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Groundwater Recharge Assessment for Small Karstic Catchment Basins with Different Extents of Anthropogenic Development

Yaakov Anker [1,2,*], Alexander Gimburg [2], Michael Zilberbrand [1], Yakov Livshitz [3] and Vladimir Mirlas [1]

[1] Department of Chemical Engineering and Materials & Biotechnology, Ariel University, Ariel 4077625, Israel; michaelzi@ariel.ac.il (M.Z.); vladimirm@ariel.ac.il (V.M.)
[2] Department of Environmental Research, Eastern Israel R&D Center, Ariel 4077625, Israel; alex@ariel.ac.il
[3] Hydrological Service of Israel, Israel Water Authority, 7 Bank of Israel St., Jerusalem 9195021, Israel; yakovl20@water.gov.il
* Correspondence: kobia@ariel.ac.il

Abstract: Climate change and anthropogenic development considerably influence groundwater resource distribution and conditions. Catchment basin groundwater recharge—discharge computation reliability is needed for effective groundwater management policy formulation and implementation and also for resolving environmental challenges in such a watershed. This paper compares groundwater recharge patterns between urbanized and nearly natural small catchment basins of Israel's Western Mountain Aquifer (WMA). The correlation between precipitation volumes and surface runoff shows that surface runoff volume constitutes 3–4% of the precipitation volume in the Natuf catchment and 1–2% in the Te'enim catchment. These assessments reflect the differences in the land use, outcrop lithology, topography and hydrodynamic properties of the WMA within the model basins. A groundwater recharge assessment based on water balance and water table fluctuation methods was performed for the mountainous karstic Te'enim and Natuf catchment basins for all the available data from 2000 to 2020. The water balance method provided reliable estimates. The groundwater recharge assessment considered land use classification and climate changes during this period. The average multiannual groundwater recharge values for the 2000–2021 period varied from 17.6 × 106–24.8 × 106 m^3 to 24.5–29.2 × 106 m^3 for the Te'enim and Natuf catchment basins, respectively. For the relatively dry period of the 2013/2014–2017/2018 hydrological years when detailed measurements of the surface runoff were available, the corresponding groundwater recharge volumes were 17.6 × 106 m^3 and 24.5 × 106 m^3. The corresponding local groundwater recharge coefficients constitute 0.46–0.57 for the mostly agricultural Te'enim basin and 0.29–0.32 for the urbanized Natuf basin. A significant difference in the groundwater recharge coefficients between the studied catchments is caused mostly by the differences in land use. It is suggested that applying such a groundwater recharge estimation for small hydrological sub-basins can improve one's understanding of the groundwater recharge distribution within a major basin, enabling the application of an accurate regional hydrogeological model that may be extrapolated to other similar regions.

Keywords: groundwater recharge; catchment basin; karstic terrains; water balance; Israel

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1. Introduction

Climate change and anthropogenic activity above a certain threshold might considerably influence groundwater distribution and recharge. In the study area and in many other regions, groundwater is a reliable source of high-quality water for industrial, domestic and agricultural applications. Reliable groundwater recharge—discharge estimation, watershed environmental issues and hydrogeological risk quantification are imperative for effective groundwater management policy implementation. Such consistent and reliable basin and sub-basin assessments are mandatory for effective groundwater management [1]. The estimation of groundwater recharge, which is the surface runoff component that infiltrates the aquifer, is considered a challenge in fractured carbonate terrains. This process is highly dependent on rock property heterogeneity in both unsaturated and saturated zones [2]. The temporal and spatial variation of groundwater recharge assessment at the local scale may rely on groundwater level monitoring and mathematical modeling that considers the fractured karst aquifer system's lithological features [3]. A similar combined study utilizing the double continuum approach of karst systems delineated saturated and unsaturated flow at a catchment scale using a simulation of recharge and discharge dynamics in a thick unsaturated zone [4].

A groundwater-level data-based groundwater recharge estimation methods review indicates that the water table fluctuation method is the most widely used technique [5]. While this approach is simple and tolerant to unsaturated zone flow mechanisms, it suffers from limited specific yield determination accuracy and assumption validity of subsurface inflow and outflow. Comparative groundwater recharge estimations using the chloride mass balance method, the water budget method, the Darcy method and the hydrograph separation method were evaluated for the Bima sandstone aquifer in the semiarid Yola area, northeast Nigeria [6], suggesting that direct groundwater-recharge-based methods are more reliable than those based on indirect groundwater recharge.

In humid regions where recharge occurs year-round, baseflow, in a manner of the baseflow index and the baseflow separation method, may supply reliable recharge estimates. In semiarid Mediterranean systems, where streamflow is ephemeral, the baseflow method needs to be customized, and even with adjustments such as in the Eckhardt method, flow continuity is assumed. An evaluation of the baseflow method against the displacement recession method and the water table fluctuation method indicated that the latter was best fitted to ephemeral semiarid regions [7].

Groundwater recharge for the Yarkon-Taninim basin in Israel (Western Mountain Aquifer, WMA), was estimated via an annually calibrated groundwater recharge balance cell model [8]; linear equations calibrated hydrological model linking groundwater recharge with annual rainfall and groundwater recharge threshold (minimum effective rain) for rainfall events of various magnitudes [9]. A hydrological model providing groundwater recharge estimates based on daily rain measurements at a constant set of 40 rain gauge stations [10]. The current regional model is based on continuous direct measurements of both the rainfall and water percolation in the epikarst Sif Cave in Wadi Sussi [11]. Three types of flow regimes were indicated in this study: "quick flow" through large fractures, "intermediate flow" through a secondary crack system, and "slow flow" through the matrix. It was found that the annual groundwater recharge (140–160 mm in different areas in the cave) constitutes 30–35% of the annual rainfall (460 mm).

By evaluating the natural water resource potential of the major watersheds of the region (Kinneret, Western Galilee, Carmel, Coastal, Lower Galilee, Northeastern Mountain, Eastern Mountain, Western Mountain (Yarkon-Taninim), the Negev and Arava) via the Israeli Hydrological Service, it was suggested that natural groundwater recharge is dependent on precipitation variability (natural and/or man-made) and on anthropogenic land development that affects infiltration and surface runoff [12]. The calculations were performed using a variety of techniques, ranging from relatively simple water balances using "cell models" to more sophisticated two- and three-dimensional numerical models (FEFLOW, MODFLOW and 2D SUTRA) based on geo-hydrological expertise [13,14] and the hydrometeorological daily recharge assessment model DREAM [11]. The HEC-HMS model was used to quantify the proportion of groundwater recharge collected during surface runoff events in a karst aquifer under local hydrogeological constraints [15].

To assess the distributed infiltration and vadose storage dynamics of the WMA, variably saturated dual-permeability flow modeling was performed [16]. Most groundwater recharge studies in the region have not considered the changes associated with anthropogenic factors (building and agricultural land use) over the past decade. One of the first attempts to assess the impact of the development of the territory (building and change in irrigated agricultural areas) on surface runoff and groundwater for the Shiloh River drainage basin [17]. This research suggests that the anthropogenic impact (widening building areas) on the Shiloh basin and similar watersheds causes surface runoff accumulation, extreme flood events and reduced groundwater recharge.

The main objective of the present study is to assess groundwater recharge in small catchment basins within the Yarkon-Taninim basin by coupling land use, urbanization and climate changes in typical karstic Mediterranean mountainous terrain. For this case study, surface runoff and groundwater recharge evaluations were performed for the Te'enim and Natuf catchment basins. These basins are characterized by different land use (urban extent) and topography. The Te'enim basin is less urbanized (a more agricultural and natural area) than the Natuf basin.

2. Main Framework

2.1. Geographical Framework

The two sub-catchment basins start at the Samaria Mountains rim with an altitude that ranges from less than 100 m above sea level (ASL) along the western contact with the coastal plain to 800 m ASL along the eastern mountain rim (Figure 1). Regardless of the elevation difference, the entire region is regarded as having a typical Mediterranean climate (Figure 2), with moderate precipitation increasing at higher elevations [18]. The Te'enim and Natuf catchment basins have areas of 126.3 km^2 and 277.3 km^2, respectively. Most parts of both catchments belong to the Yarkon-Taninim basin (approximately 1000 km^2). The average annual rainfall varies from 590 mm for the Te'enim catchment basin to 550 mm for the Natuf catchment basin. The natural drainage path for the Te'enim catchment basin is the Te'enim creek with the Abu-Jamus main tributary, and for the Natuf catchment basin, the natural drainage path is the Natuf creek with the Dolev and Modi'in main tributaries. The main soil types in the region are terra rosa and rendzina soils [19]. The Te'enim catchment basin contains both agricultural and natural areas. The built-up area consists of approximately 18% of the basin territory. The settlements are mostly small, with a population of several hundred to several thousand inhabitants. The largest city is Tulkarm, with an urban area of 5.3 km^2 within the Te'enim basin, which is mostly concentrated in the western part of the basin, and the center of the basin is natural or agricultural (mainly olive plantations). The urban areas in the Natuf catchment basin reach 23% of the basin area and are distributed evenly throughout the basin. The largest city in the basin is Ramallah, which covers an area of 12.7 km^2 and is located on its eastern border. In addition, five more fairly large settlements with built-up areas of 2.2 to 4.3 km^2 are located within the Natuf catchment basin. The rest are 45 small settlements with urban areas that do not exceed 2 km^2. Most settlements are located on elevated terrain, while mountain slopes and valleys are occupied either by agricultural lands or natural areas.

