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Simulating Seepage from Branch Canal under Crop, Land and Water Relationships

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ABSTRACT

The rapid growth of tubewells in the Indus Basin of Pakistan shows significant contribution of groundwater in the irrigated agriculture development. The dependence on groundwater has increased due to rapid growth in cropping intensity and increasing water demand. Hence, to support a long-term agricultural management the sustainability of groundwater largely depends on seepage from canals. This paper presents model simulation assessments of the time dependent seepage to groundwater under the crop, land and water scenarios, as a case study for a branch canal system in Punjab, Pakistan. Assessment of seepage from canal was performed using a surface-groundwater model, MODFLOW. Model calibrations were performed to obtain close agreement between the observed and simulated water levels over one year study period. The monthly average seepage rate from the canal was assessed as 12.10 m^3/s/million-m^2 for a monthly average flow rate of 106 m^3/s. Resultantly the contribution of seepage to groundwater is based on the water balance components including recharge flow, applied irrigation, rainfall, lateral flow and evapotranspiration from the existing cropping system. A relationship between seepage (S) and the canal flow rate (Q) was developed ($S = 0.006\ Q^{1.44}$) to quantify the seepage to groundwater from the canal for any flow rate.

Key Words: Canal; Groundwater; Irrigation; Rainfall; Simulation modeling; Water

INTRODUCTION

Canal irrigation systems, practiced in many arid and semi arid regions of the world are facing a number of structural, operational and institutional problems resulting into reduced flows at the delivery outlets. The irrigation system, mainly earthen channels in Pakistan was introduced in mid 19^{th} century and it needs annual maintenance to keep conveyance efficiency at reasonably acceptable level. Despite spending huge resources on management and maintenance sectors, the canal head efficiency is estimated at about 74% and the seepage loss from the canal network is 26% (Bashir, 1997). Conveyance and application water losses often make canal supplies inadequate for irrigation purposes. The Indus Basin is formed by alluvial deposits and is underlain by an un-confined aquifer covering about 6.7 million hectares (Mha) in surface area. In Punjab about 79% of the area is underlain by fresh groundwater, which is mostly used as supplemental irrigation water and pumped through tubewells. About 40% of the total crop water requirements are partially met from groundwater and rainfall (Ahmad, 2002) depending on its quality. Electrical resistivity survey could be helpful for the determination of lithology and ground water quality (Arshad *et al*., 2008). Besides providing irrigation water the seepage from canals is also a major source of groundwater recharge. These water losses result in inefficient supply system. However, these losses are not a true loss from the system. As these outflows from the supply system is added up to the aquifer for the beneficial uses, they are regarded as apparent losers. This shows the importance and contribution of groundwater to meet the crop water requirements. The recharge to aquifer is affected by a number of factors (i.e., climate & seepage from irrigation system components etc.). In semi arid regions, the climate is the governing factor that controls the rate of recharge (Sanford, 2002).

Seepage from canals has a major impact on surface and groundwater resources management and can be assessed by physical, empirical and mathematical (analytical & numerical) techniques (WAPDA, 1965; Bouwer & Rice, 1968; Kachimov, 1992; Yussuff *et al*., 1994). Analytical methods involve the solution of mathematical equations governing the flow of water through porous media surrounding the canal. However there are many groundwater flow problems for which analytical solutions are difficult, because of their complexity and non-linearity. The recharge contribution to the groundwater from the irrigated field can be assessed using the analytical approach (Arshad *et al*., 2005). A need exists to develop simple techniques, such as numerical modeling methods. The

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seepage contribution to groundwater could be calculated by a finite-difference-based numerical solution of the differential equation governing the seepage flow (Swamee & Kashyap, 2001).

