Water Supply

Physical modeling of sand columns application in recharge reservoir to prevent seawater intrusion

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ABSTRACT

This study aims to provide visual evidence by the physical simulation to demonstrate the sand column performance of a recharge reservoir to control seawater encroachment and confirm some previous studies. In this analysis, a two-dimensional sand tank illustrates the sand column's role in overcoming seawater intrusion. Besides using dyes, the sand tank is also fitted with sensors to observe the length of seawater penetration. Furthermore, the simulation using SEAWAT numerical modeling is used as a reference in this analysis. The criteria analyzed were the number of sand columns, the reservoir water level, and the isochlors concentration. The results revealed a reasonably close match between physical and computational modeling. It was also found that the more sand columns and the higher the reservoir water level, resulted in the decrease of seawater penetration length that occurred. Physical and computational modeling findings indicated that the optimal results are derived using three sand columns with an RMSE value of 0.76. The seawater infiltration length decreased to 84.72% relative to sand column-free conditions at a reservoir water level of 15.0 cm.

Key words: recharge reservoir, sand column, seawater intrusion

HIGHLIGHT

- Modeling the sand column to prevent seawater intrusion, comparison of model and analytical methods, performance of sand column number, decreasing of seawater intrusion, and reservoir water lever limitation.

INTRODUCTION

Bili-Bili Reservoir is a multi-purpose reservoir and the largest in South Sulawesi, located in Gowa Regency, South Sulawesi, Indonesia. One of the reservoir purposes is to provide clean water to Makassar City, Gowa, Takalar, and Maros Regency (Lukman et al. 2020a, 2020b). In 2004, a landslide occurred in the Bawakaraeng Mountain, carrying around 200 million m³ of landslide material, resulting in an increase of turbidity in the reservoir ranging from 29,000 to 52,000 Nephelometric Turbidity Units (NTU) and exceeding the permissible threshold (6,000 NTU) (Yusuf et al. 2012). This situation has a significant effect on the availability of clean water in the region (Yusuf et al. 2012). Since the landslides and sedimentation happened in the Bili-Bili reservoir, the reservoir is no longer operating. People in the city and the municipal authority are expected to use groundwater to satisfy clean water needs (Kirono et al. 2014).

In addition to increasing the growth of construction and the community's need for clean water, groundwater use for residences, hotels, and the industry has caused the population along the coast to continue to experience brackish water and even saline groundwater. Excessive groundwater exploitation to satisfy the needs of homes, hotels, hospitals, manufacturing, and other industrial activities has induced seawater intrusion in many countries, including Indonesia (Aeschbach-Hertig & Gleeson 2012). Seawater intrusion is a mechanism of seawater migration from sea to freshwater in marine aquifers (Badaruddin et al. 2017). Under normal conditions in the coastal region, groundwater flows continually into the sea in groundwater discharge (FGD). Since the saltwater's specific gravity is marginally more significant than the freshwater's specific gravity, the fresh water in the aquifer would be forced by saltwater further into the aquifer, especially at the

bottom. However, since the piezometric groundwater pressure is greater than the sea level due to groundwater recharge, this pressure can be neutralized, and the flow of water from land to ocean can be balanced by seawater and groundwater (Azis *et al.* 2019). Seawater intrusion occurs when this equilibrium is disturbed, typically caused by a lack of groundwater recharge and heavy groundwater pumping (Azis *et al.* 2020).