The terrain slope increases the surface runoff; as such, the average terrain slopes of the basins near their western boundary are 2.40 for the Te'enim basin and 2.50 for the Natuf basin. The eastern (mountainous) areas of the basins are dominated by moderate to strong slopes, and in accordance with the standard slope classification, gentle slopes are 0–9°, gentle to moderate slopes are 9° to 15°, moderate to strong slopes are 15° to 30° and very strong slopes are up to 45° [20]. The mountainous part of the Te'enim basin is dominated by gentle to medium slopes. The strong slopes adjoin only the river valleys and the most deeply incised dry wadi. The mountainous part of the Natuf basin is characterized by dominant medium and strong slopes up to very strong slopes that are located adjacent to the river valleys (Figure 3).

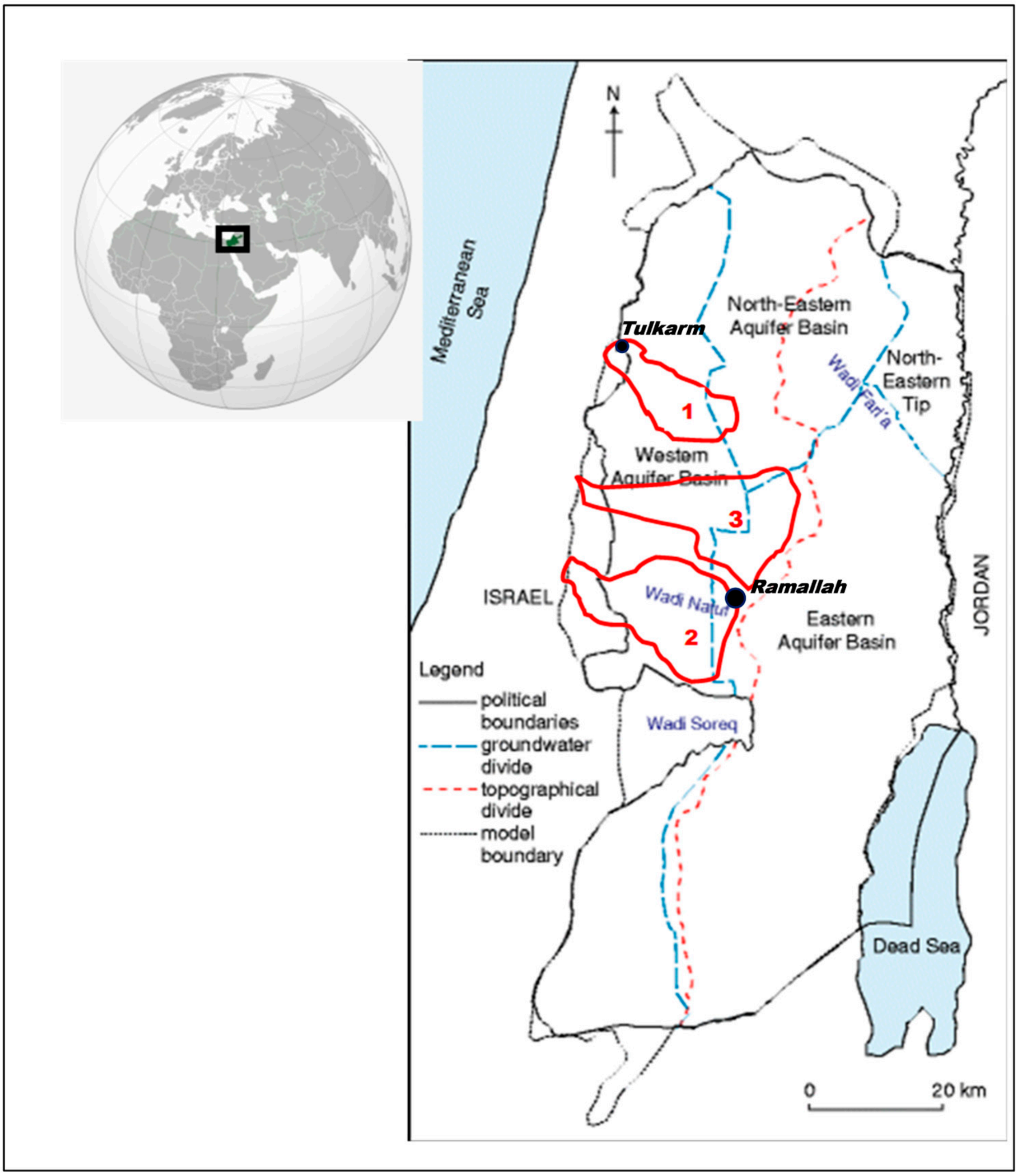

Figure 1. Study site location (red polygons) and mountain basin subdivision [21]. Catchment basins: 1—Te'enim; 2—Natuf; 3—Shilo basin (for comparison).

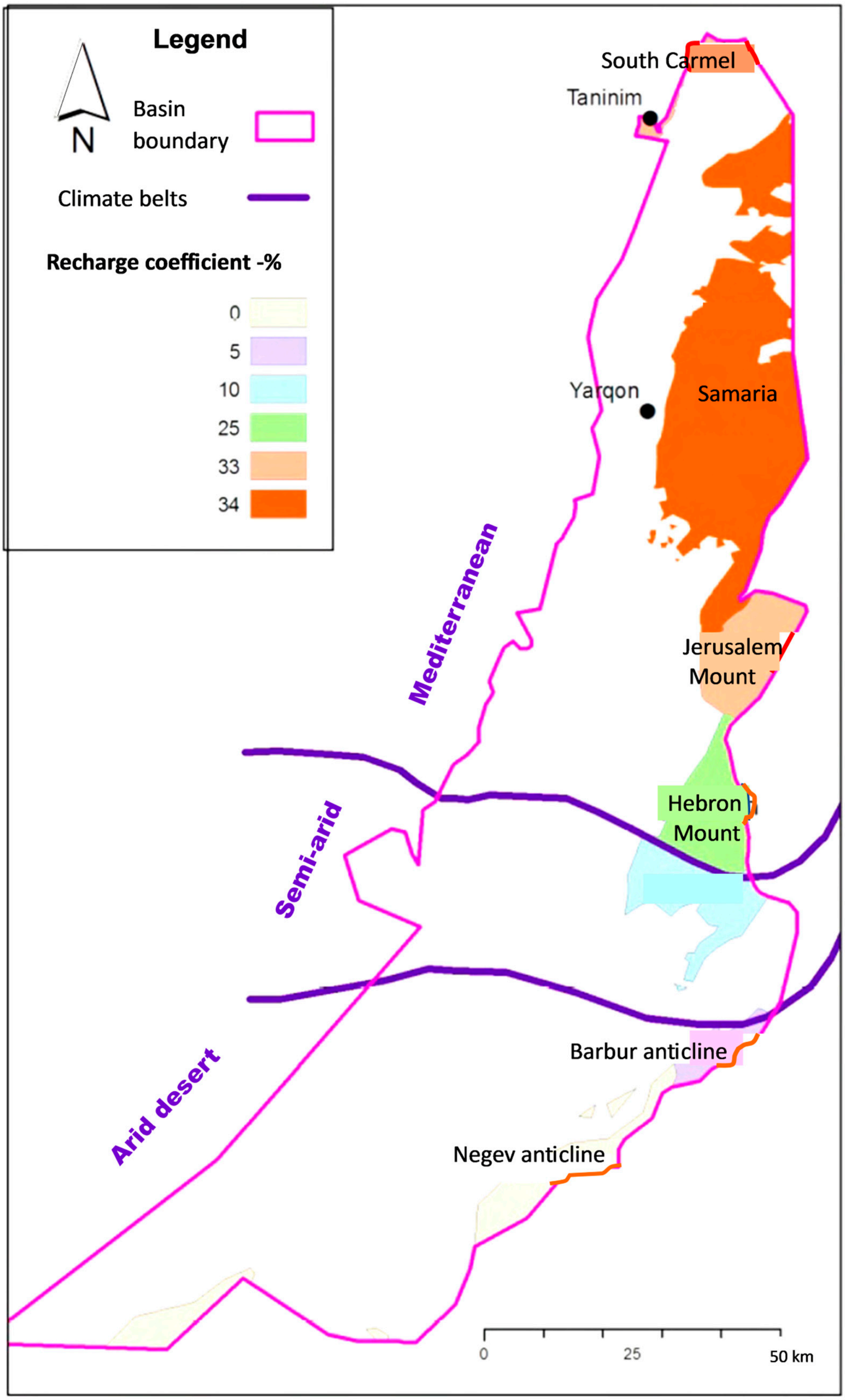

Figure 2. Zones of different climates and recharge coefficients (the ratio of the groundwater recharge to rainfall values) at the WMA outcrops (after Dafny, 2009).

