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Runoff Modeling of a Coastal Basin to Assess Variations in Response to Shifting Climate and Land Use: Implications for Managed Recharge

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Abstract

We quantified the distribution of hillslope runoff under different climate and land-use conditions in a coastal, mixed land-use basin, the Pajaro Valley Drainage Basin (PVDB), California, USA, in order to evaluate opportunities to improve groundwater supply. We developed dry, normal, and wet climate scenarios using high-resolution historic data and compared contemporary land use to pre-development land use under the different climate scenarios. Relative to pre-development conditions, urban and agricultural development resulted in more than twice as much simulated runoff generation, greater spatial variability in runoff, and less water available for recharge; these differences were most pronounced during the dry climate scenario. Runoff results were considered in terms of potential to support distributed stormwater collection linked to managed aquifer recharge (DSC-MAR), which routes excess hillslope runoff to sites where it can infiltrate and enhance groundwater recharge. In the PVDB, 10% of the annual groundwater deficit could be addressed by recharging 4.3% of basin-wide hillslope runoff generated during the normal scenario, and 10.0% and 1.5% of runoff during the dry and wet scenarios, respectively. Runoff simulation results were combined with an independent recharge suitability mapping analysis, showing that DSC-MAR could be effective in many parts of the PVDB under a range of climate conditions. These results highlight the importance of strategically locating DSC-MAR projects at the confluence of reliable supply and favorable subsurface hydrologic properties.

Keywords Hillslope runoff · Stormwater collection · Managed aquifer recharge · Groundwater management · Land use development · Climate and hydrology

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1 Introduction

Shifting climate and land use substantially impact regional hydrology around the world, including the magnitude and distribution of groundwater recharge and runoff generation. Precipitation intensity has increased in recent decades in many parts of the world (Leahy and Kiely 2011; Zhang and Cong 2014), a trend linked with anthropogenic climate change (Liu et al. 2009; Swain et al. 2018). Though the impacts of climate change on groundwater recharge are not fully understood, increasing rainfall intensity is often associated with a greater fraction of precipitation becoming runoff, and therefore less infiltration and recharge, particularly in developed areas (Tashie et al. 2016). Furthermore, as urban development has spread, increasing impervious area has also resulted in more runoff and less natural recharge (Shuster et al. 2005). These climate and land-use trends contribute to declining groundwater supplies and increasing runoff generation, but it remains unclear how simultaneous shifts in climate and land use may compound water resource challenges.

Managed aquifer recharge (MAR) is a well-established approach to improve groundwater resources, employing various techniques to enhance recharge with surface water (Bouwer 2002). In addition to increasing groundwater supplies, MAR may mitigate flooding, improve water quality, and enhance baseflow (Dillon 2005). Many spatially variable factors impact MAR project performance, including soil infiltration capacity, subsurface geology, aquifer storage capacity and transmissivity, water quality, and social/economic factors. Computational mapping studies considering such factors have played an important role in evaluating potential sites for MAR projects and selecting appropriate locations (e.g., Russo et al. 2014; Ringleb et al. 2016). These mapping studies vary in terms of overall project goals, which factors are considered, and how the factors are weighted and combined.

Stormwater runoff, diverted from hillslopes or storm drains before it reaches a stream channel, is increasingly considered a potential source of water for MAR (Page et al. 2016). Collecting hillslope runoff may require less infrastructure and lower operating costs than diverting from a surface water body, particularly if flows are passively routed using gravity. Moreover, stormwater runoff is naturally distributed throughout a watershed, providing many potential locations for managed recharge on multiple scales (Newcomer et al. 2014). In this study, we focus on “distributed stormwater collection” linked to MAR (DSC-MAR), in which hillslope runoff is infiltrated before it reaches a stream (Beganskas and Fisher 2017). We specifically target ~0.4–4.0 km^2 (~100–1000 ac) drainage areas, large enough to collect a substantial volume of runoff yet small enough to keep costs relatively low.

There is a rich literature on simulating runoff from hydrologic basins, ranging from strongly process-based models (Hohmann et al. 2018) to semi-distributed hydrologic routing models (Buccola et al. 2016) and highly-parameterized conceptual models (Nauditt et al. 2017). A critical challenge for runoff models is obtaining the data needed to discretize the simulation domain, represent highly variable properties and processes at appropriate temporal and spatial scale(s), and calibrate/validate the model against hydrologic observations (Cornelissen et al. 2016). Controls on runoff processes have been modeled at hillslope (Meyerhoff and Maxwell 2011) and catchment (Hoang et al. 2017) scales. Many modeling studies have independently evaluated how shifting climate (e.g., Fiseha et al. 2014) or land use (e.g., Du et al. 2013) impact catchment-scale hydrology; some recent studies have evaluated the simultaneous impacts of shifting both (e.g., Farjad et al. 2017).

