Groundwater Circulation Well for Controlling Saltwater Intrusion in Coastal aquifers: Numerical study with Experimental Validation

Om Prakash Vats[1] · Bhrigumani Sharma[1] · Juergen Stamm[2] ·
Rajib Kumar Bhattacharjya[1] 🔘

Abstract

Saltwater intrusion into coastal aquifers has become a prominent environmental concern worldwide. As such, there is a need to prepare and implement proper remediation techniques with careful planning of freshwater withdrawal systems for controlling saltwater intrusion in coastal marine and estuarine environments. This paper investigates the performance of groundwater circulation well (GCW) in controlling saltwater intrusion problems in unconfined coastal aquifers. The GCWs have been established as a promising in-situ remedial technique of contaminated groundwater. The GCW system creates vertical circulation flow by extracting groundwater from an aquifer through a screen in a single well and injecting back into the aquifer through another screen. The circulation flow induced by GCW force water in a circular pattern between abstraction and recharge screens and can be as a hydraulic barrier for controlling saltwater intrusion problem in coastal aquifers. In this study, an effort has been made to investigate the behavior of saltwater intrusion dynamics under a GCW. An experiment has been conducted in a laboratory-scale flow tank model under constant water head boundary conditions, and the variable-density flow and transport model FEMWATER is used to simulate the flow and transport processes for the experimental setup. The evaluation of the results indicates that there is no further movement of saltwater intrusion wedge towards the inland side upon implementation of GCW, and the GCW acts as a hydraulic barrier in controlling saltwater intrusion in coastal aquifers. The present study reveals the GCWs system can effectively mitigate the saltwater intrusion problem in coastal regions and could be considered as one of the most efficient management strategies for controlling the problem.

Keywords Unconfined coastal aquifer · Saltwater intrusion · Groundwater circulation well · Laboratory experiment · Numerical simulation · FEMWATER

✉ Rajib Kumar Bhattacharjya
   rkbc@iitg.ac.in

Extended author information available on the last page of the article

1 Introduction

Saltwater Intrusion (SI) has become a prominent environmental problem in coastal areas across the world, as approximately half of the world's population resides within 100 km of the coastline (Dose et al. 2014). The coastal community is expected to increase in the future with the increase in population, industrial growth as well as touristic development. As a result, the demand for freshwater is increasing day by day, which has eventually put pressure on the coastal aquifers. The groundwater available in an unconfined and confined aquifer is being emerged as the only reliable source of freshwater to satisfy the daily water requirements for coastal populations. As reported, the overexploitation of coastal aquifers has lowered the hydraulic potential significantly, and this has led to saltwater intrusion problems in different parts of the world (Bear et al. 1999).

Many researchers have reported the contamination of coastal aquifers as a result of saltwater intrusion in different parts of the world. Shi and Jiao (2014) reported saltwater intrusion problems have occurred in the area around the Bohai Sea, China, due to excessive groundwater pumping. Degradation of the coastal aquifer in California, the USA, was reported by Anders et al. (2014). Cary et al. (2015) also reported that deterioration of groundwater reservoir by saltwater intrusion in Recife coastal plain, Pernambuco, Brazil. Moreover, several coastal states of India have already experienced groundwater contamination problems threatened by saltwater intrusion. Pramada et al. (2018) reported that the freshwater aquifers of the Ernakulam coast of Kerala State, India, severely affected by saltwater intrusion. As stated, the leading causes of saltwater intrusion in coastal aquifers are the most excessive withdrawal of groundwater resources and improper arrangement of pumping wells (Bhattacharjya et al. 2009). Furthermore, it also adversely affects the social and economic developments of coastal communities. Therefore, efficient planning and management policies should be implemented in coastal aquifer systems to preserve them and for continued utilization of available groundwater resources on a sustainable basis under the threat of saltwater intrusion.

