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Direct groundwater recharge by rainfall in a region with a semiarid Mediterranean type climate

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Abstract Direct groundwater recharge by rainfall affects groundwater development and its potential contamination with agricultural chemicals and/or wastes disposed on or into the ground. Such recharge can be simulated using the conservation of mass concept. Application to a region with a semiarid Mediterranean type climate indicated a seasonal recharge of no more than 12% of total seasonal rain on gently sloping land. Initial soil moisture and rainfall depth were found to be the most important factors affecting direct groundwater recharge from single storm events in the region.

Key words conservation of mass; groundwater recharge; Mediterranean climate; neutron probe method; runoff plots; soil moisture distribution

INTRODUCTION

Direct groundwater recharge by rainfall affects groundwater quality and development in many regions of the world. Factors affecting such recharge include type, amount and distribution of precipitation, initial soil moisture content, soil infiltration characteristics, topography and vegetation cover.

Analysis of groundwater recharge from individual rainstorms is essential to the understanding of the recharge process. However, due to the buffer effect of the large volume in storage in an aquifer at any time, the interest is mostly in annual or seasonal recharge rather than in recharge from individual rainstorms. Like rainfall, the process of groundwater recharge by rainfall is randomly distributed.

In this paper, the process of groundwater recharge by individual rainstorms will be analysed using the conservation of mass concept. The formulas derived will be used to estimate direct groundwater recharge by rainfall in a region with a semiarid Mediterranean type climate.

THEORY

Most groundwater recharge by rainfall occurs on level to gently sloping land. Assuming dominant downward soil moisture flow and neglecting interception and evaporation, two different groundwater recharge systems may be identified:

The simple recharge system

In this system, $i(t) \leq f(t)$ or $i(t) > f(t)$ throughout the storm; $i(t)$ and $f(t)$ are respectively rainfall intensity and soil infiltration rate at time t [mm h^{-1}].

When $i(t) \leq f(t)$, no runoff is expected; hence groundwater recharge at point x is estimated from:

$$R_e = R - 1000\sum_{j=1}^{m} D_j(FC_j - \theta_j) \tag{1}$$

where R_e = groundwater recharge [mm], R = point rainfall at x [mm], D_j = depth of the layer j along the soil profile at x [m], FC_j = soil field capacity of the layer j (water content of the soil after the saturated soil has drained under gravity to equilibrium) (V_w/V_t), V_w = volume of water, V_t = total soil volume, θ_j = initial soil moisture of the layer j (V_w/V_t) and m = number of layers with different field capacity and/or initial soil moisture.

When $i(t) > f(t)$, runoff usually occurs. Groundwater recharge at point x is estimated from:

$$R_e = \int_0^{t_d} f(t) - 1000\sum_{j=1}^{m} D_j(FC_j - \theta_j) \tag{2}$$

where t_d = duration of infiltration [h]. If runoff records are available, equation (2) can be replaced by:

$$R_e = (R - R_u) - 1000\sum_{j=1}^{m} D_j(FC_j - \theta_j) \tag{3}$$

where R_u = runoff depth at x [mm].

The complex recharge system

In this system, $i(t)$ fluctuates during the storm at levels above and below $f(t)$. The equation for groundwater recharge can be put into the following general form:

$$R_e = \int_0^{t_1} i(t)\mathrm{d}t + \int_{t_1}^{t_2} f(t)\mathrm{d}t + \int_{t_2}^{t_f} i(t)\mathrm{d}t - 1000\sum_{j=1}^{m} D_j(FC_j - \theta_j) \tag{4}$$

where t_1 = time [h] before which $i(t) \leq f(t)$, t_2= time [h] after which $f(t)$ again exceeds $i(t)$ and t_f = end time of storm [h].

Runoff is expected in the complex system. If runoff records are available, equation (4) is replaced by equation (3).

In the case of multiple peak storms, each peak segment is treated as an individual storm when applying equation (4). However, application of equation (3) needs no such separation.

