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ORIGINAL PAPER

Saltwater intrusion management at different coastal aquifers bed slopes considering sea level rise and reduction in fresh groundwater storage

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Abstract

Coastal fresh groundwater management is a challenging research topic due to the relevance of these resources and the huge suffered risks due to global change and overpopulation. The geometrical features of coastal aquifers play a control role in saltwater intrusion (SWI). Seawater level rise and the reduction in aquifer fresh groundwater storage are promoting SWI. All these key factors are considered with two different numerical approaches defining schematic management criteria bottom using the numerical code SEAWAT. 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 (ABS), and hydraulic and physical methods for SWI management are considered together with SLR, recharge reduction, and over pumping. The results showed that the land side ABS cases show more SWI than sea side and horizontal ABS. Cut-off walls and check dams are effective to manage SWI in horizontal ABS more than in other slopes, also the subsurface dams, earth fill and recharge of freshwater are good methods in land side ABS while the abstraction of brackish water and combination of recharge with abstraction are better to mitigate of SWI in sea side ABS. 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 groundwater resources for different slopes aquifers around the coastal world.

Keywords Coastal · Aquifers · Management · SLR · SEAWAT · Bed slopes · Gaza

Abbreviation

ABS	Aquifer bed slopes
CC	Climate change
CWs	Cut-off walls
GCA	Gaza coastal aquifer
GS	Gaza Strip
IMT	IMT process solves the following solute transport equation
IPCC	Intergovernmental Panel on Climate Change
MCM	Million cubic meters
MODFLOW	United States Geological Survey modular finite-difference flow model MT3DMS Modular Transport Three-Dimensional Multi-Species
MSL	Mean sea level
PSB	Physical subsurface barrier
SDs	Or subsurface dams
SEAWAT	Three-dimensional variable-density groundwater flow
SID	Seawater intrusion distance
SLR	Seawater level rise
SUTRA	Saturated-unsaturated variable-density ground-water flow with solute or energy transport
SWI	Saltwater intrusion
TDS	Total dissolved solids
TECC	Technical engineering consulting company
VDF	Variable density groundwater flow

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1 Introduction

The influence of climate change (CC) on the availability of high-quality water resources is now widely recognized over the world (McDonald et al. 2011). In particular, investigation, management and mitigation of saltwater intrusion (SWI) in coastal regions are key issues for numerous coastal areas affected by water availability shortage and CC (Abd-Elaty et al. 2019; Polemio and Zuffianò 2020). Around 70% of the world's population lives in coastal areas where very high population density is observed; this percentage shows a widespread increasing trend causing the increase of freshwater demand (McDonald et al. 2011; Wada et al. 2016; Abd-Elaty et al. 2021a). Increasing freshwater demand and CC expose coastal groundwater to increasing salinization risks for SWI, especially in water-scarce regions (Polemio and Zuffianò 2020). It can get worse due to human activities and natural processes 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; El Shinawi et al. 2022). SWI management becomes necessary for protection the coastal groundwater resources 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 the global mean sea level is expected to continue. The most recent best assessment is 0.28–0.55 cm by 2100 (IPCC 2021) while it was 18 to 58 cm in 2007 by the Intergovernmental Panel on Climate Change (IPCC 2007), with a rate of rising 8 to 16 mm/year from 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. Abd-Elhamid et al. (2016) investigated the effect of different SLR scenarios on the coastal region of the Nile Delta, Egypt using the SEAWAT code. The results showed that the groundwater salinity has a significant impact 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. Bear and Cheng (1999) presented that optimization of freshwater abstraction and management of salinization risks are the main management challenges for water supply decision-makers.

Abd-Elaty et al. (2020a) used a numerical model of SEAWAT for simulation the SWI in the Gaza Strip aquifer, Palestine using different methods and scenarios to control SWI. The results indicated that the artificial recharge using the treated wastewater could mitigate the SWI compared with the other method for the abstraction of brackish water while the combination of the two methods results the best choice. Abd-Elaty et al. (2021c) simulated the effects of groundwater abstraction and desalination brine deep injection on a coastal aquifer. The results showed that the salinization of the coastal aquifer can be mitigated by reducing the concentration of the water feeding the reverse osmosis plant, i.e., mixing the extracted brackish water with lower salinity water.

Luyun et al. (2009) investigated the dynamics of residual saltwater by the 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 physical subsurface barriers (PSB) is effective to control SWI more than a single method. Abd-Elaty et al. (2022a) simulated the management of coastal aquifer salinity using inclined PSB; the results showed that the most positive impact in both cases was achieved for a slope of 1/4, indicating that a moderate vertical inclination of the PSB better preserve coastal groundwater resources.

Guo and Jiao (2007 and 2009) evaluated with simple calculations the effect of the landfill reclamation realised along the coastline on the groundwater heads and SWI. The results indicated a water table rise on old land and the seaward shift of the salt-fresh water interface. Abd-Elaty et al. (2022b) developed a numerical study using SEAWAT code to investigate the effect of different width of earth fill on the management of SWI in coastal aquifers considering SLR, showing the advantages of this solution.

In this current study, a new approach to retard SWI for sustainable fresh groundwater resources by examining the influence of ABS on SWI for different management methods including physical subsurface barriers, earth fill, check dam, abstraction, and natural or artificial recharge. The different scenarios are compared in terms of the position of the SWI interface, measured as the distance from the coastline at the aquifer bottom using the numerical code SEAWAT to provide a better understanding and a quantitative assessment of different management solutions for SWI in coastal aquifers. Simulations consider hydraulic or physical methods, together with SLR, recharge reduction, and or over pumping, with the different aquifer bed slopes (ABS), 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, the advantages of each solution are discussed. This study is useful examining the sensitivity of aquifer management under combination of SLR and decrease in aquifer storage for different coastal aquifers study slopes.

2 Materials and methods

This chapter describes the general characteristics, hypotheses, main data, and boundary conditions concerning the numerical approach to the Henry's problem and to the selected study area of coastal aquifer.

2.1 SWI management methods

Different techniques were developed and applied for SWI management (Polemio and Zuffianò 2020). Figure 1 is presented Schematic sketch the SWI management techniques. The Physical Subsurface Barrier (PSB) methods use cut-off walls (CWs) or subsurface dams (SDs), also sheet piling and earth fill (see Fig. 1a and b). The barrier creates a discontinuity between the coastal brackish portion of the aquifer and the inland portion, where fresh groundwater can be safely discharged (Abd-Elaty et al. 2019b). Land reclamation in coastal zones usually occurs by extension of the shoreline towards the sea side using the artificial filling of appropriate soil (see Fig. 1c). The natural aquifer recharge by precipitation takes place over the reclaimed new land.

Hydraulic Barrier (HB) methods use injection by wells or infiltration by ponds of low-quality freshwater or abstraction of saltwater to permit the safe discharge of fresh groundwater of high quality (see Fig. 1d). The artificial recharge technique is man's planned operation used to increase the fresh groundwater heads (Bear 1999). This method is applied to the aquifer through infiltration by surface ponds or recharge wells (Roger 2010) (see Fig. 1e).

2.2 Variable density model

The use of numerical modelling supporting the design and selection of management criteria is a reliable choice in the case of groundwater at salinization risk. Modelling can be descriptive or prescriptive, assessing the effects of a specific utilisation scenario or guiding the choice of the optimal scenario respectively (Singh 2012). Tens of scientifically relevant modelling experiences were realised using descriptive or prescriptive models in more than 20 countries (Polemio and Zuffianò 2020).

