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Spatial and temporal variability of groundwater recharge in a sandstone aquifer in a semi-arid region

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Abstract

With the aim to understand the spatial and temporal variability of groundwater recharge, a high-resolution, spatially-distributed numerical model (MIKE SHE) representing surface water and groundwater was used to simulate responses to precipitation in a 2.16 km^2 upland catchment on fractured sandstone near Los Angeles, California. Exceptionally high temporal and spatial resolution was used for this catchment modeling: an hourly time-step, a 20x20 meter grid in the horizontal plane and 240 numerical layers distributed vertically within the thick vadose zone and in the upper part of the groundwater zone. The finest-practical spatial and temporal resolution were selected to accommodate the large degree of surface and subsurface variability of catchment features. Physical property values for the different lithologies were assigned based on previous on-site investigations whereas the parameters controlling streamflow and evapotranspiration were derived from literature information. The calibration of streamflow at the outfall and of transient and average hydraulic head provided confidence in the reasonableness of these input values and in the ability of the model to reproduce observed processes. Confidence in the calibrated model was enhanced by validation through, i) comparison of simulated average recharge to estimates based on the

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applications of the chloride mass-balance method from data from the groundwater and vadose zones within and beyond the catchment (Manna et al., 2016; Manna et al., 2017) and, ii) comparison of the water isotope signature (^{18}O and ^{2}H) in shallow groundwater to the variability of isotope signatures for precipitation events over an annual cycle. The average simulated recharge across the catchment for the period 1995-2014 is 16 mm y^{-1} (4% of the average annual precipitation), which is consistent with previous estimates obtained by using the chloride mass balance method (4.2% of the average precipitation). However, one of the most unexpected results was that local recharge was simulated to vary from 0 to > 1000 mm y^{-1} due to episodic precipitation and overland runoff effects. This recharge occurs episodically with the major flux events at the bottom of the evapotranspiration zone, as simulated by MIKE SHE and confirmed by the isotope signatures, occurring only at the end of the rainy season. This is the first study that combines MIKE SHE simulations with the analysis of water isotopes in groundwater and rainfall to determine the timing of recharge processes in semi-arid regions. The study advances the understanding of recharge and unsaturated flow processes in semi-arid regions and enhances our ability to predict the effects of surface and subsurface features on recharge rates. This is crucial in highly heterogeneous contaminated sites because different contaminant source areas have widely varying recharge and, hence, groundwater fluxes impacting their mobility.

Introduction

Assessment of groundwater recharge is fundamental to create strategies for management of water resources and to estimate volumetric groundwater flow through contaminated sites. Recharge rates represent an indication of upper limit of the volume of precipitation that may be accessible for sustainable use and can govern the volume of water available to transport contaminants. Its importance is greater in semi-arid regions where dominance of evapotranspiration limits water resources. In these regions, estimated recharge rates depend on the temporal and spatial resolution

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of the investigation and the uncertainties associated with recharge values are usually large (Scanlon, 2000;Xie et al., 2018;Crosbie et al., 2018). In favorable circumstances, geochemical-based methods have proven to be especially useful for estimating recharge rates. In areas where the geologic and anthropogenic sources of chloride in the subsurface are negligible, natural chloride in the vadose zone and groundwater, deriving from atmospheric deposition, has been used to calculate long-term site-wide (Wood and Sanford, 1995;Gebru and Tesfahunegn, 2018;Jebreen et al., 2018) and location-specific recharge values (Heilweil et al., 2006;Huang et al., 2018) to determine mechanisms of flow in the vadose zone (Sukhija et al., 2003;Li et al., 2017) and to evaluate the effects of environmental changes on recharge process (Scanlon et al., 2007;Cartwright et al., 2007). Elevated tritium in precipitation derived from atmospheric releases during nuclear tests in the 1960's and transported into the subsurface has also been an invaluable tracer to determine modern recharge and mechanisms of flow in both vadose and groundwater zones (Cook and Böhlke, 2000;De Vries and Simmers, 2002). These geochemical and isotopic techniques are based on the interpretation of hydrologic process influences on the distribution of tracers in the subsurface but cannot show the transient effects nor provide a continuous spatial representation of these processes at the catchment scale.

Numerical hydrologic models that integrate surface water and groundwater flows have been developed to simulate the spatial and temporal distribution of surface runoff, infiltration, evapotranspiration and groundwater recharge. However, the application of nearly all such simulation tools have been limited to humid regions (Wheater et al., 2007) with minimal application to semiarid regions. Scanlon et al. (2006), in their review on recharge in semiarid areas reported only 7 papers providing a continuous spatial distribution of recharge, out of a total of 98 studies. These studies were conducted at Yucca Mountain (Flint et al., 2001), Hanford site (Fayer et al., 1996), Death Valley region (Hevesi et al., 2003), Great Basin (Flint et al., 2004), the semiarid southwestern US (Flint and Flint, 2007) and in the State of Nebraska (Szilagyi et al., 2005) and

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investigated large areas, from 1,039,647 km^2 (Flint and Flint, 2007) to 60 km^2 (Flint et al., 2001), using a relatively coarse spatial resolution (from 72,900 m^2 - Flint and Flint, 2007 to 900 m^2 - Flint et al., 2001). In the last decade, modeling techniques have advanced to include combined surface water-groundwater simulations. Among the commercially available models, the physically based MIKE-SHE represents the land-based hydrologic system, with an integration of the surface flows (i.e. precipitation, infiltration, evapotranspiration and runoff) and subsurface flows (i.e., percolation into the vadose zone and recharge across the water table) (Ma et al., 2016). However, the literature shows only two applications of MIKE SHE to assess recharge in semiarid areas. Liu et al. (2007) analyzed the recharge response associated with overland flow in an alluvial watershed (surface area: 91 km^2 - cell size: 2,500 m^2) in the Tarim Basin, China. Smerdon et al. (2009) distinguished and quantified the contributions of three sources to the total recharge for a valley bottom aquifer in the Oakanagan Basin (Canada) (surface area: 130 km^2 - cell size: 10,000 m^2).

In this study encompassing a 20-year period (1995-2014), we used MIKE SHE to simulate the recharge and the other hydrologic processes in a small catchment (2.16 Km^2) located on an exposed bedrock upland plateau (from 650 to 490 m asl) in the Simi Hills, near Los Angeles, California (Fig. 1). The area is semi-arid with potential evapotranspiration (CIMIS, 1999) exceeding the average annual precipitation (396 mm as the recorded average annual precipitation over the 1995 -2014 period). The bedrock consists of sandstone with interbeds of shale and siltstone, densely fractured with bedding parallel partings and vertical joints and faults (Cilona et al., 2015;Cilona et al., 2016;Link et al., 1984;MWH, 2016) (Fig. 2). The hydrogeology of the site has been investigated intensively over the past 20 years because of the chemical contamination in groundwater (Pierce et al., 2018a;Pierce et al., 2018b;Sterling et al., 2005;MWH, 2009;Cherry J.A., 2009) and construction of a 3-D flow model (FeFlow) has been an on-going effort (AquaResource and MWH, 2007). For this model, information about the spatial distribution of recharge is needed as an upper boundary condition and to refine results of previous studies. From the application at the site of the chloride mass balance (CMB), based on measurement of chloride in atmospheric deposition, surface water and groundwater, Manna et al. (2016) estimated a long-term average recharge of 19 mm y^{-1}, corresponding to the 4.2 % of the average precipitation (455 mm for the period 1878-2014). More recently, Manna et al. (2017) analyzed porewater Cl concentration profiles from the vadose and groundwater zones at 11 locations across the site. This provided spatially variable, long-term recharge values ranging from 4 to 23 mm y^{-1} and indicated that, on average, 80% of the flow in the vadose zone occurs as intergranular flow in the rock matrix and 20% as fracture flow. However, these chloride-based methods lump together hydrologic processes providing long-term recharge estimates for only few locations across a large site.

In this study, we analyze the spatial and temporal variability of recharge in a catchment representative of the varied surface and subsurface conditions found throughout the contaminated area. The catchment was chosen also because it is believed to be minorly impacted during the calibration period by the surface water controls measures in place. Given that the scope of the paper is to simulate the natural conditions, these initiatives are not considered in our modeling. To better represent the large range of surface and subsurface features and provide high-resolution representation of the spatial distribution of recharge, we used an hourly time-step and a fine grid of 400 m^2 cells for a total of 5,420 cells. In addition to the spatial variability, we also examined the seasonal dynamics of the hydrologic processes by tracking vadose zone water budgets for representative cells of the model. This analysis helped in understanding the transient conditions that determine the rates of the hydrologic processes throughout the year. The model was calibrated using measurements of runoff from instrumented outfall flows and quarterly observations of groundwater levels in 17 wells distributed across the catchment for the simulated period. The simulation results were also validated through comparison with previous independent recharge estimates based on application of the Chloride Mass Balance (Manna et al., 2016;Manna et al., 2017) and through the analysis of water isotopes from rainfall and groundwater that indicated the timing

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of recharge. Finally, we proposed a conceptual model for various recharge conditions in the fractured sandstone aquifer based on the results of the MIKE SHE simulation along with findings of previous recharge studies for the site (Manna et al., 2016;Manna et al., 2017). In particular, the MIKE SHE simulations contributed to the conceptual model concerning the role of surface variability on the hydrological processes whereas the Cl-based studies informed the flow mechanisms in the underlying portion of the system.

