Journal of Hydrology 677 (2026) 135965

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Research papers

Assessing streamflow depletion from agricultural groundwater use in headwater catchments using storage-discharge functions

Philip Georgakakos [a,*], David Dralle [b], Chris Dillis [a], Jesse Hahm [c], Dana Lapides [d], Theodore Grantham [a]

[a] University of California, Berkeley, Environmental Science and Policy Management, USA
[b] US Forest Service, Pacific Southwest Research Station, USA
[c] Simon Fraser University, Department of Geography, Canada
[d] USDA-ARS, Southwest Watershed Research Center, USA

ARTICLE INFO

This manuscript was handled by Renato Morbidelli, Editor-in-Chief

Keywords:
Subsurface
Cannabis
Streamflow depletion
Groundwater pumping

ABSTRACT

Groundwater extraction can deplete streamflow in headwater catchments, but the complexity of subsurface hydrological processes make impacts difficult to detect. Using hydrograph-inferred hillslope groundwater storage and streamflow relationships, we propose a novel approach to estimate streamflow depletion from groundwater pumping that is well-suited to areas with limited groundwater monitoring infrastructure. We apply this method in two well-studied watersheds in California's North Coast to quantify potential hydrologic impacts of cannabis agriculture, which is concentrated in the region and has been identified as a potential threat to salmon-bearing streams. We use a scenario-based approach to explore the relative effects of cannabis cultivation area, irrigation water source (groundwater pumping vs. surface diversion), irrigation efficiency, stream discharge at the onset of the growing season, and lithology on streamflow depletion risk. Our models show that *Elder Creek*, a perennial stream, could be de-watered by the late dry season with high levels (1% land cover) of cannabis irrigation from groundwater when dry season discharge is low at the start of the season (1 mm/day). In *Dry Creek*, a non-perennial stream, dry season flow cessation could be advanced by five weeks from similar levels of cannabis water demands. Streamflow impacts are more pronounced in drier years, and the impacts from well-water extraction exhibit a muted effect relative to surface water diversion of the same volume. Storage-discharge functions like those in our case study can estimate how groundwater extraction affects headwater streams wherever streamflow data exist.

1. Introduction

Unsustainable groundwater pumping is a global challenge, a recent analysis revealed that 30% of the world's regional aquifers show accelerating declines, particularly in dry regions with extensive agriculture (Jasechko et al., 2024). In California, one of the world's most productive agricultural regions, satellite data documents massive groundwater losses that have accelerated dramatically during recent droughts (Liu et al., 2022). The impacts of excessive pumping include water quality degradation through saltwater intrusion affecting coastal aquifers globally (Werner et al., 2013), widespread well failures with up to 20% of global wells vulnerable to running dry from modest groundwater declines (Jasechko and Perrone, 2021), and land subsidence reaching tens of centimeters per year in major cities and agricultural regions (Lees and Knight, 2024). Additionally, excessive groundwater extraction can reduce flow to springs and streams, converting gaining streams that receive groundwater discharge into losing streams that recharge depleted aquifers, fundamentally disrupting the hydrologic connections that sustain aquatic habitats during dry periods (Barlow and Leake, 2012). This reduction of surface waters is a growing threat to freshwater ecosystems (Arthington et al., 2018), with groundwater pumping driving declines in flows below ecologically sustainable limits in many regions of the world (de Graaf et al., 2019).

Groundwater extraction from upland catchments has the potential to deplete streamflow yet quantifying the relationship between hillslope hydrology—that is, how water moves through the unsaturated and saturated zones of upland landscapes, particularly along sloping terrain between ridgelines and stream channels—and streamflow remains

* Corresponding author.
E-mail address: pgeorgakakos@berkeley.edu (P. Georgakakos).

https://doi.org/10.1016/j.jhydrol.2026.135965
Received 16 March 2026; Received in revised form 12 June 2026; Accepted 30 June 2026
Available online 1 July 2026
0022-1694/© 2026 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

challenging. This is largely due to the difficulty of accessing remote, rugged terrain and the complexity of subsurface hillslope hydrology, in which groundwater commonly flows through fractured bedrock (Rempe and Dietrich, 2018, Welch and Allen, 2014). Current methods for monitoring and calibrating groundwater models, such as borehole observations, are expensive and offer only fixed points of reference across a hillslope. Furthermore, methods commonly used to assess streamflow depletion from groundwater extraction from large, relatively homogeneous aquifers may not be well-suited for representing the hillslope hydrologic processes that sustain streamflow, particularly in systems with more complex subsurface structure (Rempe and Dietrich, 2018, Fan et al., 2019, Zipper et al., 2022). In headwater catchments, hydrologic processes often occur at the scale of individual unit hillslopes—discrete hillslopes bounded by ridges and channels that operate relatively independently of neighboring hillslopes (Band et al., 1993). Given these challenges, new approaches are needed to assess streamflow depletion risk from water withdrawals in headwater catchments. Current approaches for modeling the impacts of pumping on stream discharge include process-based hydrological models (such as MODFLOW (Barlow and Harbaugh, 2006)) and analytical depletion functions (Zipper et al., 2019b, Zipper et al., 2026). However, these methods rely on processes and parameters that are difficult to measure in upland settings, where groundwater commonly resides below soil in fractured bedrock aquifers. Such models are also not designed for groundwater systems defined by channels and ridge boundaries (Hahm et al., 2022) and where streams rapidly respond to active hillslope hydrology on the timescale of individual storms.

Understanding the potential for groundwater pumping to deplete streamflow in upland watersheds is particularly important in regions such as northern California, where the cultivation of cannabis has rapidly expanded in recent decades (Butsic et al., 2017). California produces most cannabis marketed in the United States, and most of that production is concentrated in the region known as the "Emerald Triangle" (Dillis et al., 2021a). Owing to its historically prohibited status, cannabis cultivation has primarily occurred in remote watersheds where the risk of enforcement is lower (Dillis et al., 2021a), but where impacts on habitats for endangered species, such as steelhead trout and coho salmon, are a major concern (Bauer et al., 2015, Carah et al., 2015). Recent work has shown that cannabis farms in this region primarily rely on groundwater pumped from shallow wells, but also direct surface water diversions from streams, to irrigate crops (Dillis et al., 2020, 2021b). While some studies have estimated the water demands of cannabis relative to surface water availability in cannabis-producing watersheds (Dillis et al., 2019a, 2021b, 2023), the potential for cannabis farms to deplete streamflow from groundwater pumping in these headwater catchments remains poorly understood.

Here, we propose a new approach for evaluating the potential effects of groundwater pumping on streamflow, using cannabis agriculture in northern California as a case study. We first describe how storage-discharge sensitivity functions, developed in two well-studied watersheds (Hahm et al., 2018, 2019, 2020, Dralle et al., 2018, 2023a, b, Rempe and Dietrich, 2018, and Lovill et al., 2018), accurately simulate groundwater storage and streamflow dynamics and can be modified to simulate streamflow depletion from groundwater pumping. Next, we simulate a suite of scenarios, informed by previous studies of cannabis agriculture in the region (Butsic et al., 2017, Dillis et al., 2020, 2021a, b, 2023) to evaluate the potential for water withdrawals to deplete streamflow and accelerate stream drying. We also assess how the impacts of groundwater pumping on streamflow compare to those of direct water diversions. Further, we explore how differences in watershed lithology, streamflow conditions at the start of the irrigation season, and relative cultivation area affect streamflow depletion risk. Overall, the goals of this paper are to (i) introduce a new, generalizable method for assessing streamflow depletion risk in upland watersheds, including potential groundwater extraction impacts and (ii) build understanding of the unique risks that water demands from cannabis agriculture pose to streamflow and sensitive biological resources in northern California.

