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ORIGINAL ARTICLE

Artificial rainfall tests, soil moisture profiles and geoelectrical investigations for the estimation of recharge rates in a semi-arid area (Jordanian Yarmouk River Basin)

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Abstract To overcome the limitations posed by the limited relevant data for recharge estimation in the Jordanian Yarmouk River basin, a mass balance methodology is developed which is simple and may be easily applied to other arid and semi-arid landscapes. This is done by integrating available climatic data with new rain–runoff relationship data, as measured using a specially designed and built artificial rainfall simulator, and changing soil moisture profiles through the hydrological year, as measured in the field. The amount of moisture in the soil after rainfall events changes as a result of both evaporation and of drainage into deeper levels (recharge). The soil moisture profiles at depth are evaluated using geophysical techniques that allow for the tracking of recharge fronts. After rainfall events, the distribution of its fate between runoff, evaporation and recharge is determined. Water in the soil beyond the field capacity can be demonstrated to mostly contribute to the ultimate groundwater recharge in the area. Water stored beyond the permanent wilting point is not considered to contribute significantly to the recharge regime. Because of the irregular nature of rainfall, the amount of recharge is found to be related to the spacing of wet and dry spells during the winter months more than the actual amount of rainfall. Prolonged dry periods allow for excess water to drain into the deeper soil and thus to the groundwater, and thus allow for more uptake following subsequent rainy events. Evaporation does not significantly contribute to the drying of the soils. Reanalysis of rainfall and evaporation data from previous years suggests that recharge rates range from 20 to 37 % of total rainfall amounts, as opposed to the currently assumed 5 %.

Keywords Geoelectrical investigations · Jordan · Recharge · Soil moisture · Sprinkler tests · Yarmouk Basin

Introduction

Recharge in semi-arid areas are prone to irregular rainfall, ephemeral runoff and incomplete hydrological records, and thus has proven to be difficult to evaluate despite its manifest importance. In the Yarmouk River Basin in northern Jordan, key elements of the hydrological cycle are still poorly quantified. Specifically, the amount of recharge into the main aquifers in the area is unknown.

Optimal management of water resources in semi-arid areas requires a detailed understanding of the hydrological cycle that governs the various surface and ground water basins. This includes understanding of rainfall, runoff, evapotranspiration and infiltration. In areas where groundwater is the major source of potable water, recharge estimation is thus crucial. This will require better understanding of rain–runoff relationships and soil moisture dynamics.

Current tools for the study of recharge in arid areas rely on both hydrological and hydrochemical data. Water level data can be used as an effective tool in this regard (Scanlon et al. 2002). However, this approach is of limited use in cases where the water table is deep (>100 m) and the delay

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between recharge and water table response is long and difficult to resolve. Moreover, in heterogeneously distributed porosity aquifers (such as karstic aquifers), the volumetric meaning of water table rises are ambiguous unless porosity and specific yield can be accurately determined. Specific yields are typically calculated from water level and discharge values (Shevenell 1996). However, in cases where such data are absent or poor then there are too many variables to determine this. Attempts have also been made to determine recharge in semi-arid landscapes using simple mass balance techniques of rainfall and evaporation (Lewis and Walker 2002). However, since this approach is limited by the inability thus far to factor in runoff, it has not been widely adopted. More sophisticated approaches relying on mass balance assumptions, such as presented by Jyrkama et al. (2002), require more data than are typically available in arid areas. Moreover, situations where multiple aquifers are involved complicate the models, as movement of water between the aquifers is difficult to quantify.

The United States Department of Agriculture Soil Conservation Service (1957) method for determining runoff, known as the Curve Number method, is often used in recharge estimation (Scozzafava and Tallini 2001). In Jordan, this technique has been widely used in the past (Water Authority of Jordan 1989), presumably because of its simplicity and low data requirements. It is important to recognize that the curve number was not developed for the express purpose of determining recharge, and that much data need to be collected to prove its validity, especially in arid areas.

Combinations of isotopes, geochemical and temperature have been used to trace recharge areas, although these are limited in their ability to resolve recharge volumes (e.g., Salameh 2004; Abu-Jaber and Kharabsheh 2008). The use of stable isotopes is based on the variations seen in the isotopic composition of rainfall, which tend to change along elevation gradients. Thus, the approach can help identify distinct elevations at which recharge occurs (with a large range of error). Solutes are useful because water–rock interactions along flow paths impart specific chemical signatures, which can be used to determine sources and directions of water flow. Missing again is the quantification of recharge. Attempts have been made to quantify evaporation using the effect of Rayleigh distillation on isotopic fractionation (Abu-Jaber 2001). Larger scale attempts to use this approach have yet to be presented.

The chloride mass balance (CMB) approach was popular for a while, wherein the quantification of recharge (as opposed to evaporation) is evaluated by assuming that the increase of chloride in vadose water is caused by evapo-concentration (Wood and Sanford 1995; Gaye and Edmonds 1996; Dassi 2010). The presence of chloride-bearing salts in the soil/aquifer material complicates the calculations relying on CMB (Abu-Jaber 2001).

Thus, it becomes desirable to devise new approaches to determine where and how much recharge occurs in arid and semi-arid regions. The most direct way would be to use mass balance measurements of the water itself, as attempted by Lewis and Walker (2002), with appropriate modifications for runoff estimations. This runs into the problem of poor data availability, which led to the chemical and isotopic proxy approaches, as well as the Curve Number technique, that have become so popular. Such an approach was adopted by Schulz et al. (2013) in the Amman Zarqa basin, using the so-called J2000 model. This physical-based approach seems to be the most reliable way to determine recharge in semi-arid areas. This approach, however, relies on inferred rather than measured rain–runoff–infiltration relationships. That, and the large scale of the area in question, leads to questions regarding the validity of estimates used at smaller scales. It is, however, noteworthy that the result of this model is to upwardly revise the recharge amount estimates in the basin significantly (Schulz et al. 2013).

In Jordan, there are reasonable measurements for rainfall and (potential) evaporation, on the other hand, data pertaining to runoff, true evapotranspiration and infiltration and groundwater recharge measurements at the detail level required for basin scale management have not been conducted, although the J2000 technique is a promising starting point.

In the northwestern highlands of the country, where the highest intensity of rainfall and the greatest population density resides, demands for water have been steadily increasing for domestic, commercial and agricultural uses. Evidence for over abstraction is seen in many wells in the form of declining water levels as well as salination of groundwater. Thus, it is crucial that direct measurements of the various elements of the hydrological cycle be conducted and integrated into the management plan for the aquifers that are tapped in the area.