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

2.3 Hypothetical case study of Henry's problem

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

The seawater intrusion distance (SID) is usually represented by the 0.5 concentration contour line (isochlor) and measured along the bottom boundary from the aquifer seaside (Fig. 5d). The baseline case for the SID reached 64.50 cm in the case of SEAWAT. The results of the SEAWAT were compared with other codes by Henry (1964), Intera (1979), Voss and Souza (1987), Simpson and Clement (2004) and SVCHEM (2018) and given good agreement.

2.4 The real case study of the Gaza aquifer, Palestine

Figure 3a shows the Gaza Strip (GS, Palestine), the selected case study for the sea side aquifer slope. The total area is of 365 km^2, with 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 (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% and the density reached about 4822 capita km^{-2} in 2015 (PCBS 2015). The climate of GS is semi-arid where the average precipitation ranges between 200 and 400 mm year^{-1} (PWA 2001, 2013), and the evaporation rate is about 1400 mm year^{-1} (SWIMED 2002).

Figure 3b is presented the two formations of GS. 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

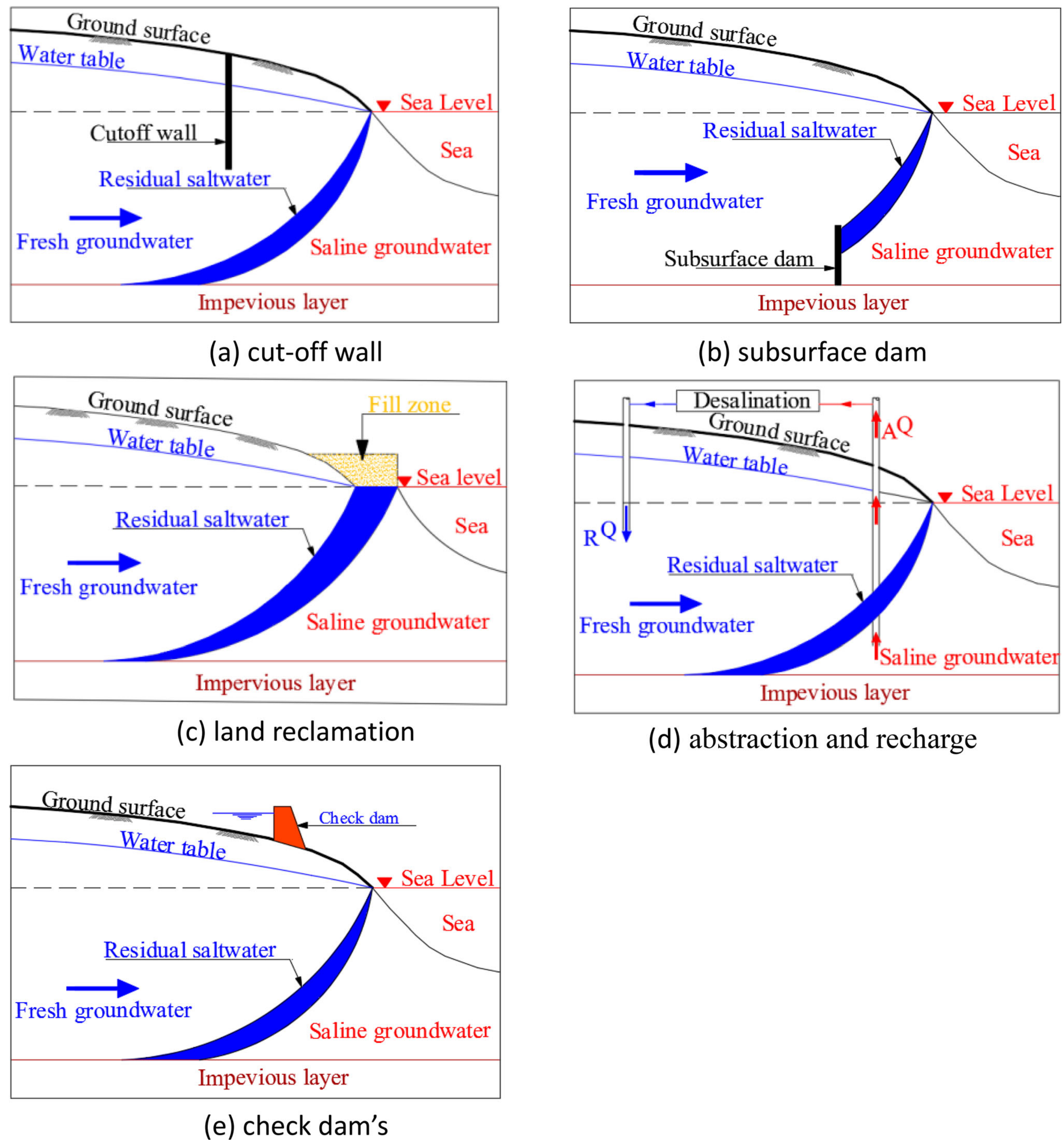


Fig. 1 Schematic sketch the SWI management techniques

deposits with thickness of 25 m; the average thickness of the Kurkar Group sequence reaches from 200 to 120 m in the south and the north respectively (Abu Heen and Muhsen 2016; Abu Al Naeem et al. (2019).

The GCA transmissivity ranges between 700 and 5000 m^2 day^{-1} with the hydraulic conductivity of K_x and K_y are between 20 and 80 m day^{-1}. The aquifer effective porosity is 35%, the specific yield ranges between 0.15 and 0.30, and the specific storage is 10^{-4} m^{-1} (PWA 2011, 2015). The longitudinal dispersivity (α_L) and transverse dispersivity (α_T) were 50 m and 0.10 m respectively (Qahman, 2004; (Sirhan and Koch 2013; and Abd-Elaty et al. 2021c). The SEAWAT model of GCA uses 180 columns, one row and 10 layers for active cells. The model is 9000 m in

