



Simulation of groundwater flow and seawater intrusion in response to climate change and human activities on the coastal aquifer of Gaza Strip, Palestine

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Abstract

This study has investigated the potential impact of human activities and climate change on the groundwater budget, water levels, and seawater intrusion in the coastal aquifer of the Gaza Strip (State of Palestine) over the next two decades. The impact of a proposed measure to use alternative freshwater provision from desalinated seawater on the future groundwater quantity and quality was also analyzed. Following extensive analysis of available observed data, a three-dimensional groundwater flow model, coupled with variable-density saltwater flow and transport components, was utilized for the investigations. Compared with the benchmark scenario (SC0), the climate change scenario (SC1) suggests that over the next two decades, an average annual aquifer recharge of 6.3 Mm³ can be expected, while the human activities scenario (SC2) indicates that the groundwater levels will decline at a rate of 0.09 m/year with expected urban area expansion. The combined human activities and climate change scenario (SC3) indicate severe groundwater storage depletion and seawater intrusion over the next two decades. The alternative freshwater provision scenario (SC4) indicates a strongly positive response in groundwater recovery (quantity and quality) over the next decades. The findings of this study emphasize strongly that the human activity impact, rather than climate change, is the driving force of groundwater depletion and that groundwater recovery interventions will be crucial in the future and should be implemented urgently.

Keywords Palestine · Climate change · Human activities · Seawater intrusion · Groundwater development

Introduction

Groundwater is considered a vital resource for preserving ecosystems and securing human adaptation to unstable global environmental changes, especially as surface-water environments are becoming increasingly unsustainable due to climate change and rapid population growth. Groundwater is strongly affected by climatic oscillations (Liesch and Wunsch 2019). Climate change is predicted to increase temperatures in the Mediterranean region and decrease precipitation, threatening the freshwater budget and conceivably

exacerbating the freshwater resource deficiencies that Mediterranean coastal areas are already facing (La Jeunesse et al. 2016). Anthropogenic drivers such as land-use changes, groundwater overabstraction, and use of illegal wells (wells unknown to the local authority) add extra challenges in providing a context for changes in groundwater characteristics that could be attributed to climate change (Amanambu et al. 2020). The fifth assessment report of the International Panel on Climate Change (IPCC) indicated that “groundwater recharge may be significantly influenced by climate change in areas that receive between 200 and 500 mm/year (like the Gaza Strip area), where the coastal aquifers are additionally vulnerable to climate change because of high rates of groundwater abstraction and sea level rise (SLR), which induces saltwater intrusion into the aquifer” (IPCC 2014b). It is essential to encourage research related to the impacts of climate change on the groundwater budget to identify cost-effective solutions and management options for water resources to guide global groundwater policy for the future (Khater 2010; Amanambu et al. 2020).

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Groundwater is the most copious source of freshwater on earth; 35% of total global water withdrawals are from groundwater (IPCC 2014a). To date, studies on the impact of human activities on groundwater storage in coastal aquifers (Eshtawi et al. 2016; Velis et al. 2017; Mushtaha et al. 2019) have suggested that groundwater quantity and quality will be degraded by human activities in most populated coastal aquifers. Zheng et al. (2018) used coupled finite element subsurface flow system models and a stormwater management model to investigate low-impact development (LID) interventions on groundwater head in the coastal aquifer of Shenzhen, China. The LIDs were simulated as small-scale environmental systems that could infiltrate, store, and retain rainfall from permeable pavements, green roofs, and vegetated swales. Their results showed that the runoff would decrease by 9% in response to a 15% total area of LID interventions in built-up areas and that a 1.7 m increase in groundwater levels could be expected. Eshtawi et al. (2016) developed a groundwater model for the coastal aquifer of the Gaza Strip, where stormwater harvesting from the flat roofs of buildings in the built-up areas was simulated. The results of the study reflected a slight improvement in the groundwater quantity and quality, which raised the question of whether this measure could be promoted as a strategic adaptation measure as part of a water plan for the Gaza Strip.

The Gaza Strip coastal aquifer provides a typical example of groundwater deterioration as a result of anthropogenic activities, where abstraction from the Gaza coastal aquifer occurs at twice the aquifer's annual average rate of recharge, and more than 96% of abstracted water is polluted due to seawater intrusion and wastewater infiltration (El-Baba 2017). Studies related to the effect of climate change on the Gaza Strip's water budget are limited but identification of the key impacts of climate change and the prioritization of adaptation measures are critical for national development and policy directions to prepare for the influences of climate change on water resources (UNDP 2009). A short-term low volume (STLV) program that includes seawater desalination is one of the main options proposed for water supply provision to reduce the pressures on the overexploited coastal aquifer in the Gaza Strip. However, a further study to assess its real impact on groundwater recovery of the Gaza Strip coastal aquifer over the next decades is needed before this proposal can be adopted (CMWU 2019).

The current paper is innovative in the sense that it provides an approach for assessment and identifies optimal solution(s) to enhance the sustainability of groundwater resources in the Gaza Strip. It provides a comprehensive view of the future groundwater system of the Gaza Strip under separate and combined impacts of human activities, climate change, and the planned recovery of the groundwater in the Gaza Strip as a part of the SVLT program. A three-dimensional (3D) groundwater flow model

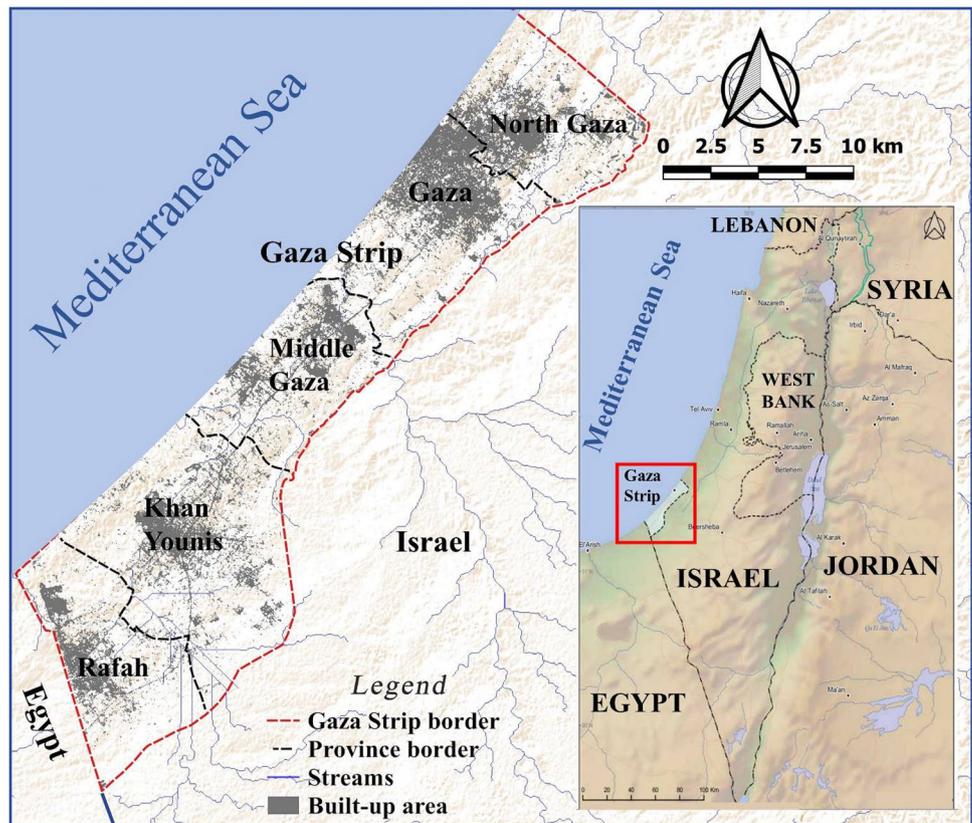
(MODFLOW-2005; McDonald and Harbaugh 1988) and a variable-density saltwater flow and transport (SEAWAT; Zheng and Wang 1999) model within the groundwater modelling system (GMS) environment were utilized in this study to investigate the variation in groundwater budget, levels, and seawater intrusion under different proposed scenarios. A comprehensive baseline assessment was performed based on the observed data and the downscaled regional climate model (RCM) output from the PF7-CLIMB (Dentoni 2012) project. Accordingly, this study assessed: (1) the severity of future groundwater depletion and seawater intrusion under climate change impact and human activities, and (2) the effectiveness of the proposed groundwater recovery program in the Gaza Strip. The findings of the study provide recommendations for future groundwater developments in the Gaza Strip coastal aquifer.

Study area

The State of Palestine has two separate areas, the West Bank and the Gaza Strip (Fig. 1), both located in the subtropical zone. The Gaza Strip (the study area) is a narrow strip along the southeast of the Mediterranean region (31°25' N, 34°20' E; PWA and CMWU 2014). The study area is located in a transition zone between the semihumid coastal zones in the north, the semiarid zone in the east, and the Sinai Desert in the south (Mushtaha et al. 2019). The Gaza Strip occupies a land area of 365 km², with a length of 45 km and a width that varies between 6 km in the Deir El Balah province and 12 km in the southern province (Baalousha 2005). The Gaza Strip coastal aquifer is part of a larger aquifer of varied depth and width that extends from the Sinai Desert in the south to the Karmal Mountains in the north (Eshtawi et al. 2016). The coastal aquifer is permeable, shallow, and unconfined with a productive zone along the coast and groundwater flows from the hinterland in the east towards the Mediterranean Sea (Baalousha 2011).

