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Quantification of Recharge and Runoff from Rainfall Using New GIS Tool: Example of the Gaza Strip Aquifer

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Abstract: The Gaza Strip forms a transition zone between the semi-humid coastal zone in the north, the semi-arid zone in the east, and the Sinai desert in the south. Groundwater is the only water source for 1.94 million inhabitants, where the only fresh replenishment water for the aquifer comes from rainfall. This study focuses on testing a newly developed GIS tool to estimate the spatial and temporal distribution of runoff and recharge from rainfall. The estimation of surface runoff was made using the Soil Conservation Services Curve Number Method, while groundwater recharge was estimated using Thornthwaite and Mather's Soil Moisture Balance approach. The new tool was applied to the Gaza aquifer for the year 1935 and for the period from 1973 to 2016. A comparison was made between the results obtained with the developed GIS tool and the frequently used Thiessen polygon method for rainfall distribution. Runoff and recharge were estimated for the year 1935 (prior to development) to compare with the current developed conditions. It was found that the built-up and sand dune areas stand in an inverse relationship, where the former is replacing the latter (built-up area expanded from 30.1 km^2 in 1982 to 92.1 km^2 in 2010). Recharge takes place in the sand dune area, whereas runoff increases in the built-up area. Due to development, runoff almost tripled from 9 million m^3 in 1982 to 22.9 million m^3 in 2010, while groundwater recharge was reduced from 27.3 million m^3 in 1982 to 23 million m^3 in 2010, even though the rainfall increased between 1982 and 2010 by 11%. Comparison between the newly developed GIS tool and the Thiessen polygon-based estimation shows that the former leads to higher values of runoff and recharge for dry years.

Keywords: GIS GRID; Thiessen polygon; Soil Moisture Balance approach; rainfall; runoff; recharge; Gaza Strip

1. Introduction

The Gaza Strip is a coastal area along the eastern Mediterranean Sea and lies at latitude 31°25′59″ N and longitude 34°22′34″ E. It forms a transition zone between the semi-humid coastal zone in the north, the semi-arid zone in the east, and the Sinai desert in the south (Figure 1). The Gaza Strip has an area of 365 km^2, where more than 1.94 million inhabitants are living (5315 persons per km^2) [1]. Groundwater is the only water source for the Gaza people, where the only fresh replenishment water for the aquifer comes from rainfall. Other recharge components are not fresh, including agricultural return flow, eastern groundwater inflow (lateral flow), water and waste water network leakage, and leakage from partially treated wastewater retention basins before dumping into the Mediterranean Sea.

The Gaza coastal aquifer consists of the Pleistocene age Kurkar Group [2] and the recent (Holocene age) sand dunes. The Kurkar Group includes marine and eolian calcareous sandstone, reddish silty sandstone, silts, clays, unconsolidated sands, and conglomerates. Regionally, the Kurkar Group is distributed in a belt parallel to the coastline, from north of Haifa to Sinai in the south (Figure 1). Near the Gaza Strip, the belt extends about 15 km to 20 km inland, where it overlies the Miocene-Pliocene age Saqiya Group, a very thick sequence of marls, marine shales, and clay stones [3]. 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 to 10 m in the South East [4,5]. Mushtaha et al. [5] have discussed the Gaza hydrogeological stratigraphy in more detail.

Groundwater recharge from rainfall is a major component in the water balance of an aquifer. Other recharge components to the Gaza aquifer are lateral inflow across the Israeli border in the south-east, and leakage from water and wastewater networks and storm water collection basins. In the present paper, we focus on recharge from rainfall.

Previous studies have shown a large variety of recharge estimations in the Gaza Strip, ranging from 24.5×10^6 m^3/year to 64×10^6 m^3/year. These studies were conducted using different methods, but did not use spatial and temporal discretization. These studies were discussed in more detail in Mushtaha et al. [5]. The latter research used temporal discretization for 41 years (daily rainfall and evapotranspiration records), land use change over time, and soil texture, accompanied with Thiessen polygon spatial discretization, and came up with long-term average recharge and runoff values of 24.5×10^6 m^3/year and 9.4×10^6 m^3/year, respectively (Table 1).

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

Study Reference	Method Used	Recharge from Rainfall (10^6 m^3/year)	Runoff from Rainfall (10^6 m^3/year)
[6]	Recharge coefficients based on soil type	41	-
[7]	Change in aquifer storage (seasonal fluctuation)	64	-
[8]	Chloride mass balance	46	-
[9]	Land use and soil infiltration coefficients (from literature)	37	13.5
[10]	Groundwater modelling	35–40	5.8–9
[11]	Cumulative rainfall departure	43.29	-
[12]	Rational runoff formula created from empirical method with GIS based on different land use categories	-	37
[13]	WetSpass model (Free University of Brussels VUB, Ixelles, Belgium [14]).	39–40	-
[15]	Soil & Water Assessment Tool model (SWAT model, United States Department of Agriculture, Washington, DC, USA) within Automated Geospatial Watershed Assessment (AGWA) tool	46.17	-
[5]	Soil Moisture Balance (SMB) and Soil Conservation Services Curve Number (SCS-CN) methods using Thiessen polygon spatial distribution	24.5	9.4

* Source: Modified after [5].

The objectives of this study are (1) to calculate the recharge and runoff from rainfall for the Gaza Strip based on actual collected historical data from 1973 to 2016 using a newly developed tool in GIS based on full spatial distribution; and (2) to compare the results with calculations carried out using Thiessen polygon method for rainfall distribution for the same period (1973–2014) by Mushtaha et al. [5].

The developed GIS tool makes it possible to calculate groundwater recharge from rainfall by Thornthwaite and Mather's [16] Soil Moisture Balance Method using daily records of rainfall and evaporation, and rainfall runoff calculated according to Soil Conservation Services Curve Number (SCS-CN) method [17] using Geospatial Hydrologic Modeling System (Geo-HMS) [18] based on the land use map, hydrological soil map, digital elevation map, and SCS reference table incorporated in ArcMap extension.