The purpose of this study is to improve our understanding of the hydrological cycle in the Jordanian part of the Yarmouk River basin, which is a cross-border groundwater aquifer with Syria, with emphasis on better understanding rain–runoff behavior, infiltration and recharge.

The Jordanian Yarmouk River Basin

The north western highlands of Jordan form the southern part of the Yarmouk River Basin (YRB), which consists of varying physiographical and climatological units. In this study, the northern part of the basin, which is in southern Syria, is not considered. The studied area of the YRB is about 1,426 km^2 (EXACT-ME 1998, Fig. 1), with elevations ranging from 1,200 in the highlands of Ajloun in the south down to 212 m below sea level at Adasia at the

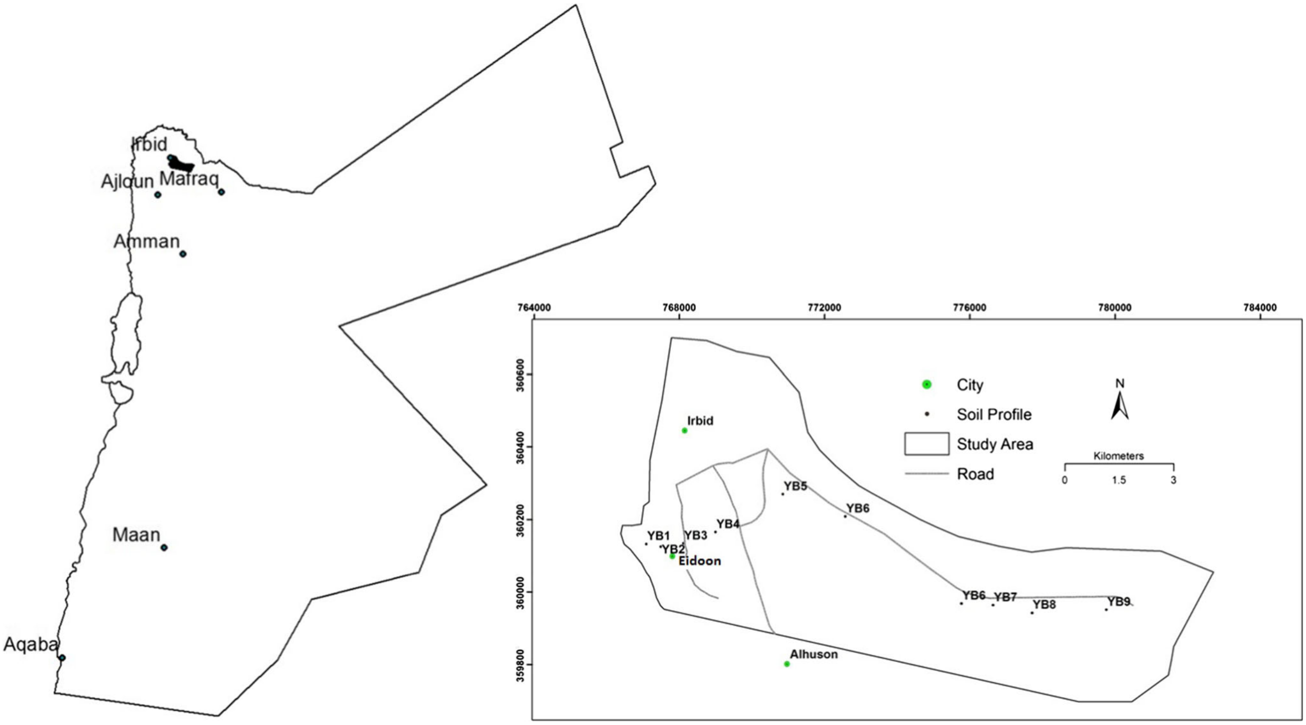

Fig. 1 Location map of the study area, with the inlay showing sampling points

mouth of the Yarmouk River in the north. Thus, the relief of the basin in the Jordanian territories reaches about 1,412 m. The area consists of Mediterranean climates in the southwest, receiving more than 500 mm/a in the Ajloun highlands with oak tree forests and around 470 mm/a in Irbid farther to the north. To the east, the YRB climate is semi-arid to arid, and rainfall diminishes to about 215 mm/a in Ramtha and lower farther east in Mafraq (150 mm; JMD 2013). The rainfall is seasonal, falling mostly in the winter months from October to April of each year, with considerable annual variability.

The Ajloun Highlands extend along the western and southern divide of the basin, where it is highest in the south and lowers towards the north down to elevations of around 800 m asl in Irbid. Towards the east and northeast, flat plains of thick red soil form the area known as the Houran Plains, which turn to more yellow soil in the eastern reaches of the basin. While the river basin is extensive, the drainage system is dry most of the year, with the only permanent running water seen in the north at Wadi Shallaleh near Ramtha, where groundwater discharges forming the beginning of the permanent river.

The Yarmouk River itself receives most of its flow from the Syrian side of the basin. In 1955, when the Johnson Plan was formulated, the plan assumed that flow of the river was 492 million cubic meters (MCM) per year based on the available data at the time. EXACT-ME (1998) showed that the river flow had since diminished to about 200 MCM/a. More recently, the Wihdeh Dam was built on the river with a capacity of 110 MCM. The Jordanian government was obliged to accept the project from the contractor in 2010 without testing because pronounced drought conditions precluded filling the dam during the four years following the dam completion. Additionally, Syrian projects for headwater diversion left the river almost completely dry. There are no dams on the Jordanian side of the catchment, because that side does not contribute much to the base or flood flow of the river.

The geology of the YRB is dominated by the Upper Cretaceous Ajloun and Balqa Groups. These consist of marine limestone, silicified limestone, marl and phosphorite formations. The most important aquifer in the YRB is the B2/A7 complex, which consists of the latest formation of the Ajloun group known as the Wadi Sir Formation (A7) and the earliest formation of the Balqa group known as the Amman Formation (B2). The Wadi Sir formation (Turonian) is a massive limestone formation that is highly karstified in the area. The Amman formation (Santonian-Campanian) is a silicified limestone which also acts as an aquifer, but has limited exposure in the northern extent of the Ajloun Highlands. The Amman formation is overlain by the Maastrichtian Muwaqqar Chalk Marl Formation which is sometimes called the B3 complex. This formation acts as an aquiclude because of the low permeability imparted by the marly clay layers that predominate.