The Gaza coastal aquifer is composed of calcareous sandstone, conglomerate, and gravel from the Pleistocene age and dunes that were formed in the recent Holocene age, with a top cover of dunes mainly in the western part of the Gaza Strip, and loess soils that dominate the eastern part. The impervious base comprises marine clays, shales, and marls (Saqiya Group; Abualtayef et al. 2017). The total thickness of the western parts of the coastal aquifer varies between 100 and 180 m; the eastern part varies between 10 and 80 m (PWA 2020). Intermediate intercalations of clayey and loamy aquitards, extending from 2 to 5 km inland, separate the aquifer near the coastline into four subaquifers, named in all studies as A, B1, B2, and C (Fig. 2a). The upper subaquifer (A) is unconfined, while subaquifers B1, B2, and C

Fig. 1 Study area in the Gaza Strip, Palestine

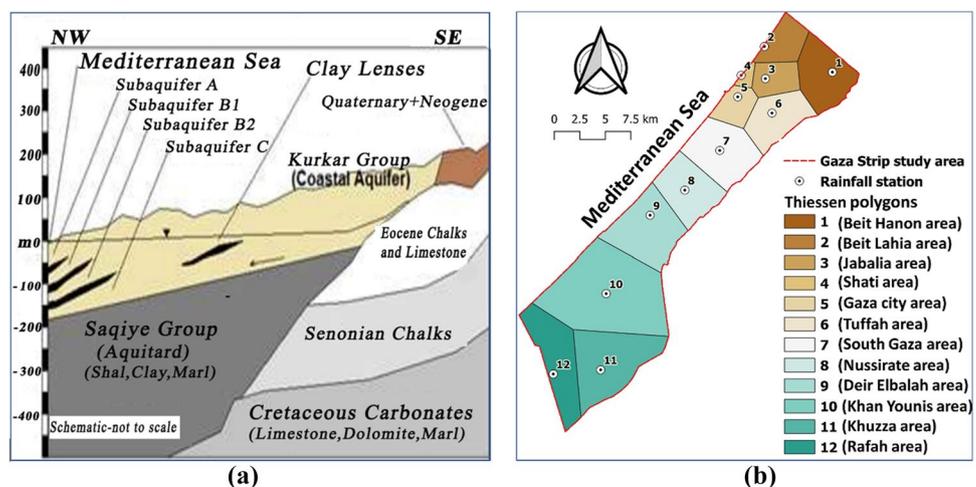


are semiconfined in the coastal area (PWA 2017; CMWU 2019; Mushtaha et al. 2019).

The Gaza Strip has a short rainy season and long dry summer (PWA and CMWU 2014). Meteorological data are available from the Ministry of Agriculture (MOA) in the Gaza Strip. Twelve rain gauge stations cover the provinces of the entire Gaza Strip (Fig. 2b). The average daily mean temperature ranges between 13.4 °C in winter and 26 °C in summer (PWA and CMWU 2014). The hottest month is

August with an average temperature of 25–28 °C and the coldest month is January with an average temperature of 12–14 °C (PWA 2017). The mean annual precipitation in the Gaza Strip is 327 mm and reduces gradually from the west (coastline) to the east (Eshtawi et al. 2016). The hydrological year of the Gaza Strip commonly starts in October or November (Eshtawi et al. 2016). The average solar radiation ranges from 8.5 to 25.6 MJ/m²/day in winter and summer, respectively, and the reference evapotranspiration (ET₀)

Fig. 2 a Typical cross-section of the coastal aquifer of Gaza (PWA 2004); b Location of rainfall gauge stations; Thiessen polygons were created with QGIS. The monthly rainfall in these 12 stations is provided in section S1 in the electronic supplementary material (ESM)



ranges from 1.8 mm/day in February to 5.7 mm/day in July (Al-Najar 2011).

Groundwater withdrawal and recharge

Since the 1930s, the groundwater abstraction from the coastal aquifer of the Gaza Strip has increased gradually as a result of population growth and agricultural area expansion (Messerschmid 2012). From 2010 to 2019, the annual groundwater abstractions from 2829 agricultural wells ranged from 76 to 99 Mm³, and the annual groundwater abstractions for domestic purposes from 319 municipal and United Nations Relief and Works Agency (UNRWA) wells ranged from 75 to 101 Mm³ (Fig. 3), according to the data acquired from the Palestinian Water Authority (PWA) (PWA 2020). Some of the municipalities in three provinces (Gaza City, Deir El Balah, and Khan Younis) have had to purchase freshwater from Israel (called Mekorot) to mix with the abstracted groundwater for a better quality water supply. The volume of purchased freshwater ranged from 3 Mm³ in 2014 to 12.5 Mm³ in 2019, whereas the quantities for the other years within the baseline period ranged between the previous values (PWA 2020). The average annual agricultural demand in the Gaza Strip during the baseline period (2010–2019) was estimated at

90–130 Mm³ during the calibration process (Fig. 3), all of which was met by abstraction of groundwater, and which constituted 49–62% of the total groundwater abstraction (PWA 2020). The returning flow from agricultural irrigation varies between 22 and 24% of the total irrigation within the Gaza Strip (Ghabayen and Salha 2013).

The aquifer recharge differs monthly and annually, depending mainly on the precipitation pattern within the study area, land-use changes with time, and other recharge components. The results of a previous study showed that the average annual aquifer recharge within the Gaza Strip area varied between 20 and 120 mm during 2009–2014, where the northern province had the highest aquifer recharge and the south had the lowest values (Mushtaha et al. 2019). From 2010 to 2019, the average water supply network efficiency was 55.3% in the northern province, while the best average efficiency was found in Rafah Province at 68.4% (PWA and CMWU 2014; PWA 2015; CMWU 2019). The overall losses of the water supply network are a result of illegal connections. Physical losses from the network contribute to aquifer recharge (CMWU 2019). The wastewater quantities are estimated at 70–80% of the consumed domestic water supply (Afifi 2006). The wastewater system efficiency was estimated at 80% (20% losses) for each province of the Gaza Strip from 2010 to

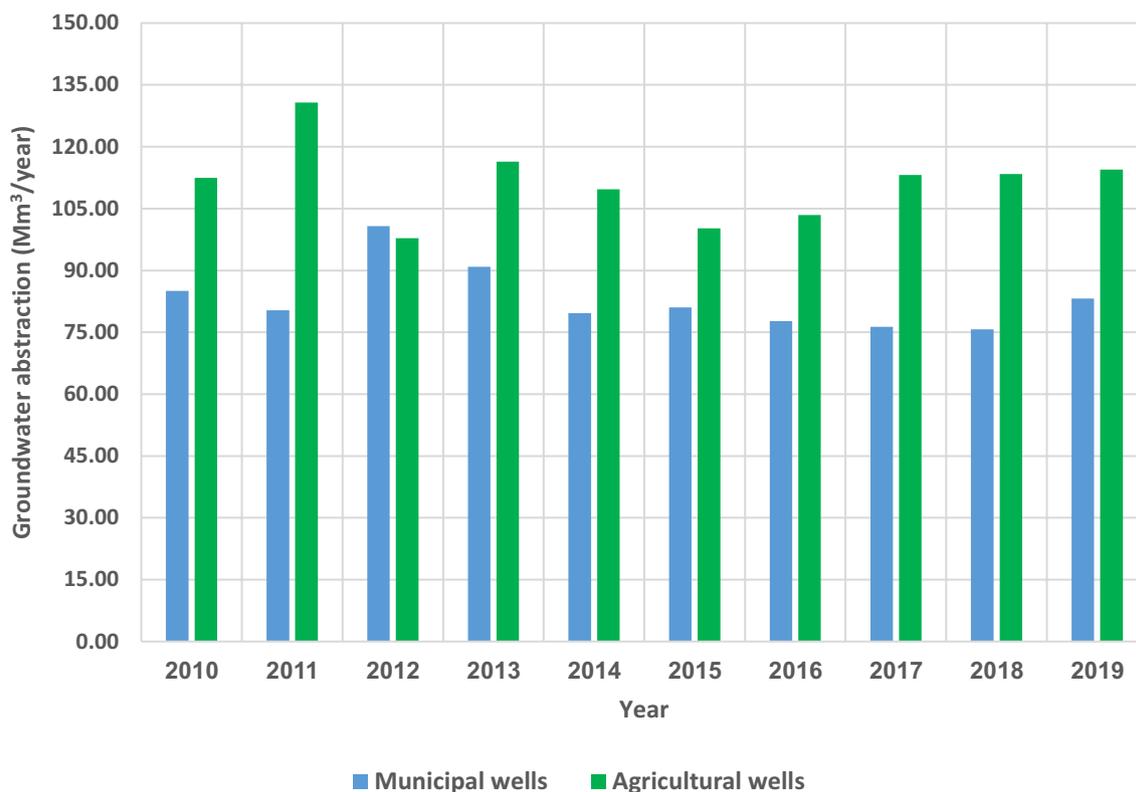


Fig. 3 The annual municipal and agricultural abstraction in the Gaza Strip from 2010 to 2019

2019 (Eshtawi et al. 2016); besides water supply network leakage, this contributes to aquifer recharge.

