



# Evolution of runoff and groundwater recharge in the Gaza Strip over the last four decades

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## Abstract

Gaza Strip is experiencing a severe water crisis caused mainly by overexploitation of the groundwater source. Rainfall is the only source of freshwater replenishment for the Gaza coastal aquifer. Groundwater level has dropped to more than 10 m below mean sea level as a result of aquifer exploitation and imbalance between recharge and abstraction in the past decades, which exposes the groundwater to seawater intrusion. As the only fresh water source recharging the aquifer is from rainfall, it is essential to estimate the annual recharge volume from rainfall. This paper is focusing on recharge estimation based on historical daily rainfall data for the past 41 years (1973–2014). An estimation of surface runoff was made using soil conservation services curve number method. An estimation of groundwater recharge has been calculated using two different methods: Thornthwaite and Mather soil moisture balance approach and chloride mass balance. Four land use maps and data have been used for the entire calculation period, three of them based on actual surveys carried out in 1994, 2004 and 2010, while the fourth map was developed based on the population expansion trend to cover the period before 1993. It was found that the proportion of built-up area has expanded from 8.25% in 1982 to 25.23% in 2010, while the sand dune area has shrunk from 31.46% in 1982 to 8.64% in 2010. Runoff has doubled from 6.9 million m<sup>3</sup> in 1982 to 13.7 million m<sup>3</sup> in 2010, while groundwater recharge was reduced from 24.4 million m<sup>3</sup> in 1982 to 18.1 million m<sup>3</sup> in 2010.

**Keywords** Evolution of groundwater recharge · Runoff · Curve number method · Chloride mass-balance method · Thornthwaite and Mather soil moisture balance approach

## Introduction

The Gaza Strip is a narrow coastal region extending in the southeast along the Mediterranean Sea. Groundwater is the only source for water supply (domestic, agricultural and industrial) in the Gaza Strip. Water percolation from rainfall is the main fresh water source for the Gaza coastal aquifer. Other recharge components are involved, such as agricultural return flow, lateral groundwater inflow, leakage of water and

waste water networks and leakage from retention basins of partially treated wastewater before dumping it to the Mediterranean Sea. All of those other recharge components are influenced by human practices and activities, which involve poor quality water being recharged to the aquifer. The only fresh groundwater recharge component is from rainfall. Overexploitation of the groundwater resource has resulted in continuous lowering of the water table [to more than 10 m below mean sea level in some areas (PWA 2017)] and gradual worsening of water quality. This is threatening the aquifer by salinization from different sources (seawater intrusion and upconing of deep saline water).

Many studies have been carried out to estimate the recharge/runoff quantities from rainfall for the Gaza Strip (Table 1). These studies estimate the recharge/runoff quantity based on different methods.

Melloul and Bachmat (1975) used recharge coefficients to estimate groundwater recharge for the Gaza Strip. They subdivided the Gaza Strip area into three zones and computed the coefficients for each zone based on a regression analysis

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**Table 1** Summary of studies carried out to estimate recharge from rainfall for the Gaza Strip

Study references	Used method	Recharge from rainfall (10 <sup>6</sup> m <sup>3</sup> /year)	Runoff from rainfall (10 <sup>6</sup> m <sup>3</sup> /year)
Melloul and Bachmat (1975)	Recharge coefficients based on soil type	41	–
WRAP (1994)	Change in aquifer storage (seasonal fluctuation)	64	–
IWACO and WRAP (1995)	Chloride mass balance	46	–
PWA (1999)	Land use and soil infiltration coefficients (from literature)	37	13.5
Moe et al. (2001)	Groundwater modeling	35–40	5.8–9
Baalousha (2005)	Cumulative rainfall departure	43.29	–
Aish et al. (2010)	WETSPASS model	39–40	–
Hamad et al. (2012)	SWAT model within AGWA tool	46.17	–
Hamdan et al. (2007)	SWAT model within AGWA tool	–	37

of soil type and average rainfall. These authors found that the annual groundwater recharge in the Gaza Strip is equal to 41 million m<sup>3</sup>/year. Their method was restricted to homogeneous soil and average rainfall for the whole of Gaza Strip, while actual rainfall is changing dramatically from the north to the south. Moreover, the regression analysis to obtain the recharge coefficients did not take the land use variation from one area to another into account.

Water Resources Action Program (WRAP 1994) used the change in aquifer storage to estimate groundwater recharge from rainfall. They used the data of seasonal water level fluctuations from 1984 to 1994 as a result of recharge from rainfall alone. Using a specific yield of 0.25, the total estimated recharge was 64 million m<sup>3</sup>/year. However, water level fluctuations in the coastal aquifer are greatly impacted by changing inflows and outflows, which was not considered in their study.

IWACO and WRAP (1995) carried out a study to estimate the net groundwater recharge in the Gaza Strip based on the chloride mass balance. This method is based on the assumption of conservation of mass between the input of atmospheric chloride and the chloride flux in the subsurface. This study was applied to the northern part of the Gaza Strip, where the top soil is composed mainly of sand dunes with high infiltration rate. Results of this study have shown that the amount of groundwater recharge in the Gaza Strip is about 46 million m<sup>3</sup>/year (IWACO and WRAP 1995). This method is being applied to the northern part of the Gaza Strip, while the results are extrapolated to the whole Gaza Strip. Thus, the authors consider the whole Gaza Strip as having the conditions of the northern part, being a sand dune area without any pumping stress on the aquifer; these conditions do not apply to other parts of the Gaza Strip, and therefore this estimate is likely affected by considerable uncertainties.

Palestinian Water Authority (PWA 1999), in the Coastal Aquifer Management Project (CAMP), used the total

effective recharge in their model. They generated the total effective recharge estimation based on land use, soil type, and literature values for runoff coefficients, whereby Gaza Strip was divided into four different areas based on total annual rainfall, ranging from 400 mm in the north, to 200 mm in the south. These four areas were then subdivided according to three categories of land use: urbanized, agricultural or open/rainfed. These were further subdivided according to soil types: clay, sand, or loess. Using estimated runoff coefficients and recharge rates (from literature), a net effective recharge of 37 million m<sup>3</sup>/year was calculated. This is equal to 33% of total average rainfall. An additional 55% was estimated to be evapotranspiration, and 12% is lost as runoff. The report states that “This approach, although more detailed than some previous estimates, is still rudimentary—it oversimplifies a number of processes, including evapotranspiration, and ignores the impact of irrigation”. Moreover, using total annual rainfall, literature coefficients for runoff and recharge rates are strong simplifications of reality. The Gaza Strip is a small area but the rainfall is varying from north to south (400–200 mm, respectively). Dividing the Gaza Strip into only four parts is not sufficient in areas of dramatic change of both land use and rainfall, and will lead to over-simplification.

Moe et al. (2001) used groundwater modeling techniques to estimate groundwater recharge from rainfall by calibration. In the model, they defined recharge zones based on soil distribution and measured rainfall at five selected stations inside the Gaza Strip. Rainfall from specified meteorological stations was assigned to those recharge zones after being reduced by factors to account for runoff (5–10%) and evapotranspiration (50–60%). They applied recharge coefficients of 70% of rainfall in sand dune areas to 15% of rainfall for silty clays. They found that the recharge from rainfall is 35 million m<sup>3</sup>/year in 1998 (steady-state simulation) and they used 40 million m<sup>3</sup>/year for long-term average recharge in their transient simulation. The model did not take into

account the land use of the Gaza Strip and its impact on recharge, and the used percentages for runoff, evaporation and recharge coefficients appear arbitrary. The model only uses five rainfall stations while 12 rainfall stations were available at the time of simulation.

Baalousha (2005) used the cumulative rainfall departure (CRD) method, which depends on the water balance principle. The data required are monthly rainfall records, groundwater level records, aquifer storativity, abstraction records, and lateral inflow and outflow. The developed CRD model was calibrated by comparing long-term average groundwater level with the simulated groundwater level. CRD method showed that the annual amount of groundwater recharge from rainfall in the Gaza Strip is 43.29 million  $\text{m}^3/\text{year}$ . The author used the CRD method because it does not require much data, but he used an assumption for the aquifer storativity, which is the most sensitive parameter required for the method. The author neglected the amount of runoff from rainfall in his calculations. He used only 8 rainfall station data while there are 12 rainfall stations with data. He tried to use static groundwater level in his model by using the monitoring piezometers in the Gaza Strip, but due to huge pumping all over the Gaza Strip, those monitoring piezometers show dynamic groundwater level rather than static groundwater level. The author depended on groundwater level contour lines to estimate the lateral flow from Israel to Gaza Strip based on the measured head differences, but he did not show any monitoring wells from outside Gaza Strip borders. The author assumed that the relationship between the groundwater level and rainfall is linear, while he ignored the effect of more than 5000 pumping wells in the Gaza Strip. According to the author, uncertainty of the estimated recharge based on the CRD method increases as the depth to the water table increases and vice versa, while he ignores that the depth to groundwater in the Gaza Strip is varying from few meters in the West to more than 50 m in the East and even more in the South.

Aish et al. (2010) used WetSpa model to estimate groundwater recharge in the Gaza Strip. WetSpa is a steady-state spatially distributed water balance model for simulating yearly or seasonal averages of groundwater recharge, evapotranspiration (soil evaporation and transpiration also as separate outputs), runoff, and interception (Liu and De Smedt 2004). The authors estimated the spatial average recharge at 108 mm/year, which corresponds to a volumetric average annual recharge of 39–40 million  $\text{m}^3/\text{year}$ . Baalousha et al. (2012) has commented on this paper in a technical note by comparing the results from Aish et al. (2010) with other studies from literature and found that the recharge was almost double in some areas.

