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To What Extent Are Groundwater Recharge Dynamics in Semi-arid Areas Controlled by Vegetation Cover?

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Abstract: Groundwater is the only source of fresh water in the semi-arid Gaza strip. This study aims at estimating the long-term spatial and temporal groundwater recharge and assessing the role of vegetation dynamics and types on the groundwater recharge. We estimated the mean annual spatial and temporal groundwater recharge for 25 years using the WetSpa-Python model. The groundwater recharge represents 27% of the annual average precipitation. The mean annual groundwater recharge values are in good agreement with results from similar studies in neighboring semi-arid regions. However, there is a great uncertainty associated with land use and soil parameters in the model. We have performed sensitivity analysis at two different levels spatial variations and seasonal variation to assess the impacts of vegetation cover on the groundwater system. Results show that vegetation cover has a significant impact on groundwater recharge, where a misclassification of different vegetation classes results in a 4 to 8% difference in groundwater recharge estimates. While incorporated crop coefficient in the model increases the recharge up to 32%. The results reveal that vegetation cover has a significant impact on groundwater recharge in the Gaza strip. Hence, proper management practices would increase the groundwater recharge in such a semi-arid region.

Key words: Gaza · Coastal aquifer · WetSpa-Python · Crop coefficient · Uncertainty

INTRODUCTION

Groundwater is one of the most important natural resources in the world to sustain human and environmental systems [1, 2]. In arid and semi-arid regions, the lack of surface water often leads to severe groundwater exploitation [1]. The use of groundwater is becoming unsustainable as nearly 25% of the world population lives in areas where groundwater is consumed faster than it can be replenished [2]. This overuse has led to a global groundwater depletion which mostly occurs in arid and semi-arid regions [3]. The resulting lowering of the groundwater table has major environmental impacts on groundwater quality, streams, lakes, wetlands and related ecosystems [4]. Also, sea water intrusion is one of the major devastating effects of groundwater depletion which occurs in coastal aquifers.

The Gaza coastal aquifer, the only source of fresh water in this semi-arid region, is severely affected by unsustainable management practices. A major consequence of overexploitation is the depletion of groundwater quality due to sea-water intrusion. Furthermore, the groundwater quality is affected by high levels of chlorides and nitrates. Nitrate is mainly derived from organic waste, being either human or animal manure [5]. Vengosh *et al.* [7] investigated the chemical and isotopic signature of groundwater of the southern coastal aquifer and confirmed that Na-rich saline groundwater, salt water intrusion and the nitrate pollution are the major sources of salinity in the Gaza strip. The total annual abstraction has increased more than 30% for the period 1995-2011, from 135 10^6 m^3(˜370 mm/y) to 180 10^6 m^3(˜494 mm/y) [7]. This has led to an increase of the coastal aquifer deficit from around 36 10^6 m^3(˜99 mm/y) [8]

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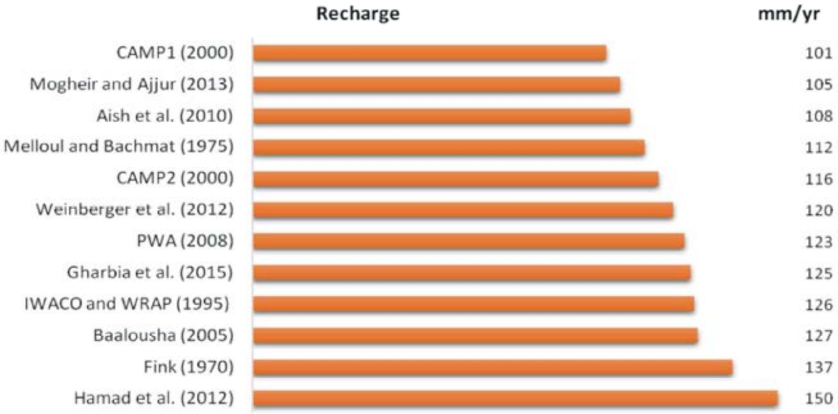

Fig. 1: The mean groundwater recharge in the Gaza strip resulting from different studies, shows a range of estimates between 101 and 150 mm/yr.

to 60 10^6 m^3(˜165 mm/y) [9]. Hence, a correct assessment of groundwater recharge can support the development of sustainable groundwater management. A reliable and sustainable water resources management is necessary for the identification of appropriate rehabilitation methods to protect and preserve these valuable resources and to meet the future human and economic development demands.

Modelling Recharge in the Gaza Strip: past Efforts: Many authors have attempted to estimate the groundwater recharge in the Gaza strip using a variety of methods based on empirical formulations, (scarce) measurements and analytical models (Fig. 1) [11, 9, 13, 15, 16, 17, 54, 13, 20, 18, 21].

Fink [11] used an empirical equation to estimate recharge based on the change in aquifer storage. Melloul and Bachmat [9] developed a water balance model to estimate the groundwater recharge based on recharge coefficients per soil type and Weinberger *et al*. [13] used the same model to estimate the yearly water balance for the Gaza strip from 1971 to 2009. IWACO and WRAP [13] used the chloride mass balance (CMB) method to estimate the groundwater recharge for the north of Gaza, which is characterized by a higher amount of rainfall and higher infiltration rates than the south of Gaza. CAMP [15] used two different methods: a land use recharge coefficient (CAMP1) and a groundwater model (CAMP2). Baalousha [16] used the Cumulative Rainfall Departure method (CRD) based on measured groundwater levels, storativity, lateral flow and pumping records. The model was calibrated by comparing measured and simulated groundwater heads. More recent researchers used GIS-based water balance modeling tools [16–18 ,20]. Aish *et al*. [17] and Mogheir and Ajjur [18] used a distributed water balance model (WetSpass) to estimate the spatial distribution of groundwater recharge. Hamad *et al*. (2012) used the AGWA model [21], which is functionally based on SWAT model [22].

As a consequence, of conceptual differences in used recharge estimation methods and periods over which the estimation was performed as well as lack of data for calibration, the recharge results strongly range from 29% to 40% of the precipitation in the Gaza strip (Fig.1). Additionally, there is high uncertainty associated with the spatial variation of recharge. For example, Gharbia *et al*. (2015) estimated the spatial distribution of the water balance components for the Gaza strip using the WetSpass model and estimated higher transpiration rates in urban areas in north Gaza (˜60 mm/y) than in the surrounding agricultural areas (˜27mm/y).

Most studies performed for the Gaza strip also ignore the effect of temporal precipitation patterns and the differences between wet and dry years. For example, the water balance model approach of Weinberger *et al*. (2012) [13] for the period 1971 to 2009 did not demonstrate any significant correlation between the annual recharge and annual precipitation rates (Fig. 2). However, according to several other authors, precipitation has the strongest effect on groundwater recharge in semi-arid regions [23-25].

These studies have used different methods yielding different temporal and spatial results mainly due to the uncertainty in the physical parameters such as soil type, land use, hydrogeological properties and to the lack of calibration data as no stream discharge or other measurements are available for the Gaza strip. Remotely

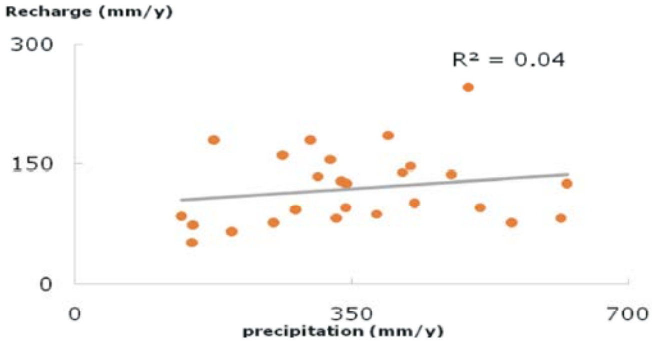

Fig. 2: Annual recharge-precipitation relationship for 1981-2005 estimated by Weinberger *et al*. (2012) did not demonstrate a significant correlation.

sensed data could be a valid option for calibrating hydrological models for the Gaza strip. For instance Gampe *et al*. [20] used remotely sensed actual evapotranspiration (ETR) derived from land surface temperature and normalized difference vegetation index (NDVI) to validate the patterns of the monthly ET values estimated by the WASIM hydrological model and found that the resulting remotely sensed ETR were in good agreement with the modeled ET.