Using the Semi-Automatic Classification Plugin (SCP) of QGIS and satellite images (Landsat 8), the temporal variation of built-up areas and agricultural areas within the model domain from 2013 to 2020 was produced—see sections S4 and S5 in the electronic supplementary material (ESM). The results indicate a continual expansion of built-up and agricultural areas over time, where the built-up areas expanded from 69 km² in 2013 to up to more than 85 km² in 2020; agricultural areas increased from 175 km² in 2013 to 220.6 km² in 2020. Previously applied land-use classifications were used in the current study to identify the spatial recharge zone of the agricultural and built-up areas simultaneously using the produced land-use maps for the calculation of natural recharge with the topsoil and land use recharge coefficients (Abd-Al Rahman 2016).

Groundwater quality

The chloride (Cl⁻) concentration is the main indicator of groundwater salinization due to seawater intrusion. The Coastal Municipalities Water Utility (CMWU 2019) analyses the hydrochemical components of the groundwater twice a year to investigate the groundwater quality variations over time. Domestic water supply, as well as the generated wastewater, indicate Cl⁻ concentrations of 210–2,500 mg/L, and the irrigation water (total dissolved solids (TDS) <1,500 mg/L) indicates Cl⁻ concentrations of 240–1,300 mg/L (PWA 2020). An average concentration of Cl⁻ of 34.5 mg/L in precipitation within the Gaza Strip area was measured in 2007/2008 (Mushtaha et al. 2019). Table 1 shows the average Cl⁻ concentration in domestic water wells and its generated wastewater, in addition to the irrigation water wells in different provinces of the Gaza Strip, from November 2009 to October 2019. The average Cl⁻ concentration of the seawater was 21,200 mg/L (Lenntech 2017). The previous Cl⁻ concentrations in each recharge area and model domain were used in the model process and calibration.

Materials and methods

Groundwater flow and saltwater transport modeling

Developing a three-dimensional (3D) coupled groundwater flow and saltwater transport model was an important objective of this study as the model is essential for investigating groundwater levels and chloride concentrations (a seawater intrusion indicator) within the Gaza Strip coastal aquifer from 2010 to 2019. The coastal aquifer was modeled using MODFLOW-2005 and SEAWAT within the groundwater modeling system (GMS) environment.

Construction of the hydrogeological conceptual model

Seven layers were conceptualized for the Gaza Strip coastal aquifer, including four subaquifers (A, B1, B2, and C), and three aquitards, considering the different aquifer properties (Fig. 4). Within the Gaza Strip model area, the north and the south boundaries were assumed to be no-flow boundaries (Sirhan 2014). On the east border, a general head boundary was specified to simulate subsurface inflow from Israel, including the agricultural return flow and the rainfall recharge in the wet period. The coastal line on the west side was specified as a constant head (zero) along the Mediterranean Sea. The bottom of the aquifer system was considered an impervious boundary. The monthly recordings for municipal well abstraction, agricultural well abstraction, artificial recharge, water supply leakage, wastewater network leakage, and agricultural return flow were specified as hydrological stresses from November 2009 to October 2019 (Table 2).

Aquifer parameters, initial heads, and initial Cl⁻

The aquifer parameters from the Coastal Aquifer Management Program (CAMP project) implemented within the Gaza Strip area (Metcalf & Eddy Inc. 2000), as well as the results of a previous study, were utilized to estimate the initial hydraulic conductivity, porosity, and specific storage in the current study (Table 3). The vertical hydraulic conductivity was assigned as

Table 1 Average chloride ion concentration in domestic water wells, generated wastewater, and irrigation water wells in different provinces of the Gaza Strip from November 2009 to October 2019

Province	Domestic water and generated wastewater average Cl ⁻ concentration (mg/L)	Irrigation water average Cl ⁻ concentration (mg/L)	Boundary inflow average Cl ⁻ concentration (mg/L) ^a
North	387	277	300
Gaza	1,566	596	300
Middle	1,130	702	300
Khan Younis	962	608	500
Rafah	1,048	543	500

^aAssumed based on transboundary inflow with lower salinity

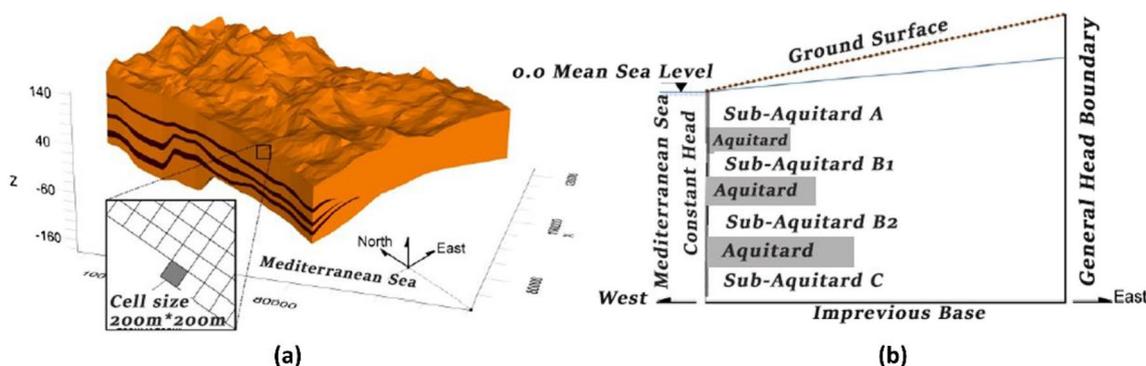


Fig. 4 A conceptual description of the model with numerical model layers: **a** in three dimensions, and **b** cross section

10% of the horizontal hydraulic conductivity. The initial heads of this study were interpolated in the model from measurements of 85 observation wells within the Gaza Strip simulation area in November 2009, acquired from the Palestinian Water Authority (PWA 2020). The chloride concentrations at the end of 2009 within the Gaza Strip model area obtained from the PWA were used as an initial Cl^- concentration in the saltwater transport model (PWA and CMWU 2014).

Numerical model set-up

The model area of the Gaza Strip aquifer was discretized with a grid cell of 200 m × 200 m in MODFLOW-2005

using the GMS environment. The model grid was oriented 42° northeast so that the model rows were parallel with the general groundwater flow direction toward the Mediterranean Sea. The model consisted of 9,087 active cells, which covered a total area of 363.5 km². Seven model layers were divided to represent four subaquifers and interbedded with three aquitards. The top elevation of model layer 1 was interpolated from a digital elevation model with a resolution of 30 m × 30 m. Constant elevations were assigned to the rest of the model layers. The western boundary was chosen at the coastal line where the specified head for the flow model and specified Cl^- concentration for the saltwater transport model were defined. The eastern boundary was located at

Table 2 The abstraction quantities and recharge components were specified as hydrological stresses from November 2009 to October 2019

Period	Municipal and UNRWA well abstraction (Mm ³ /year)	Agricultural well abstraction (Mm ³ /year)	Artificial recharge (Mm ³ /year)	Wastewater network leakage (Mm ³ /year)	Water supply leakage (Mm ³ /year)	Agricultural return flow (Mm ³ /year)
Nov. 2009 to Oct. 2010	85.04	112.43	10.84	7.92	39.47	25.86
Nov. 2010 to Oct. 2011	80.34	130.71	10.84	8.52	41.70	30.06
Nov. 2011 to Oct. 2012	100.73	97.80	10.85	9.12	43.92	22.49
Nov. 2012 to Oct. 2013	90.86	116.42	10.84	8.15	40.62	26.78
Nov. 2013 to Oct. 2014	79.66	109.69	10.84	7.13	33.97	25.23
Nov. 2014 to Oct. 2015	81.01	100.18	10.84	7.38	31.36	23.04
Nov. 2015 to Oct. 2016	77.70	103.41	10.85	7.46	29.68	23.78
Nov. 2016 to Oct. 2017	76.33	113.16	10.84	7.91	29.79	26.03
Nov. 2017 to Oct. 2018	75.72	113.37	10.84	8.04	30.19	26.08
Nov. 2018 to Oct. 2019	83.20	114.44	10.84	8.89	32.52	26.32

UNRWA United Nations Relief and Works Agency

Table 3 The parameters of the Coastal Aquifer Management Program (CAMP) pumping tests ranges, a previous study, and the initial parameter values used in this study (calibrated parameter values are provided in ESM)