In this study, we assess hillslope runoff generation as a function of climate and land use, focusing on runoff that could support DSC-MAR. Specifically, we seek to: (1) quantify spatial variations in seasonal hillslope runoff generation in a coastal, mixed land-use hydrologic basin; (2) assess how differences in climate and land use impact hillslope runoff generation in this setting, including interactions between these two factors; and (3) compare the availability of hillslope runoff throughout the basin to determine the most effective locations for DSC-MAR projects. To address these goals, we developed a series of physically-based, catchment-scale hydrologic simulations and linked them to an independent spatial assessment of landscape suitability for groundwater recharge. This approach is novel in linking local surface water supplies to recharge suitability, assessing the combined influences of climate and land use, and focusing on hillslope flows rather than discharge in defined channels.

2 Methods

2.1 Study Region

This study focuses on the 546-km^2 Pajaro Valley Drainage Basin (PVDB), Central Coastal California, USA (Fig. 1a,b). The PVDB overlies the Pajaro Valley Groundwater Basin, adjacent to Monterey Bay and the Pacific Ocean. The PVDB consists of the lower Pajaro River Watershed, the Elkhorn Slough drainage, and a small area draining from the north. The PVDB is primarily underlain by Quaternary terrace, alluvial, and eolian deposits; the Aromas Formation; and the Purisima Formation, which comprise the primary aquifer units in this area (PVWMA 2014). Land use in the PVDB is agricultural (27%), urban/residential (12%), and a mix of native and non-native vegetation (62%), but most groundwater use supports agricultural activities. Strawberries and cane berries are the most abundant crops, representing 2670 ha in 2016 (Santa Cruz County 2016).

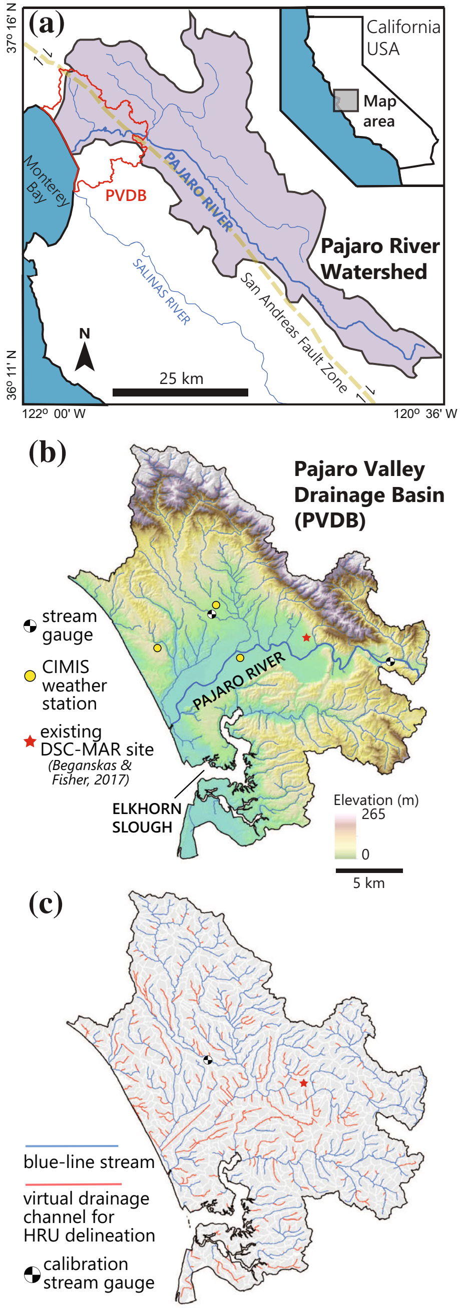
There is a strong north-to-south precipitation gradient across the PVDB, with $\geq$130 cm/yr falling to the north in the Santa Cruz Mountains and $\leq$ 50 cm/yr to the south. Precipitation is highly seasonal; most rainfall occurs between November and April. The annual hydrologic cycle in this area, as in much of the western United States, is assessed with water years (WY) that begin October 1 (e.g., WY2014 is 1 October 2013 through 30 September 2014).

Groundwater is particularly important in this region, which lacks both snow accumulation and surface water imports. The Pajaro Valley Groundwater Basin has experienced chronic overdraft for decades, decreasing groundwater supply and contributing to saltwater intrusion along the coast; the annual groundwater deficit is ~1.2×10^7 m^3/yr (~12,000 ac-ft/yr) (Hanson et al. 2014). The Pajaro Valley Water Management Agency is implementing a basin management plan to reduce demand through water conservation and enhance supply through wastewater recycling and other projects. In addition, an effort is underway to develop a set of DSC-MAR projects that could contribute an additional ~1000 ac-ft/yr of water supply benefit (Kiparsky et al. 2018), equivalent to ~8% of the annual groundwater deficit. One DSC-MAR project has been monitored since 2011 (Beganskas and Fisher 2017) and additional sites are in development or under consideration. The present study was designed to help assess how much water is available in this region for DSC-MAR and how the compounded impacts of varying climate and shifting land use could impact the success of this approach.

2.2 Precipitation-Runoff Modeling System (PRMS)

Precipitation-Runoff Modeling System (PRMS) (Markstrom et al. 2015) is a distributed-parameter watershed model developed by the United States Geological Survey (USGS).

