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The use of empirical equations for seepage estimation in comparison with observed losses from irrigation canals

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Abstract: This study analyses and presents a technical comparison of seepage estimation from 11 empirical equations with measured seepage losses by the inflow-outflow method from two lined and unlined secondary irrigation canals sub-divided into different reach lengths. A significant margin of error was observed between empirical and inflow-outflow methods, hence modifications in empirical equations were performed. Results reveal that the average seepage losses observed in unlined and lined canals by inflow-outflow method were 9.15 and 3.89%, respectively. Moreover, only the Chinese equation estimated seepage losses for an unlined canal as similar to observed losses (0.11 $m^3 \cdot s^{-1}$) whereas the Indian equation estimated similar results for a lined canal to those observed in the field (0.09 $m^3 \cdot s^{-1}$). However, the rest of empirical equations were modified in accordance with error percentage with regard to the observed losses. The empirical equations were then observed to estimate reliable results of seepage.

Keywords: empirical equations, equation modifications, seepage estimation, seepage losses, seepage rate

INTRODUCTION

Most irrigation channels worldwide are made of loose soil formations. Since the soil is a loose porous medium, a significant amount of freshwater seeps down through soil pores via channel bed and banks; in the process, a significant amount of precious freshwater resources is lost (Syed *et al.*, 2021). Thus, the irrigation system water conveyance efficiency is not fully achieved. Barkhordari *et al.* (2020) reported around 90% of water losses from the earthen irrigation network in Australia and over 40% of seepage losses in the Middle Rio Grande Conservancy District, United States. According to Kulkarni and Nagarajan (2019) and Lund *et al.* (2021), water losses during conveyance have been estimated around 20–70% of total canal flows worldwide. Barkhordari *et al.* (2020) report that in Spain around 55% seepage losses were observed from the total canal flows diverted to farmlands. Azargashb Lord *et al.* (2021) presents various estimates of water losses from irrigation networks worldwide. It reports about 50% of water losses from the irrigation infrastructure in Southern Pakistan, above 40% in Mexico, and around 45% in central India. In Ethiopia, the average seepage losses from modern, semi-modern, and traditional irrigation systems are about 26, 100, and 100% of the total water supplied to the network. In Egypt's Ismailia canal seepage accounts for more than 20% of the freshwater diverted for irrigation purposes (Elkamhawy *et al.*, 2021). Knowing that Pakistan has a vast network of earthen irrigation channels to convey irrigation water from its source to farmlands, a substantial amount of good quality canal water is lost annually by seepage (Shah *et al.*, 2020). Syed *et al.* (2021) observed over 40% water losses from tertiary irrigation networks in Sindh, Pakistan whereas Shah *et al.* (2020) observed over 45% water losses from distributary canals in Punjab, Pakistan. Seepage reduces the canal conveyance efficiency, diminishing water availability for agricultural purposes. It also results in unfavourable consumption of freshwater resources by vegetation along the canal or nearby areas via evapotranspiration. Seepage from water channels degrades productive agricultural soil leading to waterlogging. It also degrades surface water and groundwater quality, resulting in economic losses (Zörb *et al.*, 2019; Lund *et al.*, 2021). In addition, seepage-induced return flows move nutrients, salts, and trace elements into the downstream waterbodies resulting in environmental losses. Seepage from canals can never be eliminated, but it can be reduced by adopting seepage control interventions (Sazzad and Islam, 2019). Therefore, the accurate estimation of seepage losses from water channels becomes an important factor. Quantifying and controlling seepage from irrigation channels has been identified as the best management practice to preserve agricultural water quality and counteract depleting quantity (Kivi, 2018; Shultz *et al*., 2018; Aliyari *et al*., 2019; Lund *et al*., 2021). To improve the performance of irrigation canals it is necessary to determine the amount of water lost from irrigation systems (Barkhordari *et al*., 2020). Controlled seepage losses translate into higher conveyance efficiency, increased water use efficiency, as well as diminished transport of salts and other contaminants brought by irrigation-induced return flows; thus, the water quality in natural streams and their ecosystems will remain protected.