Effect of Vegetation on Recharge: Climate, soil, land use and hydrogeological conditions are the major key drivers of groundwater recharge. Climate change effects on groundwater recharge have been extensively investigated [26-32], but what is less well understood and rarely incorporated into global and regional land-surface models is the effect of vegetation on recharge as well as how changes in vegetation interact with climate and soils to alter recharge [1, 33]. Vegetation is the second major controlling factor of global groundwater recharge after precipitation [1]. The role of vegetation is even more important in arid and semi-arid regions where water resources are limited. Kim and Jackson [3] suggested that the relative difference in recharge between vegetation types is larger in arid climates and areas with clayey soils. Vegetation covers 65.8% of the Gaza strip, therefore understanding the role of vegetation types and dynamics on groundwater recharge is of importance. Surprisingly, little literature is available on this topic and hence more research is required.

In this context, our study aims at: (1) identifying the long-term spatial and temporal groundwater recharge variations; (2) identifying the effect of vegetation on spatial and temporal distribution of groundwater recharge; (3) adapting the spatially-distributed hydrological model WetSpa-Python model to account for the seasonal variation of different vegetation covers.

Study Area: Gaza is situated in the southern part of the Mediterranean Coastal Strip, which stretches from Turkey in the north to Egypt in the south. Together with the area known as the West Bank, Gaza forms the Palestinian Autonomous Territories (Fig. 3). The Gaza Strip is divided into five governorates: The Northern Governorate consisting of Beit Lahia and Beit Hanoun; Gaza Governorate as the administrative center for the Palestinian Authority, Deir El Ballah, Khan Younis and Rafah in the south bordering with Egypt (Fig. 3). The built up areas, displayed in red in Figure 6, are densely populated with 1.8 million inhabitants [34].

Gaza is generally referred to as semi-arid and despite the small area of the Gaza Strip (365 km^2), rainfall shows a significant spatial variability with an average annual rainfall for the period (1981-2005) of about 455 mm in the north decreasing to 238 mm in the south. Most rain falls between mid-October till end of March, while May to September is dry with nearly no rainfall (Fig. 4). Most of the rainfall is lost to evapotranspiration with the remaining water infiltrating into the soil, recharging the groundwater reservoir or appearing as runoff [36].

There are six soil types in the Gaza strip classified according to the percentage of sand, silt and clay [36] (Fig. 5A). The most common soil textures are sandy regosols and loessial sandy soils respectively 32% and 23%, followed by sandy loess soil over loess (16%), dark brown/reddish brown (14%), sandy loess soil (9%) and loess soils (7%). The land use of the Gaza strip [37] is derived from a 2004 SPOT image and was classified with an unsupervised approach (Fig. 5B). The most common land use types for 2004 are mixed agriculture (40.4%), built up areas (23.3%), sand (10.7%), citrus orchards (8.9%), horticulture (6.6%), natural vegetation (5.7%), greenhouses (3.8%), rainfed agriculture (0.4%) and open water (0.3%).

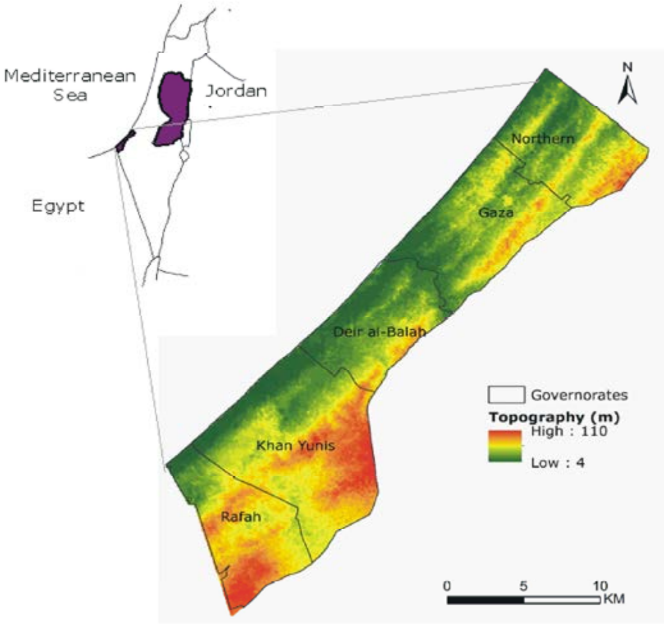

Fig. 3: Gaza is a flat coastal plain divided into five governorates.

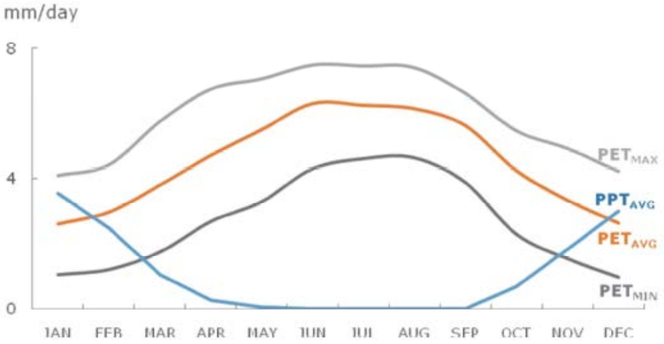

Fig. 4: The long-term monthly average potential evaporation (PET) and precipitation (PPT) (1981-2006) for Gaza city.

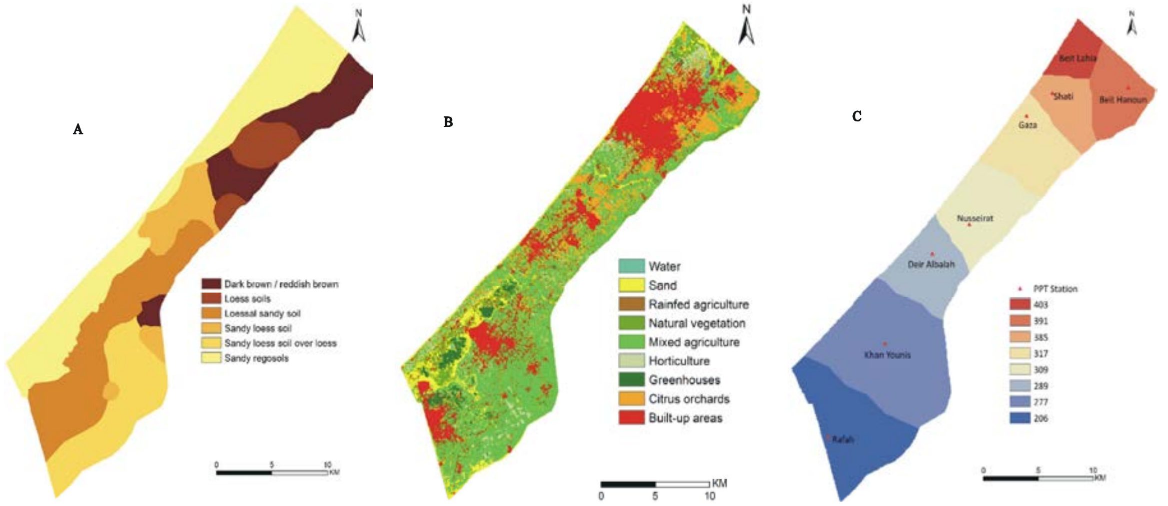

Fig. 5: (A) Soil types of the Gaza strip; the dominant soil type is sandy loam [36], (B) Land use map of the Gaza strip, with agriculture and built up areas as the main land use types [37], (C) Average annual precipitation in mm/y (1980-2005) of the Gaza strip. The mean annual average precipitation is 354 mm/y.