A three-dimensional finite difference model, MODFLOW (Harbaugh *et al.*, 2000) is a widely-used surface-groundwater flow model. It has been used to find the effect of irrigation on the height of the watertable in Lower Murrumbidgee, Australia (Punthakey *et al.*, 1996). The performance evaluation of Pat Feeder Pilot Interceptor Drain in Pakistan was also evaluated using MODFLOW on steady state basis utilizing the existing watertable profile with canal as a source of seepage (Basharat & Hafeez, 2001). The groundwater recharge from a stream, which was partially penetrated to an un-confined alluvial aquifer, was determined by using MODFLOW and its predictions were tested with SWMS-2D (simulating water flow & solute transport in two-dimensional variably saturated media) model (Osman & Bruen, 2002). The effects of various irrigation amounts and groundwater tables on seepage, percolation and drainage needs were tested using SWAP, DUFLOW and MODFLOW models. The comparison of the results showed that the results obtained using MODFLOW were good (Hollanders *et al*., 2005). The estimated seepage from a distributary using the MODFLOW was 16.5% of the inflow rate of the distributary. It was suggested that although the presented results of seepage contribution were limited to one distributary of canal irrigation system the developed methodology can be extended to the other canal systems of the Indus Basin (Arshad *et al.*, 2007).

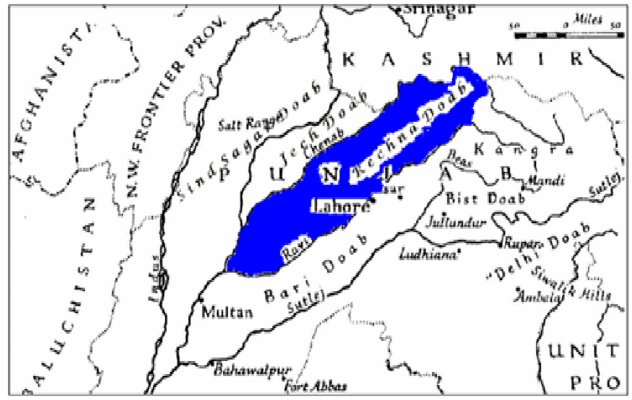
The above discussion indicates that groundwater model (MODFLOW) can be used for wide purposes in addition to assess the seepage to groundwater from different components of irrigation system. To better manage groundwater resources a need exists to evaluate the potential contribution of canal seepage to the recharge of the Indus Basin aquifer using the modeling approach. Therefore the specific objectives of this study were to calibrate MODFLOW for the aquifer in the command of the Upper Gogera Branch canal system; and assess the seepage contribution to groundwater from the canal under the crop, land and water relationship.

MATERIALS AND METHODS

Experimental site. The research was carried out in Rechna Doab, the canal irrigated area between the River Ravi and River Chenab in the province of Punjab, Pakistan (Fig. 1). The Rechna Doab lies between the $71^o–48^/$ to $75^o–20^/$ E and $30^o–31^/$ to $32^o–51^/$ N and comprises an area of 1067 km^2. The climate of the region is characterized by large seasonal fluctuations of ambient temperature and rainfall. Annual average precipitation (rainfall) is approximately 490 mm with 70% of the rainfall occurring during monsoons between Julys through September.

The area falls in the rice-wheat agro-ecological zones.

Fig. 1. Geographic location of Rechna Doab



Rice and forage crops dominate the summer (Kharif) season and wheat, sugarcane and forage are the smajor crops in the winter (Rabi) season. The Upper Gogera Branch canal having 226 m^3/s capacity is a branch of Lower Chenab Canal (LCC), which takes its water from the Chenab River. The command area of the canal is 775,000 ha. To improve the water supplies to the area, about 10,888 tubewells with an average capacity of 25 liter per second are installed in Rechna Doab. These tubewells operate more during the Kharif season, because of higher crop water requirements and conjunctive use of canal and groundwater (Sarwar, 1999).

Data collection. In order to achieve the desired objectives and considering the input requirement of the groundwater model used in this research the following primary as well as secondary data were collected.

Hydro-meteorological data. Rainfall and evaporation data for the study period were collected from Surface Water Hydrology, WAPDA, which had installed Hydrological Station in the vicinity of the Upper Gogera Branch canal. The data regarding the geometry of the canal and flow were collected from Punjab Irrigation and Power Department.

Soil data. To determine the sand, silt and clay percentage, soil samples were collected from the field at a depth of 0-30 cm, 31-60 cm, 61-90 cm and 91-120 cm and analyzed following the procedure explained by Tahir and Jabbar (1982).

Cropping system and irrigation data. The simulation of seepage was based on the planting, irrigations applied and harvesting of the rice and wheat crops during the study period, which were made (Table I, II & III) under the following planting treatments:

T_1: Direct seeding of rice (Kharif) and zero tillage for wheat (Rabi).