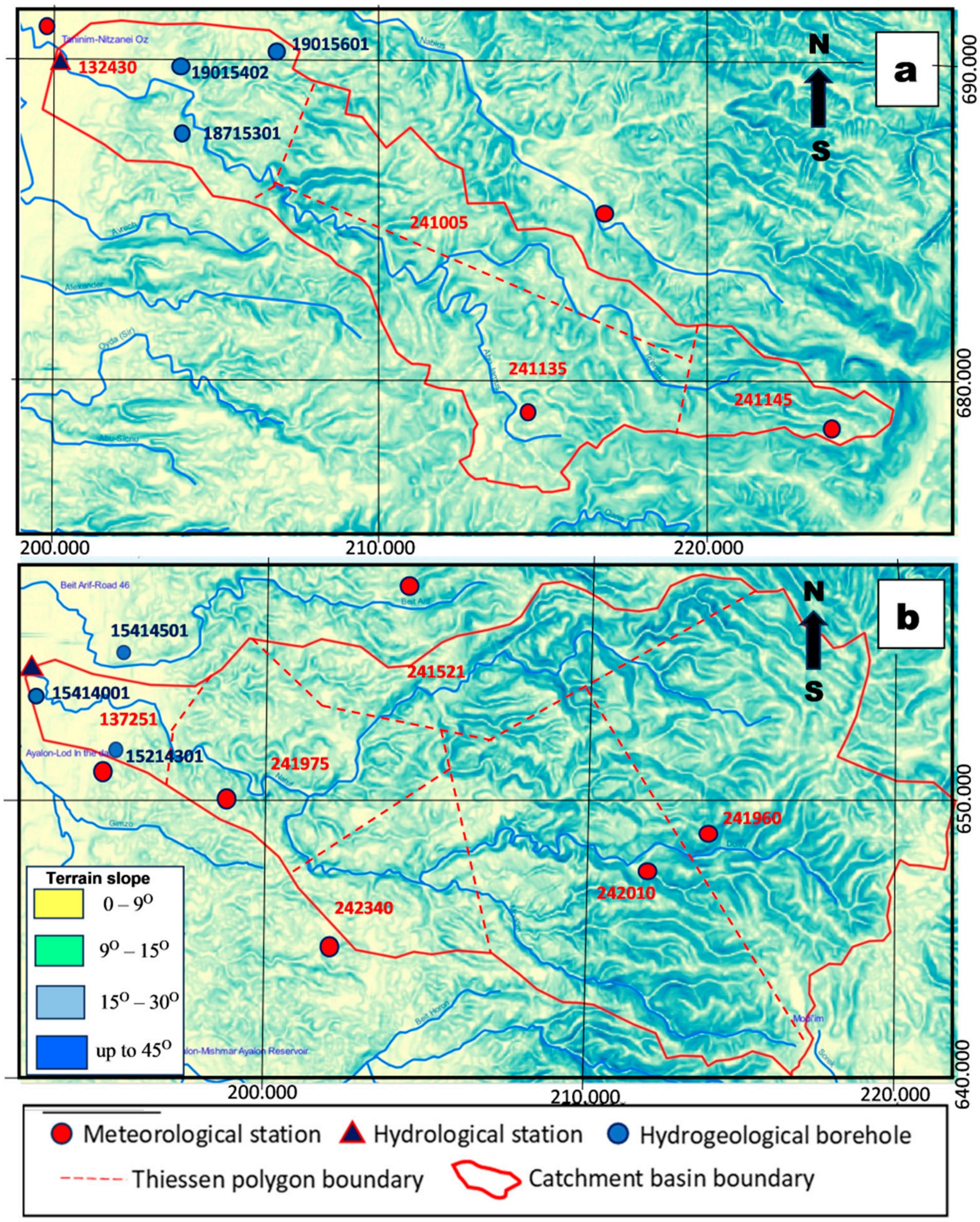

Figure 3. Terrain slope (degrees) and Thiessen polygon location of the Te'enim (**a**) and Natuf (**b**) catchment basins.

2.2. Geological and Hydrogeological Background

The WMA sediments are part of a stratigraphic unit named the Judea Group (Gr.) of the Turonian, Cenomanian and Albian ages (Figure 4), with a total thickness of 800–1000 m. The subunits are composed of a series of carbonate rocks (chalk, limestone and dolomite) with interbedded marls. At its base, the Judea Gr. is in contact with marls, clays and some sandstone of the lower Cretaceous (Hatira Gr.) and its upper confined boundary is separated from the Eocene Avdat Gr. aquitard by Mount Scopus Gr., including layers of marls, chalk and calcareous shales from the Senonian to Paleocene ages. Westward, the aquifer becomes confined under relatively thick impermeable chalks and marls of the Senonian Mount Scopus Group and the Eocene Avdat Group [22].

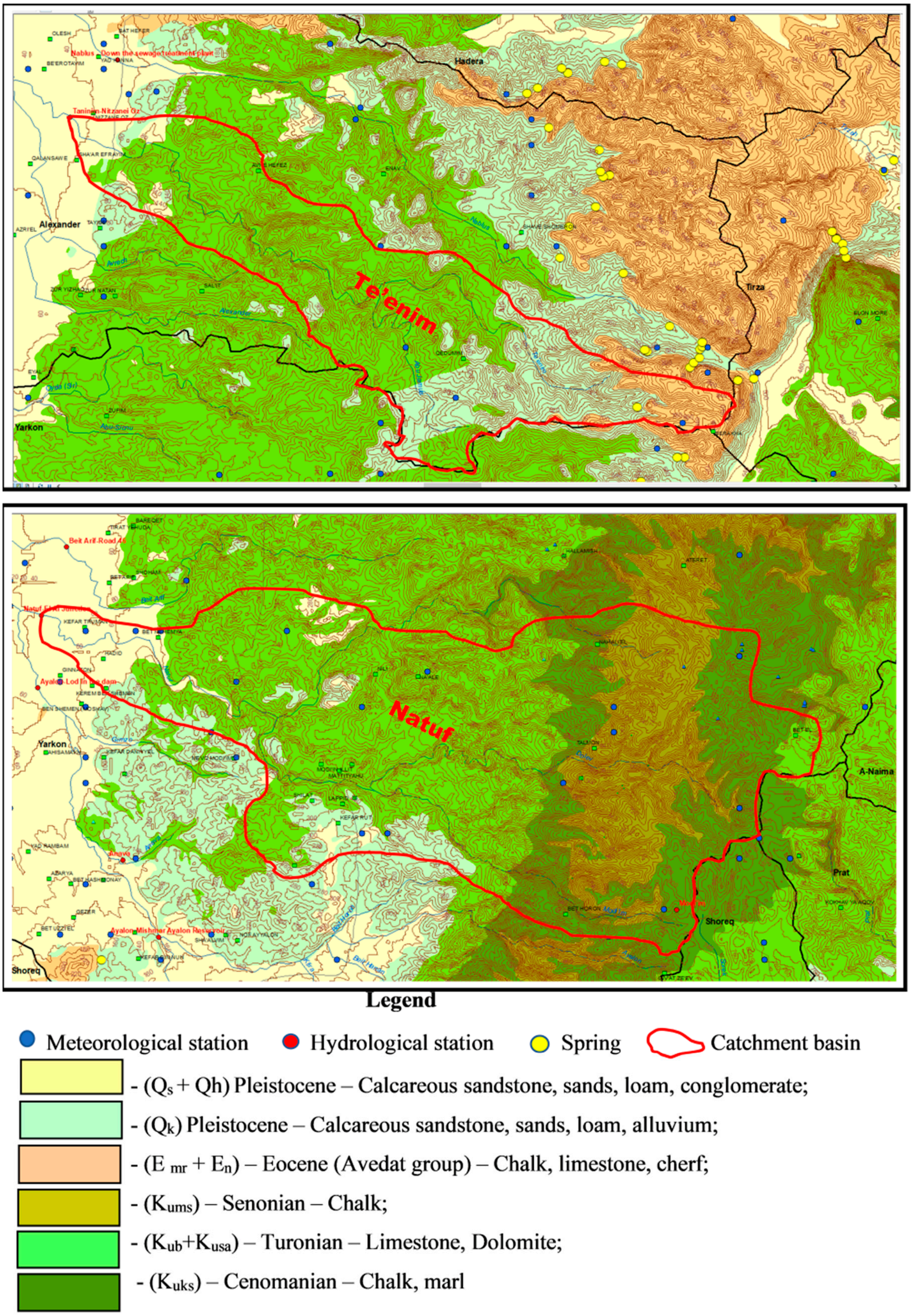

Figure 4. Geological maps of the Te'enim (Natanya Sheet) and Natuf (Ramallah Sheet) basins. Source: https://www.gov.il/en/departments/general/map-1-50000 (accessed on 9 September 2023).

The WMA is mainly of karstic nature and possesses high transmissivity (up to thousands to tens of thousands of m^2/day) and storage capacities. The aquifer extends westward, from the anticlinoria backbone of the Samaria and Judea mountains, which is also the hydrological divide, to the Israeli coastal plain [23]. The WMA contains a western confined part, under the lowland and coastal plain (11,800 km^2), and an eastern phreatic part, mostly in the mountain area (2200 km^2) [11]. The Samaria, Judea and Carmel Mountains are the main groundwater recharge areas of the WMA [13,15].

In the groundwater recharge areas that lie beneath the Samarian and Judean mountains, the WMA is directly replenished by rainfall [11], with a current average annual groundwater recharge of approximately 360×10^6 m^3 [12]. The Yarkon springs in the basin's central part and the Taninim springs in its northern part are the WMA's natural discharge outlets. In the early 1950s, when pumping from the aquifer was very small, the annual groundwater discharge values by the Yarkon and Taninim springs were approximately 220×10^6 m^3 and 110×10^6 m^3, respectively. The increase in pumping caused a gradual drop in the groundwater levels, and as a result, by the 1960s, the Yarkon springs stopped flowing. The annual discharge of the Taninim springs in the 2021/22 hydrological year was 36.5×10^6 m^3.

The phreatic parts of the aquifer, as well as the eastern confined part, contain mostly high-quality young groundwater [24]. On the mountain flanks and under the foothill strip, groundwater salinity is in the range of 50–150 mg/L of chloride, except in several sites, where it rises to 300–400 mg/L. However, in the southern part of the basin, there is a significant plume of relatively high salinity groundwater, up to 2500 mg/L of chloride [25]. The western margin of the basin is in contact with groundwater with slightly diluted seawater salinity that is characterized by chloride concentrations above 10,000 mg/L [12,24]. The main constraint of increasing pumping from the aquifer is the danger of a salinity rise due to the further lowering of the water table [26]. Currently, less than half of the aquifer volume contains groundwater with chloride concentrations of less than 400 mg/L [12].