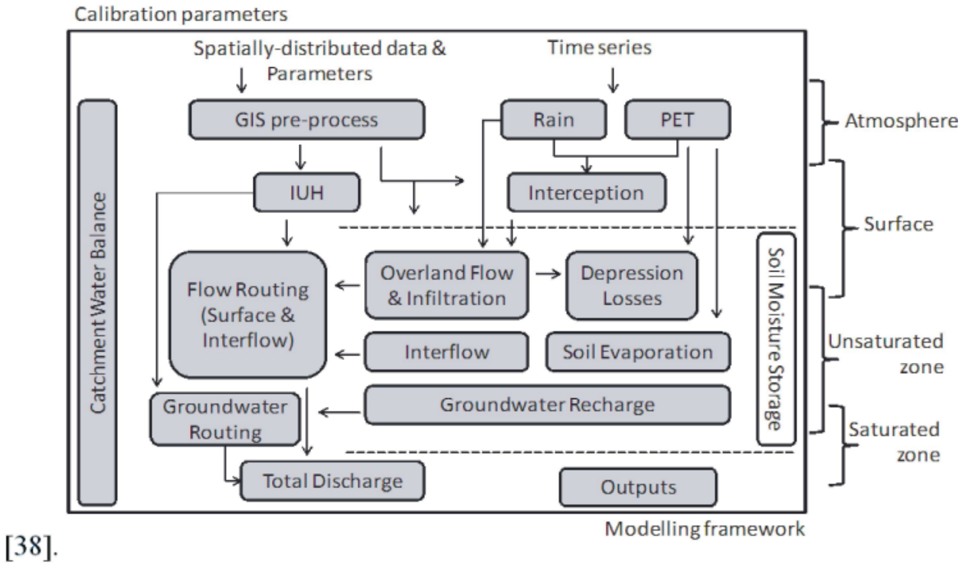

Fig. 6: Structure of the WetSpa-Python model,grey boxes represent the main WetSpa-Python components and arrows the main links among components [38].

MATERIALS AND METHODS

Overview: The study consist of two parts: in the first part we estimated the temporal and the spatial groundwater recharge for the Gaza strip for the period 1981-2005 using the WetSpa-Python model [38] at a daily time step. In the second part, the impacts of vegetation cover on the groundwater system were assessed by performing a sensitivity analysis at two different levels, investigating (1) spatial variations, i.e., lumped vegetation classes versus detailed classified vegetation classes and (2) seasonal variations, i.e., comparing the growing season and the non-growing season. Accordingly, the WetSpa-Python model was modified by introducing a crop coefficient K_c in order to better simulate the temporal variation in evapotranspiration of different crops.

Data Collection: The meteorological data is provided by the Environmental Quality Authority of Palestine. We used daily precipitation data for the period 1981-2005 of eight stations distributed over the Gaza strip (Fig. 5C) and daily potential evapotranspiration data for 1981-2005 of the Gaza station (Fig. 5C). The topographical map was created based on the digital elevation model available from NASA (2011) [39] with a resolution of 90 m. First a contour map was created, then by using spatial analysis tools in ArcGIS (topo to raster), a new DEM was created with a 25meter resolution (Fig. 1). The soil map (Fig. 5) [36] and land use map of 2004 (Fig. 6) [40] were available at 25 m resolution.

Recharge Estimation

Hydrological modelling: WetSpa-Python model: The WetSpa (Water and Energy Transfer between Soil Plant and Atmosphere) model is a quasi-physically based and spatially-distributed hydrological model for predicting river flow and major water fluxes at catchment scale. The original GIS-based model was developed by Wang *et al*. (1996) [41] and then modified by Liu and De Smedt (2004) [43] and Safari *et al*. (2012) [43]. A new PCRaster-Python version of the WetSpa model is used in this study [46,39]. The new approach allows the user to select which hydrological processes will be simulated and in which order, as well as to evaluate the impact of different parameterizations of the same process [45].

The WetSpa model simulates the water balance processes at cell level for every time step. The main considered hydrological processes are: precipitation, interception, depression storage, surface runoff, infiltration, evapotranspiration, percolation, inter-flow and groundwater drainage. Rainfall is intercepted by plants until a maximum interception storage is reached (which is controlled by literature-based parameters). The remaining watercan be distributed to three major processes: infiltration into the soil, filling of depressing storages or surface runoff [46]. The soil water is distributed between recharge and interflow and some will evaporate from the soil depending on the available soil moisture and potential evapotranspiration. Groundwater discharged is controlled by groundwater storage and a recession coefficient. The total evapotranspiration is the sum of interception, transpiration, soil evaporation, evaporation from depression storage and possible evapotranspiration from groundwater storage [43]. The structure of the WetSpa-Python model is process-based (Fig. 6). The model components interact with each other at run time and variable exchanges are managed at a higher level by the Python modelling framework [38].

The root zone water balance for each grid cell can be expressed as [41]:

$$D\frac{d\theta}{dt} = PPT(t) - IC(t) - RO(t) - IF(t) - ET(t) - RE(t) \qquad \text{Eq.1}$$

where D is the root depth [L], θ the soil moisture content [L^3L^{-3}], PPT the precipitation [LT^{-1}], IC the interception [LT^{-1}], RO the surface runoff [LT^{-1}], IF the interflow [LT^{-1}], ET the evapotranspiration [LT^{-}], RE the groundwater recharge [LT^{-1}] and t the time [T].

The groundwater recharge is estimated on basis of the Brooks and Corey (1964) relationship:

$$RE = K(\theta) = K_s(\theta - \theta_r / \theta_s - \theta_r)\frac{{}_{B+2}B}{B} \qquad \text{Eq.2}$$

where $K(\theta)$ is the unsaturated hydraulic conductivity [LT^{-1}], $K_s$the saturated hydraulic conductivity [LT^{-1}], θ_s the water content at saturation [L^3L^{-3}], θ_r the residual soil moisture content [L^3L^{-3}] and B the soil pore size distribution index [-].

The WetSpa model requires spatially-distributed input data and global calibration parameters. The first can be derived from elevation, land use and soil texture maps associated with standard tables or remote sensing data. The second consists of eight global parameters, which are calibration factors to compensate for the lack of precise field data and conceptual parameters e.g. for the groundwater system[46]. The parameters and their feasible range were tested by Shafii and De Smedt (2009) [48] and values for Gaza case study are shown in Table 1. Details of the methodology and model equations of the original WetSpa model can be found in Liu and De Smedt (2004) [42]; the methodology and structure of the new Python version can be found in Salvadore (2013, 2015) [46, 39].

Model set-up: We simulate the groundwater recharge for the period 1981-2005 using the WetSpa-Python model with the first year as warm-up period. Urban areas in Gaza are highly densely populated and most of the houses have no gardens. Therefore, we assumed a high imperviousness for the build-up class in the model (90%) instead of the 50% default value of WetSpa.

Table 1:Global WetSpa post-calibration parameters used for Gaza Strip.

Descreption	Paramter	Value*	Units
Interflow scaling factor	K_i	1	-
Groundwater recession coefficent	K_g	0.00001	h^{-1}
Initial soil moisture coefficient factor	K_{ss}	1	-
Correction factor for PET	K_{ep}	1	-
Initial groundwater storage coefficent	G_0	200	mm
Groundwater storage scaling factor	G_{max}	500	mm
Actual runoff coefficient correction factor	K_{run}	0.0001	-
Rainfall intensity scaling factor	P_{max}	10	mm

*Post-calibration values

Automatic calibration was not applied for the Gaza Strip because of lack of river discharge data. We therefore manually modified the WetSpa-Python global parameters to achieve two objectives: (i) a catchment water balance consistent with previous studies and (ii) a consistent spatial distribution of groundwater recharge, i.e., urban vs. vegetated land cover.