The MIKE SHE model

The MIKE SHE model (Refsgaard, 1995) simulations were completed at an hourly time step using the meteorological data measured on site and from stations proximal to the study area from 1995 through 2014. A portion of the rainfall is intercepted by the vegetation canopy, from which evaporation occurs. The remaining water reaches the surface, infiltrating into the subsurface with some transpired back to the atmosphere. Actual evaporation and transpiration were simulated based on the Kristensen and Jensen Evapotranspiration Model (Kristensen and Jensen, 1975), which considers potential evapotranspiration estimated using the FAO 56 Penman-Monteith method (Allen et al., 1998), available soil moisture and the crop characteristics (depth of the evapotranspiration zone, leaf area index and crop coefficient) in each grid cell (Table 1). When the rainfall exceeds the infiltration capacity, water is ponded on the ground surface and is available for runoff. The rate of runoff is simulated using a 2D diffusive wave approximation and is controlled by the topographic slope, the surface roughness and detention storage. The latter is the volume of water stored in surface depressions before runoff starts. The unsaturated zone flow is simulated as the change in soil moisture, as a result of cyclical input (infiltration) and output (recharge and evapotranspiration). It is mainly vertical, because gravity is the foremost forcing factor and is simulated using the full Richards equation (Richards, 1931). Given the variable thickness of the

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vadose zone and the low water fluxes, the model was run several times to set proper initial conditions. Our analysis began when the simulation showed that the degree of change in average recharge value from one run to the next was about 0.3% indicating near steady-state conditions. Recharge was calculated anytime that infiltration water arrives at the water table, recognizing that most precipitation events result in infiltration into the shallow subsurface which is intercepted and evapotranspired before it can become groundwater recharge. The saturated zone flow was represented using 3D finite difference Darcy equation. A fixed head boundary from the bottom of the model domain (490 m asl) was used to simulate the flow to and from the deeper groundwater system, which extends several hundred meters and thus was not explicitly represented in the integrated model (Fig. 3).

Climate data

Hourly rainfall data were collected from two stations within the catchment boundaries: the Sage Ranch station, managed by Ventura County watershed (http://www.vcwatershed.net/hydrodata/php/getstation.php?siteid=272#top) and the Simi Hills-Rocketdyne Lab, managed by Boeing Inc. The annual precipitation ranges from 99 mm (2014) to 976 (1998), with an average value of 396 mm y^{-1}. The seasonal precipitation regime is Mediterranean, with 77% of the total precipitation occurring from December to March.

Daily maximum and minimum air temperature observations were obtained from two climate stations of the NOAA network: from 1995 to 1998 data were gathered from the Cheeseboro station (https://www.ncdc.noaa.gov/cdo-web/datasets/GHCND/stations/GHCND:USR0000CCHB/detail) and from 1998 to 2015 from the Van Nuys station (https://www.ncdc.noaa.gov/cdo-web/datasets/GSOM/stations/GHCND:USW00023130/detail), respectively 6 km SW and 18 km E of the study site. Temperatures were adjusted using a dry (10 ^{0}C km^{-1}) and wet (5.5 ^{0}C km^{-1}) adiabatic lapse rate based on the elevation change between the SSFL site and the collecting station.

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July, August and September are the warmest months with an average daily maximum temperature of 30.5, 31 and 30.4 ^{0}C, respectively whereas February and December are the coldest with an average daily maximum temperature of 17and 17.4 ^{0}C, respectively. Annual average temperature is 16.7^{0}C.

Surface and subsurface parameters

The model was developed employing a 20 by 20 m finite difference horizontal plane grid to represent the surface variation in physical features, a fine vertical discretization of the vadose zone with 240 numerical layers ranging from 0.1 to 1 m thickness and 2 groundwater zone layers to represent vertical variability at, and just below, the position of the water table (Fig. 3). This resolution was selected as a compromise between representation of spatial variability and reasonable computational time. Maps of topography, vegetation, surficial geology and land use were used to assign surface parameters (Fig. 1, Fig. 2 and Fig. 4). High resolution topographic data (2 feet interval elevation contours) were obtained based on an aerial survey of the site in 2010. These topography data were used to define the ground surface elevations (Fig. 1).

The surface and subsurface hydrogeologic units include alluvium, fractured weathered and unweathered bedrock comprised of sandstone, siltstone and shale beds of varying thickness, grain size and cementation (Fig. 2 and Fig. 3). The physical properties of these units, derived from previous on-site investigations (Allegre et al., 2016;Quinn et al., 2015;Quinn et al., 2016), are summarized in Table 2.

Four land use classes were identified and delineated based on aerial imagery and local land cover datasets (Davis et al., 1998): developed areas (roads, building, parking lots); chaparral (chamise, scrub oak), coastal scrub (Black sage) and exposed bedrock (areas without vegetation) (Fig. 4). The first category represents only 5% of the study catchment whereas the two vegetation classes (chaparral and coastal sage scrub) cover 83% of the area. The remaining 12% is represented by areas of bedrock outcrop at surface. This category was subdivided into two classes: non-massive bedrock and massive bedrock based on physical appearance. Massive bedrock areas were identified based on rock masses that have resisted erosion over the decades and are presumed to be poorly-fractured and/or well cemented such that local infiltration through these rock units is very low. These cells were identified using topography and imagery analysis. First, we used the minimum downslope elevation change approach to identify topographic ridges; this algorithm calculates the minimum elevation drop to a downslope neighbor. In a second stage, we isolate from the land use map the exposed bedrock areas. Vegetation, indeed, is unlikely to grow on well cemented rock. Finally, massive bedrock areas were identified as cells with downslope elevation change greater than 1.25 meters in areas without vegetation.

Land use class-specific parameters were assigned based on literature values (Canadell et al., 1996;Scurlock et al., 2001;Chin et al., 2000) (Table 1). A crop coefficient varying monthly between 0.53 and 1.02 has been calculated for the site. The estimates are based on i) reference crop evapotranspiration rates (RET) for Zone 9 of the Reference Evapotranspiration Zones map of the California Irrigation Management Information System, that corresponds with the area the site is within (ITRC, 2003), ii) a 'Pasture and Misc. grasses' land class chosen as representative and iii) a reduction of 8% to account for bare spots in vegetation and reduced vigor (ITRC, 2003).

Unsaturated zone water budgets

To assess the temporal variability of recharge and other hydrologic processes, we analyzed the simulated unsaturated zone water budgets for two locations representing the span of variability of the catchment. Two locations were selected based on surface geology (Fig. 2) and land use category (Fig. 4): UZ1 represents a cell with alluvium at the surface covered by vegetation, whereas UZ2 an area of outcropping bedrock without vegetation. The average infiltration value over the simulated period at the two locations (UZ-1: 87 mm y^{-1}; UZ-2: 395 mm y^{-1}) matches the average infiltration

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value for all the cells of the catchments with same land use and surface geology characteristics. For these cells, we extracted the weekly time series of infiltration, evapotranspiration, storage variations and flux at the bottom of the ET zone (i.e., drainage). The latter indicates the volume of water that infiltrates into the vadose zone and will eventually become recharge upon reaching the water table. The analysis of the seasonal variability of these fluxes provided insights about their transient nature and about the effect of the surface variability on the hydrologic processes in the unsaturated zone.

Approach for model calibration and validation

In this study, calibration refers to a test of the ability of the model to reproduce observed processes and to evaluate values of model parameters, for which measurements are not available. On the other hand, validation is the comparison of model results with alternative data, independently derived, to provide confidence about the reasonableness of the results.

To calibrate the integrated surface water and groundwater model, we compared i) the simulated and observed runoff flow at the outfall of the catchment, ii) the simulated and observed average groundwater head data from 17 wells located within the catchment area and iii) the simulated time series of recharge and the observed fluctuations of water level hydrographs. For the purpose of streamflow calibration, we compared the surface runoff generated by MIKE SHE to the data collected at the catchment outfall between 2009 to 2011. This time interval had minimal occurrence of substantial anthropogenic activities and was representative of natural hydrologic conditions, as reported also by Manna et al. (2016).

For the calibration of groundwater, quarterly water level data measured manually were used. Excluded from the calibration data were: i) wells with screened interval below the bottom of the model domain (490 m a.s.l.), and ii) wells where the water table is strongly influenced by subsurface complexity not represented in the saturated zone portion of the MIKESHE mode. This

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resulted in water level data from 17 wells being used with water depths ranging from 25 to 137 meters (Fig. 1, 2 and 4). The time series at each well varies from 1 (RD-130) to 139 (WS-09B) measurements. Average values were used for comparison with average simulated values to judge the spatial distribution of model parameters. Furthermore, to test the ability of the model to simulate unsaturated zone flow processes and to reproduce the transient recharge conditions, we compared the simulated time series of recharge, obtained from MIKE SHE, with quarterly water level measurements at five locations. The depth to groundwater at these wells ranges between 2 and 60 m with seasonal fluctuations due to the recharge events. The recharge time series is obtained, extracting the average, catchment-wide, monthly recharge values.

Simulation results were validated based on the comparison with previous independent recharge estimates and evidence from isotopic data sets. Manna et al. (2016) estimated an average long-term recharge of 19 mm y^{-1} for the same catchment using the chloride mass balance (CMB) method, based on the average Cl concentration measured in the atmospheric deposition (2.6 mg L^{-1}), surface water at the outfall (4 mg L^{-1}) and groundwater (52.5 mg L^{-1}). Since chloride concentration in groundwater is proportional to the concentrating effect of water loss due to evapotranspiration, it can be used as a proxy to determine the range of variability in recharge. Chloride concentration in shallow groundwater monitoring wells ranges across the area from 17 to 162 mg/L corresponding to recharge values of 43 and 5 mm y^{-1}, respectively. Manna et al (2017) also provided insights regarding spatial variability of recharge within the catchment based on analysis of Cl profiles in porewater from the vadose zone and groundwater and indicated a range of recharge from 4 to 21 mm y^{-1} corresponding to <1 – 4.7% of the average annual precipitation for 4 locations located within the catchment area. Although the recharge values obtained from the CMB method integrate hydrologic processes occurring over longer time, from centuries to millennia, they represent a reasonable assessment of long-term, site-wide and location-specific average values and are valuable for validation purposes.