Hamad et al. (2012) used Soil and Water Assessment Tool (SWAT) within the Automated Geospatial Watershed Assessment (AGWA) tool for simulating three urbanization

scenarios (2007, 2020, and full urbanization) for the Gaza Strip. The year 2007 simulation results showed that the percolation depth of the rainfall is 126.5 mm (equivalent to 46.17 million  $\text{m}^3/\text{year}$ ). They used land cover maps for 2007 and 2020 from Ministry of Planning publications, while the 2007 land use cover map was not based on a real survey for the existing land use but was developed for master plan purposes. They used 8 rainfall station data records (instead of 12 available rainfall station data records in the Gaza Strip), and it is not clear in the publication whether they used daily rainfall records or monthly or just a yearly average in their model.

Hamdan et al. (2007) used a rational runoff formula created from the empirical method referring to Mulvancy 1851 in Kiely (1996), Kuichling 1889 in Kiely (1996) and Lloyd-Davis 1906 in Kiely (1996) with GIS based on different land use categories. The outcome shows yearly runoff of 37 million  $\text{m}^3$ . They divided Gaza Strip into seven zones based on data records from seven selected rainfall stations (instead of the available 12 rainfall stations), and they used the yearly mean value of rainfall.

All of the studies carried out to estimate recharge/runoff from rainfall for the Gaza Strip depended on either long-term average rainfall or a specific year of rainfall data, whereas the results were used as fixed quantities that the researchers and decision-makers used for water budget calculations or water management for the Gaza Strip. Moreover, the runoff calculations have a wide range of estimation (5.8–37 million  $\text{m}^3/\text{year}$ ). None of the studies used actual historical daily rainfall data to estimate the recharge/runoff from rainfall except Moe et al. (2001), who used data from only 5 out of 12 rainfall stations and at the same time they ignored the evolution of land use, substituting it by using a percentage of runoff from rainfall and using a recharge coefficient for the soil.

In this context, this study aims to calculate the recharge and runoff for the Gaza Strip based on actual historical data from 1973 to 2014. The calculations will be based on daily records for rainfall and evaporation, land use maps for different years (1982, 1994, 2004, and 2010), and a soil map. This will be the first study to calculate the runoff for the whole Gaza Strip using the soil conservation services curve number method (SCS-CN), which uses elevation, land use and soil maps. The results will be used to calculate recharge using Thornthwaite and Mather soil moisture balance approach (SMB), taking into account land use practices during the entire period and using daily rainfall and evaporation. An additional method was used to confirm the SMB method results in selected areas using the chloride mass balance (CMB).

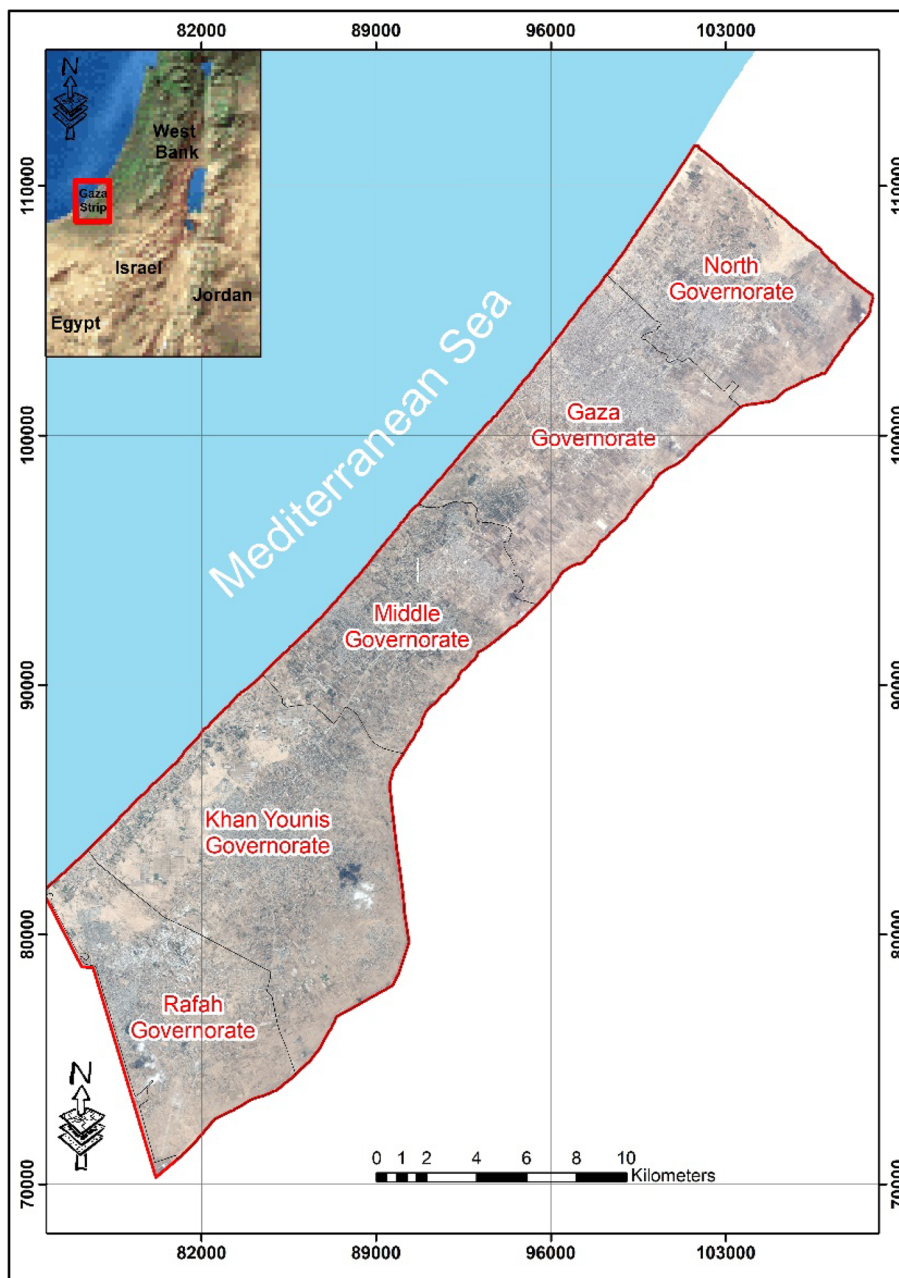
A wide variety of techniques is available for quantifying groundwater recharge (Table 1); however, choosing SMB approach is likely to be preferable to the Gaza Strip situation

due to the availability of the parameters required for this method [i.e., soil, land use, digital elevation model (DEM)], which are well known and un-changeable by factors such as pumping [more than 5000 pumping wells are operating in the Gaza Strip (PWA 2017)] and/or the uncertainty of hydraulic conductivity which both influence the groundwater level fluctuations.

### Study area

The Gaza Strip is an exclave region of the State of Palestine on the eastern coast of the Mediterranean Sea that borders Egypt in the southwest for 11 km, and Israel in the south east and north east for 51 km. It lies at latitude 31°25'59"N and longitude 34°22'34"E. The Gaza Strip forms a transition zone between the semi-humid coastal zones in the north, the semi-arid zone in the east, and the Sinai desert in the south. The Gaza Strip has an area of 365 km<sup>2</sup>, with a length of 42 km and a width ranging between 6 km in the middle and 12 km in the southern part of the area (Fig. 1).

Fig. 1 Gaza Strip location (CMWU 2013)



The long-term average daily mean temperature ranges from 25 °C in summer to 13 °C in winter, while the daily relative humidity ranges between 65% in the daytime and 85% at night in the summer, while in winter it is between 60% and 80%, respectively (Mushtaha 1999). Rainfall usually occurs during December and January with spatially variable rainfall quantities; average annual rainfall is 450 mm/year in the north and 200 mm/year in the south (CMWU 2013). Daily rainfall is being monitored for more than 41 years (1973–2014) by 12 rainfall gauge stations distributed all over the Gaza Strip.

Gaza Strip is one of the most densely populated coastal areas in the world (growth rate is 3.21% in 2017), where around 1.94 million inhabitants (year 2017) are living on 365 km<sup>2</sup> (PCBS 2017). Groundwater is the only water resource in the Gaza Strip. The saturated thickness of the aquifer does not exceed 180 m near the North West coast, 40 m in the North Eastern border and 5–10 m in the South East (Mushtaha et al. 2000). The general groundwater flow pattern is from east to west towards the sea. Gaza aquifer is classified as an unconfined aquifer in the east. In some areas near the coast lower permeability clay lenses create a confining layer as seen in Fig. 2 (after Greitzer and Dan 1967). The aquifer comprises tertiary and quaternary age formations. The bottom of the aquifer is in contact with Saqya Formation, which comprises shallow marine clays, shales

and marls. The Kurkar Formation comprises consolidated quartz sands with calcareous material forming the aquifer. The aquifer has both high permeability and high porosity (Aliewi et al. 2001).

In the year 2013, the groundwater abstraction reached 170 million cubic meter (CMWU 2013). Salinization in the coastal aquifer may be caused by a single process or a combination of different processes, including seawater intrusion, upconing of saline water from the deeper parts of the aquifer, flow of saline water from the adjacent Eocene aquifer, return flow from irrigation water, and leakage of wastewater (Vengosh et al. 1999; Vengosh and Rosenthal 1994). By the year 2025, Gaza Strip needs 212 million cubic meter of freshwater to supply the domestic and agricultural demand (CMWU 2013), which the groundwater resource cannot sustain.