Groundwater circulation well (GCW) is one of the most promising in-situ remedial techniques of groundwater. This technique was first suggested by Herrling and Buermann (1990) and Herrling et al. (1990) for remediating contaminated groundwater aquifer. In general, a typical GCW comprises two-screen segments that are separated by an impervious casing. One screen section is used to extract the contaminated water from the subsurface system. The extracted contaminated water is treated, and after the treatment, the water is injecting back into the aquifer through the other screen of that same well with equal flow rates. The extraction and injection of water create a vertical circulation flow, as shows in Fig. 1, between the extraction and injection screens (Herrling et al. 1991; Gonen and Gvirtzman 1997; Stamm 1998). The circulation flow, induced by GCW, forces the water to move in a circular pattern between abstraction and recharge screens, which eventually flushes the contaminated water within the proximity of the well. The GCW technique could be operated in two flow modes, such as standard and reverse circulation mode. In a standard circulation mode, water is pumped from the lower screen and injected it through the upper screen (Fig. 1b). Under reverse flow condition, groundwater is extracted through the top screen, as injected through the lower screen (Fig. 1c). In both the operation, groundwater circulates around the well, and no water is removed from the aquifer system. The vertical circulation flow of a GCW is illustrated in Fig. 1. Figure 1b, c demonstrate the streamline of the vertical circulation flow pattern in a plane parallel to the natural groundwater flow. In the case of no gradient in groundwater or no groundwater flow (Fig. 1a), the circulation cell extends like a sphere. As reported, the GCW
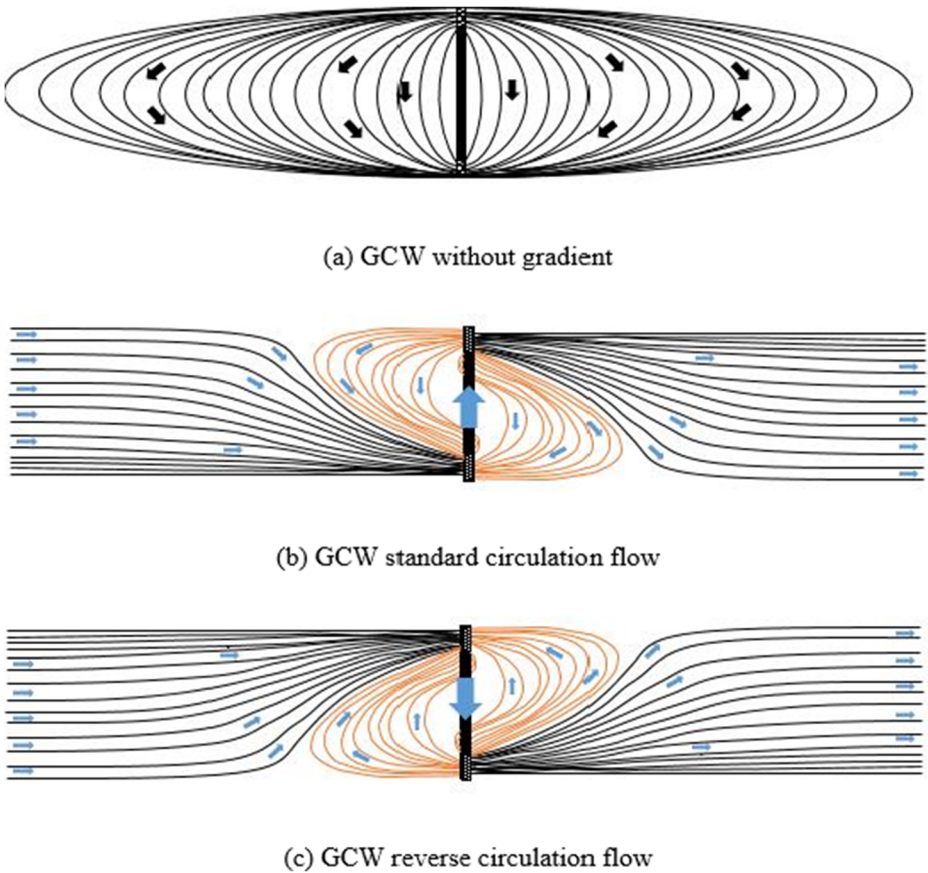
(a) GCW without gradient

(b) GCW standard circulation flow

(c) GCW reverse circulation flow

Fig. 1 GCW with **a** without gradient, **b** standard circulation flow with the gradient, and **c** reverse circulation flow with the gradient

should be used for remediation of only one aquifer and should not associate with different aquifer systems (Stamm et al. 1996).

