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RESEARCH PAPER

Numerical and Experimental Assessment of Suspended Material Effects on Water Loss Reduction from Irrigation Channels

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Abstract

In the past, seepage was the main problem in water conveyance in arid and semiarid areas. Adding soil to water and making it muddy was a common way to reduce seepage, especially in new construction earthen channels or qanats. However, this technique is used to convey water from Baladeh Qanat to farmland in eastern Iran while the large amount of its irrigation channels is lined. The present research was carried out to investigate the effects of suspended materials on water conveyance. Three channels used in experiments included a farmland channel, a hand-built channel and part of Baladeh irrigation channel. Experiments consisted of passing freshwater and muddy water while water losses were measured. This research confirmed the effect of suspended materials in earthen channels sealing. Seepage from hand-built channel decreased significantly by passing water with suspended particles. Because of high slope of the channel, no sedimentary layer was formed in this test. Seepage from the farmland channel was much more than the hand-built channel because of seepage from the places that water inter to the farmland. Seepage in an earthen part of Baladeh channel with several gates was 71 times less than one from farmland channel. Sediment laden flow for years deposited a layer of fine sediment in Baladeh channel platform. Also, it seals outflow gates by leaving sediment behind the gates. Nowadays, the main purpose of adding sediment in flow is reducing the seepage from flow gates.

Keywords Seepage · Earthen channel · Sedimentation · Clogging · Sealing

1 Introduction

Due to scarcity of water in arid areas, many inventions had been appeared to protect valuable water resources from thousands of years ago. Irrigation systems are responsible for supplying required water to farms (Jiménez et al. 2021). Seepage from channels has been one of the main problems in water conveyance. It consists of water loss due to the permeability coefficient of earthen channel and it results wasting water from irrigation outlets (Barkhordari et al. 2020). In the past, a common way to reduce water loss in earthen channels was adding soil to water. This technique was used particularly in new construction channels and qanats. However, this method has been used in Ferdows irrigation channels in east of Iran.

The permeability of the soil layers in which channel is constructed is the most important factor influencing channel seepage (Robinson and Rohwer 1959; Crosbie et al. 2014; Harvey and Gooseff 2015; Gao et al. 2019; Wu et al. 2020). However, soil permeability has varied during the time because of prolonged submergence (Bodman 1937; Brockway 1973; Ayeldeen et al. 2016). Byrnes and Webster (1981) highlight natural effects on channels sealing. Smith and Turner (1982) emphasized that a layer of sediment can effectively control the seepage. Dillon (1988) also highlights the reduction of seepage rates over time as a result of the clay deposition and rise of water table.

The seepage rate is not only influenced by suspended martial sedimentation within the surface of a channel, but also by movement of fine material into the pores of soil (Kraatz 1977). Infiltration of sediment into the soil matrix reduces

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the seepage rate in a long period of time while microbial activities are responsible for seasonal variation in permeability (Brockway 1973). Cunningham et al. (1994) further developed this theory. Their studies covered the effects of the suspended sediment concentration and water velocity on channel seepage clogging. Penetration of the suspended sediment into the soil texture and its effect on seepage reduction have been subject of river studies literature (Royal et al. 1997; Wu and Huang 2000; Goldschneider et al. 2007; Gibson et al. 2011; Ulrich et al. 2015).

Many researches conducted to use other methods in order to reduce seepage in earthen channels. Hosseinzadeh Asl et al. (2020) used a numerical simulation to investigate the effective factors on the seepage from the earthen channels. To authenticate the information at hand, some of the earthen channels in the Zayandeh-Rud irrigation network in Iran and Gediz watershed in Turkey were studied. A total of 246 numerical models, including different sections of trapezoidal, rectangular and triangular earthen channels, were performed using the finite elements method (FEM). Their results showed that, for a numerical simulation, a width of 15 times wider than the top width of the water surface in the channel would be required for the modeling of the left and right lateral boundaries. Therefore, they recommend their model to simulate seepage and mange this value with the aim of reduction. Lund et al. (2021) found that a large amount of the water diverted for irrigated agriculture seeps from earthen canals during its conveyance to fields. For reducing this seepage, they used polymer sealants which provided an economical alternative to permanent liners for reducing seepage from earthen canals temporarily. Their tests showed a decline of 69–100% in seepage rates for a period of up to three months after LAPAM application. El-Molla and El-Molla (2021) noticed that earth canals are subjected to seepage losses during the conveyance and distribution of irrigation water. They found that canal lining is a common solution to minimize seepage losses. They use SEEP/W model to investigate the effect of compacted earth lining characteristics on seepage from trapezoidal earth canals. Their results showed that compacted earth lining is an efficient method to reduce conveyance losses. 99.8% of the water lost by seepage can be saved if highly compacted soil is used on the bed and sides.

Ferdows irrigation system conveys water from a set of qanats named Baladeh to farmlands and gardens for more than 600 years. The total length of channels in this system is more than 50 km and large parts of its channels are lined in recent years. Nevertheless, the old custom of adding soil to the water in the source has continued.

This paper is trying to investigate effects of sediment laden flow on water conveyance in a real irrigation system. Experiments were conducted on four earthen channels consisting of two hand-built channels, a real earthen channel and a part of Baladeh channel. The seepage was measured with freshwater and sediment laden flow using inflow–outflow method and pondage test. Moreover, the hand-built channel was simulated numerically to evaluate the seepage rate with and without sedimentary layer. And finally, experimental and numerical results were compared with Bouwer method (1969).

2 Materials and Methods

Based on literature, seepage rate is largely affected by soil permeability, shape and length of channel, water depth, location of groundwater table, water quality, sediment load, etc. The aim of this research was to evaluate the effects of suspended sediment on seepage reduction in different situations. Then, numbers of channels were implemented and seepage rate were measured in different state.