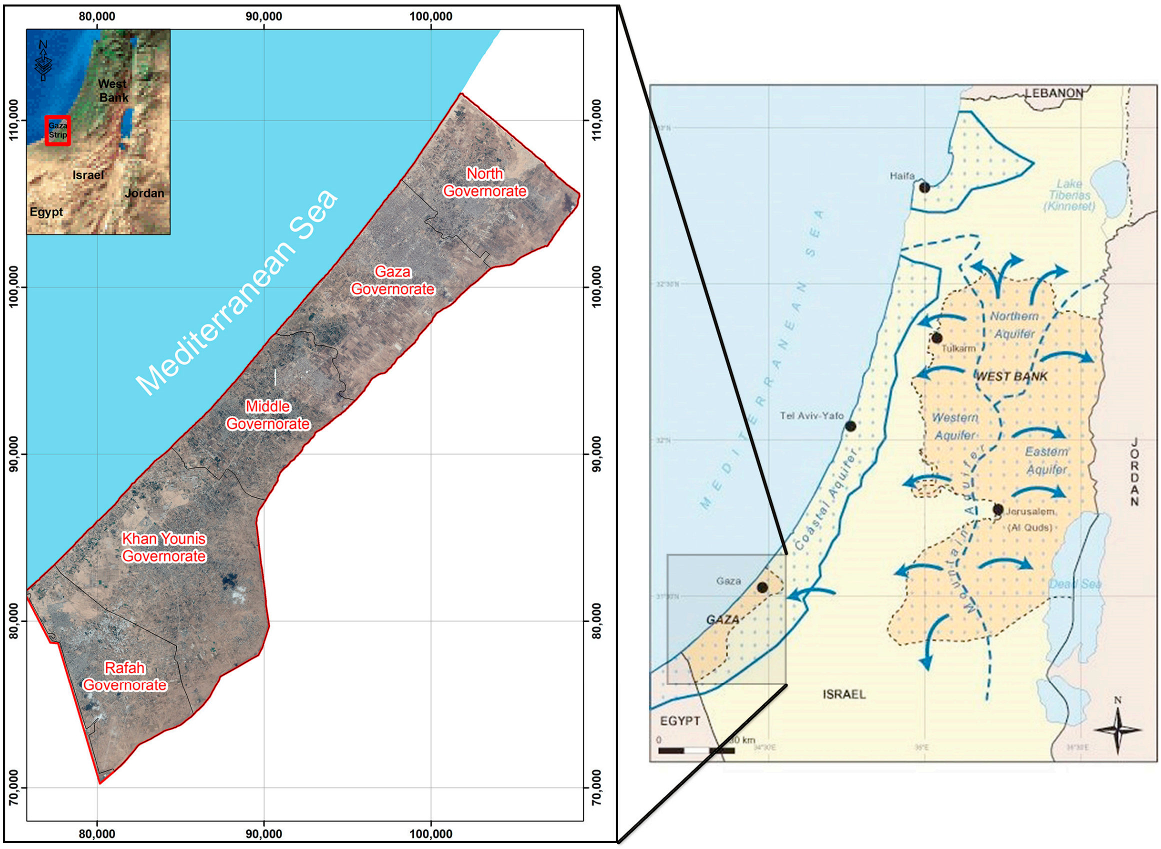

Figure 1. Regional coastal aquifer and Gaza Strip location (after [19,20]).

2. Materials and Methods

A new GIS tool was developed to estimate spatial and temporal distribution of runoff and recharge using the CN and SMB methods, respectively.

The SCS-Curve Number (CN) approach [17] was used for runoff estimation, while Thornthwaite and Mather's Soil Moisture Balance (SMB) method [16] was used for recharge estimation. These two methods were translated for use by the ESRI-GIS interface [21] using Model Builder and the Python language. The runoff and recharge calculations were performed from the year 1973 to the year 2016 (43 years). Since human activities changed over time, four land use maps were suggested for use by Mushtaha et al. [5]. This study used the same land use maps, in addition to the land use map for the year 1935, which can be considered representative of conditions prior to the strong development of the area.

The Inverse Distance Weighting (IDW) method was used to interpolate the point data within the GIS interface, because it gives greater weights to the points closest to the location of observation, and the weights diminish as a function of distance. IDW has been shown to be an appropriate method for daily rainfall interpolation [22].

2.1. Curve Number (CN) for Estimation of Runoff from Rainfall

The curve number (CN-II) estimation [17] was based on a combination of the land use maps, hydrologic soil map (Figure S1 in Supplementary Materials), digital elevation model (DEM) map, and SCS reference table (Table 2). Geo-HMS Hydrologic Modeling System [18] was used to produce five CN-II GRID maps based on the five land use maps (1935, 1982, 1994, 2004 and 2010). The GRID map cell size was set to 100 m × 100 m. Each cell has a unique CN-II value. Adjustments to CN-I for dry conditions and CN-III for wet conditions were calculated according to equations given by Chow et al. [23], based on Antecedent Moisture Conditions (Table 3). GRID maps for CN-I, CN-II and CN-III were calculated for all land use maps (3 × 5 GRID maps). The CN value was used to calculate runoff.

Table 2. Relationship between land use classification, hydrologic soil group and curve number [17].

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

Table 3. Antecedent rainfall limits for determining AMC type [17].

AMC Type	Total 5-Day Antecedent Rainfall	
	Dormant Season	Growing Season
AMC-I (dry conditions)	<12.7 mm	<35.6 mm
AMC-II (normal conditions)	12.7 mm–27.9 mm	35.6 mm–53.3 mm
AMC-III (for wet conditions)	>27.9 mm	>53.3 mm

2.2. Soil Moisture Balance (SMB) for Estimation of Groundwater Recharge from Rainfall

The Soil Moisture Balance method was used to calculate the recharge quantity to the groundwater after the plants and crops have taken their needs from water in the root zone and after reaching soil field capacity. Food and Agriculture Organization (FAO) [24] determined the specific water content at saturation, the field capacity, and the permanent wilting point, depending on soil type. The effective precipitation was obtained based on the runoff calculations that were performed (actual precipitation minus runoff depth) [5].

Plant Available Water (PAW) is one of the main parameters that need to be found in order to estimate recharge using Thornthwaite and Mather's Soil Moisture Balance (SMB) method [16]. PAW (in mm) is a function of field capacity (FC in %), permanent wilting point (PWP in %) and plant root zone depth (Zr in mm): PAW = 10 (FC − PWP) × Zr [24]. Five PAW GRID maps were produced based on the different land use maps. FC and PWP were estimated using the FAO [24] reference table.

The SMB method [16] equations are summarized in Table 4 [25], and an extensive discussion can be found in [5].

Table 4. Annual soil-water budget calculations (after [25]).

