Multiple-methods investigation of recharge at a humid-region fractured rock site, Pennsylvania, USA

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Abstract Lysimeter-percolate and well-hydrograph analyses were combined to evaluate recharge for the Masser Recharge Site (central Pennsylvania, USA). In humid regions, aquifer recharge through an unconfined low-porosity fractured-rock aquifer can cause large magnitude water-table fluctuations over short time scales. The unsaturated hydraulic characteristics of the subsurface porous media control the magnitude and timing of these fluctuations. Data from multiple sets of lysimeters at the site show a highly seasonal pattern of percolate and exhibit variability due to both installation factors and hydraulic property heterogeneity. Individual event analysis of well hydrograph data reveals the primary influences on water-table response, namely rainfall depth, rainfall intensity, and initial water-table depth. Spatial and seasonal variability in well response is also evident. A new approach for calculating recharge from continuous water-table elevation records using a master recession curve (MRC) is demonstrated. The recharge estimated by the MRC approach when assuming a constant specific yield is seasonal to a lesser degree than the recharge estimate resulting from the lysimeter analysis. Partial reconciliation of the two recharge estimates is achieved by considering a conceptual model of flow processes in the highly-heterogeneous underlying fractured porous medium.

Résumé Les analyses des percolats de lysimètres et d'hydrogrammes de puits ont été combinées pour évaluer la recharge du Site de Recharge de Masser (Pennsylvanie centrale, USA). Dans les régions humides, la recharge d'un aquifère à travers un aquifère de roche fracturée libre et de faible porosité peut engendrer des fluctuations piézométriques de grandes amplitudes sur de courtes échelles de temps. Les caractéristiques hydrauliques non saturées du milieu poreux de la subsurface contrôlent l'amplitude et la durée de ces fluctuations. Les données provenant de plusieurs ensembles de lysimètres sur le site montrent un système de percolation très saisonnier et une variabilité due aux facteurs d'installation et à l'hétérogénéité des propriétés hydrauliques. L'analyse d'événements individuels des données d'hydrogrammes de puits révèle les influences primaires sur la réponse de la nappe, à savoir la profondeur et l'intensité des pluies et la profondeur initiale de la nappe. La variabilité spatiale et temporelle de la réponse des puits est également évidente. Une nouvelle approche pour calculer la recharge à partir d'enregistrements continus des niveaux piézomètriques en utilisant une courbe principale de décrue (MRC en anglais) est ici démontrée. La recharge estimée par MRC en supposant une porosité efficace constante est saisonnière à un degré moindre que la recharge résultant de l'analyse par lysimètres. La réconciliation partielle des deux estimations de recharge est atteinte en considérant un modèle conceptuel des processus d'écoulement dans le milieu poreux fracturé sous-jacent extrêmement hétérogène.

Resumen Se combinaron análisis de infiltración con lisímetro y de hidrograma de pozo, para evaluar la recarga para el Sitio de Recarga Masser (Pennsylvania central, EE. UU.). En regiones húmedas la recarga acuífera a través de un acuífero de roca fracturada, libre y de baja-porosidad, puede causar fluctuaciones gran magnitud del nivel freático, en periodos cortos de tiempo. Las características hidráulicas del medio poroso subsuperficial no saturado, controlan la magnitud y el tiempo de ocurrencia de estas fluctuaciones. Los datos de los grupos múltiples de lisímetros en el sitio, muestran un modelo muy estacional de infiltración y muestran variabilidad debido tanto a factores de instalación, como a la heterogeneidad de las

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propiedades hidráulicas. El análisis de eventos individuales de los datos del hidrograma de pozo, revelan influencias primarias en la reacción del nivel freático, a saber, cantidad de lluvia, intensidad de lluvia, y la profundidad inicial del nivel freático. La variabilidad espacial y estacional en la reacción del pozo, también es evidente. Se demuestra un nuevo acercamiento para calcular la recarga, a partir de registros continuos de elevación del nivel freático, usando una curva patrón de declinación (CPD). La recarga estimada por la aproximación de CPD, es estacional, cuando se asume un rendimiento específico constante, a un grado menor que la estimación de la recarga resultante del análisis del lisímetro. La conciliación parcial entre las dos evaluaciones de la recarga, se logra considerando un modelo conceptual de procesos de flujo, en el medio poroso fracturado muy heterogéneo que está subyacente.

Keywords Groundwater recharge · Fractured rocks · Unsaturated zone · Lysimeters · Water-table fluctuations

Introduction

Aquifer recharge, the downward movement of water from the unsaturated zone to the saturated zone, is virtually impossible to measure directly and therefore must be estimated by indirect methods. The selection of recharge estimation methods often depends on the spatial and temporal scale of interest, the characteristics of the aquifer, and the availability of data. Nimmo et al. (2005) summarize several methods for estimating aquifer recharge rates including the "residual" approach in water budget analysis, analysis of water-table elevation time-series data, Darcian methods, tracer methods, and geophysical methods. Comparison and corroboration of multiple estimation methods is beneficial, as any single method is vulnerable to sources of error that may be recognized and corrected with results from other methods. Combined methodologies, using both soil-water accounting and water-table fluctuation data, have been used to determine effective storativity and estimate recharge (e.g., Sophocleous 1991). Crosbie et al. (2005) presented a model for continuous recharge analysis using soil-water retention and water-table data. In this study, the focus is on recharge estimation by subsurface flux measurement using lysimeters and by analysis of fluctuations in water-table elevation.

Lysimeters extending below the rooting depth of surface vegetation are considered to be the most direct way to measure recharge and have been used extensively in unsaturated-zone flux studies. The key assumption is that downward-flowing water collected at such a depth represents the amount of water that, in the surrounding undisturbed medium, would not be subject to further loss mechanisms and so would all proceed to the water table. Much attention has been paid to the differences in performance related to lysimeter design. In has been widely recognized (e.g., Haines et al. 1982; Zhu et al. 2002, 2003; Robison et al. 2004) that zero-tension pan lysimeters are prone to certain boundary effects caused by horizontal gradients in soil tension. For percolate to be collected by a zero-tension lysimeter, a perched saturated zone must develop at the zero-tension boundary which, in open-sided pan designs, can cause lateral diversion of percolating water and reduced collection efficiency. Monolith zero-tension lysimeters, which encase a block of soil on all sides and the bottom, prevent lateral losses yet still promote the formation of a perched saturated zone.

Water-table elevation data can also be used in several ways to estimate aquifer recharge (Healy and Cook 2002). The water-table fluctuation (WTF) method (or groundwater accretion method) uses the concept of specific yield to estimate recharge from observations of water-table fluctuations in wells, with the following expression:

$$R = \Delta Z_{\mathrm{WT}} \times Y_{\mathrm{s}} \tag{1}$$

where R is recharge volume per unit area (L), ΔZ_{WT} is the height of water-table rise (L), and Y_{s} is the specific yield (−) of the porous medium, traditionally defined as the volume of water released from an unconfined aquifer per unit surface area per unit decline in the water table (Freeze and Cherry 1979). Often specific yield has been estimated as the difference between the field saturated water content, θ_{fs} (−), and the field capacity, θ_{fc} (−), a definition suited for quantifying well yields at late times during pumping. In the context of a rising water table, which is the focus of the WTF method, the term effective fillable porosity, ϕ_{ef} (−), is more appropriate, but the term specific yield will be used for convenience in this study.