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For the validation of the unsaturated zone water budget, samples of rainfall and groundwater were analyzed for water isotopes (oxygen-18 and deuterium). Water isotopes are commonly used to assess evaporative processes and to determine sources and origins of different groundwaters. In this study, we compared the isotopic signature of groundwater to that of precipitation for an entire hydrological year to determine whether the timing of recharge indicated by the model is consistent with the isotopic signature for the same period of the year. For this purpose we used 1) rainfall samples collected from October 1994 to June 1995 at two rain gauge stations (B/886 and RMDF) located in a different portion of the site, 5 km from the studied watershed and 2) groundwater samples collected from monitoring wells in the studied catchment in two rounds of sampling: the first in 2003-2004 and the second in 2013 (Fig. 1).

Results

Model calibration

The ability of the model to reproduce observed conditions has been investigated to provide confidence that the model can be used to simulate the spatial and temporal variation in recharge and other water budget components. This ability to represent measured surface and sub-surface flows depends on the reasonableness of the input parameters assigned to the different land use and lithology classes (Table 1 and 2).

When analyzing measured data, streamflow at the outfall is observed in response to rainfall but interestingly some precipitation events are followed by very low or no measurable flow (Fig. 5). This is evident for precipitation events from April to June 2009, October and November 2010 and May and June 2011. In all these cases, the surface runoff, generated by the precipitation events, infiltrates into the subsurface without reaching the surface outfall (Fig. 5). These hydrologic dynamics are well simulated by MIKE SHE. The comparison between the observed and the simulated hydrographs shows a good correlation for the calibration period (R^2=0.97; average difference 4.7%). The average simulated flow is 48 mm y^{-1}, about 14.5% of the average precipitation for the 2009-2011 period (331 mm) and is almost coincident with the measured flow (46.2 mm y^{-1}) (Fig. 5). This value reflects the precipitation conditions of the 2009-2011 period and is lower than the average runoff over the entire simulated interval (110 mm y^{-1}, 28% of the annual precipitation).

In addition to the surface water leaving the catchment, the model was also calibrated by comparing simulated and observed average groundwater head data (Fig. 6). The two sets of data show a good match for the 17 locations, with almost all values falling within the 10 m confidence interval bands, with a correlation coefficient of 0.96 and a mean absolute error of 4.5 m (Fig. 6). This good correlation provides confidence about the spatial distribution of model parameters.

The ability of the model to simulate transient hydrologic conditions was also investigated through the comparison between well hydrographs at five locations and the temporal variability of recharge (Fig. 7). The recharge time series obtained from MIKE SHE (monthly time-step) ranges from 0.95 mm (November 2014) to 9.1 mm (March 2005). The latter is the response to the extraordinary rainy season that occurred between December 2004 and March 2005 (903 mm) whereas the first is due to dry conditions of the recent drought in California. The range of depth to groundwater from 1995 to 2014 at the five locations considered is 2.8 – 14.4 m at RD-09, 17.8 – 30 m at RD-35A, 16.2 – 28.7 at RD-73, 37.7 – 50.8 m at RD-36B and 33.1 – 60.1 at WS-09B. The shape of these hydrographs depends on surface (surface geology, topographic slope, land use) and subsurface (mechanisms of flow in the vadose zone) factors. For our calibration purpose, it is noteworthy that, at all the locations, the hydrographs show a good match with the recharge time series such that the peaks in recharge coincide with water table rises. The greatest rises overlap the two highest recharge periods (1998 and 2005), whereas a constant declining trend is observed from 2011 to 2014 in response to drier conditions (Fig. 7). The good correlation suggests that, at this scale, the equivalent porous media approach used is reasonable to simulate average responses in groundwater even though the bedrock has many interconnected fractures.

Spatial variability

To study the spatial variability of the water budget components, average annual maps of infiltration (Fig. 8a), evapotranspiration (Fig. 8b) and recharge (Fig. 8c) for the period 1995 – 2014 were created. Infiltration reflects the ability of water to enter the sub-surface, while recharge represents the portion of infiltration that migrates through the evapotranspiration zone (ET zone) toward the underlying water table.

Average infiltration for the catchment is 254 mm y^{-1}, corresponding to 64% of the total precipitation but single cell values span over three orders of magnitude from 9 to > 1000 mm y^{-1} (Fig. 8a). Low infiltration values are found in developed/paved (average 51 mm y^{-1}) and massive-bedrock (average 14 mm y^{-1}) cells. Due to the low infiltration capacity, more runoff is generated in these cells and, thus, infiltration is higher in nearby cells that receive the surface water. Where these neighboring cells are covered by alluvium at the surface, infiltration is even higher. On average, cells with alluvium at the surface have an infiltration value of 332 mm y^{-1}, 25% more than those where bedrock outcrops. Higher infiltration is also displayed in depressed areas such as those along the main drainages and where closed topographic depressions occur. These cells collect most of the surface runoff creating conditions for focused infiltration and recharge.

Only a small portion of water that enters the subsurface reaches the water table because the majority is lost due to evapotranspiration (Fig. 8b). The average evapotranspiration estimated using MIKE SHE is 265 mm y^{-1}, a value slightly higher than the average infiltration. This excess of ET over infiltration is attributed to canopy interception and evaporation of temporarily ponded surface water. When removing these two water-loss processes, the average evapotranspiration is 237 mm y^{-1}, which corresponds to 60% of the annual precipitation and to 94% of the total

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infiltration. Transpiration is the main process of ET contributing to about 70% of the total ET. This result is expected considering the considerable depth of the roots (up to 5 meters for Chaparral) and the fact that vegetation covers 83% of the catchment area. As for the infiltration, single cell values of ET span over three orders of magnitude, from 50 to >1000 mm y^{-1}. Since the actual evapotranspiration depends strongly on the availability of subsurface water, the spatial variability mimics the infiltration pattern and the two factors are strongly correlated (R^2=0.84). Therefore, low ET is associated with developed and massive bedrock areas and high ET values are found along the main surface drainages where infiltration water is collected to become locally available for evapotranspiration. The presence of alluvium at the surface increases the ET values on average by 25%; for example, average ET in cells with chaparral and alluvium is 400 mm y^{-1} whereas where chaparral is rooted in weathered bedrock is ~300 mm y^{-1}.

The difference of infiltration and evapotranspiration maps (Fig. 8a and 7b), results in a map of the spatial distribution of the average annual recharge (Fig. 8c). The average recharge value for the catchment is 16 mm y^{-1} equal to 4.1 % of the precipitation and 6.5 % of the infiltration. The range of variability of recharge is over three orders of magnitude and spatially variable depending on topography, surface geology and land use. It is noteworthy that 79% of the catchment has recharge less than 10 mm y^{-1} and 90% less than 30 mm y^{-1}, which indicates that the largest volumes of recharge are focused in small portions of the site. The recharge map (Fig. 8c) shows the influence of the surface parameters on recharge estimates. Recharge is high along the main drainage because of the contribution of surface water flowing from the surrounding slopes and enhanced infiltration where the topographic slope decreases abruptly. Relatively higher recharge values are also observed in areas with alluvium at the surface because the infiltration and retention capacities are higher and, therefore, water can seep from the overburden into the bedrock once the evapotranspiration demand and driving forces are met. Recharge is also higher in cells without

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vegetation cover, compared to other cells with equivalent topographic slope and surficial geology, because the evapotranspiration in these areas is lower.

Temporal variability

The seasonal variability of the hydrologic processes was examined analyzing unsaturated water budgets at two locations with different land use and surficial geology (UZ-1 and UZ-2 in Fig.1) Among the 20 years, we show the monthly average daily values from 2005 to 2007. This time span features a wet year (2005 – 978 mm), a dry year (2007 – 149 mm) and one year with average precipitation (2006 - 331 mm) and therefore is reasonably representative of the simulated period.

For areas with bedrock outcrop not covered by vegetation (UZ-1 in Fig. 1), the infiltration ranges from 0 to 2.5 mm d^{-1} (Fig. 9). The infiltration pattern shows null or minimal values during the summer and positive events during the wet season. Water that enters the subsurface between April and January replenishes the water content in the ET zone and becomes available for evaporation but not for drainage. Evaporation is null during the summer because of the lack of precipitation and because all the water stored in the first 20 cm of bedrock has been taken up by evaporation in the previous months. Downward flux at the bottom of the ET zone (i.e. drainage) only happens episodically when the water content in the ET zone is above the field capacity, at the end of the wet season (i.e., March and April) or occasionally after exceptionally high-intensity precipitation events (i.e., January 2005).

For areas with alluvium at surface (UZ-2 in Fig. 1) the infiltration has the same pattern but a different order of magnitude (from 0 to 30 mm d^{-1}) due to the higher infiltration capacity of the alluvium (Fig. 9). Here, the available water capacity of the ET zone is greater because of the different physical properties (e.g. larger porosity) of the soil and the greater depth of the ET zone. Therefore, almost all the infiltration water is taken up by the evapotranspiration. Unlike areas without vegetation, evapotranspiration is not directly related to precipitation events and occurs more continuously throughout the year. This is because alluvium stores a greater volume of water in the ET zone that is nearly completely consumed by ET. A drainage flux is observed only during high-intensity precipitation events that create near-saturation conditions such that water cannot be held by tension in the shallow unsaturated zone and downward flow is initiated.

For both cases, drainage is not steady throughout the year but occurs episodically, controlled by antecedent soil water content in the ET zone and by the intensity of precipitation. During drier-than-average years, such as 2007, drainage occurs in areas without vegetation, whereas no drainage is observed in cells with vegetation cover. After crossing the bottom of the ET zone, water arrives at the water table with a time lag depending on the magnitude of the flux and on the physical properties and the thickness of the vadose zone.

Model validation

The validation of the model requires comparison of the simulation results to other evidence, independent of those used in the calibration.

