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ORIGINAL ARTICLE

Shoreline subsurface dams to protect coastal aquifers from sea level rise and saltwater intrusion

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Abstract

Fresh groundwater in arid and highly populated regions is limited. In coastal aquifers, the deterioration of fresh groundwater is accelerated by saltwater intrusion, primarily occurring through lateral encroachment and vertical movements in the proximity of discharging wells. Coastal regions have high salinity due to saline intrusion, where many abstraction wells are turned off by this high salinity, which leads to increased freshwater supply costs. This study investigates the performance of new approach using the shoreline subsurface dams (SSDs) for mitigating the saline water wedge in coastal aquifers, where the dams are installed at the shoreline (distance from shoreline = 0). Specifically, the current study's novelty is testing the effectiveness of SSDs by different relative heights ranging from 0.05 to 0.50 in the test case (Henry problem) and from 0.09 to 0.53 relative to the aquifer thickness in the field scale aquifer (Biscayne aquifer, Florida, USA). The results showed an exponential increase in salt repulsion for increasing SSDs height, reaching a maximum of + 0.70%, + 1.80%, + 3.25%, + 5.80%, + 10.45%, and + 18.40% for the dam height to aquifer thickness ratios of 0.09, 0.18, 0.26, 0.35, 0.44 and 0.53, respectively, in the field scale case. The SSDs increase the freshwater storage at the coastal zones where the low salinity occurs and reduces the freshwater supply cost. Despite the positive impact of height on repulsion, important factors such as economics, construction aspects, geographical suitability, and environmental impacts must be considered for real applications. This is crucial to develop feasible solutions applicable globally under the growing pressure of sea level rise.

Keywords Climate change · Sea level rise · Physical barriers · Shoreline subsurface dams · Coastal aquifers management

Introduction

The high freshwater demand in coastal regions is responsible for water stress and increasing groundwater salinity (Klassen and Allen 2017; Rachid et al. 2021). The change in soil salinity caused by the advancement of seawater adversely affects agricultural production leading to crop yield declines (Tully et al. 2019). In this context, the effective mitigation for the influence of changing climate on fresh groundwater resources is a critical issue for the livelihood in coastal regions.

Climate change impacts coastal aquifers globally but differently geographically (Abd-Elaty et al. 2019a). According to the most recent observations and measurements, the sea level rise (SLR) is accelerated by the thermal expansion of oceans and melting glaciers and ice caps, affecting the coastal aquifers' salinity. The Intergovernmental Panel on Climate Change (IPCC) indicated that the SLR ranged between 1.70 to 2.30 mm year^{-1} over the 20th century and

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expected to reach 58 to 88 cm by 2100 (Abd-Elaty 2019a; Khan 2022). The coastal regions worldwide are at high risk by the inundation of inland side and saltwater intrusion (SWI) due to SLR (Ashrafuzzaman et al. 2022; Rizzo et al. 2022).

The investigation of SWI is critical for coastal regions because it negatively impacts fresh groundwater resources and requires management strategies (Abd-Elaty et al. 2022a). The most common methods include the optimization of current and future well-pumping rates, relocation of the current production wells, applying surface barriers by land reclamation, installing physical subsurface barriers (PSBs) using cutoff walls and subsurface dams, applying hydraulic methods using freshwater recharge, saline water abstraction, a combination of injection and abstraction techniques, creation of interceptor drains parallel to the coast and re-injecting wastewater, among other methods (Abd-Elaty et al. 2022a; Tansel and Zhang 2022). Among these methods, PSBs offer several advantages in comparison to other solutions, such as better control of groundwater levels and aquifer management, relatively low environmental impact, long-term effectiveness, and flexibility to various geological and hydrological conditions (Allow 2011; Chang et al. 2019).

Harne et al. (2006) simulated the SWI mitigation in coastal aquifers using a 2D finite-difference transport model to study the PSB's efficiency. They showed that the model results indicated that the barriers closer to the shoreline or the sea face boundary mitigate the SWI. Strack et al. (2016) applied an analytical solution and experimental sandbox tank to manage SWI using artificial barriers. The results showed that artificially reducing the permeability of the seaside part could decrease the SWI. Abdoulhalik et al. (2017) conducted an experimental study for managing SWI in coastal zones using mixed physical barrier where the subsurface dams (SDs) are semi-permeable, and cutoff walls (CWs) are impermeable. The results indicated that the mixed physical barriers reduced the SWI length, construction, and operation cost more than simple SDs or CWs. The mixed physical barrier of 40% pentration depth was more effective than a simple CWs with 90% penetration depth of the total aquifer thickness. Abdoulhalik and Ahmed (2017a) have further investigated the performance of cutoff walls in stratified heterogeneous aquifers. The case when a low permeability layer existed at the bottom of the aquifer impacted the effectiveness of the wall on controlling SWI. A similar observation was found in their investigation of subsurface dams (Abdoulhalik and Ahmed 2017b), where a low permeability aquifer at the bottom or the middle of the aquifer has slowed the cleanup process from SWI contamination. Abd-Elaty et al. (2019b) studied the efficiency of PSBs systems for mitigating SWI; the study showed that using the PSBs is good for managing the SWI; also, the cutoff wall could cause significantly more reduction than subsurface dams. Abd-Elaty et al. (2021) applied a numerical study for sustainable SWI mitigation using PSBs and hydraulic barrier methods; the results showed that the two methods are suitable for hyper-arid and arid regions. Applying the combination of the PSBs in dry seasons and recharge wells in wet seasons could control the SWI in semiarid and semi-humid regions.

Luyun et al. (2011) tested different heights of SDs to control SWI on an experimental laboratory aquifer. One of their main findings was that shorter dam heights had a better ability to flush seawater and keep it behind the wall in the seaside. The subsurface dam height needed to be at least the same height as the seawater wedge at the barrier location. Abdoulhalik and Ahmed (2017b) went beyond Luyun et al. (2011) by investigating the effect of aquifer stratification on the ability of SDs to manage the SWI. Their investigation showed that subsurface dams controlled SWI in layered aquifers. However, some aquifer settings, such as the low permeability layer at the bottom, weakened the ability of the dam to retain saltwater behind the wall at the seaside. Abd-Elaty and Zelenakova (2022) used SEAWAT to investigate the SWI in shallow and deep coastal aquifers, showing that the shallow aquifer of Gaza, Palestine, is more effective for SWI management using SDs, CWs and landfill. In contrast, the results showed that a hydraulic method is ineffective for the deep aquifer of the Nile Delta, Egypt and the Gaza aquifer.