Keeping in mind the above facts, this study involves on-field seepage measurement at various stretches of lined and unlined canals and shows applicability/workability of 11 different empirical equations. Since Soothar *et al*. (2015), Tavakoli (2017), and Shah *et al*. (2020) observed inaccuracies in seepage measurement by empirical equations and performed related modifications, modifications in empirical equations (where required) have also been performed considering their limitations (i.e. in case of under or over estimation in comparison with field measured seepage) in this study. As canals are used to carry irrigation water to farmers' fields throughout the year, it sometimes becomes difficult to stop canal operations in order to measure seepage using direct measurement methods. Empirical equations are a convenient way of seepage quantification. This study attempts to measure seepage using empirical equations and addresses related inaccuracies.

MATERIALS AND METHODOLOGY

STUDY AREA

The Mirpurkhas irrigation district is located in the Sindh province of Pakistan and it feeds about 378,389 ha of agricultural land with its vast canal irrigation network. With the construction of the Jamrao canal during the British period, this district gained significant importance. There are two main canals, namely Jamrao and its largest off-shoot West Branch, and off-taking distributaries which irrigate the Mirpurkhas district. This irrigation district contains a total network of 6 distributaries, 5 minors and 96 outlets drawing water from two main canals (Khan *et al*., 1998). However, the present field study was conducted on two secondary perennial canals, namely Mir and Belharo (one unlined and the other lined), both off taking from the Jamrao West Branch at 146.52 RD. The location of unlined canal is East 68°58'21.702" and North 25°21'41.7024" and a lined canal East 68°58'22.6884" and North 25°21'40.878". Moreover, the design discharge of the unlined canal is 2.06 $m^3 \cdot s^{-1}$, having silt clay loam (SCL) soil texture throughout its flowing length with the total length of over 16 km and a culturable command area of about 3,263 ha, whereas the lined canal has a design discharge of 3.03 $m^3 \cdot s^{-1}$, with reinforced cement concrete (RCC) blocks' lining and the total length of over 14 km and a command area of around 6,907 ha. Figure 1 presents a map of the study area.

DETERMINATION OF HYDRAULIC PARAMETERS

Table 1 illustrates detailed methodology adopted for the determination of hydraulic parameters, such as bed and top width, flow depth, wetted perimeter, flow area, velocity of flow, and soil texture.

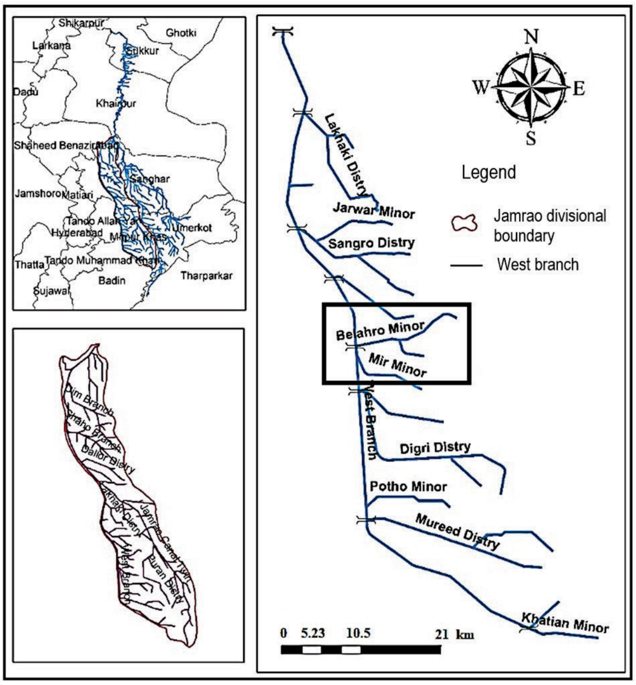

Fig. 1. Location map of area under study; source: own elaboration based on SIDA Google Earth Maps (no date)

MEASUREMENT OF CANAL DISCHARGE

The area-velocity method was used for the measurement of canal discharge using AA-type and pygmy-type current meters (Sheng *et al*., 2003). The two-point method was used where the depth of flow was 2.5 ft (76.2 cm) or above, and one-point method was used where the depth of flow was less than 2.5 ft (Solangi *et al*., 2018). Measurement with the current meters were taken at evenly spaced stations along the channel cross-section. Flow velocity at each point was observed with an exposure time of 40 s (Zhang *et al*., 2017), at three vertical positions, i.e. 0.2, 0.6, and 0.8 times the depth of flow for each station within the cross-section (Martin and Gates, 2014).