Healy and Cook (2002) identified specific yield as one of the key uncertainties in the application of the WTF method. Specific yield has been shown to be dependent on water-table depth for shallow water tables due to a truncation of the equilibrium soil-water content profile (Childs 1960). Others have noted the transience of this parameter in relation to antecedent conditions (Sophocleous 1985). Nachabe (2002) derived analytical expressions for transient specific yield based on soil hydraulic properties for water-table drainage. Crosbie et al. (2005) used knowledge of the soil characteristic curve and water-table elevation to evaluate an effective specific yield assuming equilibrium soil-water conditions and used these in a continuous WTF approach. They also recognize the importance of pre-processing the water-table elevation data to remove signals not related to groundwater recharge. In fractured rock systems, the secondary porosity is often the dominant unsaturated flow continuum, and specific yield can be very low (Zuber and Motyka 1998; Gburek and Folmar 1999; Marechal et al. 2003).

In addition to requiring a good estimate for specific yield, the WTF method also requires an accurate estimate of ΔZ_{WT}. Water tables are often in a transient state of decline due to aquifer discharge, complicating the process of water-table rise estimation. The rate of decline is related to the rate of discharge, which depends on the hydraulic head gradient from the recharge point to the discharge point. If the rate of dissipation of a groundwater mound is proportional to its height above the surrounding water table, the decline in water-table elevation will follow an exponential pattern. Hantush (1967) derived analytical solutions for the growth and decay of groundwater mounds in a homogeneous, isotropic aquifer of infinite aerial extent, showing that the water-table decline following a recharge event could be obtained by superimposing onto the rising curve, starting at the time recharge ceases, a rate of discharge equal to the original rate of recharge. Rorabaugh (1960) derived an expression for water-table recession for aquifers with simple geometry and hydraulic characteristics, also demonstrating that, under idealized conditions, water tables decline exponentially. Many well hydrographs exhibit this characteristic recession pattern after a recharge event, with a relatively sharp decline at first followed by a long tail. The repeatability of this characteristic pattern makes it useful in techniques for estimating ΔZ_{WT} in dynamically changing conditions.

Recharge processes may have additional complexities in fractured rock settings, where individual infiltration events may cause large water-table rises over short time periods. The effects of fractures on flow, contaminant transport, storage of fast preferential flow (Su et al. 2000), fracture-matrix interaction (Wang and Narasimhan 1985), film flow (Tokunaga and Wan 1997), nonlinear dynamics (Faybishenko 2004), fracture coatings, and fracture roughness and aperture distribution are active research areas. Much of the focus in unsaturated fractured rock research has been on potential hazardous-waste repository sites in arid climates with deep water tables (Peters and Klavetter 1988; Liu et al. 1998, 2003), with less attention given to fractured-rock sites in humid climates with shallow water tables. In humid regions, the proportion of active fractures (Liu et al. 1998) is expected to be greater, and water-table response to surface inputs may be very rapid. In fracture networks dominated by gravity flow, kinematic behavior is possible (Germann and Beven 1985) and communication between depths can take place via pressure waves (Rasmussen et al. 2000). Finally, air entrapment during rapid infiltration has been shown to play a role in shallow water-table dynamics (e.g., Fayer and Hillel 1986; Heliotis and DeWitt 1987; Weeks 2002). With regard to most of these effects, the transient and dynamic aspects of fracture flow may be especially important in humid environments.

In this study, the response of lysimeters and observation wells to rainfall inputs at the Masser Recharge Site near Klingerstown, Pennsylvania (USA) is analyzed to estimate recharge rates and investigate recharge processes in humid, fractured-rock settings. Specifically, the role and influence of seasonality, spatial heterogeneity, lysimeter boundary conditions, and specific yield variations in time and space are investigated. A new method of recharge estimation based on the recession characteristics of well hydrographs is applied under two different sets of assumptions to help evaluate competing hypotheses of recharge variability. This work builds on the foundation for aquifer recharge research at this site laid by Gburek and Folmar (1999) and Risser et al. (2005).

The Masser Recharge Site

Description and instrumentation

To examine recharge processes in humid regions through fractured rock, the US Department of Agriculture, Agricultural Research Service established the Masser Recharge Site (Gburek and Folmar 1999). The site is situated near the top of an elongated knoll (Fig. 1) on the northern limb of an east-plunging anticline within the Valley and Ridge physiographic province in the Susquehanna River basin. It is underlain by north-dipping Devonian aged sedimentary rocks of the Catskill Formation, mainly interbedded siltstones, and shales. Three roughly orthogonal fracture sets of varied spacing are present in the bedrock: a north-dipping fracture set corresponding to the bedding plane, a south-dipping fracture set corresponding to the primary cleavage planes, and a north-striking, nearly vertical fracture set corresponding to a secondary cleavage plane. Fracture frequency in a vertical borehole decreases with depth, ranging from approximately 10 to 25 m^{-1} in the highly and moderately fractured zones near the surface (depths less than 17 m) to less than 5 m^{-1} at depths greater than 25 m.

The bedrock at the Masser site is highly cemented and has very low porosity (approximately 1–2%) and low matrix conductivity (less than 3.5×10^{-9} m s^{-1}, as indicated by gas permeameter measurements on core samples from the nearby WE-38 watershed). Packer tests conducted by Gburek and Folmar (1999) show a decrease in hydraulic conductivity with depth. Hydraulic conductivity ranges from over 1.5×10^{-5} m s^{-1} near the surface to 2.7×10^{-6} m s^{-1} at the base of the zone of water-table fluctuations. A highly conductive interval (1.9×10^{-4} m s^{-1}) was discovered at a depth of 35.0–38.1 m in the deepest well at this site, indicating that the decrease in conductivity with depth is not without exception, and that vertical heterogeneity in hydraulic properties is significant on the scale of a few meters or less. The permeability of the rock matrix is roughly four orders of magnitude less than that of the fractured rock as a whole, which suggests that the fractures themselves comprise the dominant flow continuum.

The climate at the Masser site is humid and temperate, with a mean annual rainfall of 1.0 m and temperatures ranging from lows below 0°C in the winter to highs over 30°C in the summer. Precipitation occurs throughout the year, without distinct wet and dry seasons. The soils in the area are classified as silt loams and are thin, grading into saprolite at depths as shallow as 0.5 m (Gburek and Folmar 1999). The surface cover at the site is mowed grass over one portion and non-irrigated row crops (corn and soy, in rotation) over the rest.

Instrumentation at the Masser site includes five monitoring wells, 28 zero-tension monolith lysimeters, and a meteorological station recording rainfall, temperature, solar radiation and wind speed. Data collection began in 1994 and has continued through the present day. Data from water years 1995 through 2001 were used in this study.