A limited exposure of the Eocene Um Rijam Formation (B4/B5) is present in the extreme north of the YRB. It consists of alternating chert and limestone beds and acts as an aquifer, although its limited extent precludes it being considered a regional water resource. The aquifer, across the Houran Plains, lies under a thick cover of red soil.

The Ajloun Highlands are a domal structure, with the Wadi Sir Formation cropping out at the core. The beds of the formation in the YRB dip regionally towards the north and east, with the younger Amman and Muwaqqar Chalk Marl being exposed in the peripheral areas of the dome, especially towards the north. The Houran Plains are largely covered with soil which is underlain by the Muwaqqar Chalk Marl, creating a confined aquifer situation for the B2/A7 aquifer in that area.

The YRB is a traditionally agricultural region, be it in the Ajloun Highlands where olive groves, vineyards and orchards were cultivated or in the Houran Plains where field crops such as wheat and barley were planted. Today, the city of Irbid is expanding towards the south and east, mostly into the Houran Plains, while the Ajloun Highlands still retain their agricultural nature with but with still limited sprawl and urban expansion. The area of the Greater Irbid Municipality is about 324 km^2, most of which lies within the premises of YRB. Of these, about 118 km^2 are zoned for residential and commercial use, with the remainder still zoned as agricultural land (Abu-Jaber 2010). The current population of the city is about 650,000 people (Department of Statistics 2011).

Attempts at quantifying recharge, especially into the main B2/A7 aquifer, have yielded mixed results. Assuming an average of 300 mm rainfall over the entire YRB, this would yield around 427 MCM/a of rainfall over the basin, mostly concentrated on the higher areas to the west and south. While existing potentiometric maps show a general flow from the Ajloun Highlands towards the east and then towards the north, that ultimately discharging into the Yarmouk River and the northern Jordan Valley (Water Authority of Jordan 1989), various investigations have shown that recharge is not solely restricted to the Ajloun Highlands but it can occur throughout the YRB (Salameh 2004). Isotopic investigations show that recharge occurs in the Nueimeh (Bajjali 2006) and Ramtha (Bajjali 2008) areas, as well as in the more arid areas to the east (Abu-Jaber and Kharabsheh 2008).

While isotopic and hydrochemical data all tend to confirm basin-wide recharge, the quantification of this recharge has proven to be problematic. (Water Authority of Jordan 1989) estimated recharge to be about 21.9 MCM/a (based on a 5 % recharge rate), whereas Bajjali (2006) proposed a wide estimate ranging between 6 and 29 MCM/a. On the other hand, El-Naser (1991) suggested a value of 45 MCM based on an anomalously wet water year of 1991–1992.

There is no physical basis to assume any specific recharge percentage as is the practice used by WAJ, that assume a 5 % recharge rate. Bearing in mind that these contradictions have led to a huge discrepancy between the amount of rainfall and the amount that ultimately reaches the Yarmouk River as flood flow.

Research hypothesis

The question of recharge is a crucial element in the understanding and proper management of the groundwater of the YRB. It is herein hypothesized that a mass balance approach using direct field measurements of rain–runoff relationships under different soil moisture conditions and the tracing of soil moisture changes through the hydrological year can provide a realistic estimate of recharge in the study area.

Methodology

The methodology depends on calculating potential recharge associated with single storm events. This requires collecting data on the sum of rain for each storm event, actual evaporation between storm events, determining hydrologic soil properties such as soil moisture content, porosity, grain size, density and calcium carbonate contents. However, infiltration rates and runoff coefficient were calculated based on the subsequent measurements.

Rainfall and actual evaporation

Daily rainfall data were collected from the Jordanian Meteorological Department for two stations within the study area (Fig. 1) for the period from 2009 to 2012. Sum of each storm event was calculated for every rainfall season. Storm events with rainfall sums of less than 10 mm were ignored.

Average monthly actual evaporation were also obtained from the JMD for the same locations of the rainfall stations, which are based on evaporation pan measurements.

Soil measurements

Eight sites were chosen for detailed investigation representing the major topographical and soil variations found in the area south and southeast of Irbid (Fig. 1). These roughly form a transect from the western drainage divide southwest of Irbid towards the east and south. At each of these locations, soil pits were dug from the early fall through the spring of 2009–2012 to depths of 70 cm (Fig. 2). Samples were taken from each pit and soil moisture was measured at depth intervals of 10 cm. Soil

Fig. 2 Soil profile in the eastern part of the study area

moisture was computed by overdrying 100 g of soil at 105 °C overnight. Initial soil moisture contents before the first rainfall event were monitored during the years 2009–2012. Soil grain size analysis was carried out for sand fraction using wet sieving approach. Silt and clay were separated using the pipette method described by Folk (1972). The calcium carbonate content in the soil profiles was also measured using calcimetry.

Field studies

To better understand rain/runoff/infiltration characteristics under varying soil moisture conditions, a sprinkler to produce artificial rainfall was constructed, with adjustable flow rate ranging from 0.1 to 10 l/min using a rotating sprinkler system with a radius of 0.92 m, covering an area of 2.65 m^2. The sprinkler is adjustable to different heights ranges; 1, 2, and 3 m height with surface plots area of 2, 4, and 9 m^2 (Fig. 3).

Artificial rainfall tests were carried out on dry soil conditions and on wet soil conditions after rainfall events. Seven sites were chosen for detailed investigation representing the major topographical and soil variations found in the area south of Irbid (Fig. 1). These roughly form a transect from the western drainage divide southwest of Irbid towards the east and south.

The sprinkler was used at seven of the sites at flow rates of 2 l/min over a plot area of 2.65 m^2, which is equivalent to about 50 mm/h of rainfall intensity. The sprinkler rotates at 25 rotations per minute (rpm). Rainfall conditions were kept fixed for both dry and wet soil conditions. This was used to determine the conditions under which runoff was generated at the different locations, and the volume of runoff attained after equilibrium runoff is reached. Thus, it was possible to understand how rainwater was distributed between infiltration and runoff under different conditions. A description of the soil conditions where the artificial rainfall tests are presented is listed in Table 1.

The soil moisture tests allow for the determination of the amount of moisture stored in the soil and its movement (i.e., downward towards the water table or upwards in the form of evapotranspiration). Prior to running the tests, soil moisture profiles were measured. The calcium carbonate content in the soil profiles was also measured.

