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Comparison of the Performances of Barrier Extraction and Freshwater Recharge Wells to Control Saltwater Intrusion in Coastal Aquifers

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Climate change induced sea-level rise in combination with excessive groundwater pumping has the significant potential to increase saltwater intrusion in coastal aquifers. Saltwater intrusion is a major challenge because meeting the growing demand for freshwater supplies to the coastal community requires a considerable amount of groundwater abstraction from the vulnerable coastal aquifers. To meet this ever-increasing demand of water for beneficial purposes, judicial and sustainable utilization of available fresh groundwater supplies need to be adopted without deteriorating existing water resources in the aquifer. Sustainable water abstraction from coastal aquifers can be ensured by controlling saltwater intrusion through reversal of the hydraulic gradient along the coast by using a set of barrier extraction wells (BWs) or by creating a freshwater lens near the shoreline by utilizing a set of freshwater recharge wells (RWs). In this study, the comparative efficiencies of a set of BWs and freshwater RWs as well as the combined use of BWs and RWs are presented as a measure of salinity control in coastal aquifers. The simulation of density-reliant coupled flow and solute transport processes was performed for an illustrative 3-D multilayered coastal aquifer system using FEMWATER. Salinity concentrations were measured at specified monitoring locations (MLs) at the end of the simulation period of three years. Results revealed that salinity concentrations at the MLs can be reduced by allowing water extraction from a set of BWs in combination with the water abstraction from the production wells (PWs). In contrast, injecting water through a set of RWs did not help reducing salinity concentrations at specified MLs, rather the salinity concentrations increased from a combined operation of PWs + RWs when compared to PW pumping alone. Therefore, the results from this study demonstrated the superiority of BWs over RWs in a shorter simulation time for controlling saltwater intrusion of the illustrative coastal aquifer system.

(***Key words:*** *Barrier extraction wells, Coastal aquifer, Performance comparison, Recharge wells, Saltwater intrusion)*

The coastal regions around the globe are resource-rich areas and highly populated with around 50% of the world's total population living within the 60 km of the shoreline (Oude Essink, 2001). This increased human settlement is blessed with abundant food (agriculture and fisheries) and flourishing economic activities (trade, harbours, ports and infrastructure). As a result of this immense pressure of these increased human settlements, agricultural developments and economic activities, the coastal areas typically experience a shortage of fresh water supplies to meet the demands of domestic, agricultural, and industrial sectors in these areas. This shortage of freshwater is usually met from extracted water from coastal groundwater reserves. Over-extraction of groundwater resources often results in saltwater intrusion and subsequent deterioration of groundwater quality in coastal aquifers (Nocchi and Salleolini, 2013).

Climate change-induced relative sea-level rise, which provides an additional saline water head at the shoreline, has a considerable impact on the acceleration of salinity intrusion process in coastal aquifers around the globe. It will take several centuries to equilibrate this sea-level rise induced saltwater intrusion, even if the sea level has fallen back to its original position. Although excessive groundwater withdrawal is considered as the major cause of saltwater intrusion, relative sea-level rise, in combination with the effect of excessive groundwater pumping, can exacerbate the already vulnerable coastal aquifers. However, in this study, the effects of relative sea-level rise have not been considered in the limited three-year simulation period as the prime emphasis of

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this research is to provide a comparison of the hydraulic barriers along the coast to control saltwater intrusion.