Measurement sites in canal reach lengths were selected where the conditions of flow were favourable to accurate calculations using current meters. These flow conditions include, low turbulence waters, no obstructions in the flow path, no debris induced irregular channel perimeter, minimal sediment moment on the bed, and straight reaches (Martin and Gates, 2014). Furthermore, repeated measurements on average of 6 times were taken and the average of these measurements was taken as a mean velocity in the canal's reach.

SEEPAGE LOSSES

The losses that occur during the conveyance of irrigation water from source to farmland are seepage losses. The inflow-outflow method was used to measure seepage losses by comparing the discharge between two cross-sections of the channel, i.e. upstream, and downstream (Mangrio *et al*., 2015). Seepage quantification on large-scale during actual operating conditions of canals can be obtained through the inflow-outflow method. However, this method exhibits inaccuracies if the tested reach is not long (Trout and Mackey, 1988; Alam and Bhutta, 2004; Martin and Gates,

Table 1. Hydraulic parameters and respective methodology

Serial No.	Parameter	Methodology / Formula		Reference
1	bed width	measuring tape		Soothar *et al.* (2015)
2	top width	measuring tape		
3	flow depth	ranging rod		
4	wetted perimeter	trapezoidal	$P = B + 2y\sqrt{z^2 + 1}$	Kent (1972)
		parabolic	$P = T + \frac{8}{3}\frac{y^2}{T}$	
5	area of flow	trapezoidal	$A = (B + Zy)y$	
		parabolic	$A = \frac{2}{3}Ty$	
6	velocity	AA-type and pygmy-type current meters		Sheng *et al.* (2003)
7	soil texture (% of sand, silt and clay)	hydrometer method		Bouyoucos (1962)

Explanations: P = wetted perimeter, A = flow area, B = bed width, y = flow depth, z = side slope, T = top width.
Source: own elaboration based on literature.

2014). Therefore, in this study the reach length selected for the seepage losses measurement is 2266 m and 2000 m, in an unlined and lined canals respectively.

$$Q_s = Q_i - Q_o \tag{1}$$

where: Q_s = seepage losses; Q_i = inflow discharge at inlet/start-point of selected reach length of the canal; Q_o = outflow discharge at endpoint of reach including discharge of the off-taking outlets within reach.

However, evaporation losses in this study have not been considered since the evaporation losses make about 0.3% of total losses reported from the irrigation system and are generally not taken into consideration (Singh *et al.*, 2021; Mutema and Dhavu, 2022).

SEEPAGE RATE

The seepage rate quantifies the rate of losses in a specific flow area at any given point. The seepage rate depends upon the type of material used or soil laid at the bottom and adjacent sides of irrigation canals. The seepage rate differs from seepage losses, as it includes specific area for measuring losses. The seepage rate was calculated using the following relationship (Soothar *et al.*, 2015; Shaikh *et al.*, 2016).

$$S_r = \frac{Q_i - (Q_o + Q_e)}{A_w} 10^6 \tag{2}$$

where: S_r = seepage rate of the reach length (or section) ($m^3 \cdot 10^{-6}$ m^{-2}); Q_i = discharge at the inlet of reach ($m^3 \cdot s^{-1}$); Q_o = discharge of outlets within the reach ($m^3 \cdot s^{-1}$); Q_e = discharge at endpoint of reach ($m^3 \cdot s^{-1}$); A_w = wetted area of the reach (m^2).