The current study aimed to examine the effect of shoreline subsurface dams (SSDs) height on SWI mitigation in the Biscayne aquifer, Florida, USA. Initially, an SSDs height of 3 m was considered, while additional simulations were run for height increments of 3 m. We hypothesize that increasing the height of the SSDs enhances their effectiveness for mitigating SWI in coastal areas. A simulation considering an SLR of 84 cm was also run. To validate our hypothesis, comprehensive research and data analysis will be necessary, considering various environmental and socio-economic variables. Understanding the complex interactions between SSDs height, hydrological processes, and regional conditions will provide invaluable insights into the potential of SSDs as an effective tool in sustainable water management and combating saltwater intrusion along vulnerable coastlines.

Material and methods

Numerical model

The SEAWAT software was applied for simulating the shoreline subsurface dams (SSDs) applications using two cases: the Henry benchmark problem and the Biscayne aquifer in

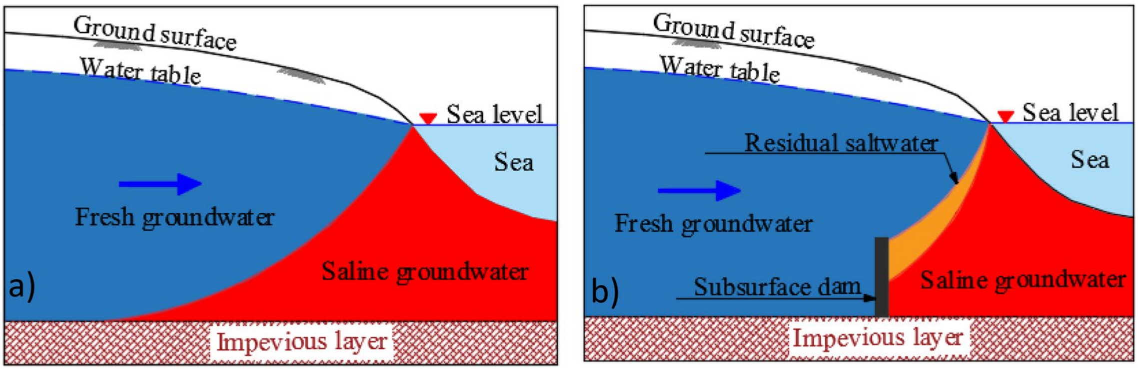


Fig. 1 Schematic illustration of saltwater intrusion **a** at the baseline case and **b** after the installation the physical subsurface dam

the Deering Estate area, Florida, USA. A coupled version of the MODFLOW and MT3DMS by SEAWAT V4 (Langevin et al. 2020) was used to solve the miscible variable-density process. This process is governed by the coupled system of flow and transport equations (Guo and Langevin 2002; Abd-Elaty et al. 2019a), Eq. 1:

$$\begin{aligned} &\phi\frac{\partial\rho}{\partial t}-\nabla\left(\frac{\rho K}{\mu}(\nabla p+\rho g\nabla z)\right)=0\\ &\phi\frac{\partial(\rho C)}{\partial t}+\nabla(\rho qC)-\phi\nabla(\rho D\nabla C)=0 \end{aligned} \tag{1}$$

where ϕ is porosity, p is pressure, K is the hydraulic conductivity tensor, ρ and μ are fluid density and viscosity, respectively, g is the gravitational constant, and so the hydraulic