2.3. Research Methodology

The groundwater recharge estimations for the studied catchments were performed using integrated water budget calculations based on precipitation, evapotranspiration and surface runoff datasets and the water table fluctuation method based on all available groundwater level datasets from 2000 to 2020 (Table 1). The boundaries of the catchments go beyond the boundaries of the WMA, and the calculated groundwater recharge also includes a portion of the recharge of the eastern aquifer. For the estimation of the real groundwater recharge that enters the groundwater of the WMA, a portion of the WMA outcrops of the total outcrop area in each catchment was considered. This is based on similar lithological and climatic conditions on both sides of the WMA's eastern boundary. The total groundwater recharge was subdivided proportionally to the areas of outcrops within and outside of the WMA.

Table 1. Hydrogeological boreholes used for groundwater recharge estimation via the water table fluctuation method.

Catalog Number	Name	Depth, m	Measurement Period	Aquifer
		Te'enim catchment		
18715301	Vaspi E. Kasim 20	110	2012–2020	Turonian and Upper Cenomanian
19015402	E. Raman and Safarani 39	135	2012–2020	Turonian and Upper Cenomanian
19015601	Hassan Muhammad Khalil 28	175	2012–2020	Turonian and Upper Cenomanian

Table 1. *Cont.*

Catalog Number	Name	Depth, m	Measurement Period	Aquifer
		Natuf catchment		
15414001	Lod Hasona Abed Hamid	21.5	2000–2008	Turonian and Upper Cenomanian
15414501	Beit Navla refugee camp	78.9	2000–2020	Turonian and Upper Cenomanian
15214301	Ben Shemen Kfar Hanor	70.4	2000–2015	Turonian and Upper Cenomanian

3. Materials and Methods

Water budget estimation was calculated using all relevant datasets from the Israeli Ministry of Agriculture Meteorological Service and Israel Meteorological Services. The meteorological station's locations are shown in Figure 3 and Table 2. Since not all meteorological stations were active during the entire research period (Table 2), the meteorological calculations were performed on averaged figures. The parameters included annual and average monthly rainfall and Penman–Monteith effective evapotranspiration (ET_0) series [27] that were assigned to the Te'enim and Natuf catchments.

Table 2. Meteorological stations used for precipitation assessment within the Te'enim and Natuf catchments.

Station Number	Name	Station Height ASL, m	Period of Measurements	Sub-Basin Area, km^2 (Thiessen Polygon Area, Figure 3)
		Te'enim catchment		
241135	Kdumim	395	2003–2021	50.9
241005	Shavei Shomron	350	2006–2021	27.2
241145	Brakha	836	2000–2021	13.7
132430	Be'erotayim	30	2006–2021	34.7
		Natuf catchment		
241521	Beit Aryeh	320	2010–2021	32.9
137251	Ben Shemen	100	2000–2021	11.8
241960	Har Hursha Automatic	770	2004–2021	87.8
242010	Talmon (Dolev)	615	2000–2021	84.4
241975	Naot Kedumim	220	2000–2019	43.5
242340	Reut	275	2007–2021	16.9

Annual precipitation in the study period varied from a maximum of 827 mm in 2002 to a minimum of 336 mm in 2000 in the Te'enim catchment basin, and from a maximum of 883 mm in 2018 to a minimum of 303 mm in 2001 in the Natuf catchment basin. During the study period, no tendency toward decreasing annual precipitation was found. The high variability in the annual precipitation values is obvious. Maximal and minimal annual precipitation values differ by 2.9 times. The average annual rainfall is 591 mm in the Te'enim basin and 551 mm in the Natuf basin (Figure 5).

Monthly rainfall over the WMA is characterized by high variability, with a maximum standard deviation of up to 77 mm in December [28]. Rainfall starts in October and ends in May. Daily precipitation over the Natuf catchment for the 2002 hydrological year with the maximum value of annual rainfall for the 2017 hydrological year and the average annual value are shown in Figure 6.

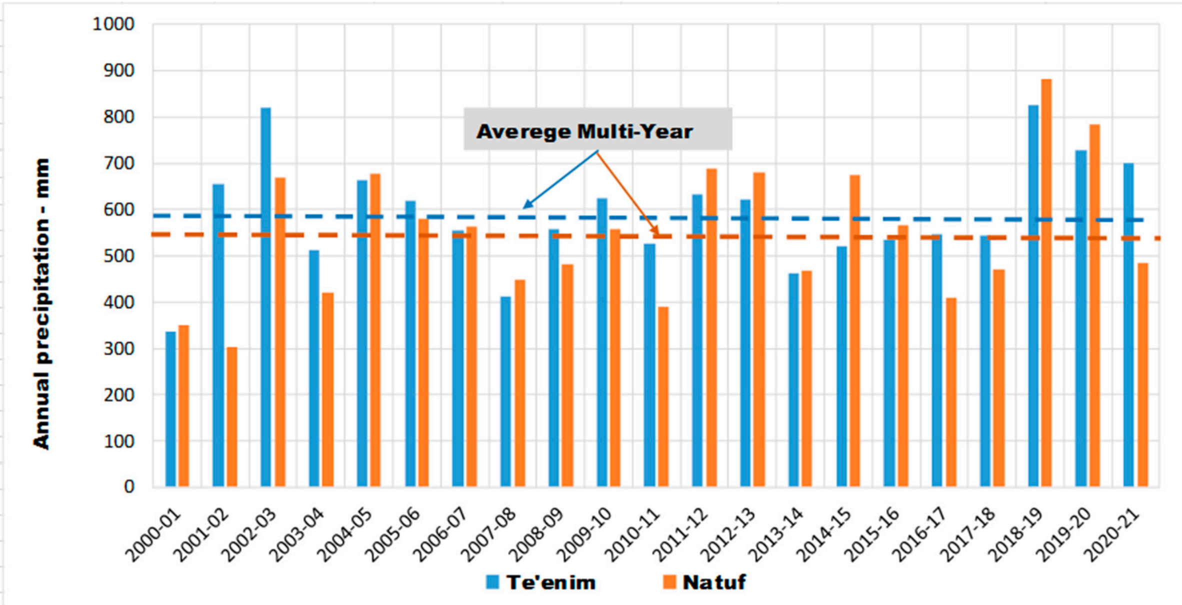

Figure 5. Annual precipitation during the period from 2000 to 2021.

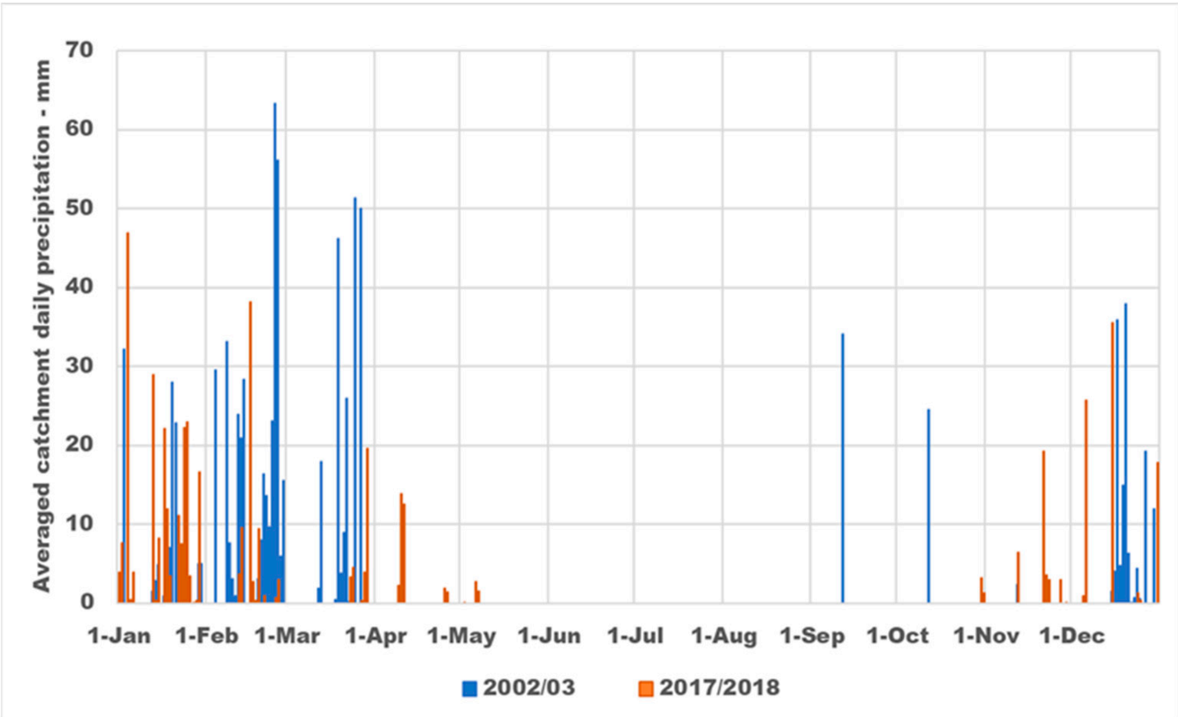

Figure 6. Average daily precipitation within the Natuf catchment basin in the 2002/03 and 2017/18 hydrological years.