### Methodology

The methodology consists of four parts. The first part comprises data preparation for the period from 1973 to 2014 based on hydrological years (starting from September and ending in August the next year). The second part consists of runoff calculations using the Soil Conservation Services Curve Number (SCS-CN) method. The third part comprises recharge calculations using Thornthwaite and Mather soil

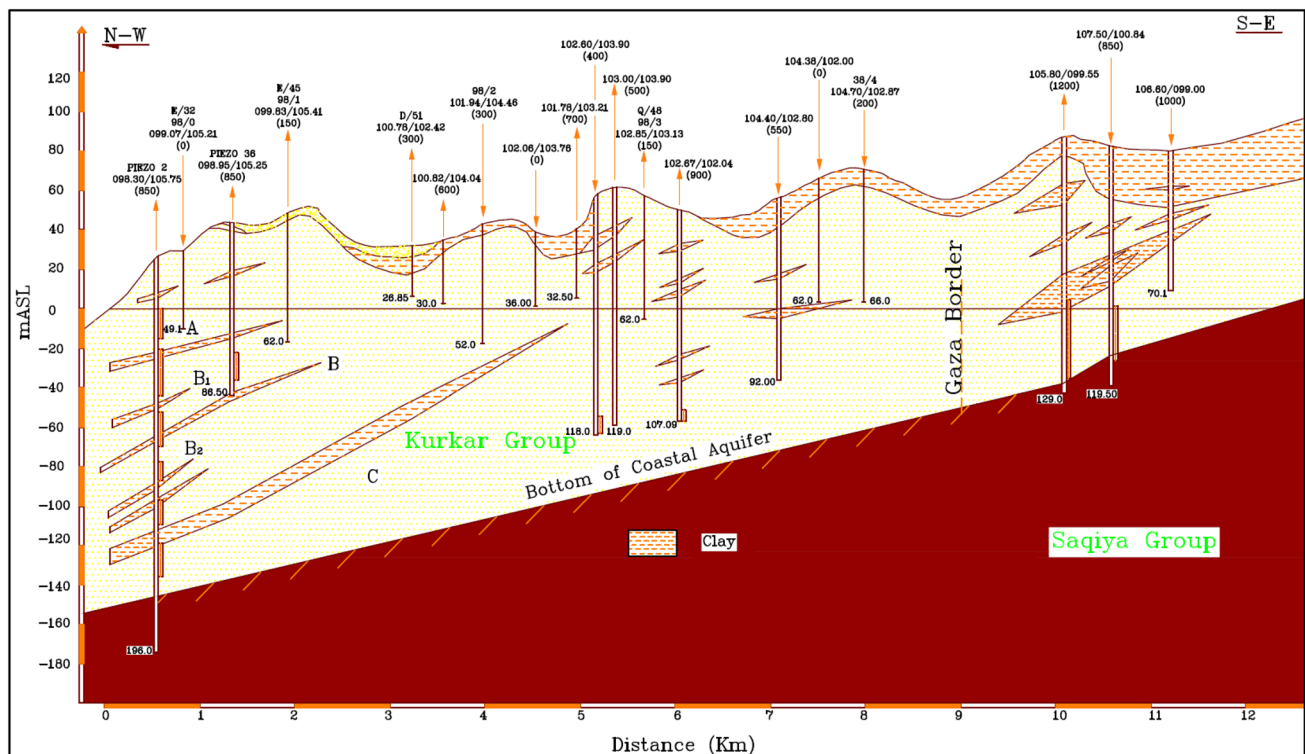


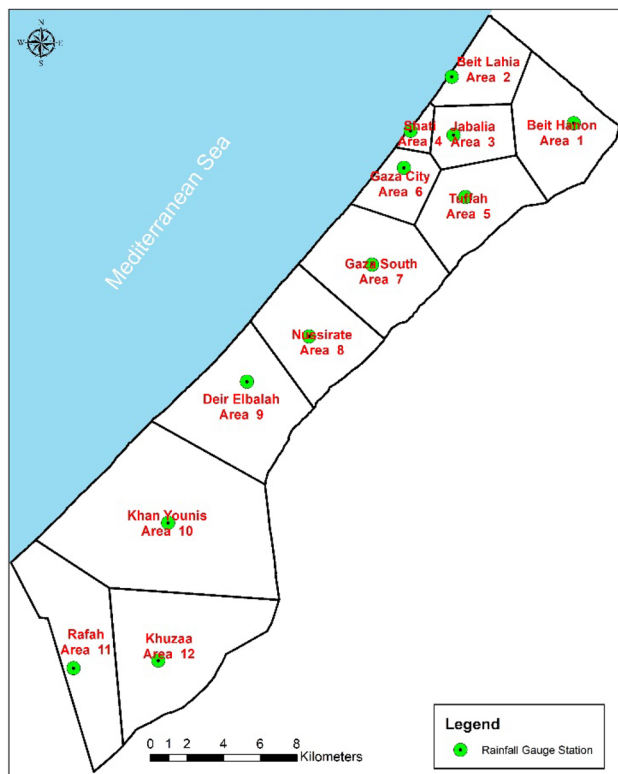
Fig. 2 Typical cross section of the Gaza aquifer (after Greitzer and Dan 1967)

moisture balance (SMB) approach, and the fourth part consists of using chloride mass-balance method (CMB) in selected areas (not affected by sea water intrusion) to check the recharge results from SMB against CMB in the same area.

## Data preparation

We used the entire period from 1973 to 2014 to calculate the runoff and recharge for the Gaza Strip, and some assumptions and interpretations have been made for the missing data during this period as described below.

Rainfall data are available at the Ministry of Agriculture on a daily basis since 1973, covering the whole Gaza Strip by 12 rainfall gauge stations distributed as shown in Fig. 3. Different methods have been developed for the estimation of areal rainfall from the rain gauge measurements. Melesse et al. (2003) found that the Thiessen method gives consistently better and more accurate results than other methods. Thiessen method splits Gaza Strip into 12 different polygons based on rainfall station location (Fig. 3). Those areas have been the base for the calculation of runoff and recharge, where an area-weighted value was obtained based on each polygon area.



**Fig. 3** Rainfall gauge stations location and corresponding Thiessen polygons

Daily pan evaporation has been monitored from 1986 to 1992 (6 years) at the Gaza Meteorological Station. Data from 1973 to 1985 and from 1993 to 2014 are missing. For the missing years, an average for each calendar day over the 6 years with data is used to fill in the gap.

The climatic data have been arranged and sorted as daily calendar, with the hydrological year starting in September as the beginning of the rainy season and ending in August the following year. This way of organizing data has the advantage of facilitating the computation of the change in soil moisture storage at the beginning of the hydrological year, because the soil moisture storage at the end of the dry season, i.e., end of August, can be considered as completely depleted. Moreover, the concept of hydrologic year reflects the natural climatic reality in the sense that it commences with the start of the season of soil moisture recharge, includes the season of maximum groundwater recharge, if any, and terminates with the season of maximum soil moisture utilization (Ritter 2006).

Digital elevation model (DEM) map has been obtained from coastal municipalities water utility (CMWU) with grid size 25 m × 25 m. The DEM map covers the whole Gaza Strip area.

Three land use maps are available for the Gaza Strip, one for the year 1994 developed by the Ministry of Planning and International Cooperation (MOPIC), and the other two maps were developed through the CLIMB project (funded by the 7th Framework Programme of the European Commission) for the years 2004 and 2010. Those three maps will cover the calculation period from 1993 to 2014 based on equal time divisions between subsequent maps: the land use map of 1994 is used for the period from 1993 to 1998, the land use map of 2004 will be used for the period 1999–2007, and the land use map of 2010 is used for the period 2008–2014. The land use practices before 1993 will have been different due to the sudden population increase after the Oslo Agreement in 1993 when 100,000 inhabitant returnees have settled in the Gaza Strip. To estimate land use for the calculation period from 1973 to 1992, the population growth for the entire period (1973–2014) was analyzed versus the built-up area percentage taken from existing land use maps (1994, 2004 and 2010). Figure 4 shows the actual population based on Palestinian data after 1993 (after Oslo Agreement) (PCBS 2017) and Israeli administrative data before 1993 (CIA World Factbook 2014). It shows that a slow gradual increase in population was occurring during the period from 1973 to 1992 (average growth rate 2.5%). This slow increase in population is unlikely to have caused major changes in land use, and therefore we considered one land use map to be sufficient to cover this period. Thus, we developed a land use map for this period, based on population data from the year 1982.