Saltwater intrusion in coastal aquifers generally occurs due to the alteration of naturally equilibrated hydraulic gradients. Unplanned over-extraction of groundwater resources is one of the major causes of this reversal of natural gradation of seawater towards the inland direction (Bhattacharjya *et al*., 2007; Ketabchi *et al*., 2016; Narayan *et al*., 2007; Roy and Datta, 2017a and 2018a; Sreekanth and Datta, 2010). Any coastal aquifer management approach should be based on optimizing beneficial groundwater extraction while maintaining salinity concentrations in the aquifer within the acceptable limits. Ideally, the aim should be to maximize beneficial water extraction that can be achieved by creating a hydraulic barrier along the coast to control saltwater intrusion hydraulically. This hydraulic barrier can be created either by implementing a set of barrier extraction wells (BWs) (Roy and Datta, 2017b; Sreekanth and Datta, 2011) or by a set of recharge wells (RWs) (Lal and Datta, 2018). Abstracted water from barrier extraction wells is unusable for beneficial purposes due to high salinity contents. On the other hand, water injection via recharge wells is associated with cost. Therefore, the objectives should be to minimize water extraction from BWs and to reduce the recharge rates through freshwater RWs. Although the potentiality of either BWs or RWs has been reported in recent literature (Lal and Datta, 2018; Roy and Datta, 2018b; Sreekanth and Datta, 2011), a comparison of these two hydraulic control measures and the combined use of them in controlling saltwater intrusion has not been conducted before. Therefore, the present study seeks to demonstrate a comparative evaluation of the potential applicability of the BWs and RWs as well as a combination of both BWs and RWs in creating a hydraulic barrier near the coast to control saltwater intrusion in a coastal aquifer system.

MATERIALS AND METHODS

An illustrative coastal aquifer study area has been considered to demonstrate the comparative performance evaluations of the proposed hydraulic control measures as an option to control saltwater intrusion. The stratified aquifer system has four distinct layers of materials with different hydraulic conductivity values in the horizontal and vertical directions. The aquifer processes were simulated using a numerical simulation code for a period of three years. A brief description of the governing equations of the simulation code and the illustrative study area is provided in the following paragraphs.

Numerical simulation modeling of saltwater intrusion processes

A 3D density-reliant coupled transient flow and solute transport numerical simulation code, FEMWATER (Lin *et al*., 1997) was used to simulate the aquifer processes under transient flow and salt transport conditions. The 3D flow and solute transport processes were solved by using the following equations (Lin *et al*., 1997)

$$\frac{\rho}{\rho_0} F \frac{\partial h}{\partial t} = \nabla \bullet \left[\mathrm{K} \bullet \left(\nabla h + \frac{\rho}{\rho_0} \nabla z \right) \right] + \frac{\rho}{\rho^*} q \tag{1}$$

$$F = \alpha' \frac{\theta}{n} + \beta' \theta + n \frac{dS}{dh} \tag{2}$$

where, F = storage coefficient, h = pressure head, t = time, K = hydraulic conductivity tensor, z = potential head, q = either a source or a sink, p = water density at chemical concentration C, p_o = referenced water density at zero chemical concentration, p^* = density of injection fluid or that of the withdrawn water, θ = moisture content, α' = modified compressibility of water, β' = modified compressibility of the medium, n = porosity, S = saturation.

The hydraulic conductivity tensor, K is represented by

$$K = \frac{\rho g}{\mu} k = \frac{(\rho/\rho_o)}{\mu/\mu_o} \frac{\rho_o g}{\mu_o} k_s k_r = \frac{\rho/\rho_o}{\mu/\mu_o} K_{so} k_r \tag{3}$$

where, μ = dynamic viscosity of water chemical concentration C, μ_o = reference dynamic viscosity at zero chemical concentration, k_s = saturated permeability tensor, k_r = relative permeability or relative hydraulic conductivity, k_{so} = referenced saturated conductivity tensor.

The 3D solute transport is expressed as

$$\begin{aligned} &\theta \frac{\partial C}{\partial t} + \rho_b \frac{\partial S}{\partial t} + V \cdot \nabla C - \nabla \cdot (\theta D \cdot \nabla C) \\ &= -\left(\alpha' \frac{\partial h}{\partial t} + \lambda \right)(\theta C + \rho_b S) - (\theta K_w C + \rho_b K_s S) \\ &+ m - \frac{\rho^*}{\rho} q C + \left(F \frac{\partial h}{\partial t} + \frac{\rho_o}{\rho} V \cdot \nabla \left(\frac{\rho}{\rho_o} \right) - \frac{\partial C}{\partial t} \right) C \end{aligned} \tag{4}$$

where, P_b = bulk density of the medium, C = for material concentration in aqueous phase, S = material concentration in adsorbed phase, V = discharge, ∇ = del operator, D = Dispersion coefficient tensor, λ = decay constant, M = qC_m →artificial mass rate, C_m = material concentration in the source, K_w = first order biodegradation rate constant through dissolved phase, K_s = first order biodegradation rate through adsorbed phase, K_d = distribution coefficient.

