1.7	1.44	−14	0.3	0.35	40	0.011	30
	145 + 700	30	34.6	16	15.7	15.71	0	10.9	11.42	5	1.9	2.2	16	1.6	1.32	−15	0.3	0.35	40	0.011	34
	156 + 160	29	18.2	−38	16.6	12.1	−27	9.95	10.81	9	1.8	1.5	−15	1.3	1.1	−17	0.3	0.32	3	0.009	44
	173 + 560	10	9.4	−7	6	5.7	−5	6.89	6.63	−4	1.5	1.65	10	0.8	0.7	−10	0.3	0.32	3	0.007	59
Sehti Wala Minor	0 + 350	14	15.5	13	8.4	9.6	14	8	9.1	14	1.6	1.5	−6	1.1	1.09	4	0.3	0.45	61	0.011	34
	20 + 230	7.1	6.1	−14	5	4.5	−10	6.1	5.74	−6	1.5	1.55	3	0.8	0.72	−12	0.3	0.5	67	0.008	48
Lagar Disty	1 + 100	35	39.2	13	20	22.9	15	12.5	14.61	17	1.8	1.71	−3	1.6	1.56	−1	0.2	0.18	−10	0.009	47
	24 + 100	28	30	6	17	19.2	13	11	13	18	1.7	1.56	−8	1.5	1.49	2	0.2	0.5	127	0.014	14
	29 + 250	17	18.1	7	11	13.4	22	9.25	10.75	16	1.5	1.35	−10	1.2	1.27	7	0.2	0.5	127	0.012	23
	59 + 100	9.9	7.4	−25	7	5.6	−20	7.49	7.67	2	1.5	1.32	−12	0.9	0.82	−13	0.2	0.5	127	0.009	43
Khikhy Disty	97 + 990	44	41.9	−3	20	20.9	4	12.6	14.89	18	2	2.01	−1	1.6	1.42	−12	0.4	0.3	−25	0.01	36
	121 + 300	9.1	5.1	−43	5	3.9	−22	6.33	5.35	−16	1.8	1.75	−1	0.8	0.71	−12	0.4	0.3	−25	0.007	59
Sillanwali Disty	1 + 400	11	12.2	8	8	7.9	−1	7.77	7.75	0	1.5	1.54	3	1	1.01	−1	0.3	0.4	60	0.01	41
	14 + 850	1.5	1.3	−10	1.44	1.2	−18	3.26	2.8	−14	1.5	1.1	−27	0.4	0.4	−9	0.4	0.5	25	0.006	64
Khadir Disty	231 + 600	47	31.4	−33	26	19.6	−25	14.8	14.07	−5	1.8	1.6	−9	1.7	1.42	−18	0.4	0.5	43	0.013	17
	260 + 100	15	15.5	1	10	11.5	15	15.3	12.33	−20	1.6	1.35	−13	1.2	1.26	9	0.4	0.5	43	0.012	23
Arain Minor – 1	21 + 900	40	39.8	−2	22.5	19.5	−13	13.1	13.49	3	1.8	1.9	6	1.4	1.42	0	0.2	0.19	0	0.008	49
	50 + 500	13	13	0	8.49	7.5	−12	7.93	7.66	−3	1.5	1.6	7	1.1	0.95	−11	0.3	0.35	40	0.009	47
IR/3R Hakra	22 + 600	53	45.9	−14	32	19.82	−38	16	15.09	−6	2.3	2.26	0	2	1.31	−35	0.3	0.5	100	0.013	21
	46 + 250	14	8.6	−40	16	5.7	−64	9	7.6	−16	1.8	1.49	−15	1.8	0.75	−58	0.3	0.4	60	0.008	51
Min				−43			−64			−20			−27			−58			−25		14
Max				16			22			18			16			9			127		64
Avg				−8			−9			1			−3			−11			45		39