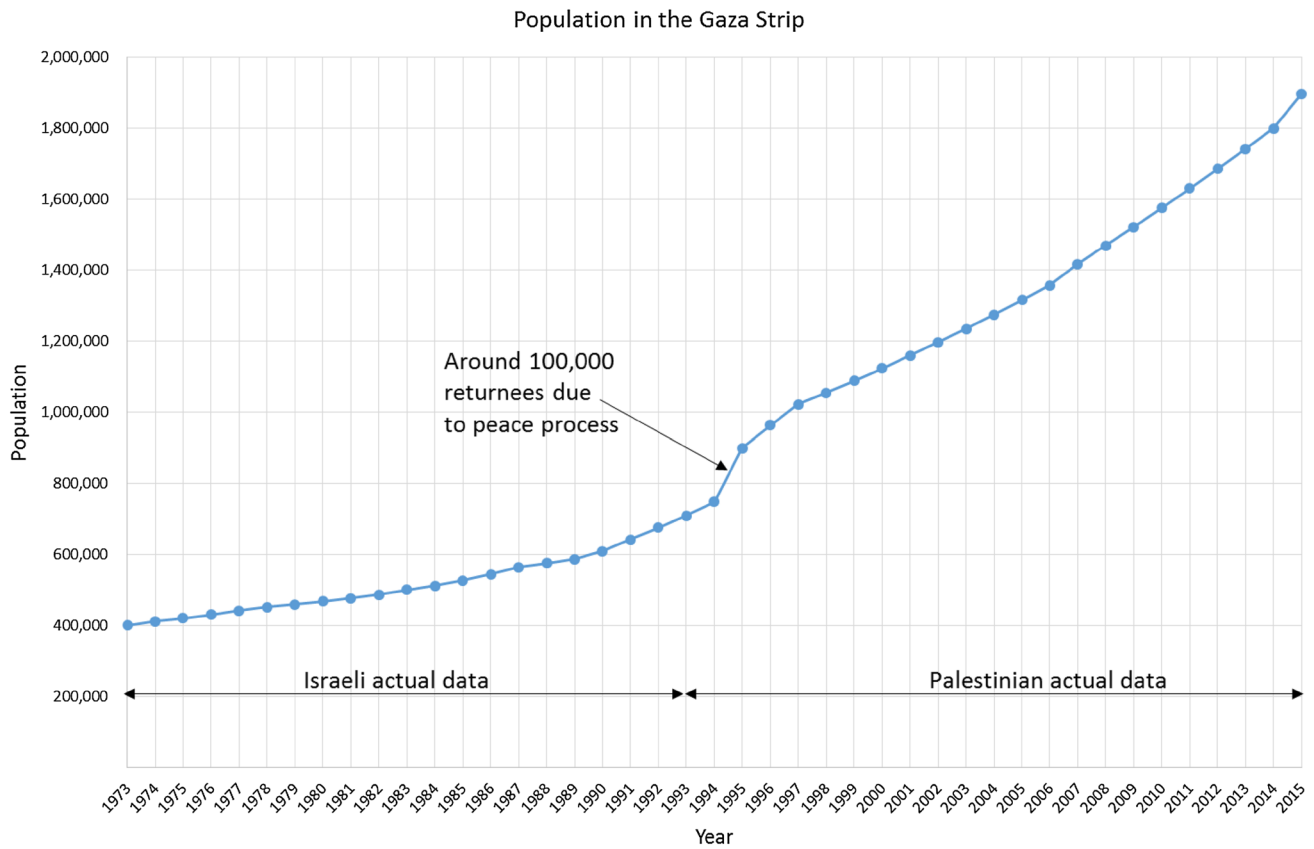


Fig. 4 Population in the Gaza Strip (1973–2015)

Table 2 Land use maps and period for which they are used

Land use map	Period of use in calculations
Year 1982	From year 1973 to year 1992
Year 1994	From year 1993 to year 1998
Year 2004	From year 1999 to year 2007
Year 2010	From year 2008 to year 2014

Table 2 shows how the different land use maps were used for the calculations for both runoff and recharge for the period 1973–2014.

The soil map is available for the Gaza Strip (MOPIC 1995) composing six soil categories (local soil classification). Goris and Samian (2001) have converted the local soil classification into soil textures based on soil samples taken in Gaza Strip during their field investigation. Those categories have been converted to hydrologic soil groups (A, B, C and D), which indicate the amount of infiltration the soil will allow. Table 3 shows the soil classifications with respect to hydrologic soil group, while the hydrological soil map has been prepared based on soil texture (supplementary electronic material, Figure I).

### Surface runoff

The daily runoff in the Gaza Strip can be estimated based on the curve number method. The curve number is based on the area’s hydrologic soil group, land use, and DEM. In this study the calculation for the runoff will take place for the entire period (1973–2014). Thiessen polygon map, soil map, different land use maps (1982, 1994, 2004 and 2010) and DEM map were used to generate curve number (SCS-CN) using Geo-HMS hydrological model extension built in ArcGIS (US Army Corps of Engineers’ Hydrologic Engineering Center 2009). For each Thiessen polygon area (out of 12 Thiessen polygons), we will obtain a weighted curve number, hence we will have for each calculation period 12 curve numbers (in total 48 curve numbers for the entire period comprising 4 land use maps). The produced curve number will be for normal antecedent soil moisture conditions (AMC), where an adjustment for dry and wet AMC conditions will be made based on specific equations described below. Details of the calculation procedure are as described below.

**Table 3** Soil classification with respect to hydrologic soil group in the Gaza Strip

Local soil classification <sup>a</sup>	Texture <sup>b</sup>	Hydrologic soil group <sup>c</sup>	Soil group characteristic <sup>c</sup>
Sandy	Sandy	A	Soils having high infiltration rates; soils in this group have low runoff potential when thoroughly wet
Loess soil Loess sandy soil Sandy loess soil over loess	Sandy loam	B	Soils having moderate infiltration rates; soils in this group have moderately low runoff potential when thoroughly wet
Sandy loess soil Dark brown/reddish brown	Sandy clay loam	C	Soils having slow infiltration rates; soils in this group have moderately high runoff potential when thoroughly wet

<sup>a</sup>MOPIC (1995)<sup>b</sup>Source: Goris and Samian (2001)<sup>c</sup>Source: USDA (2009)**Table 4** Relationship between land use classification, hydrologic soil group and curve number (USDA-SCS 1986)

Land use classification	Hydrologic soil group—CN			
	A	B	C	D
Open water	100	100	100	100
Built-up area	89	92	94	95
Greenhouses	71	80	87	90
Cultivated land	67	78	85	89
Sand area	49	69	79	84

### Curve number (CN) calculation

Estimation of the curve number is based on a combination of the land use map, hydrologic soil map, DEM map, and antecedent soil moisture conditions (AMC). The hydrologic soil groups (A, B, C and D) indicate the amount of infiltration the soil will allow. Significant infiltration occurs in sandy soils while no infiltration occurs on heavy clay or rock formations. United States Department of Agriculture (USDA 1986) has developed a reference table showing the relationship between the land use, hydrologic soil group and curve number. Table 4 shows the Gaza Strip land use classifications based on USDA reference table relationship. This table will be used as the base for developing the curve number for each zone of the Thiessen polygons in the Gaza Strip.

Antecedent moisture conditions (AMC) is an indicator of the availability of soil moisture storage prior to a storm, which will have a significant effect on the runoff depth. SCS has developed a guide for adjusting the curve number according to AMC based on the total rainfall in the 5-day period preceding a storm. Three levels of AMC are used in the curve number method: AMC-I, AMC-II and AMC-III. Table 5 shows antecedent rainfall limits for the three antecedent moisture conditions.

**Table 5** Antecedent rainfall limits for determining AMC type (SCS 1985)

AMC type	Total 5 days antecedent rainfall	
	Dormant season (mm)	Growing season (mm)
AMC-I (dry conditions)	< 12.7	< 35.6
AMC-II (normal conditions)	12.7–27.9	35.6–53.3
AMC-III (for wet conditions)	> 27.9	> 53.3

Based on the Thiessen polygon areas, each polygon area will have a weighted average curve number as described in Eq. 1:

$$CN = \frac{\sum(CN_i \times A_i)}{\sum A} \quad (1)$$

where  $A_i$  is the surface area of the cell within each Thiessen polygon area,  $CN_i$  is the curve number of the cell, and  $\sum A$  is the Thiessen polygon surface area.

Each Thiessen polygon area will have a weighted average curve number based on AMC normal conditions (AMC-II). An adjustment for AMC type will be made according to Eqs. (2) or (3) (Chow et al. 2002).

Adjustment for AMC-I (Chow et al. 2002):

$$CN_I = \frac{4.2 \times CN_{II}}{10 - (0.058 \times CN_{II})} \quad (2)$$

Adjustment for AMC-III (Chow et al. 2002):

$$CN_{III} = \frac{23 \times CN_{II}}{10 + (0.13 \times CN_{II})} \quad (3)$$



### Runoff calculation

After producing the curve number for each Thiessen polygon area, the next step is to calculate the potential maximum retention  $S$  (in mm). The  $S$  values indicate the initial abstraction of rainfall by soil and vegetation and were computed for each polygon using Eq. (4) (SCS 1985 metric units). Runoff depth  $Q$  (in mm) was calculated based on daily rainfall  $P$  (in mm) in each Thiessen polygon area using Eq. (5) (SCS 1985):

$$S = \frac{25400}{CN} - 254 \tag{4}$$

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \quad (P > 0.2S) \tag{5}$$

The following flowchart in Fig. 5 demonstrates the calculation series carried out to produce the runoff depth of the Gaza Strip using SCS-CN.

### Recharge from rainfall

We applied two different methods to estimate recharge volume from rainfall in the Gaza Strip. The first approach is the Thornthwaite and Mather soil moisture balance (SMB)

method, and the second approach is the chloride mass-balance (CMB) method.

### Thornthwaite and Mather soil moisture balance (SMB) approach

This method is used to calculate the recharge quantity to the groundwater after reaching field capacity of the soil, and after the plants and crops took their needs from water in the root zone. Hence it is depending on the capacity of the soil to store water. Each soil type has some specific water content at saturation, field capacity and permanent wilting point. The effective precipitation is based on the runoff calculations that have been performed (actual precipitation minus runoff depth).

Field capacity (FC) is the quantity of water that a well-drained soil would hold against the gravitational forces. It is the upper limit for the plant-extractable water, where the permanent wilting point (PWP) is the soil water content at which plants stop extracting water and will permanently wilt. It is as such the lower limit of the plant-extractable water (FAO 2012).