2.1 Experimental Channels

Channel 1 was a hand-built channel with a certain shape (Fig. 1a). This channel was built with high slope to not deposit sedimentary particles. Seepage rate in two cases, freshwater and suspended material in water, was measured. Channel 2 was near the first channel with low slope as a sedimentary layer was deposited after passing sediment laden flow for a few hours (Fig. 1b). Channel 3 was a part of a real irrigation channel next to pervious channels (Fig. 1c). This channel has numbers of field inlet which were closed with small dike. And channel 4 was a part of Baladeh channel (Fig. 1d). Table 1 presents some properties of all channel.

2.2 Seepage Measurement

Inflow–outflow and pondage test were used to measure the seepage rate in different channels. These methods were widely utilized in literatures (Trout and Mackey 1988; Byrnes and Webster 1981; A.N.C.I.D. 2000).

Water loss in channels 1, 3 and 4 was evaluated using inflow–outflow test. In a steady state flow in a channel, difference between the water entrance to the channel and the outflow is because of seepage and evaporation. It was taken advantage of rectangular and triangular sharp edge weirs to measure inflow and outflow (Fig. 1).

The basic equation of the inflow–outflow method for calculating seepage loss is (Trout and Mackey 1988):

$$S = \frac{Q_i - Q_0 - E - D + I}{pL} \tag{1}$$

That S is the seepage rate (length/time), Q is inflow rate (volume/time), Q_0 is outflow rate (volume/time), E is

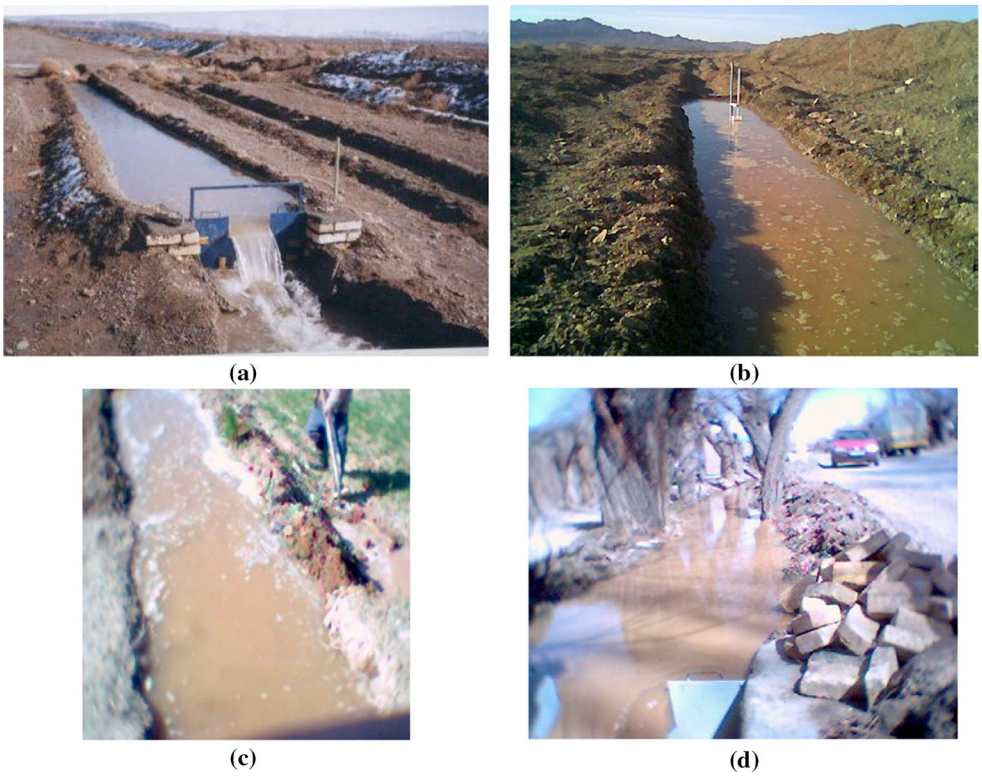

Fig. 1 The channels. **a** Flow measuement in channel 1. **b** Seepage measurement in channel 2. **c** Muddy water conveyance from channel 3. **d** Flow measurement in channel 4

Table 1 Properties of all channels

Channel number	Length (m)	Slope (m/m)	Max. flow rate (L/s)	Measurement method
1	371.40	0.02	28	Inflow–outflow
2	98.80	0.0025	25	Pondage test
3	215.50	0.02	25	Inflow–outflow
4	1205.30	0.022	65	Inflow–outflow

evaporation (volume/time), D is diversions (volume/time), I is Inflow, e.g., rainfall, runoff (volume / time), P is averaged wet perimeter (length), and L is the length of channel (length).

Since the water depth is increased behind the weirs and seepage rate is impressed, variation of the seepage rate by water depth is measured for each weir using pondage tests. Finally, the seepage rate in the channel was modified for the water was lost in the ponds behind of weirs and evaporation. Moreover, pondage test is implemented in channel 2 to measure the seepage rate.

The basic equation of the pondage test method for calculating seepage losses is (Frevert and Ribbens 1988):

$$S = \frac{WL\left(d_1 - d_2\right) - (EWL) + I}{PL\left(t_2 - t_1\right)} \tag{2}$$

That S is seepage rate (volume / area / time), W is average surface width between t_1 and t_2 (length), d_1 is water level at t_1 (length), d_2 is water level at t_2 (length), E is evaporation between t_1 and t_2 (length), R is rainfall between t_1 and t_2 (length), I is inflow value between t_1 and t_2 (volume), P is averaged wet perimeter between t_1 and t_2 (length), L is length of channel (length), t_1 is time at first section of water levels measurement (time), and t_2 is next section (time).