The GCWs have extensively been used for in-situ remediation of groundwater in porous media (Herrling et al. 1991; U.S. EPA 1995, 1998; Miller and Roote 1997; McCarty et al. 1998). Scholz et al. (1997, 1998) had performed large-scale laboratory experiments in a heterogeneous aquifer system using GCW for removing NAPL contaminants. Besides, Knox et al. (1997) completed a field-scale study with the GCW system to assess surfactant-enhanced remediation of PCE contamination in an unconfined aquifer. Some experimental investigations suggested that GCW is a very useful in-situ remediation technique for removing NAPL contaminants in groundwater (Scholz et al. 1997, 1998; Mohrlok et al. 2000, 2003; Papini et al. 2016). Furthermore, GCWs have already been applied to remove volatile organic contaminants (Gvirtzman and Gorelick 1992; Allmon et al. 1999; Zhao et al. 2016; Tawabini and Makkawi 2018) and nonvolatile organic substances (Elmore and Graff 2002) from the subsurface. With the proper placement of a GCW system, the contaminated water could be treated before it enters a domestic well (Miller and Elmore 2005).

In the last few decades, several management strategies have been proposed to prevent or mitigate saltwater intrusion problems in coastal aquifers, including the reduction in abstraction

rates from pumping wells (Bruington 1972; Sherif 1999; Narayan et al. 2003; Bhattacharjya and Datta 2005, 2009; Sherif et al. 2013), adequate relocation of pumping wells to inland areas (Van Dam 1999; Sherif and Al-Rashed 2001; Todd and Mays 2005), the construction of subsurface physical barriers (Sugio et al. 1987; Harne et al. 2006; Luyun et al. 2009), the use of recharge wells to create hydraulic barriers (Papadopoulou et al. 2005; Yuansheng and Zhaohui 2009; Luyun et al. 2011; Herndon and Markus 2014), development of extraction barriers (Sherif and Hamza 2001; Kacimov et al. 2009; Masciopinto 2013) and land reclamation (Oude Essink 2001; Guo and Jiao 2007; Hu and Jiao 2010). Apart from these methods, a combination of some of the strategies as mentioned above have been employed by many researchers to better control of saltwater intrusion problems in coastal aquifers (Zhou et al. 2003; Narayan et al. 2006; Cherubini and Pastore 2011; Javadi et al. 2015). Cherubini and Pastore (2011) suggested a solution based on a reduction of well density coupled with artificial recharge to retard saltwater intrusion for a local aquifer in Italy. Javadi et al. (2012) proposed the pump and treat technique to control saltwater intrusion in coastal aquifers. They adopted the continuous extraction of saline water adjacent to the coastline to create a hydraulic barrier. The extracted water was desalinized, and the treated water was used as a source of artificial recharge through injection wells. The authors suggested that the technique is very effective and economical for controlling saltwater intrusion problems in coastal systems. In addition to hydraulic barriers, gaseous barriers have also been proposed to mitigate this problem (Sun and Semprich 2013). However, the successful application of these barriers is a very challenging task that involves further research.

The systematic review of the literature shows that many researchers have used the GCW for remediation of groundwater contamination. However, to the best of the knowledge of the authors, GCW has not been tried to control the saltwater intrusion processes in coastal aquifers by using it as a hydraulic barrier. In the case of a conventional hydraulic barrier, the groundwater is withdrawn from the coastal aquifer to create a hydraulic gradient, which acts as a barrier. In this technique, water is taken out of the aquifer and generally thrown into the sea. On the other hand, in the case of GCW, there is no loss in aquifer water. Thus by circulating the same water, a barrier can be created, and the saltwater wedge can be pushed back towards the seaside. Therefore, in this study, we made an effort to investigate the behavior of saltwater intrusion dynamics under a GCW. To accomplish this objective, we have experimented with a laboratory-scale flow tank model under constant water head boundary conditions. The variable-density flow and transport model FEMWATER is used to simulate the flow and transport processes for the experimental setup. The experiments conducted in the lab, as well as the numerical simulation model, show that the reverse circulation well is more effective in making a hydraulic barrier to control the saltwater intrusion processes in coastal aquifers. As such, we have used the reverse circulation flow GCW for both the laboratory and numerical experiments.

