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Research Article

Study of the Process of Contaminant Transport and Pumping in a Laboratory Model

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Abstract

In this research, the objective is to study the process of contaminant transport and pumping in a laboratory model. A two-dimensional laboratory model was used in this research. The length, width, and height of the model respectively were 140 cm, 5 cm, and 57 cm. Chambers were provided on the left and right sides of the model to store water and create a constant hydraulic head. The material used in this model was glass beads, which act similarly to sand particles. Sampling tubes were installed at five points A to E along the length of the model and at three depths. Finally, at specific times after the contaminant release, a sample of the contaminant was injected and its concentration was analyzed. The research results showed that at a gradient of 0.05, the contaminant transport rate was significantly higher than at a gradient of 0.014. Therefore, the depth penetration of the contaminant is less at a gradient of 0.05 than at a gradient of 0.14. On the other hand, contaminant pumping at points C2 and D2 showed that pumping from point C2 more effectively reduced the contaminant concentration in the entire laboratory model. This holds for contaminants with other concentrations as well. Contaminant concentration and hydraulic gradient are two important factors in the amount of contaminant transport. Also, for effective contaminant pumping, the best location for pumping contaminated water is somewhere near the seepage site and in the path of the contaminant movement.

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1-Introduction

The groundwater contamination sources can be from natural or human-made sources. Natural resources include sea water intrusion, breaking down of natural minerals existing in ground strata (Eldho and Swathi, 2018). The main human-made sources are plenty ranging from domestic sources like leakages from septic tanks and sewers; improper disposal of garbage and industrial waste, extensive use of chemicals in agriculture such as fertilizers and pesticides, and many other human activities. As mentioned, other sources of pollution include improper waste disposal. When the landfill site is not well insulated, the waste leachates that contain dangerous substances such as heavy metals easily seeps and enter the groundwater and pollute it (Eldho and Swathi, 2018).

In the discussion of groundwater pollution, some researchers have identified pollutant sources (Darabi, and Ghafouri, 2007), (Guneshwor, *et al.* 2018) and other researchers have investigated various groundwater remediation methods such as in-situ phytoremediation (Mategaonkar, *et al.* 2018) or the pump and treat (PAT) system (Wang, *et al.* 2018). In any case, the design of an efficient remediation system is carried out with various objectives. In general, remediation methods have many influential components. For example, the pump and treat method has important components such as the locating of the pumping well, the pumping rate of polluted water, the remediation time, and the amount of groundwater level drawdown during pumping.

Various methods are used to solve the groundwater remediation optimization problem. Some researchers have used nonlinear programming (Gorelick, *et al.* 2018) or meta-heuristic algorithms such as AMALGAM (Darabi, and Ghafouri, 2007), (Ouyang, *et al.* 2017), probabilistic multi-objective genetic algorithm (Singh, and Minsker, 2008), (Zeynali, *et al.* 2022a), and niched pareto genetic algorithm (Kumar *et al.* 2015), (Erickson, *et al.* 2002).

One of the most important objectives of groundwater remediation is to reduce the pollutant concentration to the permissible level. The pollutant concentration can be directly or indirectly related to the carcinogenic potential of pollution in human health risk (Yang *et al.* 2018a), (Mategaonkar, *et al.* 2018), (Yang, *et al.* 2018b), (Zeynali, *et al.* 2024). Many researchers have introduced the reduction of pollutant concentration and pumping cost or, in other words, the number of pumping wells and pumping rate (Alexander, *et al.* 2018), and some others have introduced the location of pumping wells (Sbai, 2019) and the groundwater remediation time (Mategaonkar, *et al.* 2018) as the objective function of their optimization problem.

On the other hand, researchers have used various methods such as finite difference (He, *et al.* 2018), finite element (Esfahani and Datta, 2018), (Zeynali, *et al.* 2022a), (Zeynali, *et al.* 2024) and meshfree method (Boddula and Eldho, 2017), (Zeynali, *et al.* 2022b) and MODFOLW software to solve the groundwater remediation optimization problem (Seyedpour, *et al.* 2019), (Joswig, *et al.* 2018).

After literature review on the subject and the research background presented, in general, it can be said that many researchers have used numerical methods to simulate contaminant transport. Therefore, the gap seen in the research is the lack of investigation of the contaminant transport process in a laboratory model. Therefore, in this research, the process of contaminant transport in a laboratory model is studied.

2-Materials and Methods

2-1-Laboratory Model

The laboratory model used in this study was a two-dimensional model with dimensions of 140 cm (length), 5 cm (width), and 57 cm (height). Three valves were installed on both the right and left sides of the model. The distances of the right-side valves from the bottom of the model were 6 cm, 42.5 cm, and 47.5 cm, respectively. The distances of the left-side valves from the bottom of the model were 6 cm, 40.5 cm, and 45.5 cm, respectively. The thickness of the glass used in the model was 0.7 cm. Chambers were provided on the left and right sides of the model to store water and create a constant hydraulic head. Fig. (1-a) shows a view of the laboratory model. The material used in the model was glass beads, which act similarly to sand particles, as shown in Fig. (1-b).