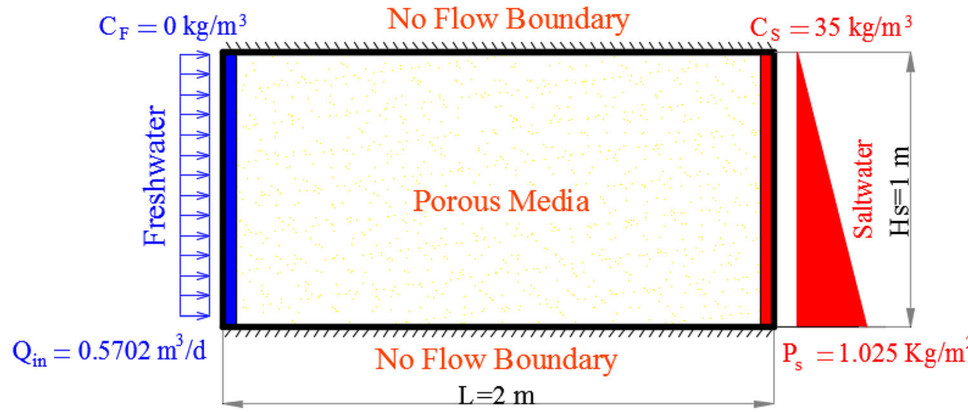


Fig. 2 H's problem for Definition sketch and boundary conditions

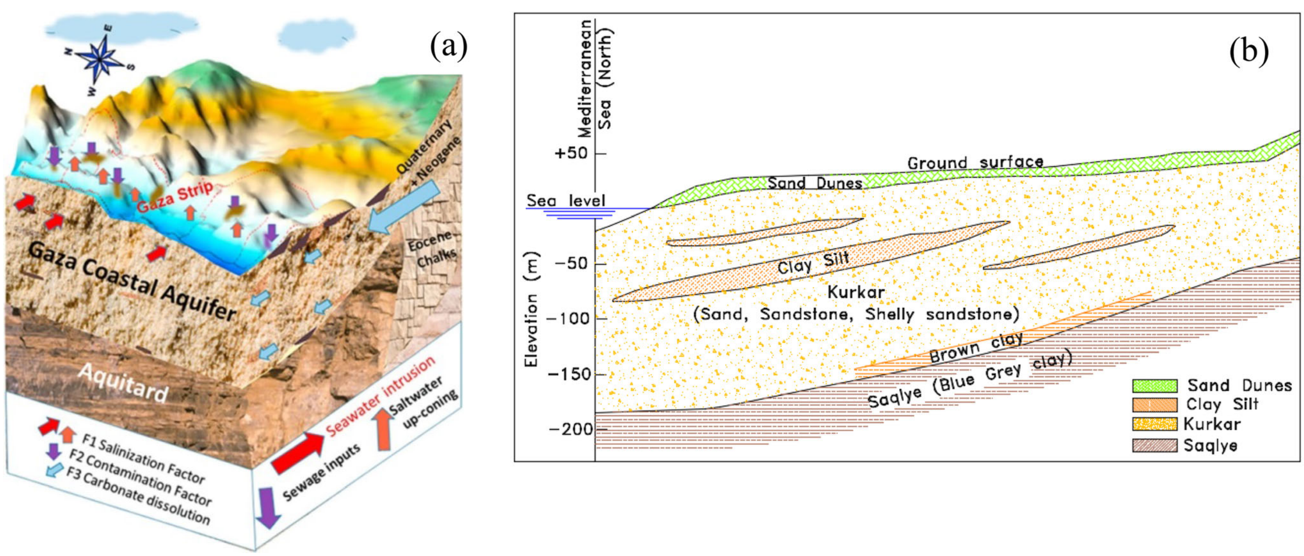


Fig. 3 Gaza Strip for Location map (Abu Al Naeem et al. 2019) And (b) Hydrogeological cross-section of Gaza aquifer from the East to the West (modified after Metacalf and Eddy 2009)

length in x-direction; topography range between + 58 to - 180 m above mean sea level (AMSL). The hydrostatic pressure is assigned at sea side to represent the saline water head while the groundwater flow on the inland side is assigned with freshwater flux using well modules to represent the freshwater recharge. The Lateral freshwater flux (q_{in}) was set 10 m^3 day^1 m^{-1}, the well abstraction rates 20.75 m^3 day^1 m^{-1}, and the vertical recharge and return flow 416.50 Mm $year^{-1}$. A constant concentration of 3500 ppm is fixed along the sea boundary while the inland boundary a value of zero ppm is applied.

Figure 4 shows the distribution of aquifer salinity by Total dissolved solids (TDS) in the GCA for the current situation (base case). The current results are compared with Sarsak (2011) and Abd-elaty et al. (2020a; 2021c). The results showed a good match between the other two models. The 0.5 isochlor reached a distance of 3177 m from the sea shoreline in the horizontal case. The calibrated model is used in the validation process to simulate different scenarios to control SWI intrusion. The total salt mass reached 5,718,820 kg.

2.5 Proposed scenarios

This study was simulated three cases of ABS including the sloping towards the sea (seaside slope) with slope by 10 (horizontal) to 1(vertical); the horizontal bed and the sloping towards the land (landside slope) by 10:1 (Fig. 5a, c and e); the 0.5 isochlor for SID reached 59.50, 64.50 and 65.125 cm, respectively (Fig. 5b, d and f). The results showed that the bed slope of aquifer has a relevant effect on saltwater intrusion, in which the land side slope has more intrusion than horizontal and seaside slopes. The study was applied by changing the sea water level at the seaside by 3 cm, 6 cm, 9 cm, 12 and 15 cm while the freshwater flux was decreased by 5%, 10%, 15%, 20% and 25% compared with a rate of (Qin) 0.5702 m^3 day^{-1} m^{-1} at the base case for the Henry's problem.

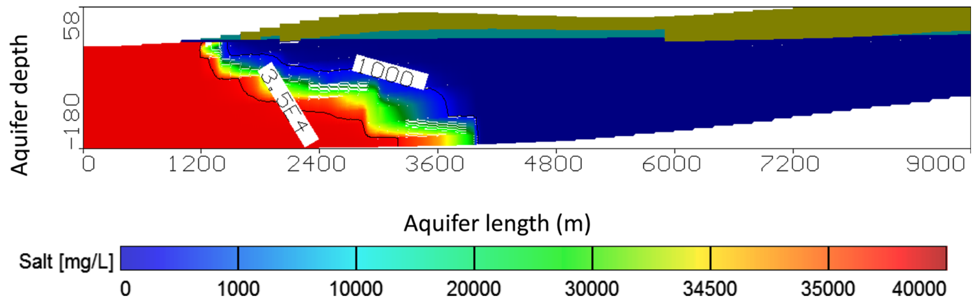


Fig. 4 Vertical TDS distribution in Gaza aquifer

For Gaza aquifer, the SLR was assigned by 23.60 cm by 2050 while the natural recharge reduction by 25%. The total of natural recharge and return flow reached 136.60 MCM yr^{-1} at 2050 compared with a value of 102.68 MCM yr^{-1} at base case, while the groundwater abstraction reached 288.52 MCM yr^{-1} at 2050 compared with 175 MCM yr^{-1} at base case. The SWI for the Henry's problem and the real case of Gaza aquifer was managed by applying the hydraulic and physical methods including physical subsurface barriers, earth fill, abstraction, recharge, combination between abstractions and recharge methods and check dam.

3 Results and discussions

The model was applied to simulate the effect of SLR, reduction in fresh groundwater by recharge and over pumping.

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

Tide log data showed that the sea level increases 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 SLR trend, decreasing the recharge due to CC, and increasing abstraction (due to increasing population and pro capita water demand) affect large world regions, including the Mediterranean Sea (IPCC 2021).

Figure 6a shows the results of combine SLR and reduction of the fresh groundwater storage for the three cases of aquifer bed slopes (ABS) for the seaside, horizontal and landside. The SEAWAT is used for the hypothetical case of Henry's problem to simulate the SWI for the three cases of ABS referred to the hypothetical steady or initial natural conditions. The sea level head was 100 cm at the ocean side and a constant flux to the aquifer by rate of (Qin) 0.5702 m^3 day^{-1} m^{-1} at the land side. The expected saline water rises were simulated by increasing sea water level at the seaside by 3 cm, 6 cm, 9 cm, 12 and 15 cm while the freshwater flux was decreased by 5%, 10%, 15%, 20% and 25%, the SID resulted was reached 65 cm, 72.50 cm, 77.375 cm, 82.625 and 90 cm compared with 59.50 cm at base case for seaside slope. The salinity was increased and reached − 14.45, − 30.34%, − 48.09%, − 67.84% and − 89.50%. Also, the horizontal slope showed that the SID reached 70.125 cm, 77.50 cm, 84.25 cm, 92.125 and 100 cm compare with 64.50 cm at base case while the salinity increase reached − 15.03%, − 31.62%, − 50.18%, − 70.76% and − 93%. Moreover, the SID reached 72.50 cm, 80 cm, 92.50 cm, 97.25 and 105.25 cm with increase in salinity and 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 land side 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 was carried out using different hydraulic and physical methods including physical subsurface barriers, earth fill, abstraction, recharge and combination between abstractions and recharge methods and check dam to control the SWI due to 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 ABS using two physical subsurface barriers with the same parameters and boundary conditions at the base case. The former is a cut-off wall, while the latter is a subsurface dam.