Water depth is measured using manometers and a calibrated evaporation pan is applied to record daily evaporation which are shown in Fig. 2.

2.3 Seepage Analysis

The effects of sediment laden flow on seepage reduction in earthen channels were analyzed using numerical and experimental methods. The study of the flow through permeable soil media was developed by Darcy in 1856. Darcy flow was presented the relation between the rate of flow with soil mass and hydraulic gradient. With considering Darcy flow and continuity equation, Laplace equation would appear.

Fig. 2 Manometers for water depth measurement

Laplace equation is solved analytically only for simple cases. Numerical methods can solve this equation with different boundary conditions with discretization the space and time and using iterative processes. Plaxis is a finite element based software which can solve water movement equation in permeable media. Plaxis is used to simulate the seepage from a channel in this research.

Bouwer (1965, 1969, 1978, 1988) studied seepage from channels in various conditions. He presented his method with some graphs that calculated the rate of seepage in steady scenarios for three conditions. Conditions A and B were related about channels which were embedded in a uniform permeable soil. In condition A, there was a high permeable layer under surface layer, however in condition B, the layer which the channel was constructed in underlain by a low permeable soil. Condition C was shown the soil in which the channel is embedded is of much lower hydraulic conductivity than the original soil for a relatively short distance normal to the channel perimeter (clogged soil or semipermeable linings).

2.4 Sensitivity Analysis

The sensitivity analysis for both inflow–outflow and pondage tests is carried out in order to investigate the errors come from measurements. In this research, the length of channels is measured with accuracy of 1 cm. Therefore, the error of this value is negligible. The cross section of channels is created with the usage of determined stencil which is shown in Fig. 3. The accuracy of this stencil is 1 mm which is ignorable. The precipitation and evaporation rates are really low and negligible in the period of experiments as well, and their errors are not meaningful. Water depth is measured with the usage of some tools shown in Fig. 2. This tool has 0.5 mm accuracy, and face the computation with the most error.

Fig. 3 The stencil for creation of channels

In the inflow–outflow test, flow rate is achieved with the rectangular weirs. The relation of these weirs is mentioned in the following equation

$$Q = Cb_e h_e^{1.5} \tag{3}$$

where h_e is the water depth and Q is the flow rate. The errors related to the creation of weirs are ignorable, due to its accurate creation. The most important error is depended to the water depth measurement. This error is presented in the following equation:

$$\frac{\mathrm{d}Q}{\mathrm{d}h_e} = 1.5Cb_e h_e^{0.5}\mathrm{d}h_e \tag{4}$$

This parameter is of high importance in pondage test as well

$$\mathrm{d}s = \frac{WL\left(d_1 \pm e - d_2 \pm e\right) - WL\left(d_1 - d_2\right)}{PL\left(t_2 - t_1\right)} \tag{5}$$

3 Result and Discussion

With measuring evaporation rate and water loss due to evaporation, it was found that the rate of evaporation was negligible in all experiments. In this study, the seepage was determined for different flow rates, and then, the percent of the water entering the channel that was wasted due to seepage was determined. The percentage of seepage along 100 m of the length of channel was also calculated and compared with that of other channels.

3.1 Experimental Results

Figure 4 shows variations of seepage compared to the inflow of channel 1. In this figure, variations of seepage over time are shown for three scenarios: freshwater flow, sediment laden water flow and second flow of freshwater. In sediment laden water scenario, samples were taken during the experiment, and the sedimentation varied between 350 and 500 ppm. During experimenting with the sediment laden water, due to relatively high flow rate, no sediment layer was deposited on the channel.

It should be noticed that, making the water muddy is done manually with the help of a person.

It can be seen that the percentage of water loss decreased from 18.15 to 12.75% in about 5 h for freshwater scenario. This reduction in seepage losses was due to saturation of the soil around the channel. It can be seen from the graph of sediment laden that the percentage of water loss decreased from 15.17 to 5.16% and then became almost constant. Comparison of seepage rates in two scenarios of fresh and sediment laden flows shows that constant seepage for the first and the second scenarios was 12.75 and 5.16% of inflow rate, respectively. In other words, the seepage rate in sediment laden flow was reduced by 60%. During the experiment with muddy water, no sediment was formed on the channel and reduction of seepage occurred due to permeation of fine particles of sediments along the flow in surface layers of soil. One day after experimenting with muddy water in channel 1, freshwater was passed through this channel again. In this experiment, the seepage was similar to the first experiment. Accordingly, the impact of the muddy water on the reduction of seepage was observed in this condition. After generation of sediment layer on the flow, it was quickly subsided and reductive effects of flow of the muddy water were no longer observed.

Channel 2 was constructed adjacent to channel 1 but with low slope with the aim of studying the effect of the formation of sediment layer. Seepage from channel 2 was measured by pondage test. Measurements were performed in two modes. The first mode related to the post-construction and after the flow of water for 2 days and the second was after flow of the muddy water and formation of a layer of sediment. Sediments formed on the bed had a thickness of 10 mm that almost linearly reached zero at the water level. Figures 5 and 6 show the test results. Pondage tests was performed with variable height. It can be seen from the figure that the seepage rate in the channel 2 was computed firstly for freshwater then muddy water about 3.24 and 1.42 m^3/day/L, respectively. With the passage of time and reduction

