Environmental coastal management for groundwater resources using different aquifer bed slopes considering sea level rise risk

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Abstract

Todays, coastal groundwater management is a challenging research topic due the relevance of these water resources and the huge suffered risks due to the global change in the coastal areas. The geometrical features of coastal aquifers play a control role on salt water intrusion (SWI). Seawater level rise (SLR), groundwater over pumping and aquifer recharge reduction promoting SWI. All these key factors are considered are considered with two different numerical approaches defining schematic management criteria. The former approach adopts the well-known Henry's problem; the latter is based on the real study case of the Gaza aquifer (Palestine). Different aquifer bed slopes, hydraulic and physical methods, including physical subsurface barriers, earth fill, check dam, abstraction, and natural or artificial recharge are considered together with SLR, recharge reduction, and over pumping. The different scenarios are compared in terms of position of saltwater intrusion interface, measured as distance from the coastline at the aquifer bottom using the numerical code SEAWAT. Useful comparing tables and considerations are defined with the purpose to guide the preliminary selections of new management solutions for reducing the effect of the global change on coastal groundwater resources around the coastal world. The land side bed slope cases show more SWI than sea side and horizontal bed slopes. Cut-off walls and check dams are effective technique to manage SWI in horizontal bed aquifers slopes more than other slopes, also the subsurface dams, earth fill and recharge of freshwater are good methods to control the SWI in land bed slopes while abstraction of brackish water and combine of freshwater recharge with brackish water abstraction are better to mitigate of SWI in sea side slopes.

1. Introduction

The influence of climate change (CC) on the availability of high quality water resources is now widely recognized over the worlds (McDonald et al, 2011). In particular, the investigation, management and mitigation of saline water intrusion (SWI) in coastal regions are a recurrent environmental problem and affected by CC (Abd-Elaty et al, 2019a; Polemio & Zuffianò, 2020). Around 70% of the world's population lives in coastal areas where very high population density is observed; this percentage shows widespread increasing trend causing the increase of water demand (McDonald et al, 2011; **Wada er al, 2016**, Abd-Elaty et al, 2021a)). Combination of increase demand and CC exposes coastal groundwater to increasing salinization risks for SWI, especially in water scarce regions (Polemio & Zuffianò, 2020). SWI can worst due to human activities and natural process by reduction in groundwater recharge, over pumping, tidal effects, ocean and seismic waves, dispersion effects, and CC including sea level rise (SLR) (Bear et al., 1999). SWI managment becomes necessary in all these cases for the coastal groundwater protection from salinization (**Abd-Elaty et al, 2021b**).

Around 95% of the world's coastal areas will be severely affected by SLR by 2100, increasing the risk of flooding and SWI (**Agren and Svensson, 2017**). The rise of global mean sea level is expected continues into the future; the most recent best assessment (IPCC, 2021) is 0.28-0.55 cm by 2100 while it was 18 to 58 cm in 2007 (IPCC, 2007), with a rate of rise 8 to 16 mm/year during 2081 to 2100 (IPCC, 2014). IPCC

(2007**and 2014**) indicated that the rainfall has increased in most mid-latitudes and high latitudes, while it has decreased in many mid-latitudes and subtropical arid regions in the 20th century.

The use of numerical modeling supporting the design and selection of management criteria is a reliable choice in the case of groundwater at salinization risk (Polemio & Zuffianò, 2020). Abd-Elhamid et al., (2016) investigated the effect of different SLR scenarios on the coastal region of Nile delta, Egypt using SEAWAT. The results showed that the groundwater salinity have a significant effect by SLR. **Mahmoodzadeh and Karamouz (2019)** indicated that the storm surge has a short-term SWI influence while the SLR has a relevant long-term SWI influence on fresh groundwater of a fully heterogenic coastal aquifer using the code SUTRA. Optimization of freshwater abstraction and management of salinization risks are the main management challenges for water supply decision makers (**Bear and Cheng, 1999**). Different techniques have been applied and developed to SWI management (**Todd, 1974;** Polemio & Zuffianò, 2020). Hydraulic Barrier (HB) methods use injection by wells or infiltration by ponds of low-quality fresh water or abstraction of saltwater to permit the safe discharge of fresh groundwater of high quality. Artificial recharge technique is man's planned operation used to increase the fresh groundwater heads (**Bear, 1979**). This method is applied to the aquifer through the infiltration by surface ponds or recharge wells (**Roger, 2010**). Abd-Elhamid and Javadi (2008a**)** applied the abstraction and desalination of brackish water, and recharge to control SWI in coastal aquifers. Abd-Elhamid and Abd-Elaty (2017**)** tested an effective management method using SEAWAT code, which consists in the treatment of wastewater to be used for artificial recharge after abstracted and desalination of brackish water and. Abd-Elaty et al, (2020a) used a numerical method for the Gaza Strip aquifer (Palestine) using different methods and scenarios to control SWI. The results indicated that the recharge of treated waste water could mitigate the SWI compare with the other method using the abstraction of brackish water, also the combine of the two methods is the best choice. Abd-Elaty et al, (2021c) simulated and management of SWI in Nile delta using combination of recharge and abstraction well system. The results showed that this technique was effective to mitigate the contamination of groundwater in coastal regions.

Physical Subsurface Barrier (PSB) methods use cut-off walls (CWs) or subsurface dams (SDs), also sheet piling and earth fill. The barrier creates a discontinuity between the coastal brackish portion of the aquifer and the inland portion, where fresh groundwater can be safely discharged (Javadi et al., 2015). **Abd-Elaty Et al. (2019b)** highlighted that the PSB technique is used to mitigate the SWI in coastal aquifers; also the cut-off walls are effective to control the SWI more than subsurface dams. Roger et al., (2009) investigated the dynamics of residual saltwater by construction of cut-off walls. Abdoulhalik et al. (2017) applied the mix of PSB by a semi-permeable subsurface dam and an impermeable cut-off wall, the results showed that mixing PSB is effective to control of SWI more than the single methods. **Abd-Elaty Et al. (2019b)** simulated PSB systems efficiency to control SWI due to SLR and aquifer recharge reduction. The simulation showed that PSB is effective to manage in coastal aquifers salinity.

Land reclamation in coastal zones is usually occurs by extension of the shore line towards the sea side using the artificial filling of appropriate soil. The natural aquifer recharge by precipitation takes place over the reclaimed new land. Guo and Jiao (2007 and 2009**)** evaluated with simple calculations the effect of the land fill reclamation on the groundwater heads and SWI in coastal areas. The results indicated a water table rise on old land and the shift of the salt -fresh water interface. Abd-Elhamid et al, (2020) developed a numerical study usin SEAWAT code to investigate the effect of using fill width on management of SWI in coastal aquifers considering of sea level rise. Different earth fill solutions were compared for control SWI with different SLR. The authors showed the advantages of this solution.

In this current study the SEAWAT is used to provide a better understanding and a quantitative assessment of different management solutions using two approaches. The former approach adopts the well-known Henry's problem; the latter is based on the real study case of the Gaza aquifer (Palestine). On these bases, advantages of each solution are discussed.

2. Materials And Methods

The general characteristics, hypotheses, main data, and boundary conditions concerning the numerical code, the Henry’s problem and the selected real study area of coastal aquifer the bed slope are described.

2.1 Variable density Model

The finite difference model of SEAWAT 2000 (version 4) was applied and simulated the SWI in the current coastal aquifers. This code is couple miscible variable-density process of MODFLOW (Harbaugh, et al., 2000) and MT3DMS (Zheng and Wang, 1999) into a single program.

The VDF process solves the following variable density groundwater flow equation (Guo and Langevin, 2002):

$$\nabla\left[\rho * \frac{\mu_o}{\mu} * K_o\left(\nabla * h_0 + \frac{\rho-\rho_f}{\rho_f} * \nabla Z\right)\right] = \rho * S_{,S,0}\left(\frac{\partial h_O}{\partial t}\right) + \theta * \left(\frac{\partial \rho}{\partial C}\right)\left(\frac{\partial C}{\partial t}\right) - \rho_S * q'_S$$

…………………. (1)

The IMT process solves the following solute transport equation (Zheng and Wang, 1999):

$$\frac{\partial\left(\theta C^k\right)}{\partial t} = \frac{\partial}{\partial x_i}\left(\theta D_{ij}\frac{\partial C^k}{\partial x_j}\right) - \frac{\partial}{\partial x}\left(\theta v_i C^k\right) + q_s C_k^s + \sum R_n$$

……………………………………………… (2)

where: ρ is the density of saline water [ML^{-3}]; μ_o is the dynamic viscosity of freshwater [$ML^{-1}\ T^{-1}$]; μ is the dynamic viscosity of saline groundwater [$ML^{-1}\ T^{-1}$]; K_0 is the hydraulic conductivity tensor of material saturated with the reference fluid [LT^{-1}]; h_0 is the hydraulic head [L]; ρ_o is the fluid density [ML^{-3}] at the reference concentration and temperature; $S_{s,0}$ is the specific storage [L^{-1}], t is time [T]; θ is porosity [-]; C is salt concentration [ML^{-3}]; q'_s is a source or sink of fluid with a density of ρ_s [T^{-1}], C^k is dissolved concentration of species [ML^{-3}]; *Dij* is the hydrodynamic dispersion tensor [L^2T^{-1}]; v_i is seepage or linear pore water velocity [LT^{-1}]; C_s^k is the concentration of the source or sink flux for species k [ML^{-3}]; ΣR_n is chemical reaction term [$ML^{-3}T^{-1}$].

