A Basin-Scale Approach to Estimating Recharge in the Desert: Anza-Cahuilla Groundwater Basin, CA

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Research Impact Statement: This research estimated the amount of naturally recharging waters in the Anza-Cahuilla groundwater basin to inform long-term groundwater management.

ABSTRACT: The Anza-Cahuilla groundwater basin located mainly in the semi-arid headwaters of the Santa Margarita River watershed in southern California is the principle source of groundwater for a rural disadvantaged community and two Native American Tribes, the Ramona Band of Cahuilla and the Cahuilla. Groundwater in the study area is derived entirely from precipitation and managing groundwater sustainably requires an accurate assessment of the water balance components, yet long-term estimates do not exist. Demand for groundwater in the region has increased and groundwater quality has decreased due to population growth and increased irrigated cropland. To characterize monthly long-term natural recharge and runoff estimates, a physically-based water balance model (Basin Characterization Model) was locally calibrated and validated using nearby streamgages and published estimates of climatic and hydrologic variables. The average modeled annual recharge and runoff from 1981 to 2010 was $5.4 \times 10^6$ and $1.2 \times 10^7$ m$^3$, respectively, for the study area. Recharge and runoff do not reliably occur in large amounts every year and recharge rarely occurs in the groundwater basin footprint. These long-term estimates can be used by water managers, stakeholders, and Native American Tribes to develop plans for sustainable management of future water resources, and as inputs to a three-dimensional groundwater model.

(KEYWORDS: recharge; runoff; ground water hydrology; surface water hydrology.)

INTRODUCTION

Increased demand and limited quantities of subsurface water supply (groundwater) in arid and semi-arid regions result in water scarcity, water quality issues, and difficulties in providing access to drinking water for the expanding populations (Scanlon et al. 2006). In addition, recharge to a groundwater basin is highly variable in space and time and is difficult and expensive to accurately measure over large spatial scales. The groundwater from the Cahuilla Valley and Terwilliger Valley Groundwater Basins (CA DWR 2016) — located in the semi-arid headwaters of the Santa Margarita River watershed in southern California — is the dominant source of water for a rural disadvantaged community and two Native American Tribes (Figure 1). Demand for groundwater in the rural Anza-Cahuilla area has increased significantly because of population growth and the establishment of irrigated crops on previously unirrigated land (Woolfenden and Bright 1988).
The population of the Anza-Cahuilla area rose 15% between 2010 and 2017 (U.S. Census Bureau 2020).

A previous study based on 1973 information (Moyle 1976) identified water-table depressions adjacent to the Cahuilla Tribal Land that had increased the hydraulic gradient and caused the groundwater beneath the tribal land to flow toward the depressions. Examination of recent water level data indicates that there are seasonal changes in water-level altitude with water levels greater in spring and lower in fall (Christensen et al., in review). Continued population growth and resulting increases in groundwater demands may cause greater water-table declines in and around the Cahuilla Tribal Land and the City of Anza. The characteristics and water budget of this groundwater basin are not well understood and are threatened by increasing water use and potential changes in water availability related to climate change. There are no contemporary estimates of natural recharge or runoff to the basin and Landon et al. (2015) documented only previous historical estimates (CA DWR 1956; Moyle 1976; Woolfenden and Bright 1988).

In 2011, the County of Riverside received a grant from the State of California Department of Water Resources (DWR)-Local Groundwater Assistance Fund to begin a program to develop groundwater management as well as evaluate and plan for groundwater monitoring in the Anza-Cahuilla area. Multiple groups have come together to plan, fund, and develop a Groundwater Management Plan to ensure the area has sustainable groundwater resources for future users (Anza Groundwater Association, https://sites.google.com/site/anzawatermgt/home). The Integrated

FIGURE 1. Location figure of study area including streamgages (NWIS, National Water Information System) and upstream drainages, climate station (California Irrigation Management Information System, CIMIS), BCM (Basin Characterization Model) recharge area, Tribal lands, and groundwater basins (CA DWR 2016). [Color figure can be viewed at wileyonlinelibrary.com]
Planning and Management Inc. Report (2011) described one of the primary tasks for the area to be planning and collecting existing available groundwater data. The United States Geological Survey (USGS) has compiled and analyzed groundwater data across a 60-year time frame and more recent work by Danielson (2018) has developed conceptual and analytical geochemical models for use in better groundwater quality management of the study area.

