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Groundwater recharge assessment in an upland sandstone aquifer of southern California

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ABSTRACT

The Chloride Mass Balance (CMB) method was used to obtain long-term recharge values for the Santa Susana Field Laboratory (SSFL) site, which features a groundwater flow system beneath an upland ridge formed of sandstone and shale beds in the Simi Hills, Ventura County, southern California. This application relied on the availability of on-site measurements of bulk atmospheric chloride deposition comprised of dry fallout and wet concentration, a large number of groundwater samples (~1490) collected over three decades from 206 wells spanning a depth range from 10 to 360 m, and measurements of chloride in surface runoff during rain events. The use of the CMB method is suited to the assessment of recharge for the study area because the mean chloride values in groundwater show minimal spatial trends, indicating no sources other than atmospheric. In addition, the Cl/Br ratio was used to exclude wells with possible anthropogenic chloride. The site-wide average recharge ranges between 1.8 and 9.5% of the mean annual precipitation (455 mm) with a mean value of 4.2%. The measured surface runoff varies from 2.3 to 10.2% with mean value of 6.1% (28 mm) and, therefore, the volume of water lost to evapotranspiration is between 95.9 and 80.3% with a mean value of 89.6% (408 mm). The long-term recharge calculated using the CMB method is consistent with tritium distribution based on a subset of groundwater monitoring wells and with an analysis of steady flow in the groundwater mound beneath the SSFL. Furthermore, the recharge value matches those in the literature for sandstone aquifers in arid and semi-arid climates. This recharge estimate has important relevance for site characterization in terms of constraining the volumetric groundwater flow rates and water balance and understanding the mechanisms of transport towards the water table. Moreover, this is the first application of the CMB in an upland area of California. Hence, the method is demonstrated to be robust and applicable to many upland bedrock areas in southern California and similar regions around the world, and can be used to quantify groundwater flow rates and supplies relevant to water resource management.

1. Introduction

Groundwater recharge to an aquifer can be defined broadly as the water that reaches the aquifer from any direction (Scanlon et al., 2002). But generally, and in this paper, the term recharge to a groundwater flow system is taken to be the volume of water that crosses the water table after infiltration through the vadose zone, expressed as the height of the water column that enters the groundwater zone per unit time. Although recharge is a basic component of the hydrological cycle, quantification is difficult because it cannot be directly measured at the spatial scale of most relevance. Therefore, indirect methods must be used to obtain recharge rate estimates in climatic, spatial scale, and temporal scale contexts. Some of the most common techniques are those based on natural tracers, such as chloride and tritium, which are soluble, can behave conservatively, and can be measured accurately (Healy, 2010). The Chloride Mass Balance (CMB) method was first applied by Schoeller H. (1941, 1962), Schoeller M., (1961, 1963) and Eriksson (1952) to estimate recharge by comparing the concentration of chloride in groundwater to the concentration of chloride deposited through wet precipitation and dry fallout. The assumptions in this method are described by Allison and Hughes (1983), Edmunds and Gaye (1994), Wood and Sanford (1995), Sami and Hughes (1996) and Alcalá and Custodio (2014). Among these, two are key: (1) the bulk atmospheric chloride deposited on the ground must be the only source of chloride to the sub-surface system; and (2) the groundwater flow system

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can be approximated as steady-state with respect to chloride input and output for the time period of interest. Therefore, the chloride concentration in groundwater will be greater than the atmospheric input by a factor proportional to the concentrating effect of water loss due to evapotranspiration (ET). Part of the precipitation that falls on the land surface contributes to surface runoff, another part evaporates, and the rest infiltrates into the vadose zone where some is lost to the atmosphere via ET and the rest becomes groundwater recharge. The CMB method is based on the premise that essentially no chloride returns to the atmosphere in the water that either evaporates from the land surface or evapotranspirates following infiltration; this is well supported by Eriksson and Khunakasem (1969) and Allison (1988). The CMB approach has been mostly applied to the analysis of chloride profiles in the unsaturated zone of arid and semi-arid regions of the USA, Africa, and Australia not only to quantify recharge (Allison and Hughes, 1978; Scanlon et al., 2006; Simmers, 1988) but also to study past climate conditions (Phillips, 1994; Scanlon, 1991; Tyler et al., 1996) and the effect of changes in land use (Gee et al., 1994; Scanlon et al., 2007). Applying the method to the saturated zone, using chloride analysis of groundwater, has been conducted less frequently and leads to the estimation of site-wide mean recharge values (Cook et al., 2001; Sami and Hughes, 1996; Wood and Sanford, 1995).