	Wet Season SUR = (P − Q) − PET > 0			Dry Season SUR = (P − Q) − PET < 0
		SM < PAW		
	SM = PAW	(P − Q) − PET ≤ PAW − SM	(P − Q)-PET > PAW − SM	
SM	PAW	SM + (P − Q) − PET	PAW	PAW × $e^{-APWL/PAW}$
R_N	(P − Q) − PET	0	(P − Q) − PET − (PAW − SM)	0
AET	PET	PET	PET	(P − Q) + ΔSM
DEF	0	0	0	PET − AET

P = precipitation (mm); Q = runoff (mm); PET = potential evapotranspiration (mm); APWL= accumulated potential water loss (mm) (PET − (P − Q)) accumulated for subsequent dry days; AET = actual evapotranspiration (mm); SM = water stored in soil: SM = PAW × $e^{-APWL/PAW}$; PAW = soil capacity (mm): maximum water content of soil, without gravitational water (= average rooting depth (mm) × water content at field capacity (in volume %); ΔSM = change in SM; DEF = deficit (PET − AET) (mm); SUR = surplus ((P − Q) − AET) (mm); R_N = natural groundwater recharge (SUR − ΔSM) (mm).

2.3. Rainfall and Evaporation

Rainfall for the year 1935 was taken from an average annual rainfall map (1931–1960), as shown in Figure 2. Twelve rainfall stations are distributed in the study area (Figure S2 in Supplementary Materials), with daily rainfall data since 1973. Daily pan evaporation data from 1986 to 1992 are available, while average daily evaporation was estimated before 1986 and after 1992. Daily rainfall and evaporation data were prepared from 1973 to 2016 as shape files on a yearly basis. The shape file attribute data include day of the year, rain gauge station coordinates (X and Y), daily rainfall (in mm), daily evaporation (in mm), and 5-day antecedent rainfall (in mm).

2.4. Land Use

Five land use maps (1935, 1982, 1994, 2004 and 2010) were prepared to estimate CN, in addition to the DEM, with a grid size of 25 m × 25 m. Mushtaha et al. In Reference [5], the land use map for 1982 was developed according to the spatial distribution of the population based on monitoring population growth since 1973, in addition to the trend of land use activities from existing land use maps (1994, 2004 and 2010). The land use map for the year 1935 was conceived as being for a pre-developed area with 72,000 inhabitants [26]. Figure 3 shows the new 1935 land use map, and Figure S3 in the Supplementary Materials shows the four different land use maps.

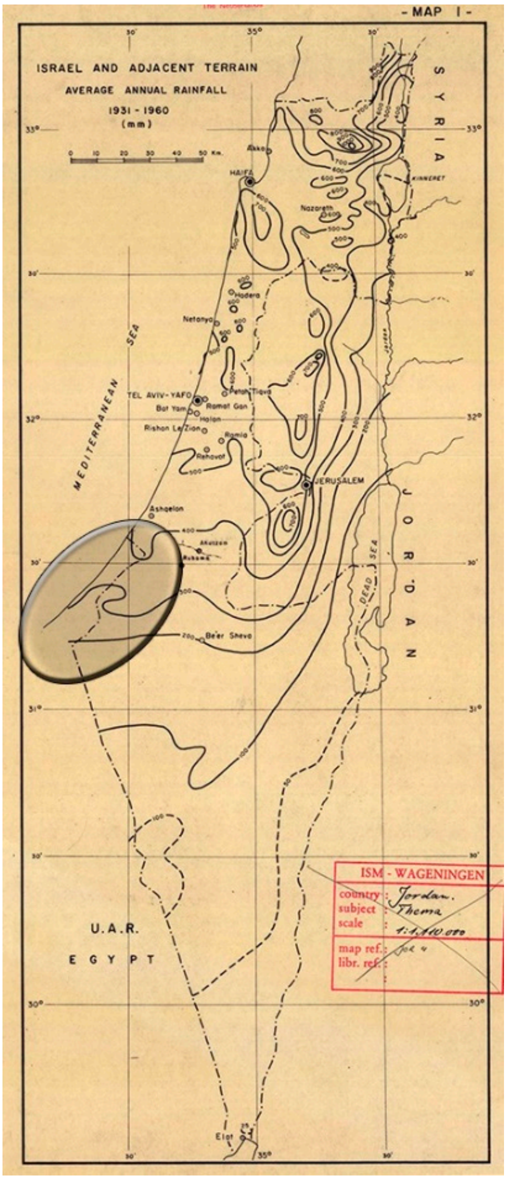

Figure 2. Average annual rainfall (1931 to 1960) [27].

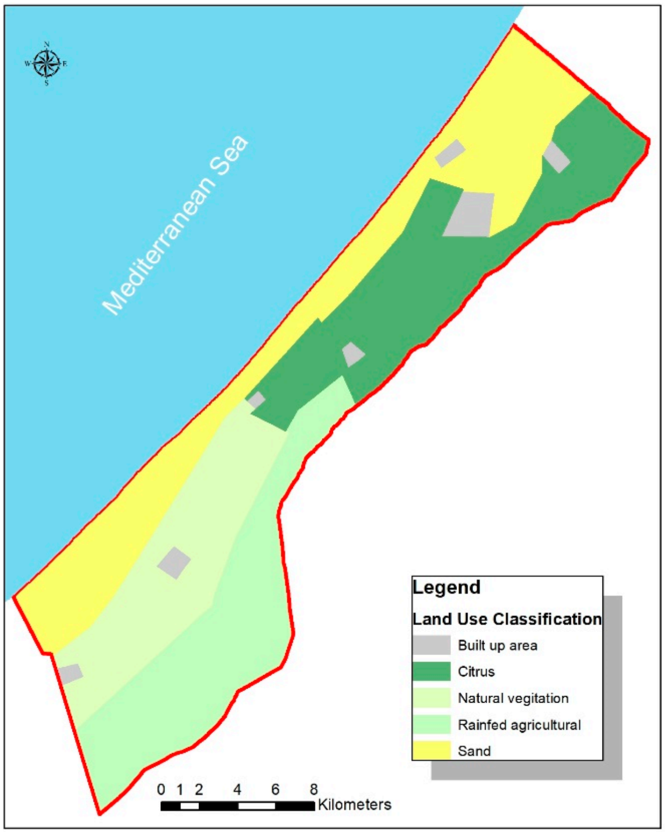

Figure 3. Land use map produced for the year 1935.