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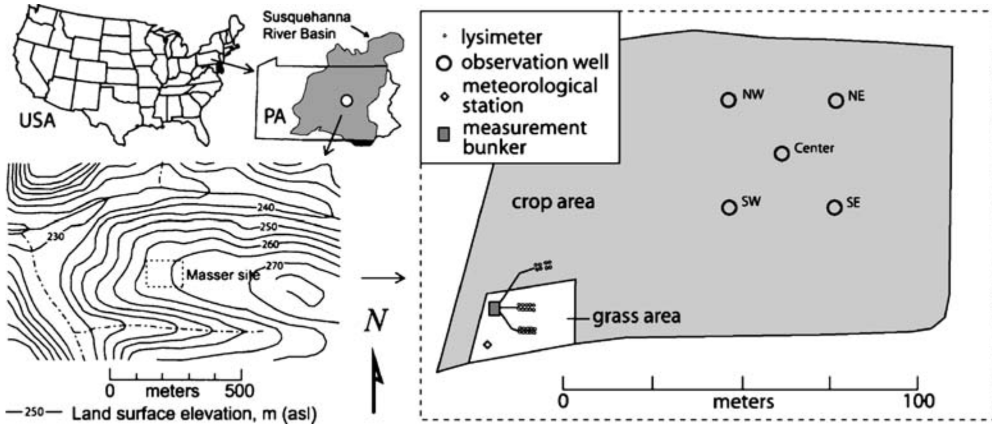

Fig. 1 Location, regional topography, and instrumentation of the Masser Recharge Site (adapted from Gburek and Folmar 1999)

The 0.16 m diameter wells are arranged in an X pattern (Fig. 1), the center well being the deepest (46 m) and the other four wells being shallower (30 m). The wells are cased to a depth of 5.5 m and are open below this. Water-table elevation was recorded at 30-min intervals in all five wells using floats and dataloggers, which have an accuracy of ±3 mm (0.01 ft).

The lysimeters consisted of a 0.61 m-diameter, 6 mm thick steel cylinder pounded into the ground, excavated with the soil column inside, placed on and welded to a collection pan containing a layer of gravel, and then replaced into the ground. Four of the lysimeter cylinders were 2 m long, and the rest were 1 m long. One of the 1-m-long cylinders containing a core sample from the grass area was removed and cut open vertically for inspection of the soil and rock inside. The installation process was apparently minimally disturbing to the soil, as individual rock fragments seem to have been sliced through by the steel cylinder rather than pushed out of the way (Gburek and Folmar 1999). Installed in the field, the collection pans connect to underground pipes that direct the water that has reached the base of the soil column by percolation (percolate) to a measuring bunker where it is collected in jars and weighed by load cells. The impermeable column walls of this design minimize lateral water losses typically associated with zero-tension pan lysimeters. Twenty lysimeters were installed in a grass-covered area and eight were installed in the crop field beneath a 50-cm covering of soil to allow continued use of farming equipment. The four 2-m cylinders were among the eight cropped-field lysimeters. All eight lysimeters installed in the cropped area and eight of the lysimeters in the grass area were monitored at 30-min intervals.

Data

A summary of the Masser site data examined in this study is shown in Fig. 2. Cumulative rainfall (Fig. 2a) increases steadily over the study period. Figure 2b shows the water-table elevations in the five wells; gaps in the data due to data-logger error are apparent. The data show a pattern of large (up to 9 m) rapid rises due to rainfall events followed by slower exponential declines. Water-table responses to an individual event vary between wells. The water-table surface at a given time is uneven, and is almost always lowest in the deeper center well, confirming that a downward gradient exists at this site in the shallowest part of the saturated zone. Figure 2c shows the average cumulative percolate measured in three sets of lysimeters: those installed under the grass area (all at 1 m depth), the 1-m lysimeters under the cropped area, and the 2-m lysimeters under the cropped area. The three sets differ in cumulative response, as discussed below.

Materials and methods

Three methods were used to evaluate recharge and recharge processes at the Masser site: (1) lysimeter-percolate analysis, (2) event-data analysis with the WTF approach, and (3) continuous well-hydrograph analysis using a master recession curve (MRC) and the WTF approach.

Lysimeter analysis

Data from the three sets of lysimeters were used to estimate recharge and to evaluate the uncertainty of the lysimeter method. The lysimeter-percolate time-series were analyzed to determine, for each set of lysimeters, the monthly and water-year percolate totals for the period from October 1994 to September 2001 (water years 1995–2001). Lysimeter data were averaged by month to examine seasonal patterns. Variability within each set was analyzed using the standard deviation and coefficient of variation.

Event data analysis

Summary variables from individual rainfall events were extracted from the continuous lysimeter and well-response time-series. Rainfall events were defined by including all non-zero rainfall intervals during which any well was rising since the start of the event. Because of incomplete records, summary variables for certain events were not discernible in all wells and lysimeters. The summary variables extracted whenever possible were: total rainfall

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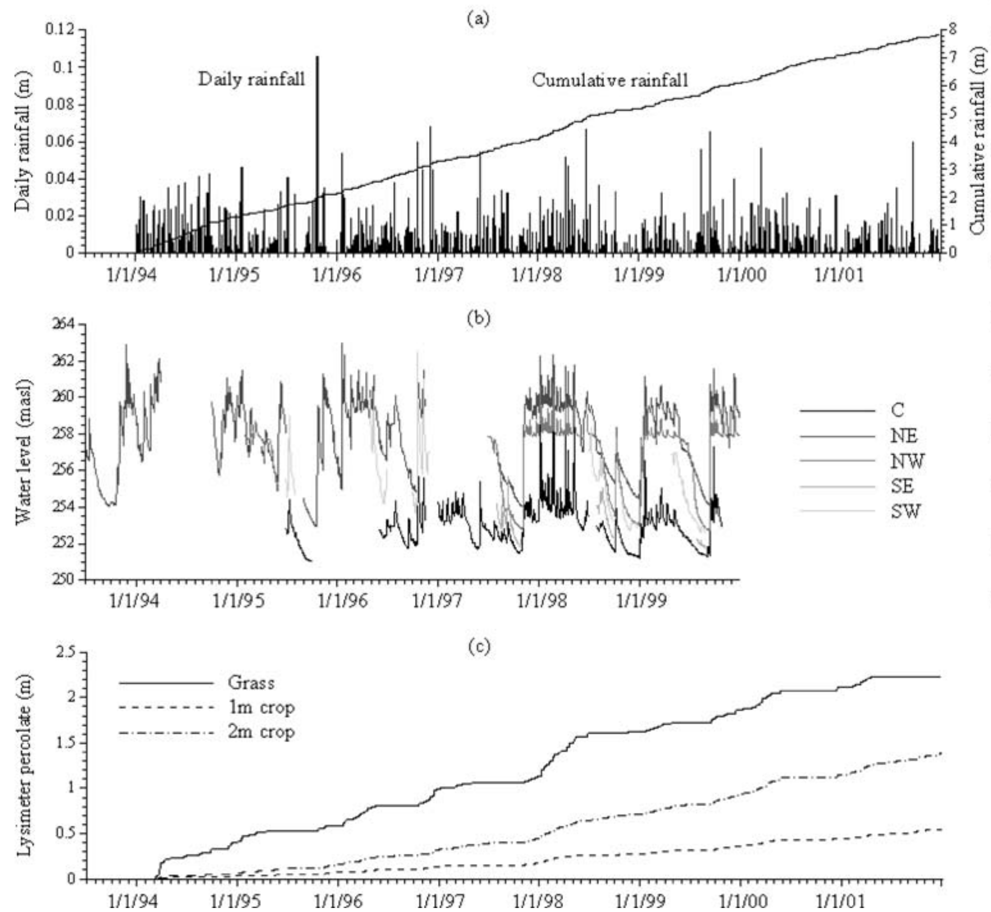

Fig. 2 Masser time-series data: **a** daily and cumulative rainfall; **b** water level, for the five wells indicated as center (*C*) and by direction from the center well; **c** average cumulative lysimeter percolate for the three lysimeter sets

(L), peak rainfall intensity (L T^{-1}), average lysimeter percolate for the grass lysimeters (L), total water-table rise in each well (L), starting and ending times for water-table rise and rainfall (hh:mm:ss), initial depth to water table in each well (L), and drainage time preceding the event (T). The drainage time was defined as the elapsed time since the cumulative annual rainfall was less by 0.00625 m. This 0.00625 m (0.25 inch) rainfall amount was chosen since it is less than the amount needed to cause a response in any well or lysimeter so no response-generating rainfall occurs during this drainage period. The following secondary variables were then calculated: average rainfall intensity (L T^{-1}), average water-table rise rate (L T^{-1}), precipitation yield (−), and signal propagation velocity (L T^{-1}). Precipitation yield, similar to effective specific yield, is the ratio of rainfall amount to water-table rise. Signal propagation velocity is defined as the initial water-table depth divided by the time between the start of the event and the centroid of mass of the response. Data were extracted in this manner from 37 different storm events giving 92 event-well pairs. Lysimeter-percolate amount (i.e., the total percolate following a rainfall event, including that which occurs after rainfall ceased) was determined for 27 of the 37 storm events.