The average recharge value for the catchment from the simulation is 16 mm y^{-1} and is consistent with previous recharge estimates obtained for the site using the CMB method (19 mm y^{-1} – 4.2% of the average precipitation, Manna et al., 2016; 16 mm y^{-1} – 3.5% of the average precipitation, Manna et al., 2017), for other sandstone aquifers in semi-arid areas in the United States (Heilweil et al., 2006) and for other study areas in semi-arid regions around the world (0.2 – 35 mm y^{-1} equal to 0 – 5% of the average precipitation, Scanlon et al., 2006) . Interestingly, the frequency distribution of recharge values from the MIKE SHE simulation (92% of the domain has average recharge lower than 40 mm y^{-1}) also corresponds well to the range of variability (from 0 to 43 mm y^{-1}) reported by Manna et al. (2016) and Manna et al. (2017). This represents a mutual validation of the two approaches, based on independent datasets and for different timescales.

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For additional information on recharge processes, we analyzed water isotopes obtained from rainfall and groundwater samples (Fig. 10). The samples show a substantial isotopic range from one precipitation event to another over the one-year collection period. ^{18}O varies between -2.8 and -12.1‰ for B/886 and -2.8 and -11.7‰ for RDMF and ^{2}H varying between -11 and -89‰ for B/886 and -12 and -85‰ for RDMF (Table 3). This large range of values is probably due to the two different trajectories of the precipitation events in southern California, one originating in the Pacific and one over the Gulf of Mexico, as found by Friedman et al. (1992). The volume weighted mean values for the two stations are -8.2 and -54.2‰ for B/886 and -8.2 and -56.2‰ for RDMF and are consistent with global-scale maps of water isotopes for precipitation in southern California.

Unlike rainfall, groundwater samples fall within a narrower range: from -6.5 to -7.5‰ for ^{18}O and from -40.2 and to -52.2‰ for ^{2}H. All the samples are aligned along the local meteoric water line (Fig. 10) suggesting little if any evaporation. This finding contrasts the results of Manna et al. (2016) who found that Cl concentrations in groundwater are, on average, 20 times greater those from atmospheric deposition because of the strong influence of evapotranspiration. The common explanation for the lack of evaporation effects on the water isotopes is that the transpiration is the main evapotranspiration process. Although it causes a concentration effect on Cl, transpiration through vegetation, does not cause fractionation of the water isotopes and therefore the groundwater samples are not enriched (Clark, 2015;Cook and Böhlke, 2000).

The lack of evaporative signature associated with high Cl concentration in porewater can also be explained by recharging water that quickly crosses the ET zone mobilizing precipitated salts without evaporation. This hypothesis supports the results of the MIKE SHE simulations, which show throughout the year only episodic flux at the bottom of the ET zone (Fig. 9). A relevant observation that corroborates this hypothesis is that the isotopic composition of groundwater is similar to that found in rainfall samples collected at the end of the wet season (March and June) or,

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on occasion, with high-intensity precipitation events (January - 203 mm) (Table 3). This similarity can be attributed to a selective recharge mechanism that causes groundwater to have isotopic composition different by 1.2‰ ^{18}O and 3‰ ^{2}H from the weighted mean of precipitation and similar to that of the rainfall that episodically crosses the ET zone (Florea, 2013;Gat and Tzur, 1967;Krabbenhoft et al., 1990). This proposed model of episodic fast flow through the unsaturated ET zone is also corroborated by the evidence presented by Manna et al., (2017) that, on average, 20% of the flow in the vadose zone occurs as fast flow through the interconnected fractured network.

Conceptual model for recharge

To summarize the findings of this study, and its relationship to the previous recharge studies at the site (Manna et al., 2016; Manna et al., 2017), we propose the following process-based conceptual model for site recharge (Fig. 11).

Recharge varies greatly across the catchment as a function of topography, surface geology, and land use. High recharge occurs where runoff water seeps into the subsurface, creating conditions for focused recharge. This condition happens where closed depressions occur and where sloped topography abruptly transitions to flat along the main surface drainages (Fig. 11a). Here, in most areas, alluvium covers the fractured porous bedrock, thus enhancing infiltration and temporary storage of infiltrated water. Infiltration from April to December (dry season) contributes to replenish the water content in the ET zone and remains available for evapotranspiration (Fig. 11b). Conversely, during the wet season, infiltration crosses the bottom of the ET zone (i.e. drainage) and migrates deeper through the vadose zone. This happens when the soil is above the field capacity (FC), which is more frequent at the end of the wet season in March or April and/or during high-intensity precipitation events, (Fig. 11c). This recharging water quickly crosses the ET zone, as

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shown by the ET zone water budgets extracted from MIKE SHE (Fig. 9), and by the lack of evaporative signature in isotope composition (Fig. 10). The occurrence of this fast/preferential flow out of the ET zone is also corroborated by the analysis of vertical chloride porewater concentration profiles in the unsaturated zone (Manna et al., 2017). The Cl concentration is high in the ET zone (up to 10,000 mg L^{-1}) and considerably lower in deeper vadose and groundwater zones (average 49 mg L^{-1}). The higher Cl concentrations in the shallow subsurface is the effect of strong evapotranspiration that takes up water but not chloride, whereas the lower concentration below is due to fast/preferential flow of water that escapes the concentrating effect of water loss in the shallower zone.

Upon reaching the deeper vadose zone, water is redistributed between intergranular matrix flow and fracture flow due to wettability and saturation concepts. The fractures and the matrix pores drain the water from the ET zone. Active flow through the fractures is possible under conditions such as ponding or intense precipitation, when a continuous slug of water lets i) the advective front move ahead into the fracture (1 in Fig. 11c); ii) the matrix water flow into the fractures (2 in Fig. 11c). Otherwise, water is drawn from the fractures into the unsaturated matrix blocks (3 in Fig. 11c) and contributes to the slow vertical intergranular matrix flow (4 in Fig. 11c). According to Manna et al. (2017), the first two mechanisms are much less frequent and contribute, on average, to only 20% of the total recharge. It is most likely that conditions for flow in the fractures occur in areas of the site with high infiltration (topographic low and alluvium at the surface) where temporary perched systems are observed.

Conclusions

For the upland bedrock catchment, the surface water-groundwater numerical model (MIKSHE), using a fine numerical grid (20 ×20 m) with calibration to streamflow and groundwater levels,

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simulated the spatial and temporal variability of recharge at a study site in a semi-arid region of southern California, USA. Simulations were judged to be reliable and strongly reflective of the natural system, based on comparisons to mean recharge values obtained independently from the chloride mass balance method (Manna et al., 2016; Manna et al., 2017) and comparisons to the timing of major recharge events indicated by water isotopes. The simulations showed that major flux events at the bottom of the evapotranspiration zone occur episodically only at the end of the rainy season and that recharge varies across the catchment between 0 and 1000 mm y^{-1}. The fine numerical grid in the horizontal plane allowed meaningful examination of recharge spatial variability. A coarser grid would obscure influences of key surface features on the hydrologic processes. This is the first study to combine MIKE SHE simulations supported by analysis of water isotopes and chloride mass balance to assess recharge in a semi-arid region.

The results obtained from the catchment-scale simulations (2.16 km^2 area) will be used to specify rules for recharge assigned to the upper boundary condition of a 3-D site-wide numerical groundwater flow model (52 km^2 area), to determine the distribution of recharge affecting groundwater flow in the fractured bedrock. Many contaminant source zones and plumes occur in the rock where the variable recharge and groundwater fluxes are a major governing factor on plume migration.

It is important to highlight that our modeling aimed to represent the natural hydrologic conditions, after site operations ceased nearly a decade ago. During historical operations from 1950's through mid-2000's, use of imported and pumped groundwater in specific areas likely caused increases to infiltration and recharge. These conditions are beyond the scope of this paper but worth further consideration as it relates to land use changes when contaminant releases occurred and may provide insights regarding how migration rates may have been influenced. Future modeling efforts will also evaluate the effect on recharge of the surface water control systems currently in place on

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the site. These storm water management measures aim to limit the volume of water leaving the catchment and, therefore, will likely influence the natural rates of the other hydrologic processes.

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References

Allegre, V., Brodsky, E. E., Xue, L., Nale, S. M., Parker, B. L., and Cherry, J. A.: Using earth-tide induced water pressure changes to measure in situ permeability: A comparison with long-term pumping tests, Water Resources Research, 52, 3113-3126, 10.1002/2015wr017346, 2016.

Allen, R. G., Pereira, L. S., Raes, D., and Smith, M.: Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56, Fao, Rome, 300, D05109, 1998.

AquaResource, and MWH: Three-Dimensional Groundwater Flow Model Report. Santa Susana Field Laboratory., 2007.

Canadell, J., Jackson, R. B., Ehleringer, J. R., Mooney, H. A., Sala, O. E., and Schulze, E. D.: Maximum rooting depth of vegetation types at the global scale, Oecologia, 108, 583-595, 10.1007/bf00329030, 1996.

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2018-531
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 5 November 2018

Hydrology and Earth System Sciences
Open Access
Discussions

Cartwright, I., Weaver, T. R., Stone, D., and Reid, M.: Constraining modern and historical recharge from bore hydrographs, H-3, C-14 and chloride concentrations: Applications to dual-porosity aquifers in dryland salinity areas, Murray Basin, Australia, Journal of Hydrology, 332, 69-92, 10.1016/j.jhydrol.2006.06.034, 2007.

Cherry J.A., Parker B. L., McWhorter D.: Site conceptual model for the migration and fate of contaminants in groundwater at the Santa Susana Field Laboratory, Simi Valley, California., 2009.

Chin, D. A., Mazumdar, A., and Roy, P. K.: Water-resources engineering, Prentice Hall Englewood Cliffs, 2000.

Cilona, A., Aydin, A., and Johnson, N.: Permeability of a fault zone crosscutting a sequence of sandstones and shales and its influence on hydraulic head distribution in the Chatsworth Formation, California, USA, Hydrogeology Journal, 23, 405-419, 10.1007/s10040-014-1206-1, 2015.