Fig. 1 Pajaro Valley Drainage Basin (PVDB). a Pajaro River watershed and PVDB (*red outline*). b Topographic map of the PVDB showing major streams, stream gauges, CIMIS stations, and an active DSC-MAR project. c HRUs (*white outlines*) with virtual drainage channels (*red*) and blue-line streams (*blue*)



PRMS was selected because it is open source, widely used, well documented, modular, and flexible in spatial discretization (see *Section SI-1*). Many studies have used PRMS to evaluate the impact of climate or land use on streamflow (e.g., Islam et al. 2012; Yazzie and Chang

2017). The most recent PRMS release (version 4, applied in the present study) uses daily time steps, which is consistent with the widespread availability of historical, spatially-distributed daily meteorological data for large continental regions (e.g., GPCC, www.esrl.noaa.gov/psd/data/gridded/data.gpcc.html; APHRODITE, www.chikyu.ac.jp/precip). A daily time step is appropriate for this study, which emphasizes seasonal hillslope runoff generation rather than response to individual storms.

PRMS includes modules to represent spatial and temporal variations in precipitation, solar radiation, interception, throughfall, evapotranspiration (ET), snow melt, sublimation, runoff, recharge, and baseflow. Many modules have multiple options to represent key processes and some modules can be omitted. For example, because the PVDB has a moderate climate and snow is rare, we omitted snow-related modules. To assess potential runoff generation in support of DSC-MAR we aggregated interflow, Hortonian, and Dunnian flows (see *Section SI-1*).

2.3 Hydrologic Response Units (HRUs)

PRMS simulates the landscape as a network of discretized Hydrologic Response Units (HRUs), each assigned static properties and dynamic variables. For each time step, PRMS calculates a mass balance to route water between reservoirs within each HRU (see *Section SI-1*) and between adjacent HRUs (see *Section SI-2.2*). We delineated HRUs topographically to closely represent the pathways water follows across the landscape. Most previous PRMS-based studies used HRUs between 10 and 100 km^2 in size (e.g., Fang et al. 2015; Ahmadalipour et al. 2017), with some using HRUs >10,000 km^2 (Markstrom et al. 2016). For this study, we delineated higher-resolution HRUs (0.1–1.0 km^2) similar in size to a runoff source area for DSC-MAR (see *Section SI-2.1*; Fig. 1c).

HRUs were assigned static parameters representing soil, vegetation, and other properties (see *Section SI-2.3*; Table S1). HRUs were also characterized by daily climate values (minimum temperature, maximum temperature, precipitation). Climate values were distributed to each HRU based on 800-m gridded data acquired from the Parameter-elevation Relationship on Independent Slopes Model (PRISM) (Daly et al. 2008). With a PRISM grid size of 0.64 km^2, these data have a similar spatial resolution to the HRUs and are the highest-spatial-resolution continuous daily climate data available for the region. Daily PRISM data were applied to each HRU using fractional area-weighting.

2.4 Calibration and Validation

We ran PRMS to simulate 33 years: six initialization years, loading storage reservoirs with antecedent moisture (WY1982–87); a 14-year calibration period (WY1988–01); and a 13-year validation period (WY2002–14). First, solar radiation and PET were calibrated by comparing simulated output from three HRUs with data from California Irrigation Management Information System (CIMIS) stations located within the same HRUs. Next, streamflow was calibrated and validated (see *Section SI-3.1*) by comparing PRMS simulation output with channel flows at a USGS stream gauge on Corralitos Creek (#11159200), the largest tributary to the Pajaro River in the PVDB (Fig. 1). The contributing area for this gauge is entirely within the PVDB and represents 13% of the study region. There is another USGS stream gauge on the Pajaro River (#11159000, Chittenden), but it is located near where the river enters the PVDB, with flows dominated by runoff from outside the study area.

We calibrated and validated the model at monthly and annual time scales. Comparing daily simulation output to daily observed channel flows would be inconsistent with available driving meteorological data and the study's focus on evaluating seasonal hillslope runoff generation (see *Section SI-3.2*). Calibration and validation were evaluated using Nash-Sutcliffe Efficiency (NSE) and normalized root mean square error (NRMSE; see *Section SI-3.1*). As an additional validation "spot check," we compared simulated output to field data from an operating DSC-MAR field site (Beganskas and Fisher 2017) for the three overlapping years of simulations and field observations (WY2012–14).

2.5 Climate Scenarios

Many regional climate models (RCMs) predict that California will become warmer in the future, but there is uncertainty concerning how precipitation patterns will change (Allen and Luptowitz 2017; Cvijanovic et al. 2017). Precipitation in California is highly variable from year to year (Liu et al. 2018) and a recent analysis projects that inter-annual variability will increase in the future (Swain et al. 2018). In light of uncertain climate projections, some watershed modeling studies have evaluated sensitivity to artificial climate perturbations rather than directly using RCM output (Vano and Lettenmaier 2014; Hohmann et al. 2018). We applied a related approach, generating a catalog of historic climate scenarios drawn from WY1982–2014. We selected five years near the 20th percentile for total annual rainfall, seven years near the 50th percentile, and five years near the 80th percentile, representing characteristic "dry," "normal," and "wet" climate conditions, respectively (Fig. S1). For each climate scenario, we ran the selected years in random order. The complete simulation sequence comprised a seven-year initialization and stabilization period using the normal scenario, a seven-year normal scenario, a five-year wet scenario, a seven-year normal scenario to reinitialize the model to normal conditions, and a five-year dry scenario.