2.2 Hypothetical Case Study of Henry's problem

Known Henry's problem (Henry, 1964) is used in the current simulation with domain of 2 m in horizontal (X-direction) to 1 m in vertical (Z-direction) with width of 0.10m (Y-direction). The model was subdivided into 4 row, 80 columns and 40 layers. The flow and contamination boundary conditions of this problem were assigned by hydrostatic saline water pressure at the sea side of the model (right side) which represented the seaside by density (ρ_s) of sea or saline water, equal to 1025 kgm^{-3}, at a constant salt concentration (C_S) of 35 kgm^{-3}. The aquifer side (left side), which represents the inland boundary where fresh groundwater is observed, corresponds to a recharge well with a constant inflow rate ($Q_{in\ or}\ Q_f$) of 0.5702 m^3day^{-1} at constant salt concentration (C_F) by zero kgm^{-3}. The top and bottom boundaries of the model are assumed to be no-flow boundaries (**Figure.1a)**. The hydraulic parameters and solution methods for Henry's problem is presented in **Table.1**.

Table 1
Boundary conditions, hydraulic parameters and solution method for the Henry's problem

Hydraulic Parameters	**Value**	**Dimension**
Porosity (n)	0.30	-
Freshwater density (ρ_f)	1000	Kg m^{-3}
Saltwater density (ρ_s)	1025	Kg m^{-3}
Specific storage	0	m^{-1}
Longitudinal dispersivity (α_L)	0	m
Transverse dispersivity (α_T)	0	m
Molecular diffusion coefficient(D*)	1.6295	$m^2\ day^{-1}$
Vertical and Horizontal Hydraulic conductivity (k) (Isotropic)	864	m day^{-1}
Model Solution Method	**Value**	**Dimension**
Implicit finite-difference solver with the upstream-weighting	(GCG)	-
Number of column (Δx=2.50 cm)	80	-
Number of raw (Δy=2.50 cm)	40	-
Initial time step	0.01	day

The problem results were verified using the results from different methods and codes. Ghyben-Herzberg model is the first model for SWI presented by Ghyben (1889**)** and Herzberg (1901) based on sharp interface. Henry (1964**)** presented the first semi-analytical solution considering the effect of dispersion. The problem was successfully studies by **Pinder and Cooper** (**1970)**, Frind (1982**)**, Rastogi et al. (2004) and Fahs et al. (2018). Recently the numerical models were applied to the problem (**Miao at al., 2019); Zhao at al., 2020; Abd-Elaty et al. 2021)**.

The seawater intrusion distance (SID) is usually represented by the 0.5 equi-concentration (isochlor) line and measured along the bottom boundary from the aquifer seaside **(Figure 2)**. SID reached 64.50 cm in the case of SEAWAT. The results of **Figure 1b** show good agreement between SEAWAT and other codes by Henry (1964**)**, Intera (1979**)**, Voss and Souza (1987**)**, Simpson and Clement (2004**) and** SVCHEM (2018**)**.

2.3 The real case study of the Gaza aquifer

Figure 2a is showed the location map for the Gaza Strip (GS) which is selected as areal case study with a total area of 365 km^2 and a coastline length of 45 km along the Mediterranean Sea, the area width ranges from 6 at the north to 12 km at the south, the average width of the study area of 9 km (Abu Heen and Muhsen, 2016). GS is the most highly populated areas in the world (PCBS, 2000), where the annual population growth is approximately 2.9% (**PCBS, 2014d**) with density reached about 4822 capitakm^{-2} in 2015 (**PCBS, 2015**).

Two formations can be distinguished in the area. The Tertiary “Saqiya formation” is located below of the GS aquifer and constitutes the aquifer bottom. It is composed by impervious clay shade rocks with thickness ranging from 400 to 1000 m. The Quaternary deposits, covering the Saqiya formation, constitute the Gaza aquifer, with thickness about equal to 160 m. These deposits include loose sand dunes (Holocene) and the Kurkar group (Pleistocene). The top of the Pleistocene deposits is covered by Holocene deposits with thickness of 25m; the average thickness of the Kurkar Group sequence reaches from 200 to 120 m in the south and the north respectively (**Figure 2b)** (**Abu Heen and Muhsen, 2016**).

The climate of GS is semi-arid where the average precipitation ranges between 200 to 400 mmyear^{-1} (**PWA, 2001**, **2013**), and the evaporation rate is about 1400 mm year^{-1} (**SWIMED, 2002**).

The average water consumption was 79.80 Liters per Capita per Day (L Capita $^{-1}$ day^{-1}) in 2014 (PWA, 2015). The estimated domestic water was 88.47 MCM yr^{-1} about 96% from local water resources and 4% was purchased from Mekorot (Israel) (**PWA**, 2015), while agriculture water was about 95.3 million cubic meters per year (MCM yr^{-1}) (**PWA**, 2014). The amount of irrigation returns flow was estimated to be 20% of the total pumping (Melloul and Collin, 1994) or between 22 to24% of the total irrigation water (**Ghabayen** and Salha,2013).

The aquifer flow by recharge was estimated to range between 100 to 120 MCM yr^{-1} from rainfall (main source), artificial recharge ponds, agriculture return flow and wastewater leakage (**PWA 2013)** (Abualtayef et al., 2017). The lateral inflow to the study area was estimated between 15 to 30 MCM yr^{-1} (**Metcalf and Eddy, 2009).** The overall water supplies losses was estimated by 45% (35% by physical losses and 10% by unregistered connections) (**PWA**, 2013).

Desalination appears to be the only viable alternative to meeting the Gaza Strip's drinking water needs for the Coastal Urban Water Plan and the Palestinian Water Authority (PWA). The water supply by desalination was about 6 $MCMyr^{-1}$ (**PWA, 2015**). Around 95% of drinking water purposes in GS depend on the desalination from small brackish water plants and home filters (**Abu-Amr and Mayla, 2010**) in addition to 10 MCM received from Mekorot water company (Shatat et al., 2018). For the long-terms, the volumes of desalinated flows were estimated by Technical Engineering Consulting Company (TECC) in GS to rise and expected by 10.57, 13, 49.13, 71,96 and 129,74 MCM by 2012, 2015, 2020 and 2035 (**PWA**, 2011).

Around 70 to 80% of the domestic wastewater generated in the Gaza Strip is discharged without treatment into the environment (Baalousha, 2008), in additional the total volume produced by wastewater plants is about 41 MCM yr^{-1} in which about 8 MCM yr^{-1} was treated and 33 MCM yr^{-1} disposed to the Mediterranean Sea (**PWA, 2012**). In 2015, this volume was estimated to 48.54 MCM (ARIJ, 2015c; PCBS, 2013c, 2015c).

Groundwater is the main water supply in GS by 95%, this water is contaminate by SWI (Qahman and Larabi 2006). For the natural conditions, the fresh groundwater flow in GS is from east to west, towards the Mediterranean Sea (Mercado, 1968). The groundwater deficit was between 40 to 60 MCM yr^{-1} for increasing the abstraction (**PWA**, 2013) and Over 96.4% of the Gaza coastal aquifer (GCA) pumping excess accepted standards (**PWA**, 2015) while the sustainable yield of Gaza coastal aquifer (GCA) is only 55 MCM yr^{-1} (**PWA**, 2011). Overall abstraction has increased continuously over the past decade from 136 MCM in 2000 to 174 MCM in 2010 (PWA, 2010a). Sarsak (2011), Sarsak and Almasri (2013) Vand Abualtayef et al. (2017) were esimulated the GCA using SEAWAT code for the current situation and the future scenarios, the results showed that the aquifer is sensitive to SLR and the treated wastewater, desalination and storm water infiltration are the future resources for SWI management in GS.

Table 2 summarises the input parameters used for the GCA modelling (Sirhan and Koch, 2013). The GCA transmissivity ranges between 700 to 5,000 m^2day^{-1} with hydraulic conductivity K_x and K_y between 20 to 80 m/day. The aquifer effective porosity is 35%, the specific yield ranges between 0.15 to 0.30 while the specific storage was 10^{-4} m^{-1} (**PWA, 2000b**). The longitudinal dispersivity (α_L) and transverse dispersivity (α_T) were 50 m and 0.10m respectively (Qahman, 2004).