The global parameters of the WetSpa-Python model were modified according to the results of CAMP (2000) [14] to achieve a consistent spatial distribution of groundwater recharge in the Gaza strip (Table 1). CAMP (2000) [14] obtained a mean annual groundwater recharge of 101 mm/y and 116 mm/y using a recharge coefficient based on distributed land use and soil and a calibrated groundwater model respectively.

Spatial and Temporal Estimation of Groundwater Recharge: The ability of the WetSpa model to simulate groundwater recharge for humid and sub-humid regions has been verified [42,43,27,44,50], but it has never been tested for arid or semi-arid regions such as the Gaza strip. Moreover, our study area is not representing a closed hydrological system, as it is the southernmost part of the coastal basin (coastal aquifer), which extends along the shore line from the Carmel mountain in the north to the Sinai Peninsula in the south (Fig. 3). We therefore do not take into account the routing processes for the long-term spatial and temporal groundwater recharge simulation with the WetSpa-Python model. One of the advantages of this version of the model is that it allows the removal of the routing processes while still being able to simulate the other processes (Fig. 6).

The land use and soil properties were reviewed and adapted to the conditions of the study area. Physical soil properties were taken from Goris and Samain (2001) [51], which are based on soil measurements across the Gaza strip (Table 3). The six soil types distributed over the Gaza strip were grouped into three major classes according to the soil classification of the WetSpa model (Table 3).

Table 2: Hydraulic parameters of the major soil types in the Gaza strip [50], expressed in m^3m^{-3}.

Soil type	WetSpa_Soil type	Field capacity	Wilting point	Residual moisture
Sandy regosols	Sand	0.085	0.008	0.059
Sandy loess over loess	Sandy loam	0.19	0.046	0.045
Loessal sandy soil				
Loess soil	Sandy clay loam	0.241	0.077	0.065
Dark brown				
Sandy loess soil				

Table 3: Physical parameters of the land use classes for the Gaza strip.

		Interception (mm)		
Land use classes	Root depth (m)	Max	Min	Manning
Beach/dune	0.5	0.2	0	0.09
Orchards	1.1	3	0.5	0.30
Horticulture	0.9	2.5	0.5	0.35
Rainfed agriculture	0.5	2	0.5	0.037
Crop land	0.8	2	0.5	0.35
Natural vegetation	0.85	2	0.5	0.30
Built up areas	0.5	0	0	0.05
Water	0.1	0	0	0.05

Table 4: Crop Coefficient Values (K_c) for land use classes in the Gaza strip.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Crop land	0.98	1.15	0.95	0.6	0.6	0.9	0.9	0.8	0.6	1.08	1.08	0.8
Built up areas	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Natural vegetation	0.3	0.3	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.3
Water	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Beach/ dune	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Orchards	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.65	0.65	0.65	0.65	0.65
Horticulture	0.9	0.9	0.9	0.65	0.65	0.65	0.65	0.4	0.4	0.4	0.4	0.9
Rainfed- agriculture	1.15	0.4	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.3	1.15

We extended the standard number of land use classes of the WetSpa model to accommodate specific features of the Gaza case, namely beach/dune, orchards, horticulture and rainfed agriculture. Physical properties and parameters were adapted accordingly (Table 4).

In order to estimate the effect of vegetation cover on the groundwater recharge, we simulated two different scenarios. In the first scenario, we used detailed vegetation classes while for the second scenario we used lumped vegetation classes in which the vegetation classes orchards, horticulture, rainfed agriculture and natural vegetation were classified as crop land (Table 4).

Effect of Seasonality: In the WetSpa model, vegetation cover affectsthe runoff coefficient, root depth and maximum and minimum interception capacity. The model accounts for seasonality through a simple sine-shaped variation curve which is calculated as:

$$IC_{i,0} = IC_{i,\min} + (IC_{i,\max} - IC_{i,\min})\left[\frac{1}{2} + \frac{1}{2}\sin(2\pi\frac{d-87}{365})\right]^b$$

Eq.3

where $IC_{i,min}$ is the minimum interception capacity in cell i (mm), $IC_{i,max}$ the maximum interception capacity, d the day of the year and b the exponent which controls the shape of the variation curve.

There were no parameters in the previous versions of the model to account for actual evapotranspiration of different vegetation covers throughout the year. We have therefore introduced a crop coefficient factor $K_c$into the model to estimate the effect of seasonality on groundwater recharge estimation. The crop coefficient K_c is the ratio of the crop evapotranspiration ET_c to the reference evapotranspiration ET_o and represents the crop characteristics and development stage of the crops [51], calculated as follows:

Table 5: Effect of temporal precipitation (PPT) patterns on groundwater recharge (RE).

Year	PPT (mm)	RE (mm)	RE (%)
1983	345	122	35
1997	345	98	28
1993	294	105	36
2001	371	85	23

$$Et_c = K_c\, ET_o \qquad \text{Eq.4}$$

where ET_c is the crop evapotranspiration [mm d^{-1}], ET_o the reference crop evapotranspiration [mm d^{-1}]; so that soil evaporation is calculated as:

$$\begin{cases} ET = K_c k_{ep}(PET - I) & \\ ET = K_c(k_{ep}PET - I)\left(\dfrac{\theta - \theta_w}{\theta_{fc} - \theta_w}\right) & if \begin{cases} \theta \geq \theta_{fc} \\ \theta_w \geq \theta < \theta_{fc} \\ \theta < \theta_w \end{cases} \\ ET = 0 & \end{cases} \qquad \text{Eq.5}$$

where K_c is the crop coefficient [-], k_{ep}[-]a correction factor for adjusting potential evaporation PET [LT^{-1}], I [LT-1] is the initial loss due to interception and depression storage, θ_{wp} [L^3 L^3] the moisture content at permanent wilting point and θ_{fc} [L^3 L^3] the moisture content at field capacity.

The crop coefficient values for each land use type were obtained from FAO papers 56 and 33 [51, 52] (Table 5) and were added to the standard tables of the WetSpa-Python model, which then creates a distributed map of K_c to calculate the spatial distribution of the ET.

RESULTS AND DISCUSSION

Recharge Simulation: The spatial long-term average maps of groundwater recharge, total evapotranspiration and runoff resulting from the WetSpa-Python model for the Gaza strip are shown in Fig. 7. The simulated mean annual groundwater recharge for the period 1982 to 2005 is 92 mm/y and the standard deviation is 61 mm/y. The mean annual groundwater recharge represents 27% of the annual average precipitation, while runoff and total evapotranspiration represent 28% and 45% respectively.