T_2: Direct seeded rice (Kharif) and wheat on beds with 2-rows (Rabi).

T_3: Transplanting rice seedlings on beds (Kharif) and wheat on beds with 3-rows (Rabi).

T_4: Random manual transplanting of rice in puddled field (Kharif) and traditional wheat planting on flat (Rabi).

Groundwater model. Considering the relative homogeneity of the aquifer characteristics and uniformity of flow conditions along canal, a model grid, 723 m in length consisted of 3 rows, 20 columns and 4 layers was developed. It contained 240 cells of which 80 (row-2) were active and 160 (row 1 & 3) were inactive. The widths of all the cells (Δy) of row-2 were 100 m. The total simulation period (357 days: February 10, 2003 to January 31, 2004) was divided into 12 stress periods (each month represents one stress period) and each stress had a single time step. The flow type was set as transient with time in days. Watertable depths for the research period were collected through the 9 observation wells (Y_1, Y_2, Y_3, Y_4, Y_5, Y_6, Y_7, Y_8 & Y_9) located at distances of 38, 43, 53, 73, 113, 193, 312, 476 and 673 m, respectively from the centre of the canal.

Based on the strata, the profile of the study area was divided into 4 layers from the ground surface, each of 5, 25, 25 m and remaining depth to the bottom of aquifer. The top layer was unconfined. The 2nd and 3rd layers were confined/unconfined (transmissivity = constant) and the 4th layer was confined. Transmissivity and storage coefficients were all set to be calculated by the model. The value of horizontal hydraulic conductivity of top layer was estimated as 20.8 m/d, while the remaining layers were 100.0 m/d. Similarly, the value of vertical hydraulic conductivity of top layer was estimated as 2.08 m/d, while the remaining layers were 10.0 m/d. The maximum ET rate (ET_m) for 12 stress periods was estimated (Table IV). The recharge from rainfall, watercourses and irrigated fields was assumed to be uniform for all the cells during each stress period and the recharge fluxes were calculated on the basis of field conditions (Table IV). The lateral flow was caused by the cell (20, 2, 1) to downstream and piezometer Y_9 was located in this cell. The watertable elevations at the start and end of 12 stress periods in this cell were measured (Table IV).

Table I. Irrigation application data for rice (summer) season 2001

Treatment	Replication	Area (m^2)	No. of irrigation	Depth of irrigation (mm)
	1	1875	27	38.45
T_1	2	1836	24	38.53
	3	1776	22	47.39
	Average	1829	24	41.46
	1	1971	21	49.69
T_2	2	1865	23	45.13
	3	2425	23	47.33
	Average	2087	22	47.38
	1	1904	30	35.00
T_3	2	1599	23	45.93
	3	1835	25	48.93
	Average	1779	26	43.29
	1	1733	21	46.80
T_4	2	1622	24	58.50
	3	1804	24	50.00
	Average	1719	23	51.77

Table II. Irrigation application data for wheat (winter) season 2001-2002

Treatment	Replication	Area (m^2)	No. of irrigation	Depth of irrigation (mm)
T_1	1	1971	4	44.69
	2	1865	4	44.67
	3	1622	4	71.91
	Average	1819	4	53.80
T_2	1	1875	4	69.83
	2	1836	4	53.16
	3	1776	3	73.24
	Average	1829	4	65.41
T_3	1	1904	4	51.26
	2	1599	4	66.35
	3	1835	4	69.49
	Average	1779	4	62.37
T_4		2425	4	57.77
		1733	4	74.57
		1806	4	104.69
	Average	1988	4	79.01

Table III. Planting and harvesting schedule for rice and wheat crops

Year	Rice		Wheat	
	Planting date	Harvesting date	Planting date	Harvesting date
2001-02	5th July	20th November	25th November	27th April
2002-03	5th July	21st November	26th November	25th April
2003-04	3rd July	15th November	-	-