To examine the gross behavior of the near-surface response the summary variables were grouped into two groups: (1) input variables, related to the rainfall characteristics and antecedent conditions; and (2) output variables, related to the resultant water-table response and percolate for each event. Pearson product-moment correlation coefficients, ρ, which range from −1 to 1, were computed for all input-output pairs of event-summary variables. Correlation coefficients were calculated separately for each well to discern differences in behavior. The correlation coefficients were then normalized by dividing by the 1% one-tailed probability value. When this normalized value is 1.0 (or greater) it indicates that there is a 1% (or less) probability that the correlation coefficient would be this high or higher by random chance alone. These normalized correlation coefficients were then averaged over all five wells, weighting each well's value by the number of events used in the calculation.

Continuous well hydrograph analysis using a master recession curve

The master recession curve (MRC) method uses the WTF principle to compute continuous recharge estimates from the high-frequency water-table elevation time-series data. Use of a master recession curve indicates, for each measurement time, the amount of water-table change that is attributable to aquifer recharge. This value is then multiplied by the specific yield to estimate recharge for that time step.

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Recession curves have been used in the context of streamflow hydrographs to determine baseflow and aquifer parameters (Rutledge 1993, 1998; Risser et al. 2005). Rutledge (2005) discussed the recession of groundwater levels, using a finite-difference groundwater flow model to examine the exponential pattern of recession. In this study, a master recession curve is a characteristic functional relationship between water-table elevation and water-table decline rate. In situations where a groundwater discharge point such as a spring or stream is near a recharge point on the land surface, the water-table elevation at the recharge point is often closely correlated with the average hydraulic gradient between the recharge and discharge points; higher water-table elevations are associated with larger gradients and vice versa. The gradient in turn determines the rate at which groundwater moves from the recharge point to the discharge point. Higher rates of movement away from the recharge point involve faster rates of water-table decline, resulting in a characteristic recession function.

The rate of water-table decline is not solely a function of water-table elevation. At early times after a water-table peak, the groundwater head profile is unstable, causing departures from the characteristic exponential recession behavior (Rutledge 2005). Other factors include the local relief and topography, the nature of the groundwater discharge point, seasonality in both weather and depth to the water table, vertical heterogeneity in subsurface hydraulic properties, and dynamic evaporative stresses.

For this study, the MRC was constructed using the bin-average approach outlined by Heppner and Nimmo (2005), following these steps: (1) the water-table elevation time-series data are manually corrected for obvious errors such as long plateaus or sudden spikes; (2) the data are imported to the model and reduced by removing successive points with the same elevation (this ensures that no points have a zero rate of change); (3) the data are converted to rates of water-table elevation change and average water-table elevation; (4) the data are divided into a number of elevation bins; (5) the average elevation and decline rate for all points in each bin are calculated; (6) the MRC is defined by pairing the average decline rates with the average elevations and interpolating linearly between points.

The difference in water-table elevation between the observed elevation and that which would result from the MRC-derived decline rate, multiplied by the specific yield, indicates recharge for that time step. When the water table declines faster than expected, the difference is negative and a negative recharge amount is assigned for that time step. This ensures that the recharge estimate is not unduly influenced by possible high-frequency oscillations that often appear in water-table data (see Heppner and Nimmo 2005).

The MRC approach outlined above was applied in this study to each well for each month using a well-specific composite MRC derived from all of the water-table data for that well. The method was applied in two different ways. First, recharge was estimated from the water-table data using the MRC method and a *constant* specific yield. Second, assuming that the grass lysimeter percolate represents true recharge, the MRC approach was used to inversely determine the *variable* specific yield for each month.

Results

Lysimeter analysis

Table 1 shows for the water years 1995–1999 the total rainfall and the cumulative percolate for the three lysimeters sets in terms of both total amount and as a percentage of rainfall. Missing monthly percolate values for all lysimeters in the summer and autumn of 2000 prevented the tallying of annual totals for water years 2000 and 2001. In the five years examined here, percolate from the grass lysimeter set ranged from 21 to 52% of annual rainfall, averaging 32%. In general, wetter years had a higher proportion of percolate, while in drier years most of the rainfall goes to evapotranspiration (ET) and runoff.

On average, the lysimeters installed under the cropped field produce significantly less percolate per year than those in the grass-covered area. The deeper set in the cropped area shows greater percolate than the shallow set. These patterns may result from soil-moisture differences within the lysimeters caused by factors including the zero-tension boundary condition at the base of the lysimeters, the location of the upper lysimeter rim, and the installation depth. Like all zero-tension lysimeters, the lysimeters used here require the formation of a perched saturated zone at the bottom in order to allow percolate to exit the soil column and be measured. As a result, the soil-water content within the lysimeters will remain higher than the soil outside at the same depth. ET losses may be higher as a result. Because the crop lysimeters' upper rim does not

Table 1 Cumulative total rainfall and lysimeter percolate for water years 1995 to 1999

Year	Rainfall	Percolate			Percolate as a percentage of rainfall		
	(m)	1 m crop (m)	2 m crop (m)	1 m grass (m)	1 m crop (%)	2 m crop (%)	1 m grass (%)
1995	0.749	0.040	0.078	0.210	5.3	10.4	28.1
1996	1.216	0.029	0.137	0.403	2.3	11.3	33.1
1997	1.057	0.043	0.143	0.284	4.0	13.5	26.8
1998	1.123	0.112	0.350	0.580	10.0	31.2	51.7
1999	0.955	0.061	0.178	0.198	6.4	18.6	20.7
Average	1.020	0.057	0.177	0.335	5.6	17.0	32.1

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extend to the ground surface, the increased soil-water contents also could cause lateral diversion of recharging water to the surrounding soil, reducing measured percolate. Only the grass lysimeters, whose top rims protrude slightly above the land surface, eliminate these lateral losses completely. The deeper (2 m) installation may result in more measured percolate because the zero-tension (saturated) basal boundary condition is farther from the open top edge, reducing the artificial augmentation of water content in the upper portions of the column that may increase water losses to ET or lateral flow.

Figure 3 shows the average monthly rainfall and percolate for each lysimeter set. Rainfall does not exhibit much seasonal variation. On the other hand, all three lysimeter sets show a decrease in measured percolate during the summer months. This seasonal percolate minimum corresponds with the growing season and also with the warmest weather, both of which are conducive to increased water flux to the atmosphere. Thus, an increase in ET is the likely explanation for the summer drop in measured percolate. The 2-m deep crop lysimeters show a less pronounced seasonality than either of the shallower sets, suggesting they have less ET than the shorter ones.