2. Methods

2.1. Storage-discharge sensitivity functions

Runoff in forested headwater catchments is commonly driven by storage in hillslope groundwater (the saturated zone). Storage-discharge functions use the recession behavior of the stream itself to empirically quantify how changes in groundwater storage translate into changes in flow. Such functions could be applied to estimate the effects of groundwater pumping on streamflow depletion risk. Reference Table 1 for definitions of all variables used in the following. The most general approach to using storage-discharge functions was described by Kirchner (2009), who assumed that stream discharge (Q) is an unspecified, but uniquely defined, function of catchment dynamic storage (S):

$$Q = f(S) \tag{1}$$

Dynamic storage is determined through a catchment-scale mass balance:

$$dS/dt = P - Q - E \tag{2}$$

where P is precipitation and E is evapotranspiration. To understand how discharge responds to rainfall, we must evaluate the sensitivity of discharge to changes in storage, represented by the derivative dQ/dS, or f'(S). However, because absolute catchment storage (S) cannot be directly measured at the landscape scale, this derivative is difficult to apply in its standard form. Kirchner (2009) circumvented this limitation by noting that if Q is a strictly increasing function of S, the function is invertible. Therefore, storage can be implicitly expressed as a function of measured discharge:

$$S = f^{-1}(Q) \tag{3}$$

Substituting this inverse function into the derivative allows us to express the sensitivity of discharge to storage entirely as a function of Q. Kirchner defined this as the catchment sensitivity function, g(Q):

$$g(Q) = f'(f^{-1}(Q)) = dQ/dS \tag{4}$$

By applying the chain rule, the rate of change of discharge over time (dQ/dt) can be linked to the mass balance:

$$dQ/dt = (dQ/dS)\cdot(dS/dt) \tag{5}$$

Finally, substituting the mass balance and g(Q) definition into the chain rule and rearranging yields a practical expression for g(Q) based purely on observable time-series data:

$$g(Q) = (dQ/dt)/(P - Q - E) \tag{6}$$

The sensitivity function can be interpreted as the mathematical sensitivity of discharge to changes in storage. That is, $g(Q)$ quantifies how much discharge will change for a given change in catchment storage

Table 1
Variables used in defining and calculating catchment storage-discharge sensitivity functions.

Variable	Definition
Q	Stream discharge
S	Catchment dynamic storage
P	Precipitation
g(Q)	Catchment sensitivity function, which quantifies how much discharge (Q) will change for a given change in catchment storage (dQ/dS)
R	Groundwater recharge term
E	Total Evapotranspiration
E_{gw}	Portion of evapotranspiration (E) that is sourced from the groundwater zone
E_{vz}	Proportion of evapotranspiration from the vadose zone

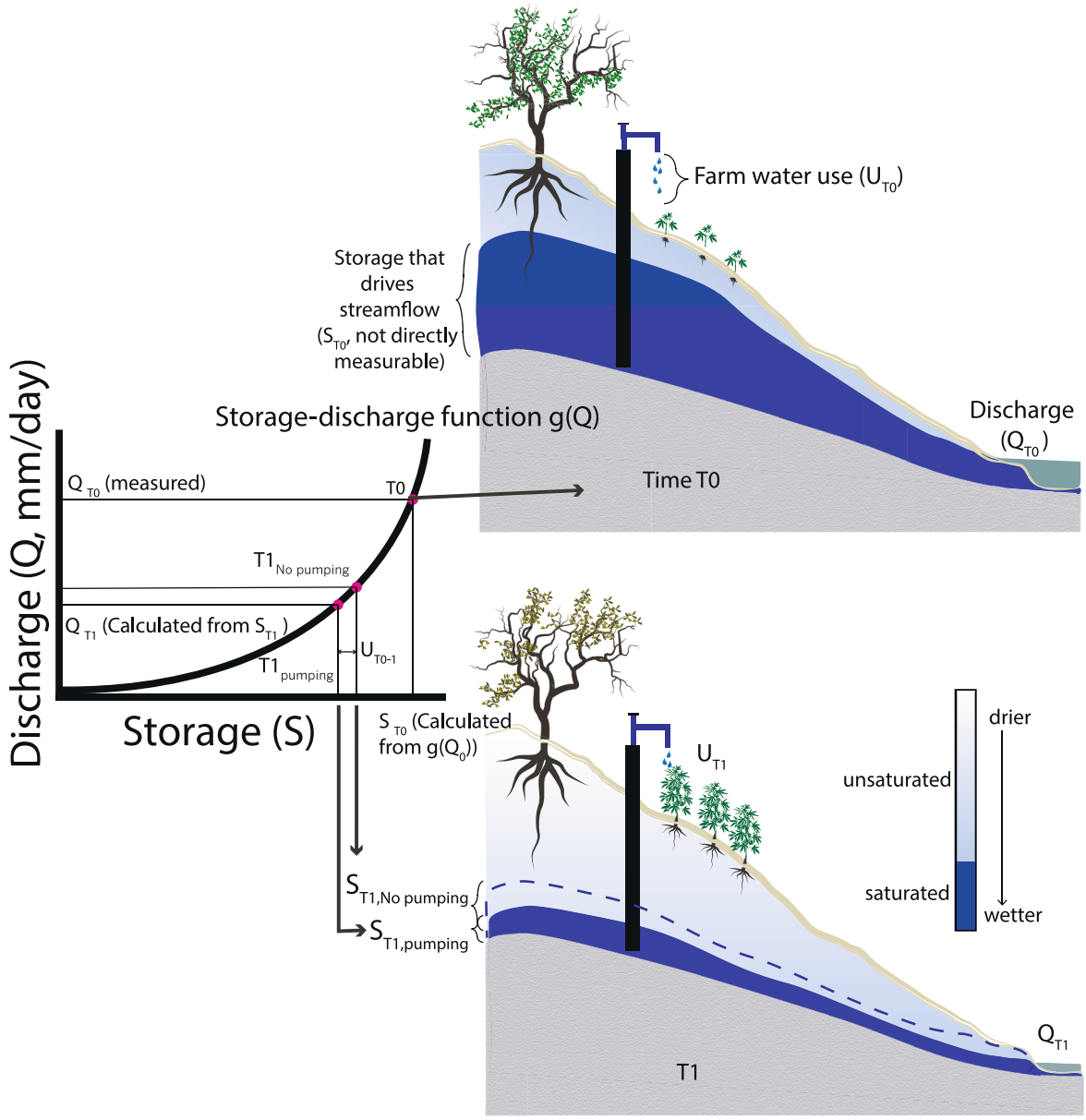

Fig. 1. Representation of the storage-discharge relationship within a hillslope at two timepoints (T0 and T1). At time T0, hillslope storage (S) is high, represented by the dark blue more saturated layer. Correspondingly discharge is high at T0. At a later time, T1, the more saturated zone has decreased with evaporation, and discharge (Q). T1 depicts both an unimpacted scenario in which the dashed blue line represents where the saturated zone would be if there were no groundwater pumping on the hillslope, and an impacted scenario where the solid dark blue zone represents the storage that contributes to streamflow with groundwater pumping. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(Fig. 1). In general, the sensitivity function is difficult to determine without knowledge of all terms in the catchment mass balance. However, when P and E are small, Equation (6) simplifies as:

$$g(Q) = dQ/dS \approx -\frac{dQ/dt}{Q} when\ P,\ E \ll Q \tag{7}$$

That is, the sensitivity function can be empirically determined during periods of time when P and E are small (e.g. on rain-free nights). Kirchner (2009) used this approach to successfully model streamflow and storage in a pair of small, humid catchments in the UK. More generally, storage-discharge functions have been applied in numerous hydrological modeling contexts (Teuling et al., 2010, Rusjan and Mikoš, 2015, Adamovic et al., 2015).