RESULTS AND DISCUSSION

Model calibration. A transient calibration of the model was done using trial and error procedure. Simulated and measured values of water levels were compared and surface and aquifer parameters (recharge flux & hydraulic conductivities) were adjusted within reasonable limits to improve the fit. The evapotranspiration (ET) surface was selected as 0.50 m below the ground surface and the extinction depth was 1.5 m. The estimates for the recharge from the watercourses and irrigated fields were assumed 15% of the water delivered as a recharge and uniform for all the model cells according to Maasland's assumptions (Ahmad & Chaudhry, 1988). All the 9 piezometers were used as fitting wells and consequently, good matches were achieved between simulated and measured water levels (Fig. 2). The simulated temporal variation of watertable elevation at piezometer Y_1, Y_5 and Y_8 presented in this paper showed a good fit with regard to both timing and amplitude. The simulated water levels at piezometer Y_1, Y_5 and Y_8 almost followed the same trend. It is important to show that there was no systematic error involved in the spatial distribution of differences between simulated and measured heads. The scatter plots and regression analyses of piezometers Y_1 (R^2 = 0.95; RMSE = 0.21 m), Y_5 (R^2 = 0.96; RMSE = 0.13 m) and Y_8 (R^2 = 0.88; RMSE = 0.25 m) indicated that the agreement between simulated and measured water levels is reasonably good and no systematic error was involved in the model (Fig. 3).

Predicted water balance components. In a given domain of activities from various resources including recharge inflow from canal, applied irrigation, rainfall and outflow due to evapotranspiration and lateral flow was worked out as:

Change in storage = Recharge from canal + Recharge from irrigation and rainfall–evapotranspiration–lateral outflow.

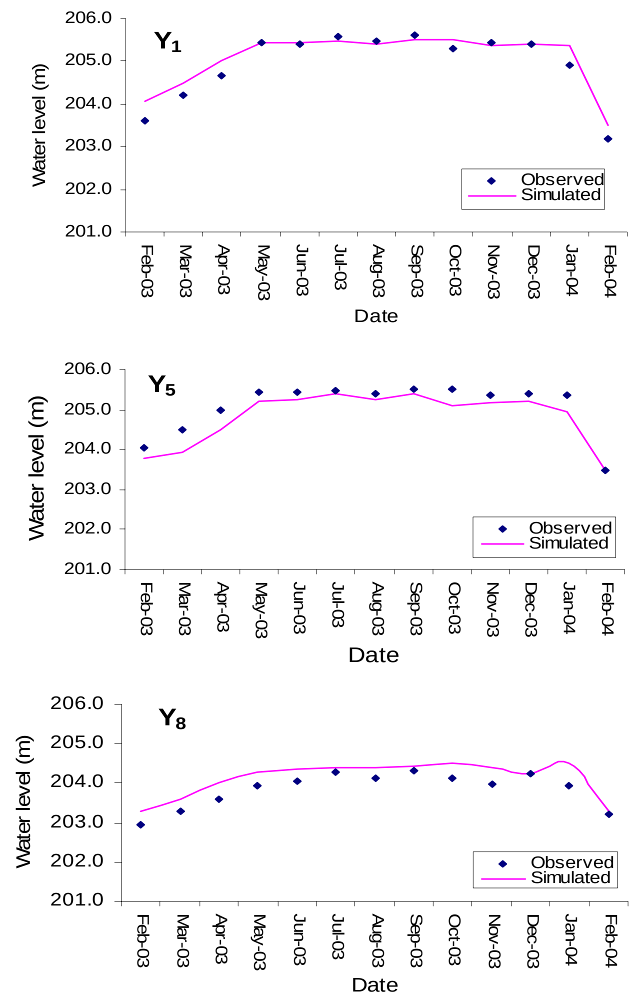
The lateral outflow calculated by the model refers to the flow rate of the water, flowing out of the cropping area considered. The months with high evapotranspiration, low recharge and less inflow than the outflow from the root zone tend to increase seepage from the canal. The seepage from the canal to groundwater ranged from 1425–1942 m^3/d/100 m of canal length during the operational period of the canal (Table V). The predicted seepage to groundwater from the canal was zero during the canal closure period (January, 2004). The seepage contribution to groundwater was low (1425 m^3/d/100 m of canal length) during February 2003. The highest seepage to groundwater was predicted during July 2003 (1942 m^3/d/100 m of canal length). The recharge from the irrigated field and rainfall to the groundwater ranged from 33–215 m^3/d and highest recharge observed during July 2003 was associated with higher rainfall during the month of July (Table V). The predicted ET for the existing cropping system from the groundwater ranged from 0-394 m^3/d. The part of predicted ET from groundwater was zero during the months of February 2003 and January 2004. This occurred due to reason that the extinction evapotranspiration surface used by the model was 2.0 m below the ground surface, so no ET took place during these months. The maximum evapotranspiration from the groundwater (394 m^3/d) was predicted during the month of July 2003. The simulated lateral flow from the aquifer, groundwater recharge stored and released in the aquifer is presented in Table V. The released storage is groundwater demand, partly met from aquifer storage component and added storage indicates that the excess groundwater recharge stored in the aquifer.