Groundwater in the study area is derived predominantly from precipitation that is not intercepted by evapotranspiration. This water moves downward into the fractures and weathered zones of the consolidated rocks and either infiltrates past the root zone and recharges unconsolidated deposits, runs off into stream channels, or recharges the groundwater system by seepage through the permeable streambeds. The quantity of groundwater in storage and therefore the water levels are dependent on a cycle of extended periods (>10 years) of relatively wet and dry conditions, where average conditions on any given year are uncommon (Woolfenden and Bright 1988). With declines in precipitation, increases in drought frequency, increases in the demand for irrigation, and increases in the variability of recharge projected in the southern California region over the next century (Underwood et al. 2018), it is vital to understand the current state of the hydrology in this area.

The sustainable management of groundwater resources in this basin requires a reasonable quantification of the natural replenishment of groundwater to the aquifer to guide decision making for natural resource managers. The first step of this assessment is a compilation of available information, including regional measurements of various components of the water balance such as precipitation, evapotranspiration, and streamflow. Using all available information, a weight of evidence approach is taken to validate measured components of the water balance and estimate the unmeasured components to assess long-term patterns of natural recharge spatially distributed across the basin. A follow-up to this assessment would consist of the complete hydrogeologic characterization of the basin and the development of a three-dimensional groundwater simulation tool or model supported by groundwater level measurements that would enable the estimation of distributed recharge to the aquifer and provide scenario testing to support sustainable groundwater management decisions.

In this study, we quantify long-term estimates of recharge and runoff for the groundwater basins and surrounding watersheds in the Anza-Cahuilla area to support the sustainable management of a limited resource using a water balance approach with a locally calibrated Basin Characterization Model (BCM). Local calibrations of the BCM model have been applied in numerous basins globally to characterize water budget components including recharge, runoff, streamflow, actual evapotranspiration (AET), and climatic water deficit (Flint and Flint 2012b; Flint et al., 2013a, 2017, 2019; Faunt et al. 2015; Thorne et al. 2015; Byrd et al. 2019). In this paper, we first describe the study area and the BCM conceptual model, then we describe the available calibration and validation data used to refine the water balance estimates. Next, we compare the BCM inputs and outputs to published estimates of precipitation, potential evapotranspiration (PET), recharge, and AET. Finally, we present long-term estimates of recharge and runoff for the groundwater basin, and describe the relationship of precipitation to recharge and the spatiotemporal variability of recharge and runoff for the study area. The quantification of recharge and runoff and natural variability through historical climate change is vitally needed to inform local stakeholders and residents who solely rely groundwater for drinking, municipal use, and farming.

Study Area

The study area is defined by the hydrologic basins shown in Figure 1, encompassing the rural areas in and around the City of Anza, Cahuilla and Ramona Band of Cahuilla Tribal Lands, and vicinity, located in the headwaters of the Santa Margarita River and San Jacinto watersheds, in Riverside County and the San Felipe Creek watershed in parts of Riverside, San Diego, and Imperial counties, California. The overall study area (henceforth referred to as Anza-Cahuilla) includes California DWR groundwater subbasin 9-6 (Cahuilla Valley Groundwater Basin), subbasin 9-006 (Terwilliger Valley), and adjoining tributary watersheds that drain to downstream streamgages used for model calibration (CA DWR 2016). The land that directly drains to the groundwater basin footprint (referred to as the BCM recharge basin) includes the Upper Cahuilla and Lower Cahuilla Creek and the Nance Canyon subbasins (hydrologic unit code-12: U.S. Geological Survey et al. 2013) (bounded by red line in Figure 1). The BCM recharge basin is consistent with groundwater footprints from previous studies (Landon et al. 2015; Danielson 2018), and slightly larger than the footprint from Moyle (1976) (Figure 1). Locally the Nance Canyon area is also known as Terwilliger Valley. The Cahuilla and Terwilliger Valleys and associated creeks and streams that make up the BCM recharge basin are approximately 334 km² in area. The Anza-Cahuilla area ranges in altitude from approximately 2,070 m in the north at Thomas Mountain to approximately 640 m at the westernmost point in the BCM.
recharge basin. The average annual temperature for the City of Anza is 13.8°C with minimum temperatures near freezing in the winter months to maximum temperature above 32°C during July and August (Climate-Data.org).