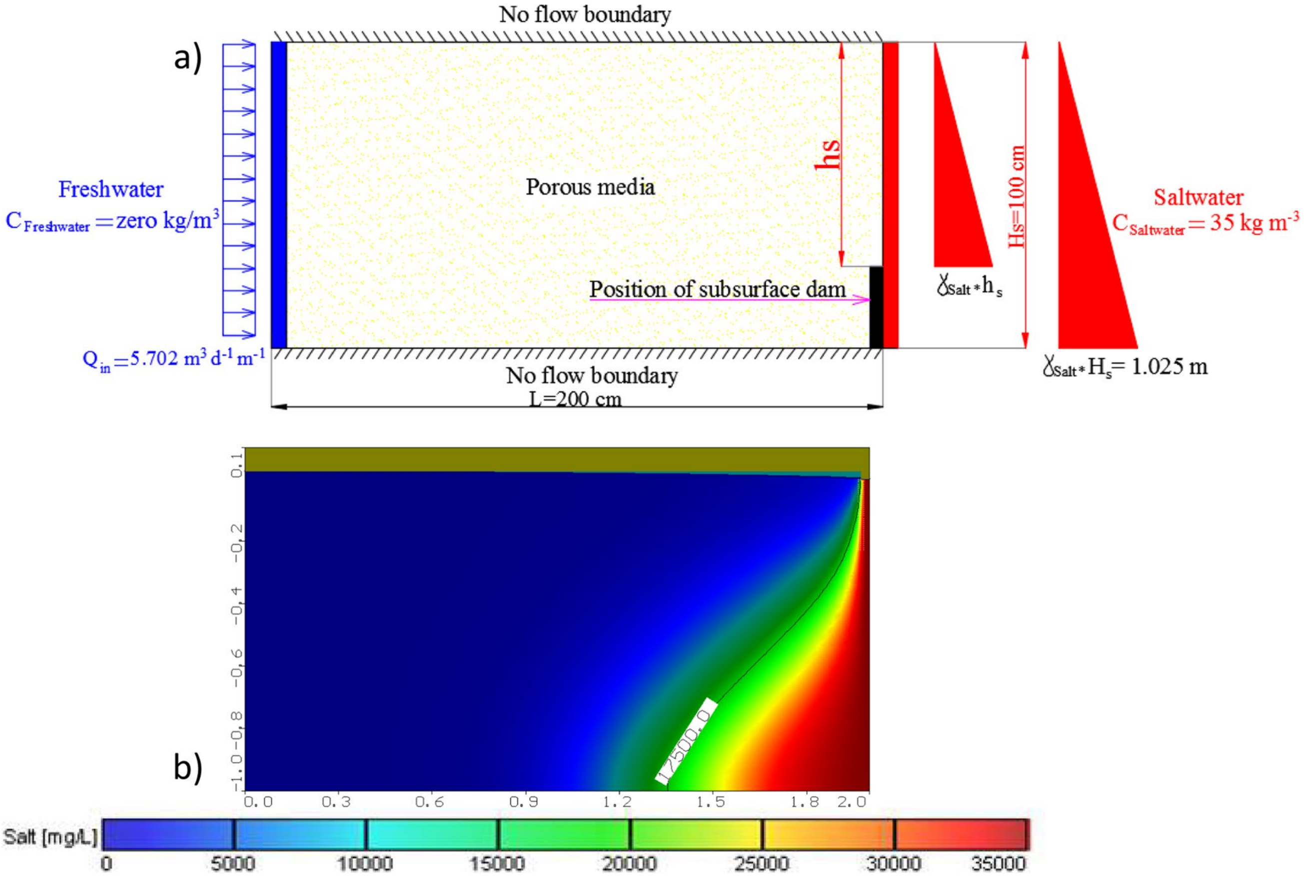


Fig. 2 Henry's problem **a** domain, boundary conditions, and shoreline subsurface dams (SSDs) at the seaside and **b** baseline case salinity results by SEAWAT for distribution of 0.5 isochlor (17,500 ppm)

head (h) is given by ($p/\rho g + z$); C is the solute (salt) concentration; $D = (\phi d + \alpha T|v|)I + (\alpha_L - \alpha_T)vv^T/|v|$ is the hydrodynamic dispersion tensor and d diffusion coefficient; α_T and α_L, respectively, are transverse and longitudinal dispersivity; $v = q/\phi$ is the fluid velocity, and the superscript T denotes transpose. System (1) is closed by specifying a constitutive relationship, $\rho = \rho_f + \beta C$, where $\beta = (\rho_s - \rho_f)/C_s$, ρ_s and ρ_f being salt and freshwater density, respectively, and C_s is the saltwater concentration.

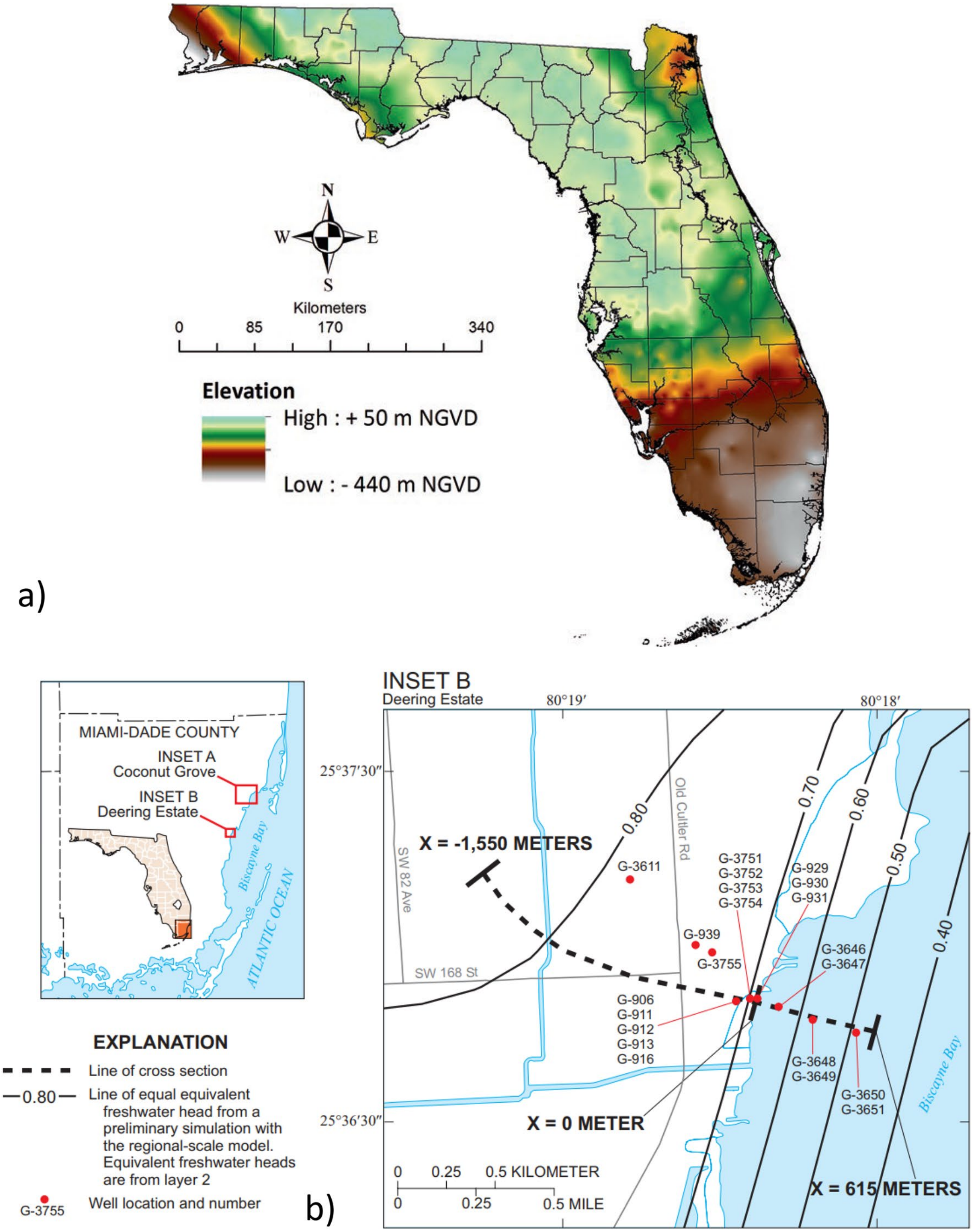


Fig. 3 Visualization of **a** depth to the top of the Floridan Aquifer System (Based on spatial data from the Florida Geological Survey) (Upchurch et al., 2019) and **b** the study area after Langevin (2001)