In the 2002/03 hydrological year, the maximum daily rainfall was 64 mm in March, while in 2017/18, the maximum recorded rainfall was 47 mm in January. The duration of the precipitation event that resulted in surface runoff varied from 2 to 13 days during the studied hydrological years. Figure 7 demonstrates the correlation between precipitation volume and rainfall event duration over the Natuf catchment basin.

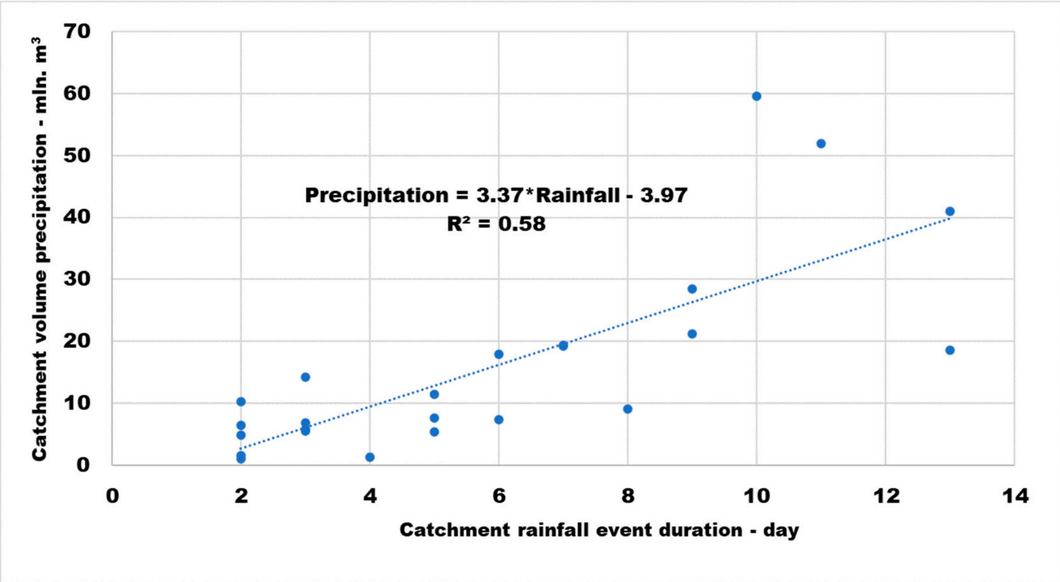

Figure 7. Correlation between precipitation volume and rainfall event duration over the Natuf catchment basin.

Precipitation volumes over the catchment area from 1–2 to 10–14 million m^3 are typical for rainfall event durations of less than 3 days. For rainfall event durations from 4 to 10 days in nearly 50% of rainfall events, the precipitation volume varied from 15 to 30 million m^3. At rainfall event durations of more than 10 days, the precipitation volume reached 60 million m^3.

The average multiannual evapotranspiration values calculated for the main groundwater recharge period from November to March for the Te'enim and Natuf basins are 44×10^6 m^3 and 114×10^6 m^3 (Table 3), respectively. The average multiannual evapotranspiration normalized according to catchment basin areas varies from 350 mm for the Te'enim catchment to 411 mm for the Natuf catchment.

Table 3. Averaged multiannual evapotranspiration values (ET).

Catchment Basin	Station	Day in Month	November	December	January	February	March	ET IX-III
			30	31	31	28	31	
Te'enim	Karney Shomron	ET mm/day	2.5	1.8	1.8	2.2	3.3	
		ET mm	75	56	56	62	102	351
		ET MCM	9.5	7.1	7.1	7.8	13	44
Natuf	Harasha	ET mm/day	3.1	2.2	2.2	2.5	3.6	
		ET mm	93	68	68	70	112	411
		ET MCM	26	19	19	19	31	114

Daily and annual surface runoff series measured at the hydrological stations of the Israeli Hydrological Survey located at the basin outlet from the mountainous catchment area are shown in Figure 3. The Te'enim–Nitzanei Oz hydrological station, located two kilometers from the mountain terrain contact with the coastal plain, was used for surface runoff estimation from the Te'enim catchment area. Surface runoff flow rates were measured during the 2013/2014–2018/2019 hydrological years. For surface runoff estimation from the Natuf catchment area, the El Al Junction hydrological station, located 4 km from the mountain terrain contact with the coastal plain, was used. Surface runoff flow rates were measured during the 1999/2000–2020/2021 hydrological years.

Groundwater level series were measured at several Israeli Hydrological Survey boreholes. Only boreholes with monthly groundwater measurements were used for estimation (Figure 3 and Table 1)

Precipitation estimation was based on annual rainfall series over the catchment's basin and on annual surface runoff series. Annual rainfall volumes were calculated as a sub-basin precipitation sum within the catchment area. Rainfall depth (mm) was calculated as Thiessen polygon averaged values [29] that were normalized according to the sub-basin catchment area. (Figure 1). The Q-GIS 3.4 platform was used to evaluate the study area's annual surface runoff flow volume, and flow rates for the multiannual surface runoff coefficient estimation were measured during each storm event. The surface runoff coefficient (C), a dimensionless coefficient relating the amount of surface runoff to the amount of precipitation, was calculated according to Equation (1) [30].

$$C = \text{Annual surface runoff (mm)}/\text{annual precipitation (mm)} \quad (1)$$

Estimation of multiannual groundwater recharge based on the water balance of the catchment's basin was made according to Equation (2).

$$R = P - (E + Q) \quad (2)$$

where R—groundwater recharge (infiltration losses into the soil); P—precipitation; ET—evapotranspiration; and Q—surface runoff. Groundwater recharge was calculated for periods with surface runoff events that occurred between November and March. October precipitation was not considered in the water balance since most October rains only wet the soil layer and do not enter the groundwater.

Based on these calculations, multiannual averages were estimated. The multiannual average monthly effective evapotranspiration during the rainy period (ET) was calculated using the Penman—Monteith equation [31] for several meteorological stations. Evapotranspiration values at the Karney Shomron station located at 325 m ASL for the Te'enim catchment and at the Harasha station located in the Dolev region near Talmon at 770 m ASL for the Natuf catchment were used for groundwater recharge estimation.

Estimation of multiyear groundwater recharge based on the water table fluctuation method [5] of the Te'enim catchment basin was made according to Equation (3).

$$R = S_y \times \Delta H, \quad (3)$$

where R is the groundwater recharge and Sy is the specific yield (dimensionless) that was used instead of the effective porosity, since in karstic rocks, the effective porosity is heterogeneous, meaning it cannot be estimated, and the specific yield is measurable and represents the rock formation under study. ΔH is the difference between the peak of the rise and the lowest point of the phreatic groundwater level (amplitude) during the year. Averaged annual values of groundwater level amplitude from the chosen boreholes (Table 1) were used for groundwater recharge calculation within the Te'enim catchment area. Within the phreatic portion of the Natuf catchment, no appropriate wells were found.

4. Results and Discussion

4.1. Multiannual Change in Surface Runoff and Its Correlation with Precipitation

The annual surface runoff volumes vary from almost 0 to 12 million cubic meters for the Natuf basin and to 2 million cubic meters for the Te'enim basin (Figure 8), depending mainly on the total volume and regime of precipitation. The calculated average multiannual surface runoff volume equals 0.65×10^6 m^3 for the Te'enim catchment basin (5.2 mm) during the 2013–2018 hydrological years. Despite using a relatively short period (5 years) of surface runoff measurements in the Te'enim catchment area, the averaged values obtained here correspond well to the estimated average values for the central portion of the WAB [12,17]. The daily maximum flow rate of surface runoff from the Natuf catchment area, measured at the El Al Junction hydrological station during the 2000–2022 hydrological years, varies from 0.02 to 92 m^3/s (Figure 9), with an average of 3.2 m^3/s. The calculated average multiannual surface runoff volume equals 3.35×10^6 m^3 for the Natuf catchment basin (12.1 mm). The correlation between the volumes of precipitation and the surface runoff is described by exponential dependencies with a squared correlation coefficient ranging from 0.92 to 0.96 (Figure 10). According to these correlations, the surface runoff volume constitutes 3–4% of the precipitation volume for most hydrological events in the Natuf catchment and constitutes 1–2% in the Te'enim catchment. Significantly smaller volumes of surface runoff from the Te'enim basin are probably caused by different land uses, outcrop lithologies and slopes.

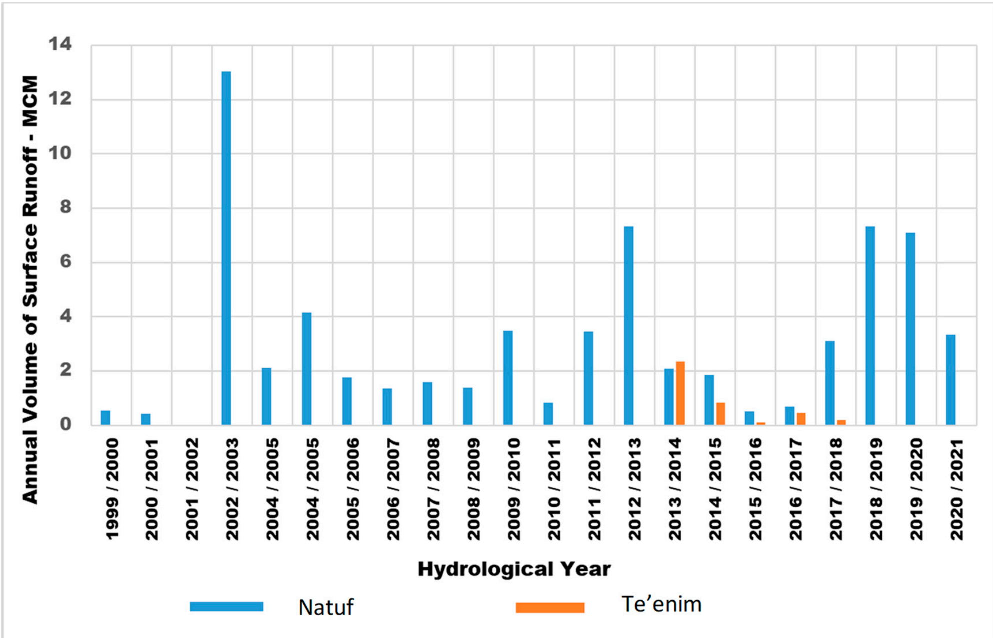

Figure 8. Annual volume of surface runoff.