Variability within each set of lysimeters was assessed with the coefficient of variation (CV; standard deviation/mean) for each set. The CV of total percolate for each month with data from October 1994 through September 2001 was calculated for each set of lysimeters. Table 2 shows the mean, minimum, and maximum of the monthly CV values for each lysimeter set. Variability on average is greatest for the shallow crop lysimeters and slightly less for the deeper crop lysimeters and grass lysimeters. Assuming that the rainfall inputs are the same for each lysimeter, and that surface runoff is negligible (Gburek and Folmar 1999), the variability in response between lysimeters of the same set may have been caused by: (1) variable vegetative water use, (2) the presence in some lysimeters of low permeability layers or other flow-impeding features, causing perched soil moisture and increased ET, (3) variability in the water retention and conductivity of the soil, again permitting more ET in some cases than in others, and (4) a heterogeneous distribution of fractures and macropores, allowing water to travel to depth faster in some lysimeters than others. The CV is generally highest in the summer, likely due in part to the fact that mean percolate during these months is low.

Table 2 Mean, minimum, and maximum coefficient of variation (CV) for monthly percolate within each lysimeter set

	1 m grass	1 m crop	2 m crop
Mean CV	0.90	1.26	0.96
Minimum CV	0.01	0.23	0.33
Maximum CV	2.83	2.00	2.00

Figure 4 shows the monthly grass lysimeter percolate for the period from October 1994 to September 2001. These are the data used in the MRC analysis to estimate the variable specific yield values for each well.

Event data analysis

The event-summary variables for all the events affecting the center well during the period of study are shown in Table 3. The data in Table 3 and Fig. 5 illustrate the large magnitude and quickness of the water-table response, with average water-table rise amounts and rates of approximately 2.6 m and 8.3×10^{-5} m s^{-1} (0.3 m h^{-1}), respectively. The ratio of rainfall to water-table rise is highly variable, while the ratio of event lysimeter percolate to water-table rise is less variable, suggesting that water-table rise is more closely linked to percolate (which is assumed to represent recharge) than to rainfall.

Table 4 shows the mean, median, minimum, maximum, and standard deviation for the ratios of rainfall to water-

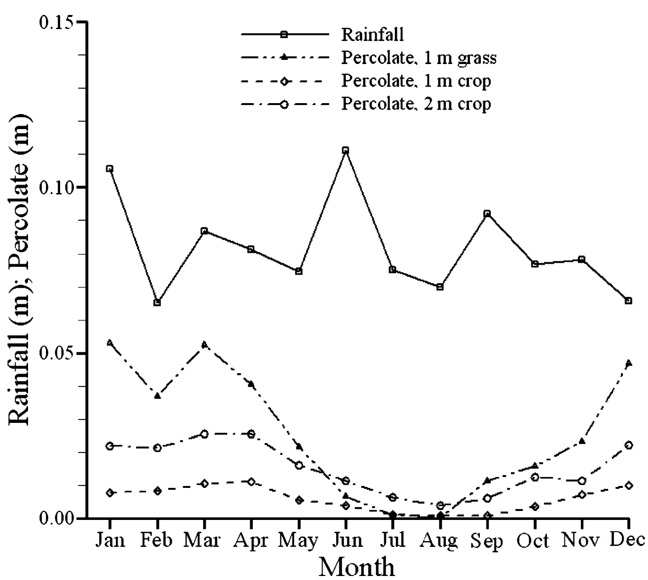

Fig. 3 Average monthly rainfall and lysimeter percolate for the three sets of lysimeters

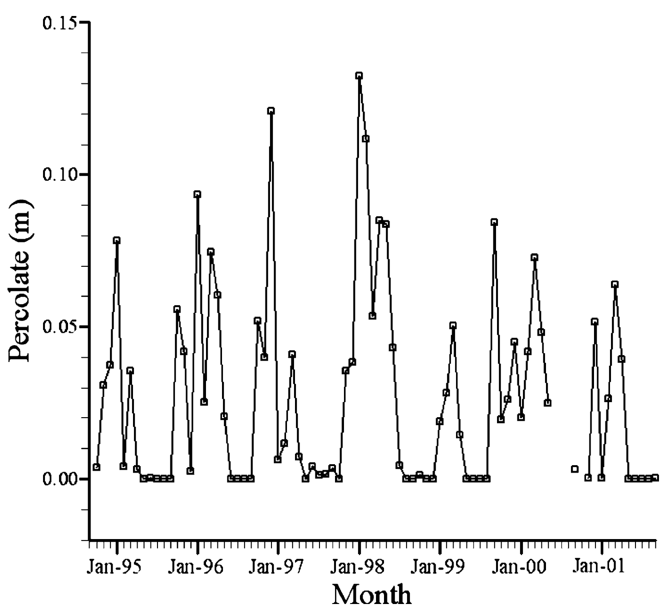

Fig. 4 Monthly grass lysimeter percolate for the period from October 1994 to September 2001

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Table 3 Summary variables for the 28 events affecting the center well during the study period