Different scenarios were applied, analysing the SWI for different wall depths and dam heights by 15, 30, 45 and 60 cm, assessing the SWI improvement in terms of SID and salt repulsion or salinity reduction (see Fig. 6a and b).The groundwater salt repulsion (%) is

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

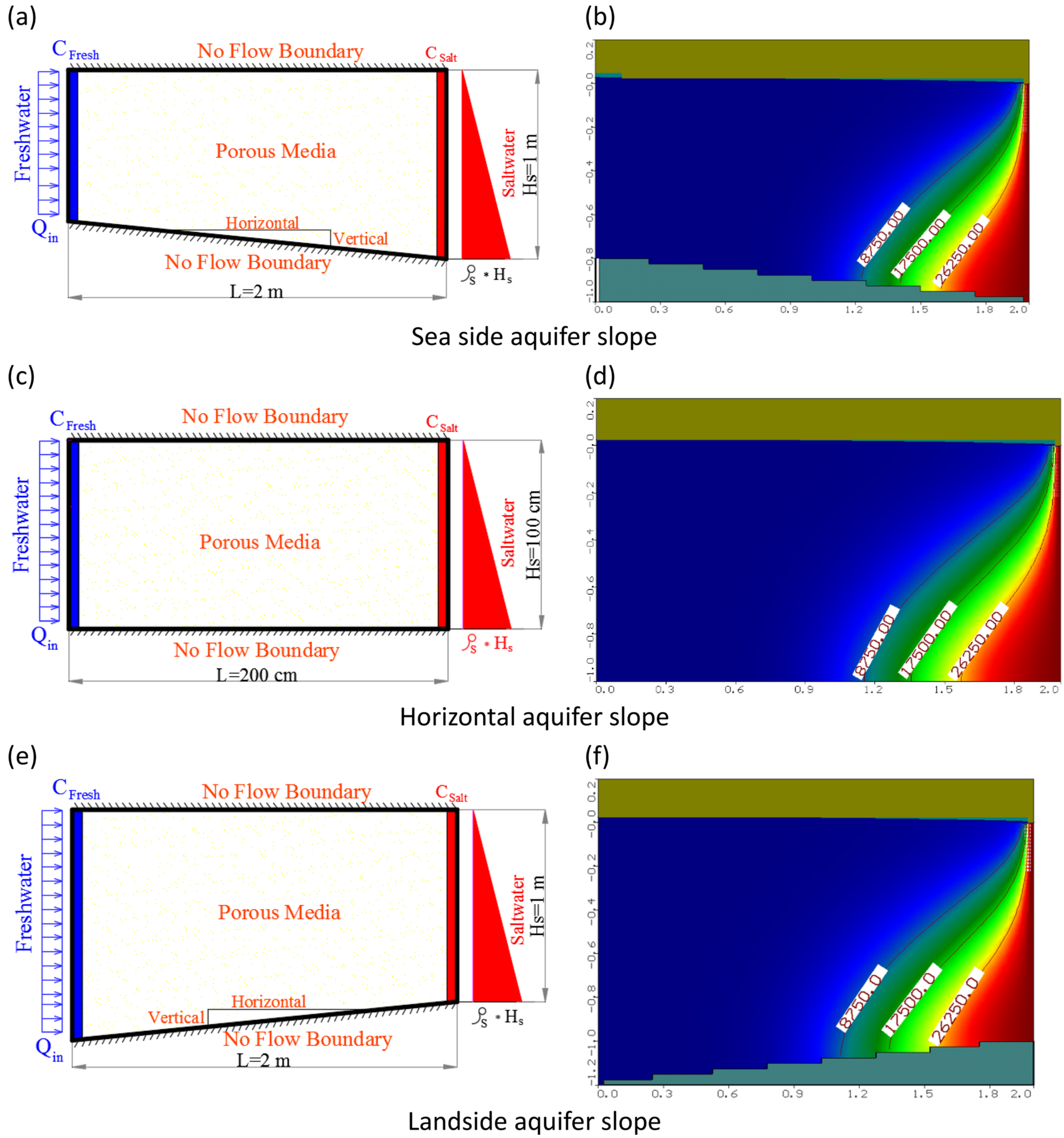
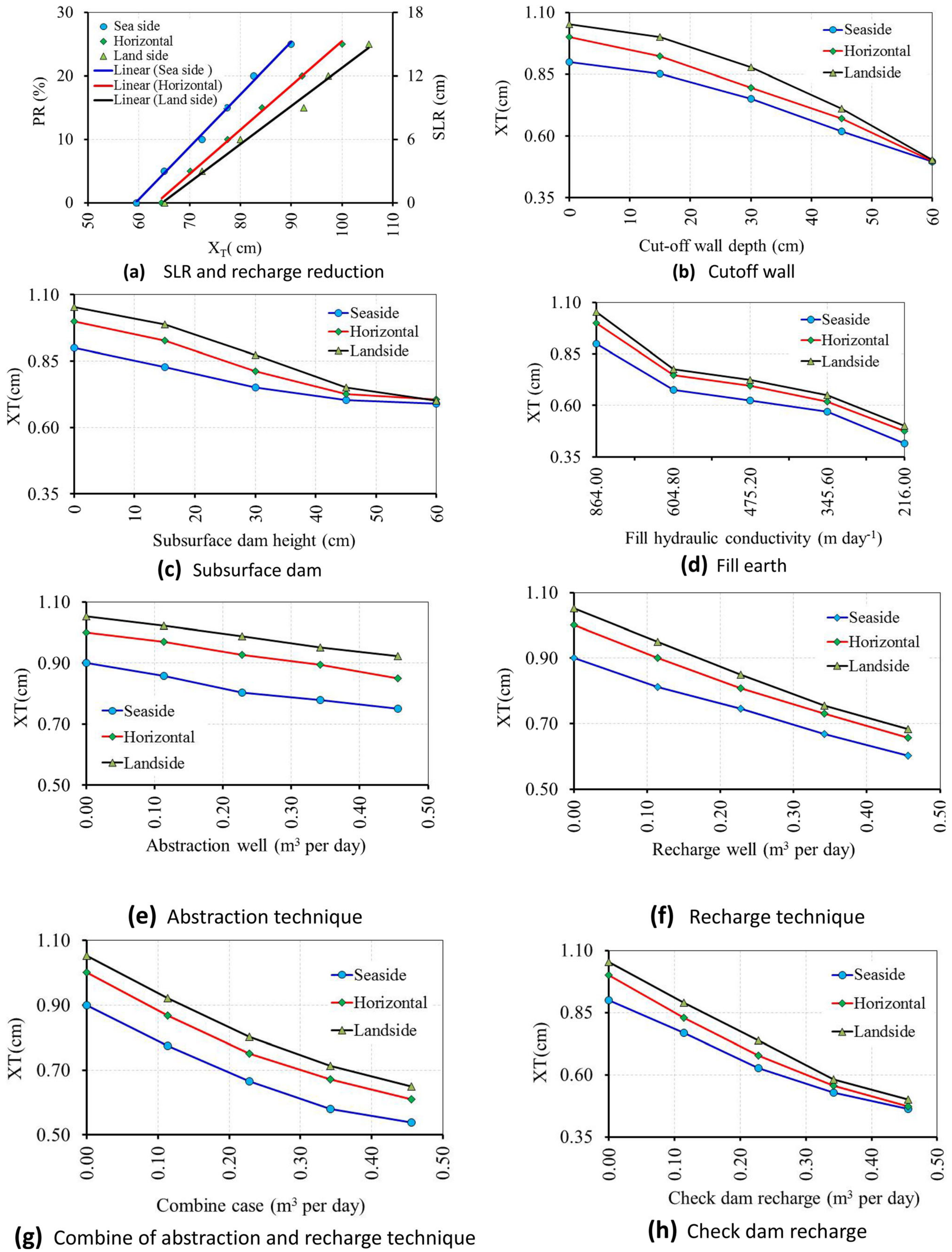


Fig. 5 Schematic sketch and equi-concentration line 17,500 ppm under different slopes of Henry's problem

where C_0 is the initial groundwater salt concentration and C is the groundwater salt concentration at the proposed scenario. Anegative repulsion value means that the groundwater salinity increased while a positive repulsion value (sign +) means that the groundwater salinity decrease.