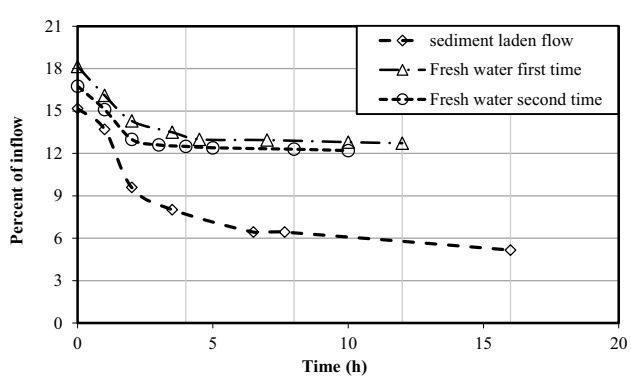

Fig. 4 The percent of seepage with time variation for freshwater and suspended sediment test

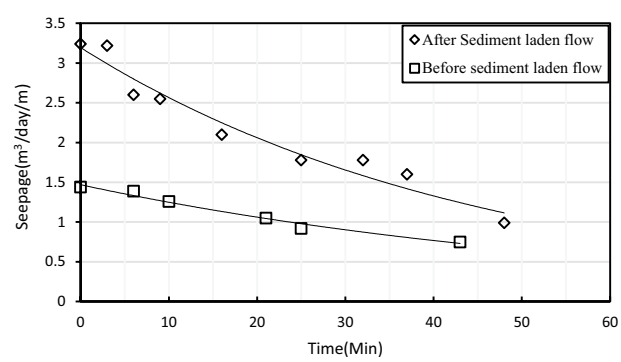

Fig. 5 Changes in the seepage with time for channel 2

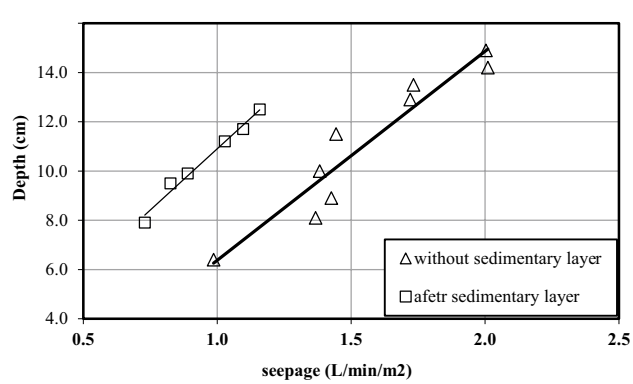

Fig. 6 Changes in the seepage rate with water depth in channel 2

of the water depth in the channel, seepage rate increased. Figure 6 shows the changes of seepage rate with water depth. In this figure, it is observed that seepage rate for depth of 10 cm was 1.9 and 1.02 m^3/day/L for freshwater and muddy water, respectively. Accordingly, the seepage rate from channel decreased by 46% due to the formation of sedimentary layer. Based on the experiments.

Figure 7 shows changes of seepage with time in channel 3 at flow of fresh and muddy water. As seen in Fig. 7, at the beginning of the measurements, seepage rate is 37.8% and after 3 h, it reached 24.75%. Thirty-four percent reduction of seepage is due to soil saturation in this channel.

Seepage in these channels in steady state is on average 0.115% per meter, which is very higher compared with channel 1 in which the percentage of water seepage is on average 0.034% per meter. This increase in seepage rater is because of the seepage from the place that water enters to the farmland. Soil used to close such places is usually taken from channel bottom or opening of agricultural land. This is where the soils are highly vulnerable to washing and soil is coarse, and therefore, it has high permeability and seepage. Seeped water from this area can be seen in Fig. 1-c.

The seepage of muddy water is computed in channel 3. Figure 7 shows the results of both fresh and muddy water in this channel. In muddy water scenario, seepage rate decreased to 8.2%. In other words, the amount of reduction was decreased by 65%.

Figure 8 shows changes of seepage in the Baladeh's channel (channel 4). The seepage rate for this channel is fixed to 1.1 lit/second or 1.85% of flow rate. In this figure, it can be seen that during the freshwater scenario, with testing the muddy water scenario, the amount of seepage increased. This was due to the gradual elimination of clogging caused by both surface layer and sediment clogging behind the gates.

In Fig. 9, seepage rate for 100 m of length in different channels is depicted. These graphs are for muddy water scenario. The amount of seepage for Baladeh's channel was 0.16%. This was 3.81% for channel 2 and 1.46% for channel 1. This graph also shows seepage from concrete channels in this region. In these channels, seepage was about 2.5% of inflow rate of channel. Most of such loss was accounted for lack of proper sealing of outflow gates from channels for gardens and farmlands.

It can be seen that the amount of losses from a concrete channel with a number of outflow gates was higher than losses from a soil channel without outflow water. Comparison of losses of concrete channels in the region and Baladeh channel showed that accumulated sediments behind the gates are well able to prevent water loss under the gate and the channel body.

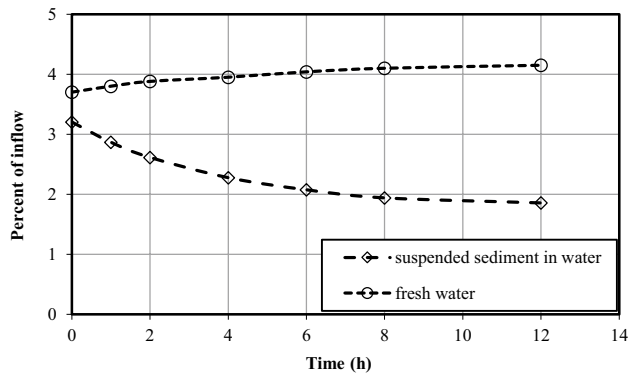

Fig. 8 Changes in the percent of seepage with time for channel 3

3.2 Sensitivity Analysis

Sensitivity analysis is carried out on the achieved results of channels. Table 2 shows this analysis for all channels. As previously mentioned, water depth parameter has the main role in this field; therefore, its effect on errors is acquired in the following table.