Sampling for the contaminant was conducted using 0.4 cm diameter tubing at various depths and distances from the contaminant source. The location and installation of the tubes in the model were carefully planned to minimize resistance to water and contaminant flow and to avoid affecting the contaminant's movement path. Since concentration changes are more pronounced near the contaminant

source than at farther distances, more sampling points were placed near the source. Accordingly, sampling tubes were installed at five points (A to E) along the length of the model and at three depths, as shown in Fig. (2).

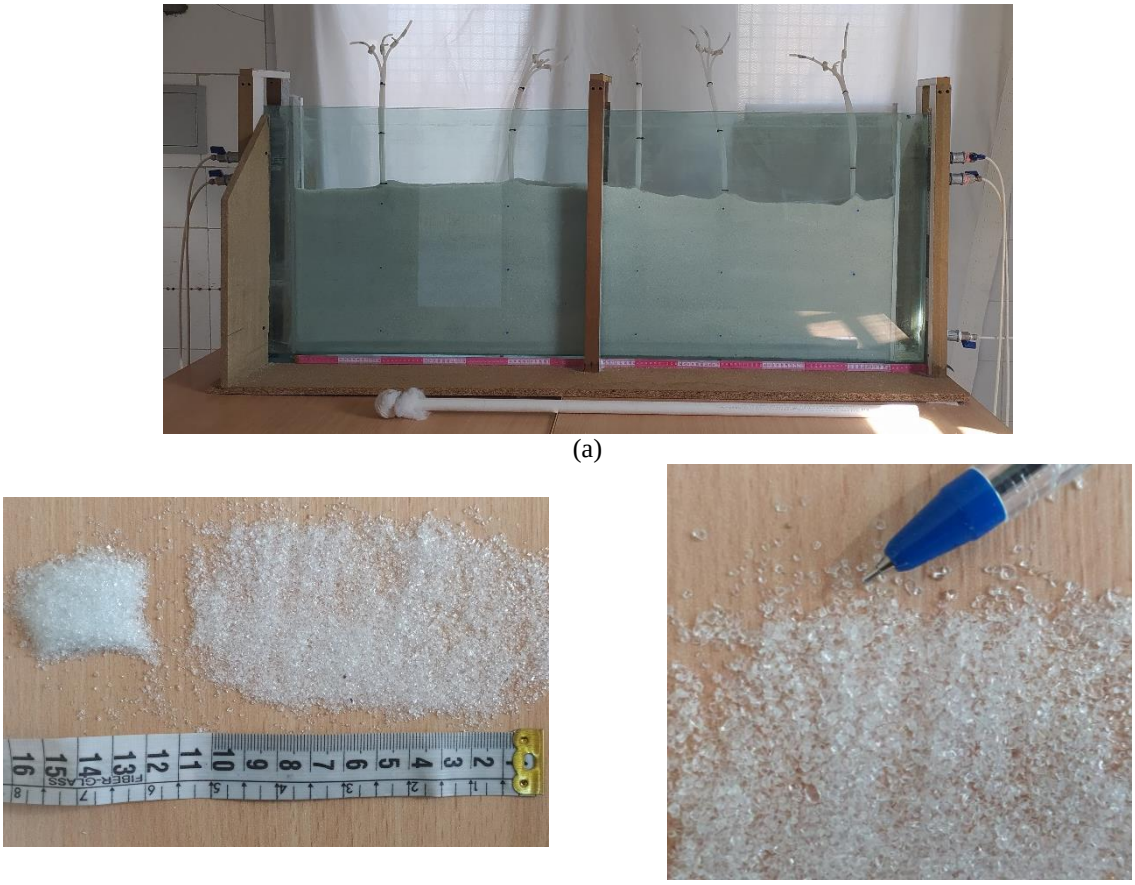


Figure 1. A view of the laboratory model and glass beads.