However, Dralle et al. (2018) demonstrated a shortcoming of the approach; storage-discharge functions inferred through this method cannot capture all aspects of dynamic storage in a watershed. Instead, because $g(Q)$ is determined through flow recession only, it can only "detect" changes in the storage that directly drive flow generation, i.e., groundwater. Other reservoirs of dynamic storage in a watershed may exist, and may play a role in runoff generation, but not *directly* affect Q. For example, near surface soil moisture may change due to plant water use from the vadose zone, but this does not necessarily lead to changes in Q, since Q is driven by hydraulic pressure in the deeper groundwater zone. This leads to problems in the interpretation of dQ/dS at the catchment scale, where not all storage changes actually result in discharge changes. Consequently, the concepts outlined by Kirchner (2009) may be easily interpretable in humid catchments, but in landscapes with significant unsaturated zone storage dynamics, there may be

large, dynamic reservoirs of water in the landscape that can change without directly impacting flow. This would confound any simple interpretation of hydrograph-inferred storage as including all storage in the watershed. Carrer et al. (2019) resolved this 'dual-storage' issue, and discussed how it may lead to significant challenges identifying a single sensitivity function that maps total dynamic storage (storage in the vadose zone and groundwater) to streamflow.

Following Dralle et al. (2023a), we therefore refine the interpretation of the sensitivity function as:

$$g(Q) = dQ/dS_{gw} = \frac{dQ/dt}{R - Q - E_{gw}} \tag{8}$$

where P has become R and is interpreted as a groundwater recharge term, and where E_{gw} (E_{gw}+E_{vz} = E) is the portion of evapotranspiration that is sourced from the groundwater zone and E_{vz} is the proportion of evapotranspiration from the vadose zone.

This formulation acknowledges that storage changes inferred through flow analysis only concern the subsurface saturated reservoir that generates flow. Once the storage discharge functions are resolved they can be applied in time periods where groundwater recharge and evapotranspiration are not minimal (Dralle et al., 2023a).

2.2. Determining $g(Q)$

We applied the modified storage-discharge function to determine $g(Q)$ in two focal watersheds: *Elder Creek* and *Dry Creek* in northern California (see study area descriptions below). We obtained daily streamflow timeseries for both streams and then imposed screening criteria to select a subset of the data. Days were determined suitable for fitting the sensitivity function if (a) there was no precipitation, (b) there was no precipitation in the preceding day, (c) discharge was lower the following day (dQ/dt < 0), and (d) the sample time was from November – March. On days that satisfied these conditions, flow derivatives were calculated using forward difference, and the binning and fitting procedure of Kirchner (2009), which results in a sensitivity function that is quadratic on log scales.

$$ln(g(Q)) = ln((-dQ/dt)/Q) \tag{9}$$

Though the sensitivity functions were calculated from November–March, our analysis occurs from May–September, which requires that the function be applied to some ranges of *Q* outside those which were used to determine *g(Q)*. Despite this extrapolation, model fit was good (Fig. 2). Currently, it is not possible to measure streamflow depletion from groundwater extraction and directly validate stream depletion models e (Zipper et al., 2022). However, in an effort to assess the accuracy of our derived storage-discharge functions, we evaluated our predicted discharge recession, assuming no additional recharge, against streamflow observations and report the goodness of fit for the recession dQ/dt vs Q for observed and modeled data (Fig. 2). For more detail see Dralle et al., 2023a and accompanying code.

2.3. Assessing changes in streamflow from groundwater pumping

The modified formulation (Eq. (6)) is particularly useful in the present context, where water withdrawals for irrigation will come from the saturated zone of hillslopes. Indeed, we might consider groundwater pumping (U) as a negative recharge from the groundwater reservoir, rewriting mass balance as:

$$dQ/dt = g(Q)(R - U - E_{gw} - Q) \tag{10}$$

During the summer months when groundwater is pumped and plant water use is primarily sourced from unsaturated soils and bedrock (Rempe and Dietrich 2018, Hahm et al., 2019), Eq. (10) can be simplified as:

$$dQ/dt = -g(Q)(U + Q) \tag{11}$$

This is a first order differential equation for Q, which can be solved under natural (i.e. U = 0) and groundwater pumping (i.e. U > 0) scenarios.

To summarize by analogy, consider a leaky bucket with storage S and discharge Q. Removing 1 mm of storage (U) will decrease storage by 1 mm and Q will correspondingly decrease following that decrease in storage. As in our watersheds, Q is a flux and S is a standing stock, so their sum (Q + S) is not required to maintain mass balance. If you remove 1 mm of storage from the top of the bucket, the water level will lower (and thus storage decreases by 1 mm). Additionally, because there is a decrease in the height of the water in the bucket, Q will decrease in response (because Q is proportional to the height of the water in the bucket). We still have only "pumped" 1 mm of storage from the bucket, even though S and Q both decrease. So, this is not a mass balance error, but instead of a reflection of the fact that storage determines the water pressure that drives leakage from the bucket.

2.4. Case study: estimating streamflow depletion risk from cannabis agriculture in northern California

2.4.1. Focal watersheds (geographic setting, watershed characteristics, and hydrology)

We focus on two intensively studied watersheds within the larger Eel River watershed, *Elder Creek* and *Dry Creek*, which represent two dominant lithologies in this region. *Elder Creek* lies entirely in the Franciscan Coastal Belt and *Dry Creek* in the Central Belt Mélange

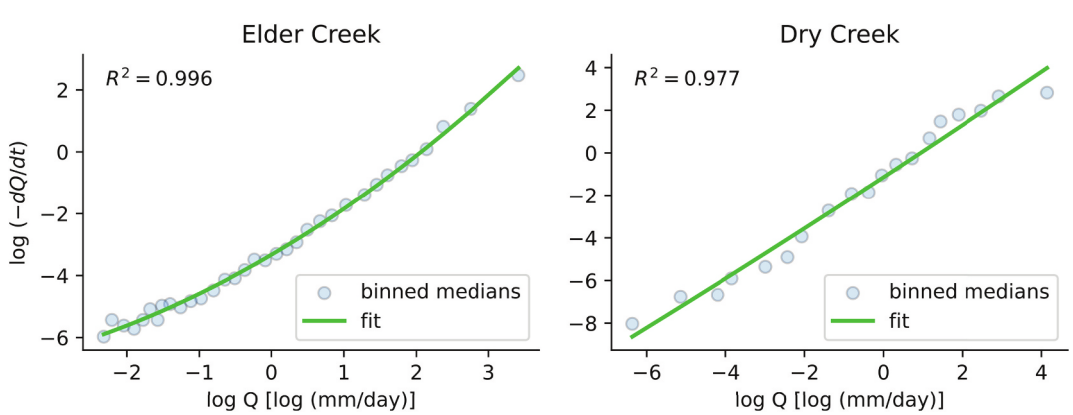

Fig. 2. Model performance of the storage-discharge sensitivity functions for *Elder Creek* and *Dry Creek*. Green points show binned observed recession behavior, plotted as the relationship between discharge and the rate of discharge change, and green lines show the fitted storage-discharge sensitivity functions used to generate synthetic recession hydrographs. High goodness-of-fit values indicate that the fitted functions reproduce observed recession dynamics well in both streams.