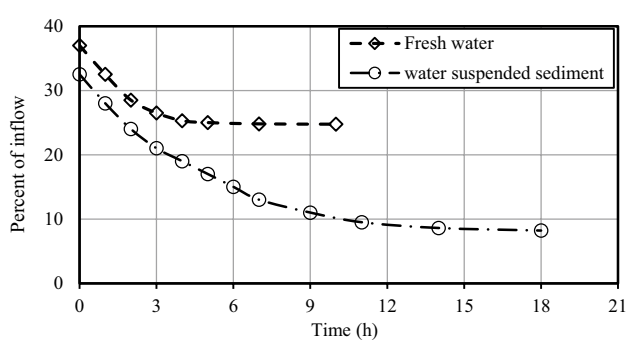

Fig. 7 Changes in the percent of seepage with time for channel 3

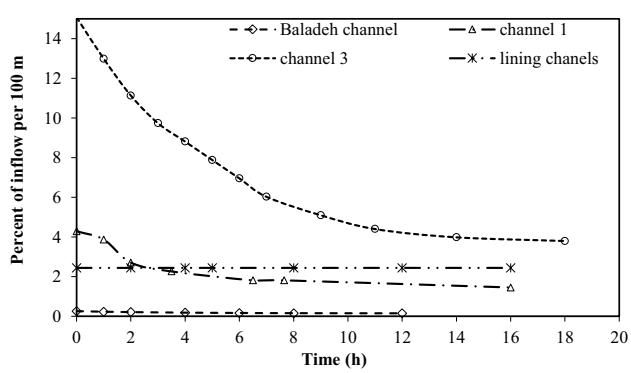

Fig. 9 The percent of seepage in 100 m channel length in different channel with suspended sediment

Table 2 Sensitivity analysis of error measurements on results

	Water depth on weir—inflow section(mm)	Water depth on weir—outflow section(mm)	Inflow rate (l/s)	Outflow rate (l/s)	Percent of seepage
Channel 1 First stage (Freshwater)	76 ± 0.5	69.5 ± 0.5	11.31 ± 0.11	9.87 ± 0.11	12.75 ± 2
Channel 1 Second stage (Muddy water) After 16 h	109 ± 0.5	105.5 ± 0.5	19.62 ± 0.14	18.67 ± 0.14	5.16 ± 1.4
Channel 1 Third stage (Freshwater) After 5 h	90 ± 0.5	82.5 ± 0.5	14.64 ± 0.12	12.82 ± 0.12	12.4 ± 1.7
Channel 2	149 ± 0.5	138 ± 0.5	15.76 ± 0.13	9.81 ± 0.14	37.8 ± 1.2
Channel 3	94 ± 0.5	78 ± 0.5	15.76 ± 0.13	11.86 ± 0.11	24.75 ± 1.5
Channel Baladeh	165 ± 0.5	163 ± 0.5	59.23 ± 0.23	58.16 ± 0.22	18.1 ± 0.1

Table 3 The characteristics of the soil in which channels 1 and 2 were contrasted and sedimentary layer after sediment laden flow

	$\gamma_s\left(\frac{kg}{m^3}\right)$	$\gamma_d\left(\frac{kg}{m^3}\right)$	$E_{ref}\left(\frac{KN}{m^2}\right)$	υ	ϕ	$C\left(\frac{KN}{m^2}\right)$
Base	2145	1867	40,000	0.3	36	0.1
Sedimentary layer	2010	1650	20,000	0.2	15	0.2

Table 4 The percent of passing

Number of sieves						
Soil in channel	#4 (4.76 mm)	#10 (2 mm)	#20 (0.841 mm)	#40 (0.425 mm)	#100 (0.15 mm)	#200 (0.075 mm)
Channel 1	100	90	70	55	45	28
Channel 2	100	85	65	50	44	22
Channel 3	100	84	61	47	38	20

3.3 Numerical Analysis

For computation of the seepage, two methods were used including Plaxis software (numerical approach) and Bouwer method (analytical method). Soil profile used in Plaxis is based on the results of achieved from soil mechanics laboratory. This information is provided in Table 2. In this table, the dry density is denoted by γ_d, saturated density γ_s of the soil, the soil modulus of elasticity E_{ref}, Poisson's ratio υ, adhesion C and friction angle of soil ϕ. Tables 3, 4 and Fig. 10 determine the soil properties in all the channels.

The permeability coefficients for three soils of channels are 2.45 (m/day) and based on the MIT soil classification system, they are all sandy loam.

The important coefficient in this problem is permeability coefficient of the soil. There are several laboratory methods to determine soil permeability, but on this problem, to determine the coefficient, a special method was used. For this purpose, soil permeability coefficient was determined using Plaxis in a way that numerical seepage is equaled to real seepage at a certain depth.