The dispersion coefficient tensor D in equation (4) is expressed as

$$\theta D = a_T |V| \delta + (a_L - a_T) \frac{VV}{|V|} + a_m \theta \tau \delta \tag{5}$$

Where, $|V|$ = magnitude of V, δ = Kronecker delta tensor, lateral dispersivity, a_r = longitudinal dispersivity, a_m = molecular diffusion coefficient, and τ = tortuosity.

Description of the study area

A multi-layered unconfined coastal aquifer system similar to the one developed by Roy (2018) as shown in Fig. 1 was used for evaluating the performance of the proposed saltwater intrusion control using hydraulic barriers. The areal extent and the total thickness of the illustrative study area were 4.35 km^2 and 80 m, respectively. The total thickness of the aquifer was divided into four distinct layers of materials. Each of the material layers was 20 m thick and the aquifer material within each layer was assumed to be homogeneous. The ratio of horizontal hydraulic conductivity in the Y-direction K_x/K_y was taken as 2.0. The value of vertical hydraulic conductivity in the Z-direction (K_z) was taken as one-tenth of the value of horizontal hydraulic conductivity in the X-direction. The southern and eastern sides of the study area were surrounded by the coastal boundary and a river, respectively. An initial head of 0 m was assigned to both ends of the seaside boundary whereas the upstream end of the river had an initial head of 1 m, which is allowed to vary along the stream. The western side of the aquifer was considered as no-flow boundary. The coastal boundary was assigned with a constant seawater concentration of 35 kg m^{-3}. The top of the aquifer was subjected to a natural recharge of 0.000137 m day^{-1}, distributed uniformly over the entire top phreatic surface of the aquifer.

Fig. 1 shows the three-dimensional view of the study area with finite element meshes and the locations of the wells. The study considered 12 production wells (PW1–PW12) to abstract water for beneficial purposes, 21