APPLICATION

Site and measurements

The preceding theory was applied to groundwater recharge in northwestern Iraq. The region has a semiarid Mediterranean type climate. The experimental site is located at Hammam Al-Alil (36°10′N, 43°20′E). During the period 1988–1992, data were

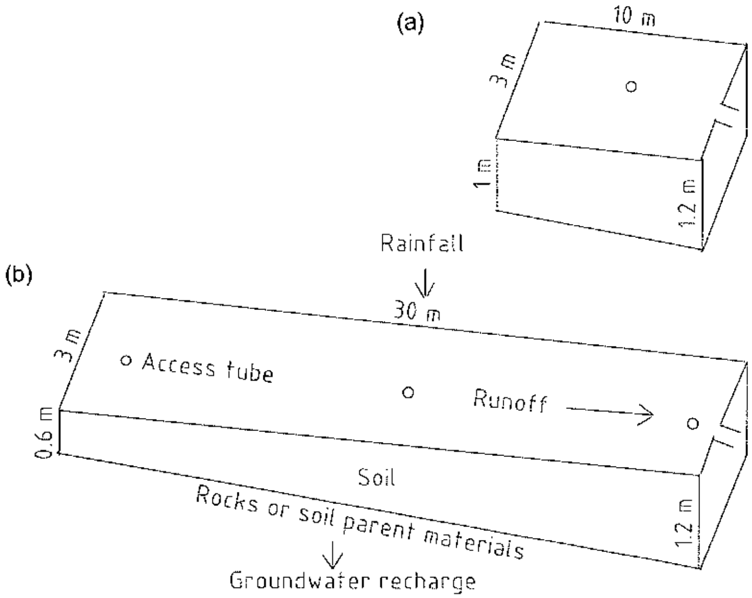

Fig. 1 Schematic representation of the natural runoff plots used in the study; (a) short plot, (b) long plot.

collected from six natural runoff plots established on a uniform area of 6% slope. The plots were three 30 m long followed by three 10 m long. Plot width was 3 m and the distance between adjacent plots was 1 m. Plot design and installation were done according to the procedure outlined by Mutchler (1963).

Access tubes for soil moisture measurement by neutron probe were installed on all plots. Each of the long plots has three access tubes located at the upper, middle and lower parts of the plot. The short plots had only one access tube situated at the middle part of the plot (Fig. 1).

The experimental site was used primarily as grazing land; its soil is classified as a fine, mixed, thermic, calcareous, Xerollic Calciorthid. Soil profile depth decreases in the upslope direction. Soil characteristics are given in Table 1.

Table 1 Soil characteristics at the experimental site.

Depth (m)	Particle size distribution (%): Clay	Silt	Sand	Bulk density (Mg m^{-3})	Saturated conductivity (mm h^{-1})
≤0.30	36	44	20	1.3	37
>0.30	43	34	23	1.4	28

The rainfall season in the region normally extends from October to May. Mean seasonal rainfall at the site is about 340 mm (Table 2). Minimum daily temperature occasionally drops below freezing point during the winter. During the summer, the maximum daily temperature is usually above 40°C. Daily records of rainfall, relative humidity, pan A evaporation, temperature and wind speed have been kept at the experimental site since 1967. Table 2 gives a summary of the recorded data.

Table 2 Recorded meteorological data at the experimental site.

Month	Mean air temperature (°C)	Mean pan A evaporation (mm)	Mean rainfall (mm)	Mean relative humidity (%)	Mean wind speed at 2 m (km h^{-1})
January	6.9	33	58	82	3.4
February	8.5	70	51	81	3.5
March	12.1	100	61	75	4.3
April	16.9	133	41	67	4.1
May	23.3	272	12	46	4.6
June	28.9	418	1	32	4.8
July	33.1	542	0	30	5.3
August	32.7	517	0	32	5.0
September	28.0	340	0	42	4.3
October	21.3	185	9	55	4.2
November	12.9	77	44	70	3.4
December	7.9	34	58	84	3.0

Each autumn, and after rain showers had moistened the soil, the plots were tilled by spading, then smoothed and left in the fallow condition throughout the rainfall season. Gramaxon was used to control weeds. After each runoff-producing rainstorm, the runoff volume in the collecting tank at each plot outlet was measured.

Soil moisture measurements using the neutron probe method were made periodically on the plots at a 0.1 m depth intervals, throughout the experiment. The period between measurements was between one and two weeks.