Average annual precipitation for the period 1981–2010 from local weather stations (stations not shown on map) ranges from about 297 mm at Hemet, approximately 40 km northwest of Anza, 300 mm at the Anza station, to 665 mm at Idyllwild, approximately 24 km north of Anza, (WRCC 2020a, 2020b, 2020c). Snowfall extremes across the study area range between 254 mm occurring in early November to late April and freeze probability of 50% or greater occurring between late November and late March (WRCC 2020b). Precipitation generally occurs in the winter months with infrequent rains in August and September related to monsoon moisture from the south. The geology (Jennings et al. 2010) and vegetation (Fire Resource and Assessment Program; https://frap.fire.ca.gov/data/frapgisdata-land_cover) in the study area are diverse (Figure 2a). The main geology types for the region and surrounding the valley fill deposits are mainly plutonic rocks and metasedimentary rock within the valley. These units of basement material vary from the hard competent basement to highly weathered or fractured, where highly weathered or decomposed the units are friable and allow for some surface infiltration and yield limited amounts of water to wells. The alluvial fill of the valley flat as mapped by Dibblee (2008) consists mainly of weakly indurated to unindurated sediments. Dominant vegetation types include chamise-redshank chaparral, coastal scrub, and mixed chaparral (Figure 2b).

METHODS

Water Balance Simulations: BCM

A physically based, gridded water balance model — the BCM that simulates monthly recharge and runoff — was refined and locally calibrated to the study area and run from water years 1896–2018. A previously calibrated California statewide BCM (Flint and Flint 2021) was clipped to the study area (Figure 1) to be calibrated locally. The BCM directly calculates estimates of natural unimpaired recharge and runoff at a monthly time step for each 270-m grid cell as part of water balance calculations driven by climate inputs (Figure 3).

In the BCM water balance conceptual model (Figure 3), rainfall that exceeds the soil storage will become runoff. Rainfall that percolates through the soil profile can become recharge if evapotranspiration does not exceed the amount of water available on a monthly time step. The basin discharge is calculated in post-processing using a set of equations that combines recharge and runoff using scaling parameters and exponential decay functions to match measured hydrographs. Recharge in this study calculated by the BCM is infiltration below the root zone that may be delayed in reaching the water table due to lateral

FIGURE 2. Geology (Jennings et al. 2010) (a) and major vegetation types (Fire Resource and Assessment Program; https://frap.fire.ca.gov/data/frapgisdata-land_cover) (b) in the study area, with the Moyle (1976) study area (black dashed line), BCM recharge basin (red line) boundaries, and groundwater basins (CA DWR 2016). [Color figure can be viewed at wileyonlinelibrary.com]
flow and large unsaturated zones (>2 m). Estimates of groundwater recharge to the aquifer require hydrogeologic characterization and a groundwater model to calibrate to measured groundwater levels. A complete description of the BCM calculations and postprocessing equations can be found in Flint et al. (2021).

Climate

Monthly climate grids (precipitation, PET, minimum and maximum temperature) used as inputs to the BCM were clipped to the Anza-Cahuilla study area (Flint et al., 2013a, 2013b). Precipitation and temperature grids were developed from Parameter-elevation Regressions on Independent Slopes Model (PRISM, www.prism.oregonstate.edu; Daly et al. 2008). The PRISM datasets are available from 1895 to present and were developed using climate station data and interpolated to 4-km grid cells for the contiguous United States. These grids were downscaled to 270 m using the Flint and Flint (2012a) method that employs Gradient-plus-Inverse-Distance Squared interpolation (Nalder and Wein 1998), which develops relationships between elevation, easting, and northing for each grid cell to spatially downscale the large grids to finer-scale grids. PET was calculated using the downscaled PRISM climate and a modified Priestley–Taylor equation (Flint and Childs 1984), incorporating topographic shading and cloudiness. The downscaled PRISM and PET were compared to a nearby CIMIS station (California Irrigation and Management Information System Hemet station 239, 40 miles northwest of Anza, Table 1), which is presented in the results section.
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fore secondary calibration data were collected to
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water balance such as precipitation, potential and
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ables were used for model validation.