The results showed that SID reached 85.25 cm, 75.125 cm, 62 cm and 49.75 cm with reduction in salinity to + 6.23%, + 19.38%, + 34.26% and + 47.64% for cut-off wall. Based on the subsurface dam results, SID reached 82.625 cm, 75 cm, 70.25 cm and 69 cm with salinity reduction equal to + 3.56%, + 10.14%, + 13.43% and + 14.38% (Table 1).



PR (%)
SLR (cm)
XT(cm)
Sea side
Horizontal
Land side
Linear (Sea side)
Linear (Horizontal)
Linear (Land side)
(a) SLR and recharge reduction
XT(cm)
Cut-off wall depth (cm)
Seaside
Horizontal
Landside
(b) Cutoff wall
Subsurface dam height (cm)
(c) Subsurface dam
Fill hydraulic conductivity (m day-1)
(d) Fill earth
Abstraction well (m3 per day)
(e) Abstraction technique
Recharge well (m3 per day)
(f) Recharge technique
Combine case (m3 per day)
(g) Combine of abstraction and recharge technique
Check dam recharge (m3 per day)
(h) Check dam recharge

◀**Fig. 6** Relationship between SWI and management techniques for different bed slopes of Henrys problem

The horizontal slope results showed that SID 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 SID reached 92.625 cm, 81.25 cm, 72.50 cm and 70.50 cm with salinity reduction of + 3.44%, + 10.58%, + 17.12% and + 18.66%.

For landside slope SID reached 100, 87.75 cm, 71 cm and 50.50 cm with salinity reduction of + 6.07%, + 19.58%, + 36.27% and + 52.71%. Also, the SID 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

Table 1 Salt repulsion percentage for the Henry problem

Run number	Protection method	Values	Salt repulsion (%)		
			Sea side slope	Horizontal slope	Landside slope
1	Cut-off wall depths (cm)	15	+ 6.23	+ 9.97	+ 6.07
2		30	+ 19.38	+ 24.74	+ 19.58
2		45	+ 34.26	+ 35.31	+ 36.27
4		60	+ 47.64	+ 50.34	+ 52.71
		Average	+ 26.88	+ 30.09	+ 28.66
5	Subsurface dam depths (cm)	15	+ 3.56	+ 3.44	+ 3.21
6		30	+ 10.14	+ 10.58	+ 10.58
7		45	+ 13.43	+ 17.12	+ 18.52
8		60	+ 14.38	+ 18.66	+ 21.90
		Average	+ 10.38	+ 12.45	+ 13.55
9	Earth fill Hydraulic conductivity (m day^{-1})	734.40	+ 3.39	+ 6.83	+ 8.78
10		604.80	+ 9.85	+ 12.62	+ 14.09
11		345.60	+ 16.67	+ 21.18	+ 22.13
12		216	+ 33.78	+ 34.96	+ 35.43
		Average	+ 15.92	+ 18.90	+ 20.11
13	Freshwater recharge rates (m^3 day^{-1})	0.11404	+ 14.38	+ 14.17	+ 14.05
14		0.22808	+ 26.17	+ 26.11	+ 26.17
15		0.34212	+ 35.92	+ 36.17	+ 36.59
16		0.45616	+ 44.04	+ 44.63	+ 45.48
		Average	+ 30.13	+ 30.27	+ 30.57
17	Brackish water abstraction rates (m^3 day^{-1})	0.11404	+ 3.05	-2.69	+ 2.44
18		0.22808	+ 6.21	-5.57	+ 5.11
19		0.34212	+ 9.26	-8.45	+ 7.85
20		0.45616	+ 12.02	-11.19	+ 10.53
		Average	+ 7.64	-6.97	+ 6.48
21	Combine of two cases rates (m^3 day^{-1})	0.11404	+ 17.51	+ 17.00	+ 16.65
22		0.22808	+ 31.14	+ 30.66	+ 30.42
23		0.34212	+ 41.24	+ 41.12	+ 41.25
24		0.45616	+ 48.33	+ 48.75	+ 49.32
		Average	+ 34.55	+ 34.38	+ 34.41
25	Check dam heads (cm)	17.50	+ 21.39	+ 22.73	+ 20.13
26		18	+ 39.67	+ 42.35	+ 37.92
27		18.50	+ 52.66	+ 55.99	+ 54.79
28		19	+ 62.27	+ 65.77	+ 62.45
		Average	+ 44.00	+ 46.71	+ 43.82

cutoff wall and subsurface dam for different bed slopes are presented in Fig. 6b and c.

3.2.2 Effect of land reclamation

The technique of earth fill is simulated by increasing the model width to 220 cm using 20 cm of fill with changing the fill hydraulic conductivity by 70%, 55%, 40% and 25% to reach 604.80 m day $^{-1}$, 475.20 m day $^{-1}$, 345.60 m day $^{-1}$ and 216 m day $^{-1}$ for the three bed slopes compare with 864 m day $^{-1}$ for aquifer hydraulic conductivity (see Fig. 6c). The 0.5 Isochlor reached a distance of 67.625 cm, 62.50 cm, 57 cm and 41.50 cm from the sea side with salinity reduction reaching + 3.39, + 9.85, + 16.67 and + 33.78% respectively. The SID reached 74.75, 69.50, 61.75 and 47.50 cm with salinity reduction 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 cm, 72.50 cm, 65 cm and 50 cm with salinity reduction reached + 8.78%, + 14.09%, + 22.13% and + 35.43%. Figure 6d is presented the relations between the intrusion length (XT) and the fill earth methods for different bed slopes.

3.2.3 Effect of combine abstraction and recharge

This technique used three cases to investigate the effect of the aquifer abstraction and recharge rates on SWI by (a) abstraction of saline groundwater, (b) recharge with wastewater or storm water, and (c) combination of both. Different settings of ABS were also examined, assessing the SWI improvement in terms of SID and salt repulsion. The recharge well was installed and located at 1 m from shoreline with depth − 0.40 m form the model top, while the abstraction well was simulated at 0.40 m from shoreline with depth − 0.85 from the model top surface 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 the wastewater recharge showed that SID is reached 85.75 cm, 80.25 cm, 77.75 cm and 75 cm with a reduction of + 3.05%, + 6.21%, + 9.26% and + 12.02%. The combination of the saline water abstraction and the freshwater recharge showed that SID reached 77.375 cm, 66.50 cm, 58 cm and 53.75 cm with a reduction in salinity of + 17.51%, + 31.14%, + 41.24% and + 48.33%, respectively.

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

For the landside slope, the SID reached 95, 85, 75.50 and 68.25 cm with repulsion of + 14.05%, + 26.17%, + 36.59% and + 45.48% at the abstraction rates. The recharge results for SID were 102.25 cm, 98.75 cm, 95 cm and 92.25 cm with repulsion equal to + 2.44%, + 5.11%, + 7.85% and + 10.53% while the combination of the abstraction and the recharge rates were reached 92.25 cm, 80.25 cm, 71.25 cm and 65 cm with repulsion of + 16.65%, + 30.42%, + 41.25% and + 49.32%, as presented in Fig. 6e–g.