SEEPAGE ESTIMATION BY EMPIRICAL FORMULAE

Various studies in literature have used and discussed empirical equations to quantify seepage from irrigation canal networks (Mowafy, 2001; Akkuzu, 2012; Han *et al.*, 2021). These equations are simple and easy to use in comparison with other measurement methods. These equations are based on the hydraulic profile of canals, such as discharge, velocity, channel geometry, and soil characteristics (Elkamhawy *et al.*, 2021). Seepage losses in the studied canals were estimated using 11 empirical equations as presented in Table 2. However, as observed by Akkuzu

Table 2. Empirical equations studied in this research

Serial No	Empirical formula	Equation	Description
1	Chinese (Zhang *et al.*, 2017)	$Q_{\text{loss}} = \sigma Q_n L$ (3)	$\sigma = \frac{A}{100 Q_n^{\ m}}$ (coefficient of water loss per km of canal); A = permeability coefficient; m = permeability index of canal bed soil (A = 2.65, m = 0.45 for silt clay loam (SCL) soil); Q_n = net inflow at channel reach ($m^3 \cdot s^{-1}$); L = section or reach length (m)

cont. Tab. 2

Serial No	Empirical formula	Equation	Description
2	Kostiakov (Zhang *et al.*, 2017)	$Q_s = \frac{a}{100} Q_{\text{in}}{}^{1-b}$ (4)	Q_s = seepage losses ($m^3 \cdot s^{-1}$); a = permeability coefficient of soil (for light clay loam or SCL 2.65); b = permeability index of soil (for SCL 0.45); Q_{in} = net inflow at channel reach or section ($m^3 \cdot s^{-1}$)
3	Davis–Wilson (Akkuzu, 2012a)	$S = \left(\frac{0.45CH_w{}^{1/3}}{4 \cdot 10^6 + 3650\sqrt{v}} \right) WP \cdot L \cdot 10^6$ (5)	S = seepage losses ($m^3 \cdot s^{-1}$); L = length of canal (m); WP = wetted perimeter (m); H_w = flow depth (m); v = flow velocity ($m \cdot s^{-1}$); C = coefficient (1 for concrete lining up to 4 inches thick and 20 for SCL soil) (Leigh, 2014)
4	Moritz A (Shah *et al.*, 2020)	$S = 0.0186C\sqrt{Q/v}$ (6)	S = seepage losses ($m^3 \cdot s^{-1}$ per mile length of canal); Q = inflow rate ($m^3 \cdot s^{-1}$); v = flow velocity ($m \cdot s^{-1}$); C = coefficient (0.34 for cemented gravel and 0.41 for SCL) (Leigh, 2014)
5	Moritz B (Shah *et al.*, 2020)	$S = 0.037C \frac{Q}{v}$ (7)	S = seepage losses ($m^3 \cdot s^{-1}$); Q = canal discharge ($m^3 \cdot s^{-1}$); v = flow velocity ($m \cdot s^{-1}$); C = coefficient (0.34 for cemented gravel and 0.41 for SCL)
6	Moritz USBR (Dolatkhah *et al.*, 2015)	$S = 0.0117CA^{1/2}L$ (8)	S = seepage ($m^3 \cdot s^{-1}$ per canal reach length or section); A = wetted area of canal (m^2); L = length of canal section or reach length (m); C = coefficient (0.34 for cemented gravel and 0.41 for SCL)
7	India-Punjab State (Kulkarni and Nagarajan, 2018)	$\left. \begin{array}{l} S = 1.90Q^{0.0825} \text{ (for unlined)} \\ S = 0.35Q^{0.056} \text{ (for lined)} \end{array} \right\}$ (9)	S = seepage losses ($m^3 \cdot s^{-1} \cdot (10^6\ m^2)^{-1}$); Q = canal discharge ($m^3 \cdot s^{-1}$)
8	Egyptian (Kulkarni and Nagarajan, 2018)	$S = C\ L\ P\ R^{1/2}$ (10)	S = seepage ($m^3 \cdot s^{-1}$); L = canal length (km); R = hydraulic radius (m), $R = A/P$; P = wetted perimeter (m); A = wetted surface area (m^2); C is a numerical parameter whose values vary from 0.0015 for clay to 0.0030 for sandy soils
9	Indian (Saha, 2015)	$S = C\ a\ d$ (11)	S = total seepage losses ($m^3 \cdot s^{-1}$); a = area of wetted perimeter (km^2); d = depth of flow (m); C = factor depends on soil types and varies from 1.1 to 1.8
10	Pakistani (Khan, 2019)	$S = \frac{5Q^{0.0652} P\ L}{106}$ (12)	S = seepage losses ($m^3 \cdot s^{-1}$); Q = discharge ($m^3 \cdot s^{-1}$); P = wetted perimeter (m); L = length of channel (m)
11	Molesworth and Yennidunia (Hosseinzadeh Asl *et al.*, 2020)	$S = 86.4C\sqrt{R}$ (13)	S = seepage losses ($m^3 \cdot s^{-1}$); R = hydraulic radius (m); C = coefficient (0.41 and 0.66 for clay and clay loam soils, respectively)

Source: own elaboration.