As mentioned above, the factors that cause infiltration of seawater include intense pumping, coastal characteristics and constituent rocks, groundwater discharge conditions to the sea, and groundwater fluctuation in coastal areas (Cha *et al.* 2014). The intrusion of seawater is even more significant if unrestricted groundwater extraction is conducted (Werner *et al.* 2013). If the seawater has reached a well, the well will become acidic and cannot be used for everyday uses (Bear *et al.* 2010). Therefore, efforts must be made by applying water to the soil, both naturally and artificially, so incorporating water into the soil may be accelerated (Azis *et al.* 2020). A way for artificial groundwater recharge is by infiltration reservoirs that may trap surface runoff. Compared to reservoirs or dams that have mainly functioned as water reservoirs, infiltration reservoirs are primarily built to enter the water into the aquifer (Luyun *et al.* 2011). However, there is a difficulty with creating an infiltration reservoir in an exceedingly particular region with low permeability and low absorption potential. It allows water to enter the aquifer layer very slowly, so the absorption reservoir function is not accomplished (Qahman & Larabi 2004). An analytical and numerical investigation was researched to resolve this, with the sand column model situated at the underside of the infiltration reservoir, which is directly connected with the aquifer layer, proven to maximize water flow through the aquifer layer (Azis *et al.* 2019). However, no physical proof can be used as a guide to verify the study findings of Azis *et al.* (2019) because their research is focused entirely on theoretical and computational solutions. As a result, this study will investigate how effective sand columns in the infiltration reservoir mitigate marine intrusion and groundwater crisis by physical modeling.

One type of artificial recharge is a recharge reservoir with the primary function as a water absorption medium to efficiently and rapidly penetrate the aquifer ground. This reservoir model is ideal for soil with shallow groundwater levels, and a vast amount of land is available. The fundamental theory behind the construction of infiltration reservoirs is minimizing surface runoff and improving the soil's ability to capture surface runoff. The recharging reservoir is separate from the usual reservoir. The recharge reservoir is composed of a reservoir foundation that is directly connected to the aquifer layer. In essence, recharge reservoirs may be classified as multipurpose reservoirs. In addition to serving as flood protection, they also improve the aquifer function's optimization by growing the water-retaining ability of the aquifer substrate. The uses of infiltration reservoirs are: to optimize the aquifer structure in such a way as to increase the water-holding potential in aquifers, to act as flood protection or drainage in downstream areas, or to work as a water supply for dry season needs.

The use of recharge reservoir technology has been dealing with the floods and droughts that impact Indonesia every year (Remondi *et al.* 2016). The rate of water infiltration in the recharge reservoir is very high (Seutloali & Beckedahl 2015). Logically, this is potentially beneficial for increasing the groundwater discharge, which is notably important in pushing the freshwater-saltwater interface to move seaward (Badaruddin *et al.* 2017). For example, Abdalla & Al-Rawahi (2013) investigated the role of groundwater recharge dam (i.e., Alkhod dam) to replenish the aquifer and control seawater intrusion in Oman and found a recession of seawater intrusion due to the dam's induced recharge Also, Shi & Jiao (2014) assessed seawater intrusion in the area around the Bohai Sea in the northern part of China and found that groundwater reservoir is helpful to minimize the magnitude of seawater intrusion in the area. Although previous studies have shown the importance of recharge reservoirs in combating seawater intrusion, most of them employ case studies and are reviewed under theoretical investigation. None of them show controlled visual evidence in the form of a physical model that shows the utilization of recharge reservoirs in controlling seawater intrusion. Therefore, in this study, a physical sand tank model is used to simulate the effect of recharge reservoir in controlling seawater intrusion, and a numerical model is developed to explore this effect in several different conditions.