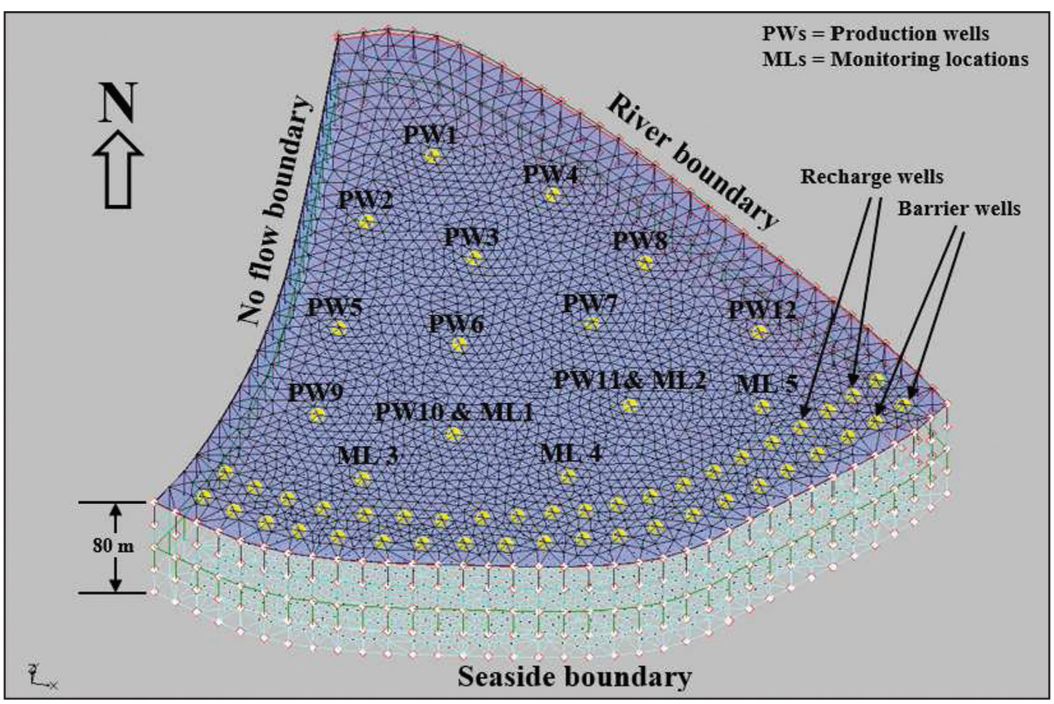

Fig. 1. *Three dimensional view of the illustrative study area (Roy, 2018)*

recharge wells (RW1–RW21) and 21-barrier extraction wells (BW1–BW21) placed near the coast to create a hydraulic barrier for controlling saltwater intrusion. The approximate distance between two adjacent wells was kept as 150 m for both recharge and barrier extraction wells to ensure a complete hydraulic barrier along the coast. Well screens were located at the second and third vertical layers of the aquifer. The entire study area was discretized into prism-shaped finite elements of 90 m. A finer mesh of 45 m was used near the wells. Total simulation period of three years was divided into three uniform time steps of one year each. However, the simulation was performed using a simulation time step of 5 days. Salinity concentrations were monitored at five monitoring locations (MLs) at the end of the simulation period of three years. The recharge water for artificial recharge was assumed to have a salinity concentration of 0.1 kg m^{-3}. Simulation parameters are shown in Table 1.

Table 1. *Aquifer parameters*

Parameters	Units	Material layers			
		Layer 1	Layer 2	Layer 3	Layer 4
Hydraulic conductivity in x-direction	m day^{-1}	5	10	15	3
Hydraulic conductivity in y-direction	m day^{-1}	2.5	5	7.5	1.5
Hydraulic conductivity in z-direction	m day^{-1}	0.5	1.0	1.5	0.3
Compressibility	md^2 kg^{-1}	1.33×10^{-15}	1.33×10^{-17}	1.33×10^{-17}	1.33×10^{-16}
Bulk density	Kg m^{-3}	1650	1600	1550	1700
Porosity	-	0.46	0.41	0.43	0.38
Longitudinal dispersivity	m	80	80	80	80
Lateral dispersivity	m	35	35	35	35
Molecular diffusion coefficient	m^2 day^{-1}	0.69	0.69	0.69	0.69
Density reference ratio	-	7.14×10^{-7}	7.14×10^{-7}	7.14×10^{-7}	7.14×10^{-7}
Recharge	m day^{-1}	0.000137	-	-	-

*Recharge is distributed uniformly over the first layer of the study area

Spatio-temporal transient groundwater extraction values from the 12 PWs, 21 BWs, and 21 RWs were generated using the Latin Hypercube Sampling (LHS) (Pebesma and Heuvelink, 1999) technique within the practical pumping limits of 0 - 1300 m^3 day^{-1}. These pumping values are generated through LHS technique from a uniform distribution within the total input space. These spatio-temporal pumping values were fed to the simulation code and the transient simulation was performed for a period of three years (1095 days divided into 219 uniform time steps of five days each). The performances of the BWs, RWs, and their combinations in terms of observed salinity concentrations at five monitoring locations (MLs) were evaluated and compared.

A sensitivity analysis was conducted to evaluate the effects of BWs, artificial recharge via RWs, and a combination of the both on saltwater intrusion processes in coastal aquifers. This sensitivity analysis was performed to identify which options had the most influential effect on reducing saltwater intrusion processes quantified by observing changes in heads and saltwater concentrations over time at specified MLs.