(2012), Soothar *et al.* (2015), Shah *et al.* (2020), empirical equations yield inaccuracies in comparison with field measured seepage. Therefore, these equations were further analysed and modified as discussed in section "Modification in empirical formulae".

MODIFICATION IN EMPIRICAL FORMULAE

Under or over estimation of seepage losses by empirical equations results in a higher/lower projection of seepage as compared to actual losses. Thus, adjustments/modifications are necessary for a specific region. Therefore, the empirical equations were adjusted using a trial-error method on Microsoft Excel, provided that the seepage estimation must not exceed the minimum and maximum levels of observed seepage losses at any of the seven sections (reach lengths) for both canals. Modifications in coefficients and equations have also been practiced by Salemi and Sepaskhah (2006), Soothar *et al.* (2015), Tavakoli (2017), Shah *et al.* (2020).

RESULTS AND DISCUSSIONS

FIELD MEASURED LOSSES

Table 3 depicts hydraulic parameters, discharge rates, and seepage losses at seven reach lengths (sections) of both secondary canals, i.e. lined and unlined, under present field study. The hydraulic parameters of both irrigation canals decreased after every consecutive section, as the discharge was released into different off-taking water bodies (i.e. minors and watercourses) along the

Table 3. Hydraulic parameters, discharge and seepage of lined and unlined secondary canals

Canal type	Section/reach No.	A (m^2)	P	T	D	Q_i	Q_o	Q_s	Reach/section length (m)	Seepage		Seepage rate (m^3·10^{-6}·m^{-2})
			m			m^3·s^{-1}				(%)	(% per km)	
Unlined	1	4.6	8.06	8.31	0.82	2.06	1.83	0.23	2,266	11.23	4.95	12.64
	2	4.1	7.50	7.14	0.78	1.74	1.56	0.18		10.34	4.56	10.60
	3	3.7	6.88	5.14	0.74	1.53	1.38	0.15		9.82	4.33	9.63
	4	2.9	5.10	4.20	0.70	1.04	0.94	0.09		9.14	4.03	8.21
	5	1.9	4.49	3.64	0.61	0.53	0.52	0.05		8.92	3.94	4.65
	6	1.5	3.92	3.02	0.57	0.41	0.38	0.03		8.26	3.65	3.83
	7	1.0	3.24	2.41	0.47	0.28	0.26	0.02		6.33	2.79	2.44
	Average									**9.15**	**4.04**	**7.43**
Lined	1	4.3	6.97	7.47	0.74	3.03	2.86	0.17	2,000	5.5	2.75	11.96
	2	4.2	6.93	7.34	0.73	3.02	2.86	0.16		5.3	2.65	11.56
	3	3.6	6.61	7.15	0.67	2.84	2.71	0.14		4.9	2.45	10.54
	4	2.4	5.34	5.75	0.52	2.27	2.18	0.09		4.12	2.06	8.77
	5	1.6	4.24	4.70	0.48	1.17	1.14	0.03		2.68	1.34	3.71
	6	1.6	4.22	4.60	0.48	0.74	0.72	0.02		3.25	1.63	2.86
	7	0.9	2.99	3.32	0.38	0.68	0.67	0.01		1.50	0.75	1.70
	Average									**3.89**	**1.95**	**7.30**

Explanations: A = flow area, P = wetted perimeter, T = top width, D = flow depth, Q_i = inflow, Q_o = outflow, Q_s = seepage losses.
Source: own study.

canal length. The unlined canal was responsible for feeding 15 off-taking watercourses, whereas the lined canal was feeding 29 watercourses and one off-taking minor. Moreover, during field study, the lined canal was observed to be in good condition while the unlined canal had deteriorated reaches either narrow or widened with silt deposition at various points within the canal length resulting in higher water losses.

