Experimental study of inorganic solute transport under different hydraulic gradients and various groundwater stresses

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Abstract. In this study, a laboratory-scale model representing a phreatic aquifer with a horizontal base was designed to examine the effects of horizontal hydraulic gradient, artificial recharge, and groundwater pumping on solute transport processes aquifers. Three different scenarios included injection of sodium chloride solution, artificial recharge with fresh water, and groundwater pumping, were examined in a sand tank. One hundred eight samples for nine tracers (sodium chloride) experiments were collected from two different monitoring well's depths. The measured concentrations were plotted against time (180 min) for each experiment. The results showed that through a higher horizontal hydraulic gradient, sodium chloride movement was enhanced, specifically in the same direction in which groundwater flows. When a constant artificial recharge was applied, the sodium chloride plume spread, and the solute concentration was decreased. Moreover, groundwater pumping speeds up the movement of sodium chloride plume in the direction of the pumping well. Such impacts of groundwater pumping and artificial recharge can be noticed more prominently when a higher hydraulic gradient is applied.

Keywords Solute Transport, Aquifer, Hydraulic gradient, Artificial Recharge, Sand tank.

1. Introduction
In the last two decades, solute transport in groundwater flow has been studied with increasing intensity due to increased concern about groundwater quality and pollution. On the one hand, the increase in groundwater exploitation and, on the other hand, the increase in the concentration of the solute in aquifers as a result of saltwater intrusion, repositories leaking, use of fertilizers, liquid waste disposal etc. have made this a subject of great importance. After these contaminants reaching the water table, they migrate in the direction of groundwater flow. So, it is important to understand solute transport processes in soil.

Many studies have investigated contaminant transport in the laboratory to understand the contaminant behaviour in porous media, among them [1-5]

The solute transport phenomenon is quite complex; it can be influenced by changing the hydraulic gradient due to changes in the solute and hydrological stresses' chemical and physical properties (an artificial recharge and groundwater pumping).

Many researchers have studied the impact of a horizontal hydraulic gradient change on the solute's transport through porous media [6-8]. Zang and Neuman [7] found, numerically, that periodic temporal fluctuations of the mean hydraulic gradient in the direction of flow, inhomogeneous porous media under quasi-steady-state, decreased the longitudinal dispersion coefficient rather than those which were under steady-state.

Solute transport is significantly affected by artificial recharge [9-13]. Li and Graham [10] showed an analytical and numerical expression that a constant recharge produced a mean velocity, which increases the plume migration in the longitudinal direction. (Rubin [9] showed the same results), while spatial variability in recharge increases, spreading in the transverse direction. Li and Graham [14] also showed numerically that spatiotemporally random recharge increased spreading of mean concentration plume in
both longitudinal and lateral direction in comparison with the no-recharge case. Chang and Yeh [13] showed that the application of uniform recharge caused an increase in the groundwater variation and thus increased the spreading of solute transport. Bouri and Dhia [15] and Ouelhazi et al. [16] experimented and analyzed artificial recharge for a coastal aquifer. Their results have shown that the recharge improved groundwater quality.

Solute transport is influenced by groundwater extraction through pumping wells. Many researchers studied the impact of pumping on solute transport [17-21]. Chen [21] used an analytical model and demonstrated that a vertically injected solute plume moves towards a fully penetrating pumping well in the homogenous confined aquifer. The pumping increases the solute plumes spreading in the longitudinal direction and limits the transverse direction's spreading.

In the present study, the artificial recharge and groundwater extraction effects were studied in conjunction with the variable hydraulic gradient. This study aimed to study the impact of varying hydraulic gradient, pumping rate, and artificial recharge on sodium chloride transport in a homogeneous aquifer.