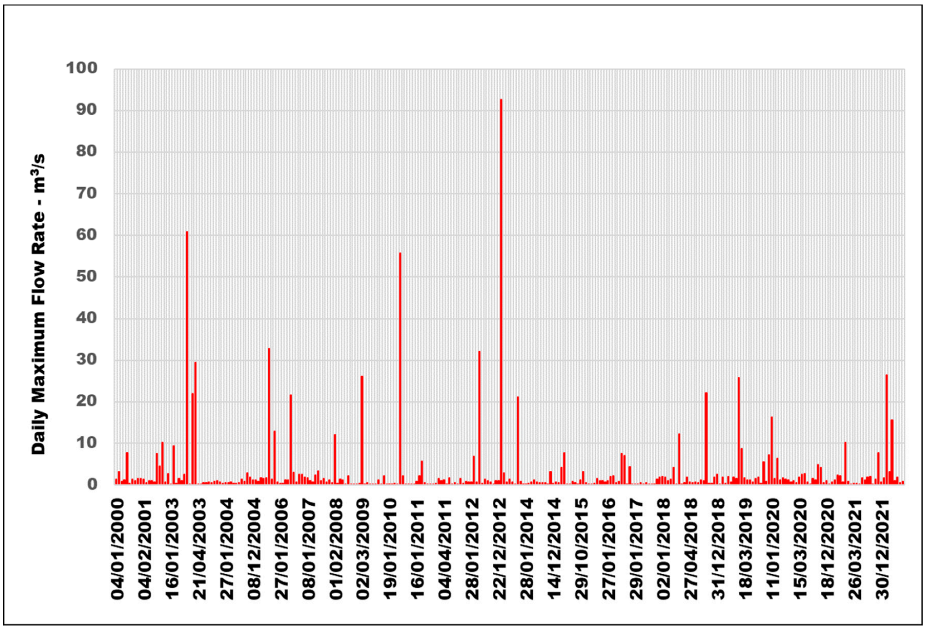

Figure 9. Daily maximum flow rate of surface runoff within the Natuf catchment area (El Al Junction hydrological station).

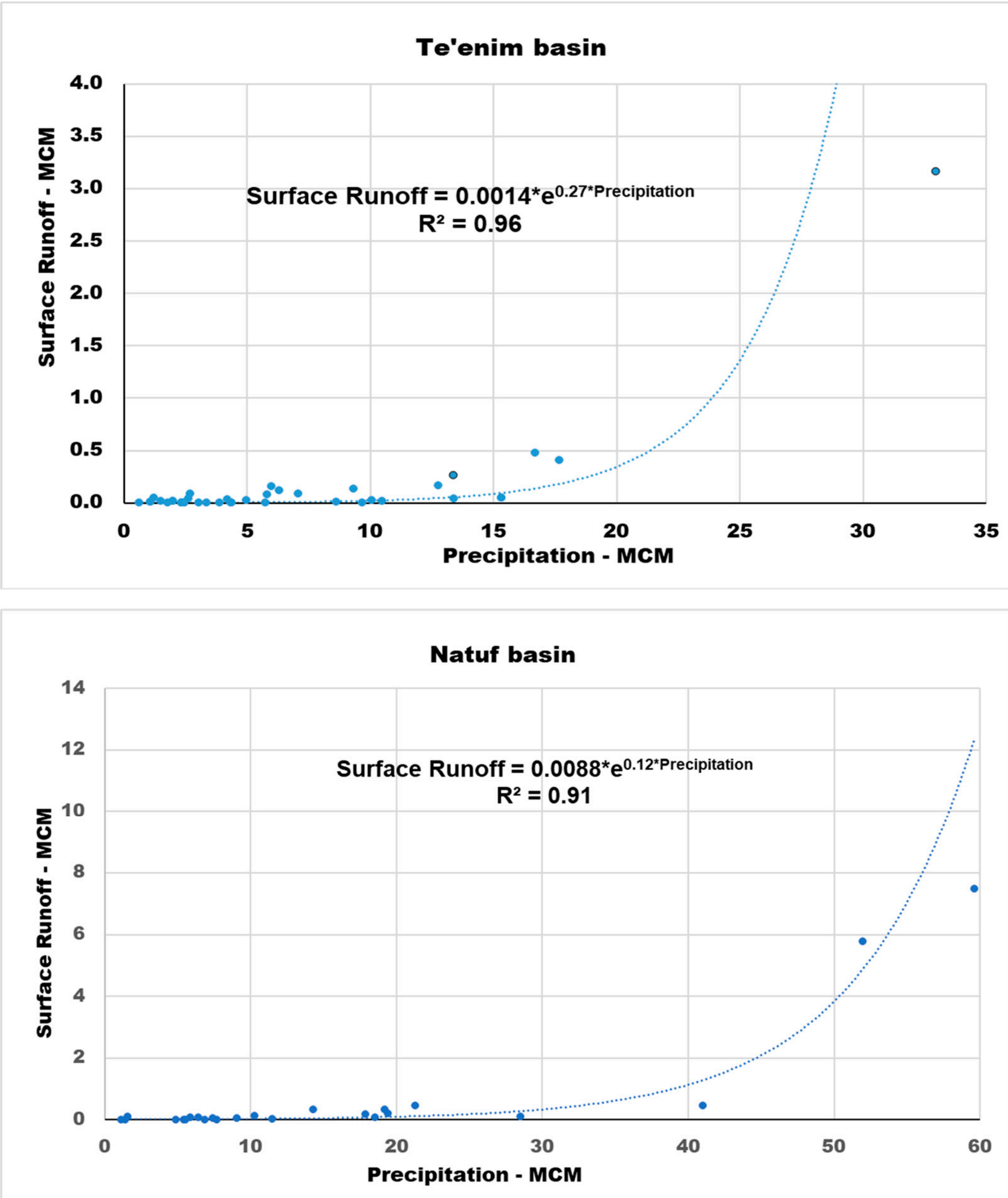

Figure 10. Correlation between precipitation and surface runoff in the Te'enim basin and the Natuf basin.

The catchment basin surface runoff coefficients, expressed as percentages of the annual precipitation volume, are shown in Figure 11. The average multiyear surface runoff coefficient equals 2.03% for the Natuf catchment basin and 1.27% for the Te'enim basin. For the Te'enim catchment basin during the 2013–2018 period, it seldom exceeded 1%, and only during 2013 did it reach 4%. For the Natuf catchment basin, the annual surface runoff coefficient usually varied from 1% to 2%, and only in 2002 did it reach 7% with the highest recorded precipitation amount (827 mm). In recent years, from 2018 to 2021, the annual precipitation was above average, reaching 800 mm (Figure 5), and the annual surface runoff coefficient varied from 2.5% to 3.2% (Figure 11).