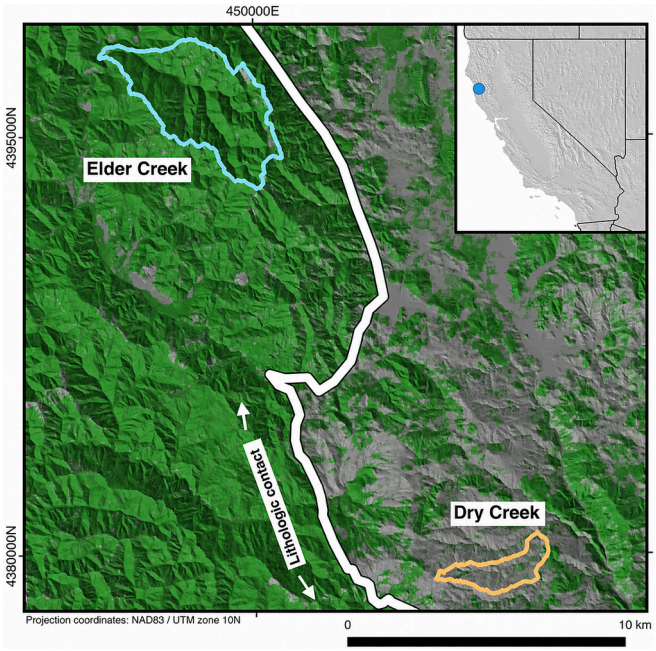

Fig. 3. Regional map depicting our two study catchments *Elder Creek* and *Dry Creek*. The thick white line plots the lithologic contact (Jayko and Blake, 1989) between the Coastal Belt (turbidites) to the west and the Central Belt (mélange) to the east. Grey to green pseudocolour represents percent forest cover from 0% to 100%, respectively (Hansen et al., 2013). Inset shows the state of California with a blue point for the study watersheds location. Adapted from Dralle et al., 2018.

(Fig. 3). We provide a brief overview of the physical and hydraulic properties of these watersheds below, but for more details refer the reader to Hahm et al. (2019) and other studies (Dralle et al., 2018, Rempe and Dietrich, 2018, Lovill et al 2018, Hahm et al., 2019, Dralle et al., 2018, 2023a, b). These watersheds represent end members on the spectrum of dominant lithologies of the South Fork Eel River (Dralle et al., 2023b). Despite differences in lithology and streamflow, these streams are only 20 km apart and thus experience similar climate and weather (Fig. 3). In both study systems rainfall exceeds the storage capacity of the subsurface each year. Dynamic storage is completely replenished each wet season, and this results in no multi-year effects of low rainfall years (Hahm et al., 2019). In both streams, summer recharge is negligible, groundwater tables decline or are static over summer at both sites (Hahm et al., 2019, Rempe and Dietrich, 2018); at *Dry Creek*, there is no dry season streamflow (Hahm et al., 2019, Lovill et al., 2018). At *Elder Creek*, dry season evapotranspiration matches storage declines in unsaturated zone (Link et al., 2014, Rempe and Dietrich, 2018). During the dry season, there is isotopic evidence at *Dry Creek* for unsaturated zone water use (Hahm et al., 2020). There is no evidence for non-channel adjacent groundwater exhibiting diurnal oscillations at a highly instrumented hillslope in *Elder Creek* (Hahm and Dralle, unpublished data). Low permeability fresh bedrock underlays the weathered material near the surface and follows surface topography, suggesting minimal inter-basin subsurface flow. Fresh bedrock is very near the surface and essentially follows surface topography. Storage-discharge sensitivity functions have been calculated for both streams in previous work (Dralle et al., 2018, 2023a) using the methods described above.

2.4.1.1. Elder creek. Elder Creek (16.9 km^2) cuts through deeply weathered, fractured shale and sandstone of the Coastal Belt of the Franciscan Formation. Hillslopes in Elder have deep weathering profiles, including fractured rock, saprolite, and soils, which contain large volumes (300 to 600 mm) of dynamic storage in unsaturated soils, unsaturated weathered bedrock, and saturated weathered bedrock. Dralle et al., (2018) estimate up to 100 mm of this dynamic water may be stored in the saturated zone, with upwards of 500 mm stored in the unsaturated zone. *Elder Creek* receives mean annual rainfall of roughly 2000 mm/year. Over the course of the dry Mediterranean climate summer, stream flow recedes, but cold perennial flow is supplied by the hillslope's large storage capacity which flows from seeps and springs (Lovill et al., 2018, Dralle et al., 2023b). Coastal Belt landscapes tend to support mixed-conifer and conifer forests.

2.4.1.2. Dry creek. Dry Creek (3.5 km^2) flows through Franciscan Coastal Belt Mélange. This Mélange is a mixture of larger bedrock blocks of varying size and lithology suspended in a clay-like argillite matrix. Mélange landscape weathering profiles are thin, with a much smaller dynamic storage capacity (200 mm) compared to that of Coastal Belt hillslopes. *Dry Creek* receives mean annual rainfall of roughly 1800 mm. In the winter months, when precipitation exceeds this low storage capacity, the water table rises until it intersects the ground surface, generating streamflow and producing flashy peak flows in stream channels. The low storage capacity of mélange landscapes cannot support perennial summer flow; *Dry Creek* discharge usually ceases within 2 months of the final storm of the wet season. Mélange landscapes tend to support Oak-Savannah habitat, with patches of more dense vegetation and springs near larger blocks of sandstone and shale suspended in the mélange matrix (Hahm et al., 2019).

2.4.2. Cannabis water use scenarios

We applied storage-discharge functions to estimate streamflow depletion risk in our two study watersheds using a scenario-based streamflow modeling approach. We combined categorical levels of irrigation source (groundwater or surface water), farm water-use efficiency, areal coverage of cannabis cultivation on the landscape, lithology, and initial streamflow conditions during the growing season as

Table 2
Parameter levels used to generate synthetic hydrographs and streamflow depletion scenarios.

Model parameter	Unit	Levels	Justification
Initial flow (mm/day)	mm/day	0.1, 0.5, 1, 5, 10	These levels encompass typical discharge at the onset of growing season in both streams and a large enough range to be relevant in aberrant future conditions (Fig. S4)
Water source	unitless	Surface diversion, groundwater extraction	Cannabis cultivation in the region frequently relies on wells and surface diversions (Dillis et al., 2019a)
Areal coverage of cannabis on landscape	%, farm area/ catchment area)	0.01, 0.05, 0.1, 0.5, 1, 5, 10	Percent covers were chosen to encompass the range of % cover observed on the landscape (Butsic et al., 2017, Fig. S3)
Farm water-use efficiency	mm/day	Percentiles of monthly farm water use median (0.5), 0.75, 0.9, 0.95	We chose to model the higher use percentiles in the distribution of water users presented in Dillis et al. (2023), (Fig. S2)
Stream type	unitless	Elder Creek (Coastal Belt, perennial), Dry Creek (Mélange, seasonally dry)	These watersheds represent the dominant stream types in the South Fork Eel River (Dralle et al., 2023)

parameters to create hypothetical scenarios that represent the wide range of potential impacts streams might experience on the landscape (Table 2). All parameters and streamflow data were in a daily timestep. By systematically designing and evaluating water use scenarios, we are able to isolate the effects of each parameter, rather than attempting to detect effects through empirical measurements of the environment. Using *g(Q)* and each combination of parameter values described above, we generated synthetic hydrographs which were then used to assess the effects of each parameter on streamflow magnitude and duration of discharge during the growing season (see section "Determining g(Q)"). By specifying all combinations of parameter values for the two watersheds, we generated and evaluated 580 unique scenarios by predicting daily discharge and number of days with zero flow ($Q = 0$) and comparing predicted values with expected, unimpaired conditions during the growing season (May – September).