2 Materials and methods

2.1 Experimental setup

We conducted a laboratory experiment in a glass-sided flow tank. The flow tank used was constructed of 6 mm thick glass sheets. The cross-section of the flow tank was rectangular,

with internal dimensions of 55.6 cm in length, 40 cm in height, and width of 6.8 cm, as shown in Fig. 2.

The flow tank model was composed of three distinct flow chambers, and the central viewing flow chamber served as the porous media (the aquifer). To model a coastal unconfined aquifer system, we filled the central flow chamber with clear glass beads of an average diameter of 0.57 mm. Glass beads as an aquifer material have been used by several researchers (Zhang et al. 2002; Volker et al. 2002; Goswami and Clement 2007; Luyun et al. 2009, 2011; Goswami et al. 2012; Kuan et al. 2012; Chang and Clement 2013) because of their specific advantages, such as high strength, chemical stability, low thermal expansion, chemically inert, non-toxic, recyclable and good flowability. Moreover, the translucent property of glass beads facilitates visualization of the color dye. The tank used was flanked by two flow chambers at either side for maintaining constant water heads at the boundary. The right and left side flow chambers were assigned to represent the coastal and inland boundary, respectively. The hydraulic head at both the chambers was controlled by vertically adjusted overflow outlets. Both saltwater and freshwater were supplied at constant flow rates into the respective chambers from two large overhead reservoirs throughout the experiment. The side flow chambers are 5.3 cm long, and the chambers are separated from the central chamber by perforated plexiglass sheet and further wrapped by a fine mesh screen to prevent the passage of glass beads from the central flow chamber to the side ones.

The saltwater solution was prepared by dissolving commercial salt (NaCl) into tap water at a concentration of 35 g/L (Lu et al. 2013; Liu et al. 2014). The solution was then dyed by adding red food color to distinguish it from freshwater, yielding an adequate concentration of 3.125 ml/L. Many researchers have previously been used food color as a dye tracer in laboratory flow tank studies (e.g., Zhang et al. 2002; Goswami and Clement 2007; Luyun et al. 2009, 2011; Goswami et al. 2012; Kuan et al. 2012; Chang and Clement 2013; Oz et al. 2014). Tap water was used as a freshwater source throughout the experiment. The density of both the freshwater and dyed saltwater was estimated to be 0.997 g/cm^3 and 1.025 g/cm^3, respectively, as measured with a specific gravity hydrometer (G8030@JAPSINR). Prior to the
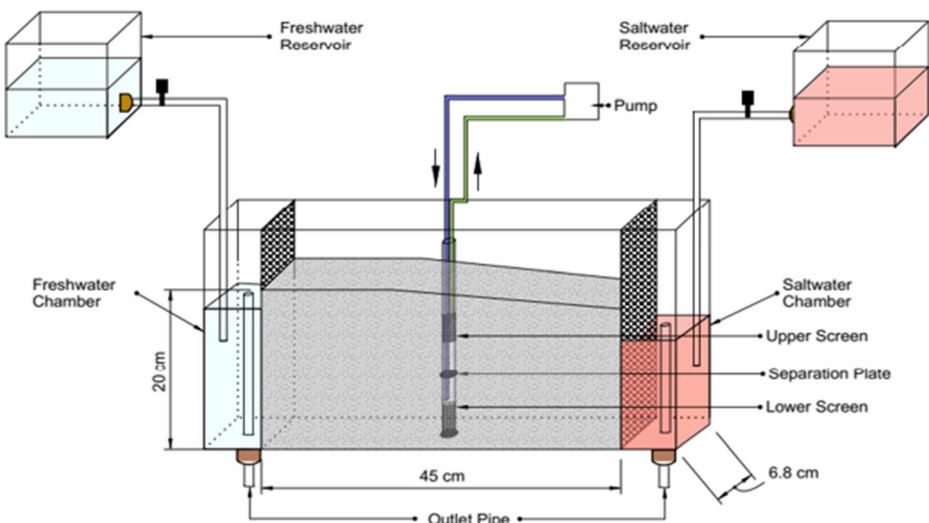

