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Numerical Investigation of Seepage from Earth Canals and Comparison with Field Measurements

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ABSTRACT: The seepage losses from the unlined channels are a major contributor to water losses in the agricultural sector. An understanding of the nature of seepage losses can help to improved water conveyance efficiency and provides solutions for solving water scarcity problems. In this research, numerical simulation was used to study the effective factors on seepage from earth channels. To verify the available information, some of the earthen channels in Zayandehrud irrigation network were used. A number of 246 numerical models including different sections of trapezoidal, rectangular and triangular earthen channels were performed using SEEP/W software. The results showed that, for numerical simulation a width of 15 times the width of the water surface in the channel would be required for the modelling of the left and right lateral boundaries. The comparison of seepage with empirical relationships showed that the empirical relationships reveal a large error in the seepage estimation, although Moritz's relation with the coefficient of determination 0.373 was better than the rest. Linear and nonlinear multivariate regression relationships provide a suitable match for seepage discharge estimation. Linear relationship was preferable due to small root mean square error (RMSE) and its simplicity. Wetted perimeter has been distinguished effective parameter in seepage from channel, but channel side slope had low effect on seepage. It is suggested that in future studies, the effect of groundwater depth on seepage from the channel should be considered.

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1. INTRODUCTION

In irrigation systems, canals are extensively used to transfer water from the reservoir to agricultural land. In most cases, the actual amount of water at the end of the canal is significantly lower than the amount of water entered at the beginning of the canal and one of the most important causes of these losses is water leakage from the canals.

Poortabari and Mazkamari [1], modeled the leakage rate in the canal using SEEP/W package for different modes and derived a mathematical relation between input and output data and compared it with other empirical equations. They presented the results in non-dimensional diagrams.

Rostamian and Abedikopai [2], studied the rate of water leakage in seven unlined canals in Zayandehrud irrigation network. The results showed that the empirical equations had a large difference with the observations and at the same time, the numerical simulation of canal leakage with the SEEP/W software was accurately matched to the measurements. Several studies have also been conducted with the SEEP/W software on water leakage from earth dams, seepage from foundation of gravity dams and the resulting uplift force. Examples include Mansurikiya et al. [3], Ahmed et al. [4], Akkuzu [5], Jain and Reddi [6]. Using SEEP/W, Salmasi and Nouri [7] investigated the effect of upstream semi-impervious blanket of embankment dams on seepage. Salmasi et al. [8] carried out the effect of longitudinal drains with underlined canals in reduction of uplift forces. Simulated models comprise 3 different drain pipe diameters; 15 different positions of pipe drains in X and Y directions; and 4 groundwater levels with respect to the canal bed

Over the past years, various researchers have provided empirical equations for calculating the leakage of water from canals. There is inadequacy of existing empirical equations due to the wide range of constant coefficients (C) in these equations. Also it is basically very difficult to choose a true value and the coefficients of the equations for the local conditions and it dictated that coefficients must be calibrated. Because the SEEP/W model has a good ability to estimate the leakage rate without requiring local calibration, the present study tends to use the soil hydraulic conductivity to estimate seepage from earth canals.

Validation of the numerical model is carried out by some of the available data from the Zayandehrud irrigation network, Iran. In numerical modelling, the effect of left and right boundaries from the center of the canal on the amount of leakage has been studied. As a result, the distance between the left and right boundaries of the canal center, where the water exchange is reduced to zero, is recommended. Three trapezoidal, rectangular and triangular sections were investigated for the leakage of canals and 246 numerical

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models were constructed. In the following, regression relations are presented from the non-dimensional factors for the application of numerical results.

2. MATERIAL AND METHODS

Various factors influence leakage from earth canals. These factors include canal geometry and hydraulic condition of the canal. In this study, it is assumed that the depth of underground water is at a great depth from the canal invert and therefore has no effect on leakage. Using the Buckingham theory, the dimensionless equation can be presented as follows:

$$\frac{q_s}{Ky} = f(\frac{P}{y}, \frac{b}{y}, \frac{R}{y}, z) \quad (1)$$

where q_s is discharge leakage ($m^3/s/m$), K is soil permeability coefficient (m/s), y is water depth in canal, P is wetted perimeter, b is canal bed width, R is hydraulic radius and z is canal side slope.