Date	Rainfall (m)	Peak rainfall intensity ($m\ s^{-1}$)	Average rainfall intensity ($m\ s^{-1}$)	Initial water-table depth (m)	Drainage time (days)	Water-table rise (m)	Average rate of water-table rise ($m\ s^{-1}$)	Signal prop. velocity ($m\ s^{-1}$)	Lysimeter percolate (m)	Lysimeter percolate/rainfall (−)	Rainfall/water-table rise (−)	Lysimeter percolate/water-table rise (−)
5/6/94	0.036	1.2E-05[a]	2.5E-06	13.786	11.5	1.823	2.7E-05	3.3E-04	ND	ND	0.020	ND
1/10/94	0.009	9.9E-07	5.4E-07	14.807	3.9	0.646	7.8E-06	1.7E-04	0.004	0.393	0.014	0.006
5/7/95	0.041	7.9E-06	2.4E-06	14.774	5.4	1.244	1.8E-05	3.4E-04	ND	ND	0.033	ND
9/7/95	0.026	8.6E-06	5.2E-06	14.064	4.1	1.518	2.8E-05	4.1E-04	ND	ND	0.017	ND
1/8/95	0.031	1.6E-05	1.0E-05	14.902	22.7	0.213	4.2E-06	4.7E-04	ND	ND	0.148	ND
19/10/95	0.110	8.8E-06	3.2E-06	16.462	5.8	9.659	6.2E-04	7.1E-04	0.056	0.506	0.011	0.006
28/6/96	0.023	1.4E-06	7.1E-07	14.670	5.1	0.741	5.3E-06	1.6E-04	ND	ND	0.031	ND
16/9/96	0.044	2.0E-06	5.2E-07	15.505	3.5	1.716	1.6E-05	1.8E-04	ND	ND	0.026	ND
17/10/96	0.088	6.6E-06	1.4E-06	15.283	8.8	8.961	1.7E-04	3.3E-04	0.031	0.350	0.010	0.003
7/11/96	0.047	2.3E-06	7.6E-07	14.606	15.6	2.981	1.1E-04	3.9E-04	0.018	0.378	0.016	0.006
15/1/97	0.016	1.3E-06	5.3E-07	13.972	17.4	1.137	2.1E-05	2.1E-04	0.000	0.020	0.014	0.000
3/2/97	0.019	1.3E-06	7.3E-07	13.491	7.6	1.012	2.1E-05	3.0E-04	0.000	0.016	0.019	0.000
4/3/97	0.009	9.9E-07	2.1E-07	13.542	1.0	1.323	1.8E-05	2.9E-04	0.013	1.424	0.007	0.010
13/3/97	0.022	2.0E-06	1.1E-06	13.677	8.7	0.972	1.1E-05	1.9E-04	0.012	0.557	0.023	0.013
1/6/97	0.056	2.5E-06	7.6E-07	15.396	7.4	3.868	6.5E-05	2.5E-04	0.003	0.054	0.015	0.001
19/8/97	0.034	2.5E-06	8.3E-07	15.173	3.2	0.552	5.9E-06	2.0E-04	ND	ND	0.062	ND
26/8/97	0.026	3.7E-06	1.8E-06	15.063	7.2	0.637	7.7E-06	2.6E-04	0.001	0.058	0.041	0.002
9/9/97	0.038	6.9E-06	3.1E-07	15.246	9.3	1.161	1.8E-05	1.7E-04	0.003	0.084	0.033	0.003
3/2/98	0.037	2.3E-06	4.8E-07	13.466	6.5	2.670	4.7E-05	2.8E-04	0.023	0.634	0.014	0.009
7/3/98	0.023	2.0E-06	5.0E-07	13.835	8.2	1.503	2.7E-05	2.9E-04	0.017	0.738	0.015	0.011
8/4/98	0.054	3.0E-06	8.9E-07	13.768	7.8	6.026	2.2E-04	2.6E-04	0.036	0.659	0.009	0.006
18/4/98	0.047	2.3E-06	8.0E-07	13.774	4.3	4.831	1.5E-04	2.5E-04	0.034	0.718	0.010	0.007
9/8/98	0.037	5.6E-06	8.3E-07	14.618	10.3	0.479	3.3E-06	1.4E-04	ND	ND	0.076	ND
6/5/99	0.030	5.2E-06	4.1E-07	14.353	14.6	0.945	5.9E-06	1.2E-04	ND	ND	0.032	ND
15/9/99	0.065	2.7E-06	1.4E-06	15.923	9.0	5.898	2.1E-04	3.9E-04	0.039	0.603	0.011	0.007
8/10/99	0.019	1.3E-06	4.6E-07	13.734	5.7	1.259	1.9E-05	1.9E-04	0.010	0.504	0.015	0.008
1/11/99	0.029	6.1E-06	2.3E-06	14.368	13.5	1.829	4.7E-05	4.3E-04	0.017	0.598	0.016	0.009
12/12/99	0.044	5.0E-06	5.1E-07	14.228	7.5	6.462	4.1E-04	1.8E-04	0.039	0.890	0.007	0.006
Average	0.038	4.4E-06	1.5E-06	14.517	8.4	2.574	8.3E-05	2.8E-04	0.019	0.483	0.026	0.006
Maximum	0.110	1.6E-05	1.0E-05	16.462	22.7	9.659	6.2E-04	7.1E-04	0.056	1.424	0.148	0.013
Minimum	0.009	9.9E-07	2.1E-07	13.466	1.0	0.213	3.3E-06	1.2E-04	0.000	0.016	0.007	0.000

[a] 1.2E-05 equals 1.2×10^{-5}

Prop propagation; *ND* data not available

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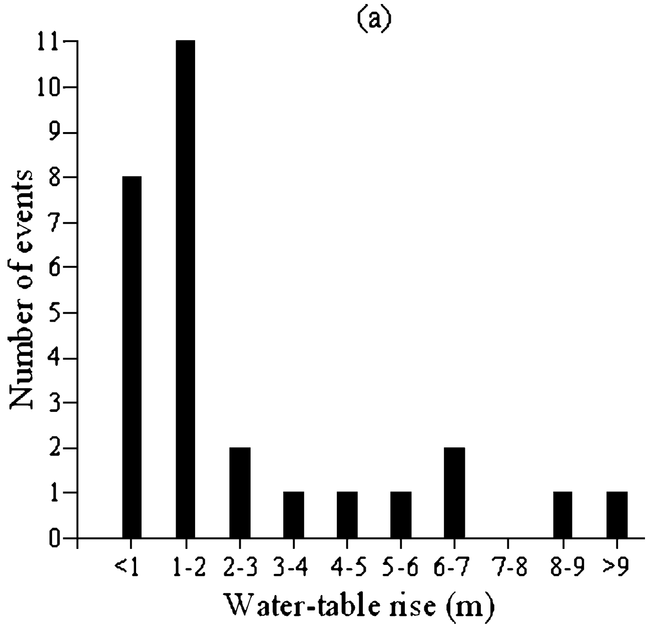

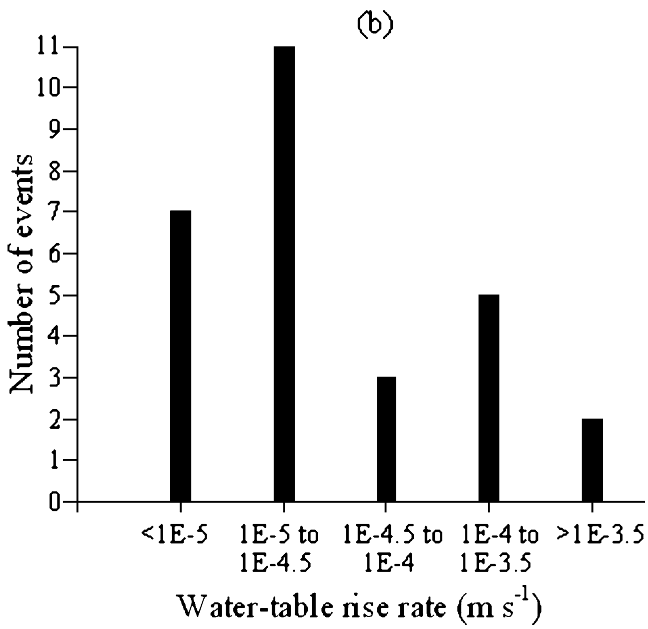

Fig. 5 **a** Histogram of water-table rise for the 28 events affecting the center well during the study period. **b** Histogram of water-table rise rate for the 28 events affecting the center well during the study period. E refers to the base-10 exponent: e.g., 1E-4=1.0x10^{-4}

table rise and lysimeter percolate to water-table rise for all five wells. In general, the ratio of lysimeter percolate to water-table rise is smaller than the ratio of rainfall to water-table rise, indicating that a portion of rainfall is lost to ET before percolating to the depth of the lysimeter collection pans. The small values for the mean and median values of these ratios, which when viewed reciprocally indicate large water-table responses for a given amount of water reaching the water table, point to the low effective storage capacity of the fractured rock medium. In addition to the variability of these ratios for a single well, demonstrated for the center well by the data in Table 3, there is also a substantial degree of variability between wells. This demonstrates that the water-table fluctuation process is not spatially uniform.