Fig. 2 Schematic diagram of the experimental setup

experiment, both the extraction and injection screens in the GCW were made of a 500-micron stainless-steel mesh of length of 2 cm. The internal diameter of the extraction/injection screens is 3 cm each. Both the screens are isolated with a separable plate provided in between the impermeable casing. This isolation of screens does not allow the accumulated water at the lower screen of the well to move upward. Hence, a small pinhole is provided in the separation plate through which the pump is connected either to extract the water from the lower section of the well or to inject in the lower section of the well. The diameter of the augured hole provided in the separation plate is 0.3 mm. The impermeable casing is constructed by a PVC pipe of the length of 7 cm. We used a 12V micropump for extraction or injection in this work.

2.2 Experimental procedures

The laboratory experiment was recorded at various intervals using a Nikon digital camera. A digital timer is used to record the experimental timing. The right bottom corner of the central chamber was considered as the origin to record experimental observations. The recorded images were cropped and presented at a suitable scale to provide better visualization.

At the start of the experiment, the porous section of the flow tank was filled with clear glass beads. The glass beads were packed under fully saturated conditions to avoid entrapment of air bubbles within the porous media. The glass beads were packed in layers of about 5 cm in the flow tank. Each of the layers was prudently compacted to satisfy a homogenous condition. The GCW was initially installed at a location of 22.5 cm from the seaward boundary within porous media before the packing of glass beads. After filling porous media, the porous section and flow chambers were initially filled with tap water at a constant rate from the overhead freshwater reservoir. The overflow outlets were adjusted to maintain a constant head of 15.5 cm and 14.5 cm in the freshwater and saltwater chamber, respectively, yielding a head difference of 1 cm. These head values were estimated from the bottom of the flow tank. This hydraulic gradient allowed to transmit freshwater towards the saltwater boundary. After a steady freshwater flow established, we used the in situ technique described by Goswami and Clement (2007) to determine the hydraulic conductivity of the porous media, and the average value was estimated to be 0.172 cm/s. The average porosity of the porous media was estimated as 0.43 using the volumetric method.

After establishing a steady-state flow, the red-dyed saltwater solution was then introduced quickly from the overhead saltwater reservoir into the saltwater chamber to replace freshwater, and once the saltwater reached a constant level, the saltwater intrusion process was initiated. The entire system was allowed to progress for some time until the steady-state saltwater wedge was achieved. After the establishment of the steady-state condition, the extraction of water from the aquifer was initiated for 5 minutes at the rate of 1.25 cm³/s. The subsequent migration pattern of saltwater intrusion wedge was observed. The GCW was introduced in the system after 5 minutes of extraction, and the entire system was allowed to continue until the end of the experiment.

2.3 Numerical simulation model and procedure

The finite-element based numerical simulation model FEMWATER (Lin et al. 1996) was used to simulate the laboratory experiment conducted in this study. It is a three-dimensional finite-element model that can simulate the density-dependent flow and mass transport through saturated-unsaturated porous media. The main goal of the simulation was to evaluate the

consistency of the experimental result with the numerical prediction, and once the numerical model is validated, the model can be used for creating different saltwater management scenarios using GCW. The numerical model comprised of a rectangular domain of dimension 45 cm long and 20 cm high. The entire model domain was split into 7749 nodes and 12800 elements with $\Delta x = 1.125$ cm, $\Delta y = 0.85$ cm and $\Delta z = 1$ cm.