3.2.4 Effect of check dams

This case represents the effect of check dams on SWI. The head of the dam is changed by 17.50 cm, 18 cm, 18.50 and 19 cm. the SID reached 51.16 cm, 39.27 cm, 30.81 cm and 24.56 cm respectively. The repulsion is + 21.39%, + 39.67%, + 52.66% and + 62.27% at the sea side slope(see Fig. 6e). The results of horizontal slopes reached 83, 67.625, 55.75 and 47.25 cm while the repulsion were + 22.73%, + 42.35%, + 55.99% and + 65.77%. For land side slope, SID reached 67.38 cm, 52.38 cm, 39.24 cm and 35.19 cm with repulsion was + 20.13%, + 37.92%, + 54.79% and + 62.45% as presented in Fig. 6 h.

The results showed that the average values for SWI repulsion were 26.88%, 30.09%, and 28.66% using cut-off wall and + 10.38%, + 12.45% and + 13.55% using the subsurface dam for ABS for the sea side, horizontal and land side respectively. 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 an advantageous method in land side slopes where the SWI repulsion reached + 15.92%, + 18.90%, and + 20.11% (see Table 1).

The use of hydraulic methods of the freshwater recharge led to repulsion of + 30.13%, + 30.27% and + 30.57%, while the using of abstraction of brackish water reached + 7.64%, + 6.97% and + 6.48% The 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 the abstraction and combination scenarios were 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 (see Table 1).

3.3 Effect of SLR and reduction the freshwater recharge on SWI for the GCA

The effects of SLR and the reduction in fresh groundwater storage by decreasing in flow to the aquifer by recharge and increasing the wells abstraction rates on GCA were simulated by 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 (see Table 2).

The aquifer return flow by leakage from the 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 done due to abstraction increase, which should be necessary to satisfy the increasing water demand by over population. 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} at 2050 compared with 102.68 MCM yr^{-1} at base case.

The groundwater abstraction should increase reaching 288.52 MCM yr^{-1} at 2050 to be compared with 175 MCM yr^{-1} at base case.

Table 2 summarizes the entire simulated modifications at 2050. The results of equi-concentration line 35,000 ppm are shown in Fig. 7, the intrusion length reached 6281 m from shore line measured at aquifer bottom and the salt mass is reached 1.04621×10^7 kg.

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 Henry's problem approach.

Table 2 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

Table 3 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

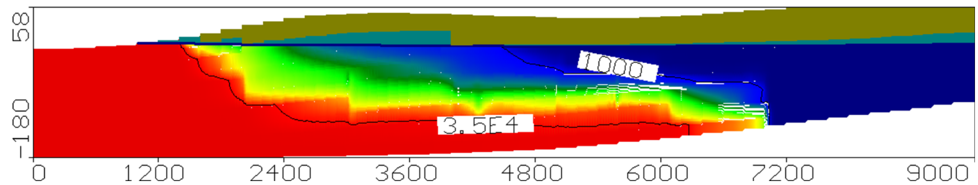


Fig. 7 Equi-concentration line 17,500 ppm under SLR by 23.60 cm and reduction in freshwater recharge for Gaza aquifer

3.4.1 Effect of physical subsurface barriers

The physical subsurface barrier is installed at 3000 m from the shoreline with hydraulic conductivity equal to 1×10^{-5} m day^{-1}, the bottom of the cut-off wall level is (-101.00) from MSL and (+ 45.00) from the ground surface, while the top subsurface dam is carried out at level (-73.00) and the bottom at level (-176.00) above MSL. The SID reached 3,035 m and 3,002 m from shoreline, the salt mass is reached 9,999,650 and 10,453,700 kg for the two cases respectively (see Fig. 8a and b).

3.4.2 Effect of land reclamation

The land fill depth is ranged from level (-9.30) to (-20.70) from MSL with a length of 1200 m from the shoreline, the fill hydraulic conductivity is 0.10 m day^{-1}. The SID reached 5510 m, as presented in Fig. 8c. The aquifer salt mass reached 9,116,411 kg.

3.4.3 Effect of combine abstraction and recharge

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

The total expected production from wastewater in the 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 will be 87.58 Mm^3/year at 2050. 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 as 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 a depth − 60.00 form MSL. The SID reached 3,350 m with a salt mass of 6,028,400 kg.

The future desalination volume is expected to 129.74 MCM yr^{-1} by 2035 for the 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. SID reached 2990 m with salt mass of 1.00089×10^7 kg. Combining recharge and abstraction wells, SID reached 2,933 m with a salt mass is 6,413,380 kg (see Fig. 8d–f).

3.4.4 Effect of check dams on SWI

In this scenario the GCA was simulated adding check dam. 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 Fig. 8g; the SID reached 4,203 m from shore line with the aquifer salt mass is 7,918,470 kg (Table 4).

Considering as reference the base case (Run 1, Table 3) of the Gaza aquifer, the global change scenario, describes huge effects with increases in terms of SID, equal to 3,104 m, and salt volume, equal to 4,743,280 kg. In terms of management initiatives, the worst solution seems the earth fill (Run 5), without improvements both in terms of SID and total salt volume. Very low is the SID improvement with cut-off wall (Run 3) and subsurface dam (Run 4) solutions, which are unable to avoid a huge increase of total salt volume.The use of recharge (Run 6) with or without abstraction (Run 8) offers the best results. Referring to the base case, the SID variation is 173 and − 244 m and the salt total volume variation is 309,580 and 694,560 for recharge and recharge with abstraction respectively.

4 Conclusion

Saltwater intrusion in coastal aquifers is a natural phenomenon which can cause increasing groundwater quality degradation due to the global change. This study was assessed numerically the efficiency of different management solutions in terms of salt repulsion and SID modifications using a conceptualised aquifer and a real aquifer. The coastal aquifers or the portion of those with a side bed slope resulted in more proneness to SWI than sea side and horizontal bed slope cases. The cut-off walls and check dams reach the best efficiency with horizontal bed coastal aquifers. The efficiency of the subsurface dams, earth fill, and recharge of freshwater prevails for aquifers with land bed slopes while the abstraction of brackish water and the combination of freshwater recharge with brackish water abstraction are prevail in the case of sea side slopes.