Table 2
Hydraulic parameters and boundary conditions for Gaza aquifer modelling

Parameters	**Confined aquifer**	**Unconfined aquifer**	**Unit**
Horizontal hydraulic conductivity (K_h)	0.20	34	m day^{-1}
Vertical hydraulic conductivity (K_v)	0.02	3.40	m day^{-1}
Effective Porosity (n_e)	0.30	0.25	—
Total Porosity (n_T)	0.45	0.35	—
Freshwater density (ρ_f)	1000	1000	Kg m^{-3}
Saltwater density (ρ_s)	1025	1025	Kg m^{-3}
Specific Storage	10^{-5}	10^{-4}	m^{-1}
Longitudinal dispersivity (α_L)	50	12	m
Transverse dispersivity (α_T)	5	1.20	m
Molecular diffusion coefficient(D*)	0.0001	0.0001	m^2 day^{-1}
Boundary Condition	**Value**		**Unit**
Lateral freshwater flux (q_{in})	10		m^3 $day^1 m^{-1}$
Well abstraction rates	20.75		$m^3 day^1 m^{-1}$
Vertical recharge and return flow	416.50		$mmyear^{-1}$
Saltwater head (h_s) ($0 \le x \le 1400$ m)	zero		m
Sea side concentration (C)	35000		mg L^{-1}
Land side concentration (C)	1000		mg L^{-1}

The SEAWAT model of GCA uses 180 columns, one row and 10 layers for active cells. The model cross section is presented in in **Figure 3a**: it is 9000 m in length in x-direction; topography range between +58 to -180 m above mean sea (MSL). The hydrostatic pressure is assigned at sea side to represent the saline water head while the constant flow on the inland side is assigned with freshwater using well modules in order to represent the freshwater recharge (**Figure 3b**). A constant concentration of 3500 ppm is fixed at seaside while the landside a value of zero ppm is applied (**Figure 3c**).

Figure 3d is presented the distribution of salinity by Total dissolved solids (TDS) in the GCA for the current situation (base case). The initial time of 0.001 day and time step of 200 day. The calibration process is done using the method of trial and errors between the calculated values by SEAWAT (current model) and the other values published by previous studies. The current results are compared with Sarsak (2011) **and Abd-elaty et al. (2020a)**. The results showed a good match between the other two models. The 0.5 isochlor reached a distance of 3177m from the sea shore line in the horizontal case. The calibrated model is used in validation process to simulate different scenarios to control SWI intrusion. The total salt mass reached 5,718,820 kg.

2.4 Proposed scenarios

The study simulated three cases of bed slopes: seaside slope, with slope by 10 (horizontal):1(vertical); horizontal bed and landside slope, by 10:1 as (**Figure 4a, c and e)**. SID reached 59.50, 64.50 and 65.125cm respectively, as presented in **Figure 4b, d and f**. The results showed that the bed slope of aquifer has a great effect of saltwater intrusion, in which the land side slope has more intrusion than horizontal and seaside slopes.

3. Results And Discussions

The model was carried out to simulate the effect of SLR and reduction in fresh groundwater recharge, also the management scenarios were applied for physical subsurface barriers, land reclamation SWI, abstraction and recharge, and check dams methods for Henry's problem and the real case of Gaza coastal aquifer.

3.1 Effect of SLR and recharge reduction on SWI for Henry's problem

Tide log data showed sea level increases of 1 mm per year over a period of 2 centuries before 1990, while the satellite and tide log data showed an increase of 3.2 mm per year after 1990(Church and Clark, 2013**)**. The trends of SLR and decrease the flow to the aquifer are due to CC in large world regions, including the Mediterranean Sea (IPCC, 2021).

Figure 5 shows the results in the case of SLR and recharge reduction for the three cases of bed slopes of seaside, horizontal and landside. The SEAWAT is used for the hypothetical case of Henry's problem to simulate the combine of SLR and reduction in aquifer recharge for the tree cases of bed slopes with the reference to the hypothetical steady or initial natural conditions, considering a sea level head by 100 cm at the ocean side and a constant recharge to the aquifer by rate of (Qin) 0.5702 m^3 day^{-1} m^{-1} at the land side. The expected saline water rise was simulated by increasing sea water level at the seaside by 3, 6, 9, 12 and 15 cm while the freshwater recharge was decreased by 5, 10, 15, 20 and 25%. The Salt rise or repulsion **(%)** in aquifer is calculated by this

% **Salt rise or repulsion = $(C_0\text{-}C)/C_0$**

Where C_0 is the initial aquifer salt concentration and C is the aquifer salt concentration at the proposed scenario, the negative sign (-) means that the salinity in aquifer is increases while the positive sign (+)

means that the salinity is decreased.SID resulted 65, 72.50, 77.375, 82.625 and 90 cm compared with 59.50 cm at base case for seaside slope. The salinity was increased to reached -14.45, -30.34, -48.09, -67.84 and -89.50%. The horizontal slope is showed that the intrusion is reached 70.125, 77.50, 84.25, 92.125 and 100 cm compare with 64.50 cm at base case, the salinity increase is reached -15.03, -31.62, -50.18, -70.76 and -93%. Moreover, the intrusion is reached 72.50, 80, 92.50, 97.25 and 105.25 cm compare with 65.125 cm at base case with increase in salinity reached -16.07, -33.87, -66.13, -75.45 and -98.46%. The results showed that SLR has a negative impact on aquifer salinity and increase SWI and the landside slope increases the SWI more than horizontal and sea side bed slope where the average percentage of increasing SWI was -57.99, -52.12 and -50.05%.

3.2 Management of SWI for Henry's problem

Management of SWI is carried out using different hydraulic and physical methods including physical subsurface barriers, earth fill, abstraction, recharge and combination between abstraction and reached methods and check dam. The hypothetical of Henry's problem and the real case study of coastal Gaza aquifer were simulated at combine of SLR and reduction in recharge and over pumping.

3.2.1 Effect of physical subsurface barriers

The simulated solution was applied on the three types of bed slope using two physical subsurface barriers with the previous parameters and boundary conditions. The former is a cut-off wall and the latter is a subsurface dam.

Different scenarios were applied and analysing the SWI for different wall depths and dam heights by 15, 30, 45 and 60 cm.

The results showed that SUI reached 85.25, 75.125, 62 and 49.75 cm with reduction in salinity of +6.23, +19.38, +34.26 and +47.64% for cut-off wall. Based on subsurface dam results, SUI was 82.625, 75, 70.25 and 69 cm with salinity reduction equal to +3.56, +10.14, +13.43 and +14.38% (Table 3).

The horizontal slope results showed that SWI reached 92.25, 79.50, 67 and 50 cm with salinity reduction of +9.97, +24.79, +35.31 and +50.34%, respectively, measured along the bed. The subsurface dam results showed that SWI reached 92.625, 81.25, 72.50 and 70.50 cm with salinity reduction of +3.44, +10.58, +17.12 and +18.66%.

For landside slope SWI reached 100, 87.75, 71 and 50.50 cm with salinity reduction of +6.07, +19.58, +36.27 and +52.71%. SUI reached 98.75, 87.25, 75.50 and 70.125 cm with salinity reduction of +3.21, +10.58, +18.52 and +21.90% for subsurface dam.

The relation between the SWI lengths (XT) and the physical barriers method for cutoff wall and subsurface dam for different bed slopes are presented in Figure 6a and 6b.

3.2.2 Effect of land reclamation SWI

The technique of earth fill is simulated by increasing the model width to 220cm using 20 cm of fill with changing the fill permeability by -70, -55, -40 and -25% to reach 734.40, 604.80, 345.60 and 216 m per day for the three bed slopes. The 0.5 Isochlor is reached a distance of 67.625, 62.50, 57 and 41.50cm from the sea side with reduction in salinity reach +3.39, +9.85, +16.67 and +33.78% respectively. The intrusion length of 0.5 equi-concentration line is reached 74.75, 69.50, 61.75 and 47.50 cm respectively are measured along the bed with salinity reduction is reached +6.83, +12.62, +21.18 and +34.96% for horizontal bed slope. Moreover the landside slope, the 0.5 Isochlor is reached 77.50, 72.50, 65 and 50cm measured along the bed with salinity reduction by -8.78, +14.09, +22.13 and +35.43%.

The relations between the intrusion length (XT) and the fill earth methods for different bed slopes are shown in Figure 6c.