2.4.2.1. Initial flow. Initial flow values represent the daily discharge (mm/day) at the start of the spring irrigation season on May 1, when streamflow is entirely fed by groundwater inflows and naturally begins to recede. Higher values are representative of more subsurface storage and lower values representative of less. Values were chosen to range from 0.1 to 10 mm/day for both streams, which includes the natural range of variation at the end of the wet season for both streams, and conditions outside of those currently observed. We chose a wider range than currently observed to encompass the range of conditions that may occur with climate change (Fig. S3).

2.4.2.2. Farm water-use. We define farm water-use as the area-normalized volume of cannabis farm irrigation demand during the growing season May – September. Dillis et al., (2023) modeled the amount of water used by both permitted and unpermitted farms to irrigate cannabis crops, and we use those estimates for farms in Mendocino and Humboldt Counties. In our scenarios, we assumed farms did not use on-site storage and thus extracted water from the environment for immediate irrigation use according to seasonal plant water demands (Fig. S1). Using water-use estimates from farms without storage (N = 7115 farms), we area-normalized monthly-water use estimates (mm/month). There was substantial variation in normalized water-use estimates and we selected median, 75th, 90th, and 95th percentiles as categorical parameter values, reflecting variation in water-use, in our model scenarios (Fig. S2). Monthly values stamped on the first of each month are re-indexed onto a complete daily timeline and all intervening days are filled by straight-line (linear) interpolation between successive start-of-month anchors, resulting in water use units of mm/day.

2.4.2.3. Areal coverage of cannabis agriculture. To determine the extent of cannabis agriculture to use in our scenarios, we evaluated the spatial coverage of cannabis farms in Mendocino and Humboldt counties reported by Butsic et al. (2017). We calculated percent coverage by dividing total coverage of cannabis farms m^2 by the area of catchments m^2. We performed this calculation at multiple scales, including hydrologic unit code (HUC) 12 watersheds, reported in the USGS 2019 National Hydrography Dataset (Fig. S2), representative of our two focal watersheds. We found that cannabis cover ranged from 0 – 13.059% (median = 0.078%, 95th percentile = 0.666%) coverage of watershed area and we chose to analyze coverage of 0.05, 0.1, 0.5, 1, 5, and 10% for our scenario analyses.

2.4.2.4. Water source. We modeled two sources of water extraction by farms: surface water diversions and groundwater pumping (wells). Wells are the most abundant source of extraction in the North Coast, but surface water diversions also occur, particularly in wetter watersheds (Dillis et al., 2019b). To calculate total daily water use (U, mm/day) within each of our scenarios, we multiplied the percent area of cannabis cultivation in the catchment by the farm water-use percentile value. We solve for Q in both water source scenarios by integrating Eq. (11) (with $U = 0$ in the solver for surface water diversions) through the growing season with the solve_ivp function from Python's SciPy package. This solver uses an adaptive Dormand–Prince Runge–Kutta method of order 5 (4) (RK45) to numerically integrate the nonlinear ordinary differential equation through time. In our surface water diversion scenarios, the pump rate (U) was subtracted from the modeled unimpaired hydrograph for that day, which resulted in the impaired discharge from surface diversions on a given day. For the groundwater pumping scenarios, $U > 0$ in Eq. (11) accounts for water used by cannabis agriculture that is removed from the dynamic storage that contributes to streamflow (Fig. 1). See section "Assessing changes in discharge from groundwater pumping" for details of how groundwater extraction was incorporated into storage-discharge functions.

2.4.2.5. Quantifying streamflow responses. For each scenario, we calculated the percent reduction in total growing season discharge (mm/growing season) and number of zero-flow days predicted to occur. These response variables were chosen for their ecological significance to native, threatened salmonids which inhabit streams in our study region (Obedzinski et al., 2018, Rossi et al., 2022). After calculating percent reduction in summer discharge and number of days without surface flow in each scenario, we used these responses to generate effect sizes of all independent variables using linear models. Four linear models were created, one for each catchment and one each for our response variables of summer discharge and number of days with zero flow. The parameter estimates from these linear models were reported as effect sizes.

2.5. Open research and data accessibility

All data management, plotting and statistical analysis were conducted Using R statistical software (Version 2023.12.0, R Development Core Team 2012) we used linear mixed-effects models (LMM, "lme4" package in R) to quantify the following parameters. Storage-discharge sensitivity functions and (un)impaired discharge time series were computed using Python (Python 3.10 using standard scientific and geospatial libraries, including NumPy, pandas, SciPy, Matplotlib, seaborn, GeoPandas, and statsmodels). The data and code used in this study are openly available on Zenodo (Dralle and Georgakakos, 2025).

3. Results

Lower initial flow (discharge at the start of the growing season), higher percent coverage of cannabis, higher pumping rates, and extraction from surface water all lead to lower summer discharge and more days of zero flow (Figs. 4–7). Initial flow had the greatest impact on summer discharge followed by extraction source, farm use efficiency, and finally areal coverage of cannabis (Fig. 5A). The number of zero-flow days was most strongly influenced by water source, followed by areal coverage, use efficiency, and initial flow (Fig. 7B). Below, we highlight specific scenarios that illustrate the effects of each parameter, which are summarized graphically (Figs. 5 & 6) and in effect-size calculation (Fig. 7).

3.1. Water source

Using g(Q) (Eq. (5)) to estimate streamflow depletion from groundwater pumping, we were able to compare the impacts of extracting similar volumes of water from surface water versus groundwater on discharge. Water extraction from wells had a muted impact on discharge relative to direct surface water diversions (Fig. 4). Water extraction from wells also resulted in less streamflow depletion over the course of the summer (Fig. 4, Fig. 5A, Fig. 6) and fewer zero-flow days (Fig. 5B). There were also significant differences in the responses of the two study watersheds to water extraction. Comparing two example scenarios in *Elder*

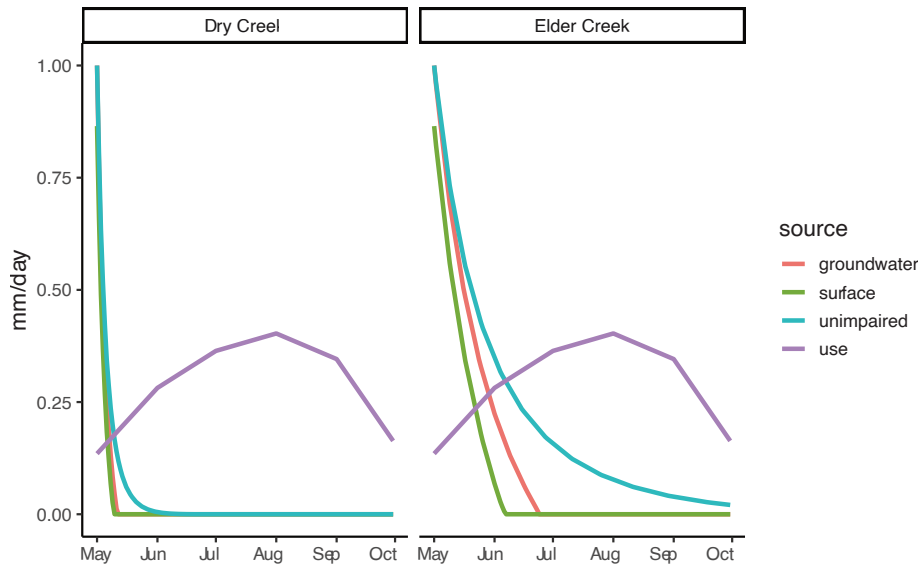

Fig. 4. Example curves from modeled scenarios with lines for modeled unimpaired discharge using storage-discharge sensitivity function (cyan), an impaired hydrograph resulting from surface water withdrawal (green), modeled impaired hydrograph resulting from groundwater pumping (red), and the modeled water use or irrigation rate (purple). Both hydrographs show the scenario for parameter values Initial discharge = 1 mm/day, 90th percentile farm use efficiency, 5% areal coverage of cannabis.