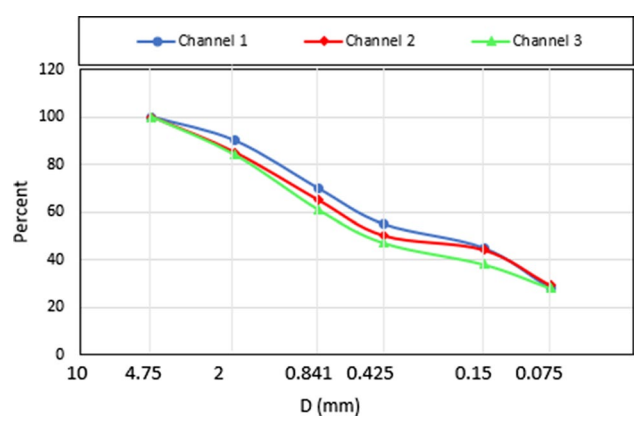

Fig. 10 The soil gradation for all channels

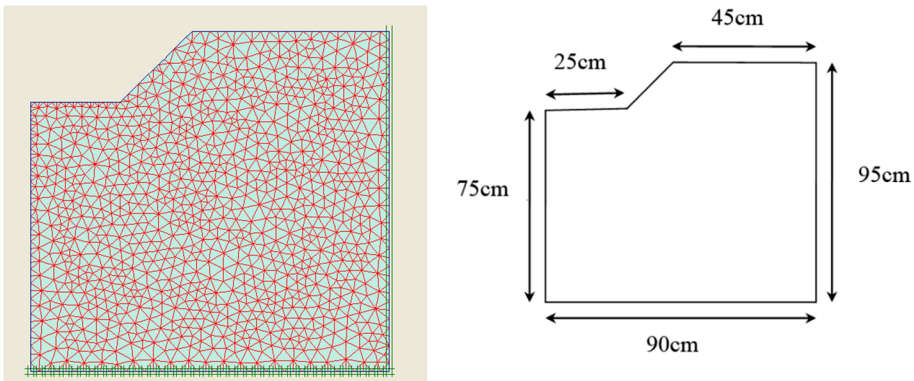

Fig. 11 Adaptive control volume

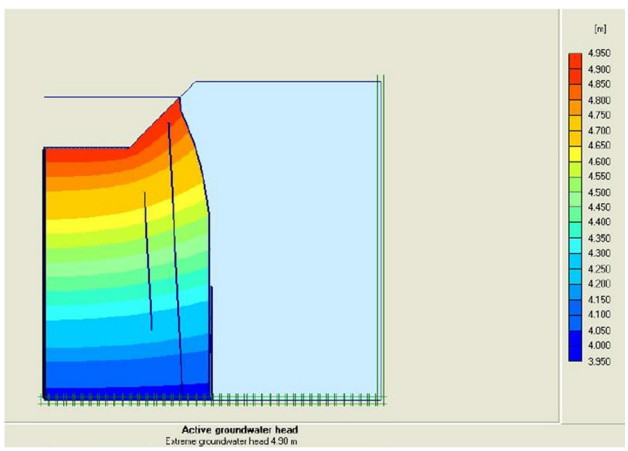

Fig. 12 Potential lines

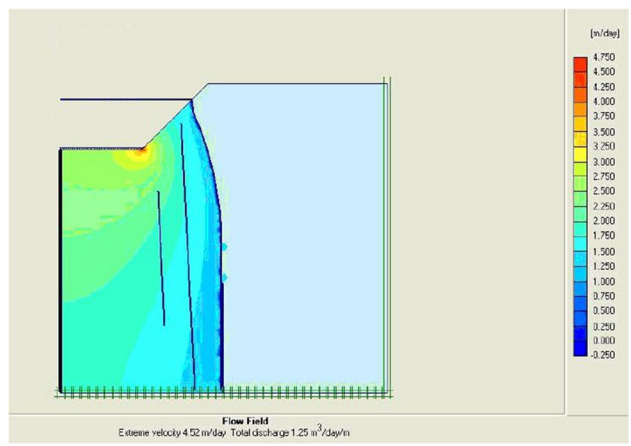

Fig. 13 Contour lines of velocity

Experiment was done in two steps for determining permeability of both soil and the sedimentary layer in the depth of 10 cm. In these tests, seepage from the channel was measured and it was 1.9 m^3/day/L, and therefore, seepage from the simulated section in Plaxis (half section of channel) was 0.95 m^3/day/L. By trial-and-error approach, when the soil permeability in Plaxis was assumed to be 2.52 m/per/day, the seepage obtained from the model equaled to the real seepage at depth of 10 cm. With computing this value, the seepage rate in different depth of water was calculated.

In analysis of seepage in Plaxis, analysis was done for half of the channel. Exact dimensions of element introduced to Plaxis were also selected by trial and error. Given flow line network and potential are independent of the coefficient of permeability soil, dimensions of element are gradually increased until results of analysis do not vary with increase in the size of element. Figure 11 shows dimensions of channel in Plaxis and the gridded element. Figures 12 and 13 also show contour lines of velocity and potential for water depth of 15 cm.

Some of the important points which were identified during the analysis are:

1. It can be seen in Fig. 13 that the highest flow rate occurred in the channel corner; in other words, the highest rate of seepage occurred from the corner of channel
2. From the same figure, it can be seen that as we move from symmetry line to phreatic line, flow rate is getting lower; in other words, the maximum velocity occurred on the symmetry line while the lowest occurred on the phreatic line.
3. It can be seen from Figs. 12 and 13 that the maximum lateral distance that the soil is saturated channel was about 20 cm away from channel 2. Figures 12 and 13 show that at the depth of 75 cm, phreatic line became vertical and potential lines became horizontal.

Seepage measured at different depths. This value which is obtained from Plaxis and Bouwer method for different depths is shown in Fig. 14.

