Assessing diffuse and concentrated recharge in average- and dry-rainfall year in a semiarid carbonate sloping aquifer, a preliminary report

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ABSTRACT

The chloride mass balance (CMB) method was applied in the unsaturated zone to estimate potential recharge (R_T) by rainfall in two small catchments of southern mid-to-high slope of Sierra de Gádor carbonate aquifer (SE Spain), in the average hydrological year 2003-04 and the unusually dry 2004-05. Unknown fractions of diffuse (R_D) and concentrated recharge (R_C) into R_T were firstly evaluated to fit average and lower R_T thresholds for modeling further long-term recharge. Daily rainfall and actual evapotranspiration (AET) from the Eddy Covariance (EC) technique provided yearly R_T of 189 mm year^{-1} in 2003-04 and 8 mm year^{-1} in 2004-05. Difference on R_T among CMB method and EC technique is ~5% in year 2003-04, increasing to ~25% in year 2004-05. R_D from soil-moisture field data was 65 mm year^{-1} (~34% of R_T) in 2003-04 and negligible in 2004-05. The use of complementary methods checks low R_T rates and identifies R_D and R_C fractions mixing in the unsaturated zone before R_T reaches the regional water-table top. The results can explain long-term variations on groundwater storage and hydrochemistry and validate lower R_T ~ R_C yearly rates from the EC technique.

Key words: recharge, diffuse, concentrated, sloping aquifer, semiarid, SE Spain.

INTRODUCTION

Groundwater potential recharge by rainfall (R_T) over large semiarid regions involves unknown and spatiotemporal variable fractions of diffuse (R_D) and concentrated recharge (R_C). R_D and R_C factions can be evaluated by using several methods of estimation and their evidences can be observed as long-term variations on the groundwater storage and hydrochemistry linked to long-term climatic cycles in most aquifers (Simmers et al., 1992; Custodio et al., 1997). In sloping carbonated aquifers, topography becomes essential to increases R_T with elevation. In semiarid aquifers with deep water-table, only extreme rainfall-year, or recurrent dry or wet periods, leaves memory of the climatic patent that control the magnitude of R_T reaching the regional water-table top as effective recharge delayed in time. The existence of intermediate groundwater discharges through local springs favoured by low permeability layers allows studying R_T in transit just below the root zone in an upper part of the unsaturated zone. Here, R_T integrates from daily to weekly events of rainfall infiltration. The influence of variable R_D and R_C fractions on discharge is unknown and it is the key for improving the knowledge of groundwater flow system in these usually ungauged environments. This paper focuses the average and lower thresholds of R_T, R_D and R_C in the high permeability carbonate aquifer of Sierra de Gádor for modelling further long-term recharge by rainfall.

STUDY AREA AND METHODS

Sierra de Gádor is an unconfined carbonate coastal aquifer (peak elevation 2246 m a.s.l.) of 670 km^2 in southeast Spain. It consists of a thick series of high permeability Triassic limestone, dolomites and calcoschists, underlain by Permian to Triassic metapelites of low permeability, extending under the Campo de Dalías coastal plain (Martín-Rojas et al., 2009). Average yearly temperature is ~18ºC at coastal plain and 9ºC at the summit. Average precipitation is from 215 mm $year^{-1}$ to 650 mm $year^{-1}$ with a coefficient of variation (mean value/standard deviation ratio, dimensionless) from 0.3 to 0.4 (Pulido-Bosch et al., 2000; Contreras et al., 2008) in this bearing. Recharge is from rainfall infiltration mixing at different altitude and varies from 40 mm $year^{-1}$ in the coast to more than 250 mm $year^{-1}$ in the high areas (Alcalá et al., 2007; Contreras et al., 2008). Pumping of 140 Mm^3 per year (~250 mm $year^{-1}$) in the coastal plain to irrigate 260 km^2 of greenhouses (70% of total surface) and to supply tourism activities and population is the main discharge (Pulido-Bosch et al., 2000).

The stable isotopic signature of rainfall and groundwater found the most suitable range for recharge from 1000 m a.s.l. to the summit (Vallejos et al., 1997; Alcalá et al., 2007). One representative area at that elevation is the Llano de los Juanes site at 1600 m a.s.l., where recharge averages from 150 to 200 mm $year^{-1}$ (Alcalá et al., 2007; Contreras et al., 2008). Their specific hydrologic boundary conditions allows to study the R_D and R_C fractions in detail: (1) summit area with input runoff = 0; (2) small flat endorheic basin of 2 km^2 without stream beds outputting runoff; (3) thin and well drainable soils with negligible weekly-to-seasonal water storage. For a time interval, the steady-state water balance in the soil is:

$$P = AET + R_D + R_C \quad (1)$$

where P = effective rainfall, i.e. the rainfall that reaches the soil surface after the interception has been discounted; AET = actual evapotranspiration; R_D = potential diffuse recharge leaving downwards the soil root zone in excess of soil moisture deficits and AET; R_C = potential concentrated recharge bypassing the soil root zone by preferred pathways (e.g., macro-pores) with a relatively high infiltration capacity.