MATERIALS AND METHODS

Physical modeling of sand columns

Two methods were used in this analysis, including numerical and physical model approaches. The two-dimensional schematic picture of the sand tank is seen in Figure 1. The internal dimensions of the sand tank are 160 cm in length, 10 cm in width, and 75 cm in height. The sand tank is made of plexiglass with a thickness of 1 cm.
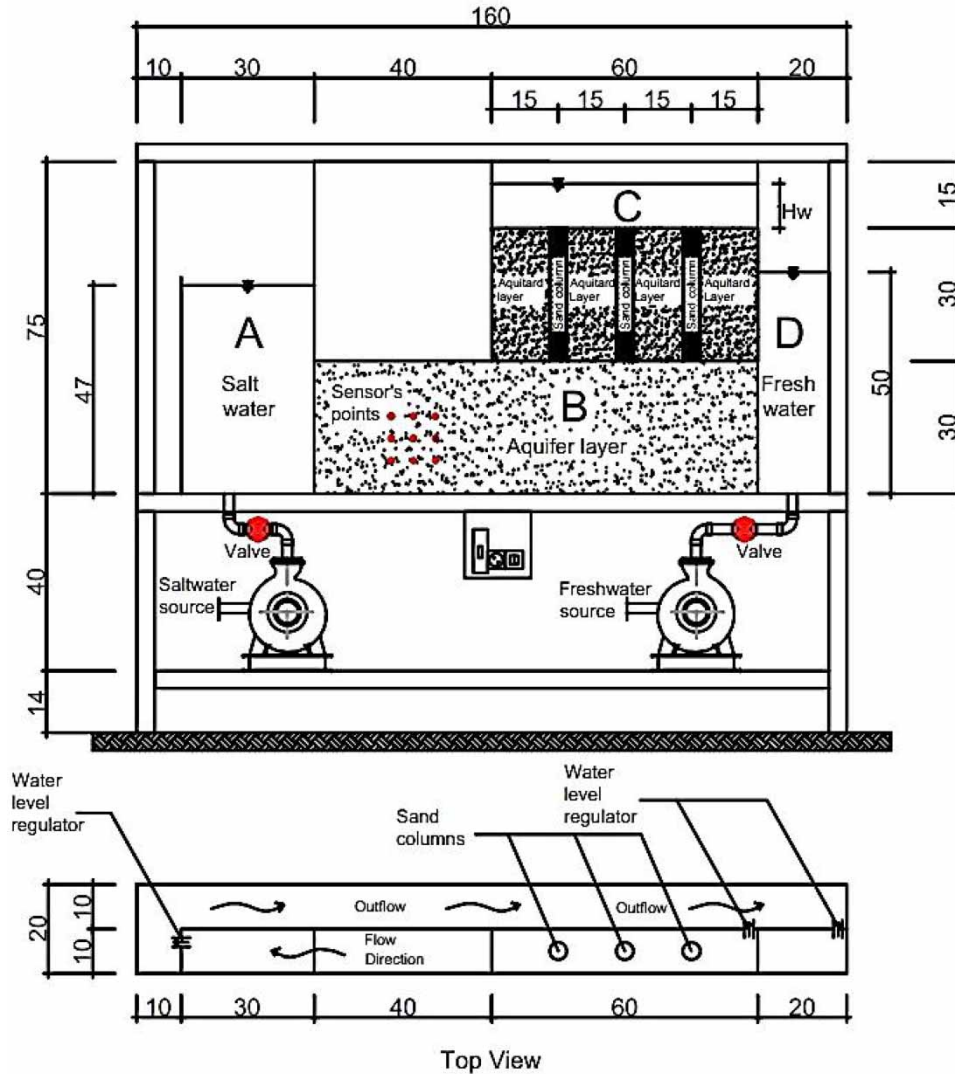
Figure 1 | Physical model of sand column in recharge reservoir (unit is in cm).

In physical modeling, the sand column is used as a tool to absorb water from the recharge reservoir into the aquifer (Figure 1). Sand columns are created by drilling holes in a low permeability layer of clay (i.e., 30 cm in height) and filling it with coarsely graded sand. Water shall be stored in a recharged tank with a fixed water volume. The water above the reservoir then flows into the aquifer through the semi-permeable layer and into the sand column, assuming that sand with a high permeability coefficient will accelerate and increase the groundwater recharge. The sand column diameter utilized in the physical model is 5 cm.