3.2.3 Effect of abstraction and recharge methods

This technique used three cases to investigate the effect of the aquifer abstraction and recharge on SWI: (a) abstraction of saline groundwater, (b) recharge with waste water or storm water, and (c) combination of both. Different settings of aquifer bed slopes were also examined and assessing the SWI improvement in terms of SUI and salt repulsion. The recharge well was located at 1m from shore line with depth -0.40m form the model top, while the abstraction well was simulated at 0.40m from shore line with depth -0.85 from the surface of the hypothetical case with recharge and abstraction rates of 0.11404 m^3 per day per meter. The intrusion of 0.5 isochlor for seaside slope reached 81.25, 74.50, 66.75 and 60.25 cm with salinity reduction by +14.38, +26.17, +35.92 and +44.04% with abstraction of saline groundwater.

The results of wastewater recharge showed that SUI is reached 85.75, 80.25, 77.75 and 75 cm with reduction is reached +3.05, +6.21, +9.26 and +12.02%.

The combination of saline water abstraction and freshwater recharge showed that SWI reached 77.375, 66.50, 58 and 53.75 cm with reduction in salinity of +17.51, +31.14, +41.24 and +48.33%, respectively.

The results of abstraction showed SUI values of 90, 80.75, 73 and 65.75 cm with salinity reduction of +14.17, +26.11, +36.17 and +44.63% for horizontal slopes. The recharge results are indicated that the SWI is reached 97, 92.75, 89.50 and 85 cm with salinity repulsion is reached +2.69, +5.57, +8.45 and +11.19%. Moreover for combine of abstraction and recharge, the intrusion is reached 86.75, 75.125, 67.125 and 61 cm with repulsion is reached +17, +30.66, +41.12 and +48.75%.

SWI results for landside slope and abstraction are 95, 85, 75.50 and 68.25 cm with repulsion of +14.05, +26.17, +36.59 and +45.48% at seaside slope. The recharge results are 102.25, 98.75, 95 and 92.25 cm with repulsion equal to +2.44, +5.11, +7.85 and +10.53% while combining abstraction and recharge reached 92.25, 80.25, 71.25 and 65 cm with repulsion of +16.65, +30.42, +41.25 and +49.32%, as presented in Figure 6d, 8e and 6f.

3.2.4 Effect of check dams

This case represents the effect of check dams on SWI. The head of dam is changed by 17.50, 18, 18.50 and 19 cm. SUI reached 51.16, 39.27, 30.81 and 24.56 cm respectively. The repulsion is +21.39, +39.67, +52.66 and +62.27% for sea side slope. The results of horizontal slope are reached 83, 67.625, 55.75 and 47.25 cm while the repulsion is reached +22.73, +42.35, +55.99 and +65.77%. For land side slope, SUI reached 67.38, 52.38, 39.24 and 35.19 cm with repulsion is +20.13, +37.92, +54.79 and +62.45%m, as presented in Figure 6g.

The results showed that the average values for SWI repulsion were 26.88, 30.09, and 28.66% using cut-off wall and reached +10.38, +12.45 and +13.55% using subsurface dam for the three aquifer bed slopes (sea side, horizontal and land side respectively) which indicate that the cut-off walls are more effective for horizontal bed slopes while the subsurface dam for land side slopes. The use of land fill is a good method in land side slopes where the SWI repulsion reached +15.92, +18.90, and +20.11%.

The use of hydraulic methods of freshwater recharge led to repulsion of +30.13, +30.27 and +30.57% while using abstraction of brackish water to +7.64, +6.97 and +6.48%, moreover combination of freshwater recharge and brackish water abstraction led to -34.55, -34.38 and -34.41%. These results indicated that recharge methods are more effective in the case of land side bed slope while abstraction and combination are more effective in the case of sea side bed slope. The check dam led to SWI repulsion of +44, +46.70 and +43.82% which indicates that check dams are effective in horizontal bed slopes.

3.3 Effect of SLR and natural recharge reduction on SWI for the Gaza coastal aquifer

The effects of SLR and recharge reduction on GCA were simulated changing boundary conditions and hydrogeological parameters. SLR consists of a change of saline water head equal to 23.60 cm by 2050. The natural recharge reduction was simulated with reduction of precipitation and lateral flow by 25%. The practical effect of these hypothesis reduced the recharge contributions to 36.15 and 19.35 MCM yr^{-1} respect to 48.20 and 26.60 MCM yr^{-1} at base case.

The aquifer return flow by leakage from for domestic, agriculture and wastewater sectors should increase to reach 62.56, 16 and 21.89 MCM yr^{-1} for each sector, to be compared with 28.50, 16 and 9.98 MCM yr^{-1} respectively. This should be due to abstraction increase, which should be necessary to satisfy the increasing water demand. The total return flow should reach 100.45 MCM yr^{-1} compare with 54.48 MCM yr^{-1} at base case.

The total of natural recharge and return flow could be considered equal to 136.60 MCM yr^{-1} compared with 102.68 MCM yr^{-1} at base case.

The groundwater abstraction should increase to reach 288.52 MCM yr^{-1}, to be compared with 175 MCM yr^{-1} at base case.

Table 4 summaries the entire simulated modifications al 2050. The results of equi-concentration line 35000 ppm are shown in Figure 7, the intrusion length reached 6281 m from shore line measured at aquifer bottom and the salt mass is reached1.04621x10^{7} kg.

Table 4
Different scenario for Gaza aquifer in 2050

Stage No.	Case	Time (year)	
		2010	**2050**
I	**Seal level rise (cm)**	**0**	**23.60**
II	Reduction in precipitation (MCM yr^{-1})	48.20	36.15
	Lateral flow	26.60	19.35
	Wastewater quantity (MCM yr^{-1}`)	49.88	109.47
	Domestic leakage (Return flow) (MCM yr^{-1})	28.50	62.56
	Agriculture leakage (MCM yr^{-1})	16	16
	Wastewater leakage (MCM yr^{-1})	9.98	21.89
	Total leakage (MCM yr^{-1})	54.48	100.45
	Total aquifer recharge (MCM yr^{-1})	**102.68**	**136.6**
III	Population (Million)	1.60	7.09
	Population increasing rate (%)	zero	4.43
	Water consumption (L Capita $^{-1}$ day^{-1})	165	110
	Domestic abstraction (MCM yr^{-1})	95	208.52
	Agriculture abstraction (MCM yr^{-1})	80	80
	Total abstraction (MCM yr^{-1})	**175**	**288.52**

3.4 Management of SWI for Gaza aquifer

The GCA is an extremely interesting case study of real sea bed slope. The results of GCA simulations permit a deeper discussion and validation of the theoretical assessments realised with the Henry's problem approach.

3.4.1 Effect of physical subsurface barriers

The physical subsurface barriers is installed at 3000 m from shoreline with hydraulic conductivity of $1x10^{-5}$ m per day, the bottom of cut-off wall level is (-101.00) from mean sea level and (+45.00) from ground surface (see **Figure 8a)**, while top subsurface dam is carried out at level at level (-73.00) and the bottom at level (-176.00) (see **Figure 8b)**. SUI reached 3035m and 3002 m form shore line, the salt mass is reached 9999650, $1.01537x10^{7}$ kg for the two cases respectively as presented in **Figure 9a and 9b.**

3.4.2 Effect of earth fill

Figure 8c presents the land fill used for GCA. The land fill depth is ranged from level (-9.30) to (-20.70) from MSL with length 1200 m from shore line, the fill hydraulic conductivity is 0.10 m per day. SWI reached 5510 m, as presented in **Figure 9c**. The aquifer salt mass is reached 9116411 kg.

3.4.3 Effect of abstraction and recharge methods

Abstraction well and recharge well to manage the SWI in the case of GCA were simulated. Three cases are considered: the first is recharge of treated wastewater, the second is abstraction of brackish water, the third is a combination of recharge and abstraction.

The total expected production from wastewater in Gaza strip will be reached 109.47 MCM yr^{-1} and the leakage is 21.89 MCM yr^{-1} so the total volume of wastewater out let will be 87.58 Mm^{3}/year (Table 5). Production of treated wastewater increases gradually by an increment of 2 MCM yr^{-1} (Sirhan, 2013). The actual value of wastewater treatment could be assessed equal to 80 MCM yr^{-1} by 2050. The excess quantity of untreated wastewater is disposed to the Mediterranean Sea; the volume is assessed equal to 31.90 and 7.58 MCM yr^{-1} by 2010 and 2050 respectively.

The recharge well was located at 6000 m from shore line with depth -60.00 form MSL.

SUI reached 3350 m with salt mass of 6028400 kg, as presented in **Figure 8d**.

The future desalination volume is expected to 129.74 MCM yr^{-1} by 2035 for long term (PWA, 2011). This modification was simulated using the same value by 2050 and installing abstraction wells from brackish water. The abstraction well was simulated at 3000 m from shore line with depth -160.00 from MSL.