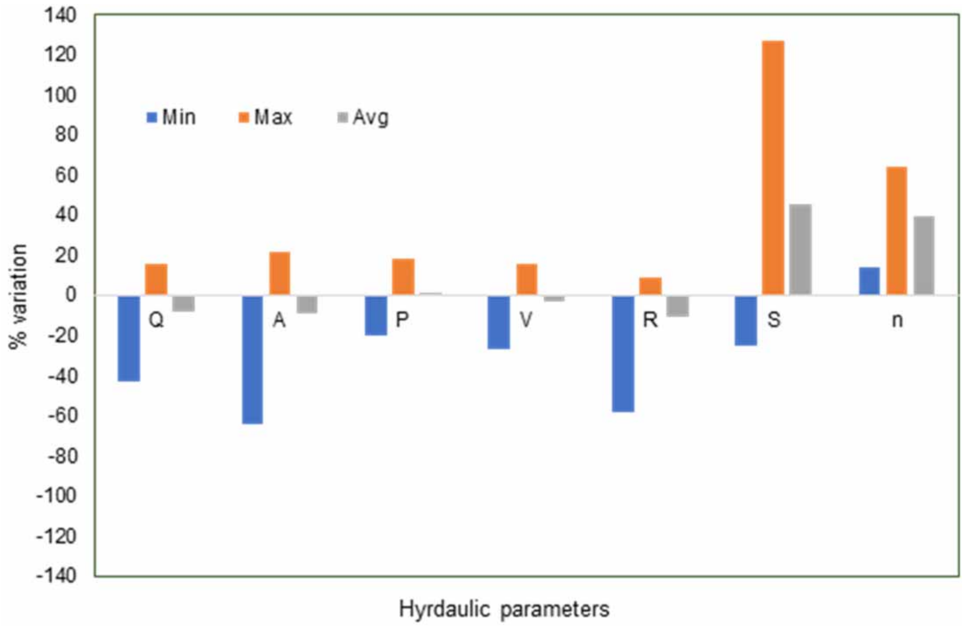
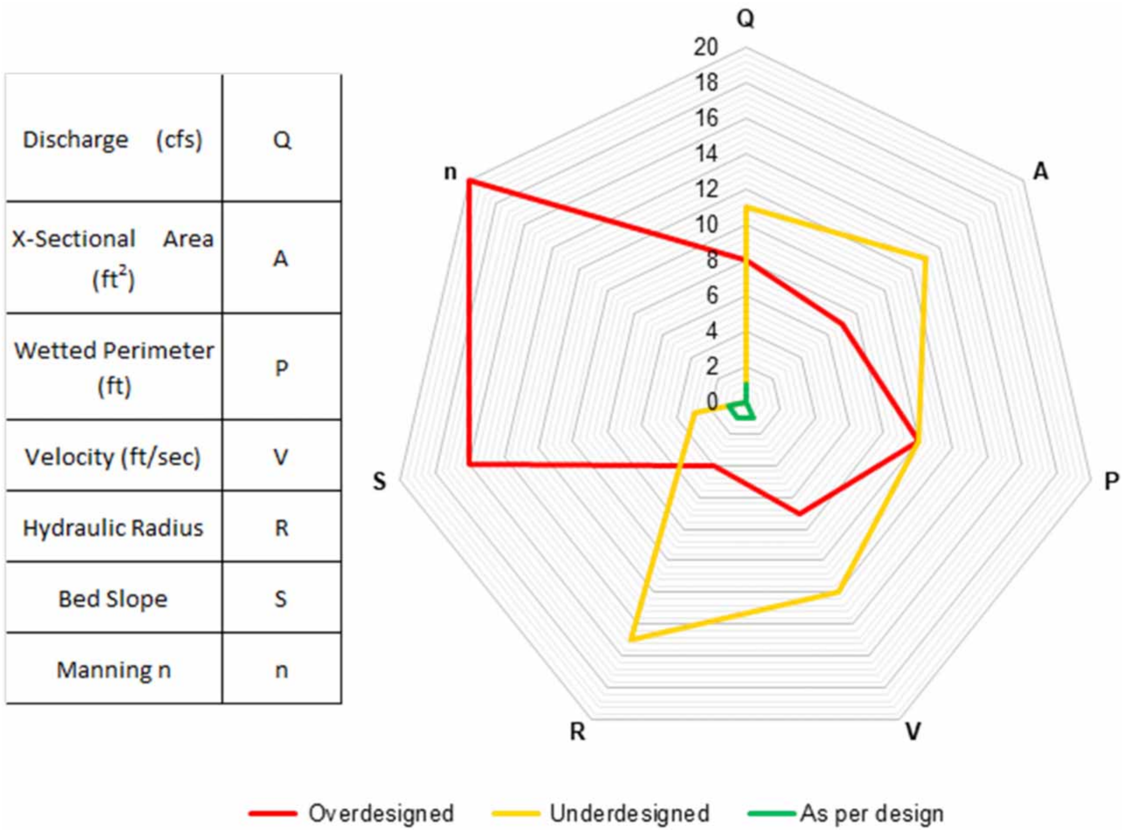


Figure 7 | Percentage variation of hydraulic parameters from design values.



Discharge (cfs)	Q
X-Sectional Area (ft^2)	A
Wetted Perimeter (ft)	P
Velocity (ft/sec)	V
Hydraulic Radius	R
Bed Slope	S
Manning n	n

Figure 8 | Number of channel sections found overdesigned, under designed, and as per design with respect to different hydraulic parameters (i.e., Q, A, P, V, R, S, n) (1 cfs = 0.0283 cumecs. 1 f^{t2} = 0.093 m^2. 1 ft = 0.3048 m. 1 ft/s = 0.3048 m/s).