Historical streamflow data in the study area are
sparse. Since the 1950s, there have been no active
streamflow gages in the BCM recharge basin.
Streamflow in the basin is generally ephemeral, rare,
and flashy, thus developing a stage–discharge rating
curve within a one-year field study would be difficult
and likely contain high amounts of uncertainty. How-
ever, streamflow response to rainfall, snowmelt, and
irrigation return events is vital to understanding the
watershed and ultimately to calibrate runoff,
recharge, and integrated hydrologic models. Stream-
flow gages in the surrounding area to the BCM
recharge basin (Figure 1; Table 1) were used to cali-
brate the BCM model. Following calibration of AET
for vegetation types in the study area to remotely
sensed based estimates of AET (Reitz et al. 2017),
monthly streamgage data were downloaded from the
National Water Information System (NWIS, https://
waterdata.usgs.gov/nwis) and used to calibrate BCM
recharge and runoff in a postprocessing method (de-
scribed in detail in Flint et al., 2013a, 2013b, 2021).

After streamflow calibration, the BCM was run for
the (water years) 1896–2018 period.

Actual Evapotranspiration

AET estimates (AETr) for calibration were down-
loaded (Reitz et al. 2017) and clipped to the study area.
The AETr dataset is a combined remote sensing and
water-balance approach to estimate AET at 1-km reso-
lution each month. Time series of PET calculated from
the BCM, AETr, and BCM AET (AETb) were extracted
from the grids for each vegetation type for January
2000–December 2013 calibration period. AETr was
divided by PET for each vegetation type to calculate a
scaling factor, \( K \), for each month that describes the
proportion of PET that becomes AETb seasonally.
To calibrate to the monthly time series of AETr
data, BCM vegetation parameters were changed itera-
tively to optimize the match of AETb to AETr following
the procedure in Flint et al. (2021). A rooting depth
parameter is adjusted first and is used to increase the
amount of available soil storage if AETb is lower than
AETr on average. Other vegetation parameters were
used to adjust the AETb rate to match AETr for each
vegetation type based on the sensitivity to changes in
annual precipitation. See Figure 4 for monthly AET
for 2000–2013 with AETb matched to AETr estimates.
The dominant vegetation types in the study area are
relatively sensitive to annual differences in precipita-
tion relative to mean conditions. Vegetation types that
actively respond to precipitation events by having a
flush of growth that generally occurs at less than a
monthly time step are considered facultative vegeta-
tion types and are parameterized to compensate for
this rapid growth. The AETr is estimated using
monthly remotely sensed images that may not accu-
rately reflect the AET of these vegetation types at a
finer temporal scale. These AET patterns are
accounted for iteratively with comparisons of total
recharge plus runoff to streamflow, and generally have
higher than measured AET, as shown for Annual
Grasslands in Figure 4.

Statistical measures of \( R^2 \) and mean error were cal-
culated for AETb and AETr for each vegetation type
for the calibration period (2000–2013). The coefficient
of determination (\( R^2 \)) represents a goodness of fit
between observed and simulated values, with a value of
1 indicating a perfect fit. The mean error is defined
as the sum of AETb minus AETr divided by \( n \).

Streamflow

In addition to the AET calibration, BCM postpro-
cessed streamflow was calibrated to observe

| BCM ID | Gage name | NWIS ID | Area (m²) | Period of record |
|--------|-----------|---------|-----------|------------------|
| 1      | Temecula Creek near Aguanga | 11042400 | 340,580,773 | 1957–2019 |
| 2      | Wilson Creek above Vail Lake near Radec | 11042490 | 308,296,220 | 1989–1994 |
| 3      | Bautista Creek at Mouth near Valle Vista | 11070070 | 122,263,505 | 2006–2011 |
| 4      | Coyote Creek near Borrego Springs | 10255800 | 404,201,565 | 1950–1983 |
| 5      | Palm Canyon Creek near Palm Springs | 10258500 | 241,438,206 | 1930–2019 |
| 239    | Hemet CIMIS station | —       | —         | 2015–2019 |