In this analysis, a rectangular reservoir consisting of four rooms: room A with an internal size of 30 cm (length) × 10 cm (width) × 100 cm (height), containing seawater that has been treated with dyes, room B containing sand, which represents a portion of the aquifer layer with an internal size of $100 \times 10 \times 30$ cm, and room C consisting of a reservoir, a semi-permeable layer and sand columns with an internal size of $60 \times 10 \times 45$ cm. Meanwhile, room D contains freshwater, which represents groundwater flow from the adjacent aquifer. According to a fixed scenario, in spaces A, C, and D, the corresponding water levels shall be retained at certain elevation levels. In this study, the density of freshwater, r_f, and saltwater, r_s, used is 1,000 kg/m^3 and 1,025 kg/m^3, respectively. The sea level is 47 cm, while room D's freshwater level is 50 cm. The difference in the number of sand columns used was 0, 1, 2, and 3. The water levels above the reservoir used were 0, 2.5, 5, 7.5, 10, 12.5, and 15 cm. Also, the drainage medium (soil layer) is saturated in the system, the length of the seawater penetration [L] in space B is determined by the color distribution that occurs and also checked by the calibrated sensors that are put at specific positions at

the back of the sand tank (see Figure 1), which measure the salinity that occurs during the experiment. Since the number of calibrated sensors is limited (i.e., nine units), it was used only to confirm the saltwater-freshwater boundary in the aquifer system. This study shows the changes in seawater penetration length due to the changing conditions of the number of sand columns and the water depth above the reservoir. Following the laboratory measuring process, the types and characteristics of soil and sand used in the physical modeling process are shown in Table 1.

Sand column model in numerical simulation of SEAWAT

In this study, numerical modeling uses the SEAWAT program (Langevin *et al.* 2008). The displayed domain is a two-dimensional rectangular model in the numerical simulation, assuming that the sea is on the left and the recharge reservoir is on the right in the sand column model. This research uses SEAWAT to examine the effectiveness of sand columns in the infiltration reservoirs structure to prevent seawater intrusion under laboratory scale, so this research can be a reference for making the physical model. The domain of the numerical model is shown in Figure 1, which is a two-dimensional model with a rectangular size, assuming the sea is on the left side, and the infiltration reservoir is on the right side in the model.

For the domain (i.e., the mesh) used in SEAWAT numerical modeling, the number of columns used is 200, and the layer is 120 with a grid size of $\Delta x = 0.50$ cm and $\Delta z = 0.50$ cm. Numerical modeling adopted a molecular diffusive D_m [L^2/T] of 10^{-9} m^2/s, and longitudinal dispersive α_L [L] was 1 cm. Following Abarca *et al.* (2004), transverse dispersivity α_T [L] was assumed to be one-tenth of α_L. Input data in the numerical model consists of several parameters, including the type and permeability of soil and sand; follow those in the physical model, as shown in Table 1. Besides, data in the form of input discharge (Q1) and seawater flow rate (Q2) are also used. Furthermore, numerical simulations will display information about the length of seawater under conditions of variations in the water level above the reservoir (Hw) and variations in the number of sand columns (Nkp) under steady-state conditions. When the soil is saturated with water, and there is an equilibrium between seawater and freshwater in the aquifer system, the next step is to measure the length of freshwater pushing the sea water in the aquifer with four variations for the number of sand columns (i.e., 0, 1, 2, and 3), isochlor concentration variation consists of 5, 50, and 95%, as well as seven variations of water height in infiltration reservoirs (Hw) (i.e., 0, 2.5, 5, 7.5, 10, 12.5, and 15 cm).

RESULTS AND DISCUSSION

Comparison between physical and numerical model

The seawater intrusion length is provided by physical and numerical models under steady-state conditions, as shown in Figure 2. There are three colored lines for various isochlor: 5, 50, and 95% from empirical water-level simulation over the