On average, the seepage from the total length of the unlined canal is 9.15%. Similar results have been observed by (Leigh and Fipps, 2009; Kulkarni and Nagarajan, 2018; Salmasi and Abraham, 2020; El-Molla and El-Molla, 2021). According to these studies, unlined water channels face high water losses of 30–50%, which eventually affects water conveyance efficiency of earthen canals and a low water supply in particular at canal tail reaches. The lower water supply in return affects crop production either in terms of less land cultivated or water volumes unsuitable to meet crop water demand. These seepage losses from unlined canals depend on various factors, such as the type of soil and its characteristics, status of groundwater table, water depth of the channel, bank or bed erosion caused by farm animals, sedimentation, trees, and plants in the water way, as well as no or less frequent maintenance.

On the other hand, under the present study, the seepage from the total length of the lined canal is 3.89%. Based on the results from the lined and unlined canals, it is inferred that lining reduces the overall water loss by about 40% and improves conveyance efficiency/water use efficiency of irrigation canals, which in return results in more water available at tail reaches, reduced waterlogging and salinity, increased command area and cropping intensities, increased revenues, and more water available for non-irrigation purposes. Such a trend is comparatively supported by (Meijer *et al.*, 2006; Lakho *et al.*, 2020; Abd-Elaty *et al.*, 2021).

ESTIMATED SEEPAGE BY EMPIRICAL EQUATIONS

The average water losses observed under field conditions from both secondary canals were compared with estimated seepage losses determined by empirical equations. Table 4 depicts the range of estimated losses along with percentage error in context to the observed water losses by the inflow-outflow method.

The results illustrated in Table 4 reveal that the Chinese equation estimated same losses as observed in the field for the unlined canal. While Molesworth–Yennidumia, Moritz USBR, Indian equation, Pakistani equation, and Davis–Wilson over-estimated the observed seepage losses by +99.72, +99.34, +95.09, +81.67, and +73.64%, respectively. Contrastingly, India-Punjab State equation, Moritz equation A, Kostiakov equation, Egyptian formula, and the Moritz equation B underestimated the actual seepage losses by −74.70, −74.03, −72.73, −72.73, and −9.09%, respectively.

For the lined canal, the Indian equation estimated same results as observed from field data. Among the other empirical equations, the Indian-Punjab State equation, Moritz A, Davis–Wilson, and Moritz B underestimated the seepage losses against field observations by −96.00, −88.89, −87.78, and −44.44% as shown in Table 4. However, the Moritz USBR, Molesworth–Yennidumia, and Pakistani equations overestimated the actual field losses by +99.21, +98.46, and +80.43%, respectively.

Table 4. Observed seepage versus estimated seepage by the studied empirical equations

Method	Unit of measurement	Average seepage losses		Range of estimated losses				Error (%)	
				unlined		lined			
		unlined	lined	max.	min.	max.	min.	unlined	lined
Field measurement	$m^3 \cdot s^{-1}$	0.110	0.09	0.230	0.020	0.17	0.01	–	–
	$m^3 \cdot s^{-1} \cdot mile^{-1}$	0.077	0.09	0.164	0.013	0.27	0.01	–	–
	$m^3 \cdot s^{-1} \cdot (10^6\ m^2)^{-1}$	7.430	7.30	12.64	2.44	11.96	1.70	–	–
Chinese formula (A = 2.65, b = 0.45, for unlined only)	$m^3 \cdot s^{-1}$	0.110	–	0.23	0.02	–	–	0.00	–
Kostiakov formula (a = 2.65, b = 0.45, for unlined only)	$m^3 \cdot s^{-1}$	0.030	–	0.04	0.01	–	–	–72.73	–
Davis–Wilson formula (C = 20 for unlined, C = 1 for lined)	$m^3 \cdot s^{-1}$	0.290	0.011	0.02	0.02	0.01	0.01	+73.64	–87.78
Moritz formula A (C = 0.41 for unlined, C = 0.34 for lined)	$m^3 \cdot s^{-1} \cdot mile^{-1}$	0.020	0.01	0.0006	0.0005	0.0003	0.0002	–74.03	–88.89
Moritz formula B (C = 0.41 for unlined and C = 0.34 for lined)	$m^3 \cdot s^{-1}$	0.070	0.05	0.11	0.02	0.09	0.02	–9.09	–44.44
Moritz USBR formula (C = 0.41 for unlined, C = 0.34 for lined)	$m^3 \cdot s^{-1}$	17.70	11.38	23.31	10.99	16.39	7.38	+99.34	+99.21
India-Punjab State formula (coefficient not required)	$m^3 \cdot s^{-1} \cdot (10^6\ m^2)^{-1}$	1.88	0.36	2.02	1.71	0.37	0.34	–74.70	–96.00
Egyptian formula (C = 0.003, for unlined only)	$m^3 \cdot s^{-1}$	0.030	0.01	0.04	0.01	0.01	0.01	–72.73	–
Indian formula (C = 1.10 for unlined, C = 1.80 for lined)	$m^3 \cdot s^{-1}$	2.240	0.09	4.12	0.53	0.16	0.02	+95.09	0.00
Pakistani formula (coefficient not required)	$m^3 \cdot s^{-1}$	0.600	0.46	0.90	0.32	0.70	0.26	+81.67	+80.43
Molesworth and Yennidumia (C = 0.66 for unlined, C = 0.10 for lined)	$m^3 \cdot s^{-1}$	39.17	5.86	43.05	32.01	6.81	4.64	+99.72	+98.46