Predicted seepage contribution to groundwater. The operational canal flow rate ranged from 56–135 m^3/s and the average monthly flow rate of the canal for the whole modeled period was 106 m^3/s (Table VI). The monthly seepage to groundwater from the canal during the operational period ranged from 10.64–14.50 m^3/s/million-m^2 (Table VI). The average seepage rate for the whole year (12 stress periods) from both halves of canal was estimated as 12.1 m^3/s/million-m^2. The minimum flow rate was observed during the months of February and March 2003 (i.e., after the canal closure) when water started to flow in the canal. Hence the seepage rate to the groundwater from the canal was also low during February and March 2003. The maximum flow rate was observed during the month of June 2003 and resultantly the seepage rate from the canal was high for this month. The seepage from canal calculated by the model refers to the change in flow rate along the length of the channel (Basharat & Hafeez, 2001). It was further estimated that the seepage contribution of canal to the groundwater recharge was 15.1% of the inflow at the head of the canal. The months with high evapotranspiration, high recharge flux and high inflow tend to increase seepage from the canal, which is in accordance with Sanford (2002).

Table IV. ET_m, recharge flux and water head in cell (20, 2, 1) of canal

Stress period	ET_m (mm d^{-1})	Recharge flux (mm d^{-1})	Water head in cell (20,2,1)	
			Start (m)	End (m)
1	2.2	1.2	202.72	202.88
2	5.2	0.8	202.88	203.19
3	9.4	2.4	203.19	203.44
4	13.1	2.5	203.44	203.52
5	12.9	2.6	203.52	203.58
6	15.0	3.5	203.58	203.53
7	6.6	2.5	203.53	203.70
8	6.4	2.5	203.70	203.64
9	3.4	0.5	203.64	203.47
10	2.5	0.7	203.47	203.80
11	1.7	0.5	203.80	203.60
12	1.4	0.5	203.60	203.13

Fig. 2. Calibration of model: observed and simulated water levels at Y_1, Y_5 and Y_8



Recharge-flow rate relationship. Using the predicted results the relationship between seepage (S) in m^3/s/million-m^2 and the flow rate (Q) in m^3/s through the canal was developed as presented in the following equation:

$$S = 0.006\ Q^{1.446} \qquad (1).$$

Table V. Water balance components of canal domain aquifer

Stress period	Month	Canal seepage (m^3/d/100 m of canal length)	Recharge from irrigation and rainfall (m^3/d)	ET from groundwater (m^3/d)	Lateral outflow (m^3/d)	Groundwater storage	
						Released (m^3/d)	Added (m^3/d)
1	Feb-03	1425.240	72.286	-0.000	-1483.735	-	13.773
2	Mar-03	1772.642	52.332	-9.059	-1653.558	-	5.316
3	Apr-03	1824.301	151.390	-70.633	-1898.548	-	5.210
4	May-03	1908.690	155.127	-111.911	-1951.502	-	0.433
5	Jun-03	1896.101	161.980	-131.938	-1925.774	-	0.843
6	Jul-03	1942.044	215.558	-394.017	-1764.093	-0.500	-
7	Aug-03	1846.132	154.504	-69.641	-1930.309	-	0.646
8	Sep-03	1727.879	153.258	-82.206	-1797.729	-	1.149
9	Oct-03	1715.271	33.019	-32.729	-1716.808	-1.303	-
10	Nov-03	1866.128	40.495	-20.727	-1886.722	-0.830	-
11	Dec-03	1517.209	33.019	-18.000	-1530.930	-	1.334
12	Jan-04	0.000	33.019	-0.000	-47.552	-14.531	-