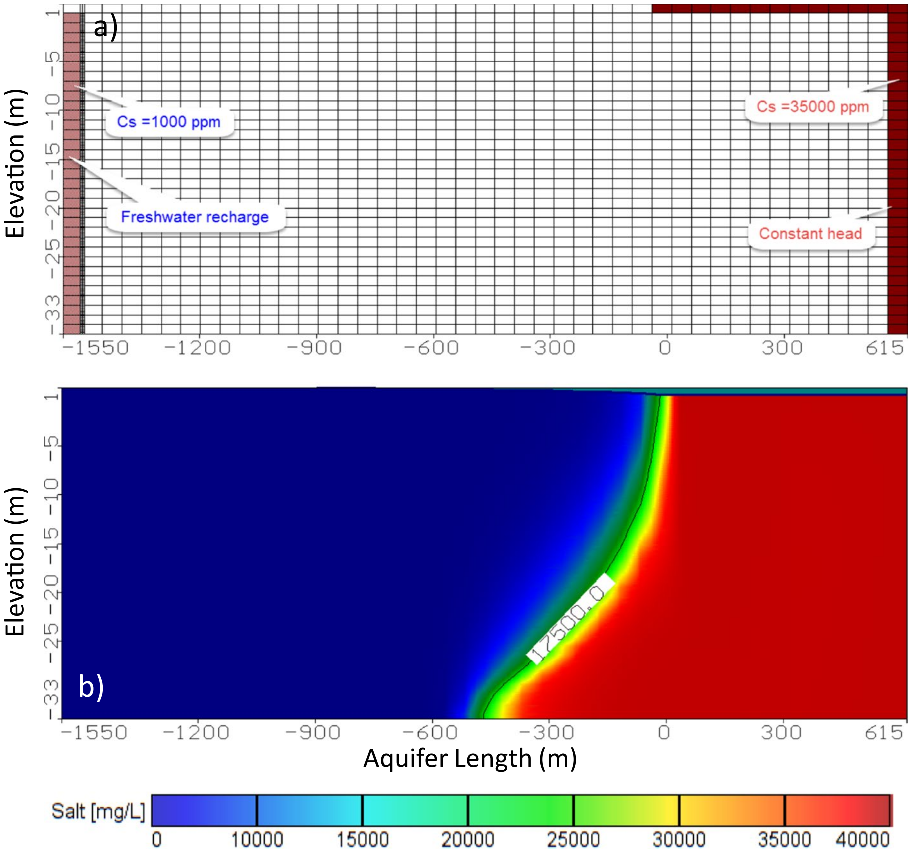


Fig. 4 Biscayne's aquifer **a** boundary conditions and **b** salinity results by SEAWAT for distribution of 0.5 isochlor (17,500 ppm)

Shoreline subsurface dams

Physical subsurface barriers (PSBs) are used to manage the SWI; the construction materials are impervious or semi-impervious along the shoreline (Hussain et al. (2019). The PSBs are an effective method and practical solution to tackle SWI in coastal aquifers although it is associated with high construction cost (Allow 2011). The installation produces a decrease or zeroing of the aquifer permeability, thus preventing the advancement of the seawater into the aquifers. The barriers are generally constructed perpendicular to the saline water wedge along the shoreline; they are classified as (i) subsurface dams (SDs), resting on the impervious aquifer bottom (Abdoulhalik and Ahmed 2017a); (ii) cutoff walls (CWs) placing at the aquifer upper part (Kaleris and Ziogas 2013). In particular, the SDs have an embedded base at the aquifer bedrock and an open crest at the upper part (Fig. 1).

The current study simulates the new SWI management method using a shoreline subsurface dam (SSD), positioned at a distance of 0 m from the shoreline (Fig. 2a). The study is applied to two cases: the test case (Henry problem) and the field scale aquifer (Biscayne aquifer). For the Henry problem the following heights were investigated: 5 cm, 10 cm, 15 cm, 20 cm, 25 cm, 30 cm, 35 cm, 40 cm, 45 cm, and 50 cm. This represents a dam height to aquifer thickness ratio of 0.05, 0.10, 0.15, 0.20, 0.25, 0.30, 0.35, 0.40, 0.45, and 0.50, respectively. The permeability of the dam was set to 1×10^{-5} m day^{-1}. The second case is the field scale aquifer of Biscayne aquifer in Coconut Grove, Florida, USA, the shoreline with heights reaching 3 m, 6 m, 9 m, 12 m, 15 m, and 18 m (Fig. 4) with dam height to aquifer thickness of 40 m below means sea level (msl), and the ratios reached 0.09, 0.18, 0.26, 0.35, 0.44, and 0.53 respectively.

Table 1 Boundary conditions, hydraulic parameters and solution methods of study cases

Study case	Henry	Biscayne	Unit
Aquifer parameter	Value		
Inland freshwater flux (Q_{in})	5.702	5	m^3 day^{-1} m^{-1}
Saltwater head (h_s) ($0 \le x \le 615$ m)	1	0.22	m
Seaside concentration (C_s)	35	35	kg m^{-3}
Landside concentration (C_L)	0	0	kg m^{-3}
Initial concentration (C_0)	1	1	kg m^{-3}
Hydraulic parameters			
Horizontal hydraulic conductivity (K_h)	864	1000	m day^{-1}
Vertical hydraulic conductivity (K_v)	864	100	m day^{-1}
Porosity (n)	0.30	0.20	
Freshwater density (ρ_f)	1000	1000	kg m^{-3}
Saltwater density (ρ_s)	1025	1025	kg m^{-3}
Specific Storage	0	$1*10^{-5}$	m^{-1}
Longitudinal dispersivity (α_L)	0	10	m
Transverse dispersivity (α_T)	0	1	m
Molecular diffusion coefficient(D*)	1.6295	0	m^2 day^{-1}
Recharge	0	380	mm $year^{-1}$
Model solution method			
Implicit finite-difference solver with the upstream-weighting	(GCG)	(GCG)	–
Initial time step	0.01	0.01	day
Time step	0.10	200	day

Henry's problem test case

The Henry problem is a benchmark for testing and studying the variable miscible variable-density problems in coastal aquifers (Henry 1964; Langevin 2003). The SEAWAT was applied to simulate the problem domain using the dimensions 2 m (length), 1 m (thickness), and 0.1 m (width) (Fig. 2a). The Henry model grids are divided into 80 columns, four rows, and 40 layers. Also, the square cell dimensions were set to be 0.000625 m^2, except the narrow of cells was set to be 0.00025 m^2 in the last column to locate the saline water hydrostatic boundary more precisely at the seaside. The benchmark problem is an isotropic, homogenous, and confined aquifer. The land side recharge of 10 cm width is 0.5702 m^3 day^{-1} with a concentration of 0 ppm; the seaside is assigned by hydrostatic saline water force 1 m by a constant head with a concentration of 35 kg m^{-3} (Guo and Langevin, 2002). The initial concentration is 0 ppm, and the simulations run with a time step of 0.01 days.