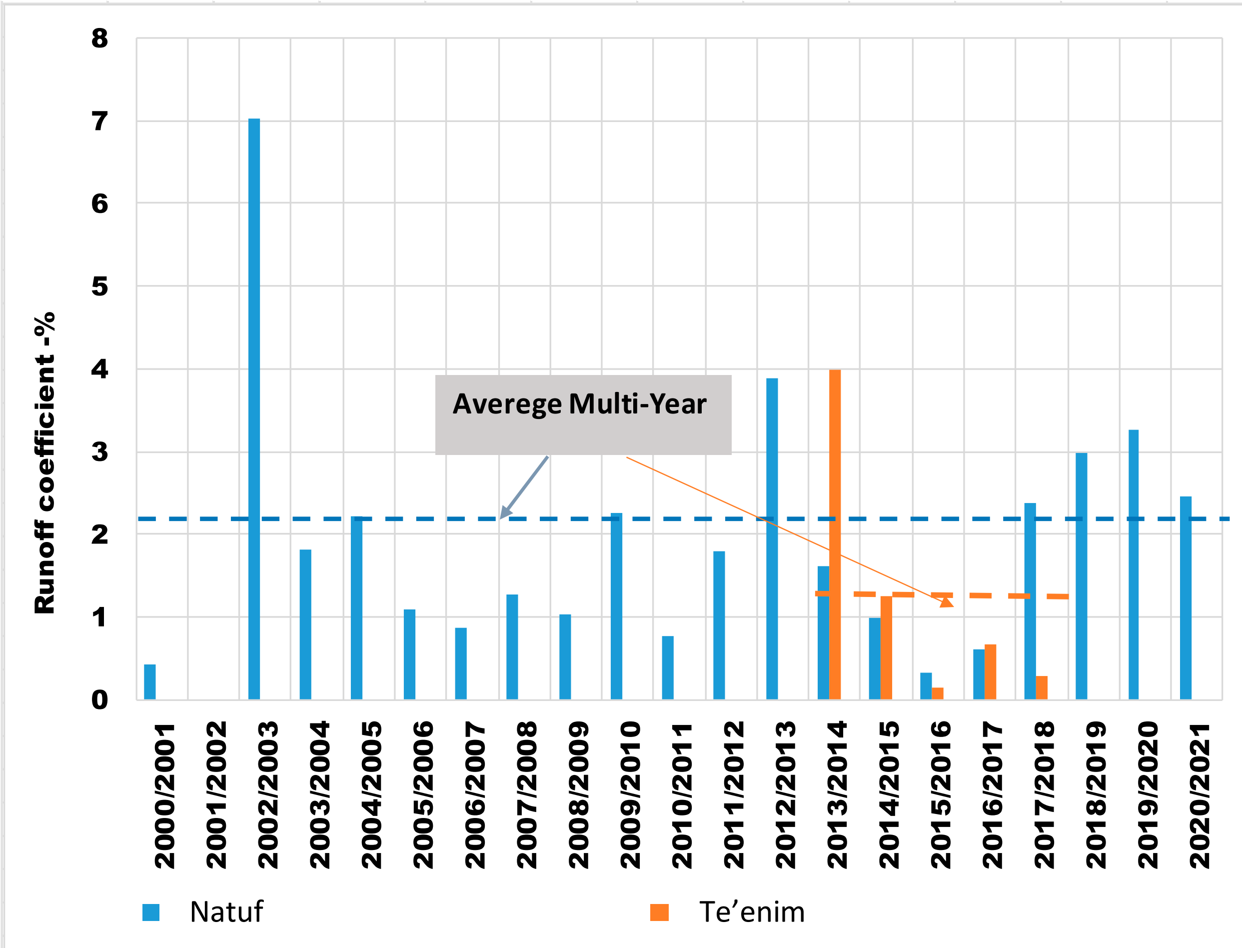

Figure 11. Annual surface runoff coefficients.

4.2. Multiannual Groundwater Recharge Estimation Based on the Water Balance of the Catchment's Basin

Since the time series in the various measurement stations were inconsistent, the groundwater recharge values were calculated according to the multiannual averaged water balance of the Te'enim and Natuf catchment basins (Figure 12), which were 235 mm (29.8×10^6 m^3) for the Te'enim basin and 127 mm (35.4×10^6 m^3) for the Natuf basin.

Within the Te'enim catchment, with a total area of 126.6 km^2, only 72.7 km^2 constitutes the outcrops of the WMA (83.3% of the total outcrop area in the catchment), whereas within the Natuf catchment, the area of the WMA outcrops is 163.6 km^2 of the total 198.2 km^2 (82.5%). Considering these portions, the annual groundwater recharge values in the Te'enim and Natuf catchments within the WMA during the 2000–2022 hydrological years are estimated as 24.8×10^6 m^3 and 29.2×10^6 m^3, respectively. The corresponding groundwater recharge coefficients (a ratio of recharge to rainfall) make up 57% of the Te'enim catchment and 32% of the Natuf catchment.

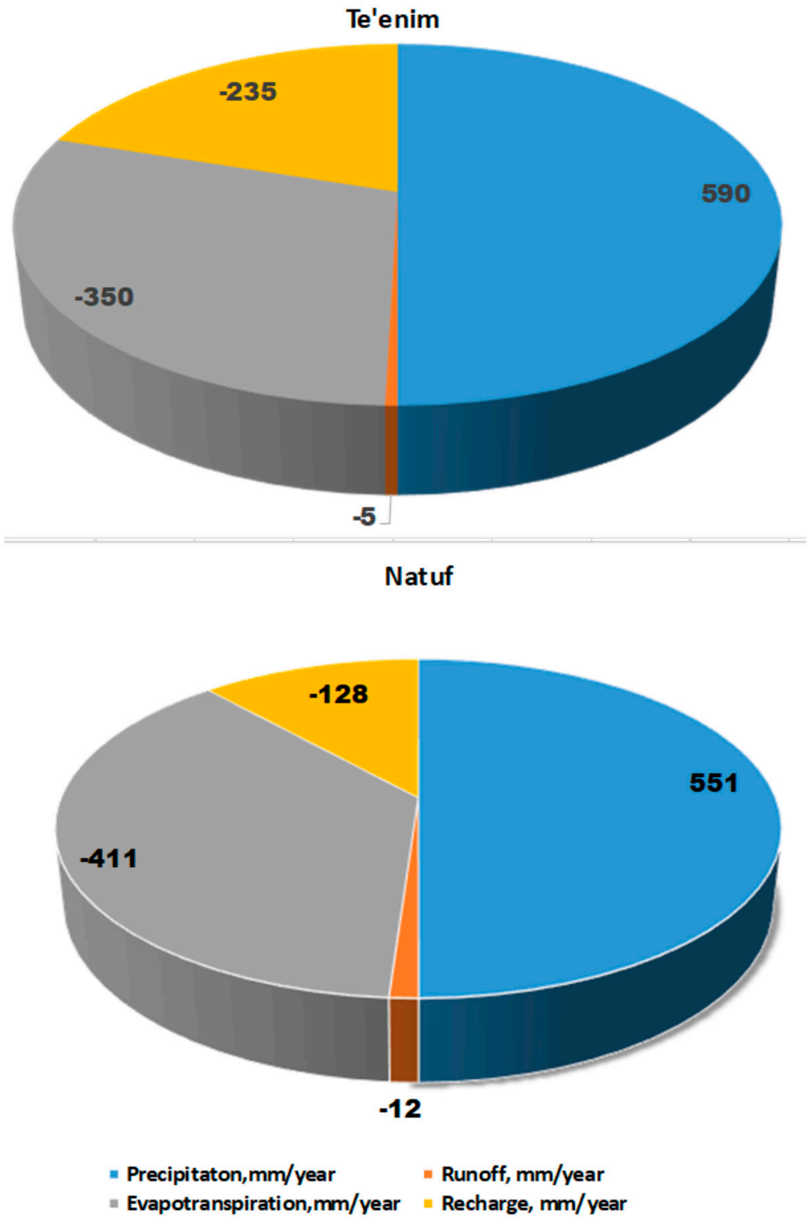

Figure 12. Water balance (in mm/year) of the Te'enim and Natuf catchment basins.

4.3. Multiannual Groundwater Recharge Estimation Based on the Water Table Fluctuation Method

There is a certain correlation between the annual precipitation and annual groundwater head amplitude observed in the monitoring boreholes (Figure 13). In the Te'enim catchment basin, the annual groundwater head amplitude varied from 1.5 m to 4.5 m during the monitoring period of 2012–2020, with the maximal groundwater level head of 4.5 m occurring in the hydrological year of 2018. The average multiannual groundwater head amplitude for the Te'enim basin was 2.5 m (Figure 13A). Since the wells used for the amplitude calculation in the Te'enim catchment are located in its western portion, they may be influenced by the local pumping wells. For the control, the average amplitude was estimated in the Einav observation well that is located to the northeast from the catchment at a distance of nearly 2 km. The average amplitude was found to be almost the same (2.52 m against 2.51 m). In the Natuf catchment basin, there are no valid observation wells in the phreatic portion of the aquifer. The average multiannual groundwater head amplitude for the Natuf basin is 1.8 m (Figure 13B).