Table 1 | Physical and mechanical properties of soil and sand

| Physical and mechanical properties	Material type	
	Soil	Sand
Grain Distribution		
Coarse fraction	46.67%	96.77%
Fine fraction	53.33%	3.23%
General characteristics of the soil		
Specific gravity (G)	2.380	2.530
Water content (w)	34.47%	6.49%
Atterberg limits		
Liquid Limit (LL)	60.29	
Plastic Limit (PL)	23.192%	
Plasticity Index (PI)	37.098%	
Porosity (n)	45.0%	40.0%
Mechanical property		
Hydraulic conductivity (K)	9.038×10^{-5} cm/s	$2.84\ 10^{-2}$ cm/s
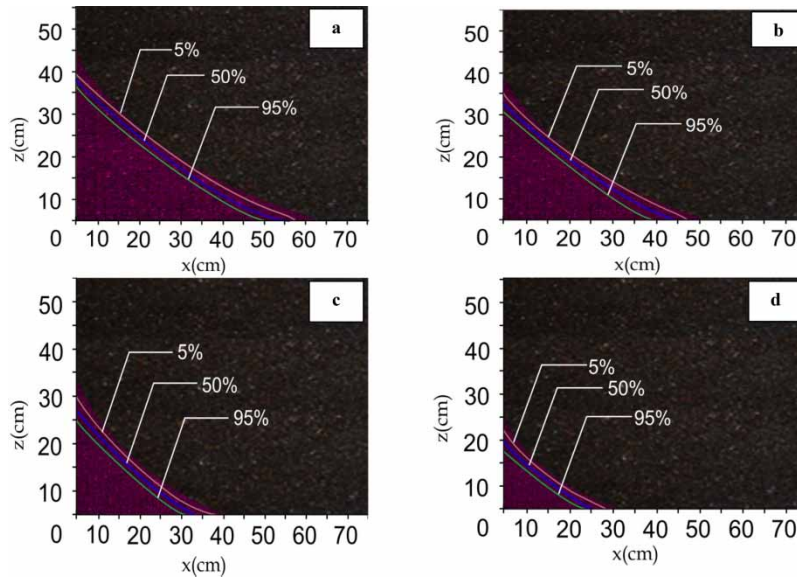
Figure 2 | The length of seawater intrusion is based on the results of physical model tests and numerical models with conditions (a) without sand columns, (b) one sand column, (c) two sand columns, and (d) three sand columns.

15 cm reservoir. The time required for the physical experiment to attain steady-state conditions for the sand column-free experiment, one sand column, two sand columns, and three sand columns is 82, 50, 35, and 20 hours, respectively. The effects of the computational simulation are at the same time. The results shown in Figure 2 indicate that in physical modeling, the maximum length of seawater intrusion obtained is 63.94 cm at the height of the water level above the reservoir 15 cm and in conditions without a sand column.

When adding a sand column, the length of seawater intrusion has decreased. It can be seen in the figure that when using one column, two columns, and three columns of sand, the maximum length of seawater intrusion is 33.76 cm, 19.31 cm, and 11.64 cm, respectively, when the value of Hw = 15 cm. The percentage reduction in seawater intrusion length was obtained from each different number of sand columns by 47.20%, 69.80%, and 81.79% for one, two, and three sand columns, respectively. From numerical modeling, it was found that the maximum intrusion length at 5% isochlor concentration obtained was 20.97 cm at a water level of 15 cm. When adding a sand column, the length of seawater intrusion has decreased (Azis *et al.* 2019). It can be seen in the figure that when using one column, two columns, and three columns of sand, the maximum length of seawater intrusion is obtained at a concentration of 5% isochlor 10.77 cm, 6.15 cm, and 3.60 cm, respectively, when the Hw = 15 cm. Compared to numerical modeling, the percentage reduction in the length of seawater intrusion due to the number of sand columns appears to be slightly larger (Azis *et al.* 2019). However, there is a reasonably good agreement between the results obtained from the physical and numerical models.

Furthermore, based on the physical and numerical modeling results, data information obtained from the simulation results shows the relationship between the number of sand columns and the seawater intrusion length, as shown in Figure 3.