Calibration tests

First artificial rainfall tests were carried out in the period from mid September to early October, 2009. Tests were performed before the start of the rainy season on dry soil. Artificial rainfall tests were carried out across different landscape elements representing different slopes in the selected study sites. The settings of artificial rainfall tests were the same in all location. Parallel to the artificial rainfall tests; Electrical Resistivity Tomography (ERT) were carried out for the characterization of soil.

Table 1 Description of the soil conditions where the runoff simulation tests were conducted

Site	Slope	Color	Texture	Notes
YB1	<0.01	7.5 year 4/4	Silty loam with gravel	Few gravels on top
YB2	<0.01	7.5 year 4/4	Silty loam with gravel	Few gravels on top
YB3	<0.01	7.5 year 4/4	Silty loam with gravel	Few gravels on top
YB4	Semi flat	7.5 year 4/4	Silt loam	Few gravels and straw on top. Extensive shrinking features
YB5	Semi flat	2.5 year 6/5	Silty	
YB6	Flat	2.5 year 6/5	Silty	Hay straw on top. Extensive shrinking cracks extending decimeters in depth
YB7	Semi flat	2.5 year 7/5	Silt	Few gravels and straw on top. Extensive shrinking features

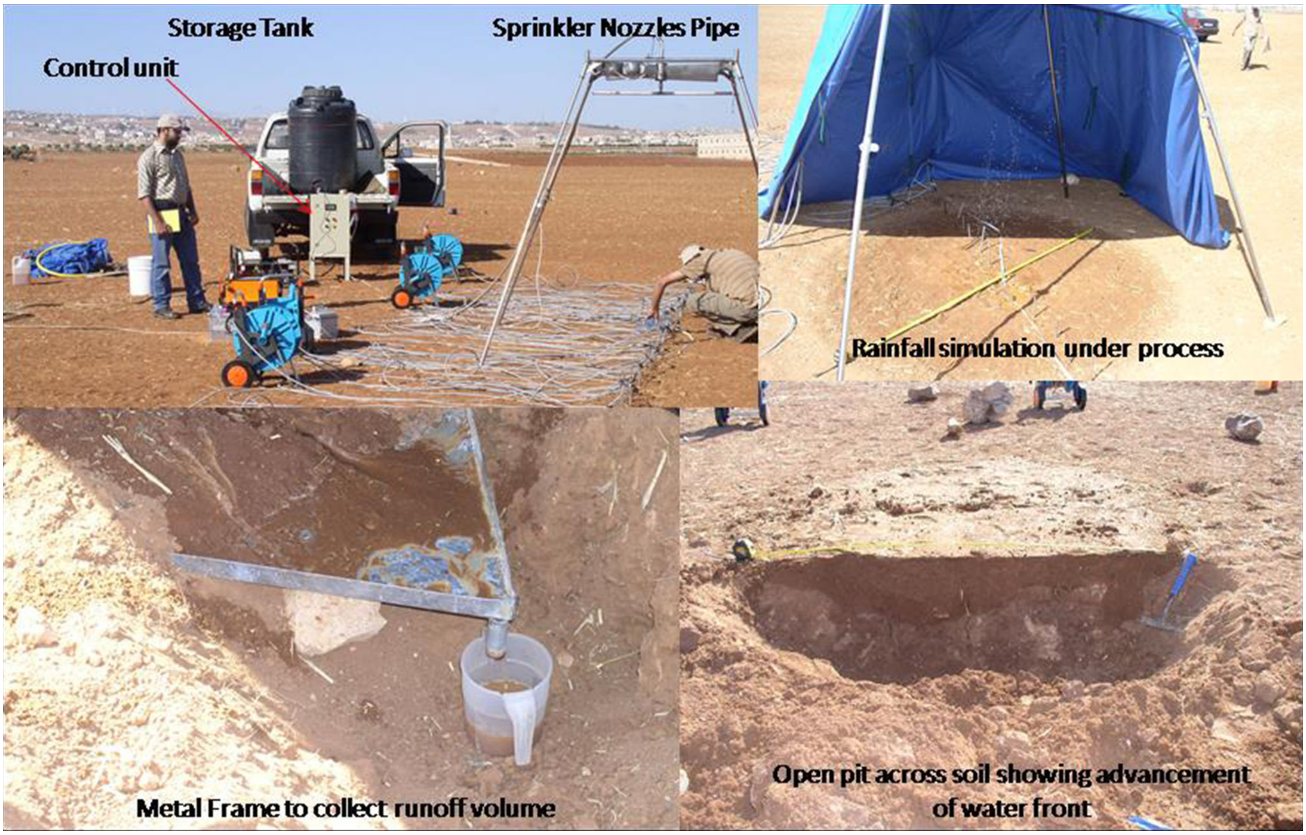

Fig. 3 Sprinkler experiment components through a simulation test

ERT surveys were conducted aiming to investigate the total thickness of the soil column, its subsurface saturation conditions, to investigate the reliability of an artificial rainfall test to cause a meaningful groundwater infiltration/recharge, and to track infiltrated rainfall water into the subsurface. Therefore, artificial rainfall tests were correlated against ERT carried out before and after artificial rainfall tests hoping to correlate measured humidity variations as seen in the soil pits with the resistivity profiles measured before and after the rainfall simulation runs.

The ERT technique is a non-invasive imaging method capable of evaluating the horizontal and vertical distributions of subsurface resistivity of a 2D and 3D subsurface media. It involves the injection of an electrical current into the ground through a given two side electrodes and monitoring voltage changes across two inner electrodes. Lateral migration of injected current across a given profile gives the ability to investigate the horizontal variation in electrical resistivity. Concurrently, the continued expansion of electrode spacing allows for deeper depths of investigations to be achieved. Commonly, electrical resistivity measurements include different electrode configurations including Wenner, Gradient, Schlumberger, Dipole–Dipole, Pole–Dipole, Pole–Pole (Reynolds 2011).

Table 2 Electrical Resistivity Tomography acquisition parameters

Task	Electrode configuration	No. of electrodes	Electrode spacing (m)	Profile length (m)
1. Characterizing soil section	Wenner, and dipole–dipole	48	0.2	9.4
2. Characterizing infiltration waterfront	Wenner, and dipole–dipole	48	1	47

The geoelectrical investigations using ERT were carried out using the ARES multi-electrode DC resistivity acquisition system (Gf-Instruments Ltd.). The system is equipped with 48 stainless steel electrodes and allows for a multi-electrode spacing of up to 5 m.