Method of analysis

Field observations indicate a nearly linear variation of soil profile depth with distance along the natural runoff plots (Fig. 1):

$$D_x = D_0 + bx \tag{5}$$

where D_x = soil profile depth at distance x from the plot upper end [m], D_0 = soil profile depth at the plot upper end [m] and b is a coefficient. Inspection of Fig. 1 shows that $b = 0.02$ for both types of plots.

Equation (5) indicates variable groundwater recharge rate along the plots. The equation for groundwater recharge from plots is:

$$R_w = x_c(R - R_u)/1000 - \int_0^{x_c}\int_0^{D_x}[FC(y) - \theta(y)]\mathrm{d}y\mathrm{d}x \tag{6}$$

where R_w = groundwater recharge per unit width of plot [m^3 m^{-1}], x_c = distance from the upper end of plot where $D = D_c$ [m], D_c = critical soil profile depth (i.e. maximum soil profile depth that groundwater recharge can occur under the specified initial soil moisture condition) [m] and y = depth below the soil surface [m].

Field measurements during this study indicated a mean field capacity in the soil profile of 0.3 V_w/V_t. If soil moisture in the soil profile is approximated in a discrete type form, equation (6) becomes:

$$R_w = x_c(R - R_u)/1000 - \int_0^{x_c}\sum_{j=1}^{m}(0.3 - \theta_j)\Delta y_j \mathrm{d}x \tag{7}$$

where m = number of layers of different initial soil moisture content (θ) in the soil profile at x and Δy_j = depth of layer j [m].

To obtain an estimate of the daily soil moisture distribution during the rainfall season, a continuous simulation model for soil moisture distribution at the experimental site was developed (Hussein *et al.*, 1993). Input to the model includes rainfall and runoff depths in addition to soil and weather data. The model uses basic evaporation and soil moisture flow principles to estimate daily soil moisture levels at a 0.3 m depth interval. The plot's lower end, which has the maximum soil profile depth, was chosen as the characteristic location in the simulation process. This characteristic location was adapted since variability in soil moisture measurements at a certain depth along the long plots was not significant at the 95% probability level (Hussein *et al.*, 1993). Measured values (average of the three replicates) compared well with the simulated values. Hence the model was used to estimate initial soil moisture before a rainfall event.

The point x_c is where:

$$(R - R_u)/1000 = \sum_{j=1}^{m}(0.3 - \theta_j)0.3 + (0.3 - \theta_{m+1})\varphi \quad m = 3,2 \tag{8}$$

where φ = depth increment [m]. If $\varphi \leq 0.1$ m when $m = 3$, no recharge occurs on the short plots. If $\varphi \leq 0$ when $m = 2$, no recharge occurs on the long plots. φ is estimated from equation (8) then used to estimate the critical depth D_c:

$$D_c = 0.3m + \varphi \tag{9}$$

With this value of D_c, x_c can be estimated using equation (5).

A simplified form of equation (7) for short plots is (Fig. 1):

$$R_w = x_c[(R - R_u)/1000 - 0.3\sum_{j=1}^{3}(0.3 - \theta_j) - ½(D_c - 0.8)(0.3 - \theta_4)] \tag{10}$$

For long plots with $x_c \leq 15$ m, the simplified form of equation (7) is:

$$R_w = x_c[(R - R_u)/1000 - 0.3\sum_{j=1}^{2}(0.3 - \theta_j) - ½(D_c - 0.6)(0.3 - \theta_3)] \tag{11}$$

If $x_c > 15$ m on long plots, the simplified form of equation (7) becomes:

$$R_w = x_c[(R - R_u)/1000 - 0.3\sum_{j=1}^{2}(0.3 - \theta_j)] - ½\,(1/2)[0.3x_c(0.3 - \theta_3)]$$
$$+ (D_c - 0.9)(x_c - 15)(0.3 - \theta_4)] \tag{12}$$

Equations (10), (11) and (12) are divided by the plot length and multiplied by 1000 to obtain groundwater recharge per unit area (R_e) expressed in mm.