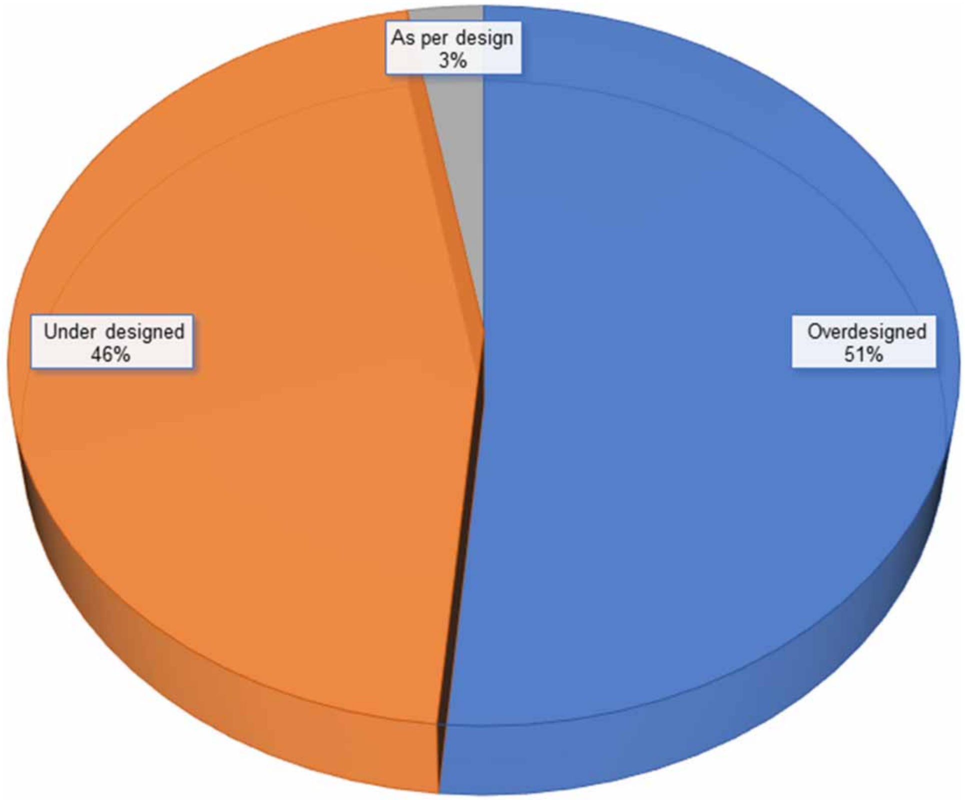


Figure 9 | Summary of channel sections from the point-of-view of as per design, under-designed, and over-designed.

3.3. Physical observations and surveys

All channels selected in DG Khan Zone are mostly silted up. Sarkanda (a local weed) and vegetation growth from both sides of the banks of channels have been observed. It was observed that silt about 6–10 inches (1 in = 2.54 cm) depth deposited in the pond site of Shaheena Disty. Panels are broken in the tail reach. In Faisalabad Zone, silt and vegetation growth have been observed in lined channels. Water was reaching at the tail of lined channels Nasrana, Lagar and Sehtiwala Minor. In Sargodha Zone sarkanda and vegetative growth along both banks of the Sillanwali Disty and silt in the bed of the canal and lined water course were observed. Water was reaching at the tail end of the Khadir Disty which was being lined. The unlined

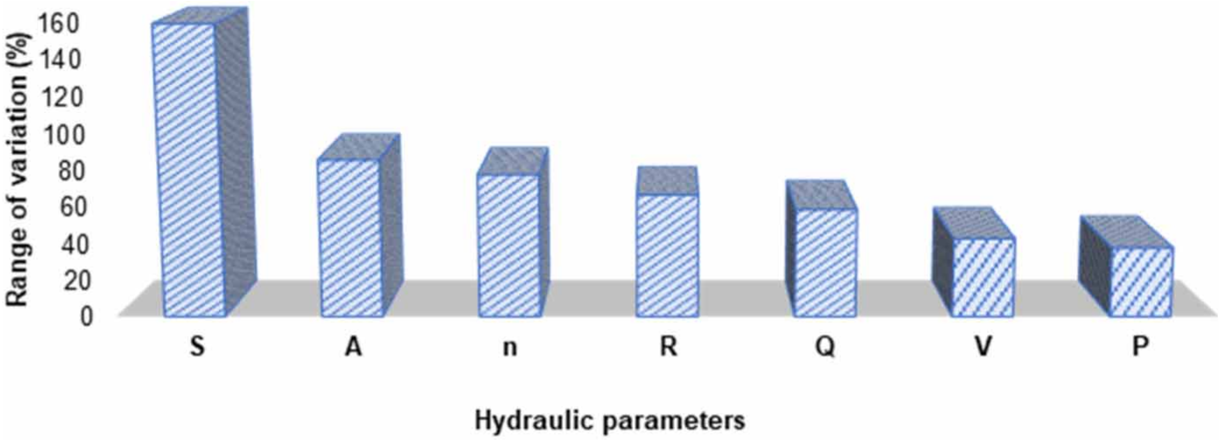


Figure 10 | Range of variation of hydraulic parameters from the design values.