A crucial point in CMB studies is the assessment of atmospheric chloride, which is deposited via two mechanisms (wet precipitation and dry fallout) and shows an exponential decrease in concentration with travel distance of humid air from the source area, typically the nearest sea. The main uncertainty is the quantification of the dry fallout, which is rarely measured and therefore in most studies only estimated. Murphy et al. (1996) found that dry fallout of Cl accounted for 60% of its deposition in south-eastern Washington and Ten Harkel (1997) measured aerosol deposition rates of Cl ranging from 7000 to 20,000 mg/m^2 per year in coastal areas of the Netherlands. Eriksson and Khunakasem (1969) and Dettinger (1989) consider the contribution of dry deposition to be 30% of the total, whereas Scanlon et al. (2007) double the wet precipitation value. Other authors use ordinary kriging to map atmospheric chloride deposition and to regionalize the data points collected (Alcalá and Custodio, 2014; Croisé et al., 2005; Delalieux et al., 2006; Gustafsson and Hallgren, 2000). This paper concerns application of the CMB approach, based on well sampling, as the primary method to estimate recharge to a site located in a semi-arid area of the Simi Hills in Ventura County, about 45 km northwest of Los Angeles, California and 25 km inland from the Pacific Ocean. The study area, known as the Santa Susana Field Laboratory (SSFL), is a decommissioned industrial research facility that was used from 1949 to 2006 and features chemical contamination of the underlying sedimentary bedrock.

This study was prompted by the need to construct a 3-D numerical model. Recharge values across the site are required as the boundary condition on the upper surface of the model domain. Moreover, the recharge rate in the areas of contaminant inputs governs the flux of groundwater available to transport contaminants in plumes (Cherry et al., 2009; MWH, 2009). This is the first application of the CMB method to an upland area in California and is based on the large number of chloride samples collected over three decades from a dense network of groundwater monitoring wells (206 over an area of about 11.5 km^2) with open intervals spanning a depth range from 10 to 360 m. Moreover, unlike other studies in the literature, streamflow chloride was measured at six locations representing the outfall of each catchment. The bulk atmospheric chloride deposition was measured from two on-site collectors for one full year and compared to the 33-year time series of the closest station of the National Atmospheric Deposition Program. The on-site measurement of the bulk deposition of atmospheric Cl and the analysis of Cl concentration in rainfall allowed the discretization of the two different deposition processes. As an independent check of the results, the distribution of atmospheric-derived tritium was analyzed for a subset of the groundwater monitoring wells. Tritium (^{3}H) has been extensively used in many flow system studies to calculate modern recharge (<60 years) in arid and semi-arid regions (Allison and Hughes, 1977; Andres and Egger, 1985; Cook and Böhlke, 2000; Solomon and Cook, 2000) because it was introduced globally into the atmosphere in a short period, with a peak between the 1950s and early 1960s resulting from above-ground nuclear weapons testing. The different timescale of the two approaches can affect the comparison of estimates made using the two methods. The time to accumulate Cl in groundwater ranges from decades to centuries while tritium distribution is relevant only in the last 60 years. Therefore, changes in climate conditions or land use can influence the recharge values as found by Cartwright et al. (2007). An additional check was performed using a Dupuit-Forchheimer approach to analyze steady flow in a groundwater mound sustained by steady recharge from above. Moreover, a comparison with previous studies in similar climatic regions and geological settings is presented.

2. Hydrogeology of the study area

The SSFL is located on a sedimentary bedrock upland, flat-topped ridge, with a maximum elevation of about 700 m asl that is 300 m above the adjacent valleys (Simi Valley and San Fernando Valley) (Fig. 1a). The bedrock of the SSFL is formed of Cretaceous sandstone belonging to the Chatsworth Formation (Yerkes and Campbell, 2005), with shale/siltstone interbeds dipping 30°NW as the result of turbidite deposition on a sub-marine fan (Link et al., 1981). About 15% of the area is covered by discontinuous-thin Quaternary alluvium (Fig. 1b). The Chatsworth Formation can be divided into Upper and Lower units encompassing a sequence of coarser-(sandstone with thickness up to 2 m and typical turbidite features) and finer- (siltstone and shale interbedded with thickness less than 1 m) grained units (Montgomery Watson, 2000). The different physical properties of the coarse- and fine-grained units can be used to identify the different hydrogeologic units. Meyer et al. (2014) recognize the different hydrogeologic units on the basis of vertical hydraulic conductivity contrasts from the analysis of high resolution head profiles obtained from Westbay® multilevel systems (MLSs).

The bedrock is densely fractured with bedding-parallel fractures as well as vertical or near-vertical joints and faults (Cilona et al., 2015, 2016; Sterling et al., 2005). Due to this structural setting, the groundwater circulation is dominated by flow in high density interconnected fractures rather than in the rock matrix between fractures. Pehme et al. (2009, 2013) use active line source (ALS) temperature profiling to demonstrate numerous active fractures intersecting each borehole. The matrix porosity ranges from 2 to 20% (geometric mean 13%) while the fracture porosity is between 0.01 and 0.0005% (Cherry et al., 2009; MWH, 2009). Because of this, the mountain has an active flow system with groundwater moving from the water table zone downward and outward mostly towards seeps, along the slopes, and deeper flow into the bedrock (Fig. 1b).

The presence of these laterally continuous finer- and coarse-grained units and the role of the geologic structures result in spatial variability in the bulk saturated hydraulic conductivity (K_b). Estimates of K_b from discrete-interval testing, single-well slug and pumping tests, and multiple-well pumping tests give a range from less than 1×10^{-9} to greater than 1×10^{-4} m/s, with older members having higher average values (Cherry et al., 2009; MWH, 2009). This interval is about one to three orders of magni-