Permeability coefficient was determined. It can be seen from Fig. 14 that gradient of curve of experimental results (measurements) is higher than analytic results. In other words, with increasing water depth in the channel, seepage increased at a higher gradient. Results from Bouwer method were very close to the experimental results (measurements),

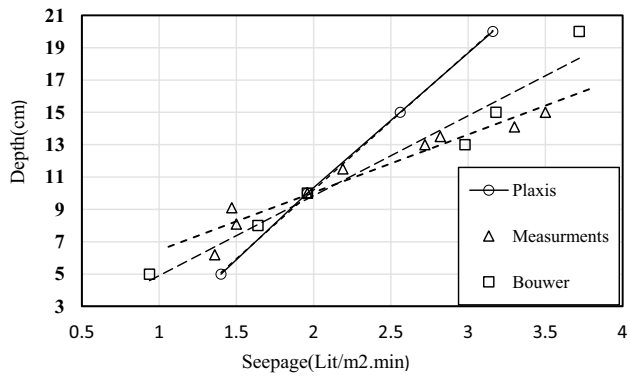

Fig. 14 Seepage variation with depth without sedimentary layer in channel 2

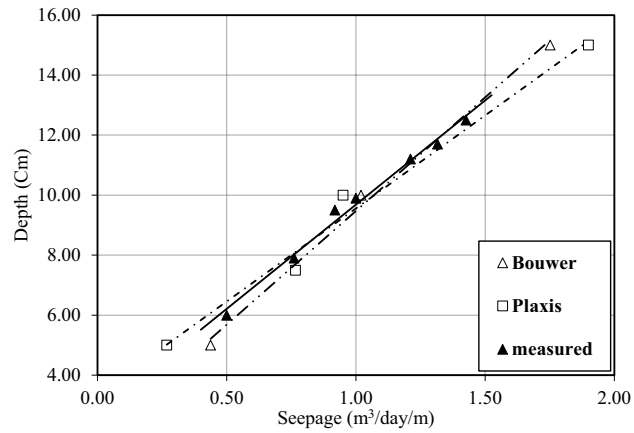

Fig. 15 Result of Plaxis, Bouwer and experiments with sedimentary layer in channel 2 (clogging state)

while the results from Plaxis had significant differences with the measurements.

In Fig. 14, we can see that despite equality of seepage for the three methods at a depth of 10 cm, seepage at 15 cm depth was 3.5, 3.18 and 2.56 m^3/day/L for experiments, Bouwer method and Plaxis software, respectively.

Errors of Bouwer method and Plaxis compared to the experiment were, respectively, 9% and 27%. It should be noted that in Plaxis, it was assumed that the soil is homogeneous. However, even if the soil of a region is uniform, soil compaction will increase with depth increment. This leads to a gradual increase in permeability with depth. The results presented in Fig. 14 show that Bouwer method can simulate these changes better based on the experimental results. This fact can express with the value of root mean square error. This parameter based on the Eq. 6 is computed. It was 3.4 and 8.2 for Bower and Plaxis, respectively. Therefore, Bower method presents results with higher accuracy that Plaxis.

$$\mathrm{RMSE} = \sqrt{\frac{\sum_j^m \left(V_o - V_s\right)^2}{m}} \tag{6}$$

where V_o, V_s indicate the observed and simulated values, respectively, while "m" is the number of samples.

In order to evaluate the effect of sedimentary layers on the surface of channel 2, according to the observations, soil layer with a thickness of 1 cm that is linearly decreased at the corners was added in element of Plaxis.

By keeping the original element soil permeability in Plaxis, permeability coefficient was determined for the sedimentary layer of channel surface by trial-and-error approach. To ensure that numerical seepage is equaled to real seepage at depth of 10 cm, permeability coefficient of this layers was obtained to be 0.076 m/day. According to Bouwer method, in channels with sediment layer, all resistance against the water flow can be attributed to sediment and original soil permeability is neglected.

Analysis was conducted on the sedimentary layers upon this assumption and using Darcy equation. The results of the test, Plaxis and Bouwer method are presented in Fig. 14. It is seen from this figure that the results of the three methods are well corresponded to each other. In other words, Bouwer method and Plaxis method have been able to simulate seepage well. As can be seen in related to Fig. 15, in this case Plaxis simulation could indicate the amount of seepage very well. This shows that sedimentary layer formed on the surface of channel was homogeneous and the problem related to the interpretation of Fig. 15 did not exist here.

Accordingly, in general, we can say that the results from analysis using Plaxis were accurate provided that the soil profile is determined with very high accuracy. According to the results, Bouwer method is good for determining the channel's seepage.

4 Conclusion

Results obtained showed that during flow of freshwater through a channel, upon saturation of the channel, seepage rate from the channel varied by about 60% in channel 1 and by 65% in channel 3. Seepage from channel at flow of freshwater in two adjacent channels, namely channels 1 and 3, was, respectively, 1.46 and 3.81% of inflow water per 100 m, and increased seepage in channel 3 was due presence of outflow gates of agricultural lands. Water losses from channel 3 were 2.61 times as much as that of channel 1. Flow of muddy water through channels 1, 2 and 3 resulted in decrease by 60, 46 and 67% of losses, respectively, compared to flow of freshwater through the same channels. Seepage from Baladeh channel at flow of muddy, selected real channel range on the farm with freshwater, was 71 times lower, compared to channel 2. Such large reduction is due

to flow of the muddy water through Baladeh channel for hundreds of years. According to the studied, before the construction of Baladeh Qanat about 600 years ago, passage of the channel had coarse-grained soil with large outflow gates, like channel 3. Currently, a layer of Baladeh channel is formed on a on a layer of fine-grained sediments with a thickness of about 3 m, with its bed's soil having very low permeability. Therefore, at the moment, the main role of muddying is associated with outflow gates. Accordingly, the purpose of muddying of water has changed during times, as in the past, the goal was to reduce seepage by creating layers and maintaining such layers, while sealing of outflow gates is the most important goal of muddying today. In testing and analysis, it was found that presence of layer could seriously lead to reduced seepage from the channel. Bouwer methods in two modes of with and without sediment layer provide good results for estimating seepage from channels. The results obtained using Plaxis software without clogging had some inconsistent with the experimental results; however, in the case of presence of layer, it provided satisfactory results.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