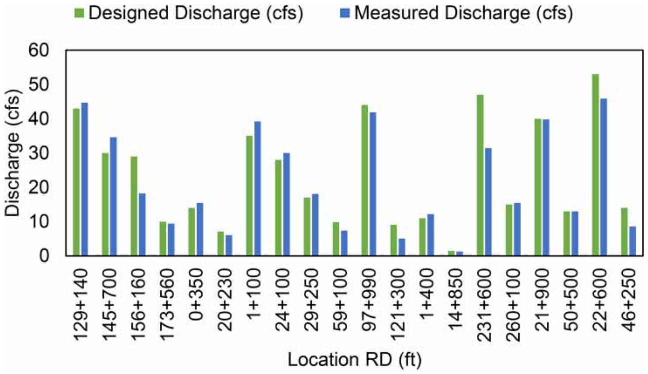


Figure 11 | Variation in the designed vs. measured discharge on different sites (1 cfs = 0.0283 cumecs. 1 ft = 0.3048 m).

Figure 12 | Variation in the designed vs. measured x-section area on different sites (1 $ft^2 = 0.093\ m^2$. 1 ft = 0.3048 m).

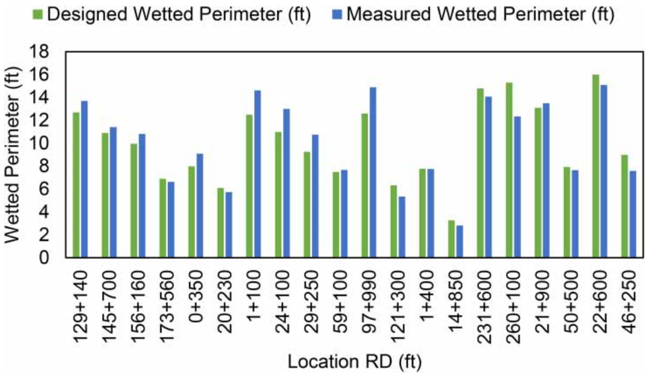


Figure 13 | Variation in the designed vs. measured wetted perimeter on different sites.

channel is in very dilapidated condition, broken banks, widened sections, vegetative growth were causing hindrances in flow, and therefore, practically was not possible to run this unlined channel at full supply level. In Bahawalpur Zone, channels were running with silt-free beds. Outlets were showing silt deposits in the bed. Vegetation was observed in the tail reach of the channels. I-R/3-R Hakra was lined with geosynthetic laid down with a cover of brick, concrete, and slab. Water was reaching at the tail of the channel. Some of the parameters observed during field visits, surveys, and investigation have been enlisted in Table 6.

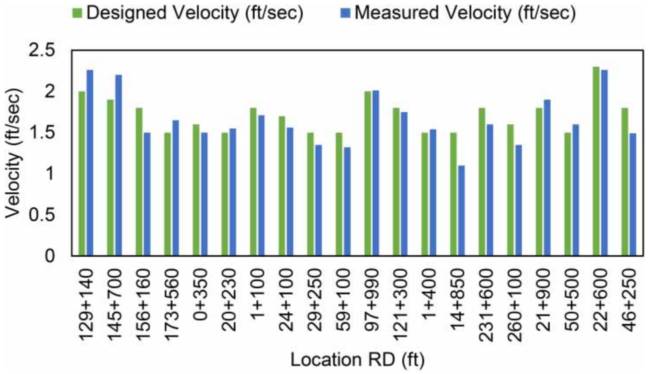


Figure 14 | Variation in the designed vs. measured velocity on different sites (1 ft/sec = 0.3048 m/s. 1 ft = 0.3048 m).