Cilona, A., Aydin, A., Likerman, J., Parker, B., and Cherry, J.: Structural and statistical characterization of joints and multi-scale faults in an alternating sandstone and shale turbidite sequence at the Santa Susana Field Laboratory: Implications for their effects on groundwater flow and contaminant transport, Journal of Structural Geology, 85, 95-114, 10.1016/j.jsg.2016.02.003, 2016.

CIMIS: Reference Evapotranspiration. Department of Land Arid and Water Resources, University of California, Davis and Water Efficiency Office, California Department of Water Resources, California Irrigation Management Unit., 1999.

Clark, I.: Groundwater geochemistry and isotopes, CRC press, 2015.

Cook, P. G., and Böhlke, J.-K.: Determining timescales for groundwater flow and solute transport, in: Environmental tracers in subsurface hydrology, Springer, 1-30, 2000.

Crosbie, R. S., Peeters, L. J., Herron, N., McVicar, T. R., and Herr, A.: Estimating groundwater recharge and its associated uncertainty: Use of regression kriging and the chloride mass balance method, Journal of Hydrology, 561, 1063-1080, 2018.

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2018-531
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 5 November 2018

Hydrology and Earth System Sciences
Open Access
Discussions

Davis, F., Stoms, D., Hollander, A., Thomas, K., Stine, P., Odion, D., Borchert, M., Thorne, J., Gray, M., and Walker, R.: The California gap analysis project–final report. University of California, Santa Barbara, CA, 1998.

De Vries, J. J., and Simmers, I.: Groundwater recharge: an overview of processes and challenges, Hydrogeology Journal, 10, 5-17, 2002.

Fayer, M., Gee, G., Rockhold, M., Freshley, M., and Walters, T.: Estimating recharge rates for a groundwater model using a GIS, Journal of Environmental quality, 25, 510-518, 1996.

Flint, A. L., Flint, L. E., Bodvarsson, G. S., Kwicklis, E. M., and Fabryka-Martin, J.: Evolution of the conceptual model of unsaturated zone hydrology at Yucca Mountain, Nevada, Journal of Hydrology, 247, 1-30, 2001.

Flint, A. L., Flint, L. E., Hevesi, J. A., and Blainey, J. B.: Fundamental concepts of recharge in the Desert Southwest: a regional modeling perspective, Groundwater Recharge in a Desert Environment: The Southwestern United States, 159-184, 2004.

Flint, L. E., and Flint, A. L.: Regional analysis of ground-water recharge, Ground-water recharge in the arid and semiarid southwestern United States, 29-59, 2007.

Florea, L. J.: Selective recharge and isotopic composition of shallow groundwater within temperate, epigenic carbonate aquifers, Journal of hydrology, 489, 201-213, 2013.

Friedman, I., Smith, G. I., Gleason, J. D., Warden, A., and Harris, J. M.: Stable isotope composition of waters in southeastern California 1. Modern precipitation, Journal of Geophysical Research: Atmospheres, 97, 5795-5812, 1992.

Gat, J., and Tzur, Y.: Modification of the isotopic composition of rainwater by processes which occur before groundwater recharge, Isotopes in hydrology. Proceedings of a symposium, 1967,

Gebru, T. A., and Tesfahunegn, G. B.: Chloride mass balance for estimation of groundwater recharge in a semi-arid catchment of northern Ethiopia, Hydrogeology Journal, 1-16, 2018.

Heilweil, V. M., Solomon, D. K., and Gardner, P. M.: Borehole environmental tracers for evaluating net infiltration and recharge through desert bedrock, Vadose Zone Journal, 5, 98-120, 2006.

Hevesi, J. A., Flint, A. L., and Flint, L. E.: Simulation of net infiltration and potential recharge using a distributed-parameter watershed model of the Death Valley region, Nevada and California, US Department of the Interior, US Geological Survey, 2003.

Huang, Y., Chang, Q., and Li, Z.: Land use change impacts on the amount and quality of recharge water in the loess tablelands of China, Science of the Total Environment, 628, 443-452, 2018.

ITRC: California Crop and Soil Evapotranspiration, ITRC Report No. R 03-001. 2003.

Jebreen, H., Wohnlich, S., Wisotzky, F., Banning, A., Niedermayr, A., and Ghanem, M.: Recharge estimation in semi-arid karst catchments: Central West Bank, Palestine, Grundwasser, 23, 91-101, 2018.

Krabbenhoft, D. P., Bowser, C. J., Anderson, M. P., and Valley, J. W.: Estimating groundwater exchange with lakes: 1. The stable isotope mass balance method, Water Resources Research, 26, 2445-2453, 1990.

Kristensen, K., and Jensen, S.: A model for estimating actual evapotranspiration from potential evapotranspiration, Hydrology Research, 6, 170-188, 1975.

Li, Z., Chen, X., Liu, W., and Si, B.: Determination of groundwater recharge mechanism in the deep loessial unsaturated zone by environmental tracers, Science of the Total Environment, 586, 827-835, 2017.

Link, M. H., Squires, R. L., and Colburn, I. P.: Slope and deep-sea fan facies and paleogeography of Upper Cretaceous Chatsworth Formation, Simi Hills, California, AAPG Bulletin, 68, 850-873, 1984.

Liu, H.-L., Chen, X., Bao, A.-M., and Wang, L.: Investigation of groundwater response to overland flow and topography using a coupled MIKE SHE/MIKE 11 modeling system for an arid watershed, Journal of Hydrology, 347, 448-459, 2007.

Ma, L., He, C., Bian, H., and Sheng, L.: MIKE SHE modeling of ecohydrological processes: Merits, applications, and challenges, Ecological Engineering, 96, 137-149, 2016.

Manna, F., Cherry, J. A., McWhorter, D. B., and Parker, B. L.: Groundwater recharge assessment in an upland sandstone aquifer of southern California, Journal of Hydrology, 541, 787-799, 10.1016/j.jhydrol.2016.07.039, 2016.

Manna, F., Walton, K. M., Cherry, J. A., and Parker, B. L.: Mechanisms of recharge in a fractured porous rock aquifer in a semi-arid region, Journal of Hydrology, 555, 869-880, 10.1016/J.Jhydrol.2017.10.060, 2017.

MWH: Draft-site wide groundwater remedial investigation report Santa Susana Field Laboratory, Ventura County, California. Prepared for The Boeing Company, NASA and U.S. DOE by MWH Global Inc., Walnut Creek, CA., 2009.

MWH: Hydrogeological Characterization of Faults. Santa Susana Field Laboratory, Ventura County, Ca. Prepared for The Boeing Company by Dr. Nicholas M. Johnson, MWH Americas Inc., 2121 N. California Blvd., Suite 600, Walnut Creek, CA 94596., 2016.

Pierce, A. A., Chapman, S. W., Zimmerman, L. K., Hurley, J. C., Aravena, R., Cherry, J. A., and Parker, B. L.: DFN-M field characterization of sandstone for a process-based site conceptual model and numerical simulations of TCE transport with degradation, Journal of contaminant hydrology, 212, 96-114, 2018a.

Pierce, A. A., Parker, B. L., Ingleton, R., and Cherry, J. A.: Novel Well Completions in Small Diameter Coreholes Created Using Portable Rock Drills, Groundwater Monitoring & Remediation, 38, 42-55, 2018b.

Quinn, P., Cherry, J. A., and Parker, B. L.: Combined use of straddle packer testing and FLUTe profiling for hydraulic testing in fractured rock boreholes, Journal of Hydrology, 524, 439-454, 2015.

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2018-531
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 5 November 2018

Quinn, P. M., Cherry, J. A., and Parker, B. L.: Depth-discrete specific storage in fractured sedimentary rock using steady-state and transient single-hole hydraulic tests, Journal of Hydrology, 542, 756-771, 2016.

Refsgaard, C.: Mike she, Computer models of catchment hydrology, 809-846, 1995.

Richards, L. A.: Capillary conduction of liquids through porous mediums, physics, 1, 318-333, 1931.

Scanlon, B. R.: Uncertainties in estimating water fluxes and residence times using environmental tracers in an arid unsaturated zone, Water Resources Research, 36, 395-409, 2000.

Scanlon, B. R., Keese, K. E., Flint, A. L., Flint, L. E., Gaye, C. B., Edmunds, W. M., and Simmers, I.: Global synthesis of groundwater recharge in semiarid and arid regions, Hydrological Processes: An International Journal, 20, 3335-3370, 2006.

Scanlon, B. R., Reedy, R. C., and Tachovsky, J. A.: Semiarid unsaturated zone chloride profiles: Archives of past land use change impacts on water resources in the southern High Plains, United States, Water Resources Research, 43, 2007.

Scurlock, J., Asner, G., and Gower, S.: Worldwide historical estimates of leaf area index, 1932–2000, ORNL/TM-2001/268, 34, 2001.

Smerdon, B., Allen, D., Grasby, S., and Berg, M.: An approach for predicting groundwater recharge in mountainous watersheds, Journal of Hydrology, 365, 156-172, 2009.

Sterling, S., Parker, B., Cherry, J., Williams, J., Lane Jr, J., and Haeni, F.: Vertical cross contamination of trichloroethylene in a borehole in fractured sandstone, Groundwater, 43, 557-573, 2005.

Sukhija, B., Reddy, D., Nagabhushanam, P., and Hussain, S.: Recharge processes: piston flow vs preferential flow in semi-arid aquifers of India, Hydrogeology Journal, 11, 387-395, 2003.

Szilagyi, J., Harvey, F. E., and Ayers, J. F.: Regional estimation of total recharge to ground water in Nebraska, Groundwater, 43, 63-69, 2005.

Wheater, H., Sorooshian, S., and Sharma, K. D.: Hydrological modelling in arid and semi-arid areas, Cambridge University Press, 2007.

Wood, W. W., and Sanford, W. E.: Chemical and isotopic methods for quantifying ground-water recharge in a regional, semiarid environment, Groundwater, 33, 458-468, 1995.