The left and right side boundaries of the model were assigned as the inland and coastal boundary, respectively. Hydrostatic pressure boundary conditions were applied on the left side boundary (C = 0%) and to the right side boundary (C = 100%). A concentration of 35 g/L was used for the saltwater boundary. The constant head of 15.5 cm was set on the freshwater boundary while that was fixed at 14.5 cm on the saltwater boundary, yielding a head difference of 1 cm for the entire numerical simulation. The initial condition used in the model was that of a totally freshwater aquifer. An impervious boundary bounded the base of the domain. No flow boundary conditions were specified at the top, the front and the backside of the computational domain. To simulate a GCW in the model, we used multiple wells to represent extraction/ injection at the same location in a horizontal direction. The location of both extraction and injection wells center was at x = 22.5 cm and y = 3.4 cm but in different model layers. Also, the flow rate at the extracted location is a negative value, and that of the injected layer is positive. The longitudinal dispersivity (α_L) was estimated using the method described in Xu and Eckstein (1995). The transverse dispersivity (α_T) was assumed to be 1/10 of the longitudinal dispersivity (Goswami and Clement 2007). The longitudinal dispersivity and transverse dispersivity values were assigned to be 7 cm and 0.7 cm, respectively. The density of freshwater and saltwater was set into the numerical model to be 0.997 g/cm³ and 1.025 g/cm³, respectively. The other numerical parameters used in this study are listed in Table 1. All other parameters were fixed at the default values in the FEMWATER.

3 Results and discussion

3.1 Experimental results

Figure 3 represents the transport patterns of seawater intrusion wedge in the flow tank. The photographs were taken at 5, 15, 32, and 47 minutes after starting the experiment. The color image taken from the flow tank experiment at the steady-state is shown in Fig. 3d. The steady-

Table 1 Parameters of numerical simulation

| Parameter	Value	Source
Horizontal length	45 cm	Measured
Freshwater elevation	15.5 cm	Measured
Saltwater elevation	14.5 cm	Measured
Freshwater density	0.997 g/cm³	Measured
Saltwater density	1.025 g/cm³	Measured
Saltwater concentration	35 g/L	Measured
Hydraulic conductivity	0.172 cm/s	Measured
Bulk density	1.443 g/cm³	Measured
Porosity	0.43	Measured
Molecular diffusion coefficient	1×10^{-5} cm²/s	Freeze and Cherry (1979)
Pumping rate	1.25 cm³/s	Measured
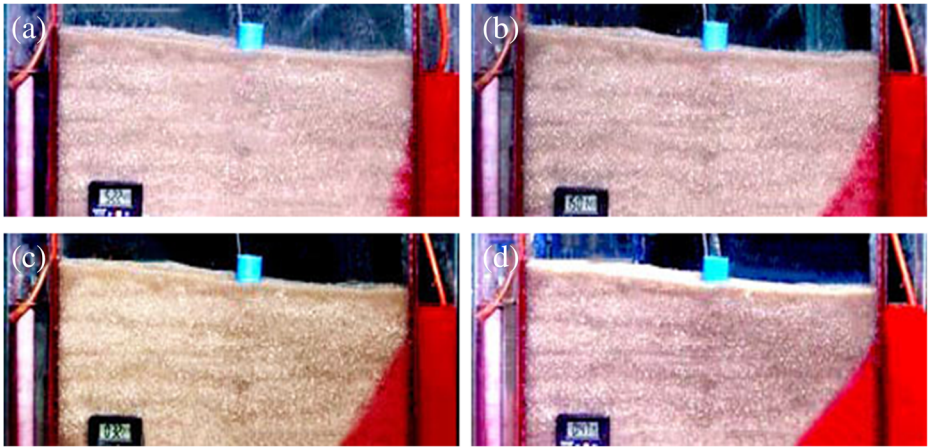
Fig. 3 Transport patterns of seawater intrusion wedge at **a** 5 min, **b** 15 min, **c** 32 min, and **d** 47 min

state saltwater wedge was obtained after about 47 minutes. At the steady-state condition, the toe of the saltwater wedge was located at 8.75 cm from the saltwater boundary, and the elevation of the wedge at the saltwater boundary (at x = 0) was 11 cm.