Aquifer parameter	Ranges of the CAMP project pumping tests (PWA and CMWU 2014)	Calibrated parameters in a previous study and initial parameter estimation			
		(Sirhan 2014)		Initial values in this study	
		Subaquifers	Aquitards	Subaquifers	Aquitards
Horizontal hydraulic conductivity, K_{xx} and K_{yy} (m/day)	20–80	34	0.2	30	0.21
Specific yield, S_y	0.14–0.3	0.18	0.05	0.21	0.01
Effective porosity	–	0.25	0.3	0.25	0.3
Specific storage (m^{-1})	10^{-4} – 10^{-5}	10^{-4}	10^{-5}	10^{-4}	10^{-5}

the Palestine–Israel boundary where the general head boundary was defined by specifying the head for the flow model and the Cl^- concentration for the transport model. Both the northern and southern boundaries were specified as no-flow boundaries since the general flow direction was parallel to the boundaries. Parameter zones were delineated for seven model layers. Model layer one (top aquifer) was divided into a large number of parameter zones based on aquifer lithology, whereas the rest of the aquifer layers had uniform parameter values. The aquitard layers were divided into two zones: one representing the actual semi-permeable layer and the other representing the aquifer layer where the aquitards were absent. The initial parameter values were assigned (Table 3); final, calibrated parameter values are provided in section S2 in the ESM. The transient simulation time was from 1 November 2009 until 31 October 2019 using the month as the stress period. All time-dependent stresses were input for 120 stress periods. A large number of recharge zones (275) for precipitation infiltration were delineated using land-use and soil maps with QGIS and infiltration coefficients were assigned. The monthly recharge rate per zone was computed by multiplying monthly rainfall by the infiltration coefficient. The estimated monthly rainfall recharge rates in some representative areas are provided in section S3 in the ESM. The leakages from pipelines and irrigation return flows were added to the total groundwater recharge (sections S4 and S5, respectively, in the ESM). The combined recharge was simulated using the MODFLOW Recharge package. The MODFLOW Well package was used to simulate groundwater abstractions for irrigation and domestic water supplies. SEAWAT was used to simulate the saltwater intrusion in the same period and was linked to MODFLOW via MT3DMS. Advective and dispersive transport was simulated using MT3DMS Advection and Dispersion packages, while the SEAWAT variable-density flow (VDF) package was used to simulate the density effects of saltwater intrusion. The initial dispersivity values were assigned based on literature studies and were adjusted in the model calibration. The final estimated values are provided in section S2 in the ESM.

Transient model calibration

In this study, the transient calibration in MODFLOW during the simulation period was implemented automatically (PEST) and manually using 85 observation wells, taking into account: (1) no calibration for the abstraction of municipal and UNRWA wells, as well as the various aquifer recharge components; (2) the observed initial heads were distributed within the Gaza Strip simulation area; and (3) the measured and/or calibrated parameters from previous studies, such as porosity and specific storage, were kept the same during the transient calibration. In order to achieve the best fit between the observed and computed groundwater heads, some parameters and values had to be adjusted, such as (1) hydraulic conductivity and specific yield, especially for the subaquifers of the seven layers that were conceptualized as shown in Fig. 4; (2) the transient general heads along the eastern border of the Gaza Strip; and (3) the estimated agricultural water demand pattern obtained from PWA. Based on the initial estimation of longitudinal dispersivity obtained from a previous study (Yakirevich et al. 1998), the transient chloride transport model (SEAWAT) was calibrated with the monthly measured Cl^- concretions from November 2009 to October 2019.

The research scenario set-up

In this study, all scenarios were simulated for the period from November 2019 to October 2050 with monthly stress periods. The benchmark scenario (SC0) was simulated to investigate future changes in groundwater head, groundwater budget, and seawater intrusion under the ‘business-as-usual’ condition. The development scenarios included the potential impact of climate change, population growth, and potential utilization of alternative sources of freshwater for domestic use and irrigation. Based on the benchmark scenario (SC0), human activities (SC1) and climate change (SC2) were simulated separately to investigate their impact on groundwater levels and seawater intrusion in the coming

three decades. Subsequently, a scenario of the combined impact of both climate change and human activities (SC3) was simulated. Finally, a scenario (SC4) of the impact of (SC3) combined with future desalinated seawater provision (to a maximum of 50% of the total domestic consumption and a maximum of 25% of the total agricultural demand) for the next 30 years was simulated to investigate its efficiency in groundwater recovery.

Benchmark scenario (SC0)

For comparative purposes, the benchmark model assumed no future changes in the boundary conditions, the groundwater abstractions, and the recharge components. In the projection period, the groundwater abstractions from municipal and agricultural wells, general head at the eastern boundary, constant head at the western boundary, water supply network leakage, wastewater network leakage, irrigation return flow, and artificial recharge were assumed to follow 2019 in terms of seasonal variation. However, the natural aquifer recharge (rainfall) was defined as the normal precipitation per year for the period 2010–2019. The average annual precipitation from 2010 to 2019 (PWA 2020) was 341 mm, which was similar to 2019, which had a total precipitation of 337 mm. Appropriately, the monthly aquifer natural recharge from rainfall in the projection period was considered to be the same as the monthly rainfall recharge in 2019.

Climate change scenario (SC1) and the involved climate model

In 2010, the European Commission funded the “Climate-Induced Changes on Hydrology of Mediterranean Basin” project (PF7-CLIMB) for assessing and quantifying uncertainties in climate change impacts in six representative subbasins within the Mediterranean region, including the Gaza Strip area, employing a comprehensive multiple models “ensemble” approach (Ludwig 2014). Fourteen regional climate models (RCMs) were run for the A1B group scenario on a 0.22° grid (resolution of 23–25 km at midlatitudes) for the six representative Mediterranean subbasins, including the Gaza Strip, with daily datasets starting from 1951 to 2100 (Deidda et al. 2013). The projected average annual precipitation (ECH_RCM outputs) for the decades 2020–2030 and 2031–2040 were 397 and 399.5 mm, respectively, which were higher than the average annual rainfall of the baseline period. These projected precipitation data were used in this study for the Gaza Strip area in the next two decades for the natural aquifer recharge calculations in each province. The downscaled RCM output from the PF7-CLIMB project did not consider the sea level rise. A study carried out by Galassi and Spada (2014) investigated the sea-level rise (SLR) up to 2050 for the Mediterranean region. The results predicted that there would be an increase of 3.93 mm/

year in the sea level over the next 50 years; this rate of increase was specified in the specified head boundary of the coastal line in the prediction period.

Human activities scenario (SC2)

In each province, the average daily consumption (L per capita per day) and the water supply network efficiencies in the coming two decades were specified, based on the latest annual report of Coastal Municipalities Water Utility (CMWU) in the Gaza Strip (CMWU 2019). The population growth rate (2.5%; PCBS 2019) and historical urban expansion during the baseline period (2010–2019) were considered during the estimation of population water demand increase and built-up area expansion in each province of the Gaza Strip. The average wastewater system efficiency and the irrigation return flow percentage from 2010 to 2019 were assumed to be the same for the next decades. Installation of new wells within the expanded urban areas was utilized to provide the required additional water supply in the coming decades. The pumping rate for the new wells was assumed to be 2,500 m³/day, which is the average pumping rate for the existing municipal wells over the last 10 years. A screen depth equal to the depth of the average screen of the existing municipal wells in each province of the Gaza Strip was used, depending on the location of each new well (PWA 2020). The new wells were distributed fairly and more appropriately relative to the adjacent existing municipal well distribution, especially concerning the distances from the coastline in each province. The operation date for each new well depended on the calculated new well numbers in each prediction year and on their location within the projected expanded urban areas. The purchased freshwater from Israel (Mekorot) was assumed to be the same as in 2019, while the transient head at the eastern boundary of the Gaza Strip was estimated to decrease by 0.5–1 m each decade, according to the average drawdown in groundwater levels along the eastern border of the Gaza Strip in the past decade.

Impact of human activities, climate change, a 25% reduction in agricultural well abstraction, and 50% reduction in municipal well abstraction (SC4)

The combined impact of human activities and climate change in the future (SC3) represents the most realistic evolution of groundwater quality and quantity if no interventions related to groundwater recovery take place in the coming decades. The SC is considered to be the first step in building an alternative freshwater source simulation (SC4), i.e., to check its impact on groundwater recovery. Accordingly, the SC4 scenario examined a proposed reduction in the current municipal and agricultural abstraction wells of 50 and 25%, respectively, as a result of desalinated seawater

provision, which is being implemented by the Water, Sanitation and Hygiene (WASH) cluster in the Gaza Strip (PWA 2018b). The new projected municipal wells were included in the abstraction reduction process in this scenario.

Results

Model calibration

Over the transient calibration period, the coefficient of determination (R^2) was 0.91 (Fig. 7a), which indicates a very good fit between the computed and observed groundwater

heads for the individual months of the transient calibration period from November 2009 to October 2019. Section S2 in the ESM spatially displays the horizontal hydraulic conductivity of subaquifers (K_x , K_y), the subaquifers specific yield (S_y), as well as the other calibrated parameters. During the calibration process, the horizontal hydraulic conductivity was the most sensitive parameter of the aquifer properties. The comparison of computed and observed groundwater heads at five representative observation wells (Fig. 5) distributed in the Gaza Strip provinces, including the northern cone of depression (E/12) and the southern cone of depression (P/48A), indicates good agreement between the computed and observed groundwater levels.