Constructing climate scenarios in this manner provides several benefits. It uses high-spatial-resolution PRISM data that accurately represent rainfall and temperature distribution across a highly heterogeneous landscape, including individual storm tracks and day-to-day persistence of wet or dry conditions. High-spatial-resolution PRISM data contrast with typical RCM grid spacing (generally ≥ 10 km^2) (e.g., Berg et al. 2013). Additionally, running five dry (wet) years in sequence resulted in drier (wetter) conditions than are observed during any individual dry (wet) year, as the hydrologic impacts accumulate over consecutive years; thus, the scenarios represent more extreme conditions than have been observed in the recent past. This approach also acknowledges uncertainty as to what future climate holds for the region. It allows water managers and stakeholders to assess the implications of both wetter and drier future conditions, rather than relying on projections from an individual RCM or an average of multiple RCMs, which tend to reduce projected extremes.

2.6 Land-Use Conditions

We represented "pre-development" conditions for comparison with contemporary land use by assigning native grass, shrubs, or mixed forest to each human-modified land-use pixel. As there currently appears to be a correlation in this region between native vegetation type and land slope, we assigned native grasses to the lowest slopes, shrubs to intermediate slopes, and mixed forest to steep slopes. Numerous spatial parameters, including soil rooting depth, vegetation density, and impervious area, were adjusted to correspond with native vegetation assignments. This simple approach allowed for a plausible, heterogeneous distribution of native vegetation types in human-modified areas. However, it neglected larger-scale landscape modification (e.g., blocking or filling in streams, flattening slopes to enhance agricultural production) that may have influenced the regional drainage network, as there are no detailed spatial data representing these changes. This part of the study aimed to assess how vegetation changes may influence the nature of hillslope runoff generation under the same climate scenarios that were applied to modern land-use simulations.

2.7 Spearman Rank Correlation

We used a Spearman rank correlation analysis (Khaliq et al. 2009) to quantify the extent to which individual parameters correlated with mean annual hillslope runoff generation in each HRU (using results from simulations with cascades turned off, see *Section SI-2.2*). Several PRMS parameters that impact runoff generation, including soil routing coefficients, were assigned the same value for each HRU (see *Section SI-2.3*; Table S1). Spearman rank correlation coefficients were generated for 20 parameters that varied between HRUs and a unique rank correlation coefficient was calculated for each climate scenario and land-use condition.

2.8 Applications for MAR Suitability

We added PRMS results to earlier MAR suitability analyses for the PVDB (Russo et al. 2014; Fisher et al. 2017), creating new DSC-MAR suitability maps that also consider hillslope runoff supply. The previous MAR suitability analyses included a surface analysis for the entire region (considering soil infiltration capacity and underlying geology), a subsurface analysis for a sub-region for which data were available (considering transmissivity, vadose zone thickness, changes in water level, and available storage), and a composite analysis combining the surface and subsurface calculations. The new DSC-MAR suitability maps in this study identify locations that are above the 40th percentile of MAR suitability ratings and generate at least 6.5×10^4 m^3/yr of hillslope runoff per 50 ha of drainage area (13 cm/yr) during each climate scenario (with contemporary land use and cascades turned on; see *Section SI-2.2*).

3 Results & Discussion

3.1 Calibration and Validation Results

Monthly and annual NSE values for streamflow calibration (0.878, 0.850) and validation (0.754, 0.627) were within the range of other studies using PRMS, including studies that used automated calibration algorithms (Fang et al. 2015; Dams et al. 2015; Yazzie and Chang 2017; Ahmadalipour et al. 2017). According to these metrics, PRMS reasonably simulated monthly and annual streamflow as well as monthly PET and solar radiation (Figs. S2, S3; Table S2).

Matching the magnitude of the largest streamflow events during calibration resulted in simulated smaller events that were too large. Conversely, accurately representing lower-intensity events resulted in under-representing many large events but was preferred for overall model fit. The model's under-calculation of large runoff events is a consequence of several factors, including the temporal resolution of driving climate data (see *Section SI-3.2*). Daily precipitation data under-represent true rainfall intensity, as high-intensity, short-duration rainfall (including short bursts during longer events) is averaged over 24 h (Berne et al. 2004). Under-representing rainfall intensity will result in conservative estimates of hillslope runoff generation, as a greater fraction of lower-intensity rainfall generally infiltrates into soil rather than becoming runoff.

Comparing runoff measurements from a single MAR field site to model predictions during three drought years showed that the model was conservative in estimating annual hillslope runoff generation and generated less year-to-year variability compared to site-specific field data (Fig. S4). Overall, the model's performance is appropriate to meet this study's objectives, which are to indicate relative differences in seasonal runoff generation around the watershed. As the model calculations for runoff from large events are conservative, potential water supply benefits from DSC-MAR are likely to be lower bounds.