2. Materials and Methods

2.1. The Sand Tank setup

The sand tank model used in this study is shown in Figure 1. The sand tank was built from transparent Plexiglas sheets (internal dimensions 208 cm x 18 cm x 50 cm) of 1 cm thickness. The laboratory model (sand tank) was placed on (PVC) framework about 80 cm above the ground surface. The sand tank was divided into three chambers using Plexiglas screens overlaid by a fine mesh of stainless steel to prevent migration of sand to the ends chambers. The two end chambers represent constant head boundaries of upstream (inlet water) and downstream (outlet water) which regulate the water level in the middle chamber (sand tank aquifer). The middle chamber (1.7 m length) was filled with silica sand after the disposal of dissolved materials attached to it, in layers about (3 cm). Two tanks for storing water on the right and the left were used to control head boundaries upstream and downstream, respectively. Four pipes were placed in the sand tank (middle chamber). These pipes represent injection well and pumping well with an internal diameter of 2cm, and two wells to monitor the concentration with an internal diameter of 1.5 cm. All these wells were made from (polyvinyl chloride) [PVC] of thickness 0.1 cm, the lower end closed by a plastic stopper and partially screened 15 cm from the well's bottom, except the injection well was screened 49 cm from the bottom. Fine mesh-covered all screens wells to prevent sand inlet. All the details that include the locations and depths of wells are listed in table 1. Infiltration basin of 1 cm thick with an internal dimension of 5 cm x 16 cm was used to recharge artificially. Three Pressure sensors were connected to the back of the middle chamber (sand aquifer). The pressure sensors were connected to a computerized data logger system, which recorded real-time water level data in the sand tank every 30 seconds.

The water level in the sand tank shown in Table 2 represents three different hydraulic gradients under the artificial recharge and pumping groundwater A constant pumping rate (0.89 m$^3$/d) from the aquifer was conducted using a peristaltic pump. The artificial recharge rate applied to the infiltration basin localized on the sand tank surface using a peristaltic pump was 34.75 rpm. The infiltration basin was located at a distance of 37.5 cm from the upstream boundary in the x-direction. The system consists of a saturated zone and an unsaturated zone. When the water percolated from the artificial recharge area (infiltration basin) to the water table, the unsaturated flow will occur. This study ignores the flow in the unsaturated zone because of the small distance (1.5 cm) between the bottom of the infiltration basin and the water table. The water quickly infiltrated to the water table. So, we considered the flow in the saturated zone only.
Figure 1. Sketch map of the experimental setup. 1, 3 chambers of the upstream and constant downstream head, 2 sand chamber, IB: infiltration basin; IW injection well; PW pumps well; CW1, CW2 monitoring concentration wells; 10, 11, 12 pressure sensors; 8, 9 tanks of storing water in the left and right; 4, 5, 6 inflow, outflow and overflow respectively, for the left tank; 13, 7 inflow and overflow for the right tank.

Table 1. Details of facilities built in the sand tank

| Name | Description                        | Location | Depth (cm) | Elevation of monitoring point above the base of the aquifer |
|------|------------------------------------|----------|------------|------------------------------------------------------------|
| IW   | To inject the salt solution        | X (cm)   | Y (cm)     |                                                            |
| PW   | To pump groundwater out            | 57.5     | 9          | 50                                                         | 1-40 |
| Sensor 1 | To measure hydraulic head        | 60       | 17         | 45                                                         | 5    |
| Sensor 2 | To measure hydraulic head        | 75       | 17         | 45                                                         | 5    |
| Sensor 3 | To measure hydraulic head        | 120      | 17         | 45                                                         | 5    |
| CW1  | To monitor salt concentration     | 70.5     | 9          | 45                                                         | 6    |
| CW2  | To monitor salt concentration     | 97.5     | 9          | 35                                                         | 16   |

2.2. Porous Media properties

The porous medium was Silica sand in the tank aquifer model. Mechanical Sieving of silica sand was conducted to obtain sand grains between (0.2-2 mm). A vibrator-type sieve shaker was used for the sieve analysis test (ASTM C136). The particle size of sand material $d_{10}$ was 0.29 mm, and $d_{60}$ was 0.6 mm. The uniformity coefficient $d_{10} / d_{60}$ was 2.06. The particle size distribution analysis indicated that the porous medium was homogeneous (medium sand). The bulk density was estimated by weighting a known volume of the silica sand, and its value was 1657.23 kg/m$^3$. The particle density was estimated by adding distilled water to the known mass material (sand) until a fixed volume was achieved. After many tests, the value of particle density was 2510.95 kg/m$^3$. The porous medium's porosity was estimated from the relationship between bulk and particle densities, and its value was 0.34. The specific yield value was 0.28,
according to Johnson [22-23]. The Hydraulic conductivity of the saturated porous media was determined using experiments of freshwater flow. When the flow reached steady-state, flow rate (Q) through the porous medium was estimated for constant heads, H1 and H2, by collecting the draining water (from the left end) over a specified time volume of water collected. Flow rate equals volume collected divided by the time. Dupuit formula for phreatic aquifer with horizontal bottom [24] was used to estimate the hydraulic conductivity values.

\[ K = \frac{2QL}{W(H_1^2 - H_2^2)} \]

(1)

Where Q is the discharge via the cross-section of porous media (m³/d), L is the length of the porous medium (m), W is the width of the porous medium (m), H1 and H2 are constant heads at both ends (m).