RESULTS AND DISCUSSION

Effects of barrier extraction and freshwater recharge wells on changes in pressure heads at different MLs

The development of heads with respect to utilization of PWs BWs, and RWs and some of their combinations are presented in Fig. 2. It can be seen from Fig. 2 that the initial head was declined due to water extracted from PWs, which was declined further when BWs were combined with PWs. Recharging freshwater through RWs combined with water extraction from PWs built up head again. Water head had fallen again when BWs were added to PWs + RWs. This fluctuation of head confirmed that operation of both of these wells reflected a balance between water coming in to and going out of the system. It is obvious from Fig. 2 that recharging freshwater through a set of RWs was associated with

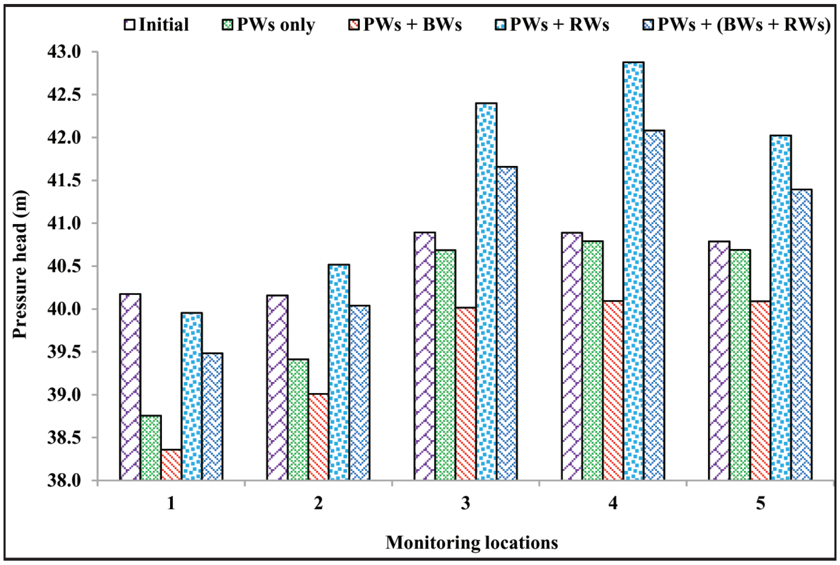

Fig. 2. *Comparison of heads at different monitoring locations for different combinations of production, barrier wells extraction and recharge wells injection at the end of the management period of three years. PWs = Production wells, BWs = Barrier wells, RWs = Recharge wells*

building up head, however, the developed head might not be sufficient to reduce salinity concentrations at the specified MLs for the specified simulation period of three years.

Effects of barrier extraction and freshwater recharge wells on changes in saltwater concentrations at different MLs

Changes in salinity concentrations over time throughout the simulation period of three years (1095 days divided into three uniform simulation time steps) is presented in Fig. 3. The salinity concentrations showed an increasing trend, as was expected, during the subsequent time steps of the simulation period. It is observed from Fig. 3 that groundwater pumping from only the PWs + BWs resulted in the lowest salinity concentrations at different simulation time steps followed by pumping from PWs only, PWs + (BWs + RWs), and PWs + RWs. It is noted that pumping from the PWs while injecting water into the aquifer through RWs resulted in the highest salinity concentrations during the simulation period. Similar trends were observed at all monitoring locations as indicated in Fig. 3.

As mentioned earlier, a simulation period of three years was considered to evaluate the effects of BW, RW, and BW-RW on saltwater intrusion in an illustrative coastal aquifer system. Salinity concentrations at five MLs at the end of the simulation period for a particular pumping pattern are presented in Fig. 4. MLs were placed at different locations to ensure the variation of salinity concentrations at these locations. It is shown from Fig. 4 that pumping from wells increased salinity concentrations in the aquifer when compared to initial states of the aquifer before pumping starts. An increase in salinity concentration resulting from water extraction from PWs could be reduced by allowing water extraction from a set of BWs. In contrast, injecting water through a set of RWs did not help reducing salinity concentrations at specified MLs, rather the salinity concentrations increased from a combined operation of PW + RW when compared to PW pumping alone. Plausible explanation of this may be that during these three years of simulation period, adequate freshwater head did not develop to prevent migration of saltwater plume. However, longer simulation period was not considered in the present study because the primary objective was to provide a guideline for developing a saltwater intrusion management model. It is noted that a longer management period is practically meaningless because of the changing physical processes of the aquifer system for a longer period.