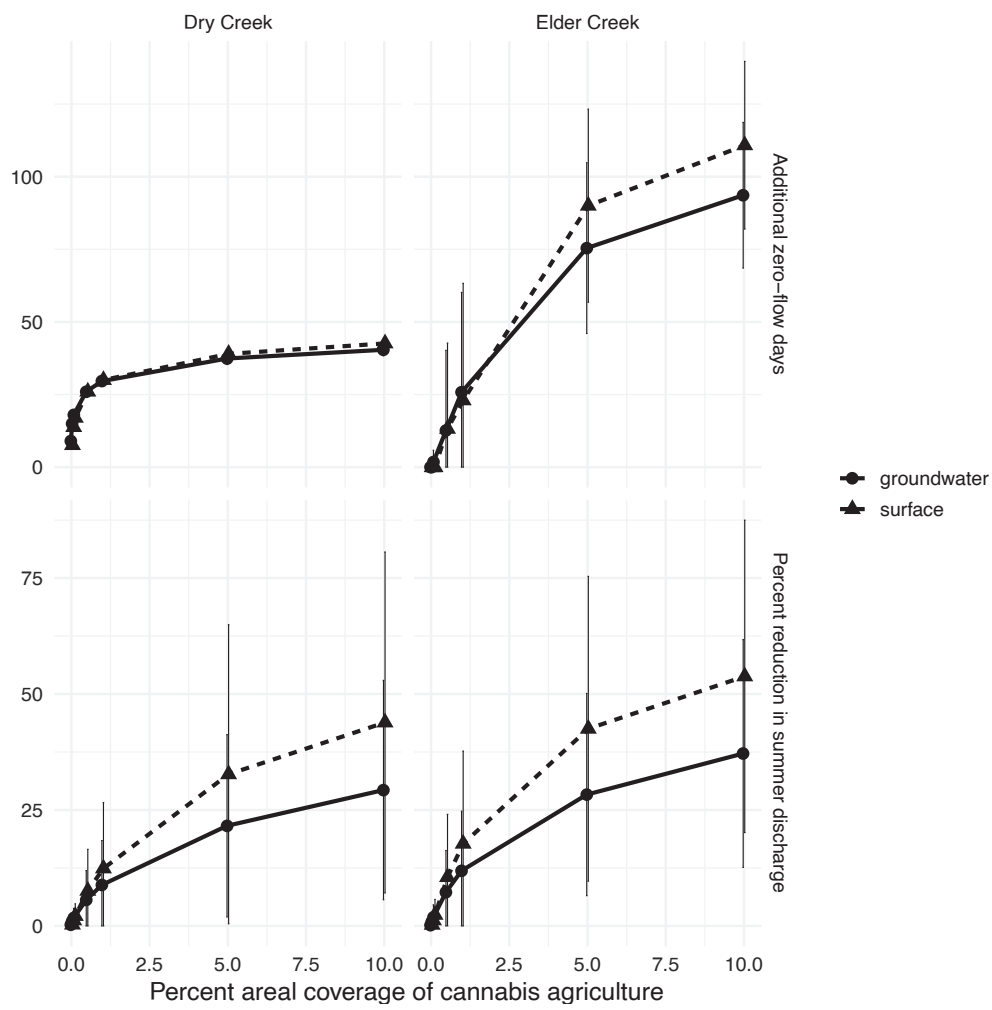

Fig. 5. Summaries of number of additional days of no flow (top row) and reduction in summer discharge (bottom row) for median farm water use. Dashed lines represent groundwater withdrawals and solid lines surface water withdrawals. Dry Creek is shown on the left panels and Elder Creek on the right. Error bars show standard deviation around estimates.

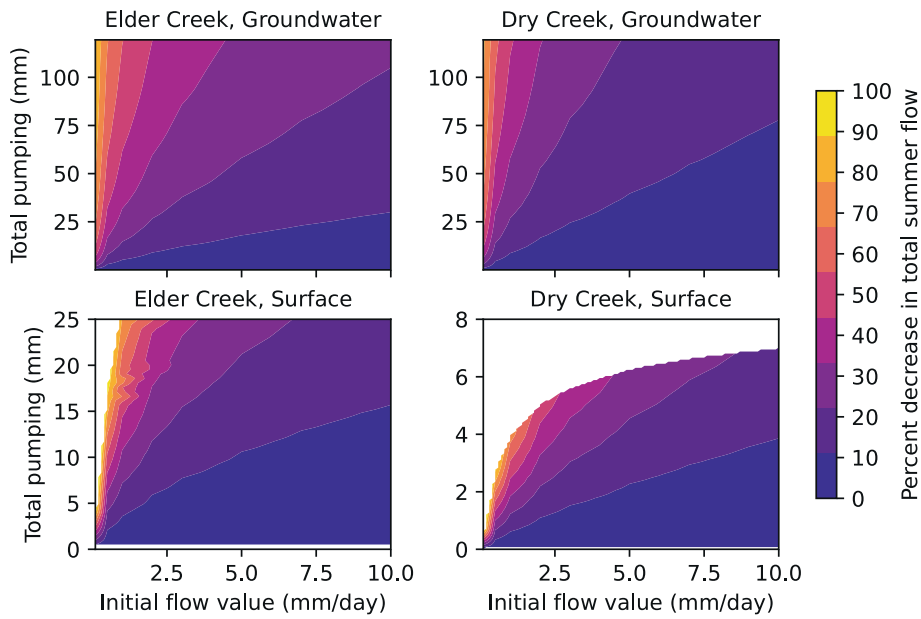

Fig. 6. Heatmaps showing the proportional reduction in summer flow resulting from combinations of different initial discharges that represent water year type and a composite water use axis (areal coverage x pumping rate). Cooler colors represent lower reductions in summer flow compared to warmer colors.

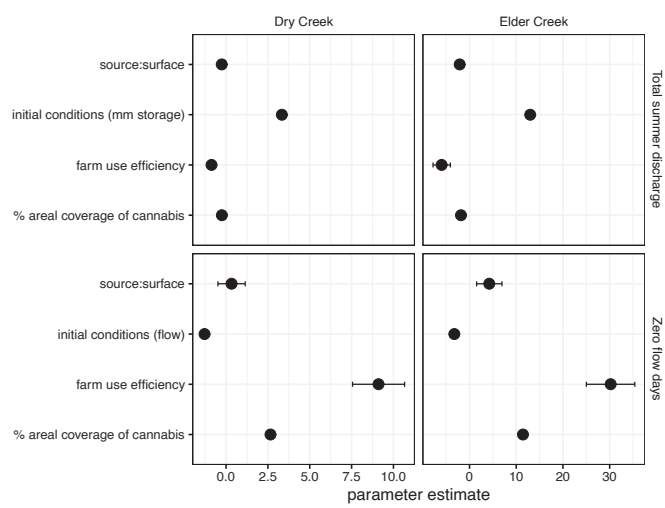

Fig. 7. Effect size plots for each of our parameters of interest that were included in the modeled scenarios, note the difference in scale of x-axis between streams. Effect sizes are parameters estimates extracted from linear models. Source:surface shows the contrast of the categorical level for water source "surface" with "groundwater" total Summer discharge shown in the top panels, and number of days with zero-surface flow in the bottom panels. Dry Creek is shown on the left panels and Elder Creek on the right. Error bars indicate standard error.