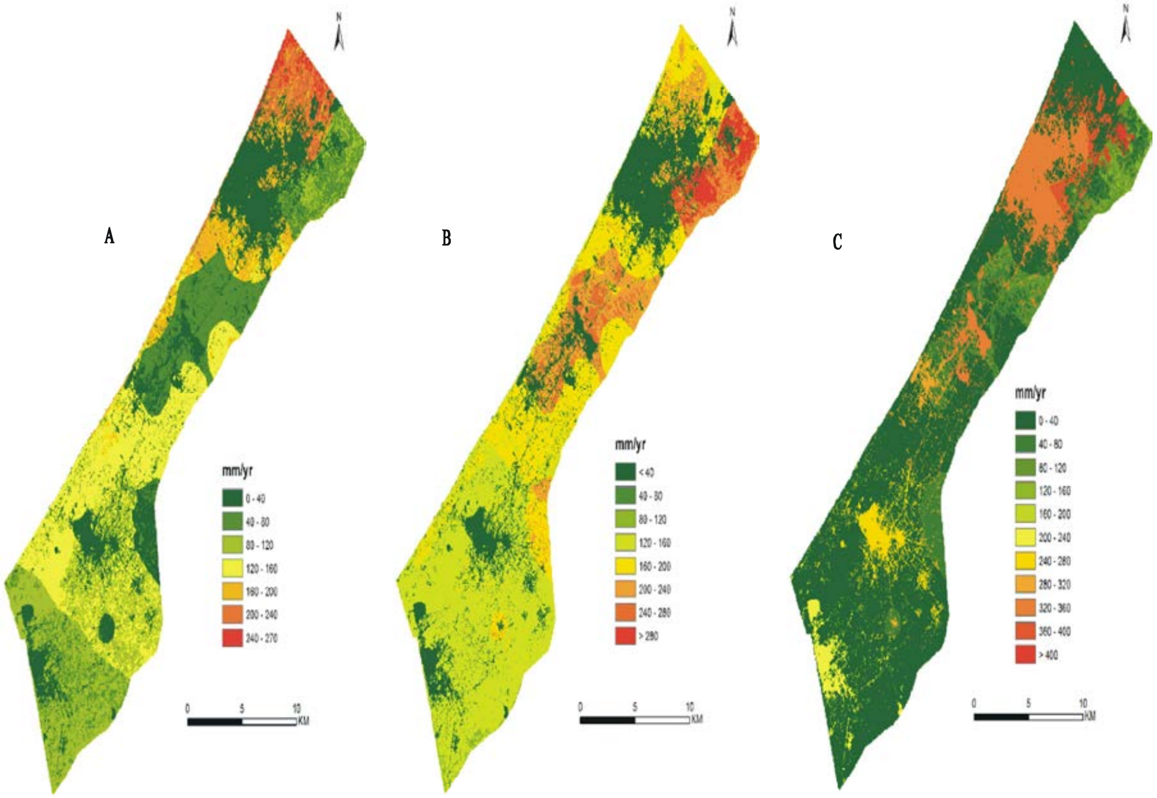

Fig. 7: Simulated mean annual long-term : (A) groundwater recharge, (B) total evapotranspiration and (C) surface runoff for the Gaza strip. The spatial variation of the groundwater recharge resembles the soil texture and current land use.

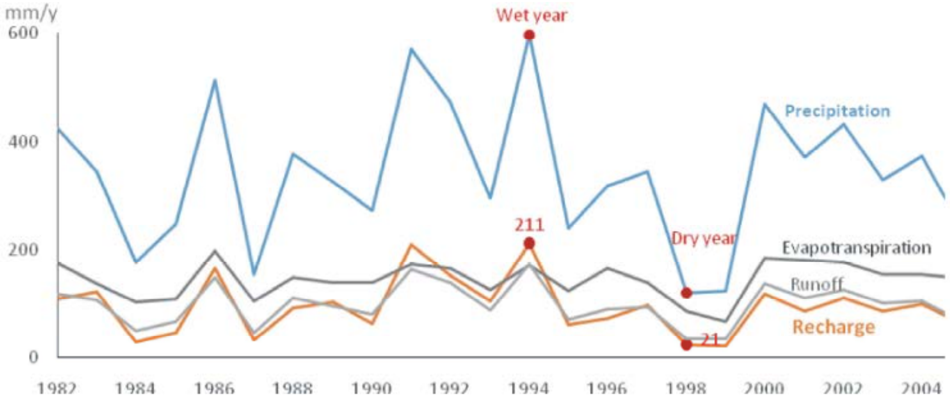

Fig. 8: Annual average groundwater recharge, runoff, evapotranspiration and precipitation for the Gaza strip. Natural groundwater recharge is highly driven by temporal precipitation patterns.

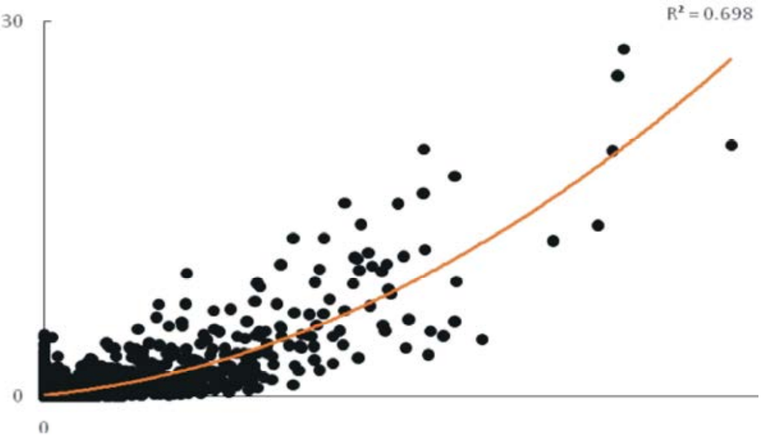

Fig. 9: Correlation between recharge and precipitation for the 25 years simulation period (1982-2005) for the Gaza Strip.

The mean annual groundwater recharge shows a large temporal variation, which resembles the precipitation temporal patterns (Fig. 8). Precipitation is the main controlling factor of the temporal variation of the groundwater recharge (r=0.78, Fig. 9). This was confirmed by Sheffer *et al*. [24] and Ries *et al*. [25] who found respectively high correlation coefficients of 0.71 and 0.88, between precipitation and recharge, for semi-arid areas.

For the 25 years simulation period, the estimated mean annual of groundwater recharge varies between 20 and 211 mm/y which represent 17% and 36% of the average annual precipitation. The highest simulated recharge percentage (36%) occurred in the wet year 1994 while the lowest simulated percentage (17%) occurred in the dry year 1999 (Figure 11). Groundwater recharge occurs only during the winter season (rainy period) from mid-September to mid-May and 75% of the recharge occurs in the peak months of rainfall (November, December and January). These results are in line with the findings of Hajhamad and Almasri (2009) [53], who have shown that December and January account for most of the recharge in north Gaza.

The simulated mean annual runoff is 95 mm with a standard variation of 125 mm (Fig. 10). It represents 28% of the average total annual precipitation, while the mean annual total evapotranspiration represents 45% (138 mm/y). Total evapotranspiration is the major component in the water balance in the Gaza strip. However, one should be aware that the actual total evapotranspiration is much higher due to irrigation, water supply network losses, shallow-groundwater evaporation and wastewater which are not taking into account in our simulation. Gampe *et al et al*. (2013) [20] modeled the water balance for the Gaza strip taking into account all water inputs and they estimated that the actual total evapotranspiration in the Gaza strip is 400 mm/y.

Rainfall intensity and duration play a major role in semi-arid regions [54]. Our groundwater recharge simulation shows significant differences for similar amounts of annual precipitation (Table 5). For example, for

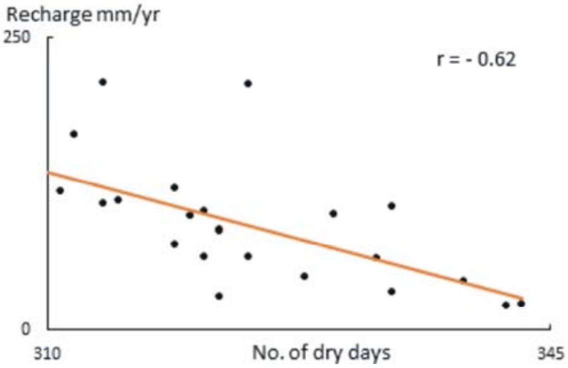

Fig. 10: Significant correlation between mean annual groundwater recharge and number of dry days for the 25 years (1982-2005). Number of dry days is one of the important controlling factors of groundwater recharge in the Gaza strip.