2.5. Development of GIS Tool

Pre-defined GRID maps (CN-I, CN-II, CN-III and PAW) have been called during the calculations according to the condition statement. Runoff and recharge equations were translated into GIS as a loop to perform calculations on daily basis for each cell. Firstly, rainfall, evapotranspiration (PET) and 5-day antecedent rainfall (AMC) were interpolated using the Inverse Distance Weighting (IDW) method in GIS using the same grid size (100 m $\times$ 100 m). Potential maximum retention (S) was produced based on a conditional statement to select the proper CN value according to Equation (1) and Table 3. The runoff (Q in mm) GRID map was produced based on the daily rainfall (P in mm) in each cell using Equation (2).

$$S = \frac{25400}{\mathrm{CN}} - 254 \quad (1)$$

CN selection is based on 5-day antecedent rainfall (Table 3) [28].

$$\mathrm{Q} = \frac{(\mathrm{P} - 0.2 \times S)^2}{\mathrm{P} + 0.8 \times S} \; (\text{if P} > 0.2\,S,\ \text{otherwise Q} = 0)\ [28] \quad (2)$$

Recharge calculation was performed based on three main components: (1) calculation of the Accumulated Potential Water Loss (APWL) based on the APWL of the previous time step, and augmented by the deficit of the new time step; (2) calculation of the effective rainfall (P_{eff} in mm = P − Q); and (3) calculation of soil moisture (SM) based on APWL. Recharge is calculated as (P_{eff} − PET) after the soil has reached field capacity. Initial pre-defined GRID maps for APWL and SM are zero and PAW value respectively, and they are changed according to the calculations at every loop based on Equations (3) and (4) in the Thornthwaite and Mather method [25]. Figure S4 in the Supplementary Materials shows a screenshot of the newly developed GIS tool for runoff-recharge estimations.

In the wet season (P_{eff} > PET), SM increases by (P_{eff} − PET) up to the soil FC and thus SM is known; APWL can be found using Equation (3). Water will percolate to the saturated zone producing groundwater recharge and AET will be equal to PET.

$$\mathrm{APWL} = -\mathrm{PAW} \times \ln\left(\frac{\mathrm{SM}}{\mathrm{PAW}}\right) \quad (3)$$

In the dry season (P_{eff} < PET), APWL increases by (PET − P_{eff}) and thus APWL is known; SM is calculated using Equation (4). AET = P_{eff} + ΔSM, and no groundwater recharge occurs.

$$\mathrm{SM} = \mathrm{PAW} \times \exp^{\left(-\frac{\mathrm{APWL}}{\mathrm{PAW}}\right)} \quad (4)$$

where Potential Evapotranspiration (PET) in mm: Effective rainfall (P_{eff}) in mm, Soil Moisture (SM) in mm, Accumulated Potential Water Loss (APWL) in mm, Actual Evapotranspiration (AET) in mm.

3. Results

In the year 1935, the average rainfall was 112.8 million m^3 over the surface area of the Gaza Strip (309 mm), while recharge quantity was 37.1 million m^3 and runoff was only 1.3 million m^3. Figures S5 and S6 show the surface runoff and recharge results for the year 1935 (pre-development conditions).

The long-term average (1973 to 2016) runoff is 13.4 million m^3/year (9.6% of the rainfall). Meanwhile, if split based on land use activities for the years 1982, 1994, 2004 and 2010, the results show 7.9%, 9.8%, 12.9% and 18.1% of the rainfall respectively (Figure 4).

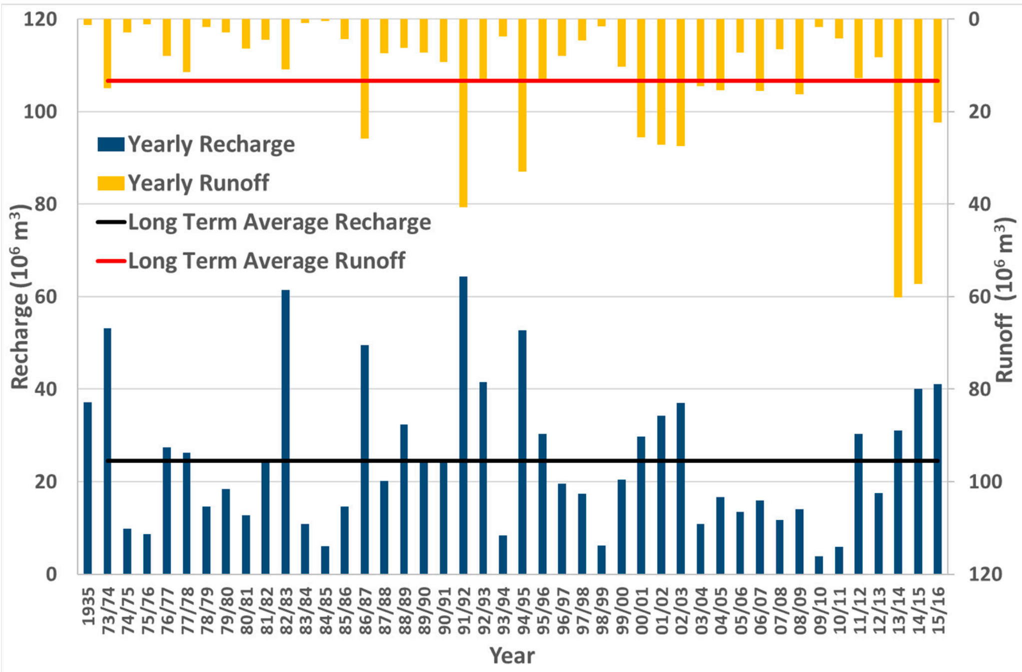

Figure 4. Runoff and recharge results (1935 and 1973–2016).

The long-term average recharge is 24.5 million m^3/year (19.2% of the rainfall). Recharge strongly varies with rainfall and intensity, but the average over the considered periods shows a tendency to decrease (Figure 4).

Figure 5 shows the long-term average spatial distribution of runoff and recharge (1973–2016) as produced from the GIS tool. Meanwhile, Table 5 shows the tabulated results of rainfall, runoff and recharge results using GRID calculations per year.

Table 5. Rainfall, runoff and recharge over the Gaza Strip for 1935 and from 1973 to 2016 using GRID calculation.