The idea behind the position of the subsurface dame being placed at the shoreline is to reduce the equivalent freshwater pressure head driving the saline intrusion from the sea toward the landward direction (Fig. 2a).

It is interesting to see the SWI results of the baseline case of Henry's problem using SEAWAT. Figure 2b presents the current codes SWI where the 0.5 isochlor intruded to 63.75 cm measured from the seaside. Moreover, the model agreed well with the other code solutions (Henry 1964; Hussain et al. (2019).

Real case study of Biscayne Aquifer

A rectangular domain was considered to represent the Biscayne aquifer in Deering Estate, Florida, USA. In some of the northern and western areas of the South Florida Water Management District (SFWMD), the surficial aquifer system provides additional water for the domestic, commercial, or small municipal supplies (FDEP, 2007). In coastal regions and in southern Florida, where the aquifer system is deeply buried (Fig. 3) and thick, the groundwater is saline, which limits the use for potable water supplies (Upchurch et al., 2019). The domain had an average length of 2165 m, a thickness of 33 m below mean sea level (msl), and a width of 1 m (Fig. 3). Eighty columns, one row, digitized the simulated model domain for the Biscayne aquifer using SEAWAT 4 code, and 33 layers corresponding to a cell dimension of 100 m × 1 m × 1 m in ($\Delta x * \Delta z * \Delta y$), respectively.

A constant head of 0.22 mm and concentrations of 35 kgm^{-3} were set along the seaside. A specified flux boundary condition and a null concentration were set on the land side (Fig. 4a).

The main hydraulic parameters of the Biscayne Aquifer were taken from Kohout (1964). Table 1 presents the boundary conditions, geologic and hydraulic parameters, and solution methods used as input values for the Biscayne aquifer at Deering Estate as reported by Langevin (2001).

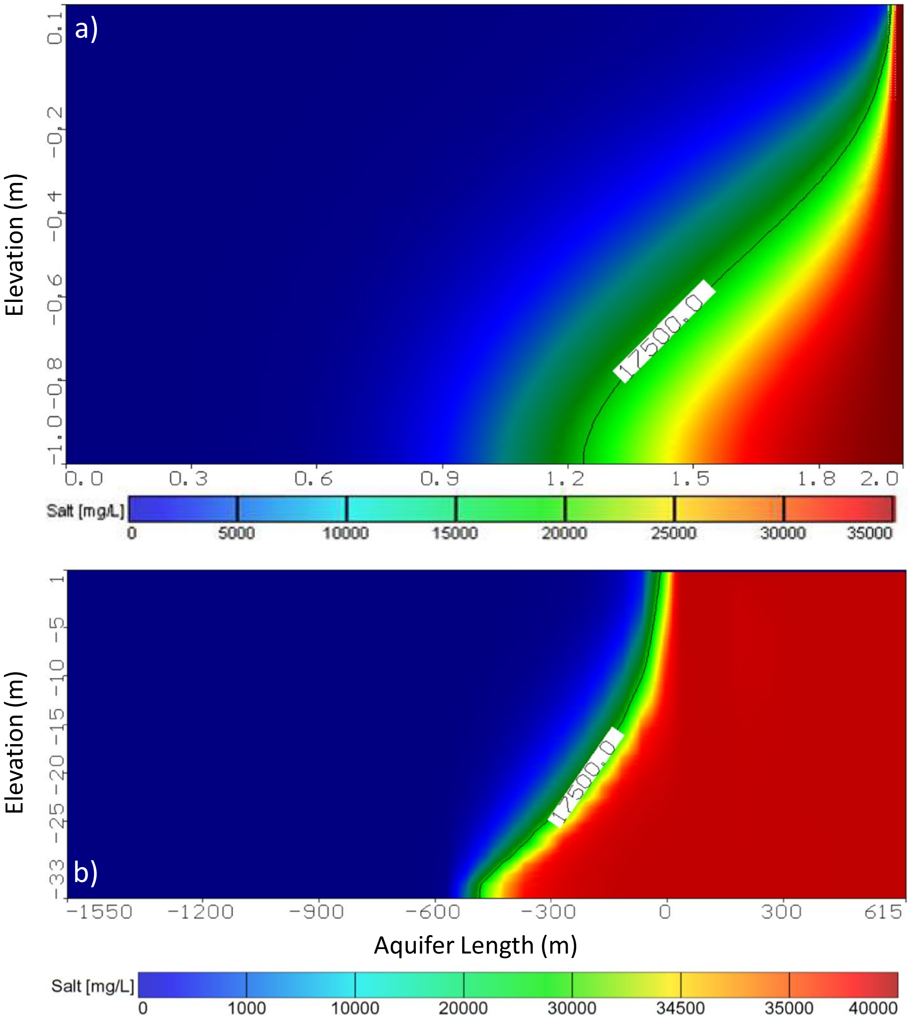
A comparison between the results of the current simulation of SEAWAT 4 under the steady state conditions for the Biscayne aquifer (Fig. 4b). A reasonable agreement was reached between the current model's results and those obtained by Langevin (2001) and Abd-Elaty et al. (2022b), where the intrusion reached 465 m from the shoreline measured at the bottom of the aquifer.

Results

Effect of sea level rise

This scenario represents the impact of SLR on SWI in coastal aquifers. The Henry problem was utilized as a simulation model, with a 8.50 cm rise in the saltwater head due to the hydrostatic force, representing the future impact of rising sea levels. For the baseline case, the model results showed that the 17,500 mg L^{-1} isochlor reached a depth of 76.25 cm within

Fig. 5 SWI distribution of 0.5 isochlor (17,500 ppm) for **a** Henry problem for rising saline water head by 8.50 cm and **b** Biscayne aquifer for rising saline water head by 85 cm



the bottom domain. The salt mass intrusion was measured at 0.51189 kg, compared to 0.39416 kg in the base case. This represents a 29.90% increase in aquifer intrusion (Fig. 5).