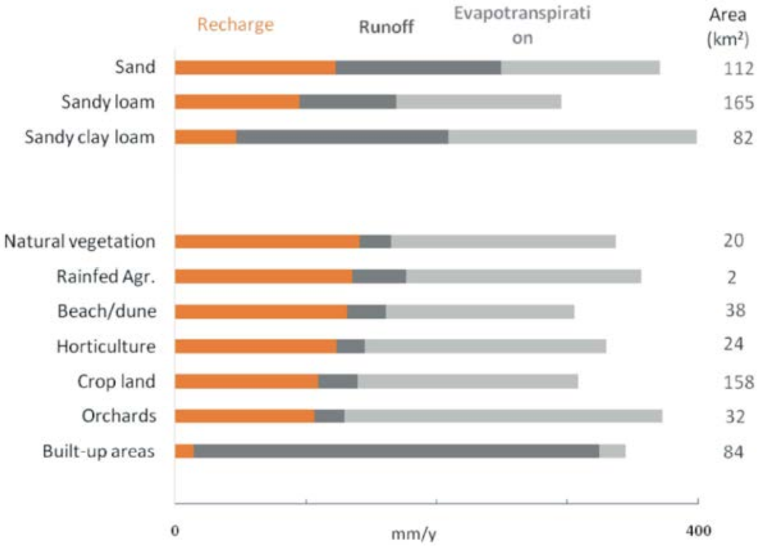

Fig. 11: Average annual groundwater recharge, runoff and evapotranspiration as a function of soil and land use type. The areal coverage of each soil type and land use class is given on the right-hand side.

the same precipitation amount of 345 mm for the years 1983 and 1997, the model yields quite different amounts of recharge of 35% and 28%, respectively. These results were confirmed earlier by Sheffer *et al*. (2010) [24] and Ries *et al*. (2014) [25]. On the other hand, some years with low precipitation rates produced higher recharge rates than years with a higher amount of precipitation, e.g., the simulated recharge for the years 1993 and 2001 accounted for 36% and 23% of the annual precipitation, although the amount of precipitation was higher in 2001 (Table 5).

For the Gaza strip, 70% of the days are dry with no rainfall in the 25-year simulation period. The significant negative correlation between mean annual groundwater recharge and the number of dry days (r = -0.62) reveals that the occurrence and duration of dry spells is one of the important controlling factors of groundwater recharge in the Gaza strip (Fig. 10). This was also concluded earlier by Sheffer *et al*. (2010) [24], who found that the length of the rainy season and the dry spells are an important controlling factor of groundwater recharge in semi-arid regions. More soil water will evaporate during prolonged dry spells, leading to a decrease in the groundwater recharge.

Soil and Land Use Effect: The spatial patterns of groundwater recharge resemble the spatial distribution of the different soil types, which suggests that soil type is a major controlling factor of groundwater recharge in the Gaza strip (Fig. 10). Sandy soil has the highest recharge, followed by sandy loam soil. For sandy clay loam soil, the recharge decreases to about half the value of sandy loam soil amounting to 47 mm. Highly runoff

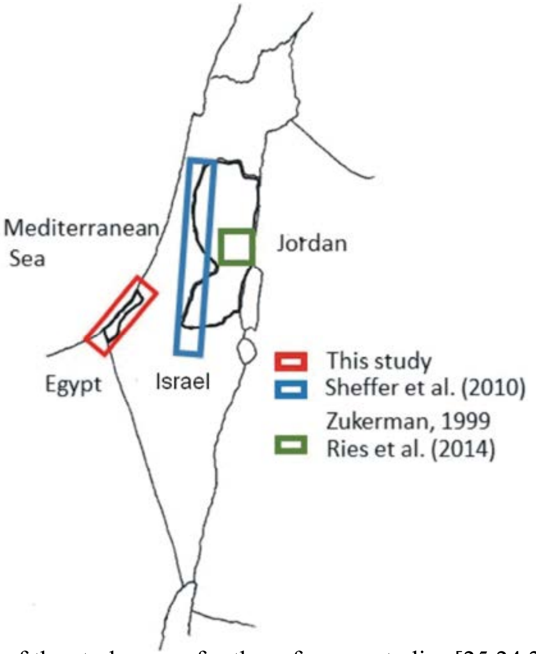

Fig. 12: Approximate locations of the study areas for the reference studies [25,24,23] used to compare the groundwater recharge results from this study.

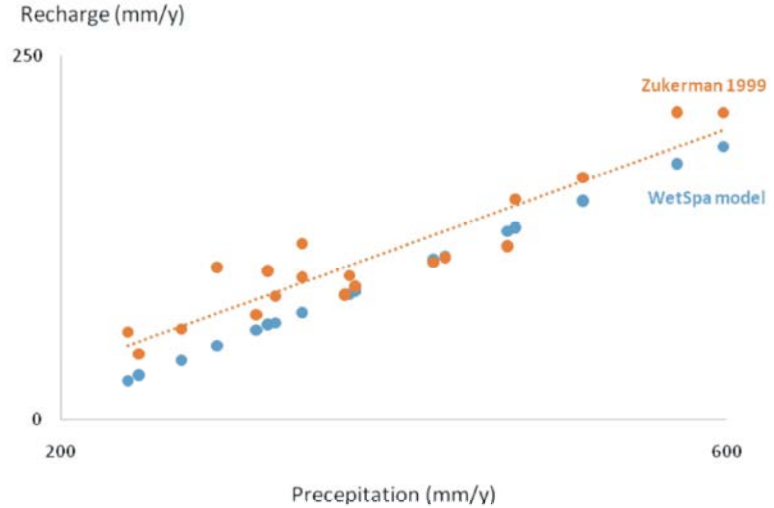

Fig. 13: Agreement between simulated relationship between recharge and precipitation from the WetSpa-Python model and the linear relationship of Zukerman (1999) [23] for the 25 year period (1982-2005) for the Gaza strip.

values are found in sandy soil compared to sandy loam soil, as the major urban areas are located in north Gaza on sandy soil.

The simulated groundwater recharge is also highly dependent on land use (Fig. 14). Urban areas comprise 23% of the Gaza strip and are mainly located in four major areas: north Gaza, Gaza city, Khan-youns and Rafah. Urban areas have the lowest groundwater recharge rates and extremely high runoff values, as they are characterized by high impervious surfaces. Natural vegetation has the highest recharge value when it is characterized by a small rooting depth and low interception values and it is located on sandy soil which allows higher infiltration rates. Rainfed agriculture has the second highest recharge but it covers less than 1% of the study area. Beach and sand dunes have higher recharge rates than crop land and horticulture that are mainly located on sandy loam and sandy clay loam soil. In general, horticulture has lower recharge values than crop land, while the mean values are higher because it is mainly

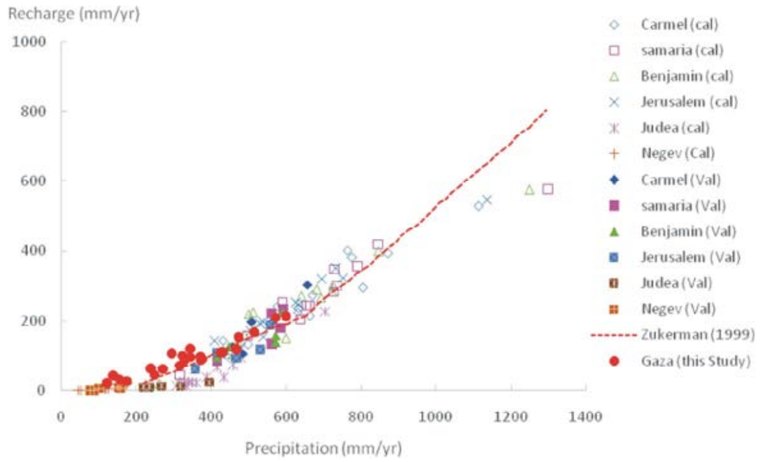

Fig. 14: Simulated mean annual groundwater recharge for the Gaza strip compared with the annual recharge values of Western Mountain Aquifer and with the empirical relationship of Zukerman (1999) [23] (Source:24).

located on sandy soil. Orchards show a low average groundwater recharge and higher evapotranspiration rates.

Evaluation of Results: No calibration nor validation data are available for the study area. We therefore evaluate the model by comparing the model results with the results of three studies in semi-arid regions close to the Gaza strip [23-25] (Fig. 12).

The first study was performed for the Western Mountain Aquifer (Yarkon-Taninim Aquifer) to determine annual recharge values [23]. In their work, a linear relationship between annual recharge (RE) and annual precipitation (PPT) was proposed for three different ranges of precipitation as follows:

$$RE = \begin{cases} 0.45(PPT - 180) & 200mm < PPT \leq 650\ mm \\ 0.88(PPT - 410) & 650mm < PPT \leq 1000\ mm \\ 0.97(PPT - 463) & PPT \leq 1000\ mm \end{cases}$$

The second and the third pattern are not applicable to our study area which has a maximum annual rainfall of only 500 mm. Our annual recharge results are in good agreement with the results of Zukerman (1999)(Fig.13).