Year	Land Use	Average Rainfall (mm)	Runoff (10^6 m^3)	Recharge (10^6 m^3)	% of Runoff from Rainfall	% of Recharge from Rainfall	Average Rainfall (mm)	Average Runoff (10^6 m^3)	Average Recharge (10^6 m^3)	% of Runoff from Rainfall	% of Recharge from Rainfall
1935	**1935**	309	1.3	37.1	1.1%	32.9%	309	1.3	37.1	1.1%	32.9%
1973/1974	**Land Use Map 1982**	449.9	15.0	53.1	9.3%	32.9%	312.7	9.0	27.3	7.9%	23.9%
1974/1975		193.4	2.9	9.8	4.1%	14.1%					
1975/1976		207.6	1.2	8.6	1.5%	11.5%					
1976/1977		283.1	7.9	27.4	7.8%	27.2%					
1977/1978		287.4	11.4	26.3	10.9%	25.3%					
1978/1979		250.9	1.7	14.6	1.9%	16.4%					
1979/1980		200.6	2.9	18.4	4.1%	25.3%					
1980/1981		208.0	6.4	12.7	8.4%	16.7%					
1981/1982		286.3	4.5	25.0	4.3%	23.9%					
1982/1983		488.6	10.9	61.4	6.1%	34.6%					
1983/1984		178.4	0.9	10.8	1.4%	17.2%					
1984/1985		196.0	0.4	6.0	0.6%	8.5%					
1985/1986		224.2	4.3	14.7	5.2%	17.6%					
1986/1987		511.9	25.8	49.5	14.0%	26.9%					
1987/1988		290.2	7.4	20.2	7.1%	19.5%					
1988/1989		335.0	6.2	32.3	5.1%	26.6%					
1989/1990		357.1	7.2	24.6	5.7%	19.5%					
1990/1991		344.9	9.3	24.9	7.4%	19.9%					
1991/1992		549.7	40.7	64.4	20.5%	32.5%					
1992/1993		410.8	13.6	41.5	9.1%	27.8%					
1993/1994	**Land Use Map 1994**	194.4	3.8	8.4	5.4%	12.0%	297.4	10.6	22.4	9.8%	20.7%
1994/1995		573.9	33.0	52.7	15.8%	25.3%					
1995/1996		370.6	13.0	30.3	9.8%	22.8%					
1996/1997		311.6	7.9	19.6	6.8%	17.1%					
1997/1998		224.7	4.6	17.4	5.6%	21.4%					
1998/1999		109.1	1.5	6.2	3.9%	15.8%					
1999/2000	**Land Use Map 2004**	281.2	10.3	20.5	10.3%	20.5%	353.9	16.6	21.1	12.9%	16.4%
2000/2001		447.0	25.5	29.8	15.8%	18.5%					
2001/2002		434.8	27.2	34.2	17.5%	22.0%					
2002/2003		471.7	27.4	37.0	16.3%	22.0%					
2003/2004		301.4	14.5	10.9	13.4%	10.1%					
2004/2005		354.7	15.4	16.7	11.8%	12.8%					
2005/2006		282.6	7.3	13.5	7.1%	13.2%					
2006/2007		377.3	15.5	15.9	11.6%	11.9%					
2007/2008		234.5	6.5	11.7	7.8%	14.1%					
2008/2009	**Land Use Map 2010**	291.0	16.2	14.0	15.6%	13.6%	346.5	22.9	23.0	18.1%	18.2%
2009/2010		204.6	1.7	3.9	2.3%	5.3%					
2010/2011		217.5	4.2	5.9	5.5%	7.6%					
2011/2012		379.2	12.8	30.3	9.4%	22.3%					
2012/2013		257.4	8.3	17.5	9.0%	19.1%					
2013/2014		425.6	60.2	31.0	38.7%	19.9%					
2014/2015		477.2	57.3	40.1	32.9%	23.0%					
2015/2016		519.9	22.3	41.1	11.7%	21.7%					
Average—43 Year (1973–2016)		**325.5**	**13.4**	**24.5**	**9.6%**	**19.2%**					

Over the entire period, 24 years were below the long-term average rainfall and 19 years were above the long-term average rainfall. Annex I and Annex II in the Supplementary Materials show the 43-year GRID maps for runoff and recharge respectively.

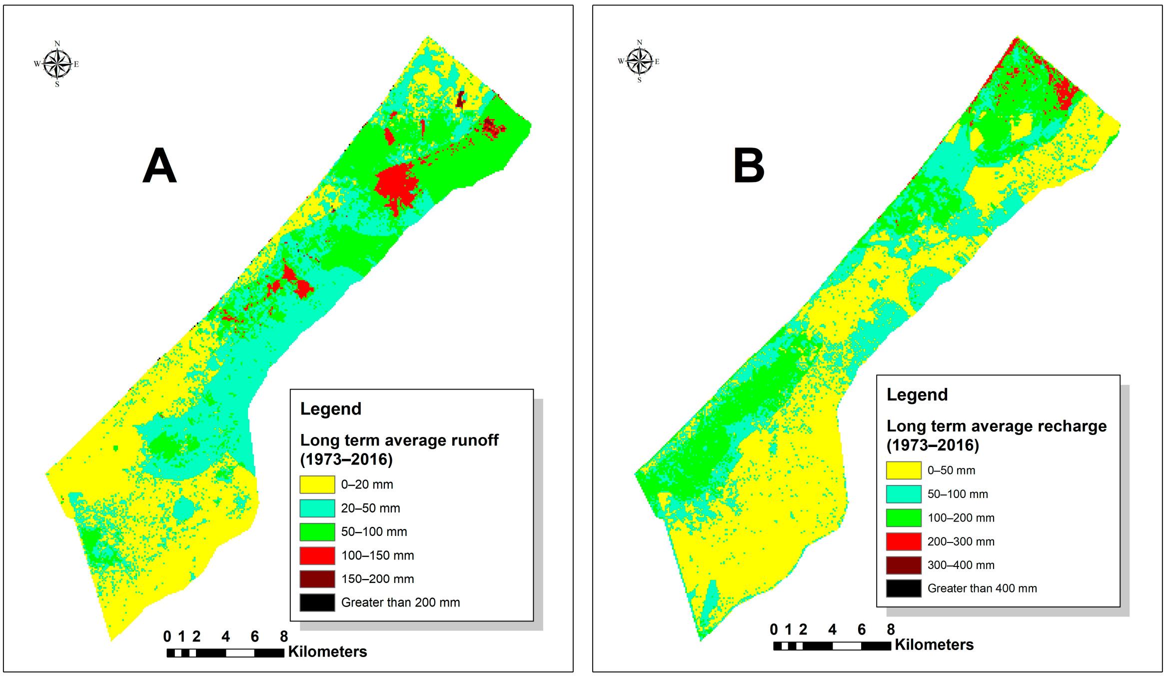

Figure 5. (**A**) Spatial distribution of long-term average runoff, (**B**) spatial distribution of long-term average recharge.

Built-up areas increased three times from the year 1982 to 2010 (from 30.1 to 92.1 km^2), while the sand dune area decreased by more than 70% (114.8 to 31.5 km^2) [5]. This dramatic change in land use activities increased the runoff from 9 to 22.9 million m^3, and recharge decreased from 27.3 to 23 million m^3 during the same land use evolution period (Figure 6).