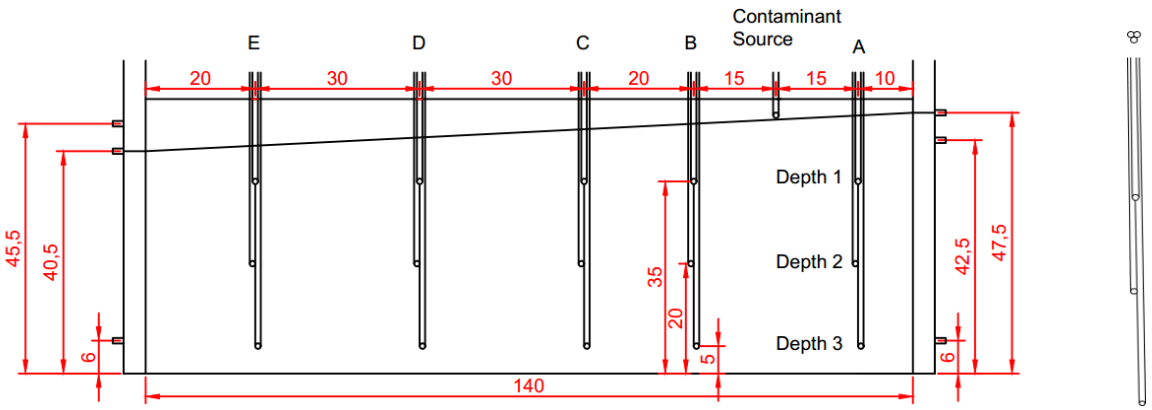


Figure 2. A view of the sampling tube in laboratory model.

2-2-Contaminant Specifications

The contaminant used in this study was a mixture of water and salt (NaCl) colored with food coloring. The food coloring was used to visualize the movement of the contaminant front. The experiments involved four different contaminant concentrations, each with two hydraulic gradients. Also in Table (1) summarizes the experimental details are given.

2-3-Method

Initially, glass beads are poured into the tank and

after the tank is filled to a height of 5 cm, the glass beads are compacted to ensure that there is no trapped air between the beads. In this way, the entire tank is filled with glass beads by filling and compacting the beads.

Once the tank is filled, water is introduced into the right-hand tank by opening the inlet valve on the right side and water enters the porous media. By adjusting the lower outlet valve on the left side, the head on the left side can be adjusted. In this study, two hydraulic gradients are tested, with the head on the right-hand boundary always fixed at 47.5 cm and the head on the left-hand side fixed at 40.5 and 45.5 cm from the bottom of the tank. The fixed head at a height of 40.5 cm is shown in Fig. (2) and at a height of 45.5 cm in Fig. (3).

Table 1. Summarizes the Experiment Details

Experiment	NaCl Concentration	Food Coloring	Hydraulic Gradient	Pumping Location
-	*(ppm)*	*(cc)*	-	-
Exp. Num.1	10000	40	0.050	C2
Exp. Num.2	10000	40	0.014	C2
Exp. Num.3	7500	30	0.050	C2
Exp. Num.4	7500	30	0.014	C2
Exp. Num.5	5000	20	0.050	C3
Exp. Num.6	5000	20	0.014	C2
Exp. Num.7	10000	40	0.050	D2
Exp. Num.8	10000	40	0.014	D2
Exp. Num.9	7500	30	0.050	D2
Exp. Num.10	7500	30	0.014	D2
Exp. Num.11	5000	20	0.050	D2
Exp. Num.12	5000	20	0.014	D2

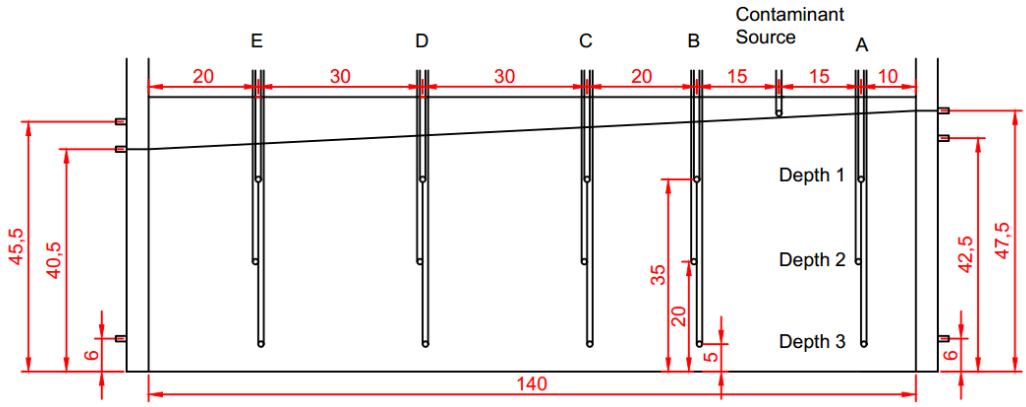


Figure 3. Hydraulic gradients equals to 0.014.

In each experiment, after the conditions have reached steady state, the contaminant is released from the contaminant source and seepage into the porous media. Sampling will be performed after that the contaminant seepage into the porous media. The contaminant source will then be removed, pumping of the contaminant will be started, and sampling of the porous media will be performed again.

3-Results and Discussion:

3-1-Details of Experiments

Twelve experiments were conducted on the laboratory model, and the details of each experiment are presented in Table (2).