References

Allison LE (1947) Effects of micro-organisms on permeability of soil under prolonged submergence. Soil Sci 63:439

ANCID, O. C. S. (2000) Control—Vol 1.1 Literature review of channel seepage identification and measurement. Prepared by Sinclair Knight Merz

Ayeldeen MK, Negm AM, El Sawwaf MA (2016) Evaluating the physical characteristics of biopolymer/soil mixtures. Arab J Geosci 9(5):371

Barkhordari S, Shahadany SH, Taghvaeian S, Firoozfar AR, Maestre JM (2020) Reducing losses in earthen agricultural water conveyance and distribution systems by employing automatic control systems. Comput Electron Agric 168:105122

Bodman GB (1937) The variability of the permeability 'constant' at low hydraulic gradients during saturated water flow in soils. Soil Sci Soc Am Proc 2:45

Bouwer H (1965) Theoretical aspects of seepage from open channels. J Hrdraul Div ASCE Proc 91(HY 3):37–59

Bouwer H (1969) Theory of seepage from open channels. In: Chow VT (ed) Advances in hydroscience, vol 5. Academic Press, NY, pp 121–172

Bouwer H (1978) Groundwater hydrology. McGraw-Hill, New York, NY

Bouwer H (1982) Design considerations for earth linings for seepage control. Ground Water 20(5):531–537

Bouwer H (1988) Surface water-groundwater relations for open channels. In: Planning now for irrigation and drainage in the 21st century. Lincoln, Nebraska, USA. 18–21/7/1988. Publ by ASCE, NY, USA, pp 149–156

Brockway CE (1973) Investigation of natural sealing effects in irrigation channels. University of Idaho, Water Research Institute

Byrnes R P, Webster A (1981) Direct Measurement of Seepage from Earthen Channels. Australian Water Resources Council, Technical Paper No. 64. Australian Government Publishing Service, Canberra, Aust

Crosbie RS, Taylor AR, Davis AC, Lamontagne S, Munday T (2014) Evaluation of infiltration from losing-disconnected rivers using a geophysical characterisation of the riverbed and a simplified infiltration model. J Hydrol 508:102–113

Cunningham AB, Anderson CJ, Bouwer H (1994) Effects of sediment laden flow on channel bed clogging. J Irrig Drain 113(1):106–117

Dillon P J (1988) Estimation of Groundwater Accessions from Irrigation Channel Seepage, Report No. 3. Centre for Groundwater Studies

El-Molla, D. A., & El-Molla, M. A. (2021). Reducing the conveyance losses in trapezoidal canals using compacted earth lining. Ain Shams Eng J (accepted)

Frevert D K, Ribbens R W (1988) Methods of evaluating canal transmission losses. In: Planning now for irrigation and drainage in the 21st century, proceedings of conference sponsored by the Irrigation and Drainage Division, American Society Civil Engineering, Lincoln, Nebraska, USA, pp. 157–164

Gao Y, Tang X, Chu J, He J (2019) Microbially induced calcite precipitation for seepage control in sandy soil. Geomicrobiol J 36(4):366–375

Gibson S, Heath R, Abraham D, Schoellhamer D (2011) Visualization and analysis of temporal trends of sand infiltration into a gravel bed. Water Resour Res 47(12):1–11

Goldschneider A, Haralampides K, MacQuarrie K (2007) River sediment and flow characteristics near a bank filtration water supply: implications for riverbed clogging. J Hydrol 344(12):55–69

Harvey J, Gooseff M (2015) River corridor science: hydrologic exchange and ecological consequences from bedforms to basins. Water Resour Res 51(9):6893–6922

Hosseinzadeh Asl R, Salmasi F, Arvanaghi H (2020) Numerical investigation on geometric configurations affecting seepage from unlined earthen channels and the comparison with field measurements. Eng Appl Comput Fluid Mech 14(1):236–253

Jiménez AF, Cárdenas PF, Jiménez F (2021) Smart water management approach for resource allocation in High-Scale irrigation systems. Agric Water Manag 256:107

Kraatz D B (1977) Irrigation Canal Lining. FAO Land and Water Development Series No. 1, FAO, United Nations Rome, Italy

Lund AR, Martin CA, Gates TK, Scalia J IV, Babar MM (2021) Field evaluation of a polymer sealant for canal seepage reduction. Agric Water Manag 252:106898

Robinson A R, Rohwer C (1959) Measuring seepage from irrigation channels. Technical Bulletin 1203. Washington, D.C., US Agricultural Research Service, Colorado Agricultural Experiment Station and US Department of the Interior

Royal D, Bursik M, Atkinson J, Depinto J (1997) Filtration enhances suspended sediment deposition from surface water to granular permeable beds. Water Air Soil Pollut 99:157–171

Smith RJ, Turner AK (1982) Measurements of Seepage from Earthen Irrigation Channels. Civ Eng Trans Inst Eng Aust CE 24(4):338–345

Trout TJ, Mackey EM (1988) Inflow-outflow infiltration measurement accuracy. J Irrig Drain Eng 113(1):256–265

Ulrich C, Hubbard S, Florsheim J, Rosenberry D, Borglin S, Trotta M, Seymour D (2015) Riverbed clogging associated with a

California Riverbank Filtration system: an assessment of mechanisms and monitoring approaches. J Hydrol 529:1740–1753
Wu F, Huang H (2000) Hydraulic resistance induced by deposition of sediment in porous medium. J Hydrauli Eng 7(547):547–551
Wu Y, Huang Z, Zhao K, Zeng W, Gu Q, Zhang R (2020) Unsteady seepage solutions for hydraulic fracturing around vertical wellbores in hydrocarbon reservoirs. Int J Hydr Energy 45(16):9496–9503