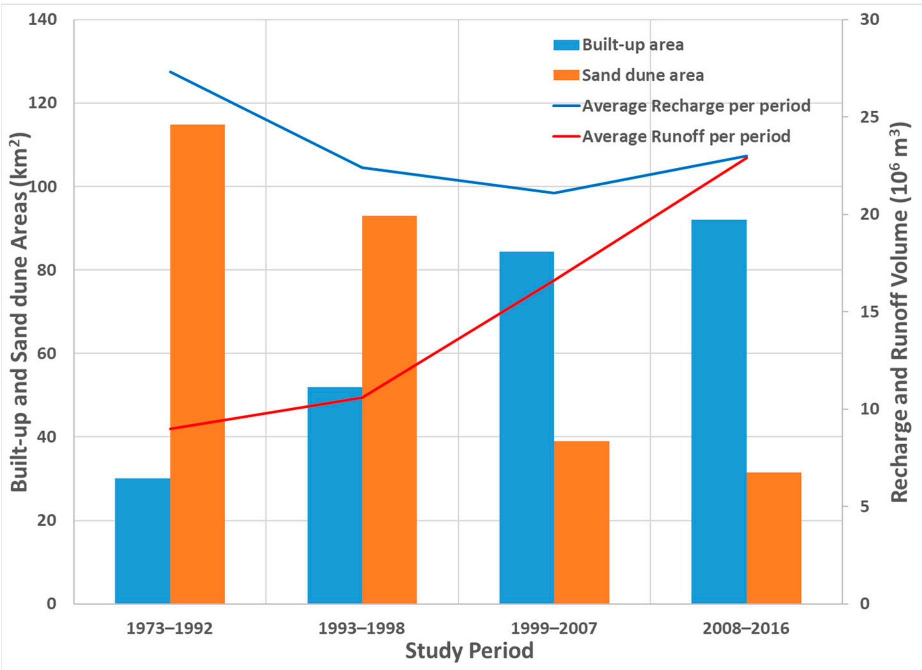

Figure 6. Relation between built-up and sand dune areas versus runoff and recharge over the entire period (1973–2016).

4. Discussion

In 1935, under pre-developed conditions in the Gaza Strip, runoff was very low, at 1.3 million m^3 compared to the runoff calculations in the period from 1973 to 2016. The results of the analysis (43 years) show that the long-term average rainfall was 119 million m^3 over the surface area of the Gaza Strip (326 mm/year), leading to long-term average runoff of 13.4 million m^3 and long-term average recharge of 24.5 million m^3.

The changes in runoff were due to expansion in built-up area at the expense of sand dune area [5], as shown in Figure 6, with an overall trend of increasing runoff by more than 1600% (from 1.3 million m^3 to 22.9 million m^3), while recharge decreased by more than 38% (from 37.1 million m^3 to 23 million m^3) over the entire period (Figure 4 and Table 5). Meanwhile, the runoff volume changed from one year to another within the same land use group (land use maps of 1982, 1994, 2004 and 2010) depending on the rainfall quantity, duration and intensity (i.e., in the years 2013/2014 and 2015/2016, the runoff reached 60.2 and 22.3 million m^3, from 426 and 520 mm of rainfall falling in 21 and 44 days, respectively).

On the other hand, recharge occurs in sand dune areas, and the presence of clayey soils limits the recharge as seen by comparing Figure S1 and Annex II in the Supplementary Materials, while the runoff is higher in built-up areas and on clayey soils as observed by comparing Figures S1 and S3 and Annex I in the Supplementary Materials.

Runoff and recharge also changed as the land use changed. For example, in the year 1973/1974, there was a total of 26 rainy days, with 164 million m^3 falling over the surface area of the Gaza Strip (450 mm/year), resulting in runoff of 15 million m^3 and an estimated recharge of 53.1 million m^3 (more than 100% of the long-term average recharge), compared to same rainfall depth in the year 2000/2001 (447 mm/year) with 42 rainy days, where runoff was 25.5 million m^3 and recharge was only 29.8 million m^3. These changes in runoff/recharge are a function of land use changes. For example, the built-up area increased from 30.1 km^2 to 92.1 km^2, corresponding to a decrease in sand dune area from 114.8 km^2 to 31.5 km^2 of the total Gaza Strip area (365 km^2) from 1982 to 2010 [5]. These changes have an obvious impact on the runoff and recharge quantities. The runoff increased by more than 150% (from 9 to 22.9 million m^3), while the recharge decreased by 84% (from 27.3 to 23 million m^3) (Figure 6).

The maximum recharge occurred in 1991/1992, where it reached 64.4 million m^3 in what was known as the year of snow (the only year Gaza saw snow and hail during storms). Long rainfall periods resulted in high recharge volumes ranging from 50% to 150% greater than the long-term average recharge volume (for example, the year 1982/1983, which had 52 rainy days). Annex II in the Supplementary Materials shows the yearly spatial distribution of recharge for the past 43 years (1973 to 2016). The analysis shows that when the rainfall duration was greater than 30 days and the rainfall quantity was higher than the long-term average of 326 mm, the recharge and runoff quantities were higher than the long-term average (for example, the year 1982/1983), see Figure 4 and Table 5.

On the other hand, in the year 2013/2014, more than 70% of the rainfall fell in five days (10–14 December 2013) and produced a runoff quantity of 60.2 million m^3, exceeding the recharge quantity of 31 million m^3. This runoff created flooding everywhere in the Gaza Strip.

The sand dune area decreased over time, as shown in the different land use maps. The change in the sand dune area from 114.8 km^2 (31.46%) of the total Gaza Strip area in 1982 to 92.9 km^2 (25.45%) in 1994 slightly increased runoff by 18% (from 9 to 10.6 million m^3/year), while between 1994 and 2010, the sand dune areas decreased by 66% (92.9 km^2 to 31.5 km^2), leading to an increase in runoff by 116% (from 10.6 to 22.9 million m^3). Annex I shows the yearly spatial distribution maps for runoff.

A comparison of the results obtained from the developed GIS GRID method and those from the Thiessen polygon method [5] for the same period (1973–2014) is found in Table 6. The comparison shows that the overall long-term average rainfall and recharge over the area did not change, while a wide variation occurred in the long-term average of runoff (42.6% difference) due to the difference in spatial rainfall estimation and the influence of parameters such as soil texture and changes in land use

(Figures 7 and 8). With the Thiessen polygon method, average values of PAW and CN were calculated for each polygon area (ranging in size from 3 km^2 to 82.5 km^2), while with the GRID method, the average was taken for every area of 100 m × 100 m. On the other hand, comparing the long-term average recharge with previous studies (see Table 1) shows a lower value than in previous studies, which is due to either the limited data used in previous studies and/or the use of assumptions, such as a soil coefficient for recharge.