The SEAWAT simulation showed increase in the saltwater head to 85 cm for the Biscayne aquifer, reflecting the expected SLR in 2090 based on the regional sea level projections available from National Oceanic and Atmospheric Administration (NOAA) Inermediate (Sweet et al., 2017). The results indicated that the SWI reached a depth of 483 m for the 17,500 mg L^{-1} isochlor. The salt mass intrusion was also measured at 175,786 kg, compared to 173,484 kg in the base case, representing a 1.40% increase.

Effect of a subsurface dam

Henry problem

The shoreline subsurface dams (SSDs) were installed at the shoreline with dam height ratios (dam height from the aquifer base to the total aquifer thickness) of 0.05, 0.10, 0.20, 0.30, 0.40, and 0.50, respectively (Fig. 6).

The salt repulsion ($(C_o – \mathrm{C})/C_0$) was calculated to check the SPSDs efficiency (i.e., C_0 and C are the initial and salt concentrations at the given SSDs ratios, respectively). The positive sign indicates that the aquifer's salinity is lower than the baseline case, positively impacting the salt reduction. Conversely, the negative sign represents that the shoreline subsurface dam has a detrimental effect on SWI, possibly causing an increase in saltwater intrusion (Fig. 7).

The intrusion distance of the 17,500 mg/L isochlor was measured and found to reach different depths inland from the seaside, as follows: 75.25 cm, 74.50 cm, 72.50 cm, 69.75 cm, 66.50 cm, 61.75 cm, 55.25 cm, 45.25 cm, 28.25 cm, and 5 cm, calculated at the aquifer bottom from the seaside. This means that the salt repulsion reached + 1.10%, + 2.80%, + 5.30%, + 8.60%, + 12.90%, + 18.25%, + 25.20%, + 33.90%, + 44.45%, and + 57.45%, respectively, compared to the base case where the shoreline subsurface dams (SSDs) did not exist. For SSD height ratios of 0.05,

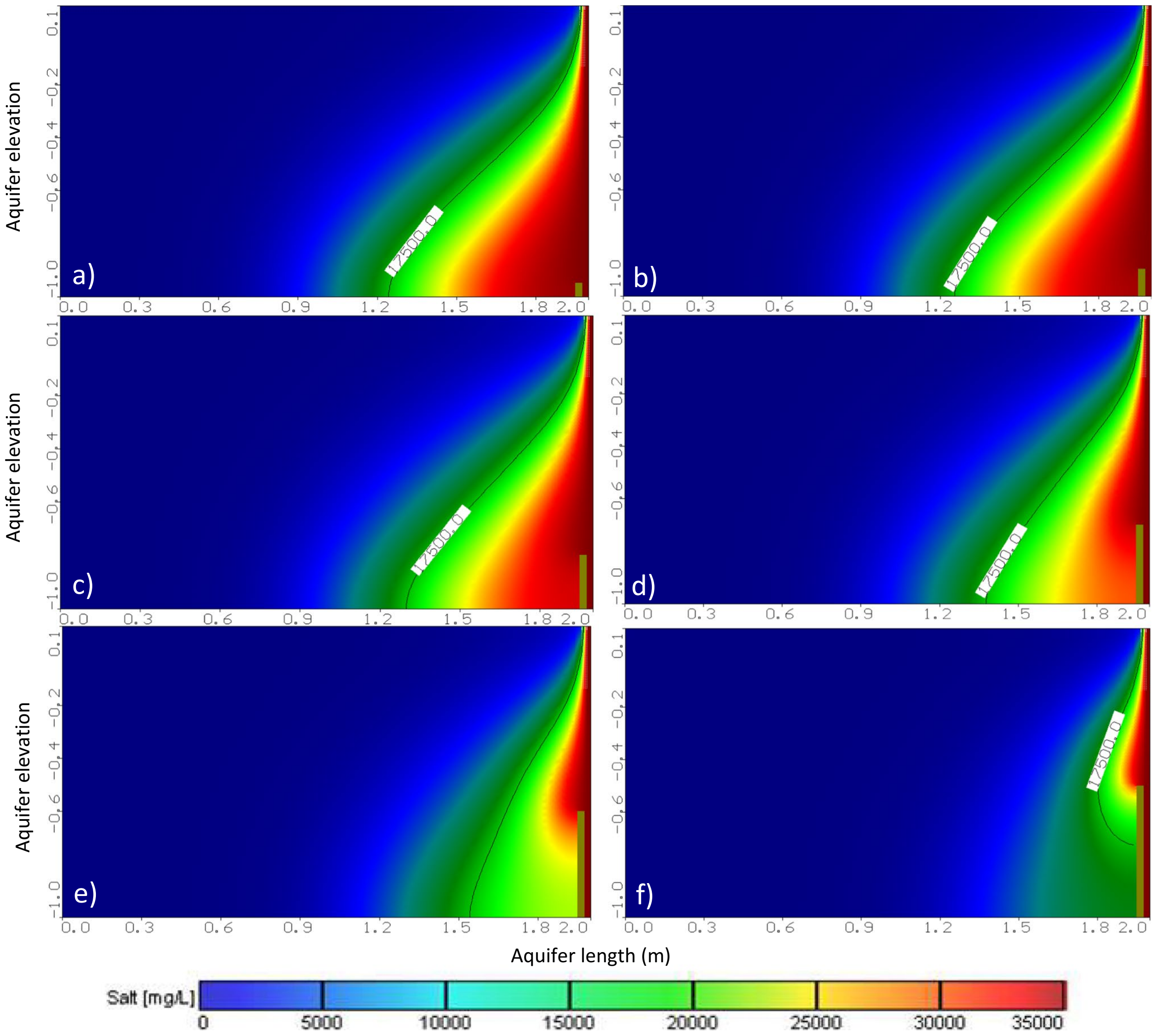


Fig. 6 Saltwater intrusion (SWI) for the Henry problem using shoreline subsurface dams (SSDs) height ratios of **a** 0.05, **b** 0.10, **c** 0.20, **d** 0.30, **e** 0.40, and **f** 0.50

0.10, 0.15, 0.20, 0.25, 0.30, 0.35, 0.40, 0.45, and 0.50. SSDs effectively delayed SWI, indicating their positive impact (Table 2).