Table 1 shows three values of K for three types of the hydraulic gradient. The mean k of the sand tank for three tests was 44.8 m/d. This value was compared with a constant head sand column (ID:10 cm to 65 cm long). The value of measured hydraulic conductivity was 44.2 m/d. So, the results were very close. The capillary fringe effect was neglected.

| Test number | Hydraulic gradient | Upstream head (m) | Downstream head (m) | Discharge (m³/d) | Hydraulic conductivity (m/d) |
|-------------|--------------------|-------------------|--------------------|-----------------|-----------------------------|
| Test 1      | 0.0176             | 0.435             | 0.405              | 0.054           | 40.47                       |
| Test 2      | 0.0471             | 0.435             | 0.355              | 0.147           | 44.14                       |
| Test 3      | 0.0794             | 0.435             | 0.305              | 0.25            | 49.08                       |

2.3. Characteristics and measurement of an injected solution

In this study, Sodium Chloride (chemical formula NaCl, molecular weight 58.44) was used as a tracer to study the solute transport behaviour under various hydraulic gradient and different groundwater stresses. Before injecting the sodium chloride into the sand tank model, a steady-state flow was established by allowing water to flow through the system for 24 h. 20 g (more or less depended on the salt rate of tap water) of sodium chloride was dissolved in one litre of fresh tap water to prepare the injection solution. 4.86 L of solution containing sodium chloride concentration of 8400 mg/l was continuously injected into the aquifer (sand tank) through the injection well in all solute transport experiments conducted in the sand tank aquifer. A peristaltic pump with a constant flow rate of 3.9x10⁻² m³/d was used to inject the solution into the injection well along with the screening interval of 49 cm above the aquifer's base. Injection time was 180 min for each test. After the injection of sodium chloride, the plume movement was monitored by collecting and analyzing the aqueous sample from two monitoring wells CW1 and CW1. The aqueous samples were collected using a 20 ml syringe connected to a Teflon tube. The samples were placed in 50 ml plastic bottles. The water samples' sodium chloride concentrations were measured immediately after collecting the samples by a portable handheld salinity/conductivity meter. The syringe and the siphon tube, samples collect tubes, and salinity meter electrode was rinsed with distilled water after each measurement. After each experiment, the aquifer was left for several days under natural water flow to eliminate sodium chloride and measure the salts' concentration in the tank before starting another experiment to ensure that the aquifer is free of salts. (The tap freshwater used in the experiments is not
completely free of salts, the percentage of salts in it ranged from 470 to 530 mg/L, and this percentage small compared to the percentage of salts in the injected solution 8,400 mg/L).

2.4. Experimental Procedure
There were three distinct conditions of hydrological stresses that represent three hydrological scenarios. Three independent experiments were carried on in each scenario under varying horizontal hydraulic gradient (low (0.0176), moderate (0.0471), and high (0.0794)). Hence nine experiments were carried on as a whole.

2.4.1. Scenario A. This scenario represents an injection hydrological condition applied to the injection well in the sand tank with no artificial recharge and no groundwater abstraction. A solution of sodium chloride with a concentration of 8400 mg/L was continuously injected through the injection well in the sand tank aquifer at a rate of $3.9 \times 10^{-2} \text{m}^3/\text{d}$ for 180 min. In scenario A, three distinct experiments were carried on by employing three horizontal hydraulic gradients to investigate the hydraulic gradient variability on the solute movement in the unconfined (sand tank) aquifer. Each experiment started with a steady-state flow condition. The duration of each experiment was 180 min.

2.4.2. Scenario B. This scenario represents an artificial recharge condition of 34.75 rpm for 180 min. The recharge applied in the infiltration basin placed on the top of the sand tank at a distance of 49 cm from the screen separator on the left Plexiglas. The recharge area (infiltration basin area) was $0.9 \times 10^{-2} \text{m}^2$. Concerning the processes of the injection of the sodium chloride solution and its concentrations and pressure measurements used in scenario B, they were similar to the procedures used in scenario A.

2.4.3. Scenario C. This scenario represents a groundwater pumping condition from the pumping well in the sand tank. The groundwater pumping rate was $0.89 \text{m}^3/\text{d}$ through the pumping well from the aquifer for 180 min. In scenario C, three experiments were carried out by employing three different horizontal hydraulic gradients to investigate the pumping rate on the solute transport in the homogeneous sand tank unconfined aquifer. The injection of sodium chloride solution and its concentration used in Scenario C was the same as used in Scenario A. For the water level in the downstream constant head chamber not to be affected by the pumping processes, tap water was supplied to the right storage tank. Each experiment in the three different scenarios started after the steady-state flow condition.