In this area, daily R_T was obtained from daily record of P and AET measured by the Eddy Covariance (EC) technique (Anderson et al., 1984). Yearly R_T is estimated grouping daily R_T values. The EC method uses two turbulent sensors measuring at high frequency (10Hz), a sonic anemometer (CSAT3, Campbell Scientific Inc., USA) measuring the three components of wind speed and a krypton hygrometer (KH20, Campbell Scientific Inc., USA) measuring fluctuations in water vapour density. Measurements were averaged and logged every 30 minutes, and corrections of the water and heat fluxes were made according to air density fluctuations and two coordinate system rotations (Kowalski et al., 1997). Hygrometer measurements were also corrected for absorption of radiation by oxygen. Rainfall amount and intensity were recorded by an automatic 0.20 mm-resolution tipping-bucket rain gauge.

Daily R_D was approached measuring continuous soil moisture (θ, in volumetric percentage, v/v%) with probes installed at 0.06 and 0.35 m depth. Local thin soils average 0.4 m. Since the decrease of θ at soil bottom between two successive days due to evaporation and/or percolation is approximated by θ_D, as current-daily θ deficit or the depth of water required for bringing the soil up to the field capacity, θ_{FC}, is the θ_D on the previous day or θ_{PD} (Rushton et al., 2006). At soil bottom, if $\theta_D > \theta_{FC}$, then soil becomes free-draining producing R_D as:

$$R_D = \theta_D - \theta_{FC} \quad (2)$$

being θ_D set to θ_{FC}. θ_{FC} was determined in laboratory as 37% when the decreasing rate of θ was less than 1L·30 min^{-1} (Bruno et al., 2006).

R_T was estimated through the chloride mass balance (CMB) method in two representative areas of the southern slope of Sierra de Gádor. Fuente Alta (1735 m a.s.l.) and Enix (825 m a.s.l.) springs catchments drain small perched aquifers. The short range of elevation and capacity for runoff generation induces the same hydrological boundary conditions that accounted for Llano de los Juanes, with runoff out-letting only in wettest periods (Martín-Rosales et al., 2007). The solute mass balance (e.g. the chloride ion) involved in the steady-state soil water balance can be expressed (Wood et al., 1997; Custodio et al., 1997) as:

$$P \cdot C_P = R_D \cdot C_{RD} + R_C \cdot C_{RC} \quad (3)$$

where AET, which is chloride-free water vapour, is neglected; C is the chloride concentration and subscripts identify the water term involved. Discharge in local springs is assumed equal to R_T with unknown fractions of R_D and R_C involved. Then, equation [3] becomes:

$$P \cdot C_P = R_T \cdot C_{RT} \quad (4)$$

being A_P = $P \cdot C_P$ the atmospheric bulk chloride deposition in the study period (g m^{-2}) or the yearly rate grouping successive periods (g m^{-2} $year^{-1}$). The C_P and C_{RT} contents (mg L^{-1}) were analyzed by the Geological Survey of Spain Laboratory following the EPA 300 1A method on filtered unacidified samples. A DIONEX 600® high-performance liquid (anionic) chromatograph was used with a precision of ±0.015 mg·L^{-1} for chloride contents less than 0.5 mg L^{-1}, which are usual in low mineralized rainwater samples (Alcalá and Custodio, 2008a,b).

RESULTS

For the average rainfall-type hydrological year 2003-04, R_T from the EC technique was 181 mm $year^{-1}$. For the dry hydrological year 2004-05, R_T was only 8 mm $year^{-1}$. Yearly R_D was 50 mm $year^{-1}$ for year 2003-04 and negligible for year 2004-05. R_D is ~34% of R_T in the average rainfall-year type decreasing progressively to be negligible for satisfying soil water demand in the dry rainfall-year type. Yearly R_D rate is expected to be ~50% of R_T in wet rainfall-year types, although the short available series prevent to quantify this amount.

In Fuente Alta and Enix springs catchments, discharge is a small fraction of regional R_T in transit intersected by the topography. Discharge was measured 2-to-3 times by season to determinate the flow-weighted groundwater chloride content, C_{RT} (mg L^{-1}). R_D and R_C fractions involved in R_T are supposedly well mixed before to be discharged. Seasonal rainfall samples collected in open rain-gauges at each site provided the rainfall depth P (mm) and its average C_P concentration (mg L^{-1}) to calculate A_P (g m^{-2}) for the period. Each sampling interval of A_P and the corresponding C_{RT} content (mg L^{-1}) allows estimating seasonal values of R_T through equation [4]. For the hydrological year 2003-04, yearly R_T were 209 and 132 mm $year^{-1}$ in Fuente Alta and Enix springs catchments respectively, while for the hydrological year 2004-05, R_T values were 44 and 18 mm $year^{-1}$. These results provide a spurious difference of ~5% among R_T estimates through the CMB method and the EC technique in year 2003-04, after correcting values with elevation, increasing up to 25% in year 2004-05. A similar magnitude of R_T among nearby places induces a similar magnitude of R_C and R_D fractions in the R_T values that can be regionalized. This means that long-term R_T keep memory of the variation of amount, intensity and frequency of rainfall with elevation, mainly with less relevance of steady-state lithology, slope, soil properties and vegetation cover.