Source: own study.

Results of seepage estimation using empirical equations are also supported by the results observed by Kumar (2017), Hosseinzadeh Asl *et al.* (2020), and Salmasi and Abraham (2020). These research studies analysed seepage estimation by empirical equations and concluded that most of the empirical equations either underestimate or overestimate seepage losses by 30 to 90% of the actual water losses. Indistinguishable results have also been observed in the present research. However, it is further inferred that, empirical equations require relative adjustments/modifications to obtain reliable results as these equations rely on various region-specific characteristics of the canals as evidenced by Akkuzu (2012a), Soothar *et al.* (2015), Tavakoli (2017), and Shah *et al.* (2020).

MODIFICATION IN EMPIRICAL EQUATIONS

Table 5 shows relative modifications to coefficient values or equation(s) of different empirical formulae. However, equation adjustment was only performed for Kostiakov, India-Punjab state, and Pakistani formulae, while all other empirical equations were studied with modified coefficient values. Adjusted equations and coefficient values were then used to estimate seepage losses in canals as practiced by Salemi and Sepaskhah (2006), Soothar *et al.* (2015), Kulkarni and Nagarajan (2018), and Shah *et al.* (2020). These studies show that the empirical equations depend on region-based specific lining type, soil, and hydraulic conditions; therefore, they should be calibrated before they are used elsewhere (different from the region of origin). As a result, they performed modifications in the empirical equations.

SEEPAGE ESTIMATION BY EMPIRICAL EQUATIONS AFTER MODIFICATION

Table 6 shows seepage estimation by the adjusted empirical equations. After adjustment, the average of estimated seepage losses was same as that of field losses determined by the inflow-outflow method. The minimum and maximum ranges of seepage estimation by adjusted equations was found to be within measured losses at all seven reach lengths of both canals.

Results of seepage assessment after adjustments are supported by Akkuzu (2012a), Soothar *et al.* (2015), Tavakoli (2017), and Shah *et al.* (2020). These studies practiced equation and coefficient adjustment and comparatively supported that the regional seepage estimation equations are proposed considering the complex category of lining-material type, soil characteristics, and the hydraulic profile of canals in any particular region, which further requires quantification of such parameters in other regions. It is also concluded that once modifications are made,

Table 5. Modification in equations/coefficient values of the studied empirical equations without changing respective units