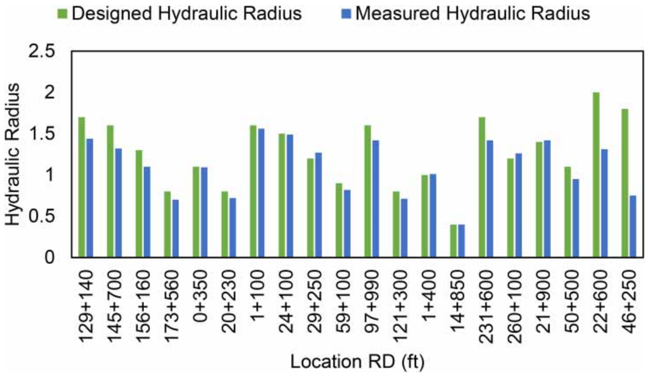


Figure 15 | Variation in the designed vs. measured hydraulic radius on different sites (1 ft = 0.3048 m)

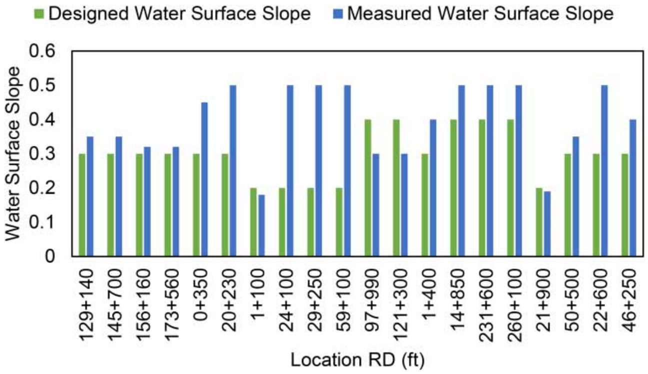


Figure 16 | Variation in the designed vs. measured water surface slope on different sites (1 ft = 0.3048 m)

3.4. Comparison with case studies

In the present study, range of seepage loss rate was found to be 3.5–9.87 cfs/mfs with an average seepage loss rate of 6.92 cfs/mfs in the unlined canals, whereas in the case of lined canals, the range of seepage loss rate was found to be 0.20–2.03 cfs/mfs with an average seepage loss rate of 1.24 cfs/mfs (1 cfs/mfs = 0.3048 cumecs/million m^2) in the lined canals. Total reduction in seepage loss rates post-lining was found to be ~78%. Figure 18 shows the comparison of reduction in post-lining seepage

Figure 17 | Variation in the designed vs. measured Manning's n on different sites (1 ft = 0.3048 m)

losses with different case studies published in literature. According to Figure 18, the present study resulted in a maximum reduction in post-lining seepage losses (i.e., up to ~78%) compared to other studies.

3.5. Limitations

Limitations of the study include:

- In certain distributaries, historic water tables and water quality data were not available or available for a limited period.
- Inflow and outflow methods of seepage measurement could have some errors due to instrument restrictions or measurement staff.
- For studying the life of lining, continuous data for many years will be required which was not available.
- For some channels, pre-lining data of required reliability was not available.

Table 6 | Summary of impacts of canal lining

Sr	Name of parameter	No change	Moderate change	Significant change
1	Cropping intensity	x		
2	Crop yields and production		Slightly increased	
3	Theft case			Reduced
4	Watch and ward			Improved
5	Water allowance	x		
6	Post-project employment opportunities	x		
7	Health conditions	x		
8	Groundwater levels	x		
8	Groundwater quality	x		
9	Canal seepage rates			Reduced (~78%)
10	Groundwater recharge		Reduced (~3%)	
11	Tail feeding		Improved	
12	Sedimentation		Reduced	
13	Vegetation growth		Reduced	
14	O&M cost		Reduced	
15	Hydraulic parameter (ref. Table 5)			Variation from design values
16	Canal bank breaches			Reduced
17	Workmanship during lining		Needs improvement	
18	Sealing of joints		Needs improvement	