FAO (2012) has defined soil physical characteristics based on various soil types (see supplementary electronic material, Table I). Plant available water (PAW) is one of the main parameters to be found to start calculating the recharge depth. PAW is a function of field capacity (FC),

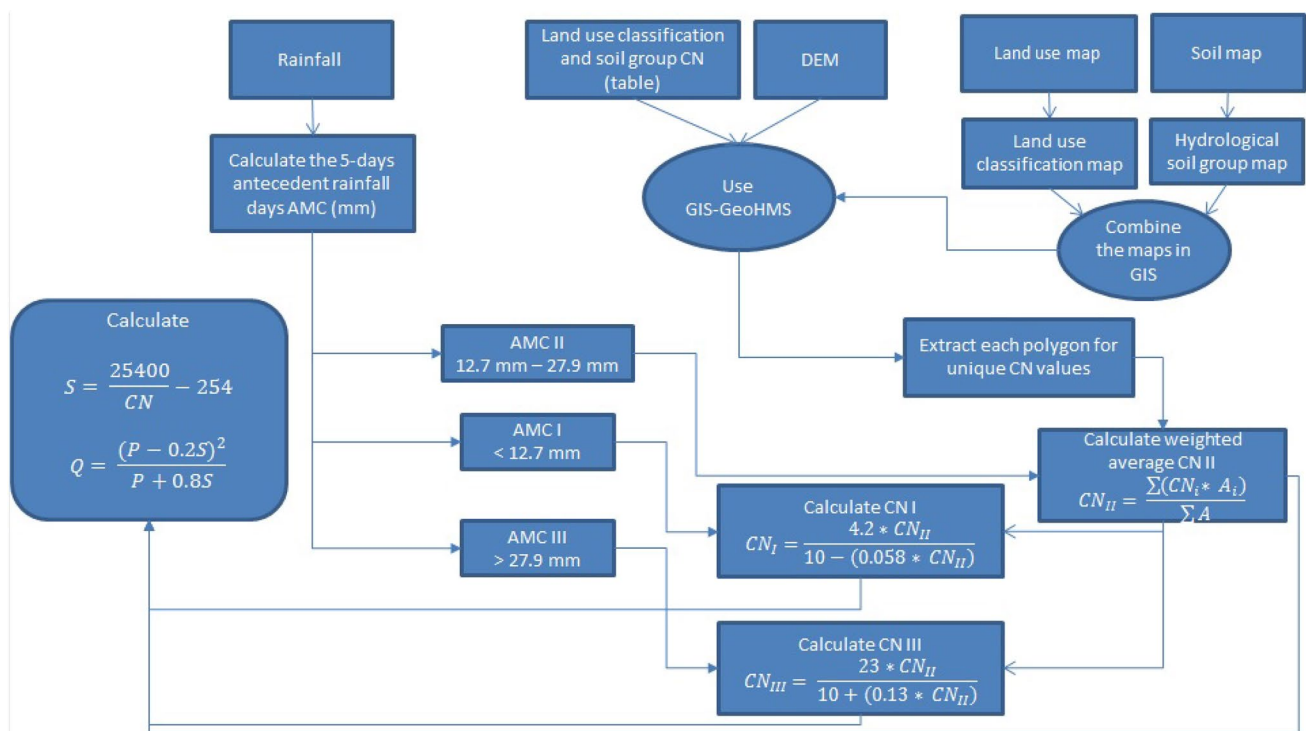


Fig. 5 Flowchart for the process to derive runoff from SCS-CN

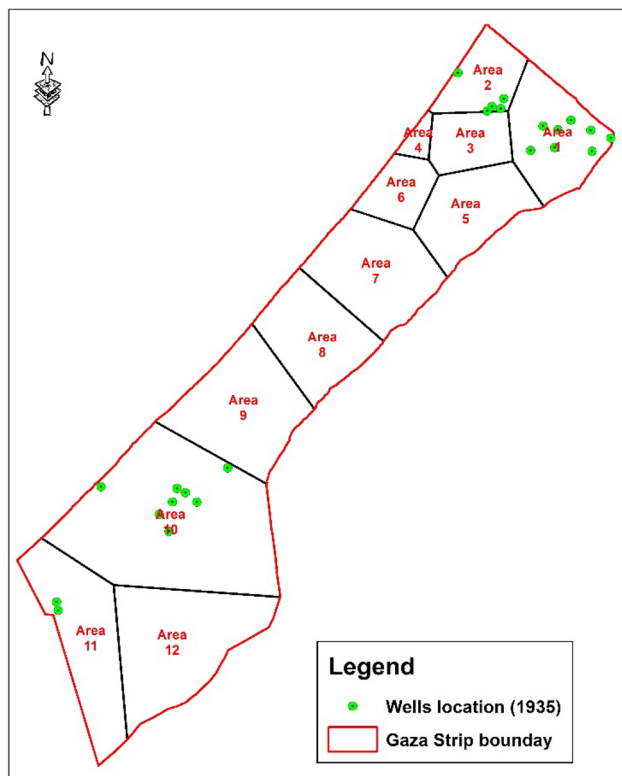


Fig. 6 Location of year 1935 wells in A1, A2, A10 and A11

Table 6 Land use classification and area percentage in different years

Land use classification	Year 1982 Area %	Year 1994 Area %	Year 2004 Area %	Year 2010 Area %
Open water	–	–	0.49%	0.54%
Built-up area	08.25%	14.25%	23.13%	25.23%
Greenhouses	02.95%	02.95%	03.77%	02.26%
Cultivated land	57.34%	57.34%	61.97%	63.33%
Sand area	31.46%	25.45%	10.65%	08.64%
Population (inhabitants)	477,000	749,000	1,274,380	1,575,102

permanent wilting point (PWP) and plant root zone depth (Zr). Equation (6) presents this relation (FAO 2012):

$$PAW = 10 (FC - PWP) \times Zr \tag{6}$$

With field capacity (FC) in vol%, permanent wilting point (PWP) in vol%, plant available water (PAW) in mm, plant root zone depth (Zr) in mm.

The soil moisture (SM) status of the soil depends on the accumulated potential water loss (APWL). The APWL is calculated by two different equations depending on whether the potential evapotranspiration is greater than or less than the precipitation. When the soil is drying [i.e., the potential evapotranspiration (PET) is in excess of the

effective precipitation (P)], the APWL is incremented by the difference of PET and P. On the other hand, when the soil is wetting (i.e., the potential evapotranspiration is less than the effective precipitation), the soil moisture content increases, and the storage in the soil (SM) is incremented by the difference between the potential evapotranspiration and precipitation until field capacity is reached and the surplus will percolate. In a mathematic formulation, the following procedure illustrates the Thornthwaite and Mather method (Bakundukize et al. 2011).

In wet season ( $P > PET$ ), SM increases to reach the soil FC; afterwards water can percolate to the saturated zone. Hence SM is known and APWL can be calculated from:

$$APWL = -PAW \times \ln \left( \frac{SM}{PAW} \right) \tag{7}$$

AET will be equal to PET and recharge =  $P - AET$ .

In dry season ( $P < PET$ ), APWL is known from (PET - P), while SM can be calculated from:

$$SM = PAW \times \exp \left( -\frac{APWL}{PAW} \right) + PWP \tag{8}$$

and  $AET = P + \Delta SM$  and  $AET < PET$ , and there is no recharge.

With potential evapotranspiration (PET) in mm, effective precipitation (P) in mm and equal to the difference of rainfall and runoff, soil moisture (SM) in mm, accumulated potential water loss (APWL) in mm, actual evapotranspiration (AET) in mm.

In the Gaza Strip, daily precipitation and potential evapotranspiration were available and were used in the Thornthwaite and Mather method for recharge calculation on a daily basis instead of using monthly average values. With the smaller time step, a better resolution in the recharge time series can be obtained (Walraevens et al. 2009; Bakundukize et al. 2011).

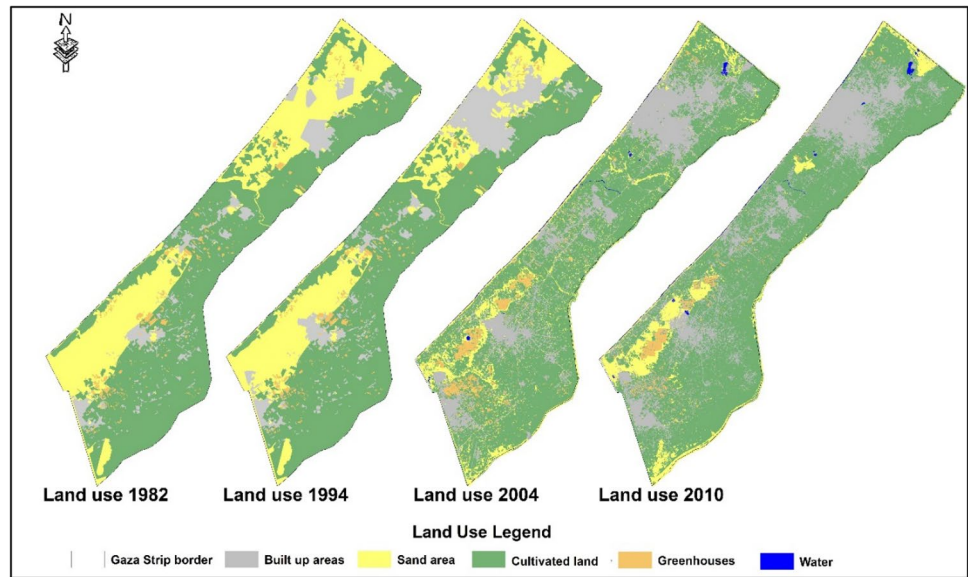
### Chloride mass balance (CMB) method

The chloride mass-balance method developed by Eriksson and Khunakasem (1969) compares total chloride deposition at the surface with chloride concentrations in groundwater near the water table, as measured in samples from shallow wells. Assuming chloride to be a conservative ion and rain water to be the only source of chloride (Cl), conservation of mass leads to a relation between precipitation and recharge (Eriksson and Khunakasem 1969):

$$P_{eff} \times Cl_p = R \times Cl_{gw} \tag{9}$$

where  $P_{eff}$  is the effective average yearly precipitation (mm);  $Cl_p$  is the average chloride concentration of precipitation (mg/l); R is the recharge (mm/year); and  $Cl_{gw}$  is the average chloride concentration of groundwater (mg/l).