Xie, Y., Cook, P. G., Simmons, C. T., Partington, D., Crosbie, R., and Batelaan, O.: Uncertainty of groundwater recharge estimated from a water and energy balance model, Journal of Hydrology, 561, 1081-1093, 2018.

Table 1 Land use class-specific parameters to model runoff and evapotranspiration. The values are based on literature: 1 Canadell et al., 1996; 2 Scurlock et al., 2001; 3 Chin et al., 2006.

Land Use Class	**Surface roughness (Manning's n)** [1]	**Detention storage (mm)** [1]	**Leaf Area Index** [2]	**Depth of the evapotranspiration zone (m)** [3]
Developed*	0.04	1	-	0.2
Coastal Scrub	0.2	7.5	1.8 - 3	1.8 - 3
Chaparral	0.2	7.5	2.8 - 4.5	3.1 - 5
Exposed Bedrock/ Massive bedrock*	0.05	3	-	0.2

Table 2 Saturated hydraulic conductivity (ks) of the different hydrogeologic units.

Hydrogeologic unit	**Lithology**	**K_s (m s^{-1})**
Alluvium	Alluvium	1×10^{-6}
Weathered bedrock	Sandstone	2×10^{-7}
Unweathered bedrock	Sandstone	1×10^{-10} to 1×10^{-5}
Unweathered bedrock	Shale/Siltstone	4.1×10^{-10} to 2.3×10^{-7}
Unweathered bedrock	Outcropping Faults	1×10^{-9} to 1×10^{-6}

Table 3 Stable isotope composition of rainfall.

Date	**B/886 Rain Gauge**			**RMDF Rain Guage**			**Average**		
	$\delta^{18}O$	**$\delta^{2}H$**	**Rainfall (mm)**	**$\delta^{18}O$**	**$\delta^{2}H$**	**Rainfall (mm)**	**$\delta^{18}O$**	**$\delta^{2}H$**	**Rainfall (mm)**
4/10/1994	-4	-19	3				-4.0	-19.0	3
25/11/1994	-5.2	-18	6	-5.1	-16	6	-5.2	-17.0	6
13/12/1994	-5.4	-23	9	-5.4	-25	9	-5.4	-24.0	9
24/12/1994	-10.3	-77	18	-10.1	-69	18	-10.2	-73.0	18
4/1/1995	-10.3	-75	94	-9.9	-69	121	-10.1	-72.0	108
11/1/1995	-6	-33	205	-7.4	-45	202	-6.7	-39.0	203
13/01/1995	-4.4	-19	20	-4.2	-20	18	-4.3	-19.5	19
16/01/1995	-2.8	-11	12	-2.8	-12	10	-2.8	-11.5	11
26/01/1995	-12.1	-89	152	-11.7	-85	150	-11.9	-87.2	151
7/3/1995	-6.8	-43	119	-6.4	-40	109	-6.6	-41.5	114
13/3/1995	-7.5	-44	NA	-7.8	-45	NA	-7.7	-44.5	NA
24/3/1995	-5.8	-22	NA	-5.5	-19	NA	-5.7	-20.5	NA
18/5/1995				-6.4	-42	34	-6.4	-42.0	34
22/6/1995	-8.6	-62	14	-8.6	-57	14	-8.6	-59.5	14
Weighted mean	-8.2	-54.2	650	-8.2	-56.2	691	-8.3	-55.2	689

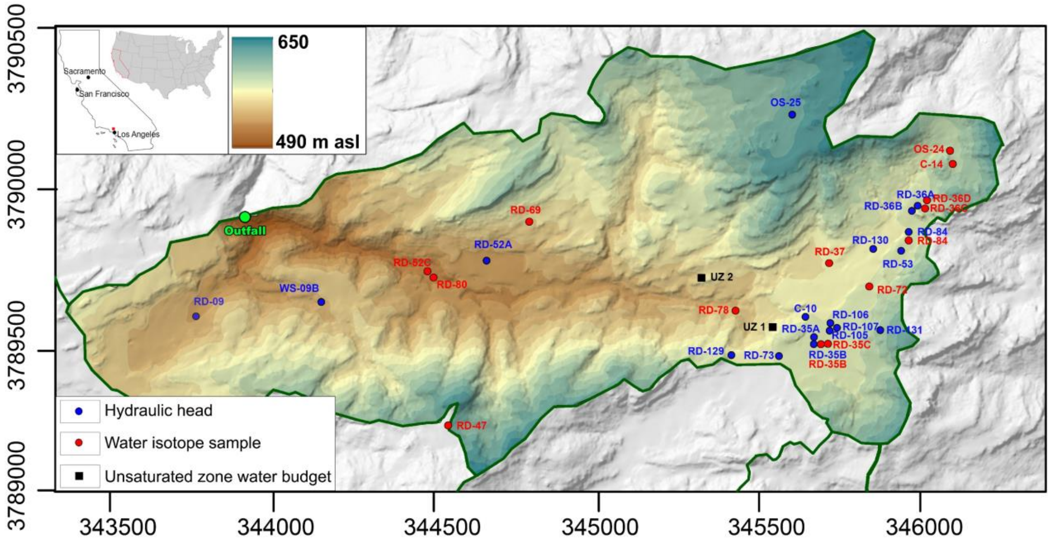

Figure 1 Topographic map of the study area and location of the wells used for calibration (blue), water isotopes sampling (red). In black the two cells where unsaturated zone water budgets were analyzed.

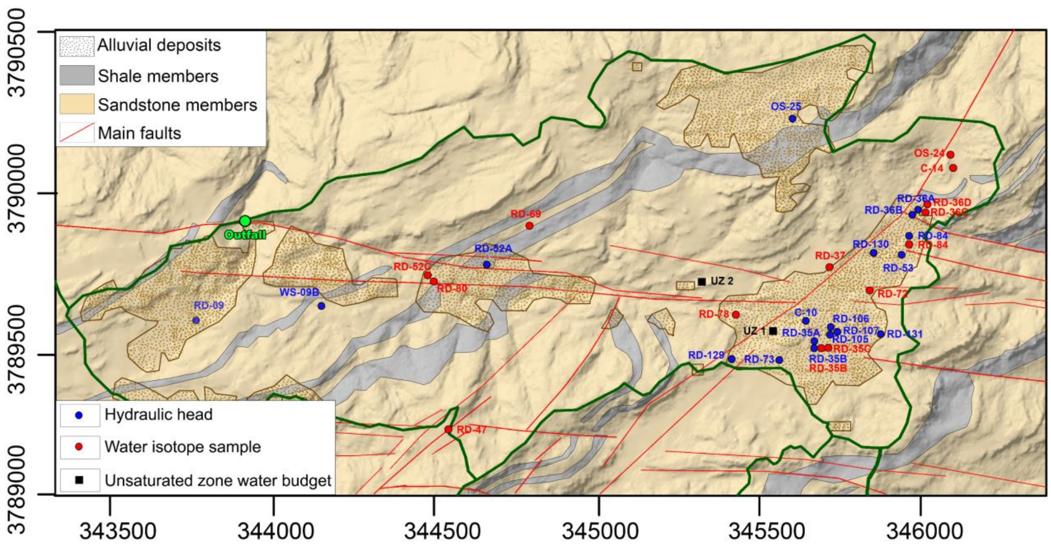

Figure 2 Geologic map of the study area and location of the wells used for calibration (blue), water isotopes sampling (red). In black the two cells where unsaturated zone water budgets were analyzed.

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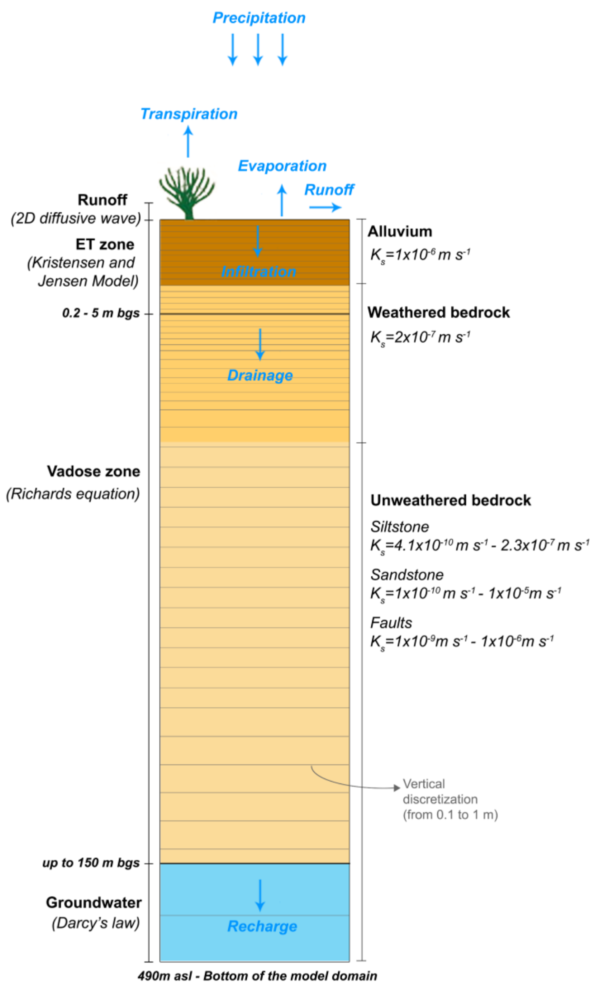

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681 *Figure 3 Description of the vertical MIKE SHE model domain*