Combined utilization of BWs and RWs were also presented in this study for comparison purposes. It is observed from Fig. 3 that this combined implementation

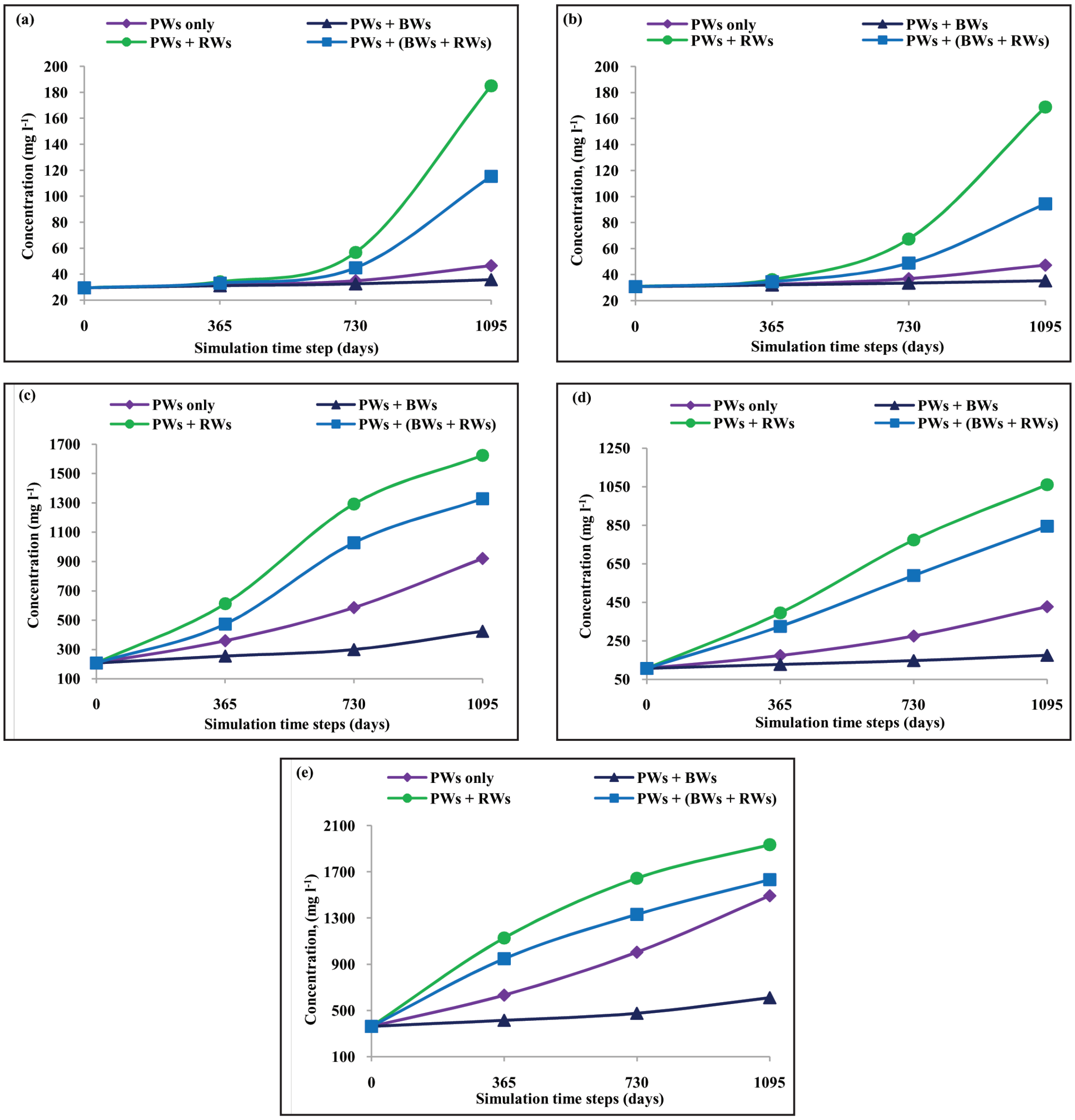

Fig. 3. *Changes in salinity concentrations over time at monitoring locations (a) ML1, (b) ML2, (c) ML3, (d) ML4, and (e) ML5*