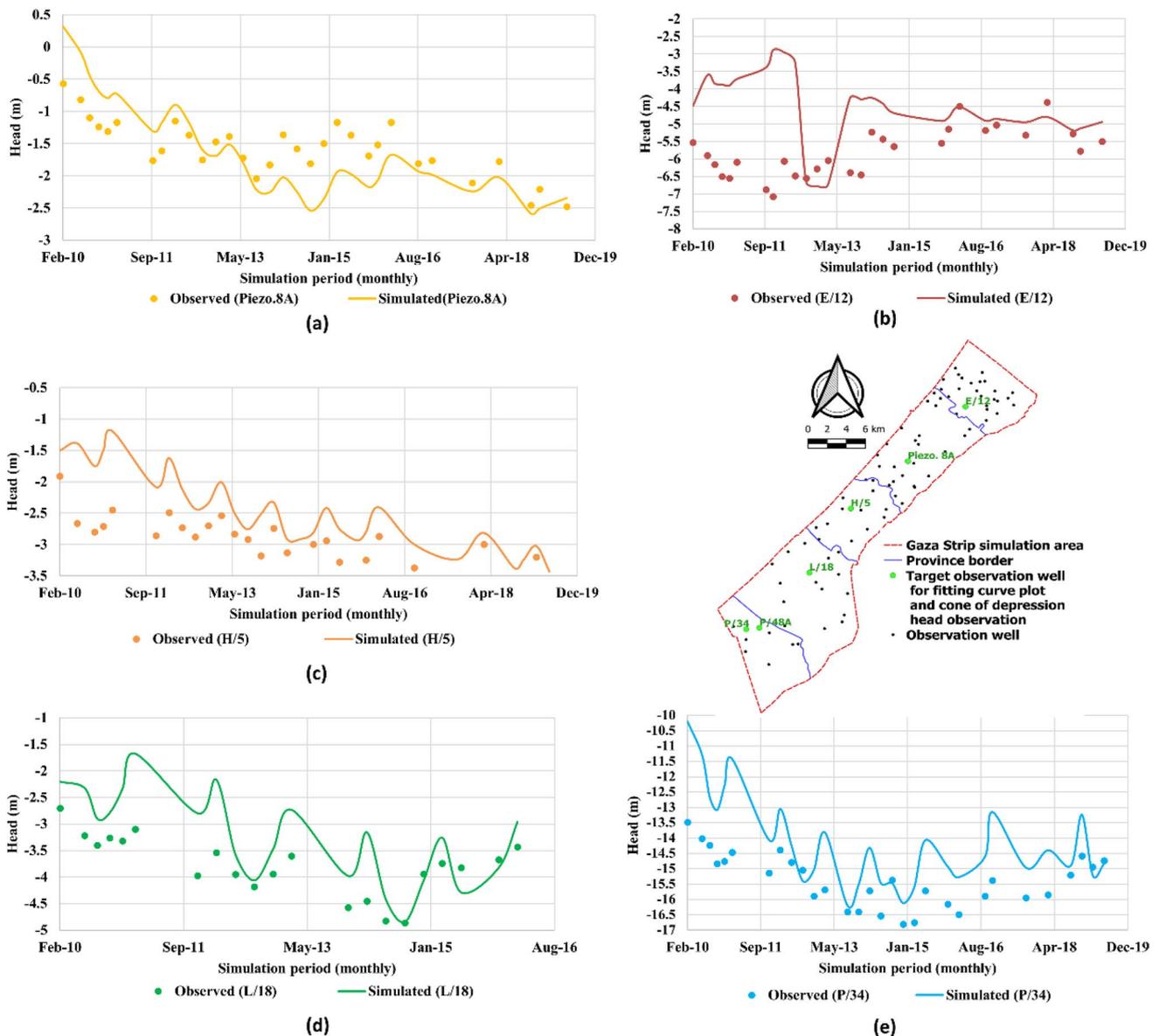
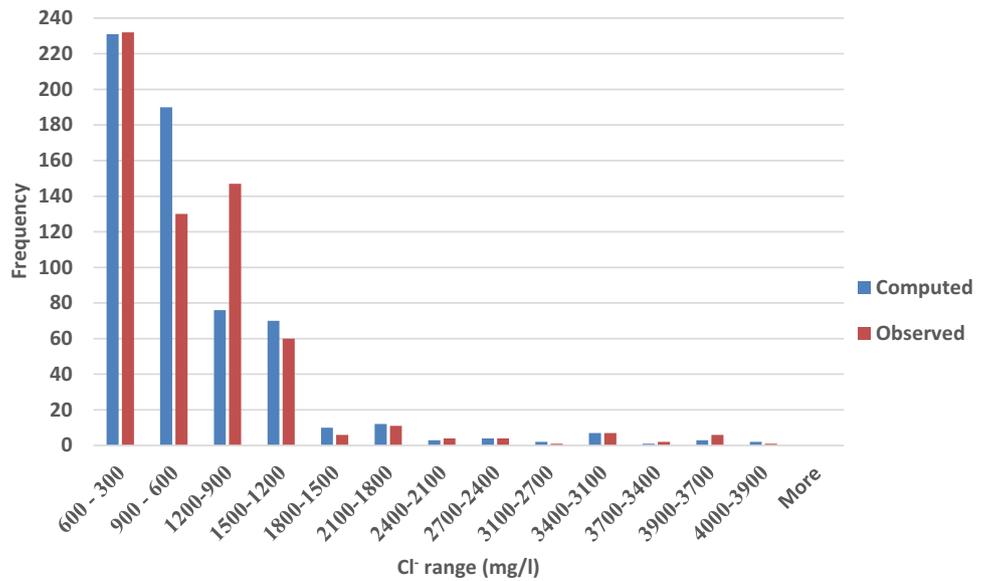


Fig. 5 Fitted curves of the computed and observed groundwater heads in each province of the Gaza Strip: **a** Gaza province, **b** North province, **c** Middle province, **d** Khan Younis province, **e** Rafah province

Fig. 6 Observed and simulated chloride ion Cl^- concentrations (mg/L) (611 records) for the individual months of the transient calibration



Depending on the calibrated parameters and the initial estimation of longitudinal dispersivity obtained from a previous study (Yakirevich et al. 1998), the transient chloride transport model was calibrated during the simulation period from November 2009 to October 2019. The coefficient of determination (R^2) was 0.81, which indicates a good fit between the computed and observed chloride concentrations (170 observation wells, 611 records) for the individual months of the transient calibration period (Fig. 7b). Figure 6 presents the histogram of the observed and simulated Cl^- , where the difference was small for most of the Cl^- ranges, except for the range of 600–1,200 mg/L, which had quite a high difference. However, the general trend of the computed Cl^- values followed the measured Cl^- values (Fig. 7b); therefore, the calibrated SEA-WAT model was used for scenario simulation and analysis.

Table 4 shows a summary of the transient transport calibration statistics. The calibrated longitudinal, horizontal,

and vertical transverse dispersivity of the subaquifers was at 10–20, 1–2, and 0.1–0.2 m, respectively, with 6, 0.6, and 0.06 m, respectively, for the aquitards. Similar values were used by Yakirevich et al. (1998). During the transient Cl^- transport calibration process, the dispersivity parameters did not indicate a high sensitivity compared with the hydraulic conductivity values for the flow model calibration. The calibrated parameter values during the baseline period (2010–2019) were used for future scenario simulations.

Scenario results

The simulation results for the benchmark scenario SC0 confirm that there will be deterioration over the next two decades in the groundwater quantities and qualities if the current practice continues. The SC0 revealed the most vulnerable area within the Gaza Strip, which is located beneath

Fig. 7 **a** Comparison of simulated and observed groundwater head ($n = 1,886$ records), **b** Comparison of simulated and observed chloride concentration (mg/L) ($n = 611$ records)

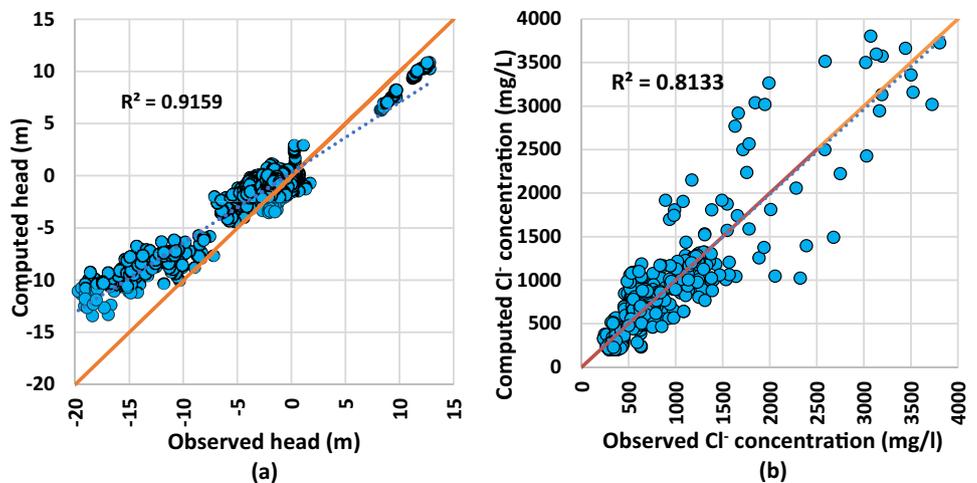


Table 4 Summary of calibration statistics (monthly basis) of the groundwater heads ($n=1,886$ records) and Cl^- concentrations ($n=661$ records)

Calibration statistics	Observed	Computed
Groundwater heads		
Average groundwater head (m)	-2.23	-1.17
SD of groundwater heads (m)	4.34	3.04
Mean residual (m)	-0.98	
Mean absolute residual (m)	1.3	
Root mean squared residual (m)	1.8	
Coefficient of determination, R^2	0.9159	
Cl^- concentrations		
Mean residual (mg/L)	-13.2	
Mean absolute residual (mg/L)	174.9	
Root mean squared residual (mg/L)	261.8	
Coefficient of determination, R^2	0.8133	

Values in *italic font* are common for both observed and computed results

SD standard deviation

the southern province, where the southern cone of depression continues to decline and expand during the projection period. Figure 8 shows the spatial groundwater levels for the years 2019, 2030, and 2040. The cone of the depression in the south becomes bigger and deeper. Figure 9 depicts the seawater intrusion (Cl^- concentration $> 4,000$ mg/L) for the first layer (subaquifer A) of the coastal aquifer for 2019, 2030, and 2040. The seawater intrusion increases

dramatically along the shoreline. The model suggests that the seawater intrusion (SWI) area within the entire simulation area of the first layer will be increased from 41.72 km² in 2019 to 51.73 km² by 2040.