The experiments began with the release of the contaminant from the source and seepage into porous media. The start of contaminant release from the source was considered as time zero. The contaminant source was then remove, and sampling was performed at various times before and after source remove. Then pumping process was started, and sampling continued from different points during this process. Table (3) provides the details of sampling and pumping times.

3-2-Spectrophotometer Calibration

To utilize the spectrophotometer, a sample was taken from the contaminant source with a

concentration of 10000 ppm. From this sample, four samples were prepared with concentrations of 2500 ppm, 1000 ppm, 500 ppm, and 250 ppm, as shown in Fig. (4). After calibrating the device with known concentrations, the concentrations of the samples collected at various times were also measured using the spectrophotometer.

Table 2. Summarizes the Experimental Details with Seepage Rate and Pumping Rate

Experiment	NaCl Concentration	Seepage Location	Hydraulic Gradient	Pumping Location	Hydraulic Conductivity	Seepage Rate	Pumping Rate
-	*(lit/min)*	-	-	-	*(cm/min)*	*(lit/min)*	*(lit/min)*
Exp. Num.1	10000	surface	0.050	C2	0.0244	0.522	0.414
Exp. Num.2	10000	surface	0.014	C2	0.0220	0.720	0.444
Exp. Num.3	7500	surface	0.050	C2	0.0199	0.762	0.414
Exp. Num.4	7500	surface	0.014	C2	0.0221	0.762	0.449
Exp. Num.5	5000	surface	0.050	C2	0.0215	0.632	0.552
Exp. Num.6	5000	surface	0.014	C2	0.0390	0.800	0.623
Exp. Num.7	10000	surface	0.050	D2	0.0226	0.779	0.558
Exp. Num.8	10000	surface	0.014	D2	0.0155	0.779	0.444
Exp. Num.9	7500	surface	0.050	D2	0.0194	0.787	0.607
Exp. Num.10	7500	surface	0.014	D2	0.0154	0.787	0.607
Exp. Num.11	5000	surface	0.050	D2	0.0474	0.799	0.667
Exp. Num.12	5000	surface	0.014	D2	0.0432	0.799	0.706

Table 3. Summarizes the Sampling Time

Experiment	NaCl Concentration (ppm)	Hydraulic Gradient	Removing Contaminant Source Time (min after starting seepage)	The end of Pumping time (min after starting seepage)	Sampling Time (min after starting seepage)				
					Num.1	Num.2	Num.3	Num.4	Num.5
Exp. Num.1	10000	0.050	30	35	10	15	25	35	-
Exp. Num.2	10000	0.014	30	45	15	20	40	45	-
Exp. Num.3	7500	0.050	30	45	10	15	25	35	45
Exp. Num.4	7500	0.014	30	45	15	25	40	45	-
Exp. Num.5	5000	0.050	25	45	10	15	25	35	45
Exp. Num.6	5000	0.014	30	45	15	25	40	45	-
Exp. Num.7	10000	0.050	30	45	10	15	25	35	45
Exp. Num.8	10000	0.014	30	45	15	25	40	45	-
Exp. Num.9	7500	0.050	30	45	10	15	25	35	45
Exp. Num.10	7500	0.014	30	45	15	25	40	45	-
Exp. Num.11	5000	0.050	30	45	10	15	25	35	45
Exp. Num.12	5000	0.014	30	45	15	25	40	45	-

Figure 4. Samples with different concentrations.

The calibration curve for the spectrophotometer is shown in Fig. (5). As can be seen, a correlation coefficient (R^2) of over 0.99 was achieved.

3-3-Summary of Results for Experiments 1-12

The experiments were conducted using three contaminant concentrations (10000, 7500, and 5000 ppm) and two hydraulic gradients (0.05 and 0.014). Two locations were also investigated for contaminant pumping: C2 and D2, as indicated in

Fig. (3). To compare the movement of the contaminant front, Fig.s (6) and (7) show the concentration distributions for different concentrations and gradients, as well as the pumping points C2 and D2, 30 minutes after contaminant release from the source.