Table 2 provides the details of the acquisition parameters used for the various ERT surveys. ERT acquisitions were carried out using the Wenner and the Dipole–Dipole electrode configurations. The Wenner array has the strongest signal strength, but it has poor horizontal coverage as the electrode spacing is increased. The Dipole–Dipole array is very sensitive to horizontal changes than to vertical changes in subsurface resistivity, whereas it has slightly higher noise

Fig. 4 Setup of high resolution resistivity imaging survey intended to calibrate rain simulation

Fig. 5 Sprinkler test (rainfall simulation) taking place at the eastern side of the study area

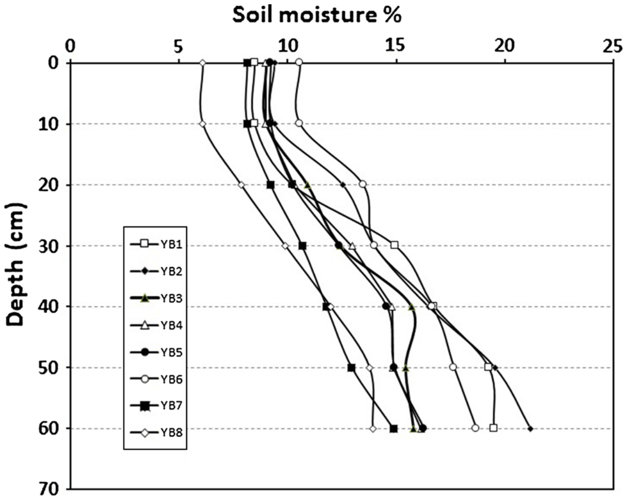

Fig. 6 Soil moisture variations with depth for eight soil profiles in the study area

levels than the Wenner array (Dahlin and Zhou 2004). Inversion of acquired data was carried out using the RES2DINV software (Loke and Barker 1996). The application of electrical resistivity for characterization of soil was reviewed by Samouëlian et al. (2005). Inversion of data was carried out using RES2DINV software (ver. 3.58). Further details about the method and about inversion process can be found in Loke (2004) and Loke and Barker (1996).

Figure 4 shows the field setup of the high resolution resistivity tomography survey with an electrode spacing of 20 cm. The experiment was conducted wherein the resistivity profile was measured above a plot prior and after a rainfall simulation. The ability to track moisture front using well-calibrated geophysical data will allow for significantly better recharge estimates for the Upper Yarmouk drainage basin and other similar areas in the mountainous areas of western Jordan. Upon the termination of the simulation run ERT surveys were carried, however, to minimize the effect of evaporation the surface plot area was covered with a protective shelter (Fig. 5).

Soil moisture variation with depth was determined at eight locations before the rainy season started (Fig. 6). Soil moisture development throughout the year was monitored and correlated with rainfall data in the basin.

The model

The model is based on single rainfall event amounts, soil water storage, runoff coefficient and actual evaporation between two consecutive rainfall events, simple spreadsheet soil–water balance was used to compute episodic recharge or potential gravity drainage during and following rainfall events. The model simply states: during any rainfall event, what infiltrates into the soil and exceeds its field capacity, percolates as gravity drainage (as recharge) to the water table. Therefore, the difference between sum of the rainfall event in one hand and the actual evaporation, runoff, and field capacity of soil storage on other hand is the episodic recharge. The detailed conceptual steps of calculating potential recharge follow.

The actual evaporation (*E*) during rainfall events (RE) was assumed to be zero because duration of the events was short and the temperature was low and the relative humidity was high through most of the survey period. The *E* of the first rainfall event (RE_{i1}) is assumed to zero. However, during dry days between two consecutive rainfall events, the *E* volume was calculated using Eq. (1).

$$E_i = \text{Average daily} \times E_i^* \text{ number of dry days} \qquad (1)$$

When i = 1, E = 0; and for i = 2 the E represents the average E for the dry days between RE_1 and RE_2 and so on.

These *E* volumes are based on average monthly potential evaporation measurements from the files of the Ministry of Water and Irrigation using evaporation pans. Obviously, these are overestimates because potential evaporation is greater than the actual. On the other hand, transpiration is ignored because plant cover growth is greatly diminished during the winter months.

The infiltration volume (F_i) during any given rainfall event ($\mathrm{R}E_i$) is calculated by subtracting the sum of rainfall event from the runoff. The runoff for a given event (R_i) is calculated by multiplying $\mathrm{R}E_i$ by the runoff coefficient value of that event (RC_i). Accordingly, the infiltration volume can be calculated using Eq. (2).

$$F_i = RE_i - (RE_i * RC_i) \tag{2}$$

The runoff coefficient is variable according to the initial saturation state of the soil, beginning at 0.08 going to about 0.3 at full saturation.

The soil moisture (*S*) resulted from the first rainfall event (SM_{i1}) is equal to the initial soil moisture ($S_{.}$) plus the infiltration volume from the first event (F_{i1}), that can be estimated using Eq. (3).

$$SM_{i1} = S_o + F_{i1} + -E_{i1} \tag{3}$$

Subsequently, the soil moisture of the second event (SM_{i2}) is equal to soil moisture resulted from the previous event (SM_{i1}) plus the infiltration volume from second event (F_{i2}) subtracted from the evapotranspiration of the second event (E_{i2}). Therefore, subsequent soil moisture (SM_{i+1}) can be calculated using Eq. 4.

$$\mathrm{SM}_{i+1} = \mathrm{SM}_{i1} + (F_{i2} - E_{i2}), \tag{4}$$

and so on for the other events.

When $\mathrm{SM}_{i+..}$ > field capacity (0.403) then the recharge will be equal to ($\mathrm{SM}_{i+..} - 0.403$). However, when $\mathrm{SM}_{i+..}$ (Eq. 4) is equal or exceeds the field capacity volume then the equation becomes:

$$\mathrm{SM}_{i+1} = 0.403 + (F_{i+} - E_{i+}) \tag{5}$$

Results

Grain size analysis of the soils analyzed show that it consists of silty loam to silt (Fig. 7), with significant amount of gravel especially in the western parts of the study area, which generally consists of moderate permeability characteristics. The initial soil moisture profiles are presented in Fig. 6. Late summer conditions show that most of the drying occurs in the upper 20 cm, with rapid moisture increasing up to depths of 40–50 cm. Variations in moisture content between wet and dry conditions at two locations are presented in Fig. 8. It is noteworthy that the winter profiles show rapid drying in the upper 10 cm, whereas the elevated moisture levels remain consistent below that. Soil calcium carbonate profiles are given in Fig. 9. Only one profile (YB7) shows any evidence of carbonate accumulation with depth.