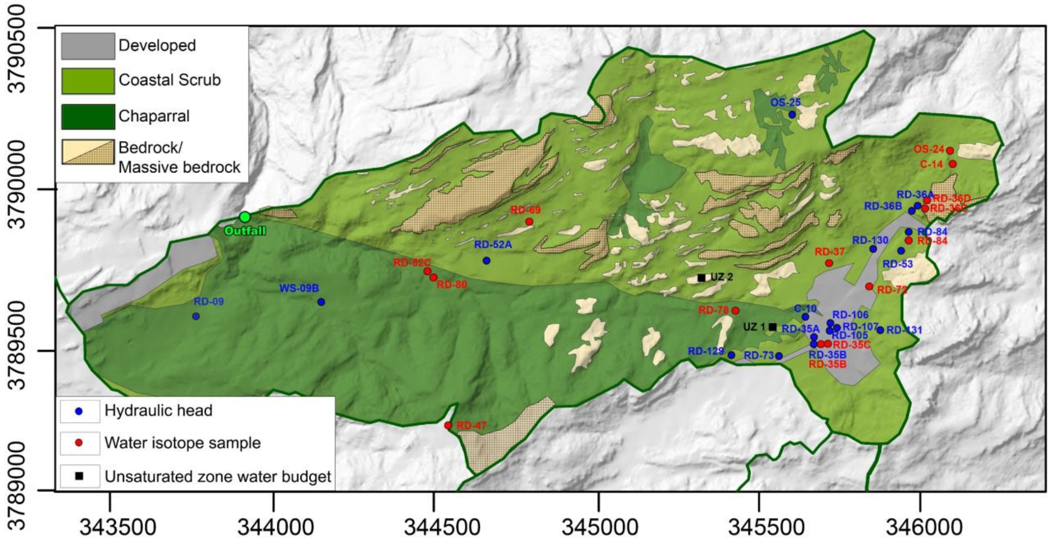

Figure 4 Land use map and location of the wells used for calibration (blue), water isotopes sampling (red). In black the two cells where unsaturated zone water budgets were analyzed.

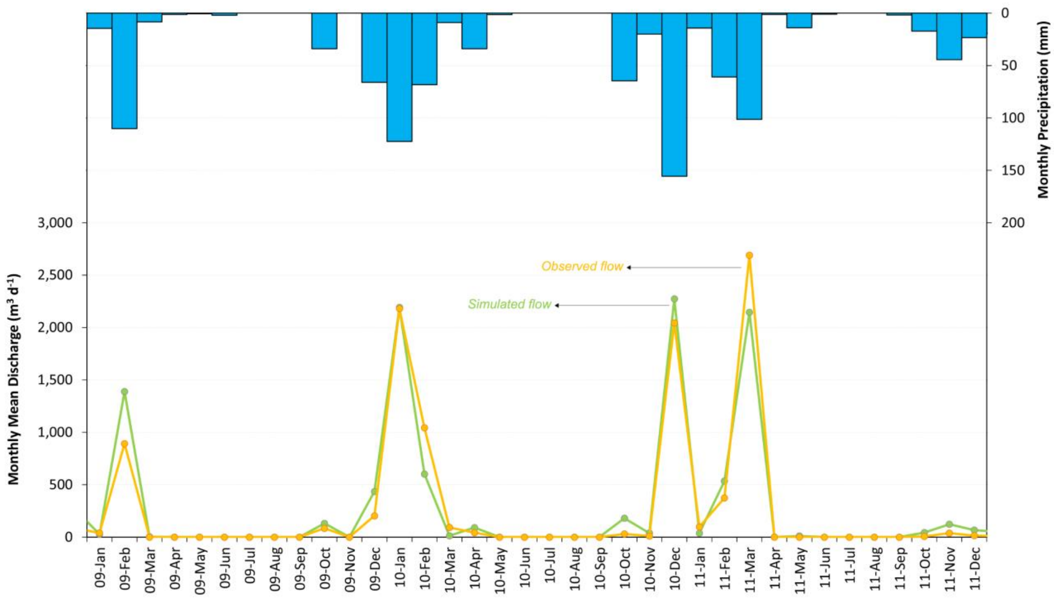

Figure 5 Monthly precipitation values and comparison between simulated (green) and observed (red) runoff flow at the outfall of the catchment from January 2009 to December 2011.

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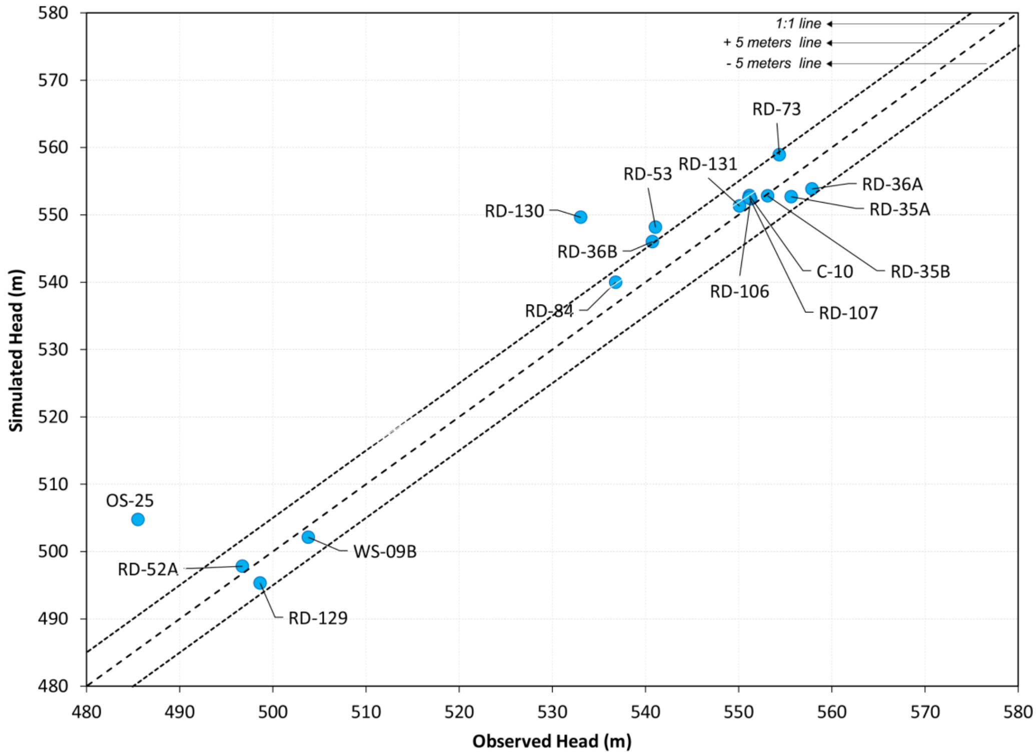

Figure 6 Comparison between simulated and observed groundwater head data for the 17 wells.

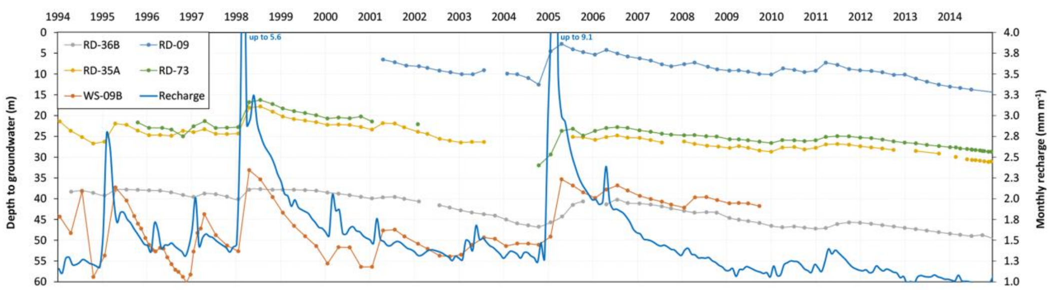

Figure 7 Comparison between the monthly recharge time series and the depth to groundwater at five locations across the catchment.

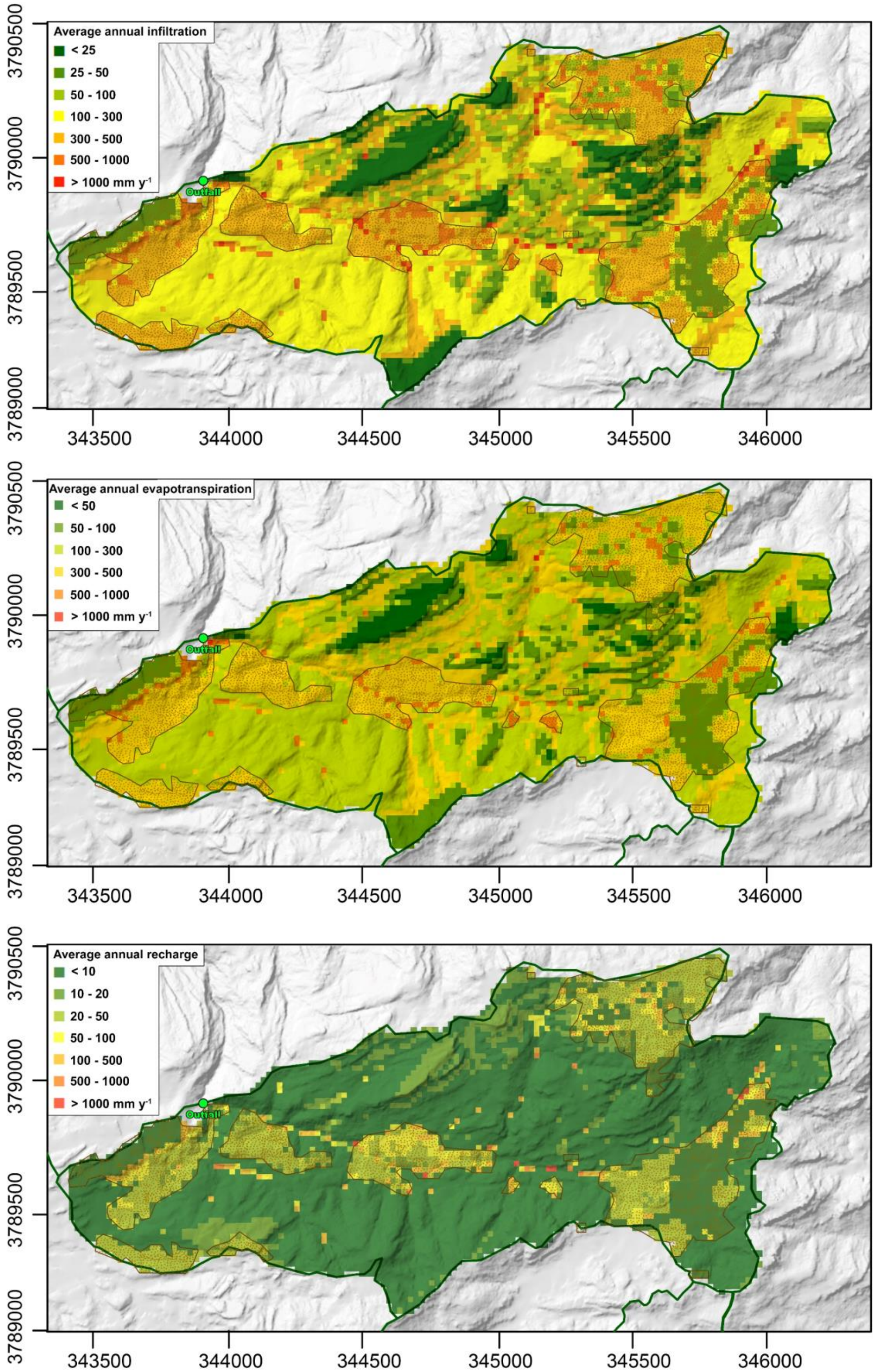
Average annual infiltration
< 25
25 - 50
50 - 100
100 - 300
300 - 500
500 - 1000
> 1000 mm y^{-1}
Outfall
Average annual evapotranspiration
< 50
50 - 100
100 - 300
300 - 500
500 - 1000
> 1000 mm y^{-1}
Outfall
Average annual recharge
< 10
10 - 20
20 - 50
50 - 100
100 - 500
500 - 1000
> 1000 mm y^{-1}
Outfall
3790500
3790000
3789500
3789000
343500
344000
344500
345000
345500
346000