3.2 Hillslope Runoff Generation for Different Climate Scenarios

Months with substantial rainfall (>7.5 cm) occurred at least once per year during all climate scenarios, but the wet scenario had the most consecutive rainy months (Figs. 2, S5). For all simulations, little runoff was generated during the first rainy month of each year, whereas consecutive rainy months were associated with much more runoff generation. Comparing the monthly runoff-precipitation ratio (*RPR*) with total precipitation during the previous month resulted in a steeper best-fit line and tighter 95% confidence interval than comparing monthly *RPR* with precipitation during the current month (Figs. 2, S5); this indicates that total precipitation during the previous month more strongly predicts *RPR*. Regardless of land use, total rainfall was not an especially accurate predictor of runoff generation at a monthly time scale, suggesting that other factors, including rainfall intensity and soil antecedent moisture, play important roles (Brocca et al. 2008).

With contemporary land use, there were large differences in runoff generation between the three climate scenarios. During the dry scenario, 1.5×10^7 m^3/yr (12,000 ac-ft/yr) of runoff was generated throughout the PVDB, equivalent to 2.8 cm/yr (1.1 in/yr) normalized by basin area. There was much more runoff generated, and a greater *RPR*, during the normal and wet scenarios (Table S3). To put these numbers in perspective, addressing 10% of the annual groundwater deficit in the PVDB would require recharging 4.3% of basin-wide runoff generated during the normal scenario, and 10.0% and 1.5% of runoff during the dry and wet scenarios, respectively. Thus, there may be opportunities for DSC-MAR to substantially improve groundwater supply over a range of climate conditions in this region.

There was considerable spatial variability in simulated hillslope runoff generation throughout the PVDB (Fig. 3). During the dry scenario, there was less spatial variability in mean annual runoff generation and runoff generation was concentrated in a smaller area than during the normal and wet scenarios (Fig. S6). For example, the 10% of the basin area that generated the most runoff accounted for 46% of basin-wide runoff during the dry scenario and just 31% in the wet scenario. During the dry scenario, the median runoff generated by an HRU was 1.8 cm, but the maximum was 33 cm, which is greater than the wet-scenario median runoff generation. A DSC-MAR project, if properly located, could thus collect substantial runoff even during dry years; field measurements confirm that a DSC-MAR project in the PVDB is viable during a drought (Beganskas and Fisher 2017).

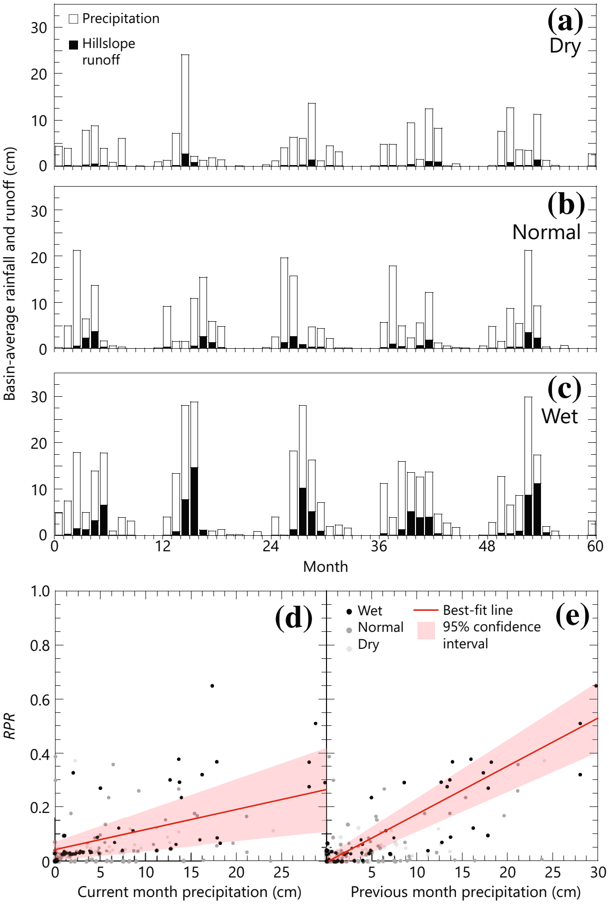


Fig. 2 Monthly basin-average precipitation and runoff generated for each climate scenario with contemporary land use. a-c Simulated runoff (*solid bars*) overlain on precipitation (*open bars*). d Simulated *RPR* plotted against current month precipitation. e Simulated *RPR* plotted against previous month precipitation

3.3 Hillslope Runoff Generation for Different Land-Use Conditions

Basin-wide, much less runoff was generated with pre-development land use than with contemporary land use (Table S3), a reasonable result considering the prevalence of contemporary impervious surfaces, which tend to favor runoff generation (Shuster et al. 2005). The disparity between contemporary and pre-development land use was most pronounced during the dry scenario: More than twice as much runoff was generated with contemporary land use during the dry scenario, whereas ~50% more runoff was generated with contemporary land use during the wet scenario. Especially during the dry scenario, many HRUs that generated little to no runoff with pre-development land use generated significant runoff with contemporary land use (Fig. 3).