The second comparison study was performed by Sheffer *et al*. (2010) [24], who developed a soil water balance model (DREAM) for the same area (Western Mountain Aquifer) to calculate the annual recharge values for the period 1978 to 2002. Groundwater level and spring discharge data were used to calibrate the model. They estimated an average annual recharge equal to 29% of the annual precipitation, which is in line with our average annual results of 27% of the annual precipitation for the Gaza strip. Their results were in very good agreement with the results of Zukerman (1999) [23] (Fig. 14). As a means of comparison and evaluation of our results, we plotted our annual recharge values on top of the recharge evaluation figure of Sheffer *et al*. (2010) [24]. In general, our results are in good agreement with their results, especially for the high precipitation values. For low precipitation, our values are slightly higher compared to the results of the Negev which is on the southern border of our study area.

Ries *et al*. [25] estimated point groundwater recharge fluxes of the Jordan valley region in a karst aquifer for 62 years using a soil water balance model (Hydrus-ID) combined with soil moisture measurements. Three soil moisture plots were used to represent different soil moisture conditions to assess their impact on groundwater recharge. They estimated the average groundwater recharge as 28% of the total annual precipitation, which is in very good agreement with our average simulated recharge value of 27%. They also found that recharge of only seven individual years provided one-third of the total recharge. In our study, five individual years account for more than 37% of the total recharge for the 25 years simulation period. To verify their results, they compared the point simulated recharge values with similar studies in karst aquifers for a large-scale area (Fig. 15) and their results were in the range of these studies. We also plotted our annual recharge values on top of the comparison figure of Ries *et al*. (2014) [25] to evaluate our results (Fig. 15). Our simulated recharge values are more comparable for the high precipitation values than for the lower ones.

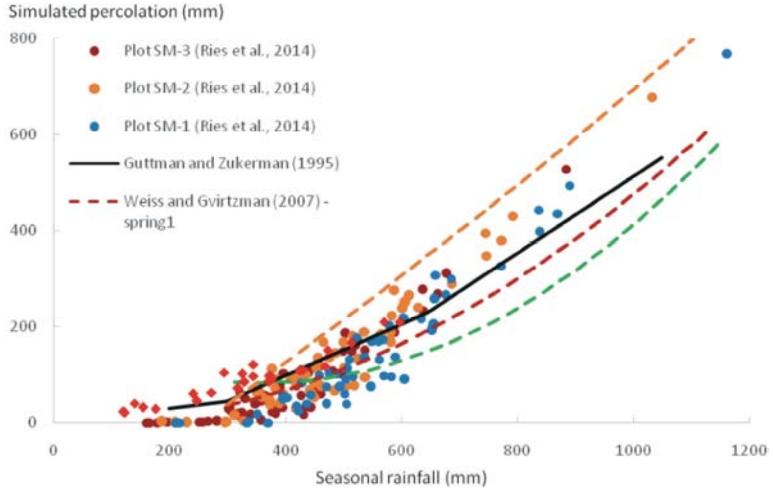

Fig. 15: Simulated mean annual groundwater recharge for Gaza strip in comparison to groundwater recharge fluxes of the Jordan valley region in a karst aquifer. Our simulated recharge values compare better for the higher precipitation values than for the lower ones (Source:25).

Although our recharge simulation is comparable to previous studies, there is a large uncertainty associated with land use parametrization and soil parameters in the model. Also, the geology of the different catchments used in the comparison studies is very different and this will of course influence the groundwater recharge.

Land use has an important effect on water balance components (Fig. 14). Therefore, it is also very important to point out that we used the land use map of 2004 for the whole simulation period. This has probably resulted in an underestimation of the groundwater recharge in the past between (1982 and 1994), since the major urban expansion occurred after 1994 [55]. Since this was ignored and the degree of sealing was kept constant for urban areas, runoff is probably overestimated and evapotranspiration and groundwater recharge are probably underestimated. Another limitation is that the model does not account for artificial recharge (the amount of water that infiltrates to the groundwater aquifer through irrigation, water spills and wastewater leakage), which could increase soil moisture content and could affect the total groundwater recharge.

Impact of Vegetation Cover on Groundwater Recharge: We have performed two groundwater recharge simulations to assess the effect of vegetation properties on groundwater recharge in the Gaza Strip. In the first simulation we used detailed vegetation classes, while for the second we combined all vegetation classes into crop land (Table 4). The spatial pattern of the long-term average difference in groundwater recharge between the results based on lumped and detailed vegetation classes for the 25 years of simulation is shown in Fig. 16.

The mean annual average of groundwater recharge for the Gaza strip is the same for the two simulations. However, at the pixel level the change in groundwater recharge ranges from 4 to 8%. The highest changes are found for orchard and horticulture classes, where recharge increases up to 4% and 8% respectively. These vegetation classes are characterized by high rooting depths and interception capacities and are located on sandy soil, so that by converting to crop land the evapotranspiration and the runoff reduce and the groundwater recharge increases. One should also be aware that orchard and horticulture have a high irrigation demand compared to other vegetation covers. For rainfed agriculture the process was reverse; i.e., the groundwater recharge was reduced up to 8% due to the increase in evapotranspiration.

The results reveal the importance of land use parametrization on groundwater recharge estimation. Vegetation cover has a significant impact on groundwater recharge in the Gaza strip. Hence, proper management practices could increase the groundwater recharge in such a semi-arid region.

Impact of Seasonal Variation on Groundwater Recharge: We have introduced the crop coefficient factor (K_c) (Eq.4) to determine the effect of seasonal variation on groundwater recharge. The spatial pattern of the long-term average difference in groundwater recharge between the results based on recharge simulation with K_c and

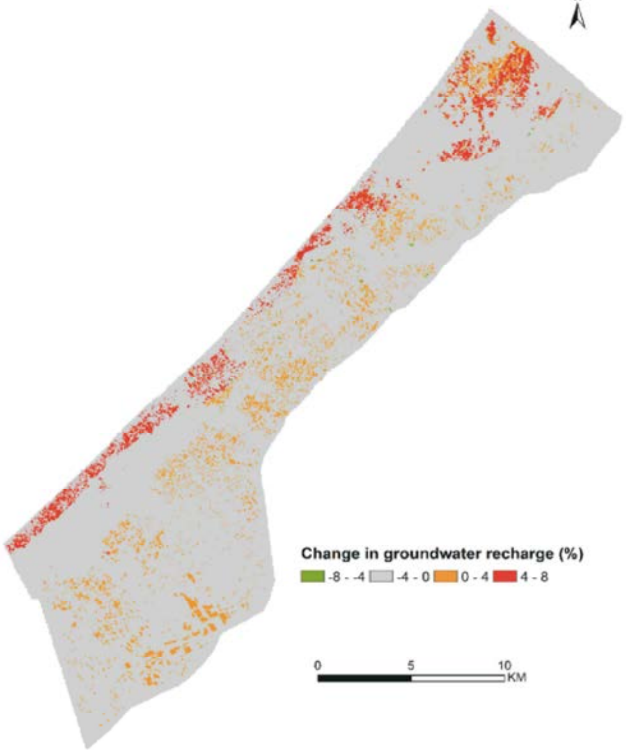

Fig. 16: Spatial distribution of the simulated difference (lumped minus detailed vegetation cover) for long-term averaged groundwater recharge for the 25 years.