Biscayne coastal aquifer

The Biscayne simulations examined the shoreline subsurface dams (SSDs) with heights reaching 3 m, 6 m, 9 m, 12 m, 15 m, and 18 m (Fig. 8) with dam height to aquifer thickness ratios of 0.09, 0.18, 0.26, 0.35, 0.44, and 0.53, respectively. The SSDs were consistently placed in the same position in all cases to assess the influence of the dam height on SWI.

The results indicate that using SSDs effectively moved the saline wedge at the seaside to distances of 175,530, 172,650, 170,072, 165,594, 157,448, and 143,462 m. The corresponding salt repulsion equals to + 0.70, + 1.80, + 3.25, + 5.80, + 10.45, and + 18.40% (Fig. 9). These findings reveal an exponential relationship between land width and repulsion and the effectiveness of salt repulsion achieved through SSDs installation (Table 2).

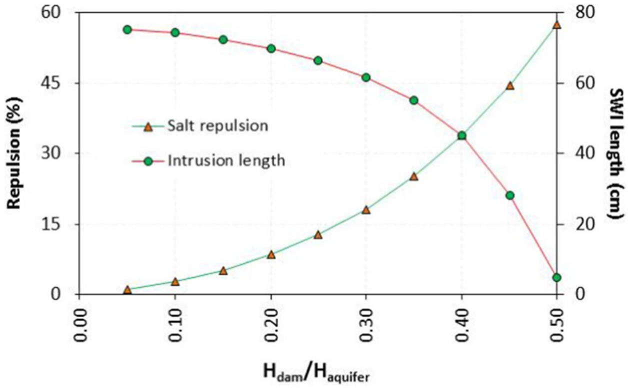


Fig. 7 Saltwater repulsion (%) and lengths of saltwater intrusion (SWI; cm) for the Henry problem under different shoreline subsurface dams (SSDs) height ratios

Discussion

The fresh groundwater deposited in coastal aquifers varies globally, especially where increasing populations put additional pressure on the available fresh surface water resources. The natural equilibrium between freshwater and seawater is unbalanced by over-pumping and accelerated SWI that impact the fresh groundwater resources and the land salinity (Abd-Elaty et al. 2021; Wu et al. 2020). Various measures were introduced to control SWI; nevertheless, their effectiveness depends on many factors, such as the aquifer, sea level rise, and the intensity of groundwater withdrawal (Abd-Elaty et al. 2022b; Kaleris and Ziogas 2013; Tansel and Zhang 2022). This study investigated the influence of the shore subsurface dams (SSDs) on the repulsion of the SWI. Subsurface barriers are extensively used to avert SWI around the world. Physical subsurface barriers (PSBs) prevent groundwater from moving toward freshwater aquifers and the sea (Chang et al. 2019). This study found that placing SSDs perpendicular to the seawater direction reduces SWI considerably. We hypothesized that increasing the SSDs height would increase the SWI repulsion further. After several simulations of SSDs with different heights, namely 3 m, 6 m, 9 m, 12 m, 15 m, and 18 m, placed at the shoreline in the Biscayne aquifer, the result show that salt repulsion increased for taller dams and reached 0.70%, 1.80%, 3.25%, 5.80%, 10.45%, and 18.40%, respectively.

This study's results agree with the findings of Harne et al. (2006). It showed that barriers closer to the shoreline or the sea face boundary mitigate the SWI in coastal aquifers. Abd-Elaty et al. (2019b) showed that the subsurface dams (SDs) must be installed above the initial saltwater intrusion line. Also, SDs are effective tools for SWI mitigation when increasing the dam depths and decreasing the distances from the seaside. Chang et al. (2019) showed that increasing the distance of the SDs from the coast seems more economical during construction as it needs shorter subsurface dams. However, it produces a larger inland soil salinity and pollutant accumulation. Wu et al. (2020) simulated the change in seawater volume using SEAWAT-2000 (Guo and Bennett 1998) for preventing SWI and enhancing safe pumping by impermeable subsurface barriers. The current results showed that the SSDs installed at the shoreline (distance from shoreline = 0) resulting in the maximum change in seawater volume. Although our findings prove to be technically promising in reducing SWI; still, the effectiveness of the SSDs should be carefully analyzed case by case, as the dynamic of the seawater and groundwater movement depends on several global and local factors such as seawater level rise and groundwater aquifer typology, the selection of SDs site is therefore an optimization task in order to achieve both the engineering cost and ecological environmental effects. (Chang et al. 2019). Therefore, to come up with more comprehensive and global recommendations, future studies should be focusing on testing the effectiveness of SSDs and other subsurface barriers considering different typologies of aquifer and climate conditions. Also, to see if such measures are economically justified, a detailed economic analysis is needed to be done in future studies.

Conclusions

Saltwater intrusion is the main problem of the fresh groundwater resources along coastal regions. The current study used SEAWAT to investigate the shoreline subsurface dam (SSDs) impact on groundwater salinity. The rise in sea levels increased the SWI by 29.90% and 1.35% for the Henry problem and the real case study of the Biscayne aquifer, respectively. The study presented a novel method for SWI management by the placement and construction of a SSDs along the shoreline distance of 0 m. The results indicated that SSDs are effective for SWI management. For Henry problem, the salt repulsion after installing SSDs at heights to aquifer thickness ratios of 0.05, 0.10, 0.15, 0.20, 0.25, 0.30, 0.35, 0.40, 0.45, and 0.50, respectively, reached + 1.10%, + 2.80%, + 5.30%, + 8.60%, + 12.90%, + 18.25%, + 25.20%, + 33.90%, + 44.45%, and + 57.45%. In the Biscayne aquifer case study, the SSDs reduced SWI by + 0.70%, + 1.80%, + 3.25%, + 5.80%, + 10.45%, and + 18.40% at SSDs height to aquifer thickness ratios of 0.09, 0.18, 0.26, 0.35, 0.44, and 0.53, respectively. This study introduced a new method exploring the SSDs implementation for SWI management. This solution should be integrated with other water conservation and management practices (e.g., rainwater harvesting, water recycling, efficient irrigation techniques) to support

Table 2 Intrusion length and repulsion percentage for the different cases using shoreline subsurface dams (SSDs)