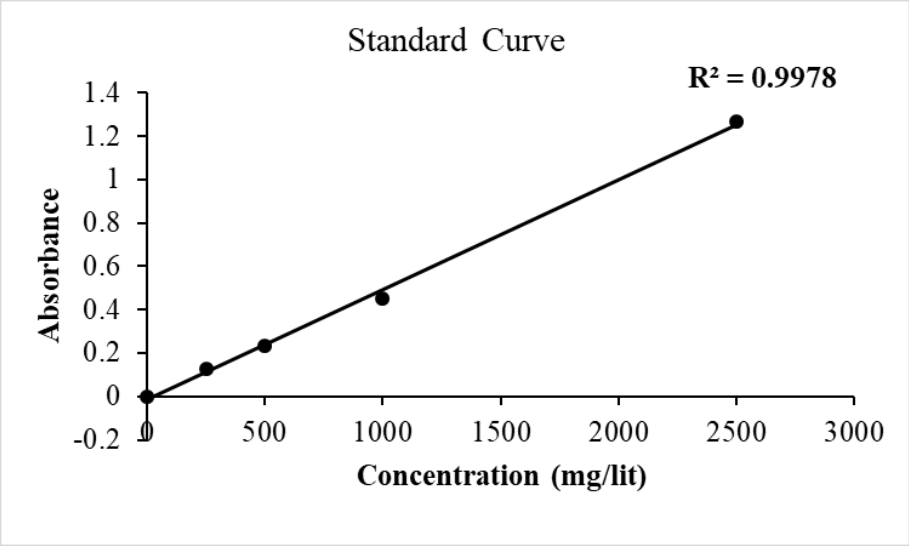


Figure 5. Calibration curve.

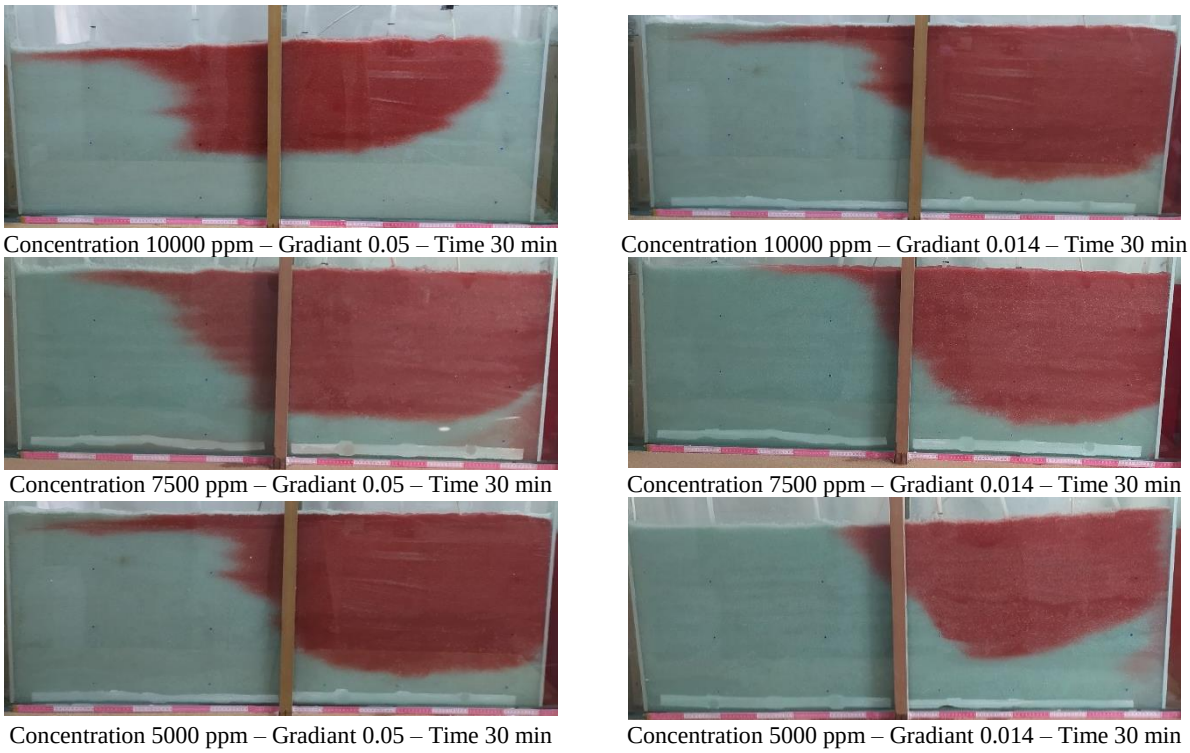


Figure 6. Movement of the contaminant front from starting seepage to before pumping (pumping location : C2).

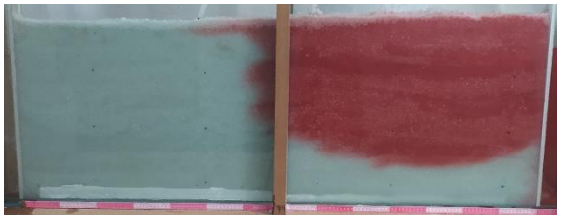
Fig.s (8) and (9) show the concentration distributions for different concentrations and gradients, as well as the pumping points C2 and D2, 40 minutes after contaminant release from the source.