Highly seasonal precipitation in the PVDB, where each water year ends with dry conditions, allows for little long-term change in soil moisture. Given consistent inter-annual conditions in soil and other storage reservoirs, the additional runoff generated with contemporary land use (above that generated with pre-development land use) must be a consequence of changes to ET

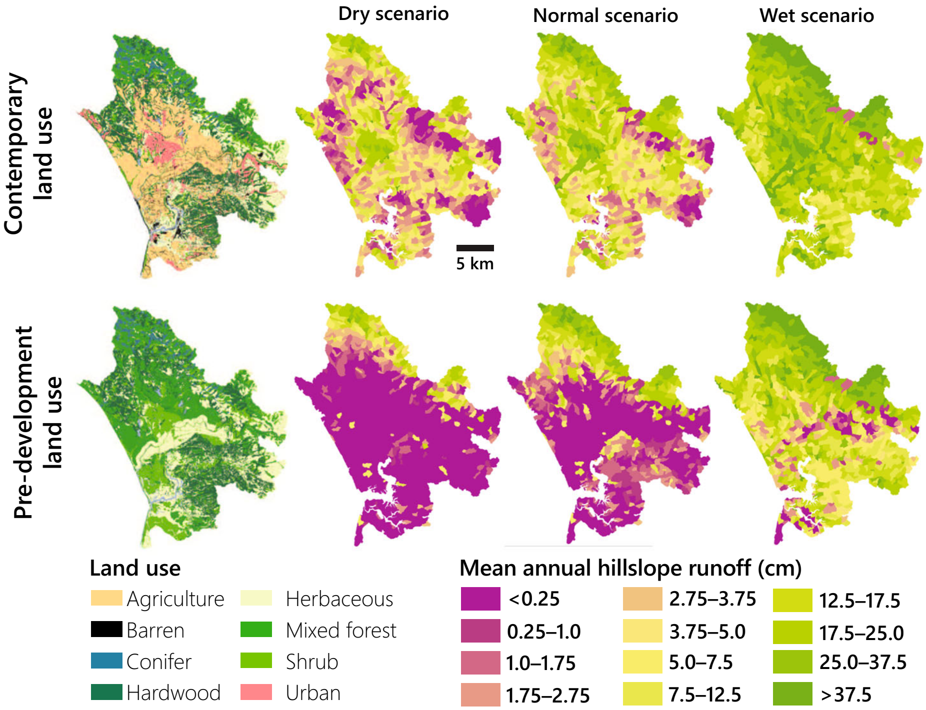


Fig. 3 Mean annual hillslope runoff in the PVDB for each climate scenario and land-use condition

and/or recharge. PRMS simulations were calibrated on channel discharge (after independently assessing solar radiation and PET); observational data are not available for this region that would allow calibration to actual ET or recharge fluxes. While ET was likely higher with pre-development land use due to increased vegetation coverage, it is also likely that some of the additional runoff generated with contemporary land use would instead have infiltrated and become recharge under pre-development land use. Thus, regional landscape modifications associated with urbanization and agricultural development may have resulted in less basin-wide diffuse groundwater recharge. PRMS simulations neglect irrigation water applied to crops and the resultant ET and deep percolation, but because there is no imported water in this region and most irrigated agriculture is supplied by groundwater, this activity must also comprise a net loss for the regional groundwater budget (Hanson et al. 2014).

With both contemporary and pre-development land use, more runoff tended to be generated in the northern PVDB, where precipitation was greatest for all scenarios (Fig. S7). However, runoff generation with pre-development land use had much less spatial variability, and much more closely matched the distribution of precipitation, than did runoff generation with contemporary land use.

3.4 Factors Influencing Hillslope Runoff Generation with Shifting Climate and Land Use

Many soil and vegetation parameters strongly influenced the runoff response and the relative influence of different parameters varied with both climate and land use (Fig. 4). With contemporary land use, impervious area was the parameter that had the strongest rank correlation with runoff generation during the dry scenario, whereas this rank correlation was 0.0 during the wet scenario. In contrast, soil storage and routing parameters had strong rank correlations with runoff generation during the wet scenario and relatively weak rank correlations during the dry scenario. During wetter years, shallow soils are more likely to become fully saturated, preventing additional infiltration (essentially acting as impervious surfaces) and causing additional precipitation to become Dunnian runoff (Dunne and Black 1970). The amount of water that can be stored in the soil and how quickly it can be routed elsewhere help determine the likelihood that shallow soils will become fully saturated during a rainstorm. But regardless of soil properties, shallow soil saturation is unlikely during dry years; this means that soil parameters have a reduced impact on dry-year runoff generation relative to wet-year runoff generation. With pre-development land use, there was almost no impervious area and vegetation conditions were more homogeneous throughout the basin, which meant that factors such as total precipitation, slope, and soil storage became relatively more impactful in determining how much runoff was generated. These differences further emphasize that land-use development substantially impacts the processes controlling runoff generation (Shuster et al. 2005).