SEEP/W software is based on the finite element method. In soil, flow discharge follows the Darcy's law:

$$q = -KA\frac{\partial h}{\partial x} \quad (2)$$

where A is cross section of water flow (m^2) and $\partial h/\partial x$ is the hydraulic gradient of the flow. The equation governing the flow of water in a porous medium is the Poisson's equation, which is the generalized form of the famous Laplace's equation:

$$K_x\frac{\partial^2 h}{\partial x^2} + K_y\frac{\partial^2 h}{\partial y^2} = q \quad (3)$$

where K_x and K_y are the hydraulic conductivity of the soil in both horizontal and vertical directions (m/s) respectively, h is the water potential in the soil (m), and q the flow rate of the inlet or outlet to the soil mass (m^3/s per unit area). Equation 3 is valid for flow in a steady state condition.

Solving the Poisson's equation is one of the most complex mathematical problems. The SEEP/W software is one of the software used to solve the Poisson's equation using the finite element method. In this study, *quads* and *triangles* elements have been used (Fig. 1).

In general, the boundary conditions can be divided into two categories:

- Boundaries with known potential (total head)
- The boundary with known input-output discharge or with known hydraulic gradient

The application of boundary conditions in a canal in this study is shown in Figs. 2 and 3. The bottom invert of the canal and the canal side walls have boundary conditions of known potential (head=13 m from datum). The boundary conditions for the model walls and the bottom of the model, was assumed to be no-penetrating, and set to '*Total Flux=0*' (Fig. 3).

3. Results and Discussion

3.1. Study the effect of lateral boundaries

Fig. 4 provides the required distance in *x* direction for reasonable modeling. Fig. 5 shows the variations in leakage and error rates relative to the ratio of L/W in the trapezoidal section. According to the Fig. 5, L/W =14 in model 12 is acceptable with error less than 1% and therefore it is recommended in future studies to consider for the distance between the lateral boundaries in trapezoidal canals. This

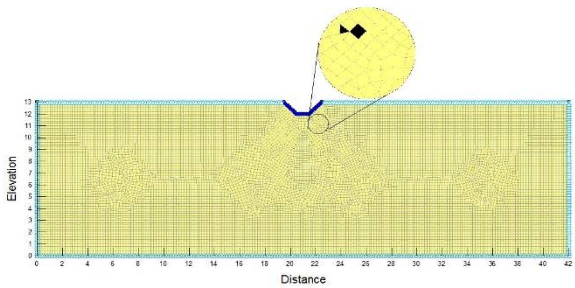

Fig. 1. Elements used in the models of this study, 4-node or 3-node type

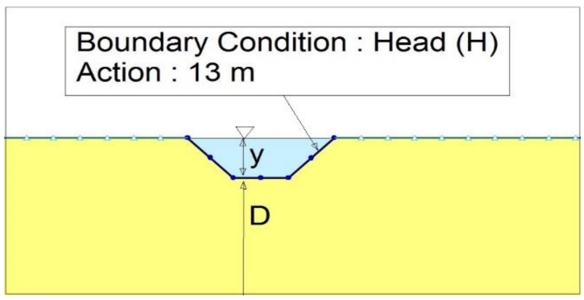

Fig. 2. Boundary condition for the bottom and side walls of the trapezoidal cross section

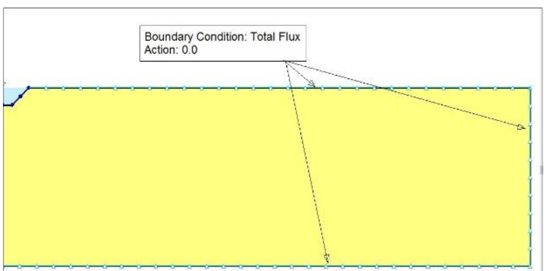

Fig. 3. Impermeable boundary conditions for the bed and walls of the trapezoidal earth channel model (half of the channel is seen on the left).