Table 4 Mean, median, standard deviation, minimum, and maximum values for two selected event-summary variables

Variable	Well Center	NE	NW	SE	SW
Rainfall/water-table rise (−)					
Mean	0.026	0.051	0.055	0.017	0.022
Median	0.016	0.016	0.025	0.014	0.011
SD	0.029	0.087	0.092	0.008	0.026
Minimum	0.007	0.006	0.009	0.010	0.007
Maximum	0.148	0.343	0.414	0.030	0.089
Lysimeter percolate/water-table rise (−)					
Mean	0.006	0.009	0.010	0.006	0.005
Median	0.006	0.009	0.011	0.007	0.005
SD	0.004	0.003	0.005	0.005	0.003
Minimum	0.000	0.002	0.003	0.001	0.000
Maximum	0.013	0.013	0.019	0.013	0.009

SD standard deviation

Table 5 shows the weighted-average normalized correlation coefficients for summary variable pairs extracted from event data from all five wells. The following correlations are significant (i.e., they have weighted-average normalized correlation coefficients greater than 1.0):

- Initial water-table depth–rainfall amount
- Rainfall amount–water-table rise
- Rainfall amount–average rate of water-table rise
- Average rainfall intensity–peak rainfall intensity
- Average rainfall intensity–signal propagation velocity
- Peak rainfall intensity–signal propagation velocity
- Water-table rise–average rate of water-table rise

These results indicate that rainfall amount is the primary determinant of the magnitude and rate of water-table rise, confirming the notion that the observed water-table rises are caused by rainfall-driven recharge events. Furthermore, there is a strong correlation between the rainfall intensity (both peak and average) and the signal propagation velocity, indicating that the timing of the water-table response depends in part on the severity of the rainfall event. This is true even though the signal propagation velocity is not highly variable, as shown for the center well events in Table 3. The magnitude and rate of water-table rise for individual events are strongly correlated. Finally, the correlation between initial water-table depth and rainfall amount suggests that large rainfall events are more likely to occur when the water table is deep, which typically occurs in late summer or autumn.

Continuous well hydrograph analysis using a master recession curve

The MRC method was used to investigate both recharge with a constant specific yield and transience in specific yield using lysimeter recharge estimates. These compli-

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Table 5 Weighted-average normalized correlation coefficients for event-summary variable pairs

	Initial water-table depth	Drainage time	Rainfall	Peak rainfall intensity	Average rainfall intensity	Water-table rise	Average rate of water-table rise	Signal prop. velocity	Rainfall/ water-table rise
Initial water-table depth	–								
Drainage time	−0.02	–							
Rainfall	1.15[a]	−0.07	–						
Peak rainfall intensity	0.61	0.86	0.71	–					
Average rainfall intensity	0.42	0.51	0.31	1.42[a]	–				
Water-table rise	0.82	−0.16	1.61[a]	0.31	0.11	–			
Average rate of water-table rise	0.90	−0.04	1.53[a]	0.51	0.24	1.72[a]	–		
Signal propagation velocity	0.71	0.33	0.88	1.10[a]	1.40[a]	0.82	0.92	–	
Rainfall/water-table rise	0.22	0.54	−0.24	0.49	0.39	−0.92	−0.63	−0.22	–

[a] Values whose absolute value exceeds 1.0 are statistically significant at the 1% confidence level

Prop propagation

mentary approaches address the question of transience in specific yield from two opposite sides. Figure 6 shows the MRC-estimated recharge for each month in the period of record when a constant specific yield of 0.01 is used, corresponding roughly to the specific yield values determined by Gburek and Folmar (1999). Comparing Fig. 6 with Fig. 4, it is clear that the MRC estimates of recharge are larger in the summer and smaller in the winter than the lysimeter-estimated recharge amounts. Whereas the lysimeter percolate drops to essentially zero in the summer the water-table data show significant responses during those months (see, for example, the event of 1 June 1997 in Table 3). These water-table movements are interpreted as recharge by the MRC algorithm. Figure 7 shows the average MRC-predicted monthly recharge based on all five wells when using a constant specific yield of 0.01. There is a slight seasonal trend in the predicted recharge, but not as pronounced as the seasonal trend in lysimeter percolate. The average annual recharge is 0.28 m, which is 27% of precipitation for water years 1995–1999.

As a second approach, the specific yield required to make the MRC-estimated recharge for each well agree with the lysimeter recharge estimates was computed for each month and each well. Figure 8 shows that the range of this back-calculated specific yield is large, ranging from a small fraction of 1% to several percent for some

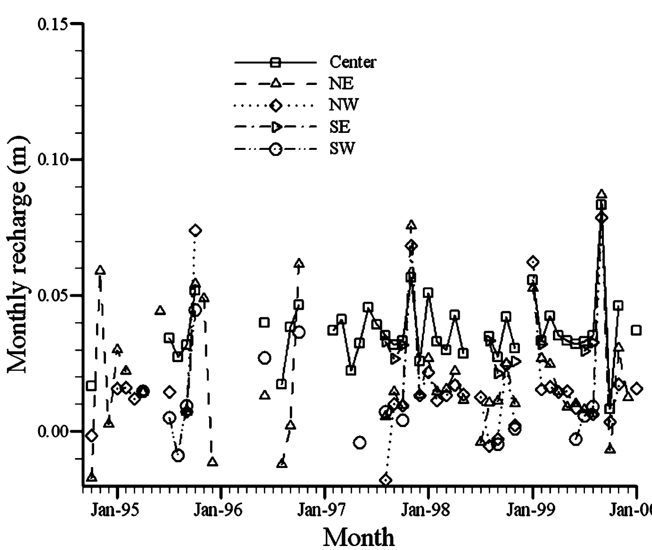

Fig. 6 MRC-estimated recharge for the period from October 1994 to January 2000 when a constant specific yield of 0.01 is used

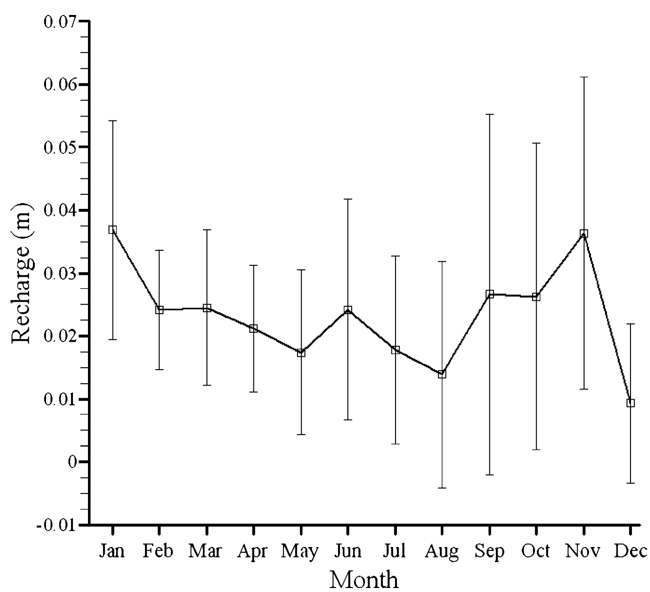

Fig. 7 Monthly MRC-predicted recharge, averaged for data of 6 years, computed with a constant specific yield of 0.01, based on all five wells. The *error bars* represent one standard deviation

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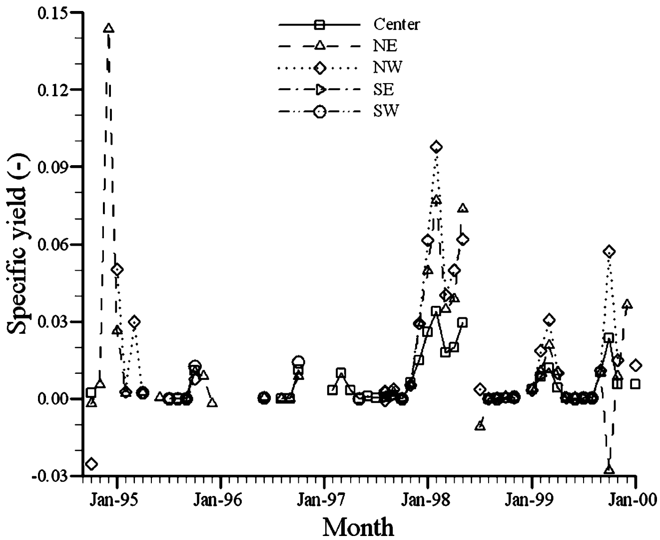

Fig. 8 Specific yield required to make the MRC-estimated recharge agree with the lysimeter-estimated recharge for each well for the period from October 1994 to January 2000

individual wells. There are a few negative values, indicating that the MRC algorithm regarded the month as a net discharge month while the lysimeter data showed positive recharge. An important feature of the data in Fig. 8 is the high degree of seasonal variability. To match the lysimeter estimates of recharge the MRC approach requires the specific yield to be very low (or even zero) in summer, and to nearly equal or exceed the total matrix porosity of 0.02 (Gburek and Folmar 1999) in winter.