This analysis also allows exploration of the interactions between concurrent shifts in both climate and land use. For example, the rank correlation strength between precipitation and runoff varied with climate, but how these rank correlations varied with climate also depended on land use. With pre-development land use, the rank correlation between precipitation and

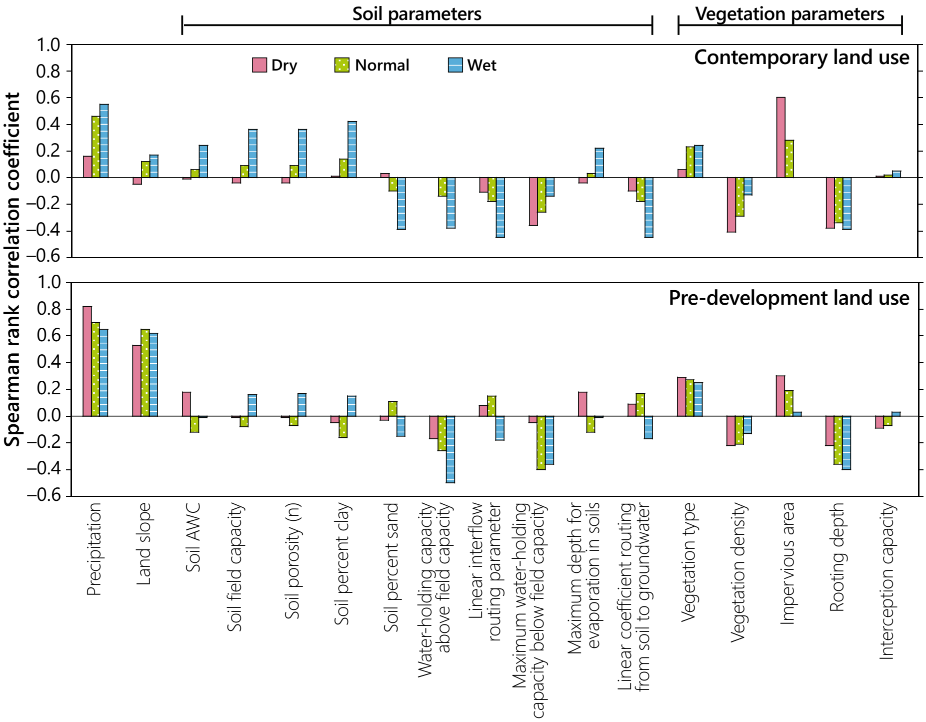


Fig. 4 Spearman rank correlation coefficients between runoff generation and input parameters vary by land-use condition and climate scenario

runoff was strongest for the dry scenario, when runoff was only generated in a small area that received the most rainfall (Fig. 4). In contrast, with contemporary land use, the dry scenario had the weakest rank correlation between precipitation and runoff (Fig. 4), because impervious surfaces in developed areas allowed for runoff generation even when there was little rainfall. In this way, interactions between shifting land use and climate change can amplify the hydrologic response to these regional perturbations.

3.5 Incorporating Hillslope Runoff Supply into MAR Suitability Analyses

Spatial heterogeneity in runoff generation throughout the PVDB implies that some locations are more appropriate for DSC-MAR than others. During the dry scenario, 3% of land area (16.8 km^2) met the criteria set for DSC-MAR suitability and 31% (176 km^2) met the criteria during the wet scenario (Fig. 5). Thus, many locations that could meet supply goals during wet (or normal) years may not during dry years. Infiltration basins are typically <0.02 km^2 in area; thus 16.8 km^2 could potentially provide space for dozens of infiltration basins. In Central Coastal California, inter-annual precipitation variability necessitates that DSC-MAR projects be carefully designed to handle large flows during wet years and be situated to collect runoff where it is most likely to occur during dry years.

Field data provide important validation for mapping and modeling efforts. The active DSC-MAR project location was not expected to generate enough simulated runoff to be considered suitable for DSC-MAR during the normal or dry scenarios but was found suitable during the wet scenario (Fig. 5). In practice, the project collected relatively little runoff (~1/3 of its operating goal) during three drought years (WY2012–14) yet collected substantial runoff, exceeding its design goal, during another drought year (WY2015) in which there was a series of intense storms (Beganskas and Fisher 2017). Even during a dry year, an intense storm can result in runoff generation similar to that seen during wet years. While the infiltration basin met the DSC-MAR suitability criteria during the wet scenario, the drainage area supplying water to this basin did not meet the criteria during any scenario because it has relatively clayey soils (Fisher et al. 2017). Clayey soils could limit recharge rates below an infiltration basin, but the