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Figure 8. Distribution of average annual infiltration (a), evapotranspiration (b) and recharge (c). Dashed polygons represent areas with alluvium at the surface.

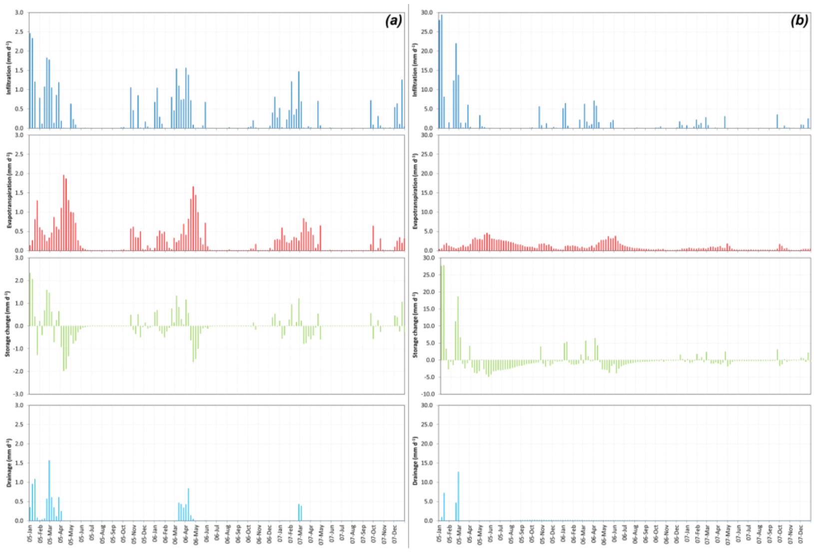

Figure 9 Unsaturated zone water budget for ET zone from January 2004 to December 2007 for two cells representative of the domain: (a) UZ-1 area with outcropping bedrock without vegetation; (b) UZ-2 area with alluvium deposit covered by vegetation.

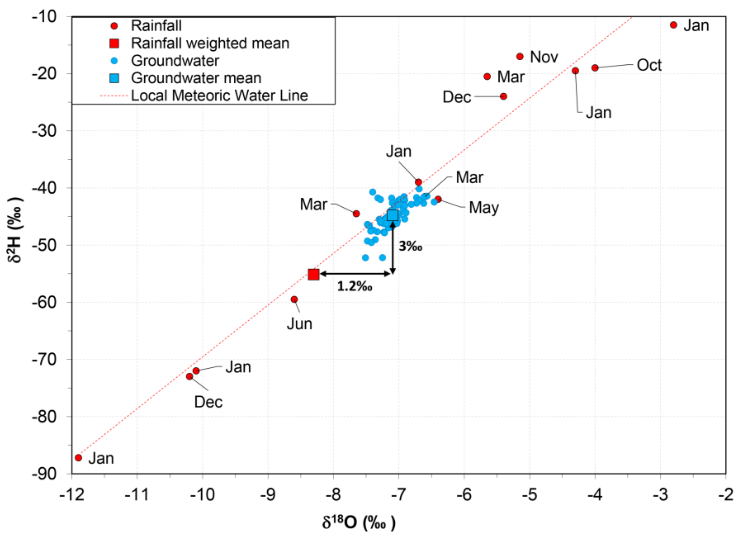

Figure 10 Water isotopes plot for rainfall samples collected at two rain gauge stations and groundwater samples from 16 wells of the catchment.

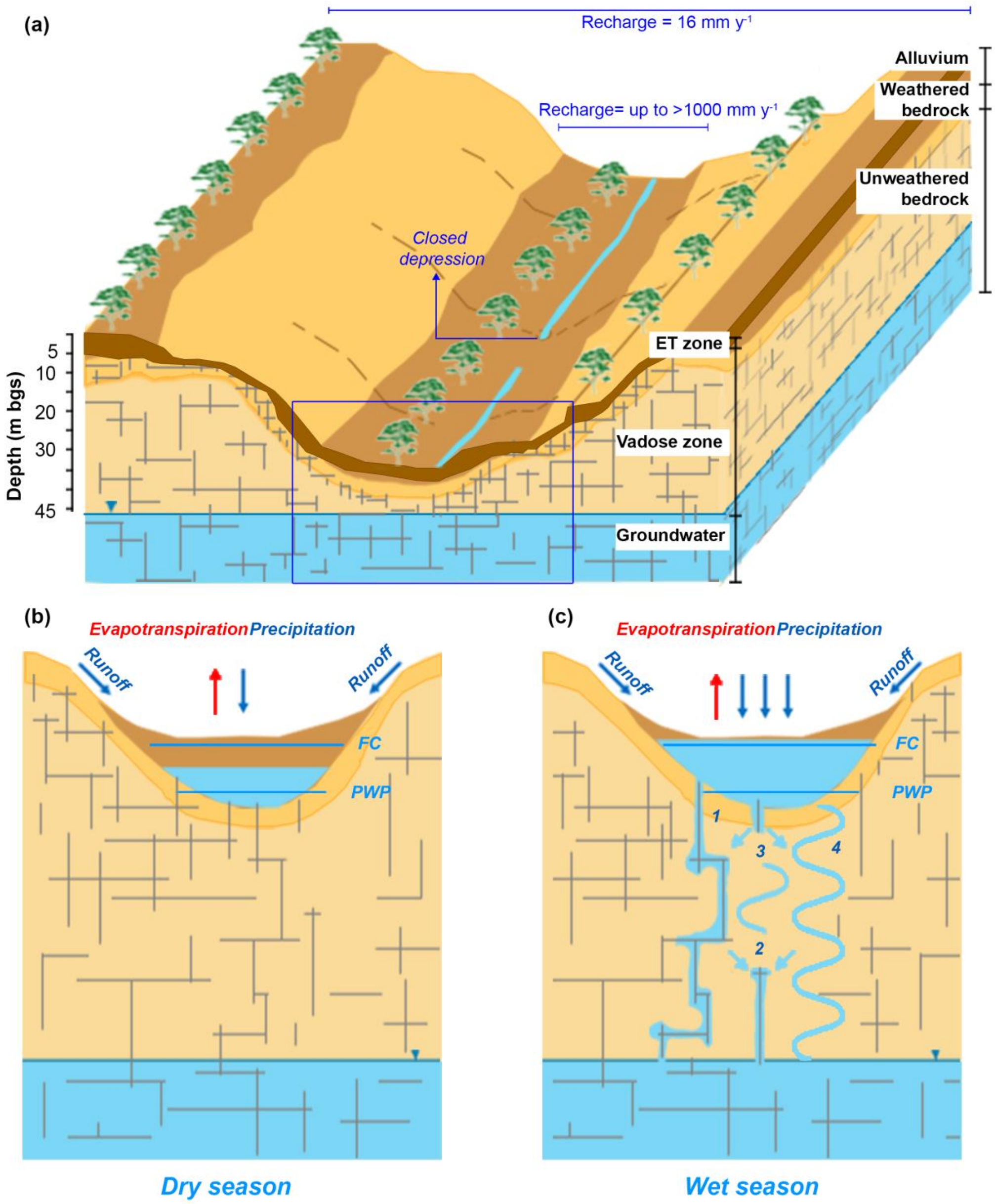

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Figure 11 Conceptual model for recharge at the site. (a) Spatial 3-D conceptual model of the catchment showing where high recharge occurs. 2-D schematic of the unsaturated zone hydrologic process during (b) dry season and (c) wet season. During the dry season water content is between the field capacity (FC) and the permanent wilting point (PWP) and therefore is consumed by evapotranspiration. Conversely, during the wet season, water content is above the FC and seeps into the underlying bedrock. Numbers describe mechanisms of flow in the vadose zone: 1 is fracture flow; 2 is water flowing from matrix into fractures; 3 is water flux from fractures into matrix; 4 is intergranular matrix flow.