TABLE 1. Streamflow calibration gages (BCM ID 1–5) from NWIS for BCM streamflow basins, and CIMIS station (ID 239) used in climate comparison with station name, number, contributing area in m², and period of record.
streamflow gages in the surrounding area due to no gages being located within the BCM recharge area (Figure 1; Table 1). Streamflow calibration was done iteratively with the AET calibration to ensure realistic results. To assess modeled basin discharge against observed data, statistics were calculated for all available streamgages including $R^2$ and the Nash–Sutcliffe efficiency statistic (NSE; Nash and Sutcliffe 1970). The NSE statistic is a normalized statistic that determines the relative magnitude of the residual variance ("noise") compared to the measured data variance, and is calculated as:

$$
NSE = 1 - \frac{\sum_{i=1}^{n} (Q_{i}^{\text{obs}} - Q_{i}^{\text{sim}})^2}{\sum_{i=1}^{n} (Q_{i}^{\text{obs}} - Q_{\text{mean}})^2},
$$

where $Q_{i}^{\text{obs}}$ is the $i$th observation, $Q_{i}^{\text{sim}}$ is the $i$th simulated value, $Q_{\text{mean}}$ is the mean of the observed data, and $n$ is the total number of observations. NSE ranges between $-\infty$ and 1.0, with NSE = 1.0 as the optimal value, and negative values indicating that the mean observed value is a better predictor than the simulated value.

**RESULTS**

**AET Calibration**

Time series of monthly AETr and AETb for the calibration period (2000–2013) for four major vegetation types show a good fit between the datasets (Figure 4). Although the comparisons are performed against modeled data, utilizing estimates of other process-based estimates calibrated to remotely sensed data and constrained by water balance calculations ensured realistic estimates of AET in absence of measured data. Some of the peaks were over or underestimated by the BCM AETb compared to AETr (Figure 4), however, the general patterns and magnitude of AET matched well and helped provide a line of evidence of validity for the dominant water balance component. Overestimation of peaks by the BCM was partially due to the sub-monthly response of plant growth that was undersampled by the AETr and thus compensated for by the BCM calibration for these facultative vegetation types.
TABLE 2. Vegetation type, percent of study area, $R^2$ and mean error between calibration data (AETr) and BCM estimates of AET (AETb).

| Vegetation type              | Percent of study area (%) | $R^2$  | Mean error (mm/month) |
|------------------------------|---------------------------|--------|-----------------------|
| Chamise-redshank chaparral   | 40                        | 0.56   | 3.1                   |
| Mixed chaparral              | 22                        | 0.71   | 3.9                   |
| Desert scrub                 | 11                        | 0.17   | 1.0                   |
| Coastal scrub                | 6                         | 0.5    | 5                     |
| Juniper                      | 3                         | 0.10   | 6.4                   |
| Annual grasslands            | 2                         | 0.43   | 0.7                   |
| Cropland                     | 2                         | 0.26   | 8.7                   |
| Sagebrush                    | 2                         | 0.28   | 3.6                   |

Note: $R^2$, coefficient of determination.

In addition to visual comparisons, statistics were calculated to compare AETr with AETb (Table 2) for the simulation period and showed a reasonably good representation ($R^2 = 0.56–0.71$) of the AETr data for the vegetation types that dominated the study area, chamise-redshank chaparral and mixed chaparral (62% of the study area). Coastal scrub and annual grasslands, covering 8% of the area, had $R^2$ of 0.43–0.5, but desert scrub and juniper, covering 14% of the area had poor $R^2$ fits of <0.17. The mean error was on average $–1.1$ mm/month, and was generally less than $±5$ mm/month except for Juniper and Cropland, which were 6.4 and $–8.7$ mm/month, respectively. Cropland was the least accurate vegetation AET calibration, due to the BCM model not accounting for irrigation and water diversions. The AET calibration data incorporates remote sensing, which accounts for irrigation practices, leading to discrepancies between calibrated and BCM “natural” AET estimates. Vegetation types not included in the table were not refined from the statewide calibration as they each comprised <1% of the study area.