After obtaining the steady-state saltwater wedge, the extraction pump was started at a rate of 1.25 cm³/s, and the subsequent migration pattern of the saltwater intrusion wedge was observed. The time of the start of the extraction pump was noted as 47 minutes. After the extraction pump was initiated within the system, the saltwater wedge rapidly advanced through the system towards the freshwater boundary (Fig. 5b). It could be observed from the experimental data that a considerable mixing of saltwater and freshwater flows has occurred during the intrusion period. The mixing takes place due to the advection occurs as a result of pumping.

The GCW was then initiated within the system at 52 min and continued till 2 hrs 40 min. It can be observed that the position of the wedge is shifted towards the seaward boundary after the start of the GCW. The GCW has been acting as a hydraulic barrier. Figure 4 shows the shifting and the change in intensity of the saltwater wedge towards the seawater boundary, indicating the clear movement of the wedge towards the coastline. The toe of the saltwater wedge was measured as 6.5 cm from the coastline at 2 hrs 40 min. It proves that upon implementation of the GCW, there is no further movement of saltwater intrusion wedge towards the inland side, and hence it acts as a hydraulic barrier in controlling saltwater intrusion in coastal aquifers.

3.2 Numerical simulation results

The numerical model has been built up to simulate the flow, and transport processes for the experimental setup and simulations have been carried out to verify the physical phenomenon of saltwater intrusion dynamics under the effect of a GCW. The experimental results indicate that there is further movement of the saltwater wedge towards the well due to the extraction of water. Even though recirculating the freshwater by using the GCW, the saltwater wedge was subsidized and pushed towards the saltwater boundary to achieve a new steady state. At the steady-state condition, the toe of the saltwater wedge was 8.75 cm in the physical model, whereas in the numerical simulation, it was 8.98 cm. Later, under the presence of GCW, a new steady-state wedge position was achieved at 6.5 cm and 6.75 cm, respectively, in the laboratory experiment and
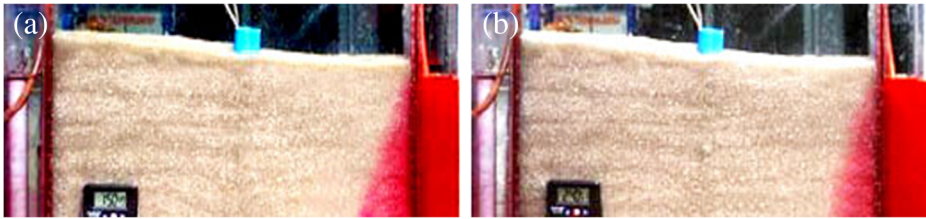
Fig. 4 Effect of Groundwater circulation well on the saltwater wedge at **a** 1hr 50 min, and **b** 2hr 40 min

numerical simulation. The comparison of the numerical and experimental results shows that the numerical prediction is in good agreement with the experimental results (Fig. 5).

To analyze the actual scenario in the field, however, a standard GCW was modeled with extraction at lower screen and injection at the upper screen, keeping the same parameters as it was considered in the physical model. It can be observed from the simulation results that the saltwater wedge gets migrated fully towards the bottom of the well, as shown in Fig. 6. This indicates that the standard GCW is not effective in making the hydraulic barrier to control the saltwater intrusion processes in coastal aquifers. However, the reverse circulation flow GCW is very effective in creating the hydraulic barrier to control saltwater intrusion and could be implemented in the field.