Figure 3 shows the effect of using the number of sand columns on the length of seawater intrusion. In numerical modeling, in conditions without a sand column, the maximum length of seawater intrusion was 61.73 cm at a reservoir water level of 15 cm. The results obtained are much higher than when the system uses a sand column. Also, it can be seen that using one, two, and three columns of sand, the maximum length of seawater intrusion is 31.55 cm, 17.02 cm, and 9.43 cm when the Hw = 15 cm. The addition of the number of sand columns in numerical modeling can reduce the length of seawater intrusion by 48.89%, 72.43%, and 84.72%. The same phenomenon has occurred in physical modeling. The physical model's measurement (Figure 3) indicates that seawater intrusion has decreased significantly when the system is added to a sand column. It is evidenced when the system is not provided with a sand column; the maximum seawater intrusion value obtained is 63.94 cm. When the system was added with one, two, and three sand columns, there was a significant decrease in seawater intrusion length, namely 33.76 cm, 19.31 cm, and 11.64 cm, respectively. It shows that increasing the number of sand columns in physical modeling can reduce seawater intrusion length by 47.20%, 69.80%, and 81.79%.
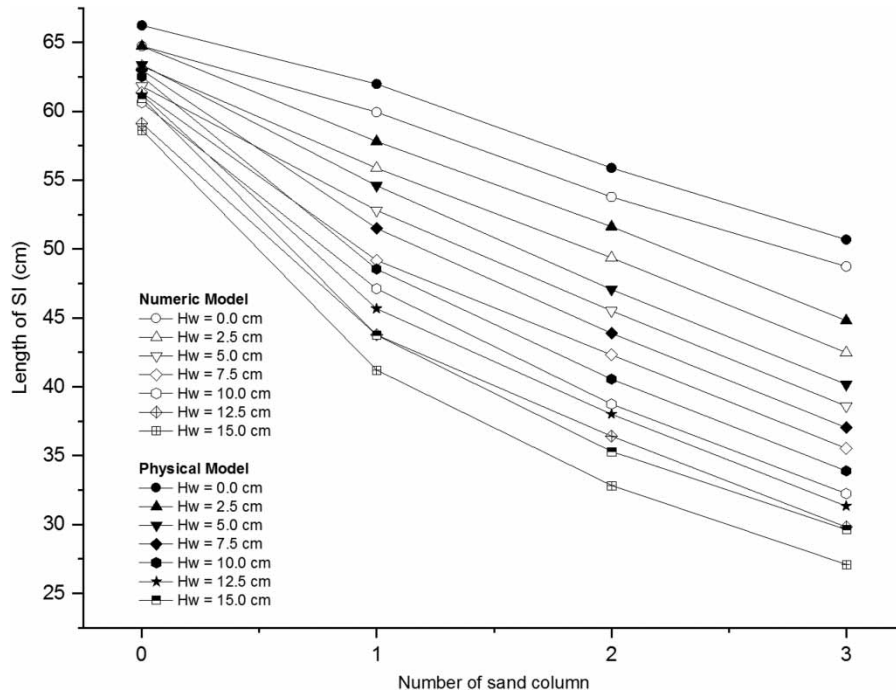
Figure 3 | The relationship between the number of sand columns and the sea water intrusion length using physical and numerical models.