**Fig. 7** Land use maps in different years



**Table 7** Curve number ( $CN_{II}$ ) calculation based on soil, AMC, DEM and land use

Area	1982	1994	2004	2010
Area 1	70.3	72.1	76.3	76.5
Area 2	56.4	58.3	67.8	68.1
Area 3	60.1	74.5	83.2	83.7
Area 4	60.6	76.6	85.1	85.5
Area 5	79.6	81.4	83.6	83.9
Area 6	52.9	80.0	85.0	85.8
Area 7	72.8	72.9	77.1	77.5
Area 8	77.9	77.9	80.7	80.9
Area 9	72.7	72.7	76.8	77.2
Area 10	68.4	69.0	74.4	74.6
Area 11	67.9	69.0	74.2	74.5
Area 12	75.8	75.8	75.7	75.7

We applied this method to two areas in the north and two areas in the south of the Gaza Strip, covering the areas 1, 2, 10 and 11 of the Thiessen polygon area map (Fig. 3). To make sure that the selected areas are not yet affected by sea water intrusion, we used the year 1935 chloride data, which makes those areas suitable to estimate the recharge using the CMB method.

A long-term average for the equation parameters must be considered because there is no immediate relation (at the same time) between the rain water chloride concentration and the groundwater chloride concentration. Eight wells in Area 1 (Beit Hanoun), 5 wells in Area 2 (Beit Lahia), 8 wells in Area 10 (Khan Younis) and 2 wells in Area 11 (Rafah) have been chosen from chloride analyses available for the year 1935 (Fig. 6) (PWA/USAID 2000), for which the arithmetic average chloride concentration has been calculated for

each area. The average rain water chloride concentration is analyzed to be 34.5 mg/l based on 4 rainwater samples taken in the year 2007/2008 in the north of Gaza Strip (Hamdan et al. 2011).

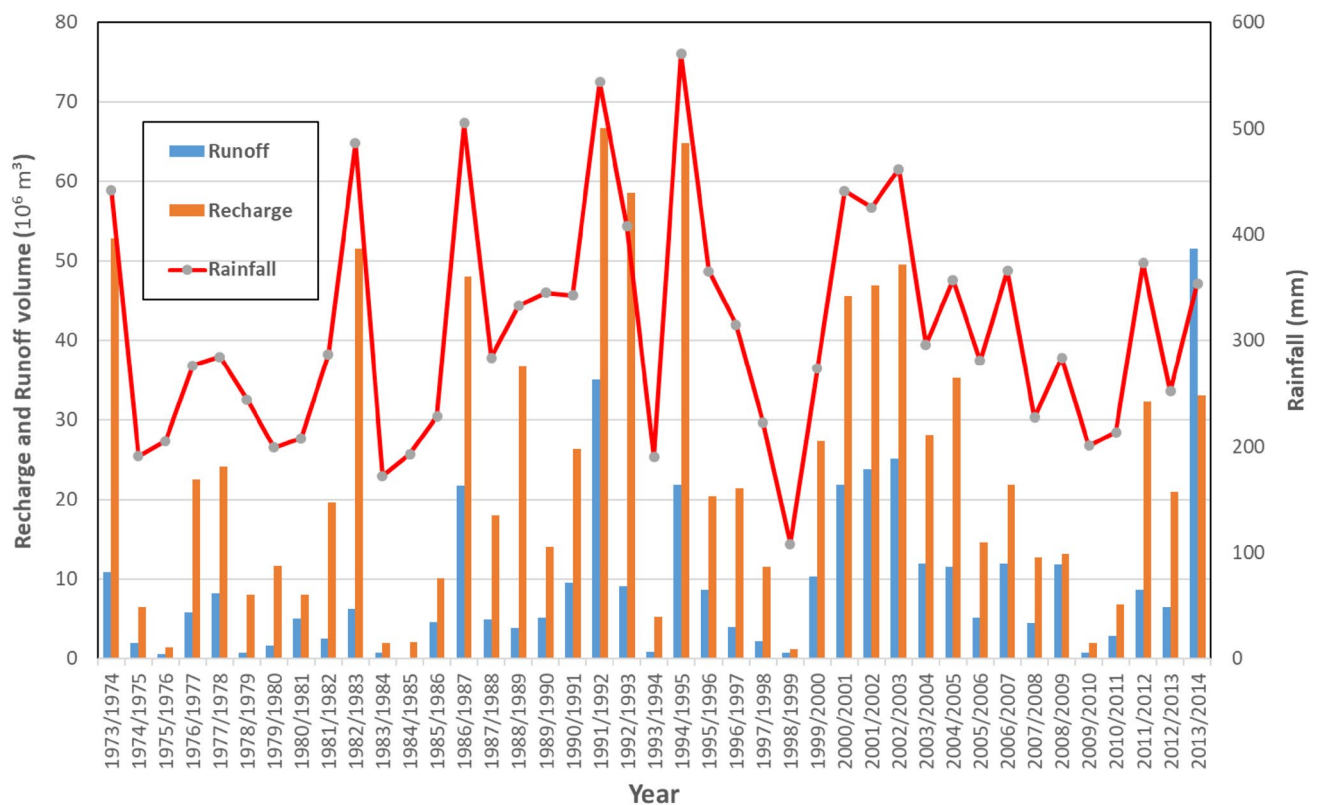
## Results

### Data preparation

To re-build the land use map for 1982, we should know the main changes in land use during the different years. Hence the percentage distribution of the land use classes on existing maps was assessed as shown in Table 6. The major changes were found in sand dune areas for the benefit of built-up area expansion, while the other classes show minor changes through different years. Based on population percentage versus built-up area in existing land use maps (1994, 2004 and 2010), a linear regression was performed, that allowed to assess that in the year 1982, when population was 477,000 inhabitants, the built-up area must have occupied 8.25%, while the sand dune areas covered more than 30% of the Gaza Strip area. Figure 7 shows all the land use maps in different years including the new map for 1982.

Table 7 shows the obtained curve number as a combination of land use, soil, DEM maps and AMC, where 48 values were obtained in four land use maps. The CN ranges from 52.9 to 85.5. As the changes between 2004 and 2010 land use maps were only small, the obtained CNs are very similar.

Supplementary electronic material, table II shows an example of PAW values calculation as per the soil texture and land use classification for Area 1 using 1982 land use map, while supplementary electronic material, table III



**Fig. 8** Weighted average annual rainfall, runoff and recharge over Gaza Strip from 1973 to 2014

represents the used final PAW for each polygon area and each calculation period. The PAW values range from 21 to 84 (supplementary electronic material, table III).

For recharge calculation with CMB method, we used 23 chloride analysis from wells located in the northern and southern areas, which cover Areas 1, 2, 10 and 11 of Thiessen polygons. The average chloride concentration was calculated for the year 1935 as 123.75 mg/l, 69.17 mg/l, 254.4 mg/l and 305 mg/l, respectively. The only rain water chloride data were found for the hydrological year 2007/2008 (Hamdan et al. 2011), the average of which is 34.5 mg/l, which was used in the calculations.

### Surface runoff

Figure 8 shows the surface runoff on a yearly basis, classified according to the relevant land use map. The long-term average runoff is 8.2% of rainfall (9.4 million  $\text{m}^3/\text{year}$ ), while if splitted based on the land use for the years 1982, 1994, 2004 and 2010, it is 6.1%, 5.9%, 11% and 13.4%, respectively. The runoff volume is changing from 1 year to another depending on the rainfall quantity, duration and intensity as shown in the year 2013/2014, when the runoff reached 51.5 million  $\text{m}^3$  from 353.7 mm rainfall fallen in 16 days, while the largest

rainfall amount (270 mm) occurred in a storm during only 5 days (10 Dec.–14 Dec. 2013).

### Recharge from rainfall

#### SMB method

By using the SMB method, the long-term weighted average recharge is 21.6% (24.5 million  $\text{m}^3$ ) of the total weighted rainfall over the Gaza Strip (Fig. 8). Yearly recharge strongly varies with rainfall, but the weighted average accounting for surface area over the considered periods (1973–1993, 1993–1999, 1999–2008 and 2008–2014) shows a tendency to decrease, except for the unusually wet year 1999/2000.

The maximum recharge occurred in 1991/1992, which was a year of snow (the only year Gaza saw snow and hail storms), when recharge reached 66.7 million  $\text{m}^3$ . In the years 2001/2002, 2002/2003 and 2003/2004, the recharge and runoff were above the long-term average due to long rainfall periods of 46, 34 and 51 days, respectively.

**Table 8** Recharge estimation based on CMB (year 1935)—(a) Area 1, (b) Area 2, (c) Area 10 and (d) Area 11

(a) North of the Gaza Strip—Area 1 (Beit Hanoun)		
Average chloride concentration in groundwater in year 1935 (mg/l)		123.75
Effective average precipitation (mm)		357.1
Average chloride concentration in rain water (mg/l)		34.5
Long-term average rainfall (mm)		395.1
Recharge using CMB method ( $P_{\text{eff}} \times Cl_{\text{rain}}/Cl_{\text{GW}}$ ) (mm)		99.56
Recharge percentage from rainfall		25%
Long-term average recharge percentage from rainfall using Thornthwaite and Mather method		23%
Difference error between the two applied methods		2%
(b) North of the Gaza Strip—Area 2 (Beit Lahia)		
Average chloride concentration in groundwater in year 1935 (mg/l)		69.17
Effective average precipitation (mm)		382.1
Average chloride concentration in rain water (mg/l)		34.5
Long-term average rainfall (mm)		405.7
Recharge using CMB method ( $P_{\text{eff}} \times Cl_{\text{rain}}/Cl_{\text{GW}}$ ) (mm)		190.6
Recharge percentage from rainfall		47%
Long-term average recharge percentage from rainfall using Thornthwaite and Mather method		38%
Difference error between the two applied methods		9%
(c) South of the Gaza Strip—Area 10 (Khan Younis)		
Average chloride concentration in groundwater in year 1935 (mg/l)		254.4
Effective average precipitation (mm)		258.2
Average chloride concentration in rain water (mg/l)		34.5
Long-term average rainfall (mm)		273.8
Recharge using CMB method ( $P_{\text{eff}} \times Cl_{\text{rain}}/Cl_{\text{GW}}$ ) (mm)		35
Recharge percentage from rainfall		13%
Long-term average recharge percentage from rainfall using Thornthwaite and Mather method		18%
Difference error between the two applied methods		5%
(d) South of the Gaza Strip—Area 11 (Rafah)		
Average chloride concentration in groundwater in year 1935 (mg/l)		305
Effective average precipitation (mm)		217.1
Average chloride concentration in rain water (mg/l)		34.5
Long-term average rainfall (mm)		224.9
Recharge using CMB method ( $P_{\text{eff}} \times Cl_{\text{rain}}/Cl_{\text{GW}}$ ) (mm)		24.6
Recharge percentage from rainfall		11%
Long-term average recharge percentage from rainfall using Thornthwaite and Mather method		14%
Difference error between the two applied methods		3%