4 Summary and Conclusions

Saltwater intrusion is a common environmental problem encountered in coastal groundwater aquifer. As such, there is a need to prepare and implement proper remediation techniques in
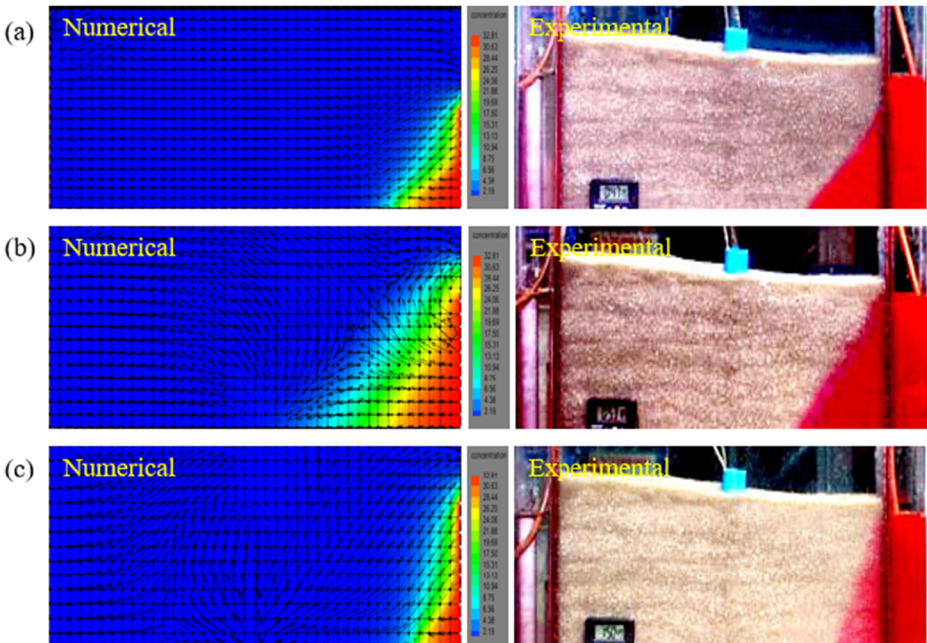

Fig. 5 Comparison of numerical and experimental results for **a** Steady State, **b** 5 min extraction, **c** with GCW
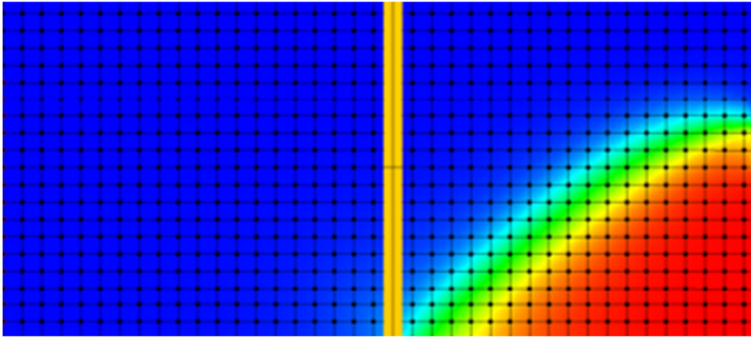
Fig. 6 Numerical simulation results for standard GCW

controlling saltwater intrusion for coastal environments. In this study, an effort has been made to investigate the behavior of saltwater intrusion dynamics under the effect of a groundwater circulation well (GCW) using both experimental and numerical approaches. An experiment has successfully been conducted in a laboratory-scale flow tank model under constant water head boundary conditions. The variable-density flow and transport model FEMWATER is used to simulate the flow and transport processes for the experimental setup, and simulations have been carried out to study the dynamics of saltwater intrusion under a GCW. The experimental results show that a considerable mixing of saltwater and freshwater flows is observed during the initial intrude period. The evaluation of the results indicate that there is no further movement of saltwater intrusion wedge towards the inland side upon implementation of GCW, and act as a hydraulic barrier in controlling saltwater intrusion in coastal aquifers. The present study reveals the GCWs system can effectively mitigate the saltwater intrusion problem in coastal regions and could be considered as one of the most efficient management strategies for controlling the problem.

Compliance with ethical standards

Conflict of Interest   None

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Affiliations

Om Prakash Vats[1] · **Bhrigumani Sharma**[1] · **Juergen Stamm**[2] · **Rajib Kumar Bhattacharjya**[1]

[1]   Department of Civil Engineering, Indian Institute of Technology Guwahati, Guwahati, Assam 781039, India

[2]   Faculty for Civil Engineering, Institute for Hydraulic Engineering and Technical Hydromechanics, Technical University Dresden, Dresden 01062, Germany