Streamflow Calibration

Streamflow gage data from NWIS was plotted against BCM streamflow and precipitation for visual comparisons. Figure 5 shows a time series of monthly observed (blue) streamflow and BCM modeled basin discharge (red) for Basins 1 (a) and 2 (b), illustrating BCM results for a basin with high streamflow volumes and one with low streamflow. Note that Temecula Creek in Figure 5a has far greater discharge than Wilson Creek in Figure 5b, which only had five years of data available for calibration.

Most of the gages showed a good modeled to observed fit for $R^2$ and NSE of >0.7 (Table 3), even if the peaks were periodically over or undersimulated. The poor calibration result at Coyote Creek (BCM Basin 4) could be due to diversions not accounted for in the BCM, or the inability of the BCM to capture the temporal variability of a flashy ephemeral system. Generally, the streams with higher flows had better calibration statistics than streams that were mostly dry, possibly emphasizing the limitations of the BCM to reflect evaporation from or infiltration into streambeds.

Comparison of BCM to Previously Published Data

BCM inputs (precipitation and PET) and calibrated outputs (AET, runoff, and recharge) were compared to available published data to validate recharge estimates in absence of physical quantitative measurements. Whenever possible, results from this study were extracted or averaged over the same footprint or point location as the respective published estimates. Multiple precipitation estimates were available for varying periods, and gridded precipitation inputs used for the BCM (downscaled PRISM climate) were compared to other published data (Table 4). The long-term estimates of precipitation from Moyle (1976) were temporally averaged but varied spatially across the study area. The annual averages from the Moyle (1976) study were calculated using station data and the long-term spatial distribution of precipitation. The California DWR (CA DWR) estimates were from precipitation gages in or near the study area, and comparisons of precipitation from this study were averaged over the BCM recharge basin (Figure 1). The precipitation and PET point estimates were from the nearby CIMIS station (Hemet, Figure 1) and WRCC stations. For each station, downscaled PRISM precipitation or BCM PET was extracted for the same grid cell for comparison. There is an excellent agreement between previous estimates and the downscaled PRISM data, except for water year 2017 CIMIS precipitation estimates. An analysis of nearby stations and data flags indicated a ~50% underestimation of precipitation at that CIMIS station for that year. Using this station alone to drive water balance calculations would cause the considerable error and subsequent underestimations of recharge and runoff.

Recharge estimates from the BCM align closely with previously published estimates from Moyle (1976) for the same contributing area. Although the AETb estimate is about 30% lower than Moyle’s calculation, the BCM recharge is only slightly higher than Moyle’s recharge estimate. To calculate the average annual AET, Moyle used a constant consumptive use of native pasture of 406 mm/year, or 95% of rainfall, whichever was smaller. AETb calculations are based on the BCM water balance and
calibrated as described in the “Calibration and Validation” section.

Recharge and Runoff Estimates

Long-term natural recharge estimates are difficult to quantify, especially in areas without detailed field surveys or groundwater models. Recharge and runoff are highly temporally variable in the BCM recharge basin: runoff ranged from zero to $5.8 \times 10^7$ m$^3$ or 50,000 ac-ft per month (Figure 6) for water years 1896–2018. Recharge is generally lower than runoff in the study area and ranged from zero to $1.4 \times 10^7$ m$^3$ or 11,000 ac-ft per month for water years 1896–2018. In wetter years the ratio of recharge to runoff decreases. In drier years, the recharge to runoff ratio is higher, and recharge can be equal to or higher than runoff in some areas. The occurrence of recharge and runoff can be unreliable with several years between any substantive amount. The relation of recharge to precipitation is exponential in arid and semi-arid regions and often requires the exceedance of a precipitation threshold to produce substantial recharge or runoff (Figure 7), and the long-term average is highly dependent upon which years are used. Flint et al. (2012) illustrate this as well and describe the episodic nature of recharge in semiarid and arid environments, at both local and global scales. At or above
around 300 mm of precipitation, the BCM recharge basin begins to produce significant amounts of recharge and higher increases for a given increase in precipitation. Between 1998 and 2018, only four years (green squares in Figure 7) of 21 had greater than the 1981–2010 average recharge (purple “X” in Figure 7) and dry years occurred more frequently than wet years relative to the 300 mm precipitation threshold. The average annual recharge and runoff from 1981 to 2010 over the BCM recharge basin (larger than the Moyle study area) were $5.4 \times 10^6$ and $1.2 \times 10^7$ m$^3$, respectively. However, the long-term average value for recharge is not a reliable estimate for any given year in this region due to the extreme interannual variability. Calculating the long-term average for the 1971–2000 period includes the highest peak on record in February 1980 and thus increases the long-term averages of recharge and runoff to $7.3 \times 10^6$ and $1.6 \times 10^7$ m$^3$, respectively.