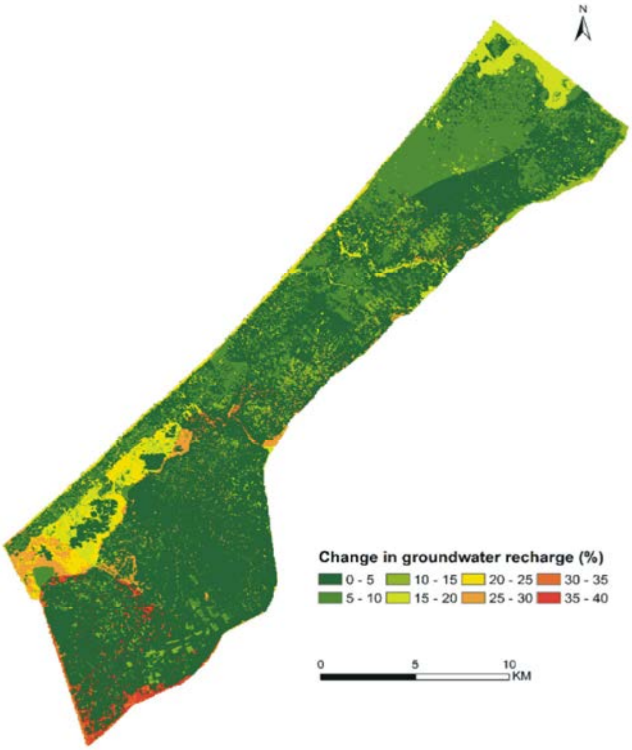

Fig. 17: Spatial distribution of the simulated differences (with crop coefficient K_C minus without K_C) for long-term averaged groundwater recharge for the 25 years.

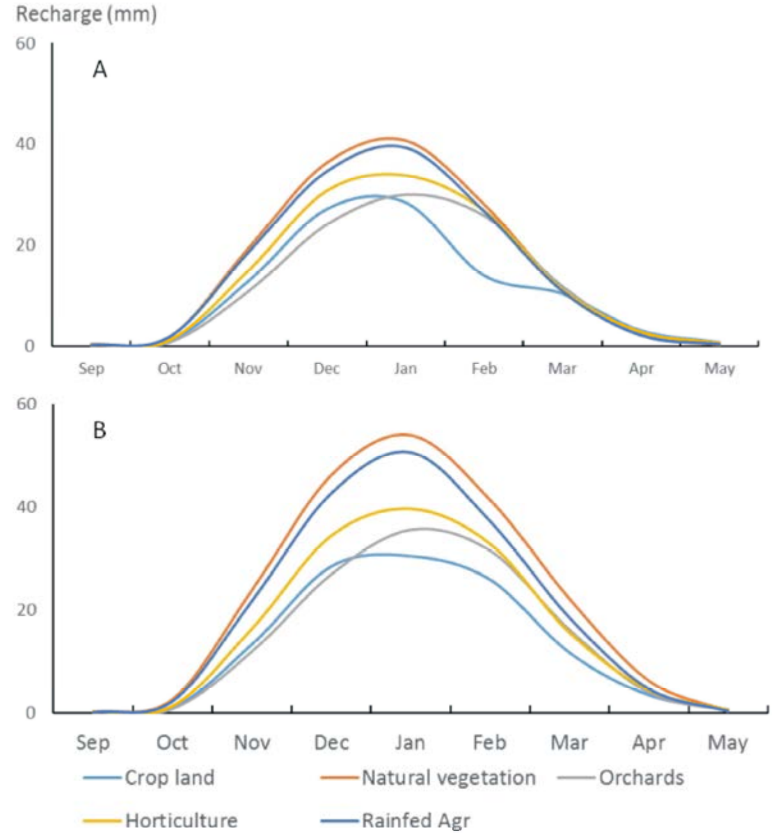

Fig. 18: Mean monthly average of groundwater recharge for the Gaza strip (A) without crop coefficient and (B) with crop coefficient.

simulation without K_c is shown in Fig. 18. The mean annual simulated groundwater recharge increases up to 32% for the Gaza strip if K_c is taken into account. This is mainly due to a decrease in crop evapotranspiration after taking into account the seasonal variation of each vegetation cover.

The groundwater recharge varies with the crop coefficient of different vegetation covers. Natural vegetation has the lowest crop coefficient which leads to an increase of recharge up to 30%, followed by rainfed agriculture were recharge increases up to 20%. The groundwater recharge for horticulture and orchard increases up to 10% (high crop coefficients). The lowest increase of 5% is found on crop land, where the crop coefficient is a combination of two growing seasons and it is mainly located on sandy loam soil.

The mean monthly average of groundwater recharge demonstrates the effect of the crop coefficient K_c in determining the difference of crop transpiration, which leads to differentiation of the groundwater recharge between different vegetation covers (Fig. 18. For example, the groundwater recharge of March and April was almost the same for all vegetation covers, while by taking into account the crop coefficient, the groundwater recharge varied according to the growing season of each vegetation type.

The results demonstrate that seasonal groundwater recharge estimates increasewhen taking into account the seasonal variation through introducing the crop coefficient. However, one should be aware of the uncertainty of K_c values, which were based on literature values, hasa great effect on the actual evapotranspiration rates and therefore also on the groundwater recharge.

CONCLUSION

Wehave used the WetSpa-Python model to estimate the spatial and temporal patterns of groundwater recharge in a semi-arid region and to assess the impact of seasonal variations of vegetation cover on the groundwater recharge.

Up to now, the WetSpa-Python model has not been used for arid and semi-arid regions. Therefore, the use of the WetSpa-Python model to estimate groundwater recharge in the Gaza strip represents a new and unique application. This study improves upon previous recharge estimates to account for daily temporal precipitation, groundwater recharge, runoff and evapotranspiration patterns and by including a crop coefficient factor to determine the impact of the vegetation cover on groundwater recharge, which has never been done before for the Gaza strip. A similar methodology can then be used to estimate groundwater recharge in other semi-arid coastal regions with scarce data.

The simulated mean annual natural groundwater recharge for the period 1982 to 2005 is 92 mm/y. The mean annual groundwater recharge represents 27% of the annual average precipitation, while runoff and total evapotranspiration represent 28% and 45% respectively. Precipitation is the main controlling factor of the temporal variance of groundwater recharge, where rainfall intensity and duration play a significant role in this semi-arid region. The spatial patterns of groundwater recharge are strongly controlled by the spatial distribution of soil and land use types.

It is very hard to assess the accuracy of the model simulation in the absence of calibration data. Therefore, we have evaluated model results by comparing them with results from other studies in similar semi-arid conditions in nearby areas. In general, our results are in good agreement with the results of previous studies, especially for high precipitation values. However, there is a great uncertainty associated with the land use and soil parametrization in the model. The land use map and the percentage of impervious area was kept constant for the 25 simulated years, therefore runoff is probably overestimated and evapotranspiration and groundwater recharge are probably underestimated mainly due to urban development and intensification. The main limitation of the model, for this particular application, is that it does not account for irrigation return flow and water network and wastewater leakage, which could affect the soil moisture content and therefore the groundwater recharge.

The impact of the spatial variation of the vegetation cover was identified by comparing the spatial patterns of the difference between long-term average groundwater recharge using detailed and lumped vegetation classes. In general, a differentiation in vegetation classes resulted in a 4 to 8% difference on the groundwater recharge. These results indicate that the vegetation cover has a significant impact on groundwater recharge in the Gaza strip and that proper management practices could increase the groundwater recharge in such a semi-arid region.

Introduction of a crop coefficient factor (K_c) to estimate the effect of seasonal variation on groundwater recharge results in simulated increases of up to 32%. This shows potentially a very large temporal uncertainty on the recharge estimates, the literature-based K_c values contribute further to this aspect. More research is needed to investigate the role of K_c values in the evapotranspiration of WetSpa-Python.

The application of the WetSpa-Python model to the Gaza strip represents a challenging test of the model capability to estimate recharge in semi-arid areas. The results of this study are in the line with similar studies in the region indicating that the model could produce reliable estimates of spatial and temporal rates of groundwater recharge in semi-arid areas. However, to confirm the conclusions, measuredin situ data (i.e., soil moisture, actual evapotranspiration rates, etc.) to validate the model are recommended.

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