DISCUSSION AND CONCLUSION

The accurate R_T estimation through the EC technique and the tentative appraisal of R_D from soil moisture field data allows firstly calibrate yearly R_T in transit and secondly to estimate the expectable R_D and R_C fractions involved in R_T before becoming effective recharge susceptible to be pumped, both for average- and dry-rainfall years. This work provides a conceptually simple route for assessing R_T in ungauged sloping carbonate aquifers, as a source of knowledge for other mid-latitudes carbonate landscapes. The CMB method application is well-know for regional recharge estimation, and it is accurate at local scale when specific hydrogeological boundary conditions, such as R_D and R_C fractions involved in R_T, are well-conceptualized and parameterized.

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REFERENCES

- Alcalá, F.J. & Custodio, E. 2008a. Atmospheric chloride deposition in continental Spain. *Hydrological Processes*. 22, 3636-3650.
- Alcalá, F.J. & Custodio, E. 2008b. Using the Cl/Br ratio as a tracer to identify the origin of salinity in aquifers in Spain and Portugal. *Journal of Hydrology*. 359, 189-207.
- Alcalá F.J., Custodio E., Contreras S., Araguás L.J., Domingo F., Pulido-Bosch A. & Vallejos Á. 2007. Influencia de la aridez climática, la altitud y la distancia al mar sobre el contenido en cloruro y en $\delta^{18}O$ del agua de recarga y del agua subterránea en macizos carbonatados costeros del SE peninsular español. Caso de Sierra de Gádor. In: Pulido-Bosch, A., López-Geta, J.A. and Ramos, G. (Eds.) Coastal aquifers intrusion technology: Mediterranean countries. IGME, Madrid, 871-885.
- Anderson, D.E., Verma, S.B. & Rosenberg, N.J. 1984. Eddy correlation measurements of CO_2, water vapour and sensible heat fluxes over a crop surface. *Boundary-Layer Meteorology*. 29, 167-183.
- Bruno, R.D., da Rocha, H.R., de Freitas, H.C., Goulden, M.L. & Miller, S.D. 2006. Soil moisture dynamics in an eastern Amazonian tropical forest. *Hydrological Processes*. 20, 2477-2489.
- Contreras, S., Boer, M.M., Alcalá, F.J., Domingo, F., García, M., Pulido-Bosch, A. & Puigdefábregas, J. 2008. An ecohydrological modelling approach for assessing long-term recharge rates in semiarid karstic landscapes. *Journal of Hydrology*. 351, 42-57.
- Custodio, E., Llamas, M.R. & Samper, J. (Eds.) (1997). La Evaluación de la Recarga a los Acuíferos en la Planificación Hidrológica [in Spanish with abstract in English]. IAH Spanish Chapter and ITGE, Madrid, 1-455.
- Kowalski, A.S., Anthoni, P.M., Vong, R.J., Delany, A.C. & Maclean, G.D. 1997. Deployment and Evaluation of a System for Ground-Based Measurement of Cloud Liquid Water Turbulent Fluxes. *Journal of Atmospheric and Oceanic Technology*. 14, 468-479.
- Martín-Rojas, I., Somma, R., Delgado, F., Estévez, A., Iannace, I., Perrone, V. & Zamparelli, V. 2009. Triassic continental rifting of Pangaea: direct evidence from the Alpujarride carbonates Betic Cordillera, SE Spain. *Journal of the Geological Society*. 166, 477-458.
- Martín-Rosales, W., Gisbert, J., Pulido-Bosch, A., Vallejos, Á. & Fernández-Cortés, Á. 2007. Estimating groundwater recharge induced by engineering systems in a semiarid area (southeastern Spain). *Environmental Geology*. 52, 985–995
- Pulido-Bosch, A., Pulido-Lebouf, P., Molina, L., Vallejos, A. & Martín-Rosales, W. 2000. Intensive agriculture, wetlands, quarries and water management. A case study (Campo de Dalías, SE Spain). *Environmental Geology*. 40, 163-168.
- Rushton, K.R., Eilers, V.H.M. & Carter, R.C. 2006. Improved soil moisture balance methodology for recharge estimation. *Journal of Hydrology*. 318, 379–399.
- Simmers, I., Hendrickx, J.M.H., Kruseman, G.P. & Rushton, K.R. 1997. Recharge of phreatic aquifers in (semi)arid areas. International Contributions to Hydrologeology 19. IAH. Balkema, Rotterdam. 1-277 pp.
- Vallejos, A., Pulido-Bosch, A., Martín-Rosales, W. & Calvache, M.L. 1997. Contribution of environmental isotopes to the knowledge of complex hydrologic systems. A case study: Sierra de Gador (SE Spain). *Earth Surface Processes and Landforms*. 22, 1157–1168.
- Wood, W.W., Rainwater, K.A. & Thompson, D.B. 1997. Quantifying macropore recharge: examples from a semi-arid area. *Ground Water*. 35, 1097-1106.