SUI reached 2990 m with salt mass of $1.00089x10^{7}$ kg. Combining recharge and abstraction wells, SUI reached 2933m with salt mass is 6413380 kg (**See Figure 9d, 9e and 9f**).

Table 5
Quantity of produced of treated wastewater and desalination in 2010 and 2050 at Gaza Strip

Year	Case	2010	2050
Wastewater	Production (MCM yr^{-1})	39.90	87.58
	Treatment (MCM yr^{-1})	8	80
	Disposal to Mediterranean Sea (MCM yr^{-1})	31.90	7.58
Desalination	Desalination (MCM yr^{-1})	6	129,74

3.4.4 Effect of check dams on SWI

In this scenario GCA was simulated adding check dam as presented in **Figure 8e.** The head of dam is **+7.00** AMSL and distance from 1400 to 1800 m from shore line.

The results of this scenario are presented in **Figure 9g;** SUI reached 4203m from shore line with salt mass is 7918470 kg.

Table 5
Salt repulsion percentage for Gaza aquifer

Run number	Case	Unit	Values	Intrusion length for Eqi-line 35000 (m)	Salt volume (kg)
1	base	-	-	3177	5718820
2	SLR	cm	23.60	6281	10462100
	Reduction in precipitation	MCM yr^{-1}	36.15		
	Reduction in recharge	MCM yr^{-1}	19.35		
	Over pumping	MCM yr^{-1}	288.52		
3	Cut-off wall	depths (m)	100	3035	9999650
4	Subsurface dam	depths (m)	100	3002	10453700
5	Earth fill	Permeability (m day^{-1})	0.10	5510	9116411
6	Recharge using treated wastes water	Rates (MCM yr^{-1})	80	3350	6028400
7	Abstraction from brackish water	Rates (MCM yr^{-1})	129.74	2990	10008900
8	Combine of recharge and abstraction	Rates (m^3 day^{-1})	80 (R) and 129.74 (A)	2933	6413380
9	Check dam	Heads (m)	+7.00	4203	7918470

4. Conclusions

Saltwater intrusion in coastal aquifers is a natural phenomenon which can cause groundwater quality degradation. This study aims to identify the impact of bed slopes for seaside (10:1), horizontal and land side (10:1) on SWI considering the possible impact of SLR and reduction in natural recharge, also investigate the effect of using different control methods. The study was carried out using SEAWAT for Henry problem and land side bed slope of Gaza aquifer, Palestine.

The land side slopes increase the SWI by 57.99% compare with 52.12 and 50.05% for horizontal and sea side bed slopes. SWI repulsion were reached 26.88, 30.09, and 28.66% for using cut-off wall and reached

10.38, 12.45 and 13.55% using subsurface dam while using land fill led to SWI repulsion of 15.92, 18.90, and 20.11% respectively. Also, applying the hydraulic methods of recharge of freshwater led to repulsion of 30.13, 30.27 and 30.57 while using the abstraction of brackish water to 7.64, 6.97 and 6.48%, moreover combination of two cases led to 34.55, 34.38 and 34.41%. The check dam led to SWI repulsion of 44, 46.70and 43.82% for the three aquifer bed slopes of sea side, horizontal and land side.

Declarations

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Availability of data and material

(Upon request)

Code availability

(Upon request)

Authors' contributions:

Ismail Abd-Elaty: Conceptualization, Software; Data curation; Writing, ***Maurizio Polemio***, Reviewing and Editing Methodology, Original draft preparation, Supervision.

Ethics approval

(Not applicable)

Consent to participate

(Yes)

Consent for publication

(Yes)

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Tables

Table 3 is available in the Supplementary Files section.

Figures

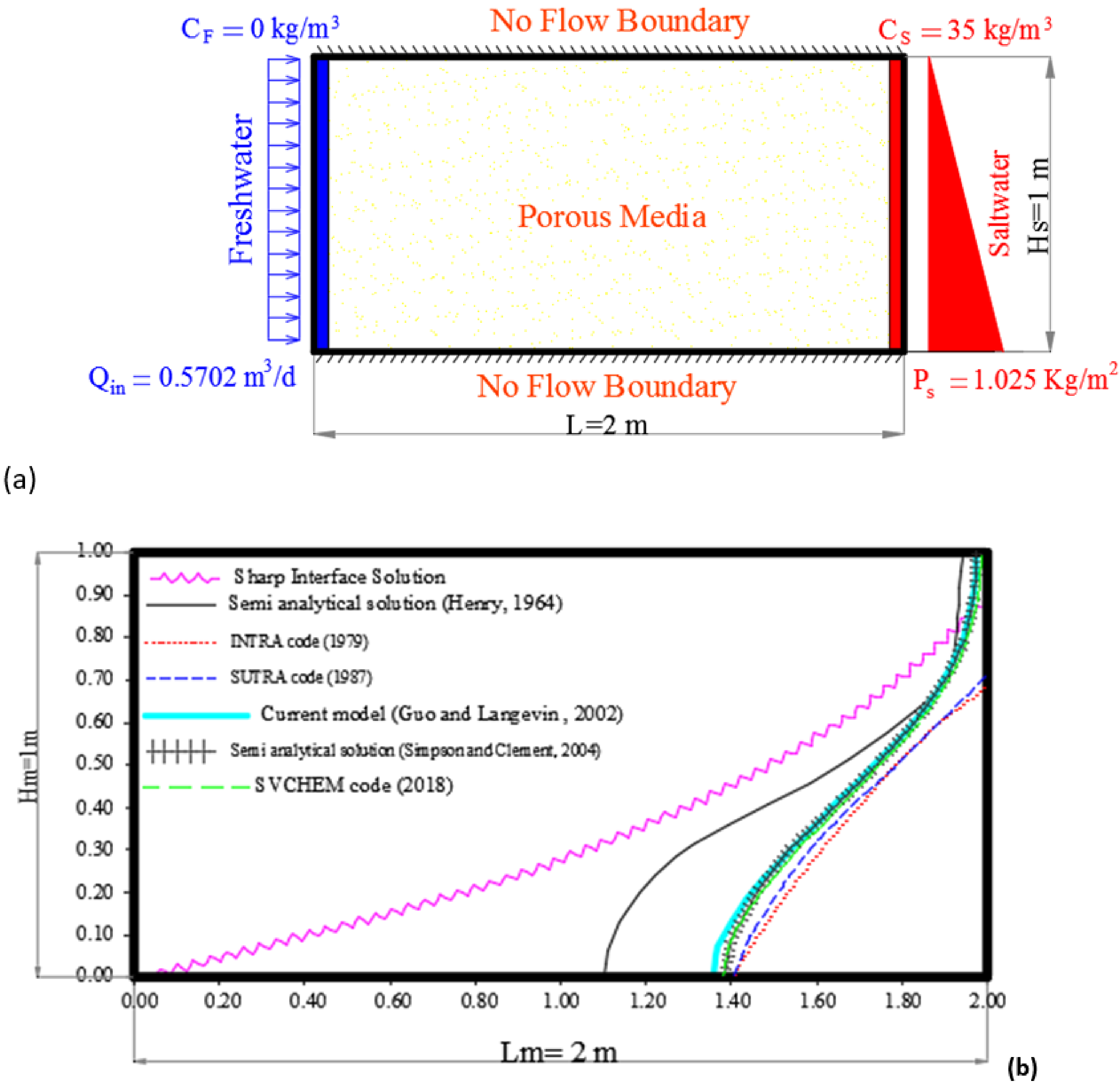
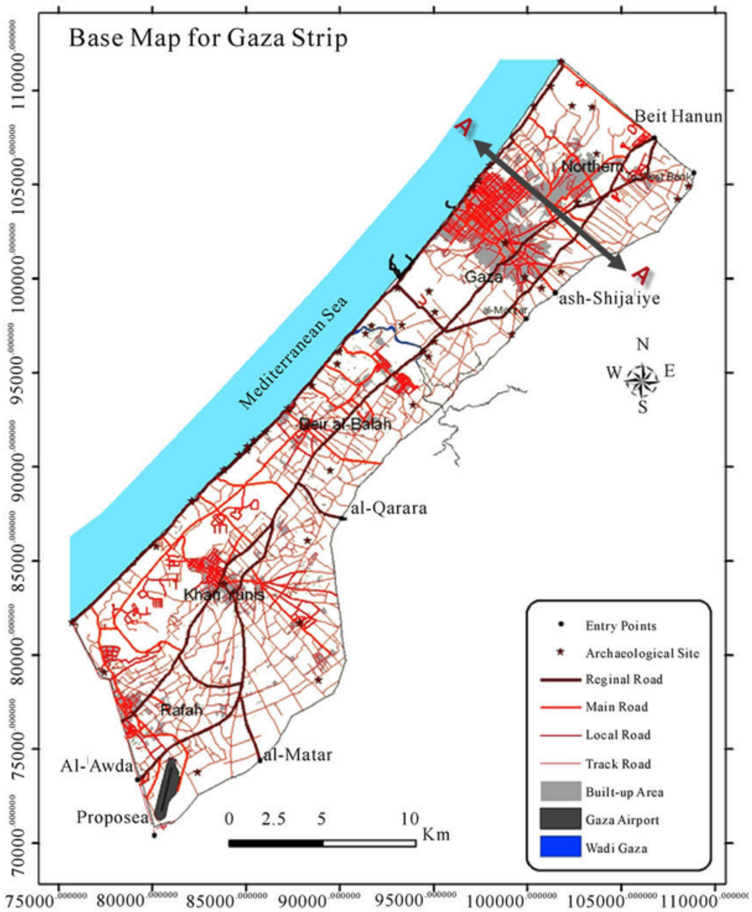
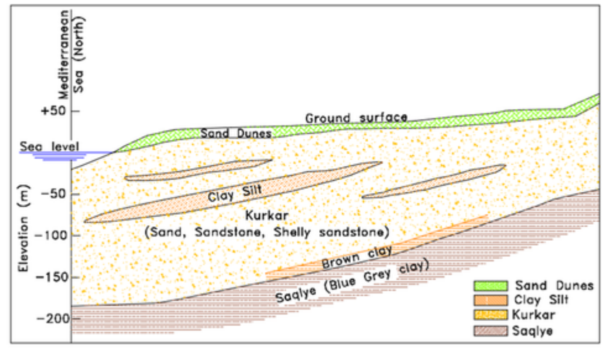