partly compensated the ill-effects of using RWs alone. Therefore, it can be inferred that BWs were more effective saltwater intrusion control measures than RWs and BWs +RWs in this example problem that utilized an illustrative coastal aquifer study area. The methodology developed in this study has the potential to be applied for a real-life coastal aquifer study area. The use of BWs over RWs is also well justified when considering the shortage of global freshwater supplies. While good quality water should not be used for injecting into the aquifer due to the demands for this water in other sectors, the poor quality water might contaminate the aquifer. On the other hand, water extracted from BWs can easily be disposed off to the sea or can be used for aquaculture thereby reducing the environmental degradation.

This study presented the relative effectiveness of a set of barrier extraction wells (BWs), freshwater recharge wells (RWs) and a combination of these wells in reducing the extent of saltwater intrusion processes in coastal aquifers. Results indicated that BWs were more effective in controlling salinity intrusions in the illustrative coastal aquifer system for the specified simulation period of three years. While increase in the pressure head was observed in the specified MLs when freshwater was recharged through recharge wells, the developed head might not be sufficient to create a

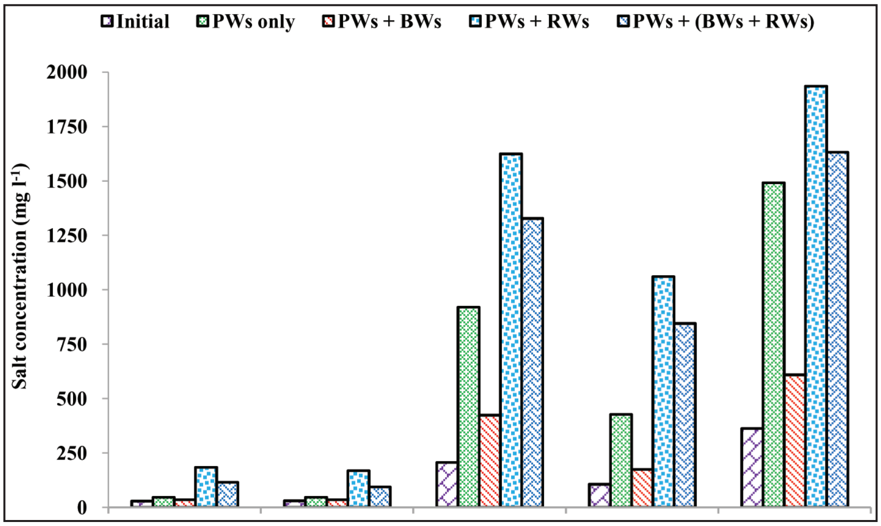

Fig. 4. *Comparison of salinity concentrations at different monitoring locations for different combinations of production, barrier wells extraction and recharge wells injection at the end of the management period of three years. PWs = Production wells, BWs = Barrier wells, RWs = Recharge wells*

freshwater lens to prevent saltwater intrusion, especially within this limited simulation period. Since the physical processes of a dynamic coastal aquifer system might change within a very short period and as the primary aim of simulating the aquifer processes was to aid in developing management policies for optimized pumping from the aquifer, a simulation period of three years was considered optimal for illustrative purposes. While the effect of climate change-induced sea level rise on saltwater intrusion processes is inevitable, this effect may be considered insignificant for a simulation period of three years. As such, this effect was not incorporated in the simulation of the saltwater intrusion processes of the study area. Future research may opt to use the finding of the present study in the simulation process for aiding in developing a management model for a real-life coastal aquifer system.

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