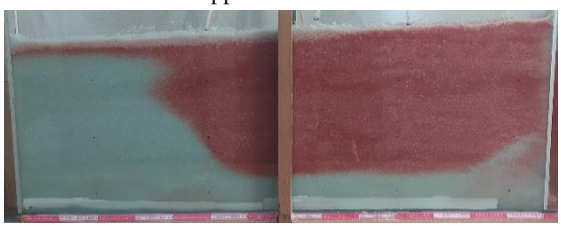
3-4-Investigating of the Effect of Contaminant Pumping from Points C2 and D2

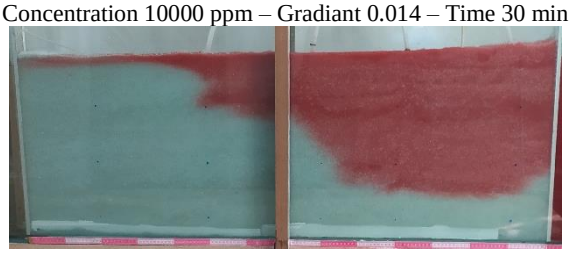
To investigate of the effect of contaminant pumping from points C2 and D2, movment of contaminat front was modeled in lablatuary model.

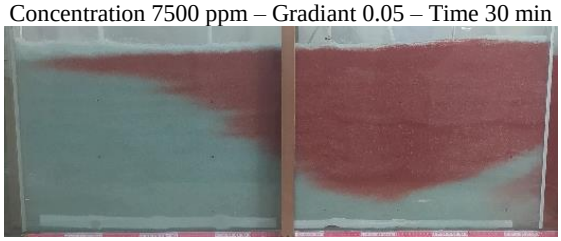
For this purpose, contaminant with a concentration of 10000 ppm in a gradient of 0.014 was investigated for example. movment of contaminat front with a concentration of 10000 ppm in the laboratory model is shown in Figure (10).


Concentration 10000 ppm – Gradiant 0.05 – Time 30 min


Concentration 10000 ppm – Gradiant 0.014 – Time 30 min


Concentration 7500 ppm – Gradiant 0.05 – Time 30 min

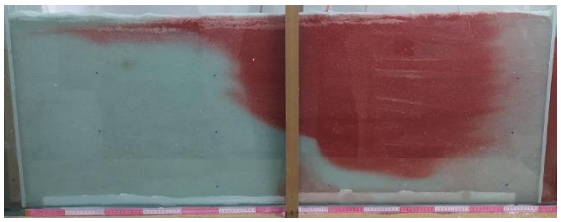

Concentration 7500 ppm – Gradiant 0.014 – Time 30 min

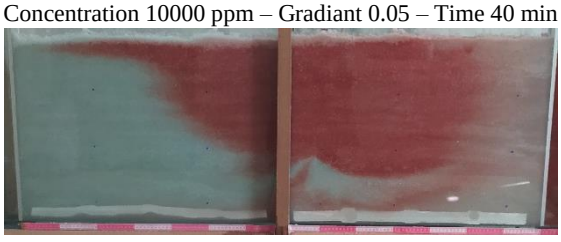

Concentration 5000 ppm – Gradiant 0.05 – Time 30 min

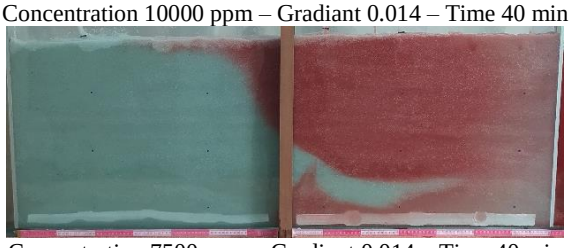

Concentration 5000 ppm – Gradiant 0.014 – Time 30 min

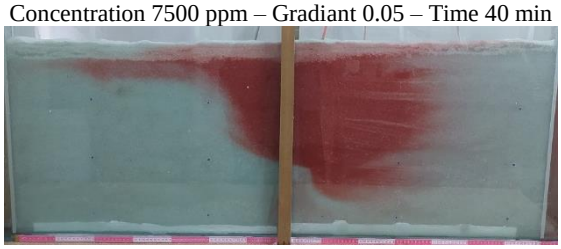
Figure 7. Movement of the contaminant front from starting seepage to before pumping (pumping location : D2).