The simulation result of the climate change scenario SC1 during the projection period (2020–2040) predicted that the quantities of the annual aquifer recharge, as expected, would increase by an average of 6.34 Mm³ compared to the SC0. The simulated spatial groundwater levels (Fig. 10) indicated that by 2040, there would be no considerable differences in groundwater level between SC1 and SC0. By 2040, the groundwater head of SC0 and SC1 at the center of the northern cone of depression (E/12) would be -4.7 and -4.6 m, respectively, and at the center of the southern cone of depression (P/48A), -16.4 and -15.7 m, respectively. This indicates that by 2040, the climate change impact is likely to have a slight improvement on groundwater heads compared with SC0. By 2040, SC1 suggests a reduction in SWI area for the first layer by 4 km², which is 7.7% less than that obtained by the benchmark scenario SC0.

By 2040, the predicted groundwater head of SC0 and the human activities scenario SC2 at the center of the northern cone of depression (E/12) was -4.7 and -7.44 m, respectively, and at the southern cone of depression (P/48A) was -16.4 and -18.1 m, respectively.

Using the linear regression method, the long-term trend-line slope of the average groundwater heads from 2013 to 2040 was produced by calculating the mean values between the average 25% lowest heads and the average 25% highest

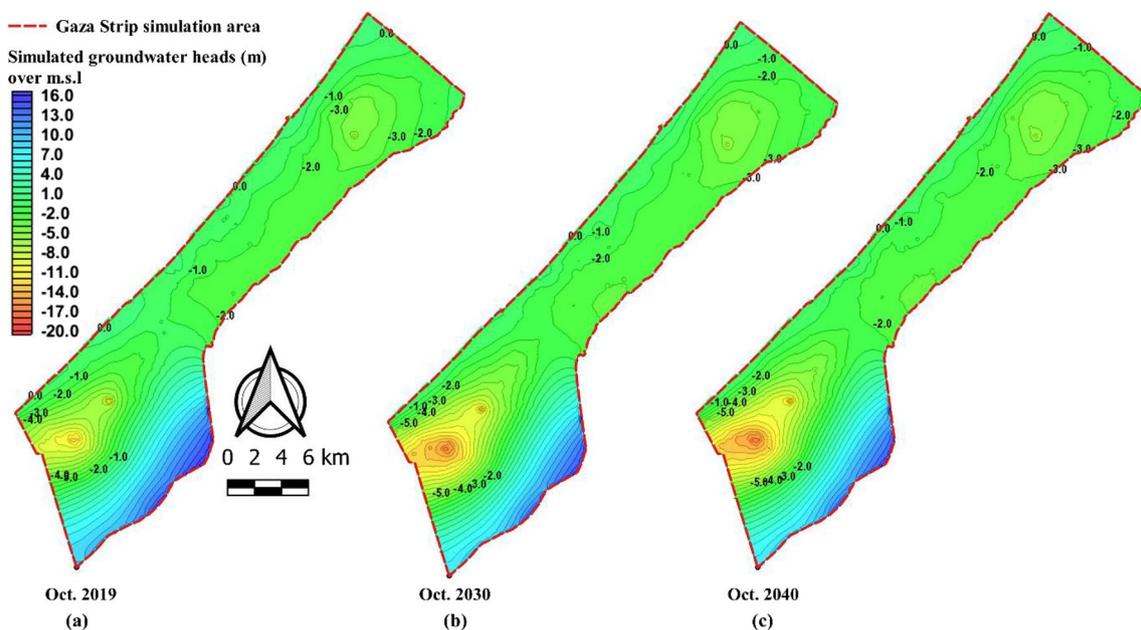


Fig. 8 Simulated groundwater (GW) heads for years **a** 2019, **b** 2030, and **c** 2040 under the benchmark scenario (SC0) in the ‘business-as-usual’ situation

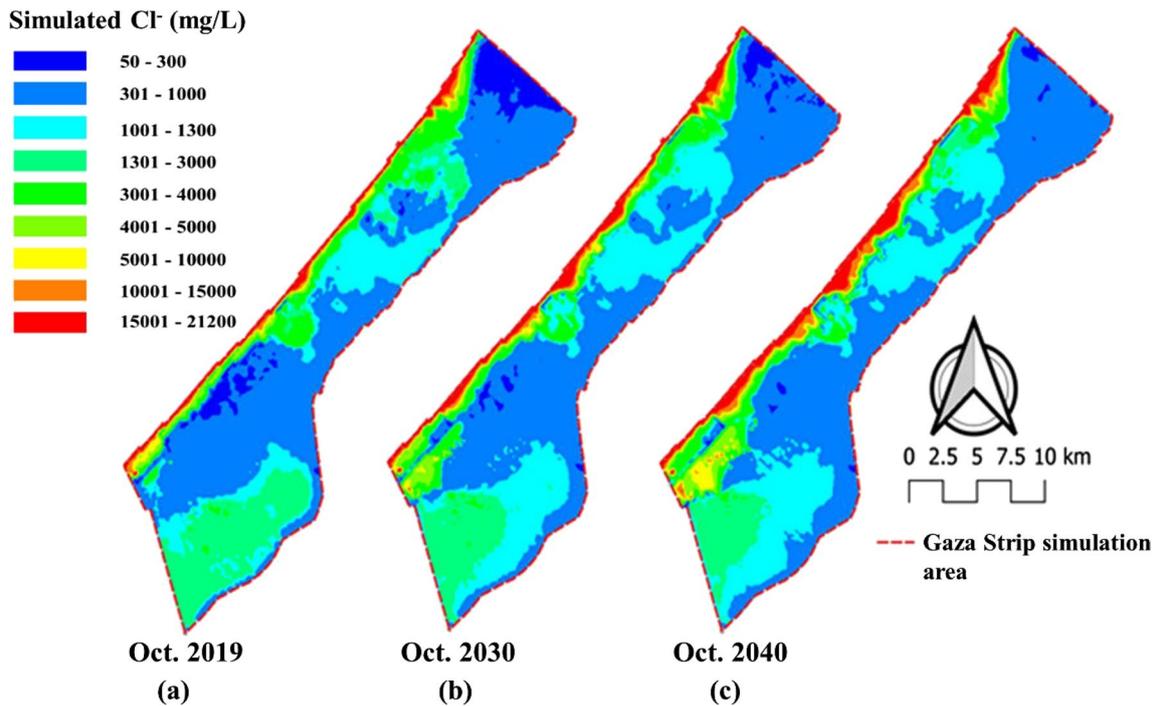


Fig. 9 Simulated Cl^- concentrations for years **a** 2019, **b** 2030, and **c** 2040 under the benchmark scenario (SC0)

heads for 85 observation wells in each year. This results in a trendline slope of -0.0902 , which means that there is an expected decrease in the average groundwater heads of 0.09 m/year as a result of human activities (SC2).

The simulated spatial Cl^- concentration differences between the SC0 and SC2 in Fig. 11 suggest a severe seawater intrusion in each province's coastline, where the total SWI area will dramatically increase to 56.8 km² by 2040. Compared with the SC0, by 2040, the projected human activities in the next 20 years are likely to contribute an additional 5 km² of SWI for the first layer, which is reflected by an increase in Cl^- concentration ranging from $3,000$ to $15,000$ mg/L in most coastal areas compared with the SC0. The increased SWI area in SC2 is 9.5% higher than in SC0.

The human activities and climate change scenario (SC3) simulation results did not indicate substantial differences in groundwater quantity and/or quality compared to the human activities scenario (SC2). The SC3 simulation predicted a continuous seawater intrusion into the coastal aquifer of the Gaza Strip of a higher magnitude than in the SC0; simultaneously, the freshwater deficit increased dramatically as a result of the impact of human activities. Over the next 20 years, the coastal aquifer under (SC3) will receive $\sim 1,425$ Mm³ of saline water, where an additional 158 Mm³ of seawater will intrude into the aquifer compared with SC0 as a result of the combined effect of projected anthropogenic activities and predicted climate change. Furthermore, $\sim 1,630$ Mm³ of freshwater depletion is likely to occur over the next two decades.