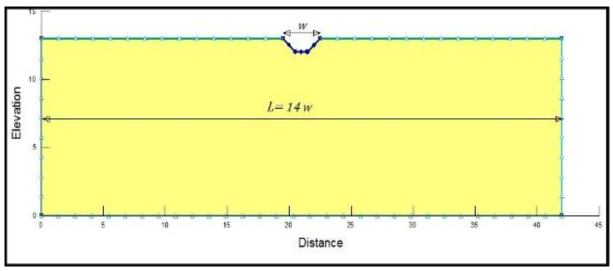

Fig. 4. Trapezoidal channel and recommended lateral distance .for determining boundary condition

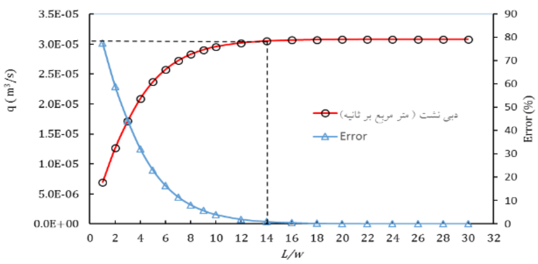

Fig. 5. The seepage and error changes relative to the L/W in the trapezoidal section.

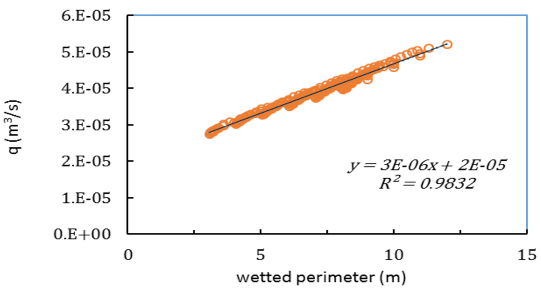

Fig. 6. The effect of the wetted perimeter on the seepage discharge in different trapezoidal, rectangular and triangular sections

distance (L) was obtained for rectangular canals 15 times the width of the canal (W).

3.2. Software performance verification

In Table 1, the statistical parameters obtained from different methods of estimating leakage from Zayandehrud irrigation network (in Iran) are presented. It is noted that the empirical methods of Davis and Wilson, Molsewerth and Yennidumia, Moritz, and Ingham did not have a proper leakage estimate, while the Moritz's method had a better performance than the rest of the methods. The comparison between the SEEP/W model and the leakage measurement data in Zayandehrud irrigation network canals indicates a very accurate accuracy of the SEEP/W numerical model.

3.3. Study of the effect of wetted perimeter on seepage

In Fig. 6, the results of numerical simulation of 246 canals with different trapezoidal, triangular and rectangular sections with different hydraulic characteristics are presented. According to Fig. 6, there is a linear relationship between the wetted perimeter and the leakage rate (R^2=0.98).

Equation 4 provides the linear regression relationship for non-dimensional leakage with a coefficient of determination of R^2=0.925, root mean square error (RMSE) equal to 4.978 for different trapezoidal, rectangular and triangular sections.

$$\frac{q_s}{Ky} = 3.5\frac{P}{y} + 14.741\frac{R}{y} - 1.127\frac{b}{y} - 9.36 \tag{4}$$

The nonlinear multivariate regression relationship for the discharged discharge was obtained as Equation 5, with R^2=0.927 and RMSE=4.908 for different trapezoidal, rectangular and triangular sections. In addition, the accuracy of the non-linear Equation 5 is greater than the linear value of 4. However, considering the ease of the linear equation in calculating and finding the leakage rate of canals, this study suggests using the linear equation. It should be noted that Equation 4 is valid in the range of:

$$0 \le z \le 2.5\,,\; 2.83 \le \frac{P}{y} \le 40.39\,,$$

$$0 \le \frac{b}{y} \le 35\,,\; 6.39 \le \frac{q_s}{Ky} \le 98.85\,.$$

$$\frac{q_s}{Ky} = 7.419 \times (\frac{P}{y})^{0.886} \times (\frac{R}{y})^{0.95} - 2.318 \times (\frac{b}{y}) \tag{5}$$

To calibrate and validate Equations 4 and 5, 70% of the dimensionless information was considered as training phase and the remaining 30% was considered as test phase. Table 2 shows the results of the calibration and verification steps of a linear and non-linear multivariate regression model for dimensionless leakage flows. The results of this table indicate that both linear and nonlinear multivariate regression models have desirable performance and there is no significant difference between the calibration and verification steps.