Concentration 10000 ppm – Gradiant 0.05 – Time 40 min


Concentration 10000 ppm – Gradiant 0.014 – Time 40 min


Concentration 7500 ppm – Gradiant 0.05 – Time 40 min


Concentration 7500 ppm – Gradiant 0.014 – Time 40 min


Concentration 5000 ppm – Gradiant 0.05 – Time 40 min

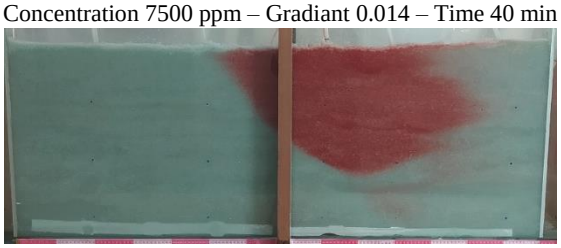
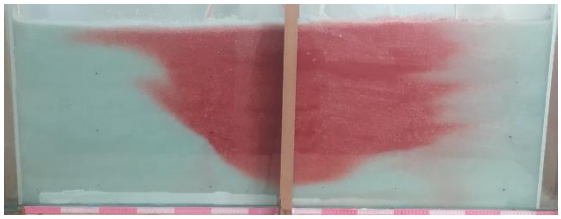
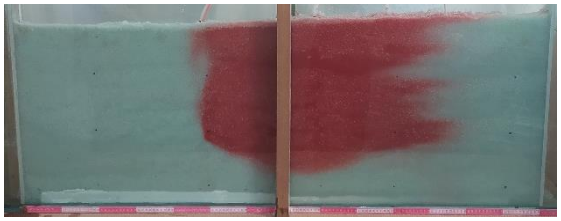
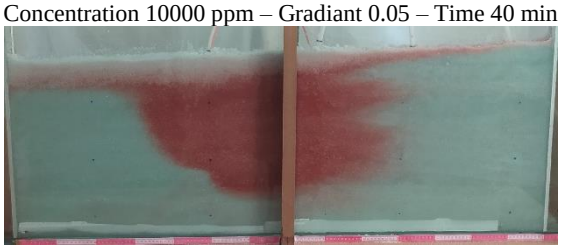
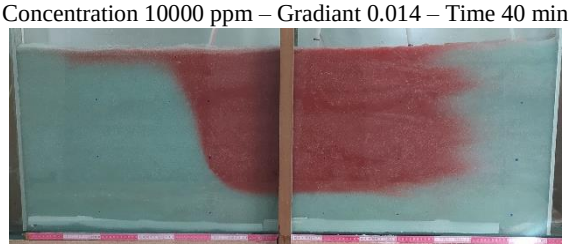

Concentration 5000 ppm – Gradiant 0.014 – Time 40 min

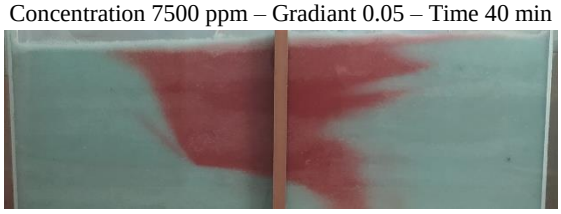
Figure 8. Movement of the contaminant front (pumping location : C2)


Concentration 10000 ppm – Gradiant 0.05 – Time 40 min


Concentration 10000 ppm – Gradiant 0.014 – Time 40 min


Concentration 7500 ppm – Gradiant 0.05 – Time 40 min


Concentration 7500 ppm – Gradiant 0.014 – Time 40 min


Concentration 5000 ppm – Gradiant 0.05 – Time 40 min

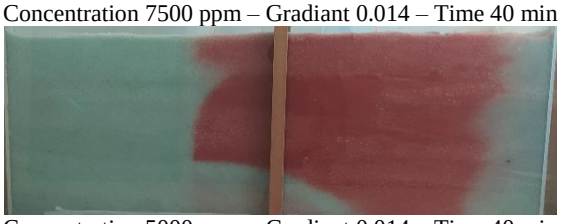

Concentration 5000 ppm – Gradiant 0.014 – Time 40 min

Figure 9. Movement of the contaminant front (pumping location : D2).

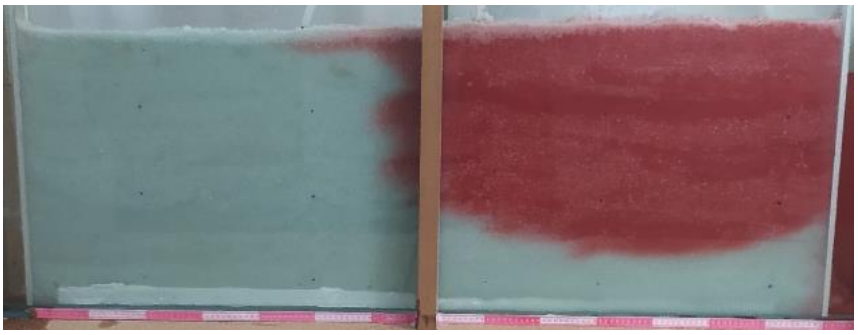
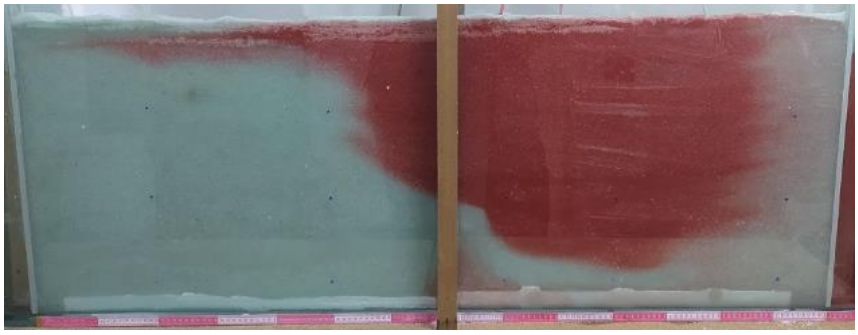


Figure 10. Transport (concentration=10000 ppm, gradient=0.014 and time=30 min).