From both Fig. 6 and Fig. 8, it is clear that there are differences in the MRC-estimated recharge between different wells. For example, the center well has consistently higher recharge estimates than the NE and NW wells. This could reflect actual spatial variability of recharge, or it could point to inter-well variability in the appropriate specific yield caused by heterogeneity in fracture storage properties.

Discussion

Interpretation of lysimeter and WTF results

There are at least two reasonable hypotheses for how recharge varies with seasonality in climatic inputs. The first, lysimeter-favoring, hypothesis is that the grass lysimeter data represent a true measure of recharge and, therefore, recharge and specific yield are both highly seasonal. The second, well-favoring, hypothesis is that recharge and specific yield are not as dramatically seasonally variable as the lysimeter data would suggest, and that the lysimeters significantly underestimate recharge in summer.

The lysimeter-favoring hypothesis relies chiefly on the fact that the lysimeter percolate data show a pronounced minimum in summer. Though not measured here, ET is surely greater in the summer growing season so that a greater proportion of rainfall is lost to ET in the summer and less goes to recharge. Therefore, given the relative seasonal steadiness of rainfall, the decrease in summer percolate is expected. However, the consistent and substantial differences between the different lysimeter sets (Figs. 2 and 3; Table 1) show that the different types of lysimeters respond differently, suggesting that lysimeter design affects percolate collection efficiency. This raises questions about the overall accuracy of the lysimeter recharge estimates. The lysimeter-favoring hypothesis also requires a mechanism whereby the specific yield in the zone of water-table fluctuations is highly seasonal with a minimum in the summer (Fig. 8). Possible mechanisms of specific yield reduction include air entrapment and higher antecedent moisture conditions in the near surface zone, but such mechanisms do not have an obvious seasonal character.

The well-favoring hypothesis, that specific yield is constant throughout the year and the lysimeters underestimate summer recharge due to such causes as (1) drier soil conditions than in winter, which prohibit percolate from leaving the lysimeter, and (2) increased ET from the lysimeters relative to the surrounding soil due to their wetter conditions, is supported by several observations. First, there are summer rainfall events associated with significant water-table rises that have no associated lysimeter response, which suggests that recharge is occurring without appearing in the lysimeter record. Second, the different lysimeter groups vary in their cumulative responses, possibly because of boundary effects, discussed previously (see section Lysimeter analysis), that reduce percolate collection efficiency for shallower lysimeters and for those installed under crop cover below a layer of soil. Third, it is possible to obtain a seasonally variable-recharge estimate from the MRC method using a constant specific yield (Fig. 7). The data, however, do demonstrate spatial variability between wells, in both individual event response and in monthly recharge predicted with the continuous MRC approach.

Fractures or macropores exist at all depths in the near surface at the Masser site, with some exhibiting much greater conductance than others; evidenced, for example, by the high conductivity reported for one deep interval from the packer tests of Gburek and Folmar (1999). Water that encounters a highly conductive fracture in the soil or near its base can move quickly down to the water table and become recharge, or at least propagate a fast pressure signal. Whereas the 0.61-m-diameter lysimeters with impermeable sides sample only a small surface area, the wells, uncased below 5.5 m, effectively sample a much greater extent of the fractured medium. It is likely that some of the fast, possibly tortuous, flow paths do not fit entirely within the volume of a single lysimeter. This would give the wells a higher probability of being influenced by highly conductive fractures, and therefore a stronger response to rainfall. It also follows that while the lysimeters fail to respond to some summer events due to dry near-surface conditions, the water table could respond by way of water delivered through the highly conductive fractures. To the extent that spatial variability

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among lysimeters in the same group is evident in the data (see Table 2), the role of fracture/macropore heterogeneity in causing variable recharge is demonstrated. Wuest (2005) has demonstrated that the blocking of lateral preferential flow paths by infiltration rings pressed into the soil substantially inhibits infiltration, a mechanism that is likely to inhibit both infiltration and recharge in lysimeter rings pressed into the soil. This effect might be more severe in summer if preferential flow paths are more critical to recharge because of the relative dryness of the soil.

Variability in both individual well responses and individual lysimeter responses within a lysimeter set may result almost entirely from spatial heterogeneity of the subsurface media. Soils and rocks normally are very heterogeneous in the characteristics that control saturated, and especially unsaturated, flow; and the abundance of macropores and fractures at the Masser site make flow phenomena even more likely to vary strongly in space.

Advantages and disadvantages of each method

The lysimeter-percolate analysis provides the most direct measurements of vertical flux through time at the depth of installation, and, with multiple lysimeters, gives a first estimate of the spatial variability in near-surface response to rainfall. However, lysimeter installation is costly and usually involves significant physical disturbance to the shallow subsurface. In regions with substantial fracture heterogeneity, a large number of lysimeters may be needed to capture the range of fluxes. Lysimeters only allow for measurement of downward flux, and are subject to systematic errors associated with boundary conditions—for example, the perturbation of soil-water content if the outflow boundary is held at a matric potential different from that of the surrounding soil at that depth.

The event-summary data analysis reveals general system behaviors, and is useful in identifying the main inputs and outputs of this cause-and-effect system. It does not, however, estimate recharge directly.

The MRC method uses water-level data that are often easily obtained with existing wells. Combined with the WTF approach, it gives event-based or continuous estimates of recharge. Data requirements are few (although a long continuous water-table record is highly desirable) and the computations are inexpensive. However, the method's success depends on reliable estimates of specific yield, a parameter which may be transient and spatially variable. Reliable estimates of specific yield are especially problematic in fractured, low-storage aquifers because recharge estimates are highly sensitive to small absolute errors in specific yield. Application of the MRC method to arid environments is possible if the water table is deep enough to be unaffected by ET (i.e., the only mechanism of water-table fluctuation accounted for is groundwater recharge/discharge). Additionally, this method has not been tested and may need to be modified for situations where significant transient human influences on water-table elevation (i.e., pumping) occur.

Summary

Lysimeter and water-table fluctuation estimates of aquifer recharge for the Masser Recharge Site (PA) were compared. A new approach for computing continuous estimates of recharge from water-table records using a master recession curve was demonstrated. Average annual recharge estimates for the site, based on data from eight lysimeters in a grass plot and on the WTF-MRC method using data from all wells and a constant specific yield of 0.01, are 32 and 27%, respectively, of annual precipitation. Although observed precipitation displays very little seasonality, recharge estimated by both methods was less during the summer, substantially so for the lysimeter-based estimates. Difficulties in reconciling the different degrees of seasonality in the recharge estimates from lysimeters and WTF methods may be partially resolved by considering the effect of widely spaced conductive fractures in the subsurface. In addition to the importance of having good water-table data, the accuracy of the WTF method can be improved with better estimation of specific yield, especially if transient effects are considered.

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