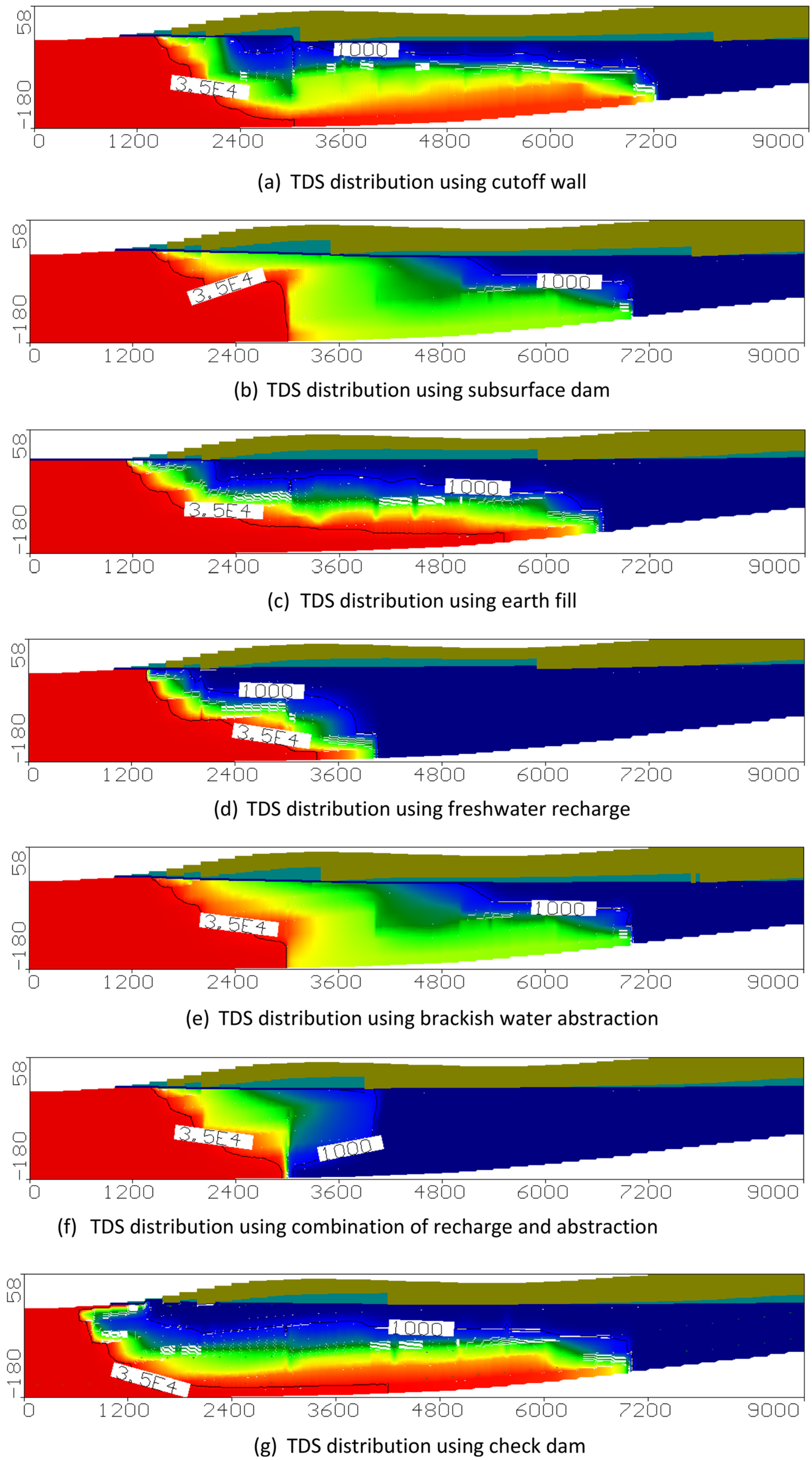


Fig. 8 Salinity distribution using different management techniques for sea bed slopes of Gaza aquifer

(a) TDS distribution using cutoff wall

(b) TDS distribution using subsurface dam

(c) TDS distribution using earth fill

(d) TDS distribution using freshwater recharge

(e) TDS distribution using brackish water abstraction

(f) TDS distribution using combination of recharge and abstraction

(g) TDS distribution using check dam

Table 4 Schematic main solutions and results for Gaza aquifer

Run number	Case	Unit	Values	Intrusion length (SID, m)	Salt volume (kg)
1	Base	–	-	3177	5,718,820
2	SLR	cm	23.60	6281	10,462,100
	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	9,999,650
4	Subsurface dam	Depths (m)	100	3002	10,453,700
5	Earth fill	Hydraulic conductivity (m day^{-1})	0.10	5510	9,116,411
6	Recharge using treated waste water	Rates (MCM yr^{-1})	80	3350	6,028,400
7	Abstraction from brackish water	Rates (MCM yr^{-1})	129.74	2990	10,008,900
8	Combine of recharge and abstraction	Rates (m^3 day^{-1})	80 (R) and 129.74 (A)	2933	6,413,380
9	Check dam	Heads (m)	+ 7.00	4203	7,918,470

The efficiency of these solutions was tested for the Gaza coastal aquifer, a real sea bed slope aquifer, the type more prone to SWI. The main results showed the huge relevance of global change effects on this aquifer but also highlighted the optimal management solutions, mainly focused on the recharge with treated wastewater. Future research efforts will concern a real aquifers with different slopes bed and efforts to enlarge the research to the effects of the third dimension, operating with tank laboratory experiments and real aquifers.

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Code availability Upon request.

Declarations

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Consent to participate Yes

Consent for publication Yes

References

Abd-Elaty I, Abd-Elhamid F, Qahman K (2020) Coastal aquifer protection from saltwater intrusion using abstraction of brackish water and recharge of treated wastewater: case study of the gaza aquifer. J Hydrol Eng Issue 7(25):81. https://doi.org/10.1061/(ASCE)HE.1943-5584.0001927

Abd-Elaty I, Hany FA, Nezhad M, M (2019b) Numerical analysis of physical barriers systems efficiency in controlling saltwater intrusion in coastal aquifers. Environ Sci Pollut Res. https://doi.org/10.1007/s11356-019-06725-3

Abd-Elaty I, Pugliese L, Straface S (2022) Inclined physical subsurface barriers for saltwater intrusion management in Coastal Aquifers. Water Resour Manag 36:2973–2987. https://doi.org/10.1007/s11269-022-03156-7

Abd-Elaty I, Saleh OK, Ghanayem HM, Grischek T, Zelenakova M (2021) Assessment of hydrological, geohydraulic and operational conditions at a riverbank filtration site at Embaba, Cairo using flow and transport modeling. J Hydrol Reg Stud 2:37. https://doi.org/10.1016/j.ejrh.2021.100900

Abd-Elaty I, Sallam G, Strafacec A, Scozzari A (2019) Effects of climate change on the design of subsurface drainage systems in coastal aquifers in arid/semi-arid regions: case study of the Nile delta. Sci Total Environ J 672:283–295. https://doi.org/10.1016/j.scitotenv.2019.03.483

Abd-Elaty I, Shahawy AE, Santoro S, Curcio E, Straface S (2021c) Effects of groundwater abstraction and desalination brine deep injection on a coastal aquifer. Sci Total Environ 795:148928

Abd-Elaty I, Straface S, Kuriqi A (2021) Sustainable saltwater intrusion management in Coastal Aquifers under climatic changes for humid and hyper-arid regions. Ecol Eng 3:171. https://doi.org/10.1016/j.ecoleng.2021.106382

Abd-Elaty I, Zelenakova M (2022c) Saltwater intrusion management in shallow and deep coastal aquifers for high aridity regions. J Hydrology: Reg Stud 40:101026. DOI:https://doi.org/10.1016/j.ejrh.2022.101026

Abd-Elhamid HF, Abd-Elaty I, Mohsen M, Sherif, (2020) Effects of aquifer bed slope and sea level on saltwater intrusion in coastal aquifers. Hydrology 7(1):5. https://doi.org/10.3390/hydrology7010005

Abd-Elhamid HF, Javadi A, Abdelaty I, Sherif M (2016) Simulation of seawater intrusion in the Nile Delta aquifer under the conditions of climate change. Hydrol Res 47(6):1198–1210. https://doi.org/10.2166/nh.2016.157

Abdoulhalik A, Ahmed A, Hamill GA (2017) A new physical barrier system for seawater intrusion control. J Hydrol 549:416–427

Abu HZ, Muhsen S (2016) Application of vertical electrical sounding for delineation of sea water intrusion into the freshwater aquifer of southern governorates of Gaza strip, palestine. IUG J Nat Stud Peer-Rev J Islamic Univ Gaza 24(2):07–20

Agren J, Svensson R (2007) Postglacial land uplift model and system definition for the new Swedish height system RG 2000. Gävle, Lantmäteriet