Table 6. Comparison between Thiessen polygon method and GIS GRID method on a yearly basis.

Year	Average Rainfall (mm)			Runoff (10^6 m^3)			Recharge (10^6 m^3)		
	Thiessen Polygon	GRID Calculation	Difference %	Thiessen Polygon	GRID Calculation	Difference %	Thiessen Polygon	GRID Calculation	Difference %
1973/1974	441.8	449.9	1.8%	10.9	15	37.6%	52.9	53.1	0.4%
1974/1975	190.7	193.4	1.4%	1.9	2.9	52.6%	6.5	9.8	50.8%
1975/1976	205.2	207.6	1.2%	0.5	1.2	140.0%	1.4	8.6	514.3%
1976/1977	276.3	283.1	2.5%	5.8	7.9	36.2%	22.5	27.4	21.8%
1977/1978	284.3	287.4	1.1%	8.2	11.4	39.0%	24.1	26.3	9.1%
1978/1979	244	250.9	2.8%	0.7	1.7	142.9%	8	14.6	82.5%
1979/1980	199.2	200.6	0.7%	1.6	2.9	81.3%	11.6	18.4	58.6%
1980/1981	207.8	208	0.1%	5	6.4	28.0%	8	12.7	58.8%
1981/1982	286.3	286.3	0.0%	2.5	4.5	80.0%	19.7	25	26.9%
1982/1983	486.1	488.6	0.5%	6.2	10.9	75.8%	51.5	61.4	19.2%
1983/1984	172.1	178.4	3.7%	0.7	0.9	28.6%	1.9	10.8	468.4%
1984/1985	192.8	196	1.7%	0	0.4	40.0%	2.1	6	185.7%
1985/1986	228.4	224.2	−1.8%	4.6	4.3	−6.5%	10.1	14.7	45.5%
1986/1987	505.2	511.9	1.3%	21.7	25.8	18.9%	48	49.5	3.1%
1987/1988	283.7	290.2	2.3%	4.9	7.4	51.0%	18	20.2	12.2%
1988/1989	332.6	335	0.7%	3.8	6.2	63.2%	36.7	32.3	−12.0%
1989/1990	345	357.1	3.5%	5.1	7.2	41.2%	14	24.6	75.7%
1990/1991	342.5	344.9	0.7%	9.5	9.3	−2.1%	26.3	24.9	−5.3%
1991/1992	543.8	549.7	1.1%	35	40.7	16.3%	66.7	64.4	−3.4%
1992/1993	408.2	410.8	0.6%	9.1	13.6	49.5%	58.6	41.5	−29.2%
1993/1994	190.6	194.4	2.0%	0.8	3.8	375.0%	5.3	8.4	58.5%
1994/1995	570.3	573.9	0.6%	21.8	33	51.4%	64.8	52.7	−18.7%
1995/1996	365.1	370.6	1.5%	8.7	13	49.4%	20.4	30.3	48.5%
1996/1997	315.1	311.6	−1.1%	3.9	7.9	102.6%	21.4	19.6	−8.4%
1997/1998	222.3	224.7	1.1%	2.2	4.6	109.1%	11.5	17.4	51.3%
1998/1999	108.1	109.1	0.9%	0.7	1.5	114.3%	1.2	6.2	416.7%
1999/2000	273.7	281.2	2.7%	10.3	10.3	0.0%	27.3	20.5	−24.9%
2000/2001	441.3	447	1.3%	21.9	25.5	16.4%	45.6	29.8	−34.6%
2001/2002	425.6	434.8	2.2%	23.8	27.2	14.3%	46.9	34.2	−27.1%
2002/2003	461.8	471.7	2.1%	25.1	27.4	9.2%	49.5	37	−25.3%
2003/2004	295.9	301.4	1.9%	12	14.5	20.8%	28.1	10.9	−61.2%
2004/2005	357.1	354.7	−0.7%	11.5	15.4	33.9%	35.3	16.7	−52.7%
2005/2006	280.8	282.6	0.6%	5.1	7.3	43.1%	14.6	13.5	−7.5%
2006/2007	365.6	377.3	3.2%	11.9	15.5	30.3%	21.8	15.9	−27.1%
2007/2008	227	234.5	3.3%	4.5	6.5	44.4%	12.7	11.7	−7.9%
2008/2009	283.5	291	2.6%	11.8	16.2	37.3%	13.2	14	6.1%
2009/2010	200.7	204.6	1.9%	0.7	1.7	142.9%	2	3.9	95.0%
2010/2011	213.5	217.5	1.9%	2.8	4.2	50.0%	6.8	5.9	−13.2%
2011/2012	372.9	379.2	1.7%	8.7	12.8	47.1%	32.3	30.3	−6.2%
2012/2013	252	257.4	2.1%	6.4	8.3	29.7%	21	17.5	−16.7%
2013/2014	353.7	425.6	20.3%	51.5	60.2	16.9%	33.1	31	−6.3%
Average	**311**	**325.5**	**1.8%**	**9.4**	**13.4**	**42.6%**	**24.5**	**24.5**	**0.4%**

The differences between the two methods (GIS GRID vs. Thiessen polygon method) show a wide range for both yearly runoff and recharge. The largest differences occur in the dry years, where rainfall is lower than the long-term average (326 mm), as shown, for example, in the year 1975/1976. Figures S7 and S8 in the Supplementary Materials show a comparison between the two methods for selected years of lower and higher than long-term average rainfall, respectively. In general, it is indicated that the GIS GRID method provides a higher estimation than the Thiessen polygon method for both runoff and recharge when the rainfall is lower than the long-term average rainfall. In years with rainfall that was higher than the long-term average rainfall, the two methods' estimations are similar.