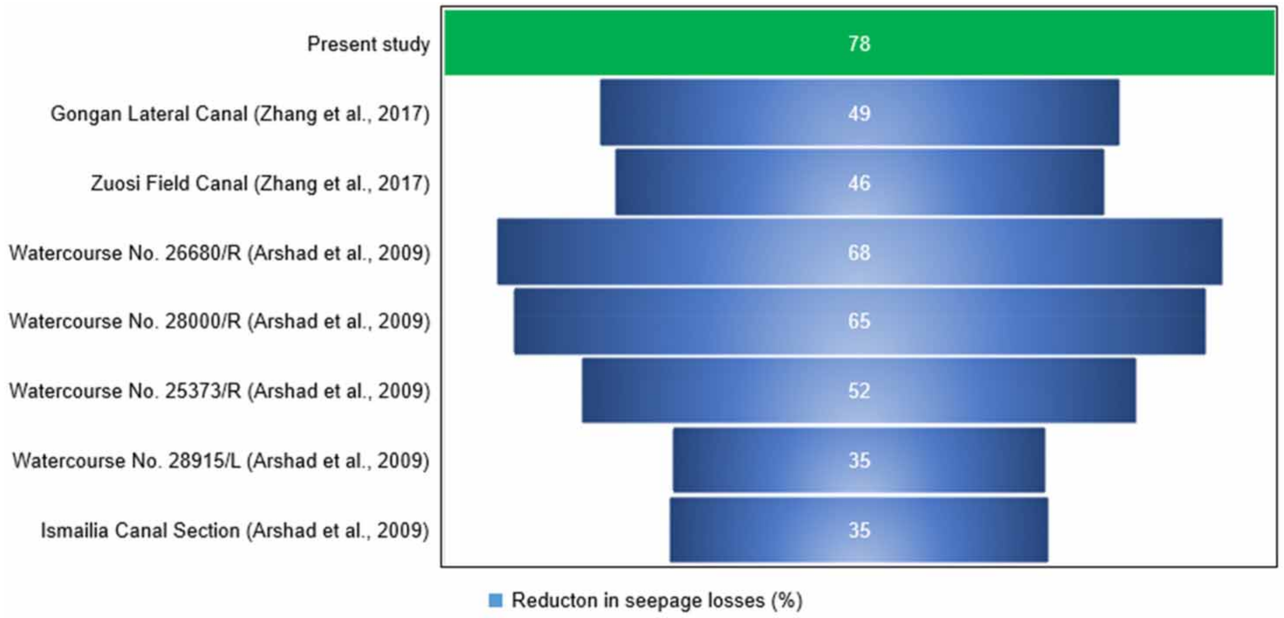


Figure 18 | Comparison of reduction in post-lining seepage losses with different case studies (Arshad *et al.* 2009b; Zhang *et al.* 2017.

- Some of the sample sites were restricted to conduct the research, keeping in view, alternates sites were selected.
- Well-calibrated current meters have been used to measure the discharge of channels, which can be further improved by using an acoustic Doppler current profiler (ADCP) (Kinzli *et al.* 2010).
- Data on hydraulic parameters for the pre-lining conditions were not available, therefore, the actual existing/lined channels' parameters have been compared with the design values.
- Data on groundwater levels and quality for both pre and post-lining period for the selected canal command areas were limited.

3.6. Future research directions

Canal lining and hydraulic efficiency are important research areas in the field of irrigation management. Some potential future research directions in these areas could include (i) developing new and more advanced canal lining materials, (ii) investigating the long-term effects of canal lining on water quality, (iii) modeling the interactions between canal lining and groundwater, and (iv) investigating the economic benefits of canal lining.

4. DISCUSSION

Sedimentation and growth of vegetation decrease the carrying capacity and increase the maintenance cost of the canals. In general, an average velocity of 2–3 ft/s (1 ft/s = 0.3048 m/s) will prevent sedimentation when the silt load of the flow is low, and a velocity of 2.50 ft/s is usually sufficient to prevent the growth of vegetation. Hence, the minimum permissible velocity can be assumed in the range from 2.50 to 3 ft/s (Kraatz 1977). Velocity is a critical parameter to transport silt-loaded water. The alluvial channels of Punjab were recommended to always run at higher than 70% of the design discharge to avoid siltation. It was also recommended that the spatial variation in the velocity should not be much different from the discharge variation along the canal to avoid the siltation and scouring caused by the imbalance of stresses along the canal prism.

The design velocity values of the selected 14 lined channels ranged from 1.01 to 2.10 ft/s with an average of 1.71 ft/s. The variation in measured and designed values of flow velocities ranged from −4 to + 3%, whereas the measured velocity on average is about 8% higher than the design velocities (IRI 2019). This evaluation of velocity values suggests that the design and measured values of velocities in the constructed channels are reasonably close. However, with the velocity values adopted for the design of sample lined channels, silt deposition both on the bed and sides of the channels is noticed. It is also noticed that even with higher velocities, a fungus appears on expansion joints and sides of the channel. This fungus formation entraps fine silt and clay and is considered one of the causes for the increase in Manning's 'n' value. The design of lined irrigation channels involves the fixing of discharge and slope. The full supply levels in the lined channel are fixed based on availability and desired command of different outlets. While fixing the water surface slope, the availability of control points such as falls is also reviewed for achieving the design slope which generates self-cleaning velocities. This is not always possible in Punjab as the land slopes are relatively flat and an increase in slope is not possible. Therefore, accurate bed slope values are important for the most economical and functional design of lined channels. The variation in designed and actual bed slopes is 8% more than the design slope. The average variation in designed and measured water surface and channel bed slopes is less than 10% which suggests the construction of channels in the field was done according to the design guidelines. In the newly constructed concrete-lined channels with well-finished smooth surfaces the 'n' is usually around 0.013 (Kraatz 1977). With the passage of time the surfaces get rough due to the sticking of silt particles and the growth of fungus and vegetation, the 'n' value increases to about 0.018 and in some cases up to 0.02. The 'n' value used in the design of sample lined channels was 0.016. The average measured value of 'n' is about 11% higher than the design values and 39% lower (IRI 2019).