Bd-Elaty A, Kushwaha I, Grismer NL, Elbeltagi ME, Kuriqi A, A (2022b) Cost-effective management measures for coastal aquifers affected by saltwater intrusion and climate change. Sci Total Environ 836:155656. DOI:https://doi.org/10.1016/j.scitotenv.2022.155656

Bear J, Cheng AH, Sorek S, Quazar D, Herrera I (1999) Seawater intrusion in coastal aquifers, concepts, methods and practices. Kluwer Academic publisher, Dordrecht

Church JA, Clark PU (2013) Sea Level Change. Climate change 2013: the physical science basis, contribution of Working Group 1 to the Fifth assessment report of the intergovernmental panel on climate change. IPCC, Geneva

El Shinawi A, Kuriqi A, Zelenakova M, Vranayova Z, Abd-Elaty I (2022) Land subsidence and environmental threats in coastal aquifers under sea level rise and over-pumping stress. J Hydrol 608:127607. DOI:https://doi.org/10.1016/j.jhydrol.2022.127607

Guo H, Jiao JJ (2007) Impact of coastal land reclamation on ground water level and the sea water interface. Ground Water 45(3):362–367

Guo H, Jiao JJ (2009) Coastal groundwater system changes in response to large-scale land reclamation. Nova Science Publishers,Inc, New York

Guo W, Langevin CD (2002) User's guide to SEAWAT: a computer program for simulation of three-dimensional variable-density groundwater flow, US Geological Survey Techniques of Water Resources Investigations 6-A7. US Geological Survey, Tallahassee, Florida

Harbaugh AW, Banta ER, Hill MC, McDonald MG (2000) MODFLOW-2000, the U.S. Geological survey modular ground-water model—user guide to modularization concepts and the groundwater flow process: U.S. Geological Survey Open-File Report 00–92, p 121

Henry HR (1964) Effect of dispersion on salt encroachment in coastal aquifers. US Geol Surv Water-Supply Pap 1613:70–84

IPCC (2021) The IPCC has finalized the first part of the sixth assessment report, climate change 2021: the physical science basis, the working group i contribution to the sixth assessment report. It was finalized on 6 August 2021 during the 14th Session of Working Group I and 54th Session of the IPCC

IPCC (2014) Climate change 2014: synthesis report. In: Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.) Contribution of working groups I, II and III to the fifth assessment report of the intergovernmental panel on climate change. IPCC, Geneva, Switzerland, pp 151

IPCC (2007) An Assessment of the Intergovernmental Panel on Climate Change. Adopted section by section at IPCC Plenary XXVII (Valencia, Spain, 12–17 November 2007), represents the formally agreed statement of the IPCC concerning key findings and uncertainties contained in the Working Group contributions to the Fourth Assessment Report

Intera EC (1979) Revision of the documentation for a model for calculating effects of Liquid Waste Disposal in Deep saline aquifers. US Geol Surv Water Res Publ 79–96:72

Luyun R Jr, Momii K, Nakagawa K (2009) Laboratory-scale saltwater behavior due to subsurface cutoff wall. J Hydrol 377(3–4):227–236. https://doi.org/10.1016/j.jhydrol.2009.08.019

Mahmoodzadeh D (2019) Seawater intrusion in hetero-geneous coastal aquifers under flooding events. J Hydrol 568(Jan):1118–1130. https://doi.org/10.1016/j.jhydrol.2018.11.012

McDonald RI, Green P, Balk D, Fekete BM, Revenga C, Todd M, Montgomery M (2011) Urban growth, climate change, and freshwater availability. Proc Natl Acad Sci 108:6312–6317. https://doi.org/10.1073/pnas.1011615108

Metacalf and Eddy (2009) Geophysical survey in the Gaza governorate. Blackhawk geometrics project number 2009. Gaza Strip

Naeem MFaroukAAl, Yusoff I, Ng TF, Maity JP, Alias Y, May R, Alborsh H (2019) A study on the impact of anthropogenic and geogenic factors on groundwater salinization and seawater intrusion in Gaza coastal aquifer, Palestine: an integrated multi-techniques approach. J Afr Earth Sc 156:75–93. https://doi.org/10.1016/j.jafrearsci.2019.05.006

PCBS (2000) Population, housing and establishment census 1997. Palestinian National Authority, Palestinian Central Bureau of Statistics (PCBS), Ramallah, pp 19

PCBS (2015) Palestinians Population Status in the Palestine, 2015. Ramallah-Palestine. Retrieved from http://www.pcbs.gov.ps/Downloads/book2135.pdf

Palestine Palestinian Water Authority, PWA (2015) Water resources status summary report/Gaza Strip. PWA, Palestine

Palestinian W, Authority PWA (2011) The Gaza Emergency Technical Assistance Programme (GETAP) on water supply to the Gaza Strip, the comparative study of options for an additional supply of Water for the Gaza Strip (CSO-G), the updated final report. PWA, Palestine

Palestinian Water Authority (PWA) (2013) Archived data. PWA, Gaza

Palestinian W, Authority PWA (2001) Hydrogeological report for the Gaza strip. Technical report, Volume 2, Palestinian Water Authority (PWA), Palestine, pp 67

Polemio M, Zuffianò LE (2020) Review of utilization management of Groundwater at risk of salinization. J Water Resour Plan Manag 146(9):20. https://doi.org/10.1061/(ASCE)WR.1943-5452.0001278

Qahman K (2004) Aspects of hydrogeology, modeling, and management of seawater intrusion for Gaza aquifer-Palestine, PhD, Thesis. Universite Mohamed V–AGDAL, Morocco, pp 181

Roger LJ, Kazuro M, Kei N (2009) Laboratory-scale saltwater behavior due to subsurface cutoff wall. J Hydrol 377:227–236
Roger LJ, Kazuro M, Kei N (2010) Effects of artificial recharge and flow barrier on seawater intrusion. Ground Water
SVCHEM (2018) Soil vision systems Ltd. Saskatoon, Saskatchewan, Canada
SWIMED project (2002) Sustainable water management in mediterranean coastal aquifers
Sarsak RF (2011) Numerical Simulation of seawater intrusion in response to Climate Change Impacts in North Gaza Coastal Aquifer using SEAWAT, MSc, Faculty of Graduate Studies. at An-Najah National University, Nablus, Palestine
Simpson MJ, Clement TB (2004) Improving the worthiness of the Henry problem as a benchmark for density-dependent groundwater flow models. Water Resour Res 40(1):1–11
Singh A (2012) An overview of the optimization modelling applications. J Hydrol 5:466–467. https://doi.org/10.1016/j.jhydrol
Sirhan H, Koch M (2013) Numerical modeling of the effects of artificial recharge on hydraulic heads in constant-density ground water flow to manage the Gaza Aquifer, Coastal Palestine, South. In: Proceeding 6th international conference on water resources and environment research, pp 114–147. Doi: https://doi.org/10.5675/ICWRER
Voss CI, Souza WR (1987) Variable density flow and solute transport simulation of regional aquifers containing a narrow freshwatersaltwater transition zone. Water Resour Res 23:1851–1866
Wada Y, Flörke M, Hanasaki N, Eisner S, Fischer G, Tramberend S, Satoh Y, van Vliet MTH, Yillia P, Ringler C et al (2016) Modeling global water use for the 21st century: the water futures and solutions (WFaS) initiative and its approaches. Geosci Model Dev 9:175–222. https://doi.org/10.5194/gmd-9-175-2016
Zheng C, Wang PP (1999) MT3DMS, a modular three-dimensional multi species transport model for simulation of advection, dispersion and chemical reactions of contaminants in groundwater systems: documentation and user's guide. U.S. Army Engineer Research and Development Center Contract Report SERDP-99-1, Vicksburg, MS, pp 202