Figure 1

Henry's problem for (a) Definition sketch and boundary conditions and (b) SWI results for SEAWAT results and other codes



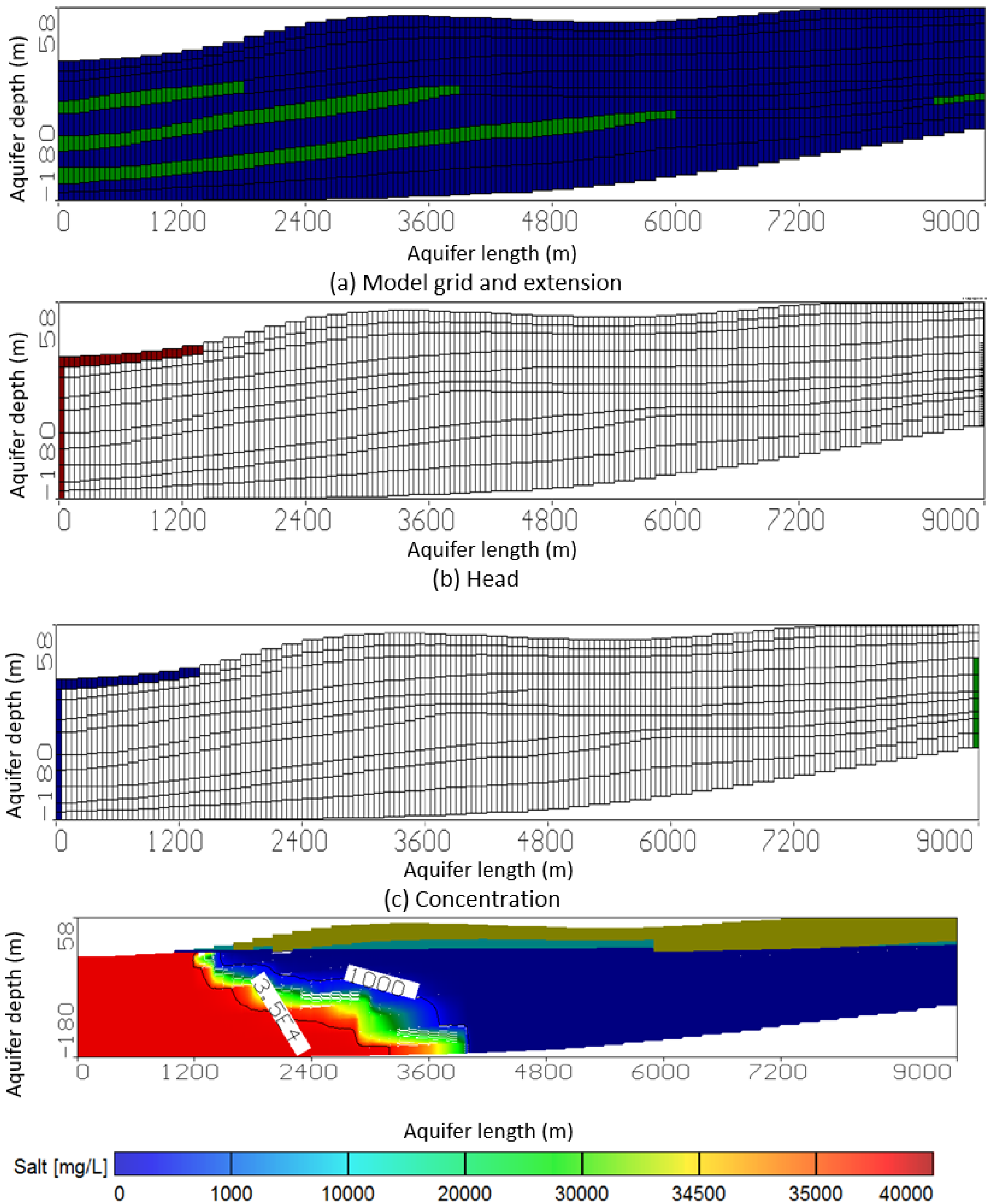
(a) Location map (Shomar et al., 2010)



(b) Hydrogeological cross-section of Gaza aquifer (modified after Metacalf and Eddy, 2009)

Figure 2

Gaza Strip Location and hydrogeological



(d) TDS distribution in Gaza aquifer by SEAWAT for the current study

Figure 3

Vertical section of Gaza aquifer for with boundary conditions and SEAWAT results

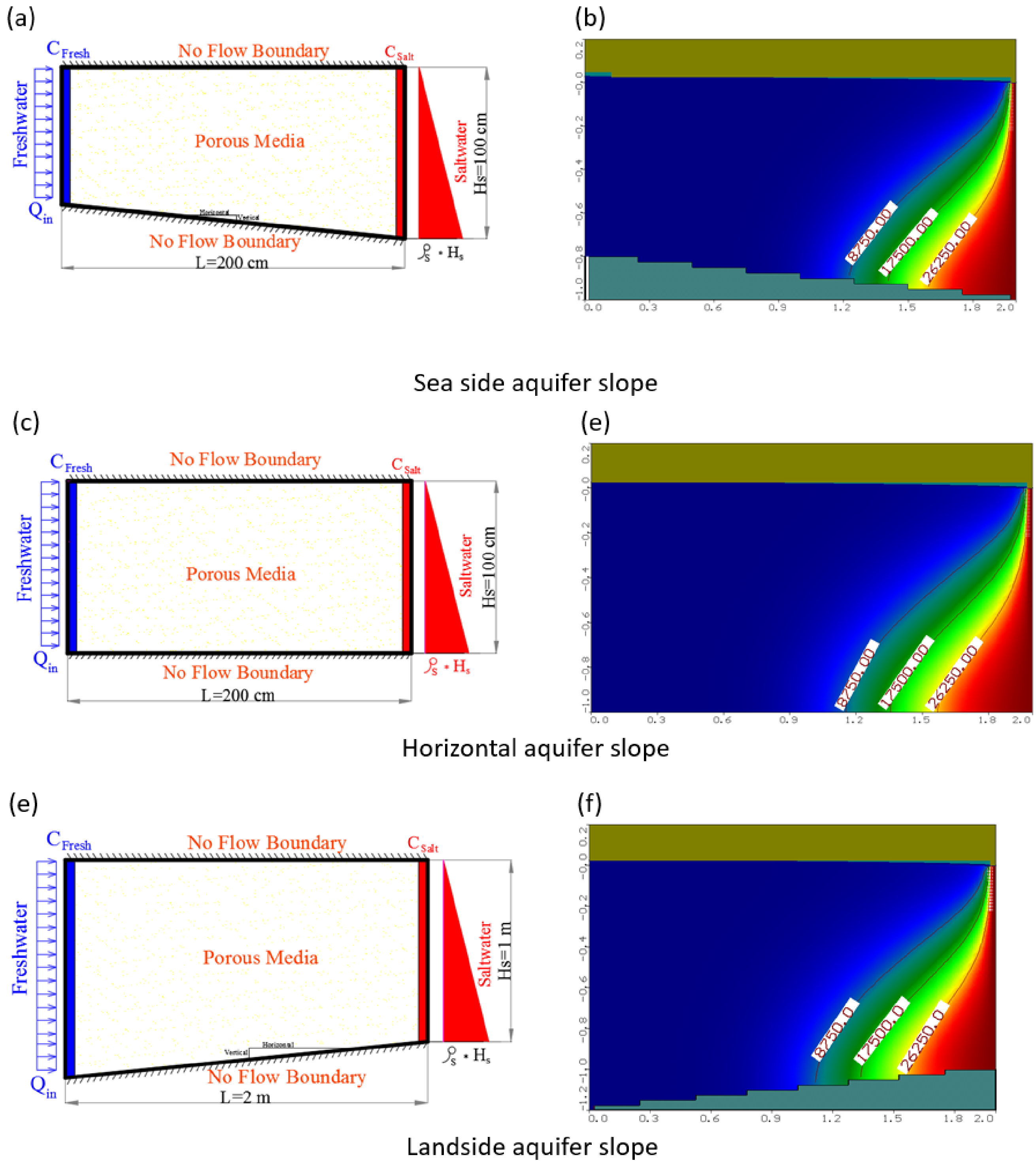


Figure 4

Schematic sketch and equi-concentration line 17,500 ppm under different slopes of Henry’s problem