Moreover, Figure 4 compares seawater intrusion length from physical and numerical modeling results with variations in the water level above the reservoir. Figure 4 showed that the reservoir water level dramatically affects the length of seawater intrusion. At the value of Hw = 15 cm, the highest value of seawater intrusion is obtained and then decreases with the number of sand columns in the system.
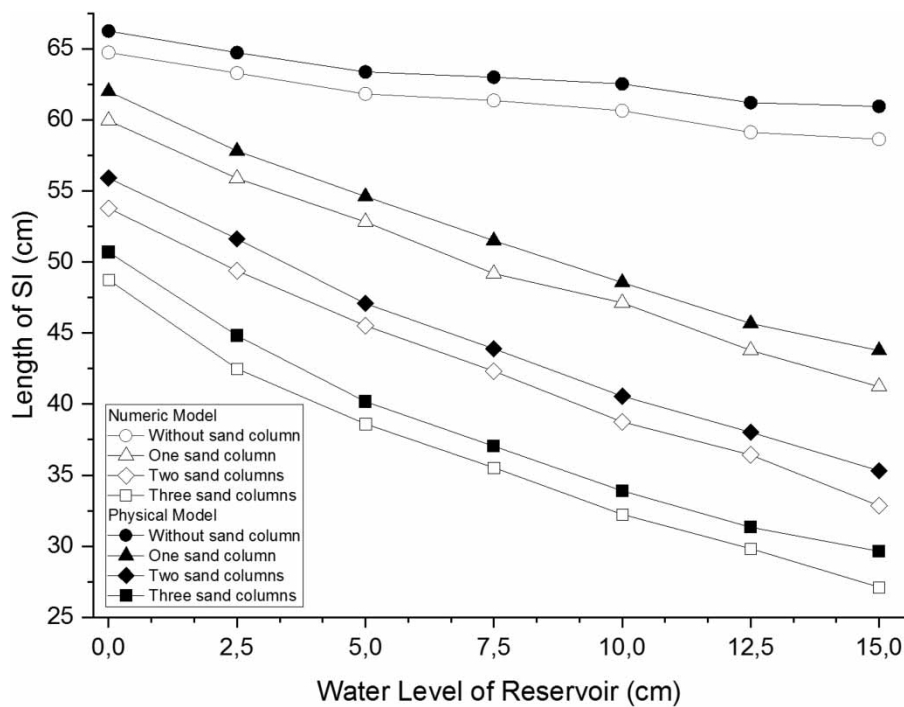

Figure 4 | Relationship between reservoir water level and sea water intrusion length from the results of physical and numerical models.

The physical modeling results showed that seawater intrusion's maximum length was 11.64 cm at conditions Hw = 15 cm. It was also obtained from physical modeling that the length of seawater intrusions was 32.69 cm, 26.81 cm, 22.71 cm, 19.04 cm, 15.89 cm, 13.33 cm, and 11.64 cm for Hw of 0, 2.5, 5, 7.5, 10, 12.5, and 15 cm, respectively. The percentages of reduction in seawater intrusion for the addition of water level above the reservoir from physical modeling were 52.79%, 60.41%, 66.59%, 71.15%, 75.74%, 79.24%, and 81.79%, respectively. Meanwhile, from numerical modeling, the maximum length of seawater intrusion was 9.43 cm at conditions of Hw = 15 cm. Furthermore, the lengths of seawater intrusion obtained were 30.19 cm, 24.54 cm, 20.12 cm, 16.94 cm, 13.96 cm, 11.15 cm, and 9.43 cm for Hw of 0 cm, 2.5 cm, 5 cm, 7.5 cm, 10.0 cm, 12.5 cm, and 15.0 cm, respectively. The percentages of seawater intrusion reduction for the addition of the water level above the reservoir from numerical modeling results were 54.23%, 63.01%, 69.02%, 73.69%, 77.98%, 82.04%, and 84.72%, respectively.

DISCUSSIONS

Based on the numerical and physical model results, it was found that the seawater intrusion value was more significant in the numerical model simulation results with a deviation value in the range of 1.43 cm to 2.54 cm and value RMSE is 0.76. It is probably due to soil heterogeneity, which is quite varied during the physical experiment, and which is not accommodated in numerical modeling. Although there are differences between the physical and numerical models, the results are relatively the same and suitable (Azis *et al.* 2019). The physical model test results can validate the results of the numerical model. To further examine the effect of increasing the number of sand columns and the water level above the reservoir on changes in the system outflow discharge, a graph is made showing changes in the discharge groundwater flow towards the sea, as in Figure 5. There is a significant increase in discharge due to the additional sand column numbers and the water level above the reservoir (Azis *et al.* 2019). At maximum conditions (three sand columns and 15 cm water level above the reservoir), it is known that there is an increase in discharge of 707.6 cm^3/hour or about 63% and 372.3 cm^3/hour or about 33% compared to conditions without sand column and water level above the reservoir 2.5 cm, respectively.