The concrete lining has reduced the seepage losses in the selected channels in the range of 58–94%, on average by about 78%. This reduction in seepage loss is very important, especially in areas where irrigation water is pumped. Reduced water losses mean more water in the system is available to meet crop water requirements and less need for pumping groundwater and thus less pumping costs are involved (IRI 2019). The lined channels have reduced the dimension of the channel section by 10–30%. In many cases the land saved by lining the channels is being used by the farmers as service paths and for cultivation or tree plantation. To evaluate the reduction in the maintenance cost due to lining, five-year maintenance costs before and after lining the channels were collected from the concerned field offices. The comparison of these costs suggests that there is about a 20% reduction in maintenance costs with the lining of channels (IRI 2019). The most used canal cross-section in irrigation and drainage is the trapezoidal cross-section. The PISIP project of the PID has adopted the trapezoidal section for canal lining which has many advantages (Martin & Gates 2014; IRI 2019). As a part of the current study, performance of various types of canal linings was evaluated. These included P.C.C, geomembrane, and brick lining. Based on many factors, 1:2:4 P.C.C lining seems to be more suitable for future canal lining projects in Punjab (IRI 2019). Out of 14 sample canals selected for this impact assessment study, one canal was lined in 1999 and one in 2006, nine in 2014, and two canals in 2015. Data from earlier concrete and brick-lined canals were also collected to address the issue of the life of lining in Punjab. Based on findings of the evaluation of sample canals and data collected from earlier canals, it has been concluded that channels lined with 1:2:4 P.C.C can last up to 50 years whereas brick-lined canals can last up to 20–25 years, while geosynthetics can have the age of more than 50 years (IWASRI 1995; IRI 2019).

Future lining of canals must be linked with a pre-feasibility research study which may consider the factors like soil strata (sandy or clayey), channel section (cutting or filling), seepage loss rates (high rates more priority), groundwater levels (deeper or shallow), groundwater quality (fresh or brackish- brackish zones to get priority), location of reach (rural or urban- urban areas to be prioritized), annual O&M cost (low or high), no of breaches per year, frequency of theft cases, value of land (expected to be saved by lining), use of groundwater (irrigation, domestic, and industrial-drinking water zone to get less priority for lining), type of channel (perennial, non-perennial-perennial to get priority), cropping intensity and patterns in the area, social and environmental implication of lining, stability of canal banks, flooding of adjacent farmlands (waterlogging and salinity threats), surface water availability (water allowance), channel physical condition, annual expenditure on desilting and maintenance, sediment load in the water, infiltration or permeability rates, and any other site-specific issues.

The above feasibility will yield a set of criteria to evaluate the canal lining financially, economically, socially, environmentally, hydrologically, hydro-geologically, before making investment in the lining of canals. Canal seepage as a source for groundwater recharge and water supply source to wetlands should be evaluated before making the decision for canal lining. The detailed seepage loss measurements from unlined canals suggest that maximum seepage takes place from the canal banks. Therefore, the future lining may be restricted to canal banks only. Nominal seepage from canal beds will help to recharge the aquifer which is currently feeding more than 1.2 million agricultural tube wells in the Indus Basin. Concrete lining should be given priority as it is more durable, relatively impermeable, hydraulically efficient and due to the availability of technical know-how with the local contractors. Concrete lining is also suitable for both small and large channels and with high and low flow velocities.

Strict care and vigilance are required for quality control during execution, which is generally lacking. Poor workmanship has been observed in the field, which is a major cause of the failure of lining at certain locations. Provision of the adequate number of channel crossings, buffalo-baths, and cloth-washing spots at suitable locations, preferably near the villages, should be provided to facilitate the communities with respect to their daily needs. Plantation of trees on berms of lined canals should be discouraged to enhance the trouble-free life of lined channels. Instead of this, tree plantation can be accommodated in the right of way (ROW) of the canals. Damaged lined channel sections should be repaired immediately. Regular inspections of embankments for damage identification from rodents or burrowing animals should be undertaken immediately to avoid further deterioration of the channel. Before starting the concrete lining, embankments and the base of the channel should be properly compacted and consolidated to avoid settling and damage to the lining, which have been observed during field surveys.