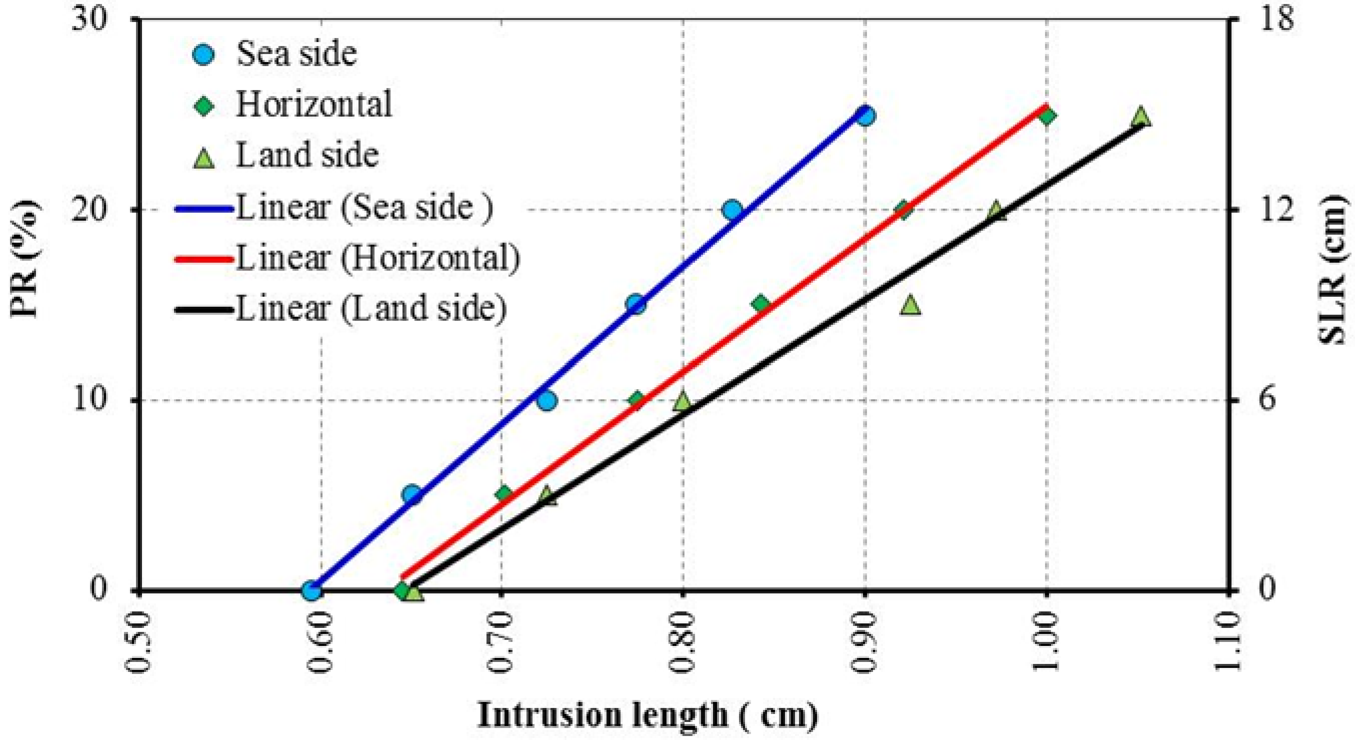


Figure 5

SWI results in the case of SLR and recharge reduction.

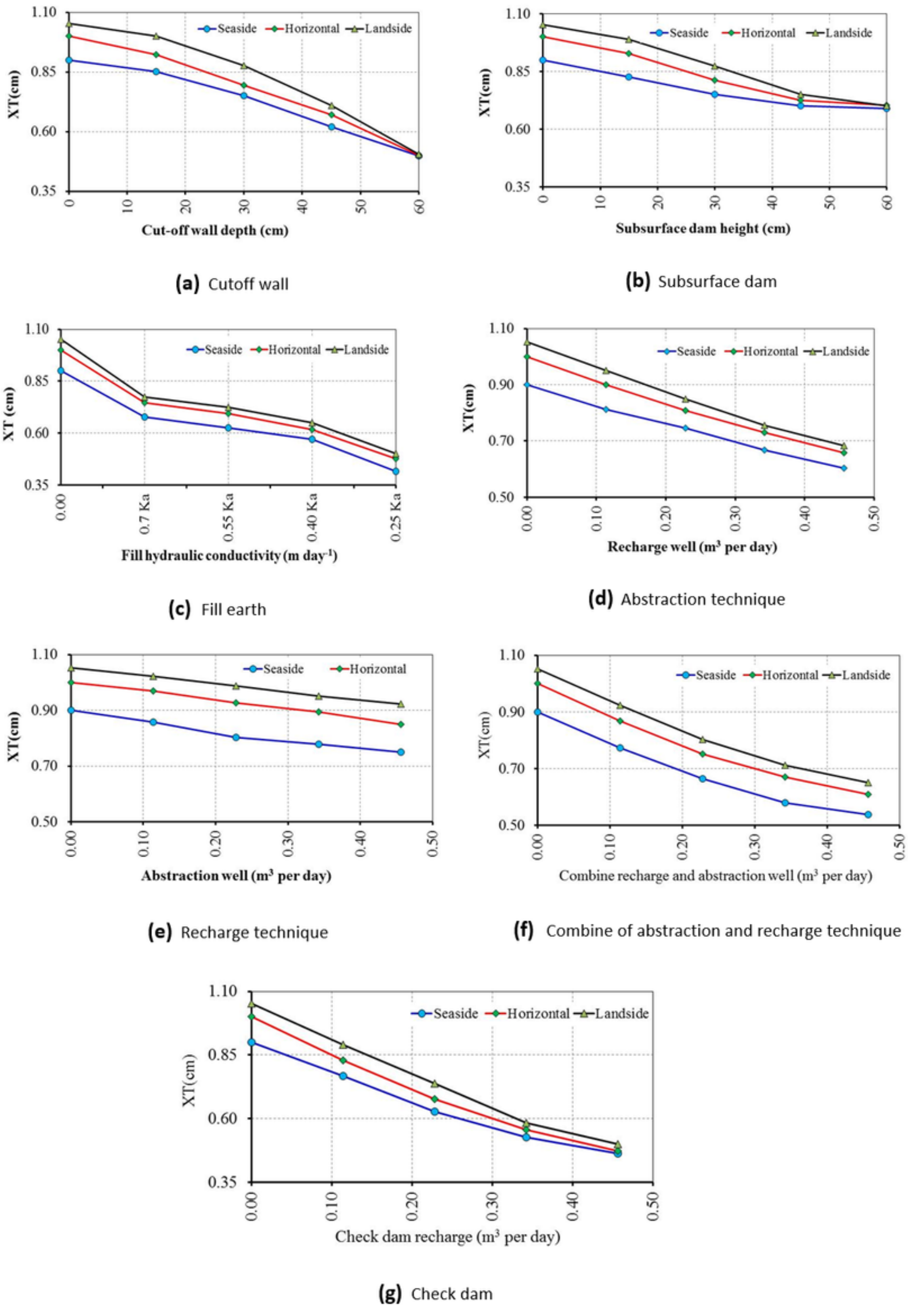


Figure 6

Relationship between SWI and management techniques for different bed slopes of Henrys problem