The simulation results of the physical model provide the same information that adding a sand column to the system and the higher the reservoir water level given, the further it reduces the length of seawater intrusion. These results indicate that the
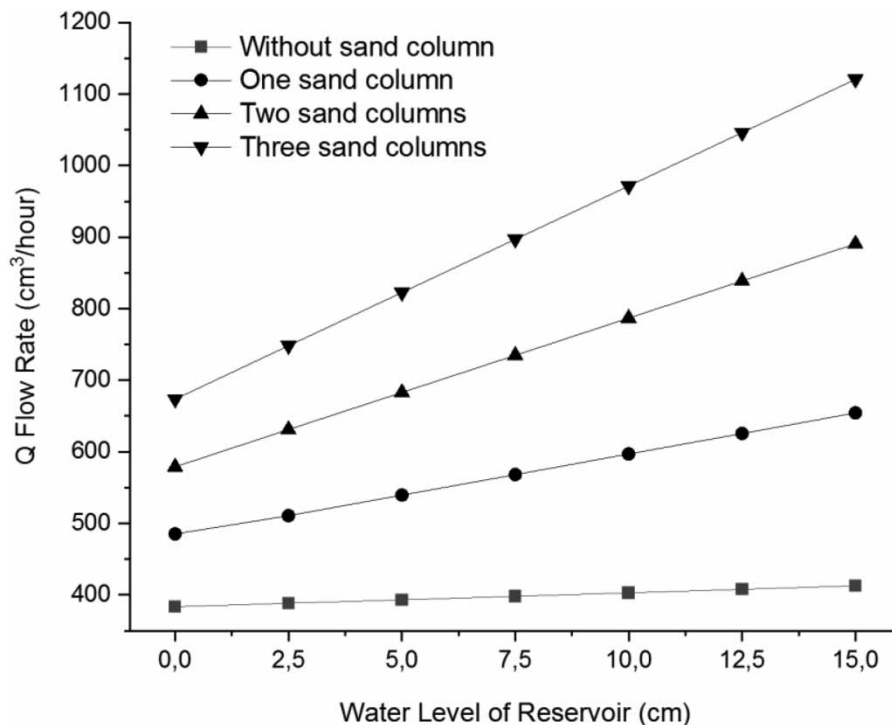

Figure 5 | The relationship between the water level above the reservoir and the number of columns to the outflow discharge in the numerical model.

sand column in the infiltration reservoir is feasible and can be used to overcome seawater intrusion (Badaruddin *et al.* 2015). However, more controlled laboratory situations (i.e., spatial heterogeneity and dispersion parameter) need to be considered in future research to understand the effect of recharge reservoirs in controlling seawater intrusion in more complex situations.

CONCLUSIONS

Based on the results obtained, it can be concluded that the higher the water above the reservoir (Hw) and the more the number of sand columns (Nkp), the lower the length of seawater intrusion. The seawater intrusion length towards the land can be prevented due to freshwater discharge from the infiltration reservoir through the sand column. It can be seen from the results of the research on numerical models and physical models, which show that the effect of the number of sand columns is very significant in preventing the length of seawater intrusion. The increase of the reservoir water level from 60 to 75 cm also affects seawater intrusion length: without a sand column decrease of 9.42%, using one sand column decrease of 31.23%, two sand column decrease 38.94%, and three sand columns decrease 44.38%. This is supported by salinity sensor readings, which show similar results, implying that sand columns in infiltration reservoirs effectively resist seawater intrusion. The numerical and physical model results are similar and appropriate, indicating that the physical model of the sand column can be used to control seawater intrusion. The physical model is valuable indeed, but for examining different designs of the actual sand column application.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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