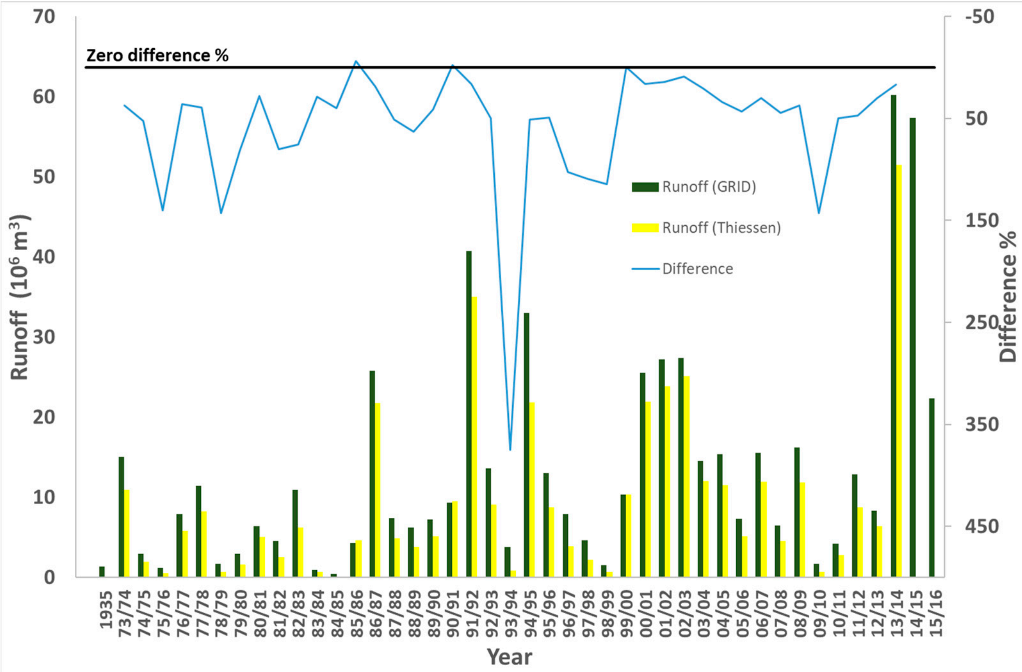

Figure 7. Runoff comparison between Thiessen polygon and GIS GRID methods with yearly difference.

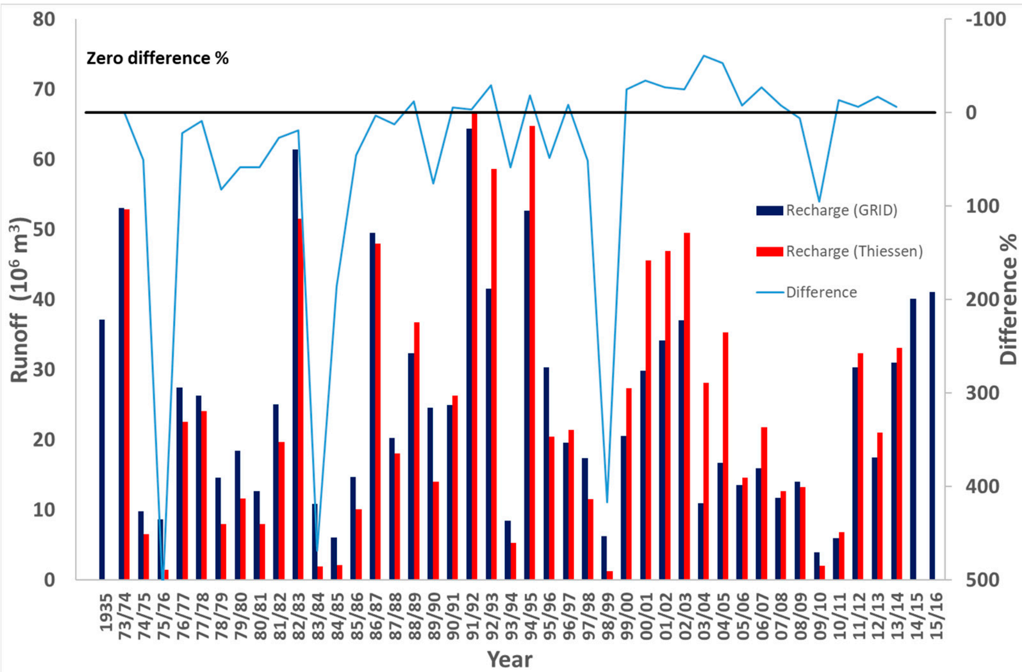

Figure 8. Recharge comparison between Thiessen polygon and GIS GRID methods with yearly difference.

5. Conclusions

This study uses spatial daily rainfall and evapotranspiration variations for the past 43 years to estimate the runoff and recharge in the whole Gaza Strip. The long-term average (43 years) rainfall is 326 mm, average runoff is 13.4×10^6 m^3/year (9.6% of rainfall), and average recharge is 24.5×10^6 m^3/year (19.2% of rainfall). These results were obtained using a newly developed GIS tool based on daily records of rainfall and evapotranspiration with pre-defined GRID maps for topography, soil texture and land use.

The results obtained from the new GIS tool were compared with the Thiessen polygon method for the same period. This shows that the Thiessen polygon method is not accurate in estimating recharge or runoff because it does not provide a meaningful spatial distribution of rainfall, and because land use and soil texture, in reality, are changing within the Thiessen polygons. The GIS tool results in higher values of runoff and recharge for low rainfall years compared to the Thiessen polygon method.

The main factor of increasing runoff is the evolution of built-up area, where before 1992, the total built-up area was 30.1 km^2 of the Gaza Strip and the average runoff (1973 to 1992) was 7.9% (9 million m^3) of the rainfall; after development of the area, the total built-up area was 92.1 km^2 of the Gaza Strip, and the runoff had increased to 18.1% (22.9 million m^3) of the rainfall.

On the other hand, the decreasing size of the sand dune area affects the recharge quantities, where before 1973, the sand dune area was 114.8 km^2 of the Gaza Strip, and the average recharge (1973 to 1992) was 23.9% (27.3 million m^3) of the rainfall; after development of the area, the total sand dune area was 31.5 km^2 of the Gaza Strip, and the recharge had decreased to 18.2% (23 million m^3) of the rainfall.

Water planners and decision-makers in the Gaza Strip will benefit from the collected historical data and results of this research in securing runoff and recharge spatial distribution and volumes when making a proper plan to beneficially use the runoff to recharged the groundwater, while at the same time identifying vulnerable areas where most recharge takes place, in order to avoid changing these areas into built-up areas.

Supplementary Materials: The following are available online at http://www.mdpi.com/2073-4441/11/1/84/s1, Figure S1: Soil texture map, Figure S2: Rainfall stations location, Figure S3: Land use maps in different years, FigureS4: Screen shoot for developed new GIS tool for runoff and recharge estimations, Figure S5: Spatial distribution of runoff in 1935, Figure S6: Spatial distribution of recharge in 1935, Figure S7: Recharge and runoff for selected years with rainfall less than long term average (326 mm), Figure S8: Recharge and runoff for selected years with rainfall greater than long term average (326 mm), Annex I: Runoff GRID maps (1973 to 2016), Annex II: Recharge GRID maps (1973 to 2016).

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