In addition to being temporally variable, recharge and runoff are spatially variable across the region (Figure 8). The BCM recharge basin covers the groundwater basin as well as the surrounding hillslopes. Recharge frequently occurs outside of the groundwater basin and rarely over the groundwater basin footprint (Flint and Flint 2007). Most of the precipitation occurs in the northern and southern corners of the recharge basin, outside of the groundwater basin. Even with two wet years in the 2011–2018 period (Figure 8a), the BCM recharge basin was still slightly drier than the long-term average of 16 mm/year with an average of only 15 mm/year (Figure 8b).

Average annual recharge indicates the highest amount of recharge generally occurs in locations with higher than average precipitation, but not necessarily the area with the most amount of precipitation. Differing vegetation types will variably compete for available water prior to infiltration, and different geologic types will control the rate at which available water can recharge below the root zone.

### DISCUSSION

Accurate long-term estimates are vital for the sustainable management of groundwater resources, and

| Variable | Period | Point or area comparison | Source | Published estimate mm | This study mm |
|----------|--------|--------------------------|--------|-----------------------|--------------|
| Precipitation | 1897–1947 | Moyle recharge basin | Moyle (1976) | 406–762 | 419 |
| Precipitation | 1956 | Moyle recharge basin | Moyle (1976) | 132 | 210 |
| Precipitation | 1943 | Moyle recharge basin | Moyle (1976) | 568 | 427 |
| Precipitation | 1949–1954 | BCM recharge basin | CA DWR (1956) | 364 | 337 |
| Precipitation | 1953 | BCM recharge basin | CA DWR (1956) | 298 | 298 |
| Precipitation | 1951 | BCM recharge basin | CA DWR (1956) | 185 | 261 |
| Precipitation | 1981–2010 | Anza (Point) | WRCC (2020b) | 300 | 321 |
| Precipitation | 1981–2010 | Idyllwild (Point) | WRCC (2020c) | 665 | 627 |
| Precipitation | 1981–2010 | Hemet (Point) | WRCC (2020a) | 297 | 307 |
| Precipitation | Water year 2016 | Hemet (Point)$^1$ | CIMIS | 177 | 174 |
| Precipitation | Water year 2017 | Hemet (Point)$^1$ | CIMIS | 181 | 364 |
| Precipitation | Water year 2018 | Hemet (Point)$^1$ | CIMIS | 128 | 129 |
| PET | Water year 2016 | Hemet (Point)$^1$ | CIMIS | 1,634 | 1,468 |
| PET | Water year 2017 | Hemet (Point)$^1$ | CIMIS | 1,588 | 1,471 |
| PET | Water year 2018 | Hemet (Point)$^1$ | CIMIS | 1,693 | 1,475 |
| Recharge | 1973 | Moyle recharge basin | Moyle (1976) | 5,551 | 5,589 |
| AET | Average annual 1897–1947 | Moyle recharge basin | Moyle (1976) | 105,463 | 76,846 |

1CIMIS Hemet station, https://cimis.water.ca.gov/.
no direct spatially distributed measurements currently exist. Modeled recharge estimates cannot be directly validated without expensive large-scale field measurements that still only represent the point location being measured. The BCM calculates “natural” recharge spatially across the entire watershed on the basis of multiple gridded datasets, all of which can be tested or validated. Natural recharge in this
study is defined as the total water that makes it through the root zone, and therefore may be different from actual recharge to the groundwater aquifer due to lag times between the unsaturated zone and the aquifer where evapotranspiration losses as well as seepage back into the surface water can occur and does not include perching layers or redistribution of water within the saturated zone. BCM natural recharge estimates do not include irrigation or water imports from other basins and do not account for differences in streambed hydraulic conductivity.