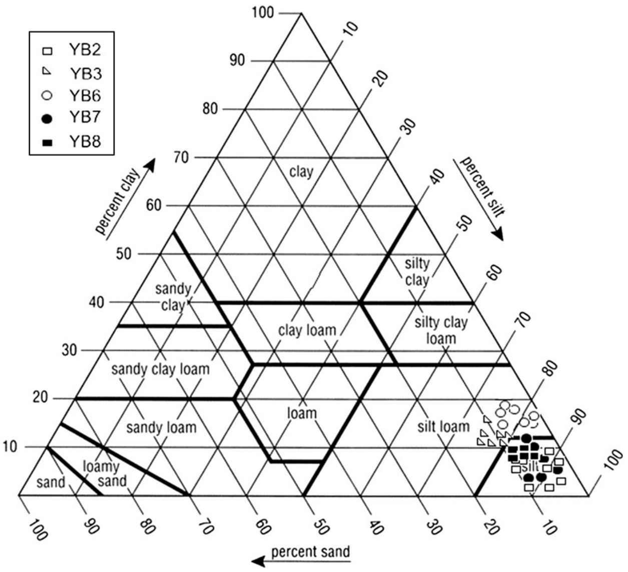

Fig. 7 Texture of the soil in the study area

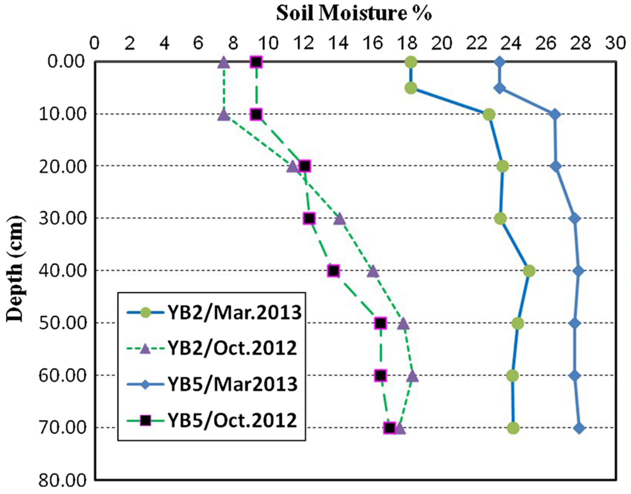

Fig. 8 Seasonal variations in soil moisture profiles at two locations

Summary of the results of artificial rainfall tests on dry conditions is presented in Tables 3 and 4. Examples of the runoff simulation conditions and results are presented in Fig. 10 and 11, and summarized in Table 4.

Artificial rainfall test results show high initial water infiltration rates in the low lying, deep (about 3 m thick), coarse (gravelly to sandy clay) soils in the western parts of the study area (Fig. 10) (Eidoon area). Infiltration rates in this area exceeded 120 mm in 4 h of rainfall. In the same area (Eidoon), but in high topographic area near the

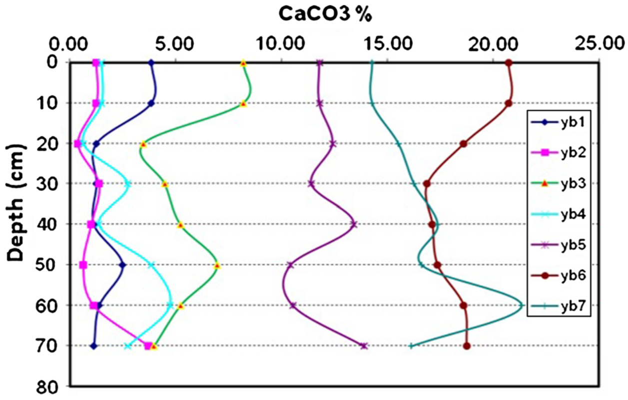

Fig. 9 Calcium carbonate contents within the various profiles

drainage divide soil has less thickness (about 50 cm) with coarse texture and initial infiltration rates reach about 50 mm in 75 min. On the other hand, simulation testes carried out within the eastern parts of the study area, across the Sareeh and Nueimeh plains having more than 3 m soil thickness (Fig. 11), showed different behavior. Field observations and texture analysis indicated that these locations have a thick finer texture with well-developed soil structure. In the eastern parts of the study area lower initial infiltration rates are seen, reaching about 40 mm in 90 min. Figure 12 shows the results of the resistivity imaging survey taking place before and after the rainfall simulation. Comparing these images with the exact location of the infiltrated waterfront from open soil pit (Fig. 13) suggests the applicability of the rainfall simulation run to generate acceptable groundwater infiltration process.

Discussion

General

The soil moisture profiles show consistent drying patterns between the spring and end of summer measurements, which is to be expected. Figure 8 shows this trend for two sites in the west and east of the profiles. The upper parts of the profiles drop rapidly in moisture content in the spring (with the upper 10 cm). The late summer profiles show a less dramatic trend, with a more gradual loss of moisture with depth. In the subsequent model implementation, the moisture loss between the two measurements is considered to be the differential between field capacity and permanent wilting point, which, after considering potential evaporation, will be considered to be the recharge volume.

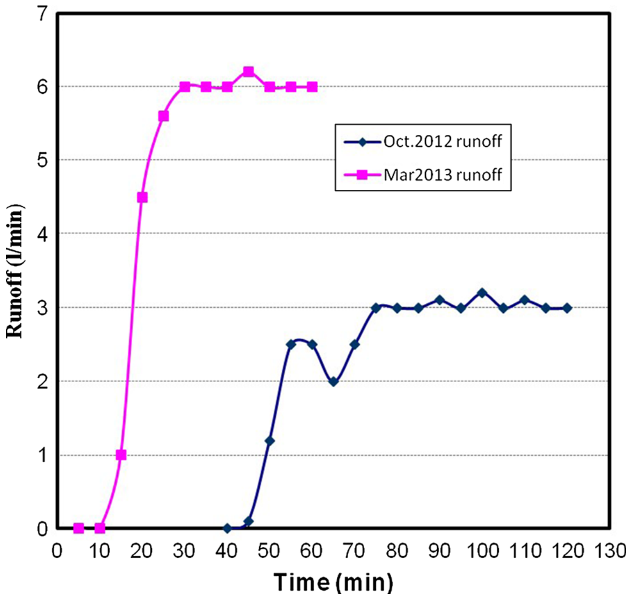

Fig. 10 Sprinkler test result variations at site YB2

For further elucidation of the significance of evaporation within the soil profile, the buildup of calcium carbonate within them is considered. Figure 9 shows the $CaCO_3$ profiles, and they show a number of interesting trends. The profiles in foothill in the west of the study area (YB 1–4) have distinctly lower carbonate buildups (less than 10 %) than those to the eastern plain areas (YB 5–7). In the western profiles, there are slightly higher carbonates in the top of the profiles than the lower parts. This can be either due to substantial near-surface evaporation or due to the presence of primary limestone fragments derived from the mother rock. In the eastern profiles, the carbonate content