In Fig. 7, the variation of q_s/Ky calculated by SEEP/W is compared with q_s/Ky (using Equation 5). It is seen that the fitting regression equation is such that it estimates the value of q_s/Ky close to the value of numerical simulation.

Fig. 8 shows the relation between b/y and q_s/Ky for different *z* values based on Equation 6. Equation 6 provides a nonlinear regression relation with R^2=0.929.

Table 1. The statistical parameters obtained from different methods of estimating seepage from the earthen channels.

Method	R^2	*RMSE*
Davis and Wilson	0.093	48.793
Molsewerth and Yennidumia	0.067	49.631
Moritz	0.373	12.356
Ingham	0.183	23.421
SEEP/W	0.879	6.604

Table 2. Calibration and verification results of linear and nonlinear regression models

Nonlinear regression of Eq. (5)		Linear Regression of Eq. (4)		
RMSE	R^2	*RMSE*	R^2	
4.32	0.927	4.37	0.927	Calibration
6.06	0.918	6.16	0.917	Verification

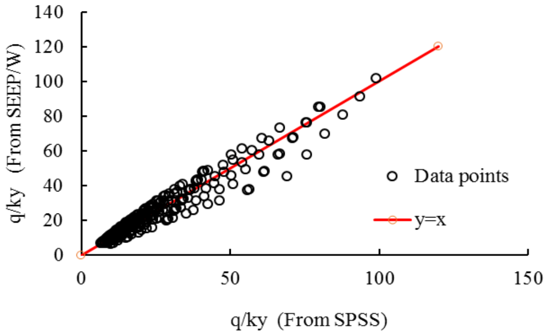

Fig. 7. Comparison between SEEP/W simulation with regression (Equation 5) using SPSS software

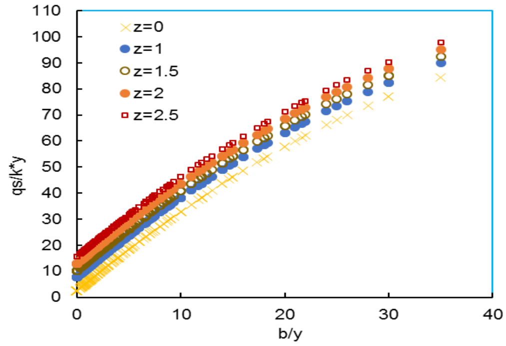

Fig. 8. Relationship between b/y and q_s/Ky in different values for z

$$\frac{q_s}{Ky} = -0.028\times(\frac{b}{y})^2 + 3.341\times(\frac{b}{y}) + 5.313\times z + 2.349 \quad (6)$$

As shown in Fig. 8, by increasing the ratio of b/y, the relative seepage (q_s/Ky) increases with a nonlinear trend. Also, milder slope (z=2.5) yields an increase in leakage.

4. CONCLUSION

The results showed that:

1-For numerical simulation, a width equal to 15 times the width of the water surface in the canal will be required for the neglecting of the effect of lateral boundaries on the leakage discharge.

2- The comparison of leakage with empirical equations showed that these equations provides large error in the leakage estimation, although the Moritz's relation with the smaller RMSE (12.356) and higher R^2 (0.373) were better than the rest.

3- Numerical simulation showed a strong linear relation between the wetted perimeter (P) and relative seepage discharge (q_s/Ky).

4- Hydraulic conductivity plays an essential role in estimating the amount of leakage from the unlined canals.

5- It is suggested that in future studies, the effect of groundwater depth and soil non-isotropy on leakage from the unlined canals should be investigated. In the last case, $k_x \neq k_y$ and it will have an effect on the amount of leakage.

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