RESULTS AND DISCUSSION

Groundwater recharge from individual rainstorms during the period 1988–1992 is shown in Table 3. As indicated by Table 4, these storms constitute only a small fraction of the total number of storms considered.

In most cases, groundwater recharge occurred over the entire plot (i.e. x_c = plot length). Table 3 indicates that the initial soil moisture content prior to the rainfall event

Table 3 Groundwater recharge from single storms (S = short plots, L = long plots).

Date (Julian)	Rain (mm)	Runoff* (mm)		Initial moisture at the specified depth (V_w/V_t):				Recharge: (mm)		x_c: (m)	
		S	L	0–0.3	0.3–0.6	0.6–0.9	0.9–1.2	S	L	S	L
89073	46.2	5.28	3.19	0.26	0.26	0.23	0.23	0	4.31	–	13.6
89087	46.9	5.28	3.19	0.27	0.28	0.28	0.28	16.62	19.71	10	30.0
90093	10.0	1.05	0.30	0.29	0.30	0.30	0.30	5.95	6.70	10	30.0
90096	6.0	3.67	2.98	0.30	0.30	0.30	0.30	2.33	3.02	10	30.0
92040	32.5	0	0	0.30	0.26	0.22	0.22	0	4.38	–	12.8
92054	10.0	1.80	0.70	0.30	0.30	0.30	0.30	8.20	9.30	10	30.0
92056	10.0	1.80	0.70	0.30	0.29	0.29	0.29	0.36	4.10	6	30.0
92065	11.0	0	0	0.30	0.29	0.29	0.29	3.00	5.75	10	30.0
92066	11.0	2.73	0.28	0.30	0.30	0.30	0.30	8.27	10.72	10	30.0
92083	16.0	0	0	0.28	0.28	0.28	0.28	0	0.67	–	10.0

* Average of the three replicates.

should be near the field capacity for significant groundwater recharge occurrence. The next important factor is the depth of infiltrating water, which depends on rainfall depth and intensity, soil type and soil surface conditions.

All groundwater recharge resulted from rainstorms which occurred during the period from early February to early April (Table 3). This is because soil moisture is at its highest level during this period of the year (Hussein *et al.*, 1993). Since the basic soil infiltration rate is significantly reduced at this time of the year due to surface crust development (Awad *et al.*, 1992), most storms produced runoff.

Table 4 summarizes groundwater recharge on a seasonal basis. Such seasonal data are needed mainly for groundwater management purposes. Table 4 shows that generally, less than 12% of total seasonal rain is recharged to the groundwater at the site. Total seasonal recharge on a particular soil depends on total seasonal rain, its distribution during the season, the characteristics of individual rainstorms in addition to runoff and evaporation losses during the season. No measurements were made during the 1990–1991 rainfall season. The 1988–1989 rainfall season has the lowest total rainfall but it exceeded in its groundwater recharge the 1989–1990 season due to the greater runoff losses in the latter season. The recharge ratio (ratio of groundwater recharge to rainfall) for the long plots was higher compared to the short plots due to the lower runoff ratio (ratio of runoff to rainfall) and the relatively shallow up slope soil profile depth on the long plots.

Table 4 Seasonal groundwater recharge at the experimental site.

Season	No. of storms	Total rain (mm)	Total runoff (mm):		No. of recharge storms	Seasonal recharge (mm):		(% total rain):	
			S	L		S	L	S	L
1988–1989	12	256	21	10	2	16.6	24	6.5	9.4
1989–1990	21	301	102	82	2	8.3	9.7	2.8	3.2
1991–1992	34	310	56	35	6	19.8	34.9	6.4	11.3

Seasonal recharge varies from less than 9 mm per season from the short plots during the 1989–1990 rainfall season to more than 34 mm per season from the long plots during the 1991–1992 season. This low seasonal groundwater recharge is probably the main reason for the relatively deep and saline groundwater in the region (Abdul-Jabbar *et al.*, 1987).

CONCLUSIONS

Groundwater recharge from individual rainstorms can be simulated using the conservation of mass concept.

Application to a region with a semiarid Mediterranean type climate indicated that only a small fraction of total seasonal rain percolates beyond the soil profile. Such limited groundwater recharge affects any large-scale groundwater development in the region.

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