Creek with differing water sources (with median water use, initial discharge of 10 mm/day, and 1% cannabis on the landscape), surface water diversions resulted in a 2.6% decrease in cumulative summer discharge no (0) zero-flow days occurred. In contrast, when all diversions were from groundwater, *Elder* had a 1.9% decrease in summer flow (and also no zero-flow days). In *Dry Creek*, surface water diversions resulted in 1.7% decrease in cumulative summer discharge and 124 zero-flow days (Table 3). When all diversions were from groundwater, *Dry Creek* had a 1.35% decrease in summer flow and 123 zero-flow days (Table 3).

3.2. Initial flow

Initial flow greatly impacted the amount of summer discharge (Fig. 6) and number of zero-flow days in both of our study streams, but had a greater impact on *Elder Creek* than *Dry Creek* (Fig. 7B). Initial flow also modulated the sensitivity of the streams to flow depletion from cannabis irrigation (Fig. 7). For example, when total volume of water extracted was held constant (at 1% areal coverage of cannabis, median water use, and surface water extraction), the percent reduction in summer discharge at 0.5 mm/day and 10 mm/day initial flow in *Elder Creek*'s summer discharge was 19.4% (3.66 mm decrease from unimpaired) and 2.6% (3.67 mm decrease from unimpaired), respectively. *Dry Creek's* total summer discharge decreased 13.0% (0.39 mm decrease from unimpaired) when initial discharge was 0.5 mm/day, but only a 1.7% (0.59 mm decrease from unimpaired) with 10 mm/day of initial discharge (Table 3). In the 0.5 mm/day initial condition scenarios (corresponding to a wet season with low precipitation and storage), *Elder Creek* was predicted to experience 22 days additional of zero-flow (22 total) and Dry Creek, 30 (130 total). When initial flows were increased to 10 mm/day (corresponding to a wet season with high precipitation and storage), *Elder Creek's* predicted number of additional zero-flow days were 0 and Dry Creek 31 (124 total, Table 3).

3.3. Cannabis farm water use

Higher area-normalized water use by farms decreased cumulative summer discharge and increased the number of zero-flow days. Comparing two similar scenarios (groundwater pumping, initial flow of 10 mm/day discharge, and 1% areal coverage of cannabis), median water use in *Elder Creek* was predicted to have a 1.9% decrease in total summer discharge and no zero-flow days. However, when farms were less efficient and used more water, estimated from the 95th percentile of observed area-normalized water use, percent reduction in summer discharge increased to 5.9% and zero-flow days increased to 30. In *Dry Creek*, similar scenarios with the same parameter levels and median water use produced a 1.35% decrease in cumulative summer discharge and 30 additional zero-flow days (123 total), while 95th percentile use resulted in 3.2% reduction in summer discharge and 36 additional zero-flow days (129 total) (Table 3).

Table 3
Selected scenario runs which showcase the impacts of each parameter on response variables of cumulative summer flow and number of zero flow days.

Catchment	Extraction source	Initial flow (mm/day)	% areal coverage cannabis agriculture	Farm use efficiency percentile	Percent reduction in summer flow	Number of days with zero flow	Additional zero-flow days
Dry	surface	0.5	1	0.5	12.95	133	30
Elder	surface	0.5	1	0.5	19.43	22	22
Dry	surface	10	1	0.5	1.7	124	31
Elder	surface	10	1	0.5	2.6	0	0
Dry	groundwater	10	1	0.5	1.35	123	30
Elder	groundwater	10	1	0.5	1.89	0	0
Dry	groundwater	10	0.1	0.5	0.21	111	18
Elder	groundwater	10	0.1	0.5	0.19	0	0
Dry	groundwater	10	1	0.95	3.2	129	36
Elder	groundwater	10	1	0.95	5.85	30	30
Elder	groundwater	10	10	0.5	6.9	68	68
Dry	groundwater	10	10	0.5	12.58	135	42

3.4. Areal coverage of cannabis agriculture

With greater area of cannabis agriculture in our scenarios, cumulative summer discharge decreased and the number of zero-flow days increased. At 0.1% cannabis coverage, (holding groundwater pumping, initial flow of 10 mm/day, and median water use constant), *Elder Creek* had a predicted percent loss of cumulative summer discharge of 0.19% and 0 zero-flow days. Under the highest level of aerial coverage observed in the region (10%), however, summer discharge losses increased to 12.6% and zero-flow days increased to 68. *Dry Creek* in these same scenarios had a predicted percent loss of cumulative summer discharge of 0.21% and 18 additional zero-flow days (111 total) at 0.1% cover and 6.9% loss of summer discharge and 42 additional zero-flow days (135 total) at 10% cover (Table 3).

4. Discussion

Storage-discharge relationships have previously been used to predict streamflow patterns (Kirchner, 2009), estimate the amount of hillslope storage that does not directly contribute to streamflow (Dralle et al., 2018), and infer groundwater recharge (Ajami et al., 2011, Dralle et al., 2023a). In this novel application, we remove water from storage that represents an agricultural demand on the landscape, and use this to calculate changes in discharge throughout the summer streamflow recession period. Overall, our findings are qualitatively similar to those found using other streamflow depletion methods. Zipper et al. (2019a) estimated approximately 5–7% streamflow depletion from one year of pumping for cannabis cultivation in the Navarro river. The areal coverage of farms in this system is roughly 0.1%. In our scenarios, for 0.1% areal coverage in *Dry Creek* and *Elder Creek* we estimated percent reduction in summer flow would range from 0.04 − 11.49% (mean 1.6%, median 0.52%), depending on study stream, farm water use, and discharge at the onset of the growing season. Additionally, surface water extraction has a larger impact on streamflow than groundwater pumping (Barlow & Leake 2012), and in other systems realistic pumping levels lead to stream dewatering (as in, e.g., Konikow & Leake, 2014, Condon & Maxwell, 2014, Fienen et al., 2018). Modeled streamflow depletion due to groundwater pumping varies substantially throughout other regional contexts and model types from negligible streamflow depletion to stream drying (Kollet and Zlotnik, 2003, Nyholm et al., 2002, Woolfenden and Nishikawa, 2014, Konikow & Leake, 2014, Condon and Maxwell 2014, Fienen et al., 2018, Zipper et al., 2019a). Currently, the validation of streamflow depletion models from groundwater extraction with observational data is not possible (Zipper et al., 2022). However, working towards such validation would be extremely valuable for comparing not only this approach, but other streamflow depletion models. This application of storage-discharge relationships fills a much-needed gap in simulating groundwater dynamics in upland headwater catchments and potentially improves our ability to manage water resources for both human and environmental use in these systems. Though our case study focused on cannabis cultivation, which is a major agricultural crop in headwater catchments in Northern California's (Butsic et al., 2018), these methods can readily be applied to estimate the impacts of other uses of groundwater and surface water in headwater streams.

Storage-discharge functions can be powerful tools for simulating headwater stream dynamics, but the scale of data and inference must be considered carefully. Storage-discharge relationships are relevant for *catchment*-scale assessments. For example, diversions are not represented as discrete points on the landscape, but are considered as an aggregated flux of water out from catchment storage (e.g., conceptually analogous to a uniform drawdown of groundwater storage across all points in the landscape). However, in reality, cannabis farms are often clustered on landscapes and hillslopes, and this clustering likely concentrates impacts within catchments (Butsic et al., 2017). Because adjacent hillslopes that feed streamflow in the same catchment act independently (Hahm et al., 2019), the absence of cannabis cultivation on some of these contributing hillslopes could prevent complete stream dewatering of downstream reaches. In addition, some wells might have an outsized impact, like those positioned immediately adjacent to water sources (Zipper et al., 2019a), such as springs draining sandstone blocks in Central Belt mélange drainages, like *Dry Creek* (Lovill et al., 2018). Extraction from these sources and riparian areas likely influence surface water dynamics more like surface water diversions, impacting the organisms that rely on these wet refuges in otherwise dry landscapes. Wells positioned close to stream channels may also have the same effects as surface water extraction. Overall, our methods are useful for understanding the impacts at the catchment scale and allow for isolation of the effects of different parameters on streamflow. However, future studies at the sub-catchment scale are needed to understand how storage-discharge methods can be used to explore the spatial distribution of extraction networks within catchments differentially affect streamflow.