Table VI. Seepage contribution from the canal under study

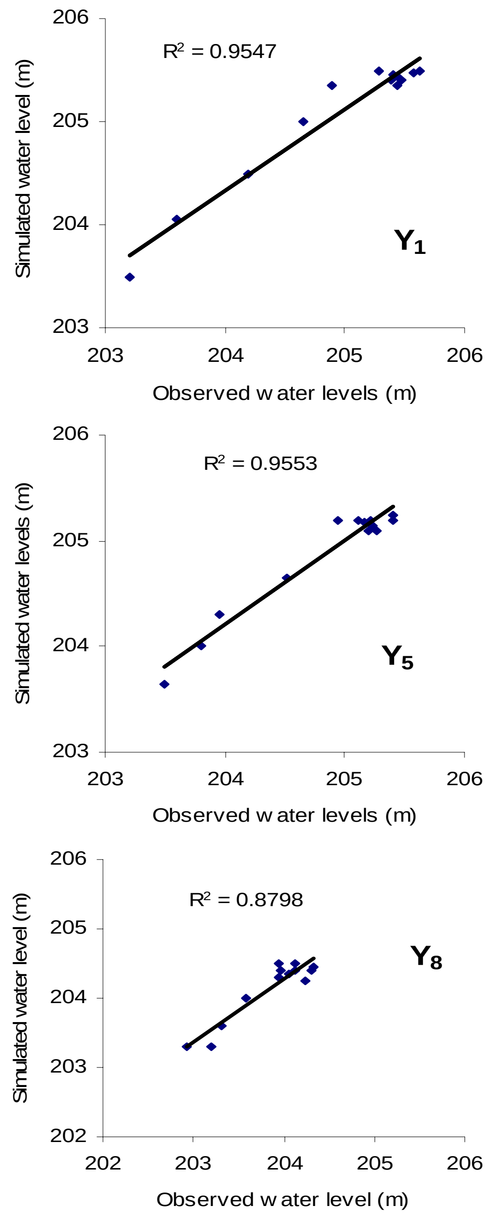
Stress period	Month	Flow rate (m^3/s)	Stage (m)	Seepage from one half (m^3/s/million-m^2)	Seepage from canal (m^3/s/million-m^2)
1	Feb-03	56	0.98	5.32	10.64
2	Mar-03	56	0.98	6.62	13.24
3	Apr-03	126	2.18	6.81	13.62
4	May-03	131	2.29	7.13	14.26
5	Jun-03	135	2.34	7.08	14.16
6	Jul-03	131	2.27	7.25	14.50
7	Aug-03	134	2.32	6.89	13.78
8	Sep-03	131	2.29	6.45	12.90
9	Oct-03	125	2.17	6.40	12.80
10	Nov-03	130	2.26	6.97	13.94
11	Dec-03	116	2.02	5.66	11.32
12	Jan-04	000.00	0.00	0.00	0.00
Average	-	106	1.84	6.05	12.10

This is the general relationship and can be used for estimation of seepage contribution to groundwater from the Upper Gogera Branch canal for any flow rate at any reach as reported for the distributary (Arshad *et al.*, 2008). IWASRI (1994) also used a relationship to correlate canal seepage with the canal discharge for number of canals. IWASRI calculated seepage at the rate of 300 mm/d for a flow rate of 53 m^3/s from the Lower Gogera Branch canal, which is in accordance with the seepage rate from Upper Gogera Branch canal (1045.2 mm/d) for the canal flow rate of 150 m^3/s. Therefore the predicted seepage rate for the Upper Gogera Branch canal is reasonably agreed with the results of IWASRI.

CONCLUSION

The predicted water levels successfully mapped the observed water levels in all nine observation wells. The contribution of groundwater toward evapotranspiration was zero during the wheat season (January, February) due to deep water table, low precipitation and canal closure period during these months. The model predicted that the average monthly seepage rate to groundwater from the canal was 12.10 m^3/s/million-m, which refers to the change in flow rate along the length of the channel. The estimated seepage contribution of canal to the groundwater recharge was

Fig. 3. Comparison of observed and simulated water levels at Y_1, Y_5 and Y_8



15.1% of the inflow at the head of the canal. A relationship between S and the canal flow rate (Q) was developed ($S=0.006\ Q^{1.44}$) to quantify the seepage to groundwater from the canal for any flow rate. These results are useful to frame the policies for the management and development of the irrigation system in Indus Basin of Pakistan.

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