Table 3 Summary of results for all rainfall simulation tests (on dry conditions, October, 2012)

Test #	Appearance of water ponding (min)	Appearance of runoff (min)	First liter collected (min)	Runoff equilibrium reached (min)	Runoff equilibrium volume (l/min)	Runoff coefficient
1	10	74	81	75	0.4	0.07
3	8	65	70	90	0.5	0.07
4	15	43	56	80	0.3	0.05
5	10	45	50	75	0.6	0.13
6	3	19	23	50	0.7	0.16
7	4	64	10	80	0.3	0.04
8	4	7	9	20	1.0	0.14

No simulation test on site number 2

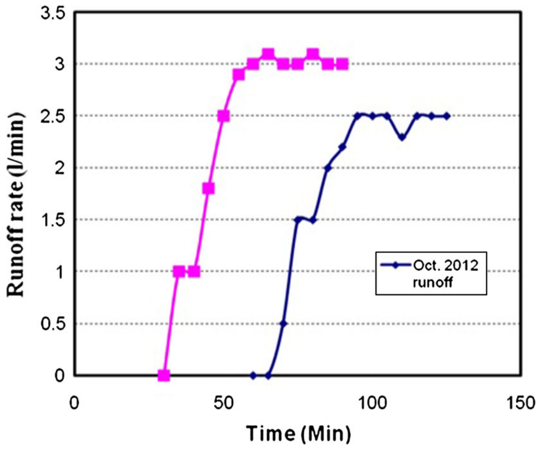

Fig. 11 Sprinkler test result variations at site YB5

is either almost constant with depth (YB 5), shows leaching with depth (YB 6) or shows buildup with depth (YB 7). Field observations of these profiles show that carbonates present are largely secondary precipitates. This thus show that in one case (YB 7) there is evidence that evaporation within the soil profile is high enough for the water to reach supersaturation with respect to calcite. On the other hand, the other profiles either show carbonate leaching (YB 4 and YB 6) or inconclusive evidence of calcium carbonate behavior within the profiles in question. The western profiles (YB 1–4) show no real evidence of secondary carbonate buildup, and this water loss within them is more likely to be drainage than evaporation.

The artificial rainfall tests (Figs. 10, 11) show consistent seasonal patterns. The spring tests show more rapid and higher runoff values than the late summer ones. This is the result of the soil being dryer in the late summer, thus requiring more water to exceed infiltration capacity and to begin runoff. Even after exceeding infiltration capacity, the volume of runoff at both sites is lower in the late summer tests, suggesting more rapid drainage into deeper levels of the soil, which is also an indication of greater recharge under those conditions. Site YB 2 (Fig. 10) shows that the runoff in the late summer is half of that in the spring, and shows no evidence of increasing even after prolonged testing. Site YB 5 (Fig. 11) is similar, but shows more runoff in the late summer compared with the spring tests.

In coupling the carbonate profiles with the rainfall simulation tests, it seems evident that water uptake and drainage through the soil profile seems to be greater in the western sites than those in the east, with no to low carbonate buildup in the profiles, and lower runoff volumes after the initiation of runoff. The more rapid initiation of runoff in the western profiles can be attributed to the higher slopes.

The tracking of the infiltration fronts using the resistivity profiles (Fig. 12) as well as visual evidence (Fig. 13) indicates that these fronts drive ahead of them a dry front. Entrapment of air and increased air pressure in the soil has been shown to increase runoff values in some cases (Delfs et al. 2013). Similar phenomena have been observed in radon profiles as they respond to recharge events in the eastern part of the YRB (Ershaidat et al. 2009). As observed in this case, however, the penetration of the recharge fronts to below the zones where significant evapotranspiration might occur happens rapidly, which corresponds with the observations made by the artificial rainfall tests.

In general, all of these tests and observations point to a crucial fact, which is that water in the area penetrates the soil quickly with relatively little runoff. The loss of moisture through the summer months is more likely to be through the drainage to deeper zones (recharge) than from evaporation. This is clearly seen from the artificial rainfall tests, the carbonate profiles and the geophysical modeling. The quantification of these factors using real climatological data follows.

Model implementation

Soil moisture for the upper first meter was monitored for four consecutive years (2009–2012). The average initial soil moisture during dry conditions (i.e., average soil moisture before the rainy season starts at the end of

Table 4 Summary of rainfall simulation tests performed on dry and wet conditions

Test #	Appearance of water ponding (min)	Appearance of runoff (min)	First liter collected (min)	Runoff equilibrium reached (min)	Runoff equilibrium volume (l/min)	Runoff coefficient
4 October 2012	15	43	56	80	1.2	0.05
March 2013	6	10	15	30	0.6	0.25
5 October 2012	10	45	50	75	0.6	0.13
March 2013	10	28	40	60	0.5	0.12