The result of the desalinated seawater provision scenario SC4 indicates that a considerable rise in groundwater levels can be expected in the next two decades, and groundwater recovery in the Gaza Strip becomes feasible (Fig. 10). Compared with SC0, the spatial groundwater level simulation results in the desalinated SC4 show that by 2040, the cones of depression (north and south) are likely to be much less severe and smaller in area. By 2040, the maximum rise in groundwater levels will occur in the Rafah Province (by 9.5 m), whereas in the northern parts of the simulation area, the maximum head difference will be 4 m higher than the SC0. By 2040, the groundwater of SC0 and SC4 at the center of the northern cone of depression (E/12) will be -4.7 and -0.6 m, respectively, and -16.4 and -7 m, respectively, at the center of the southern cone of depression (P/48A).

Figure 11 indicates that considerable seawater retreat will occur as a result of freshwater flushing under scenario SC4 by 2040, particularly in the northern, Khanyounis, and north-western Gaza provinces. Compared with SC0, changes in groundwater quality (seawater intrusion) are clear in SC4, where, by 2040, the SWI area will have reduced substantially from 51.73 km² in the SC0 to 23.6 km² in scenario SC4. The decrease in Cl^- concentration is from $7,000$ to $21,200$ mg/L in most coastal areas, as compared to the SC0 (Fig. 11).

Figure 12 illustrates the simulated cumulative freshwater deficit and cumulative seawater intrusion quantities over the next two decades for scenarios SC0 and SC4, relative to 2019. The SC4 simulation predicts that the

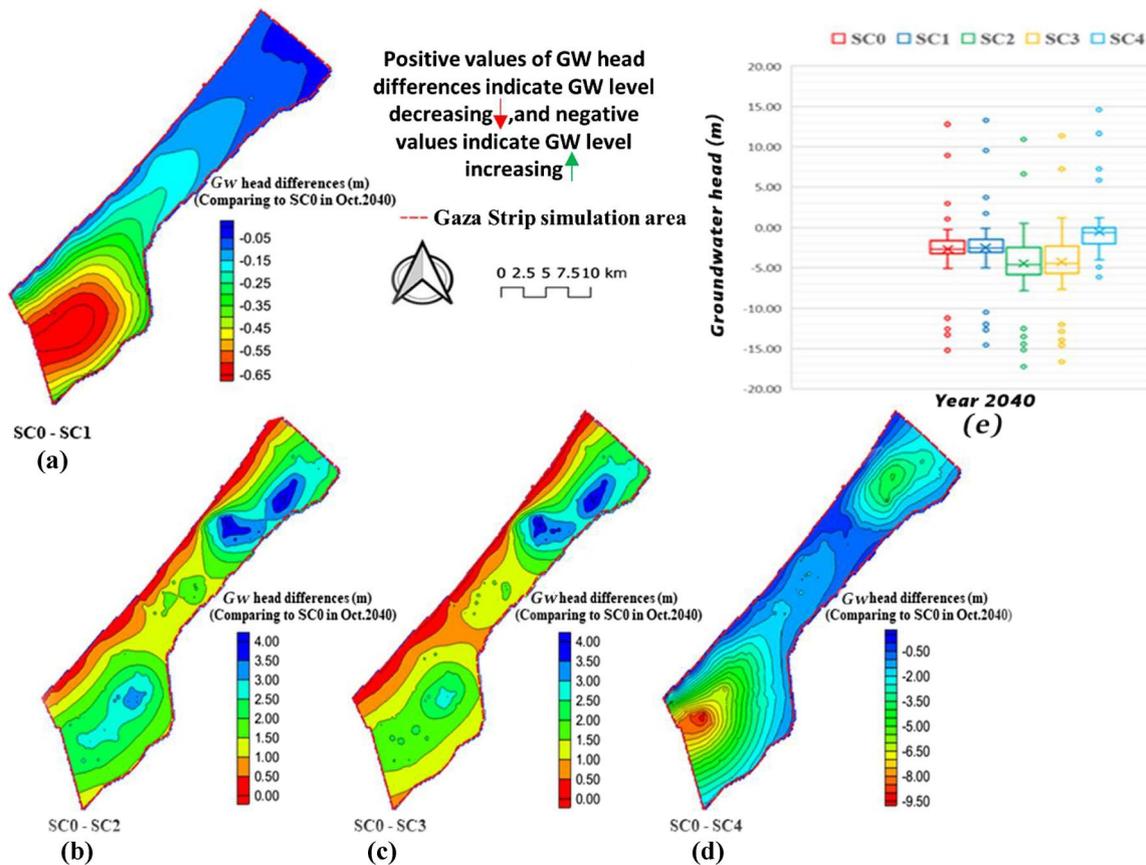


Fig. 10 The differences in simulated groundwater heads in 2040 among the four scenarios relative to the benchmark scenario (SC0): **a** the climate change scenario (SC1), **b** human activities scenario (SC2); **c** com-

binated human activities and climate change scenario (SC3), and **d** alternative freshwater provision scenario (SC4), and **e** boxplot outcomes (from 85 observation wells) for all scenarios in 2040

freshwater deficit will decrease dramatically after 2020, with the lowest deficit reaching 39 Mm³ by 2022, increasing gradually to reach its highest deficit of 337 Mm³ by 2040, at an increasing rate of 16.5 Mm³/year. Over the next 20 years, the coastal aquifer under (SC4) will receive ~420 Mm³ of seawater and 965 Mm³ of seawater reduction compared with the SC0.

Discussion

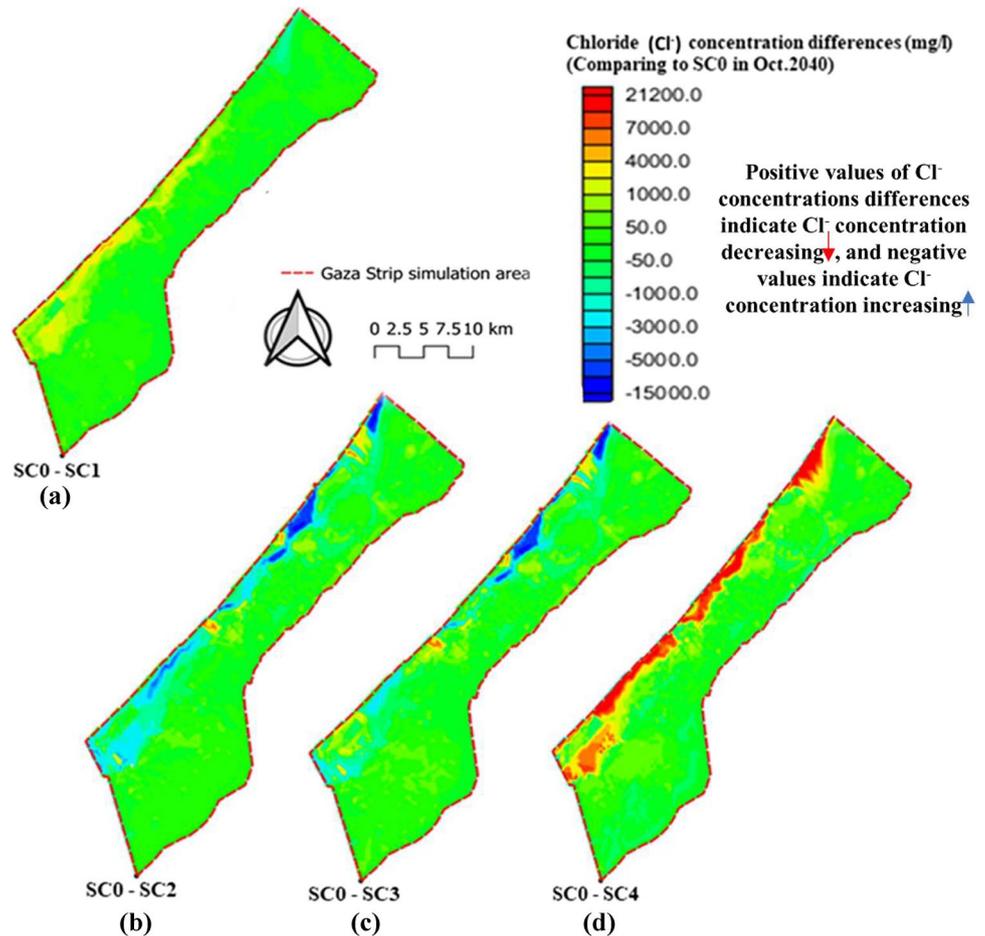
This study investigated the potential impact of human activities and climate change on the groundwater budget, levels, and seawater intrusion for the coastal aquifer of the Gaza Strip within the next two decades. In addition, the study assessed the effectiveness of alternative freshwater provision plans on the future groundwater quantity and quality.

The results of the benchmark scenario (SC0) revealed that, despite no changes regarding human activities and/or climatic data projection, the groundwater would continually deteriorate in quantity and quality over the next decades. The

continual coastal aquifer deterioration under SC0 implies that the outflow of freshwater is higher than the inflow under the current situation of land-use and average rainfall, which confirms the statement of the (PWA 2018a) that the discharge in the Gaza Strip aquifer is larger than the recharge.