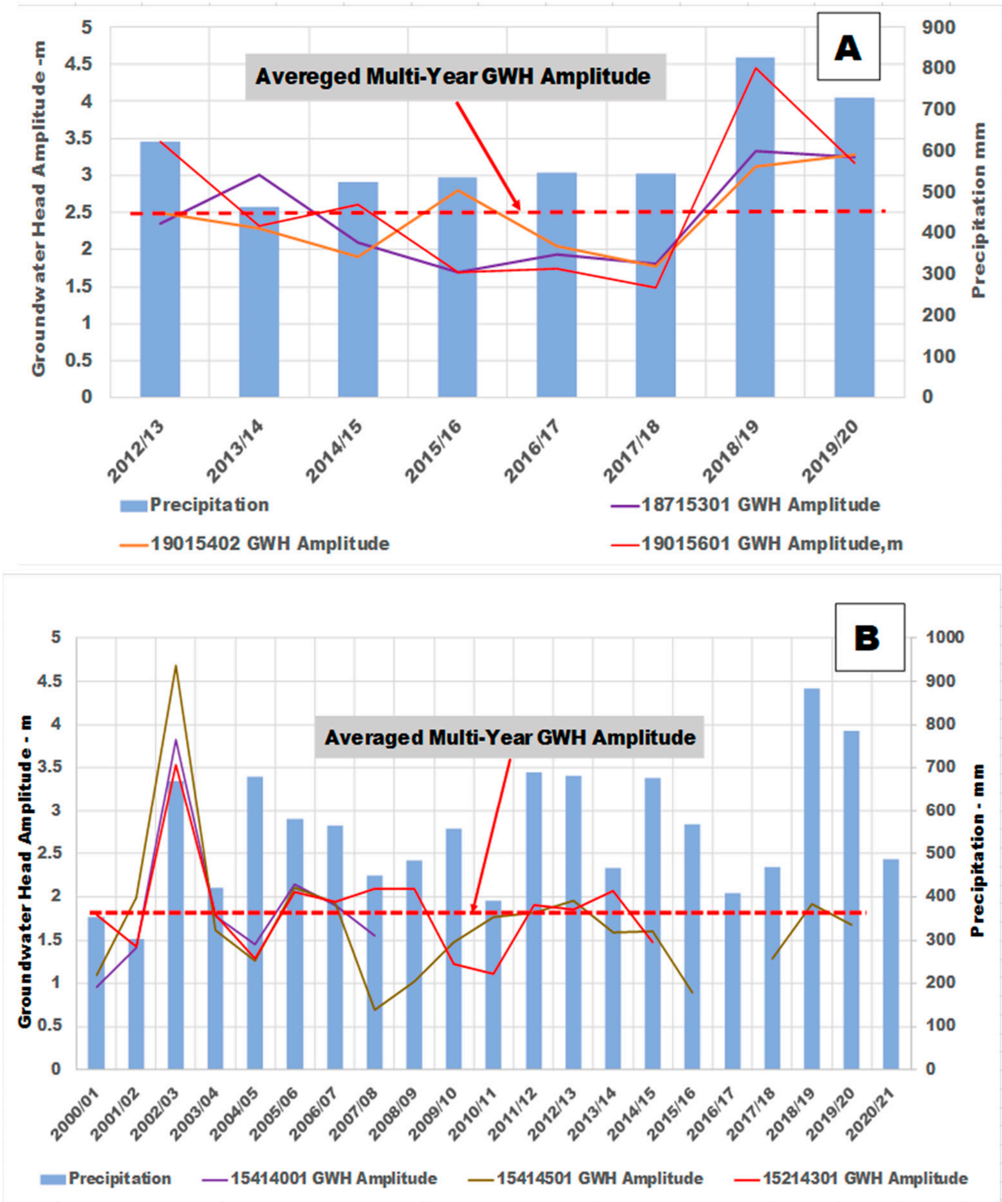

Figure 13. Annual precipitation and groundwater head amplitude. (**A**) Te'enim catchment basin; (**B**) Natuf catchment basin.

An average specific yield of 0.146 was calculated from the pumping test data [3]. The calculated groundwater recharge of the Turonian and Upper Cenomanian sediments in the Te'enim catchment basin within the phreatic portion of the aquifer varies from 240 mm for the minimum value of the averaged GWH amplitude to 537 mm for the maximum GWH amplitude value. The estimated average value of the groundwater recharge equals 365 mm (26.5×10^6 m^3 within the outcrops of the WMA).

A comparison of the groundwater recharge values calculated using the water balance method and using the water table fluctuation method (Table 4) shows that the groundwater recharge value obtained using the water table fluctuation method is overstated and is approximately 1.6 times greater than the values calculated using the water balance method. This difference in the results of the groundwater recharge calculations using the water balance method and the water table fluctuation method is probably due to difficulties in reliably averaging the non-continuously-measured highly fluctuating water levels in karstic and fissured rocks with low storability.

Table 4. Results of the average multiannual groundwater recharge (in 10^6 m^3) estimation using the two methods.

	Water Balance Method	Water Table Fluctuation Method
Te'enim basin	24.8	38.4
Natuf basin	29.2	*

* There are no measured water wells in the phreatic portion of the aquifer.

When the regional hydrogeological models are calibrated, the groundwater recharge is usually set to be constant within definite zones defined by location, outcrop lithology, land cover, climatic characteristics, etc. [32]. The WMA's most updated model contains six such zones (Figure 2). The estimation of the groundwater recharge for numerous relatively small hydrological basins can improve one's understanding of the groundwater recharge distribution within the uniform zones defined in regional hydrogeological models and, in this way, make the modeling results more precise.

Both the Te'enim and Natuf hydrological basins are located within a large zone with a groundwater recharge coefficient of 34% [13]. At the assessed average annual rainfall values of 0.59 m and 0.55 m, the estimates of the groundwater recharge for the Te'enim and Natuf hydrological basins within the WMA outcrops are $0.59 \times 0.34 \times 72.7 \times 10^6 = 14.6 \times 10^6$ m^3 and $0.55 \times 0.34 \times 163.6 \times 10^6 = 30.6 \times 10^6$ m^3, respectively.

The hydrological model of the WMA [33] was calibrated by setting constant groundwater recharge coefficients within zones with similar lithological and climatic conditions (Figure 2). The studied catchments are located within a zone with a groundwater recharge coefficient of 0.34. The groundwater recharge value calculated for the studied catchments by using Dafny's groundwater recharge coefficients is similar to our estimate for the Natuf catchment but is essentially lower for the Te'enim catchment (Table 5). The latter can probably be explained by the prevailing agricultural development of the catchment, which was not considered in the model.

Table 5. Estimates of the WMA groundwater recharge (in m^3) in the studied basins using both the water balance method and water table fluctuation model compared with the average values received from the regional hydrogeological model of the WMA [13].

	Water Balance Method	Water Table Fluctuation Method	Regional Model
Te'enim basin within WMA	24.8×10^6	34.5×10^6	14.6×10^6
Natuf basin within WMA	29.2×10^6	-	30.6×10^6

At the average annual rainfall values of 590 mm and 550 mm at the outcrops of the Te'enim and Natuf catchments, the corresponding local groundwater recharge coefficients, which are the ratios of the groundwater recharge to the precipitation, constitute $24.8 \times 10^6/(0.59 \times 72.7 \times 10^6) = 0.57$ for the Te'enim basin and $29.2 \times 10^6/(0.55 \times 163.6 \times 10^6) = 0.32$ for the Natuf basin. Their use in the refined model may provide a more reliable picture of the groundwater levels and solute distributions.

It should be noted that the groundwater recharge assessed by the water balance also includes surface water percolation along the river channels. It should be much less compared to the direct groundwater recharge at the outcrops; however, it is difficult to estimate it directly.

The comparison of the water balance method calculations for the mutual 5-year period (2013/2014–2017/2018) with the available surface runoff measurements shows (Table 6) that the groundwater recharge coefficient for the Te'enim catchment (0.320) is higher than that of the Natuf catchment (0.306). This result corresponds to the smaller built-up area and larger development of agriculture in the Te'enim catchment that caused the lesser surface runoff here. The estimated groundwater recharge coefficients are smaller than the averaged multiannual groundwater recharge coefficient (0.34) from Dafny's model of the WMA [13].

This may probably be explained by the relatively smaller average rainfall in the catchments for the 2013–2018 period (89–94% of the multiyear average).

Table 6. Characteristics of the different catchment areas in the 2013/2014–2017/2020 hydrological years using the water balance method.

Characteristics of the Sub-Basins	Te'enim	Natuf	Shilo *
Total catchment area, km^2	127	277	400
Total outcrop area in a catchment, km^2	87.7	198	
Outcrop area in the WMA, km^2	72.7	164	
Urbanized area in a catchment, km^2	18	23	
Slopes near the western boundary, degrees	2.4	2.5	
Surface runoff, % of the rainfall	1–2	3–4	
Total groundwater recharge in a catchment, mm	167	107	124
Catchment area within the WMA, km^2	72.7	243	
Groundwater recharge at the WMA outcrops, 10^6 m^3	17.6	24.5	
Average rain at the outcrops, mm	523	518	524
Average rain at the outcrops, 10^6 m^3	38	84.7	
Recharge coefficient	0.46	0.29	~0.24

* The averaged data from our previous study [17].

For comparison, the groundwater recharge coefficient estimated for a large and highly built-up Shilo catchment area is smaller than that for the essentially lesser built-up Te'enim catchment area.

5. Conclusions

The groundwater recharge assessment of karstic aquifer systems is a challenge that is becoming complex and essential as the region becomes urbanized, such as in the WMA recharge area. In the reported study, such an assessment was based on the water balance and groundwater table fluctuation methods for two catchments, the Te'enim catchment basin, as an example for a relatively natural sub-basin, and the more urbanized Natuf catchment basin. The assessment was performed with all available meteorological and hydrological datasets between 2000 and 2020, considering the present land use classification and the current state of the changing climate. The water balance method was found to provide more reliable estimates, with average multiannual groundwater recharge values varying from 17.6×10^6–24.8×10^6 m^3 to 24.5–29.2×10^6 m^3 for the Te'enim and Natuf catchment basins, respectively. For the relatively dry period of the 2013/2014–2017/2018 hydrological years, when detailed measurements of the surface runoff were available, the corresponding groundwater recharge volumes were 17.6×10^6 m^3 and 24.5×10^6 m^3. The corresponding local groundwater recharge coefficients were 0.46–0.57 for the mostly agricultural Te'enim basin and 0.29–0.32 for the urbanized Natuf basin.

The average multiannual surface runoff coefficient equals 2.03% for the Natuf catchment basin and 1.27% for the Te'enim basin. The correlation between the volumes of precipitation and surface runoff, described by exponential dependencies, shows that the surface runoff volume constitutes 3–4% of the precipitation volume for most cases of hydrological events in the Natuf catchment and 1–2% of the precipitation volume in the Te'enim catchment.

The above estimates of the groundwater recharge generally correspond to the previously obtained values for the entire area of the WMA and the available information on the land use in the catchments. Distinct differences between the sub-basins enable us to assess the impact of the anthropogenic development of a basin on groundwater resource replenishment. The Te'enim catchment is mostly an agricultural area with better conditions for rainwater percolation. In contrast, in the Natuf catchment, the building area preventing percolation is larger. Both factors explain the larger recharge coefficient in the Te'enim catchment.

The differentiation of the groundwater recharge assessment to small catchment basins using several combined methods allows for an accurate determination of the groundwater resource recharge distribution over the WMA area and, to some extent, allows us to predict the changes occurring due to the urbanization of specific sub-basins within the WMA.

This case study suggests that the recharge estimation of hydrological sub-basins can improve one's understanding of the karstic aquifer system recharge distribution after validating similar properties of sub-basins in a defined regional hydrogeological model, which makes the modeling results more precise.

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