### CMB method

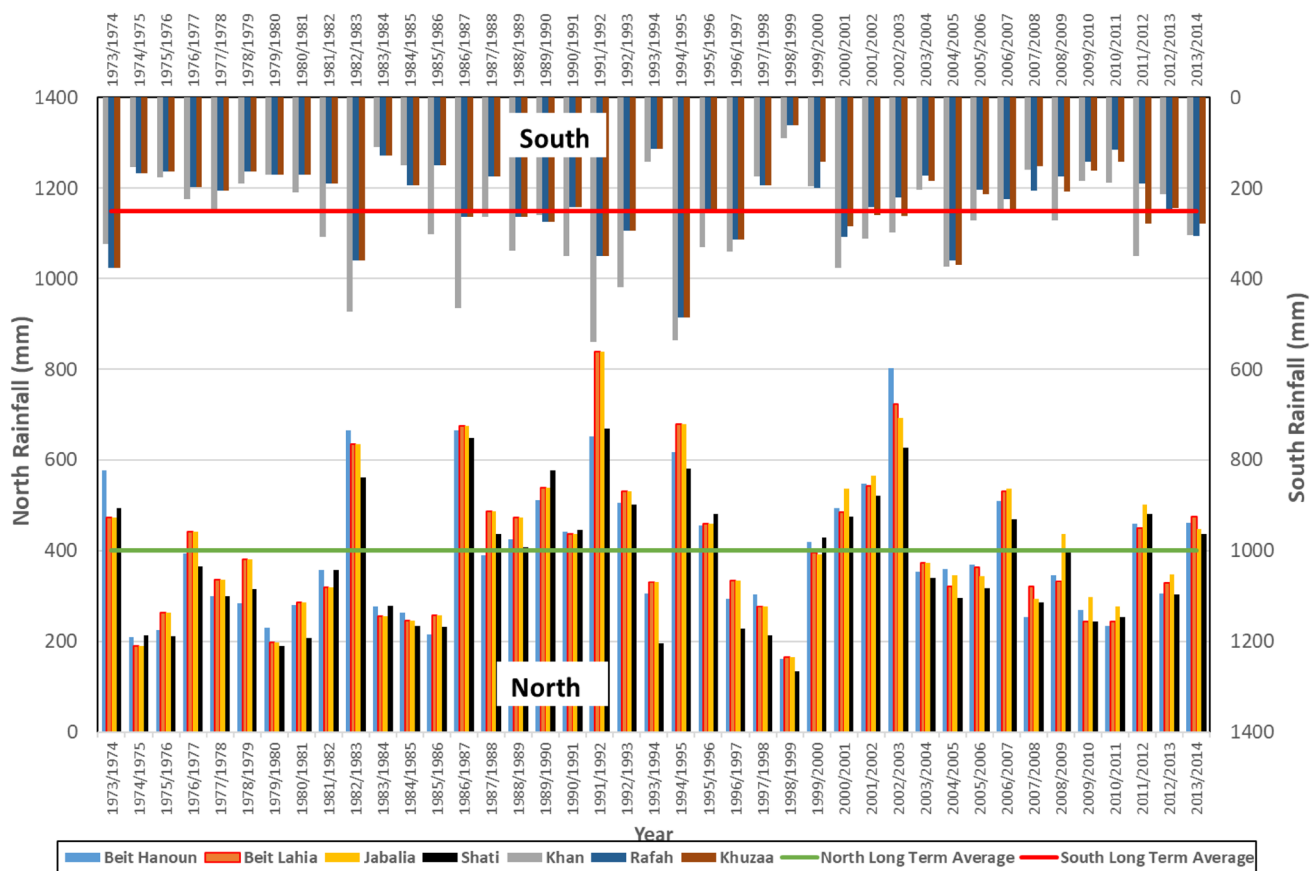
Table 8 shows the calculation results of the average recharge in the four areas. A comparison with SMB method results in a difference ranging from 2 to 9%.

### Discussion

The results of the analysis show that the long-term weighted average rainfall (over 41 years) is 311 mm/year, while a spatial variation occurs from north to south of the Gaza Strip (within 42 km distance) with 401 mm/year in the north and 250 mm/year in the south (Fig. 9). Even

though Area 1 “Beit Hanoun” and Area 2 “Beit Lahia” are located at the northern part of the Gaza Strip (Fig. 3) and have almost the same rainfall quantity (395 mm and 406 mm, respectively), they show a variation in runoff and recharge (Fig. 10a–d). This variation is mainly due to the presence of clayey soils in Area 1, while Area 2 does not have this soil type (supplementary electronic material, Figure I). The recharge is higher in Area 2 than in Area 1 due to soil texture distribution, while for the same reason, the runoff in Area 1 is higher than in Area 2.

The main factor for runoff variation is the evolution of the built-up area: before 1993, the total built-up area was 8.25% (30.1 km<sup>2</sup>) of the Gaza Strip and the average runoff (1973–1992) was 6.1% of the rainfall (6.9 million m<sup>3</sup>),



**Fig. 9** Weighted average annual rainfall in the north and south of the Gaza Strip (41 years)

while after development of the area, the total built-up area has become 25.23% (92.1 km<sup>2</sup>) of the Gaza Strip and the runoff increased to 13.4% of the rainfall (13.7 million m<sup>3</sup>). On the other hand, the sand dune area has been decreasing over time, as shown in the different land use maps (Table 6). Changing from 31.46% of the total Gaza Strip area in 1982 to 25.45% in 1994 has slightly increased runoff by 8.7%, while between 1994 and 2004, the sand dune areas decreased by 42% (92.9 km<sup>2</sup>–38.9 km<sup>2</sup>), which led to increase the runoff by 120% (from 6.3 to 14 million m<sup>3</sup>).

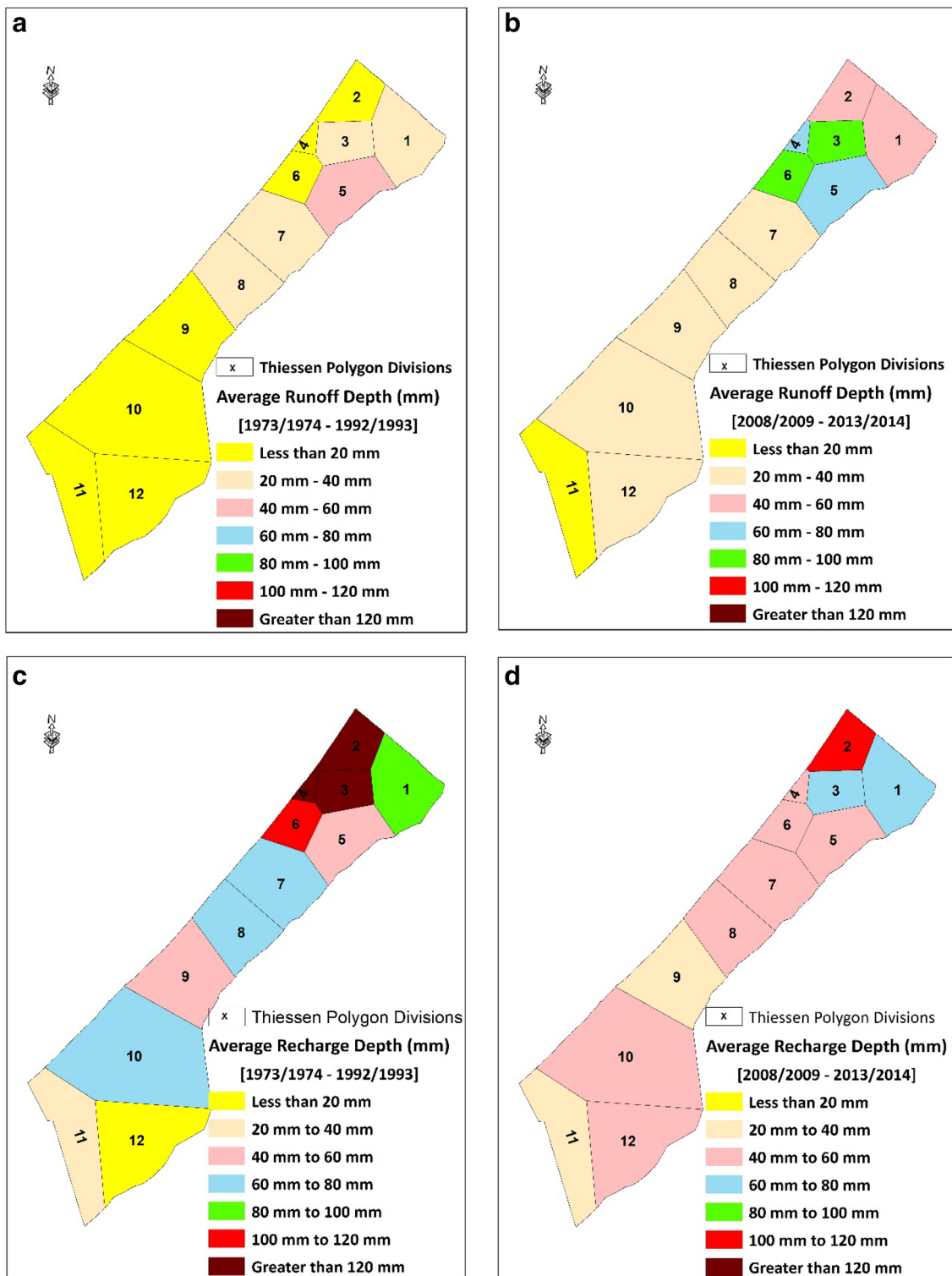
Runoff and recharge are also affected by rainfall quantity and intensity. For example, in the year 2013/2014, more than 70% of the rainfall has fallen in 5 days (10–14 Dec. 2013) and produced a runoff quantity of 46.6 million m<sup>3</sup>, exceeding the recharge quantity of 31.15 million m<sup>3</sup> (refer to Fig. 11a, b). This runoff has created a flooding everywhere in the Gaza Strip, as was personally observed by the first author, and was reported in the media. On the other hand, when the rainfall duration is greater than 30 days and its quantity is higher than the long-term average rainfall, then the recharge and runoff quantities will be higher than the long-term average as shown in the years 1982/1983, 1986/1987, 1991/1992,

1992/1993, 1994/1995, 2000/2001, 2001/2002, 2002/2003 (refer to Figs. 8, 11a, b).