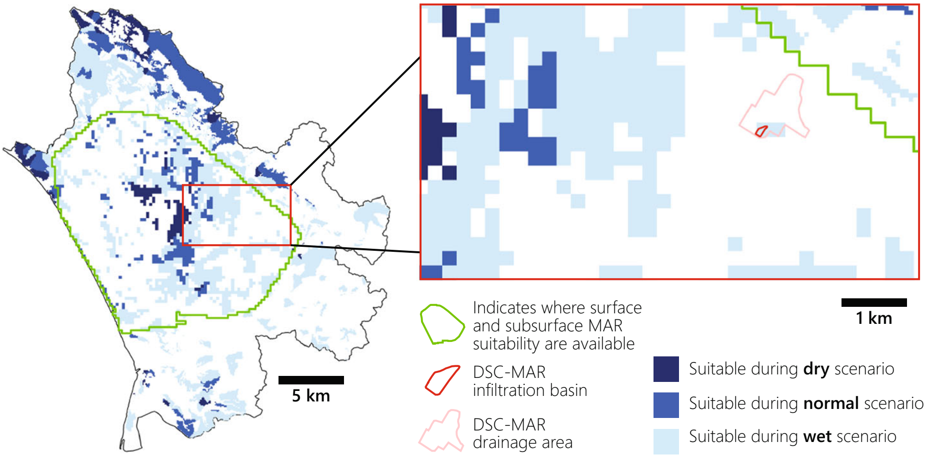


Fig. 5 Regional DSC-MAR suitability analysis incorporating runoff simulation results finds many potentially effective locations for DSC-MAR. Inset shows drainage and infiltration areas for an existing DSC-MAR project

same soils located higher in the watershed could contribute to a successful DSC-MAR project by limiting infiltration and generating runoff.

3.6 Study Limitations

This study is limited by the spatial and temporal resolution of available climate, streamflow, soil, and vegetation datasets for this region. While we acquired relatively high-spatial-resolution (0.64 km^2) climate data, the daily time step precludes accurate prediction of runoff at the scale of individual precipitation events (which are often most intense for a few hours at a time) and tends to result in conservative seasonal runoff estimates (see *Section SI-3.2* for a detailed discussion). Because PRMS simulations underestimate peak flows, the results presented here likely underestimate the potential for DSC-MAR projects to exceed their capacity during intense storms. It is important that DSC-MAR projects have capacity for extreme events and/or are designed to safely route excess flows and avoid flooding.

Using a catalog of recent historical conditions to assess runoff under different climate scenarios does not allow prediction of future conditions. The comparatively lower spatial resolution of RCMs and uncertainty in future rainfall predictions—for California and elsewhere—also present challenges for predicting future runoff. Instead, we focused on how this region might be expected to respond during periods of drier-than-average, “normal”, and wetter-than-average climate conditions. It seems likely that some combination of these will occur in the future (Swain et al. 2018). The lack of detailed pre-development land-use and topographic data precluded an assessment of the hydrologic impact of historical agricultural and urban development. Rather than predicting absolute differences, this study emphasizes understanding relative changes in runoff generation under different conditions.

4 Implications and Conclusions

We developed hydrologic simulations to assess stormwater runoff generation throughout a watershed under different climate scenarios and land-use conditions, focusing on hillslope runoff generation for MAR rather than channel discharge. Contemporary urban and agricultural development reduced the threshold for runoff generation relative to pre-development land use; the associated reduction in infiltration also reduced the amount of water available for groundwater recharge. These differences were most pronounced during the dry climate scenario. Climate and land use each impacted the rank correlation of many parameters with runoff generation, suggesting that under different climate and land-use conditions, different factors are more dominant in controlling runoff generation. In the PVDB, impervious area was a dominant parameter during drier scenarios, whereas soil storage and routing parameters were more dominant during wetter scenarios; precipitation depth played a weaker role with contemporary land use than with pre-development land use. Shifting climate and land use each substantially impact the amount and distribution of basin-wide hillslope runoff generation, and land-use development may amplify the impact of a shifting climate.

These results have implications for DSC-MAR in the PVDB and more broadly. That contemporary land use is associated with significantly more runoff generation (and possibly less recharge) provides quantitative motivation to develop DSC-MAR projects that collect excess runoff to augment recharge: these projects help restore hydrologic system function that has been lost because of shifting climate and land use. New DSC-MAR suitability maps that combine runoff supply with surface and subsurface properties demonstrate opportunities for DSC-MAR to improve groundwater supply in the PVDB (and potentially in other basins) across a wide range of climate scenarios. During the dry scenario, significant runoff generation was focused within a more limited area, highlighting the importance of strategically locating DSC-MAR projects to maximize potential water supply benefit. A comparison with field data demonstrated that model runoff predictions may be conservative, that intense storms during dry years can mimic wetter conditions in terms of runoff generation, and that it is important to consider properties of both the MAR infiltration system and the drainage area supplying runoff.

In a region with large inter-annual precipitation variability, DSC-MAR projects must be designed to handle large inflows during wet years and positioned strategically to operate successfully during dry years. Incorporating runoff simulation results into MAR suitability mapping studies can help delineate relative differences in water supply available for MAR under different climate conditions. Every MAR project has individual objectives and constraints, and these tools are flexible enough to be customized for specific recharge goals. This approach could also be useful for assessing runoff processes and impacts we did not explore, including erosion, sediment or nutrient transport, and aquatic habitat sustainability.

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Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

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