Top two rows for YB2 (Late summer and spring) and bottom two for YB5

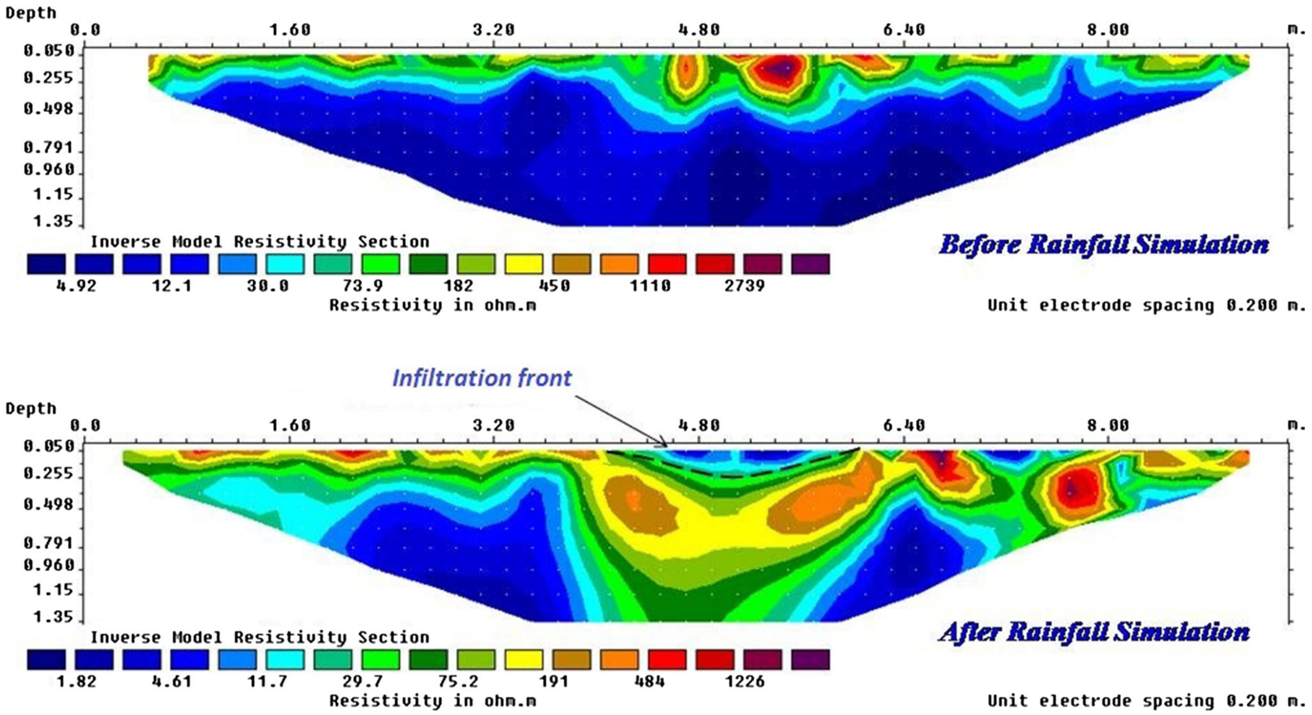

Fig. 12 Resistivity tomography results for 2 surveys taking place before and after rainfall simulation

Fig. 13 Soil pit showing the extent of simulated rainfall water infiltration front following the sprinkler experiment

summer), for soil profiles of 1 m depth was determined to 0.14 (by mass). Field capacity for silt loam soil is estimated to be 0.31 by volume (Fetter 2003). Soil water gravity drainage (recharge) occurs only when soil moisture content exceeds field capacity. Additionally, average soil dry bulk density was determined to be 1,300 kg/m^3. Soil porosity was thus estimated to be about 0.5.

Rainfall runoff tests during various soil moisture conditions revealed an approximate runoff coefficient of 0.08 when soil moisture was below the wilting point 0.12 by volume (Fetter 2003), 0.15 when soil moisture between wilting point and field capacity (0.12–0.31 by volume) and 0.20 when soil moisture exceeded field capacity. Permanent wilting points used for the soil are literature values that are consistent with late summer moisture contents measured in the field.

For each cubic meter of soil, the average initial volume of water is estimated by 0.182 m^3, soil moisture volume at a field capacity is 0.403 m^3, and maximum soil moisture content (porosity) is 0.650 m^3.

According to these equations, calculations of recharge of the Yarmouk Basin based on rainfall event basis for five consecutive years from 2004/2005 to 2009/2010 were estimated. While these water years do not correspond to the study period, they are the years for which we were able to obtain daily data measurements. Clearly, the nature of the soil had not changed in the meantime. As an example, recharge for the water year 2004/2005 is presented in Supplementary Table 5 suggesting a total recharge of 0.18 m. The calculations can be done for other years using the spreadsheet supplied as supplementary material.

These calculations show that the recharge during the studied water years ranges between 20 and 37 % of the amount of precipitation, which is considerably higher than the working assumptions for the Water Authority of Jordan (5 %). These conclusions are consistent with three other observations noted in the area. First the significant amounts of water needed to realize runoff, the second is the moderate volumes of runoff seen after soil becomes saturated and equilibrium is realized, and third is the trivial amounts of water stored in the Wihdeh Dam (unfortunately there are no gauging stations upstream measuring only the runoff from the Jordanian side of the YRB, specifically due to the fact that the runoff is observed to be negligible).

Moreover, there is no evidence to salination or calcite build up in the soil profile, and thus there is no reason to believe that near-surface evaporation is enough to explain all the near-surface water loss, unlike what is seen in more arid areas (Abu-Jaber 2001). Water flushes through rapidly with no evapoconcentration, as is evident from the soil calcium carbonate profiles (Fig. 9).

Another case study for recharge estimation using water balance model at Amman Zarqa basin in Jordan showed that recharge is 19 % higher than previously estimated (Schulz et al. 2013). The discrepancy in recharge estimation results between previous methods adopted by the MWI in Jordan and the soil water mass balance approach is mainly attributed to the soil map used to identify the soil group. MWI uses the CN method to estimate runoff which depends mainly on four identified soil groups (Soil Conservation Services 1957). The soil map developed for Jordan is very generalized and of low resolution (1:250,000), for example it assigned Yarmouk basin as one soil type (clayey soil). While, high resolution study of the basin's soil reveals that it consists of gravely loam, loam and silty soil (Ababneh 2013). Therefore, choosing the wrong soil group in the CN method will be misleading.

The use of soil moisture balance approach is basically a direct measurement of water movement through the soil profile. Not only is it more robust and consistent with what is observed in the drainage basin, but it an approach that is designed specifically for cases where water is deep, data are poor and the problem of interconnected aquifers precludes using discharge as an approximation for recharge in what would otherwise be a steady state system. Clearly, the technique can be improved by collecting more data and enhancing knowledge of transpiration in the area based on variations in land use and plant cover.

Conclusions

The mass balance approach described within is an effective and robust tool for estimating recharge in the area. The results conform to a number of observations seen in the field. It is easy to use as a simple Excel sheet (Supplementary material), and it can be readily modified as more data are collected and it can be integrated into GIS to examine the spatial variations in recharge over a wide area. The assumptions which underpin the approach are well defined and can easily be defended. These results strongly suggest that the recharge regime in the semi-arid YRB is significantly more effective than previously assumed. The water year studied shows a recharge rate of 20–37 % of precipitation, as opposed to the current working assumption of 5 %, which is based on the miss use of the Curve Number method. The integration of this approach into larger scale modeling on a basin scale (Schulz et al. 2013) would provide more accurate estimates of recharge than the geochemically and physically inferred recharge estimates currently being employed.

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