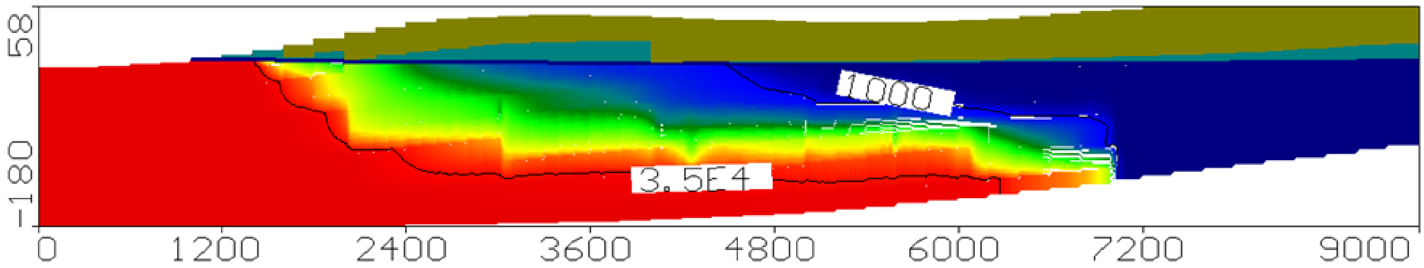


Figure 7

Equi-concentration line 17,500 ppm under different conditions in Gaza aquifer

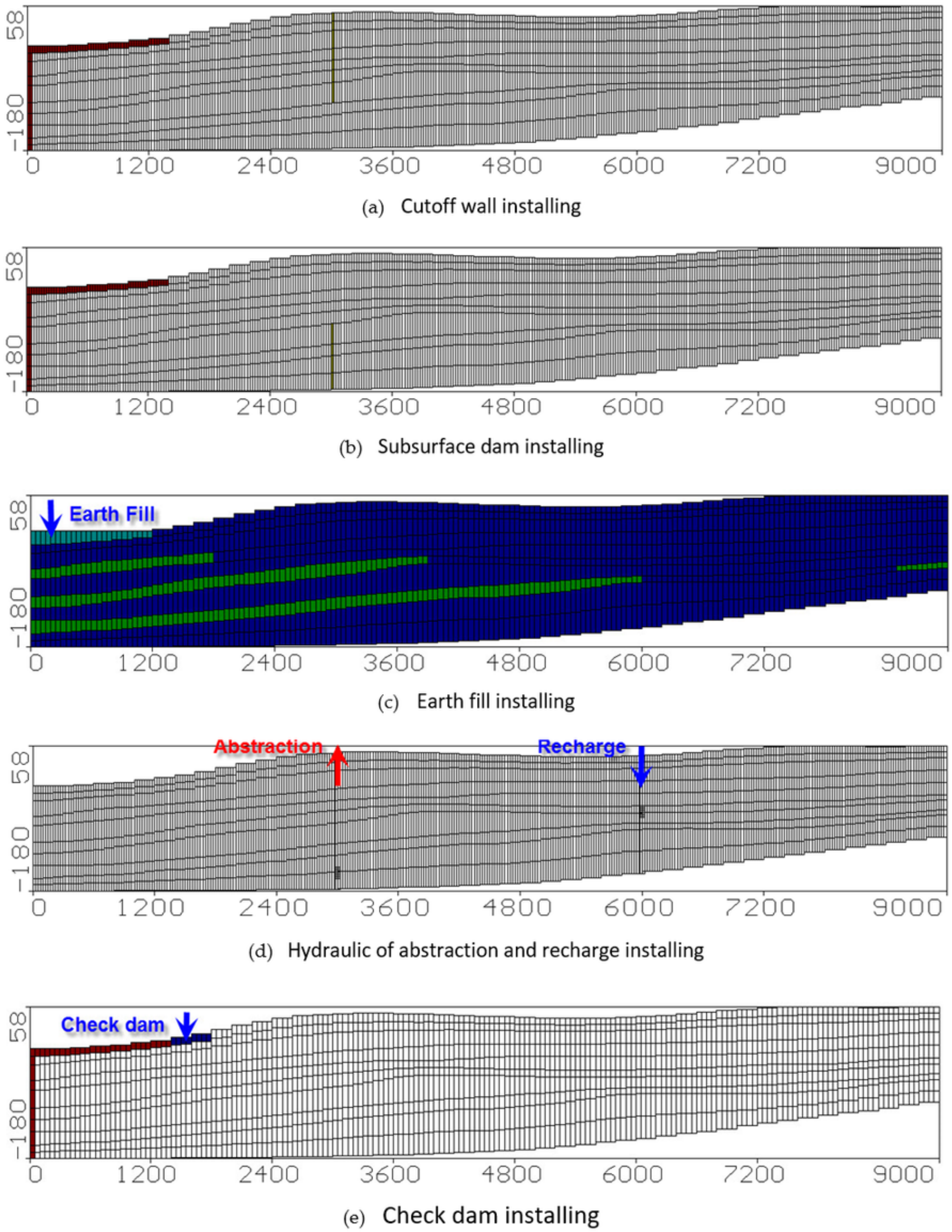


Figure 8

Installing different management techniques for the GCA (a real case of sea bed slope)

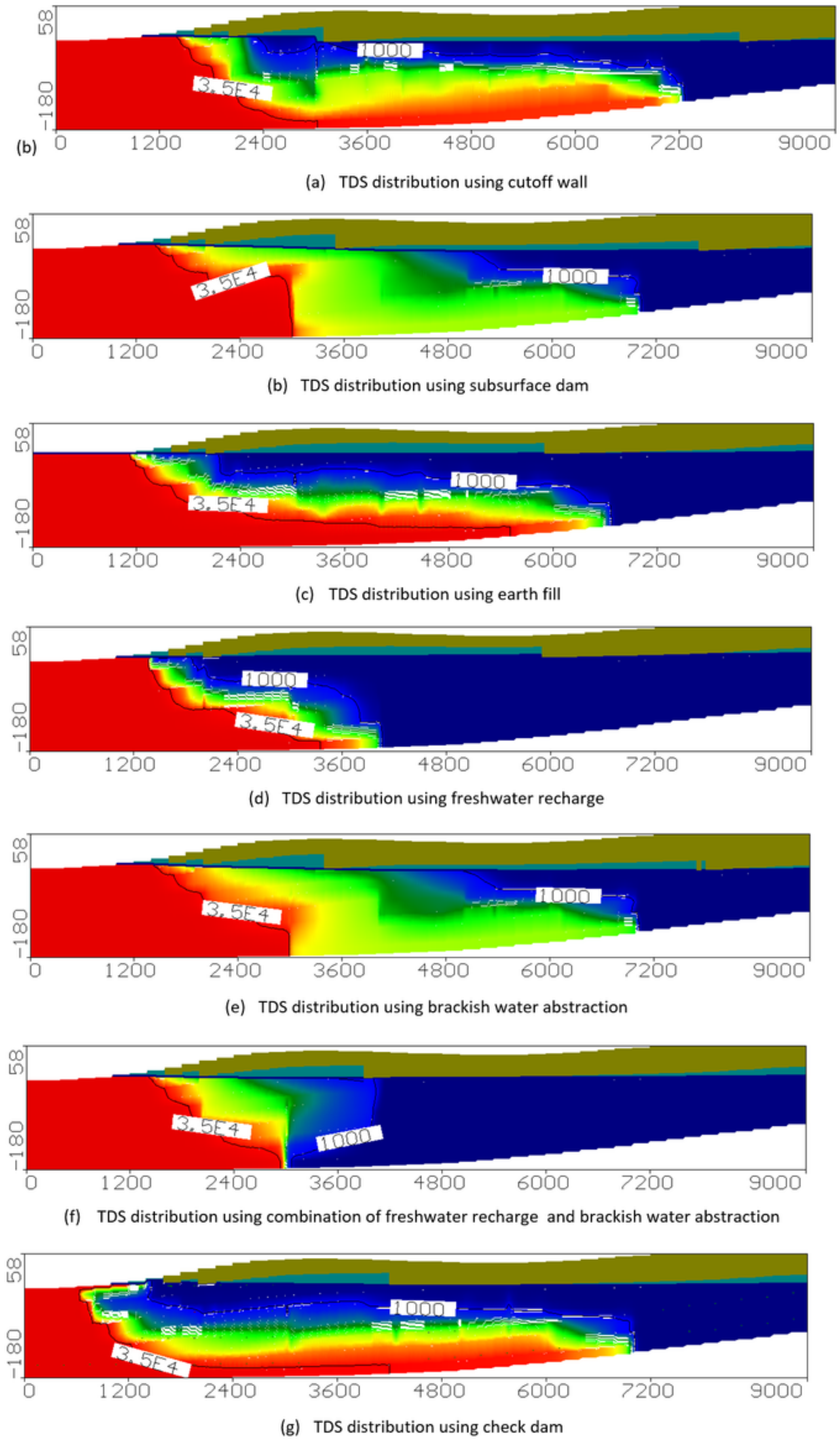


Figure 9

Salinity distribution using different management techniques for sea bed slopes of Gaza aquifer

Supplementary Files

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- Table3.docx
- GraphicalAbstract.docx
- Highlights.docx