Geosynthetics can be used as lining material more effectively if laid properly. Manning's 'n' value of 0.016 should be used in concrete-lined channels for optimum cross-section and for better hydraulic performance of the channel. A minimum permissible flow velocity of 1.5 ft/s in the concrete-lined channels should be used to safeguard the concrete-lined channels from erosion and silting. A cost comparison study of lining with concrete and with geosynthetic is also required to be conducted under field conditions. Geosynthetics are new materials and can result in longer life if installed and protected properly. Construction of lined channels must be ensured strictly in accordance with design parameters to achieve optimum results of huge investments. Further site-specific studies must be carried out making use of modern and innovative tools like tracer techniques, isotopes studies, remote sensing and geographic information system (GIS) tools, geophysical methods, X-rays, and radar techniques (Engelbert *et al.* 1997; Benjamin 2005; Kinzli *et al.* 2010; Pognant *et al.* 2013). Further research is recommended by handling the limitations of the current study.

5. CONCLUSIONS

Evaluating the hydraulic efficiency of lined irrigation channels in the IBIS is important for understanding the performance of the irrigation system and for identifying areas where management actions may be needed to improve efficiency. The IBIS provides irrigation support to agricultural lands across the country however hydraulic efficiency of the water conveyance system is impacted due to seepage losses. Lining of irrigation channels is considered a potential solution for improving hydraulic efficiency. In the present study, the impact of canal lining on hydraulic efficiency of the canals in the Punjab province of Pakistan have been experimentally investigated. Overall, 14 channels/distributaries/minors (total length 226 km) were monitored in terms of hydraulic performance in different irrigation zones. The hydraulic, geometrical, and socioeconomic parameters of channel/distributaries/minors including roughness coefficient, sediments, flow velocity, wetter perimeter, breaches, theft cases, bed, side-slope, water surface profile, hydraulic radius, crop yield, and vegetation growth area have been experimentally observed.

According to the results, it can be concluded that (i) the linings that have imperfections result in a small reduction of seepage losses and life of lined canals, (ii) canal lining has reduced seepage losses by ~78% on average from selected 14 channels which varies from site to site, (iii) the comparison of design and constructed channel cross-sections suggests that the cross-sections built are ~5% bigger than the design cross-sections, (iv) average variation in designed and measured values of wetted perimeter recorded is ~15%, (v) the average measured hydraulic radius is ~15% more than the design value, (vi) the average measured bed slope of the selected channels is ~8% more than the design value, (vii) the measured velocity is 8% more than the design flow velocities of the surveyed channels, (viii) roughness coefficient value of 0.016 used in the design of channels can be reduced to 0.012 which will result into smaller channel cross-section and saving in the lining cost, (ix) more detailed and continuous field data collection and its analysis is needed to justify the lining of earthen canals, (x) concrete lining with 1:2:4 P.C.C. appears to be more suitable for future canal lining in the Punjab, (xi) from a socioeconomic point of view, canal lining has improved equity and reliability of water distribution and generally, has reduced weed growth, (xii) damage to the lined channels is mainly caused by poor compaction of the subgrades before lining which results in cracking and settlement of lining, (xiii) maintenance cost of lined channels is less than that of the unlined channels, (xiv) life and effectiveness of rigid lining depends on the compaction of base and quality of construction, especially the workmanship, (xv) period for which a lining would remain physically useful depends on several factors such as exposure to weather, extent of variation in temperature (freezing and thawing), quality of water and soil, quality of materials and construction, workmanship during construction, and post-lining maintenance, (xvi) the useful physical life of 1:2:4 P.C.C. good quality lining is around 30–50 years, brick-lined channels ~20–25 years, and channels lined with protected geosynthetics can last more than 50 years, (xvii) canal lining has reduced the recharge to groundwater, and (xviii) sedimentation, cracks, erosion of bed and sides, vegetation growth, failure of joints have also been observed during the field survey of selected channels at different locations.

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AUTHOR CONTRIBUTIONS

G. Z., J. F. P. and M. A. K. conceptualized the whole article; G. Z., J. F. P., M. A. K., M. A. and G. S. developed the methodology; G. Z. and H. A. provided the software; G. Z., J. F. P., M. A. K., M. S., Q. N. and F. M. validated the article; G. S., J. F. P. and H. A. conducted a formal analysis; G. Z., J. F. P., M. A., G. S. and M. S. conducted the investigation; G. Z. and M. A. K. brought resources; G. Z., M. A. K., J. F. P. and G. S. conducted data curation; G. Z., M. A. and G. S. wrote the original draft; G. Z., H. A., M. S., Q. N. and F. M. wrote the review and edited the article; H. A., Q. N. and F. M. visualised the process; M. A.K., J. F. P. and M. S. supervised the work; G. Z., M. A. K. and G. S. administered the project; G. Z., Q. N. and F. M. conducted funding acquisition. All authors contributed to the article and approved the submitted version.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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