Climate forcing data like precipitation and air temperature are one of the greatest sources of uncertainty in water balance modeling (Gourley and Vieux 2005), and fine-scale gridded estimates can provide a more robust spatial and temporal estimate of precipitation in areas that have little to no nearby long-term station data (Moriasi and Starks 2010; Flint and Flint 2012a; Vergara et al. 2014). Gridded datasets, such as PRISM, use station data along with other physiographically sensitive algorithms for interpolation (Daly et al. 2008), and when coupled with spatial downscaling to finer scales can provide an accurate model input. However, even with the limitations of input data uncertainty and model uncertainty, the overall water balance components can be determined from this study.

**CONCLUSION**

Long-term estimates of natural recharge and runoff were calculated for the Anza-Cahuilla groundwater basin using a water balance model and were found to be highly variable across space and time. The BCM is a physically based water balance model that simulates monthly recharge and runoff for each 270-m grid cell, and was refined from a California-wide model and locally calibrated to the study area. Using limited available calibration data, a weight of evidence approach was taken to validate measured components of the water balance and to estimate the unmeasured components to assess long-term patterns of natural recharge and runoff spatially across the basin. Climate inputs and hydrologic outputs of the model were compared to previously published estimates in or near the study area over identical locations and footprints and were found to be consistent.

Annual recharge and runoff ranged from zero to $2.6 \times 10^7$ and $7.7 \times 10^7$ m$^3$, with average values of $6.1 \times 10^6$ and $1.2 \times 10^7$ m$^3$, respectively from water years 1896 to 2018. Recharge estimates calculated for the 1981–2010 period decreased to $5.4 \times 10^6$ m$^3$, however, the runoff estimate was similar to the 1896–2018 period. In the last 20 years, only four years reached or exceeded the long-term average, highlighting the interannual variability and suggesting that ten-year periods of alternating wet and dry periods no longer describe the climatic patterns in this area. Recharge and runoff do not occur in large amounts every year, and when very wet years occur, most of the water becomes runoff and a lesser component becomes recharge. A nonlinear relationship of precipitation to recharge was shown, where <200–300 mm/year of precipitation produced negligible recharge. This finding is consistent with other studies in arid and semi-arid environments (Scanlon et al. 2006). In drier years, a larger proportion of the precipitation can become recharge, depending on precipitation intensity. Recharge infrequently occurs within the recharge basin and even less frequently in the groundwater basin footprint. Instead, recharge tends to occur in the surrounding higher elevation areas in the northern and southern corners of the BCM.
recharge basin. The spatial distribution of recharge is controlled across a watershed by varying climatic patterns, soil properties, and geology characteristics, and may not occur within the footprint of the underlying groundwater basin.

Water managers can use estimates of historical natural recharge to develop plans for the sustainable use of groundwater in the future, and results from this study can be used as inputs to a three-dimensional groundwater model that can account for unsaturated zone flow processes to the groundwater basin. Future climate scenarios could be applied to this model to determine the uncertainty in future groundwater availability through changes in climate. Though the values represented in this study are consistent with previous investigations, the actual values may vary. The values presented should be validated and adjusted as appropriate by calibrating to measured groundwater level changes using an integrated hydrologic model that couples recharge, streamflow, precipitation, and aquifer properties.

DATA AVAILABILITY

Model input and BCM outputs are online and available to the public through a U.S. Geological Survey data release (Stern and Flint 2021): https://doi.org/10.5066/P9BAMCP4.

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AUTHOR CONTRIBUTIONS

Michelle A. Stern: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Project administration; Resources; Software; Validation; Visualization; Writing-original draft; Writing-review & editing. Lorraine E. Flint: Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Resources; Software; Supervision; Validation; Visualization; Writing-original draft; Writing-review & editing. Alan L. Flint: Conceptualization; Data curation; Investigation; Methodology; Software; Validation. Allen H. Christensen: Conceptualization; Funding acquisition; Writing-original draft; Writing-review & editing.

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