In contrast with the findings of Gharbia et al. (2015b), the climate change impact scenario (SC1) suggests that in the next 20 years, an additional 6.3 Mm³/year aquifer recharge compared with SC0 can be expected in the Gaza Strip area. This is a result of a higher rainfall predicted by the CLIMB project (Ludwig 2014). The difference with the Gharbia et al. (2015a, b) study is that they predicted a reduction in the amount of precipitation in the next 20 years based on a single model and IPCC global projection. However, the global scenarios cannot immediately be translated into regional scenarios (Galassi and Spada 2014). The CLIMB project (Ludwig 2014) used 14 regional climate models for the Gaza Strip case with high resolution (0.22°). In this case, the predicted rainfall was validated during the historical period (1981–2010) and the bias was corrected in eight rainfall stations distributed

Fig. 11 The differences in simulated Cl^- concentrations in 2040 among the four scenarios relative to the benchmark scenario (SC0): **a** the climate change scenario (SC1), **b** human activities scenario (SC2); **c** combined human activities and climate change scenario (SC3), and **d** alternative freshwater provision scenario (SC4)



over the Gaza Strip area. In addition, the amount of rainfall for the northern and southern areas of the Gaza Strip was separated in the current study; therefore, the CLIMB project (Ludwig 2014) results were adopted in the current study because the uncertainties of the projected precipitation were considered to be lower. The additional natural recharge in the climate change scenario (SC1) may partially compensate for the abstracted groundwater and the seaward hydraulic gradient will be slightly stronger, which could mitigate the intrusion of the seawater. However, the estimated 1,000 illegal wells within the Gaza Strip increase the uncertainty of the real impact of climate change in the next 20 years. The illegal well number is approximately a quarter of the registered agricultural wells. The average annual abstraction for agricultural wells during the baseline period was 111 Mm^3 for the almost 3,000 registered agricultural wells. Thus, the 1,000 illegal wells may consume $\sim 35 \text{ Mm}^3$ for agricultural purposes each year, which is six times higher than the additional predicted annual aquifer recharge in the climate change scenario SC1. Overall, the probable expansion of illegal wells could pose a serious problem for water management and planning in the Gaza Strip in the future.

For the human activities impact scenario (SC2), the findings confirm the fact that expansion of the built-up areas is likely to curb the aquifer natural recharge quantity due to increases in runoff and evaporation within these areas (Hamad et al. 2012; Mushtaha et al. 2019). In addition, the exponential freshwater demand for future population growth increases groundwater deterioration several times more than during the recent decades. The predicted aquifer recharge cannot compensate for the population demand for freshwater in the coming decades.

The combined impact of human activities and climate change (SC3) over the next two decades represents the most realistic future change on the coastal aquifer if no groundwater management measures are implemented. The simulation results reveal the likely destructive impact of humans on the groundwater system. Thus, the additional aquifer recharge from climate change impact, compared with the normal rainfall period in the baseline, is not enough to overcome the incremental increase in domestic water demand over the next 20 years. The SC3 results confirm that the impact of human activities is the most important threat to groundwater sustainability in the Gaza Strip over the next two decades. New water measures for groundwater recovery are crucial;

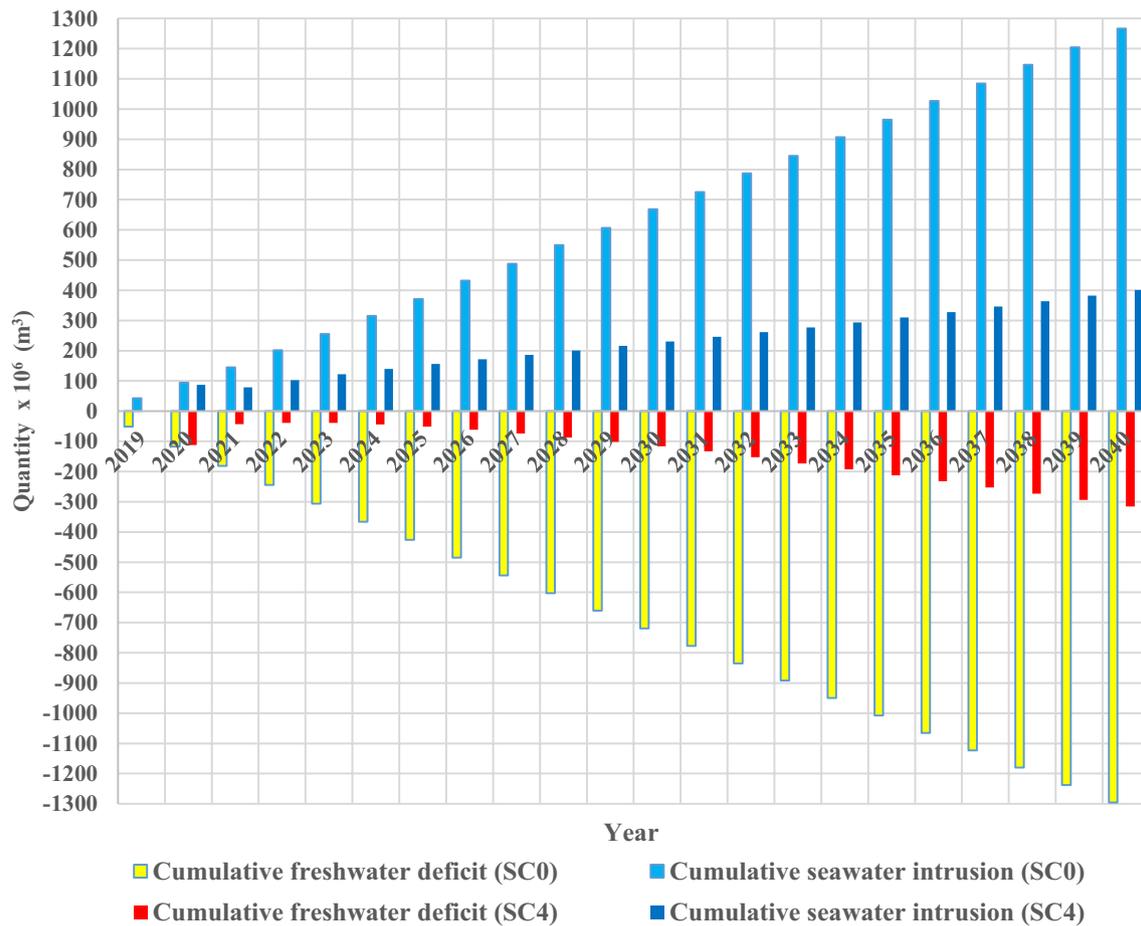


Fig. 12 Projected cumulative change in storage and cumulative seawater intrusion quantities for the projection period (2020–2040) for benchmark (SC0) and alternative freshwater provision (SC4) scenarios, relative to the year 2019

otherwise, the groundwater is likely to be severely depleted in the next decades and any delayed actions or interventions makes future groundwater recovery hard to achieve.

Interestingly, the simulation results in the desalinated seawater provision scenario (SC4) indicate that the next two decades are likely to produce a considerable rise in groundwater levels for the entire simulation area of the Gaza Strip, and that groundwater recovery in the Gaza Strip is feasible. The alternative freshwater intervention (50% for domestic and 25% for agriculture) will strengthen the seaward hydraulic gradient as a result of an overall rise in groundwater levels for the entire simulation area, which will cause a considerable seawater retreat as a result of freshwater flushing, especially in the northern, Khanyounis, and the north-western Gaza provinces.

The limitations and assumptions made in this study may have caused uncertainties in the model results. A major limitation is the lack of data on illegal irrigation wells; groundwater abstraction may be underestimated by 30%. For the prediction of agricultural water demand in the next 20 years,

the irrigation demand was considered the same as in 2019. However, the demand could be less or more, depending on future water management and/or future irrigation practices; thus, further research should be undertaken on agricultural demand in the future, which will be essential for water resources management in the future.

Conclusions

This paper provides insights into the impact of climate change, human activities, and the use of non-conventional freshwater on the groundwater budget, water levels, and seawater intrusion in the coastal aquifer of the Gaza Strip over the next two decades. Four scenarios, derived from the proposed water resources management plan for the area, were investigated—namely human activities, future climate change, and desalinated seawater provision to the water system. The spatio-temporal variation of the groundwater head, as well as quality, were assessed for

proposed scenarios (SC1–SC4) compared to a benchmark scenario (SC0). Under the ‘business-as-usual’ (SC0) scenario, groundwater storage will be continuously depleted and the fresh/seawater interface will move further inland in the Gaza Strip. Climate change may increase groundwater recharge slightly as a result of a projected small increase in precipitation over the next two decades. The projected incremental population growth, as well as urban sprawl in the next decades, will have the largest impact on the deterioration of groundwater depletion compared with other scenarios. The proposed use of desalinated seawater to substitute groundwater abstraction can effectively mitigate groundwater depletion and seawater intrusion in the coming decades, and this measure should be adopted in the Palestinian Water Authority’s strategic plan for groundwater recovery.

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Declarations

Conflict of interest The authors declare no conflict of interest.

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