An increase by 99% of runoff is observed due to an increase of the built-up area by three times (1982–2010). On the other hand, in Areas 1, 5, 7 and 8 (Fig. 3), the main factor for high runoff was the clayey soil texture (see supplementary electronic material, Figure I), knowing that the land use remained almost the same during the different years (Fig. 7). Areas 4 and 6 (Figs. 3, 7) were not developed before 1992/1993 (western side of the area) and due to presence of sand dune areas, the runoff was almost zero (average of 2–5% of the rainfall from 1973 to 1993) and a high percentage of recharge was achieved (average of 31–43% of the rainfall from 1973 to 1993), while after development the average runoff was 17–19% of the rainfall and, as a consequence, the recharge decreased to an average of 19–22% of the rainfall.

In Area 2 (Figs. 3, 7), where the sand dunes are still present, the recharge rate is larger than in the other areas.

In previous studies, the average annual recharge was found in the range from 35 × 10<sup>6</sup> to 64 × 10<sup>6</sup> m<sup>3</sup>/year, while in this study, the annual average recharge is 24.5 × 10<sup>6</sup> m<sup>3</sup>/year (lower than all previous estimates) and the annual average runoff is



**Fig. 10 a** Spatial distribution of average runoff according to the Thiessen polygon area (1973–1993). **b** Spatial distribution of average runoff according to the Thiessen polygon area (2008–2014). **c** Spatial

distribution of average recharge according to the Thiessen polygon area (1973–1993). **d** Spatial distribution of average recharge according to the Thiessen polygon area (2008–2014)

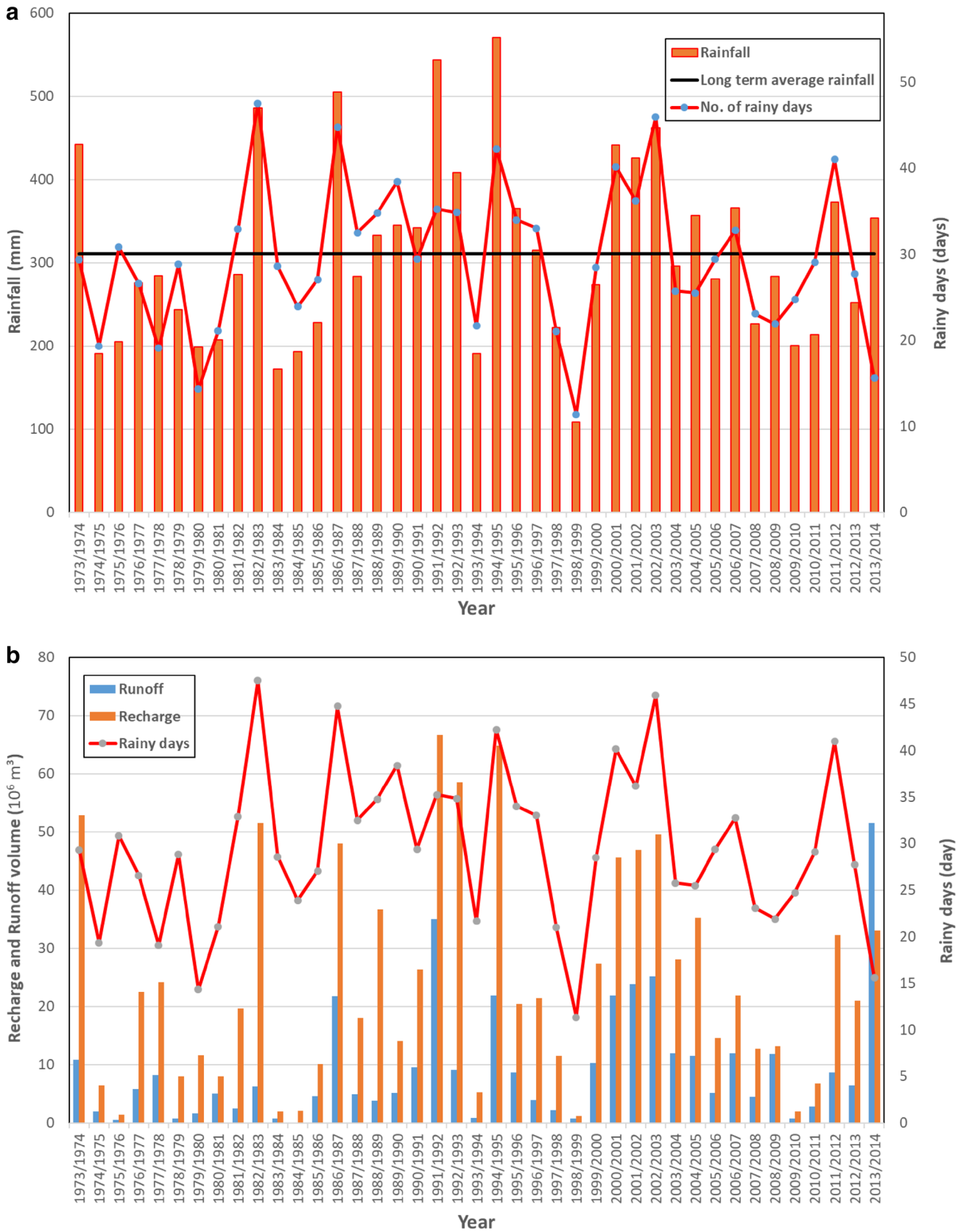


Fig. 11 a Rainy days versus rainfall. b Rainy days versus recharge and runoff



$9.4 \times 10^6 \text{ m}^3/\text{year}$ . These lower recharge values are attributed to using more accurate and correct data, such as actually measured evapotranspiration, taking runoff into account and taking into consideration an accumulation of soil moisture day by day until soil moisture reaches field capacity. The previous studies discussed in this paper did not account for evapotranspiration, soil moisture condition and/or runoff at the same time step of recharge calculation. In addition, they used total rainfall quantities (monthly and/or yearly) as the basis for the recharge estimation. Previous methods were based on mostly very rough assumptions and simplifications, but in this study, the estimation was improved by using daily spatial precipitation, soil, land use and DEM data and maps. Additionally, an important added value of our study certainly is the historical reconstruction we made of runoff and recharge, based on the temporal variability of meteorological data and land use.

The CMB method has been applied for a period prior to important groundwater exploitation, in which no salt water intrusion was taking place (the year 1935). The chosen wells were shallow and the chloride found in the shallow groundwater was derived from rainfall. The wells are located in four Thiessen polygon zones. The resulting recharge based on CMB in each zone was compared against the long-term average recharge in the same zone obtained from SMB. The difference between the two methods varies from 2 to 9%. Hence a good correspondence between SMB method and the CMB method gives confidence in our results.

## Conclusions

Gaza Strip depends on groundwater for the water supply system. Over decades the aquifer is being exposed to salinization due to overexploitation, while the only fresh water replenishment to the groundwater is coming from rainfall. Hence it is useful to review previous recharge estimates and compare it with another method (Thorntwaite and Mather SMB approach). Also the spatial distribution of recharge quantities is important to the decision-makers in the Gaza Strip for better management. Surface runoff has been computed as a first step towards computing the groundwater recharge from rainfall. The runoff was estimated based on daily rainfall and according to SCS-CN method. An alternative method was used to confirm the SMB method results in selected areas using CMB.

Previous studies discussed in this paper show a large variety of recharge estimations in the Gaza Strip ranging from  $35 \times 10^6$  to  $64 \times 10^6 \text{ m}^3/\text{year}$ , where none used small time discretization (daily rainfall and evapotranspiration records), land use changing over time, and soil texture. This study uses daily rainfall and evapotranspiration for the past 41 years, and land use changing over time based on different land use maps.

The findings of this study show that the long-term average recharge is  $24.5 \times 10^6 \text{ m}^3/\text{year}$  (21.6% of rainfall), which is lower than the previous recharge studies. This could be due to: (1) the neglecting of evapotranspiration in previous studies; (2) our calculation of the recharge input parameters from the runoff output, and (3) we used smaller time step discretization which most likely corresponds to a better approximation of reality. The CMB method confirmed our recharge estimation with SMB approach.

Over the past 41 years, changing land use resulted in increasing built-up area at the expense of sand area. This has led to doubling of runoff and decreasing groundwater recharge. This finding has important implications for water and land management in Gaza Strip.

This study gives a comprehensive spatial and temporal distribution of both runoff and recharge for the study area from 1973 to 2014. The results improve understanding of the Gaza Strip water budget and will hopefully aid for a better aquifer management.

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