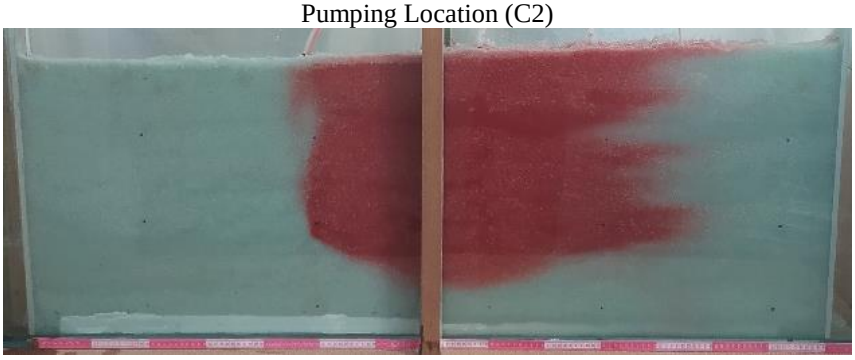
After 30 minutes of movment of contaminat front and transport in the laboratory model, pumping from points C2 and D2 was performed, and the results are shown in Fig.s (11-a) and (11-b), respectively.

Comparing Fig.s (11-a) and (11-b), it can be observed that when pumping from point D2, the contaminant front covers a smaller area. However, this does not mean that the concentration has decreased. To investigate the contaminant concentration, samples were taken from different points at different times. The third sample, taken at 40 minutes, coincides with the images presented in Fig.s (11-a) and (11-b). The contaminant concentration values at different points are presented in Table (4). The samples taken from different points show that the total contaminant concentration in the entire laboratory model is 24131 mg/L and 25112 mg/L when pumping from points C2 and D2, respectively. These results indicate that pumping from point C2 can reduce the total contaminant concentration in the entire laboratory model.

The results of this study showed that locations near the contaminant source and in the path of contaminant movement are suitable options for pumping contaminant from the aquifer. The results of this study are consistent with those of Zeynali *et al*. (2022a), who concluded in a study that the best pumping system arrangement is near the contaminant source and in the path of contaminant movement, not necessarily at the source itself.



Pumping Location (C2)



Pumping Location (D2)

Figure 11. A view of the pumping from points c2 and d2 (time=40 min).

Table 4. Samples Concentration from Contaminant Concentration with 1000 ppm Value

Sampling Point	Contaminant Concentration - Pumping Location:C2	Contaminant Concentration - Pumping Location:D2
-	*(ppm)*	*(ppm)*
B3	8427.27	8920.99
C3	8586.22	7336.26
D3	301.32	202.09
A2	400.30	187.16
C2	6416.25	8465.80
Sum	24131.36	25112.30

4-Conclusion

This study considered the process of contaminant transport and pumping in a laboratory model. A two-dimensional laboratory model was used for this purpose, with dimensions of 140 cm (length), 5 cm (width), and 57 cm (height). Chambers were provided on the left and right sides of the model to store water and create a constant hydraulic head. Various experiments were conducted with three different contaminant concentrations, two hydraulic gradients, and two contaminant pumping locations, resulting in a total of 12 experiments. Samples were also taken from the contaminant at 15 points at specified times. Sampling was conducted at five points along the length of the laboratory model and at three different depths. The results of the study showed that the contaminant transport rate is significantly higher at a gradient of 0.05 than at a gradient of 0.014. Therefore, the depth penetration of the contaminant is less at a gradient of 0.05 than at a gradient of 0.014. On the other hand, contaminant pumping at points C2 and D2 showed that pumping from point C2 more effectively reduced the contaminant concentration in the entire laboratory model. The result suggests that pumping contaminant from a point near the contaminant source and in its path can effectively improve the performance of the pumping and treatment system. But it is recommended to use laboratory models with a larger width in future studies so that the contaminant transport can be examined in three dimensions.

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Declaration of competing interest

All authors have no financial or personal relationships that could potentially bias the content or findings of this research.

Authors contribution statement

M.J.Z. conceived of the presented idea. M.J.Z. and M.N.T. developed the theory and performed the computations. Additionally, M.J.Z., M.N.T., and O.MRP. verified the analytical methods. All authors discussed the results and contributed to the final manuscript.

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