3. Results and Discussion
To examine the effects of the different horizontal hydraulic gradient and groundwater stresses (artificial recharge and groundwater pumping) on the solute transport, a physical (sand tank) model represents a phreatic aquifer with a horizontal base was designed. Results obtained from different scenarios described in the previous sections were shown in Figures 2, 3 and 4. When the experiment started, the tracer began to spread gradually and occupied the aquifer's flow domain, and this spread is called hydrodynamic dispersion.

In scenario A, Figure 2 Shows the measured sodium chloride concentration against time at various depths of the two monitoring concentration wells (CW1 and CW2). The measured concentrations of three hydraulic gradients appear in the first monitoring concentration well (CW1). The measured concentrations' values do not appear at the low and medium hydraulic gradient because of its distance from the injection well. Still, they appear in the high gradient because the groundwater velocity increased at the high hydraulic gradient. Suppose one compares the values of the concentrations in scenario A at low, medium and high hydraulic gradient shown in Figure 2 a, b and c, respectively, for a specified time.
In that case, one can find that the concentration increases when the hydraulic gradient increases; this indicates that the velocity of spread and transport sodium chloride increases with the increase of the hydraulic gradient. These results demonstrated that the hydraulic gradient was one of the important factors affecting sodium chloride transport.

\[ \text{Figure 2} \] Scenario A, measured sodium chloride concentration at CW1 and CW2 against time: (a) test 1 $\Delta h/L = 0.0176$; (b) test 2 $\Delta h/L = 0.0471$; (c) test 3 $\Delta h/L = 0.0794$

In scenario B, Figure 3 Shows the measured sodium chloride concentrations against time at various depths of the two monitoring concentration wells (CW1 and CW2). Comparison of measured sodium chloride and, at the same time, measurement of hydraulic gradient, for scenario A Figure 2 with scenario B Figure 3. Indicates that sodium chloride in scenario B spread and reached CW1 faster than in scenario A (the concentration 940 mg/L in scenario A and 3650 mg/L in scenario B at time 60 min from starting the experiment for the low hydraulic gradient), this indicates that the recharge increased the flow velocity and hence increased the spread of sodium chloride. The effect of artificial recharge on sodium chloride transport is greater at the higher hydraulic gradient. Also, our results showed that the maximum concentration in scenario B was 7800 mg/L, while the maximum concentration in scenario A was 8090 mg/L. These results demonstrated that the recharge reduced solute concentration and improves groundwater quality.

In scenario C, Figure 4 Shows the observed sodium chloride concentration against time at various depths of the two monitoring concentration wells (CW1 and CW2). The concentration values for CW2 in scenario C were higher than the concentration values for CW2 in Scenario A and were larger under a high hydraulic gradient. The results showed that the aquifer's groundwater extraction process enhanced sodium chloride's spread towards the groundwater pumping well.
Figure 3 Scenario B, measured sodium chloride concentration at CW1 and CW2 against time: (a) test 1 $\Delta h/L = 0.0176$; (b) test 2 $\Delta h/L = 0.0471$; (c) test 3 $\Delta h/L = 0.0794$

Figure 4 Scenario B, measured sodium chloride concentration at CW1 and CW2 against time: (a) test 1 $\Delta h/L = 0.0176$; (b) test 2 $\Delta h/L = 0.0471$; (c) test 3 $\Delta h/L = 0.0794$
4. Conclusion
This research aimed to examine how sodium chloride transport is influenced by the hydraulic gradient variability, the groundwater pumping from the aquifer, and the artificial recharge of fresh water. For this purpose, many laboratory experiments were conducted in a homogenous unconfined (sand tank) aquifer. After conducting nine different experiments, we concluded that the hydraulic gradient variability controls the sodium chloride transport where the spreading of sodium chloride became higher under a high hydraulic gradient. Artificial recharge significantly affected the transport of sodium chloride. Artificial recharge enhanced sodium chloride spread, especially at the high hydraulic gradient, and reduces sodium chloride concentration, thus improving water quality. The extraction of groundwater from the aquifer increased sodium chloride transport towards the pumping well and was greater at a high hydraulic gradient.

This study is also useful for estimating solute transport parameters (average pore water velocity, dispersion coefficient and dispersivity) from breakthrough curve results and groundwater pollution management.

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