Formula	Modification in equation or coefficient		After adjustment	
	unlined	lined	unlined	lined
Chinese formula	no adjustment (due to good prediction)	no adjustment (because this equation is only valid for unlined canal)	–	–
Kostiakov formula	equation	no adjustment (because this equation is only valid for unlined canal)	$Q_s = \frac{a}{25}\, Q_{in}{}^{1-b}$	–
Davis–Wilson formula	coefficient value	coefficient value	C = 86.20	C = 44.70
Moritz formula A	coefficient value	coefficient value	C = 0.48	C = 0.42
Moritz formula B	coefficient value	coefficient value	C = 0.45	C = 0.53
Moritz USBR formula	coefficient value	coefficient value	C = 0.0025	C = 0.0028
India-Punjab State formula	equation	equation	$S = 0.76Q^{2.419}$	$S = 3.05Q^{1.2344}$
Egyptian formula	coefficient value	coefficient value	C = 0.0124	C = 0.0129
Indian formula	coefficient value	no adjustment (due to good prediction)	C = 0.0517	–
Pakistani formula	equation	equation	$S = \frac{Q^{0.0652} P\, L}{115}$	$S = \frac{Q^{0.0652} P\, L}{115}$
Molesworth and Yennidumia	coefficient value	coefficient value	C = 0.0019	C = 0.0015

Explanations as in Tab. 2.
Source: own study.

Table 6. Estimated seepage losses after modification in empirical equations

Formula		Average seepage losses						Error (%)	
		unlined canal			lined canal				
		average	range of estimation		average	range of estimation			
			max.	min.		max.	min.	unlined	lined
Field measurement	$m^3 \cdot s^{-1}$	0.11	0.23	0.02	0.09	0.17	0.01	–	–
	$m^3 \cdot s^{-1} \cdot mile^{-1}$	0.077	0.164	0.013	0.09	0.27	0.01		
	$m^3 \cdot s^{-1} \cdot (10^6\ m^2)^{-1}$	7.430	12.64	2.44	7.30	11.96	1.70		
Kostiakov formula ($m^3 \cdot s^{-1}$)		0.11	0.16	0.05	–	–	–	0.00	–
Davis–Wilson formula ($m^3 \cdot s^{-1}$)		0.11	0.17	0.06	0.090	0.0139	0.0482	0.00	0.00
Moritz formula A ($m^3 \cdot s^{-1} \cdot mile^{-1}$)		0.78	0.10	0.05	0.081	0.16	0.05	1.28	10.00
Moritz formula B ($m^3 \cdot s^{-1}$)		0.11	0.17	0.04	0.09	0.17	0.03	0.00	0.00
Moritz-USBR formula ($m^3 \cdot s^{-1}$)		0.11	0.14	0.07	0.09	0.13	0.06	0.00	0.00
India-Punjab State formula ($m^3 \cdot s^{-1} \cdot (10^6\ m^2)^{-1}$)		7.43	14.41	0.18	7.31	11.95	1.88	0.00	0.08
Egyptian formula ($m^3 \cdot s^{-1}$)		0.11	0.17	0.05	0.09	0.14	0.04	0.00	0.00
Indian formula ($m^3 \cdot s^{-1}$)		0.11	0.19	0.02	0.09	0.16	0.02	0.00	0.00
Pakistani formula ($m^3 \cdot s^{-1}$)		0.11	0.17	0.06	0.09	0.13	0.05	0.00	0.00
Molesworth and Yennidumia ($m^3 \cdot s^{-1}$)		0.11	0.12	0.09	0.09	0.10	0.07	0.00	0.00

Source: own elaboration.

empirical equations can estimate efficient and acceptable results as evidenced in this study.

Furthermore, it is inferred that these adjusted equations can also be used for all the unlined canals having silt clay loam (SCL) soil texture throughout their flowing length and the lined canals having reinforced cement concrete (RCC) lining with Z:1 side slope, all across Pakistan and elsewhere having climatic conditions similar to Pakistan.

CONCLUSIONS

Seepage is the most dominant phenomenon in water conveyance systems and does not only adversely affect the amount of water delivered but has a number of other negative consequences. Therefore, seepage should be carefully studied in order to control the phenomenon in canal networks. The literature on seepage describes many direct and indirect seepage measurement methods, with indirect methods being more practical where direct measurement methods are not feasible due to unfavourable field conditions. This research carried out a comparative study to analyse the reliability/workability of the indirect seepage measurement method (empirical equations) over the direct measurement method (inflow–outflow). It was observed that most of the empirical equations either underestimate or overestimate the actual amount of seepage losses and are limited by region-based complex nature of soil characteristics, lining material, or climatic conditions. Therefore, these equations must be modified before they are used elsewhere (beyond their origin) to get correct estimates of seepage from irrigation canals in order to manage water resources more efficiently.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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