Henry problem				Biscayne aquifer			
	Case	Intrusion (cm)	Repulsion (%)		Case	Intrusion (m)	Repulsion (%)
	Base	63.75	–		Base	465	–
	SLR by 8.50 cm	76.25	−29.90		SLR by 85 cm	483	−1.35
Shoreline subsurface dams (SSDs) height	5	75.25	+ 1.10	Shoreline subsurface dams (SSDs) height	3 m	483	+ 0.70
	10	74.5	+ 2.80		6 m	475	+ 1.80
	15	72.5	+ 5.30		9 m	463	+ 3.25
	20	69.75	+ 8.60		12 m	442	+ 5.80
	25	66.5	+ 12.90		15 m	373	+ 10.45
	30	61.75	+ 18.25		18 m	5	+ 18.40
	35	55.25	+ 25.20				
	40	45.25	+ 33.90				
	45	28.25	+ 44.45				
	50	5	+ 57.45				

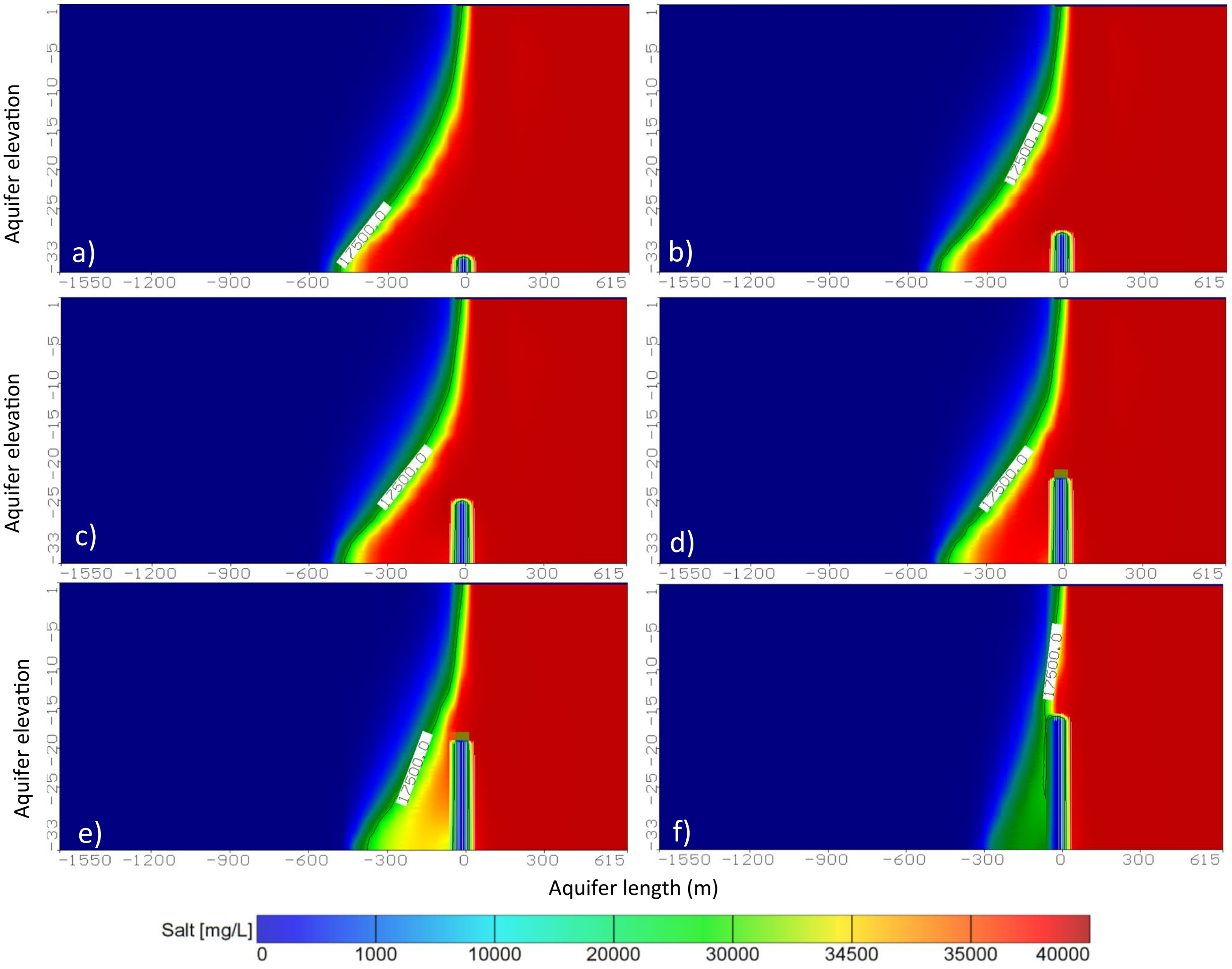


Fig. 8 Saltwater intrusion (SWI) for the Biscayne aquifer using shoreline subsurface dams (SSDs) height ratios of **a** 0.09, **b** 0.18, **c** 0.26, **d** 10.35, **e** 0.44 and **f** 0.53

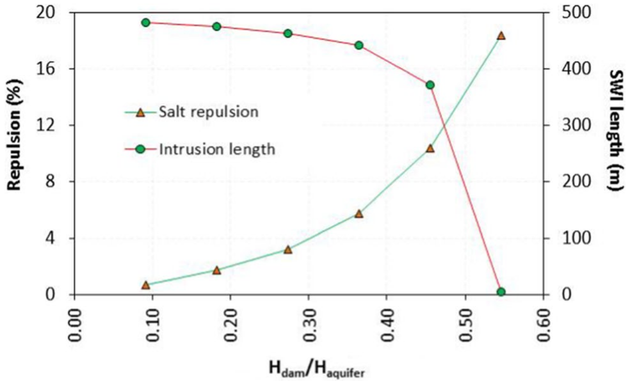


Fig. 9 Salt repulsion (%) and lengths of SWI (m) for the Biscayne aquifer under different shoreline subsurface dams (SSDs) height ratios

more sustainable water management in arid and semiarid regions strongly impacted by climate change.

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Authors' contributions IA-E and AA involved in conceptualization, methodology, investigation, formal analysis, and data curation. IA-E, AK, LP and AA involved in visualization, writing–original draft, writing–review and editing, resources, and supervision.

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