Here we demonstrate that cannabis agriculture in California's North Coast has the potential to substantially reduce streamflow. However, our results also suggest that farms could substantially decrease their impact by using more efficient irrigation practices. There is wide variation in modeled area-normalized irrigation rates of farms (Fig. S1, Dillis et al., 2023). Users withdrawing the largest amounts of water per unit area have an outsized impact. Drip irrigation, soil moisture sensors, and further understanding of plant water demand could potentially decrease the volume of water being applied to plants without reducing yield. Additionally, on-site storage in the form of ponds or tanks can decouple plant demand from water extraction so that the late-summer overlap of high demand and low streamflow is minimized (Dillis et al., 2020). Economic incentives for farmers to implement otherwise cost-prohibitive storage options could reduce the impacts of irrigation during the summer months, which coincide with the most stressful periods for many aquatic organisms. Finally, it is worth noting that most catchments in Mendocino and Humboldt have relatively small areal coverages of cannabis (median 0.078%, Fig. S2). This suggests

widespread impacts in these systems are likely to be limited. Nevertheless, the high coverage of cannabis in some catchments, and the propensity of cannabis to cluster in concentrated areas of the landscape (Butsic et al., 2017), indicate that the potential for local impacts is still significant and warrants attention from natural resource managers.

Our study demonstrates groundwater pumping is predicted to have a muted effect on streamflow relative to surface water withdrawals of comparable magnitude. However, groundwater extraction still has the capacity to greatly influence the amount and timing of streamflow (Figs. 4–7). Groundwater pumping might result in a marginally smaller reduction in discharge and also fewer zero-flow days over the course of the growing season, relative to direct surface water diversions, (Table 3, Fig. 5 and 6), but still has the potential to substantially decrease streamflow. In catchment systems where subsurface storage is greater than annual precipitation, pumping could have multi-year impacts by reducing groundwater reserves with resulting time-lagged impacts on streamflow (Zipper et al., 2019a). Additionally, extracting water from groundwater may disproportionately influence certain organisms, particularly phreatophytic vegetation, that could have used water on its path through the hillslope to the stream channel (Doble and Crosbie, 2017). Farmers and resource managers should therefore carefully consider potential impacts, location of wells, and groundwater storage capacity of the catchment of interest in designing farm water systems.

The underlying lithology, and thus hydrogeology, of our study streams influenced how streamflow responded to water extraction. Mélange landscapes such as Dry Creek have less storage capacity relative to those dominated by coastal belt lithology (Hahm et al., 2019). Because of this, similar volumes of water extraction impact mélange landscapes, and the streams that flow through them, more intensely, particularly at low extraction volumes. In our simulations, we saw substantially earlier de-watering of Dry Creek at cannabis coverages that are represented on the landscape (Table 3, Fig. 5, 6). This earlier drying could catastrophically impact stream dependent organisms that live near their physiological limits in these seasonally dry systems. In contrast, the potential impact to coastal belt streams is particularly intense at high extraction volumes (cannabis area × extraction rate). While the impacts on intermittent mélange streams tend to plateau, perennial coastal belt streams can be completely de-watered, removing key habitat for cool water organisms that rely on these habitats.

The hydrologic impacts of water withdrawals in turn have consequences for the ecology of the stream and riparian communities in these systems. Earlier drying of naturally intermittent streams, such as Dry Creek, can impact aquatic organisms by disrupting phenology, or the timing of life history events, and create mismatches between organisms and their environment. For example, a more rapid onset of intermittency may lead juvenile salmonids to outmigrate from streams before they can take advantage of seasonal peaks in food production (Dralle et al., 2023b). Fish that are unable to migrate are often confined to isolated pools, where they experience high mortality from elevated water temperatures, low dissolved oxygen, increased predation risk, and/or desiccation (Rossi et al., 2023; Obedzinski et al., 2018). Any reduction in water availability from withdrawals could be expected to intensify these effects. Despite their seemingly harsh conditions, in wet years, intermittent streams are heavily used by native aquatic species (Wigington et al., 2006; Obedzinski et al., 2018). The reduction or loss of these important habitats from water withdrawals could therefore be particularly detrimental to salmon populations (Wigington et al., 2006). The reduction of streamflow in perennial streams, such as Elder Creek, can also have significant ecological effects. Under very large extraction volumes, even historically perennial streams like Elder Creek could experience a state change to intermittency (Figs. 4–7). For organisms in these streams that are adapted to cool perennial flows, a shift to intermittent conditions would represent a significant disturbance (Bogan and Lytle 2011).

5. Conclusions

In this study, we advance the application of storage-discharge relationships to predict how groundwater extraction influences streamflow in headwater catchments. Subsurface water dynamics are inherently difficult to observe in hillslopes, and storage discharge relationships can help predict impacts to streamflow in moderate- to high-gradient catchments affected by human land- and water-use pressures. We demonstrate the application of these methods with cannabis agriculture in northern California, and found groundwater pumping can impact streamflow but is predicted to have less impact than surface withdrawals of the same volume. Our scenarios also show that greater percent covers of cannabis, lower discharge at the start of the growing season, and higher area normalized water use rates all decrease discharge and accelerate drying over the course of the growing season. Though we showcase this method with cannabis cultivation, parallel approaches could be used to investigate the impacts of other agricultural practices, or other activities that extract groundwater or surface water from mountainous regions of the world.

Credit authorship contribution statement

Philip Georgakakos: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **David Dralle:** Writing – review & editing, Writing – original draft, Software, Formal analysis, Conceptualization. **Chris Dillis:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation. **Jesse Hahm:** Writing – review & editing, Writing – original draft, Formal analysis, Conceptualization. **Dana Lapides:** Writing – review & editing, Writing – original draft, Conceptualization. **Theodore Grantham:** Writing – review & editing, Writing – original draft, Resources, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Philip Georgakakos reports financial support was provided by California Department of Cannabis Control. Theodore Grantham reports financial support was provided by California Department of Cannabis Control. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

California Department of Cannabis Control funding (Grant # 64955).

Appendix A. Supplementary data

Supplementary material provides the empirical basis and context for initial flow, farm water-use, and areal coverage of cannabis parameters used in the scenario-based streamflow-depletion analysis. Parameter ranges were selected from observed data and published studies, including modeled farm water-use, catchment-scale cannabis cultivation cover, and observed discharge in *Elder Creek* and *Dry Creek*. Supplementary data to this article can be found online at https://doi.org/10.1016/j.jhydrol.2026.135965.

Data availability

The data are availible on Zenodo: cannabit: Scenario-based modeling of streamflow depletion from cannabis agriculture [Dataset], [Software]. Zenodo. https://doi.org/10.5281/zenodo.14902190.

References

Adamovic, M., Braud, I., Branger, F., Kirchner, J.W., 2015. Assessing the simple dynamical systems approach in a Mediterranean context: application to the Ardèche catchment (France). Hydrol. Earth Syst. Sci. 19, 2427–2449. https://doi.org/10.5194/hess-19-2427-2015.

Ajami, H., Troch, P.A., Maddock, T., Meixner, T., Eastoe, C., 2011. Quantifying mountain block recharge by means of catchment-scale storage-discharge relationships. Water Resour. Res. 47, 2010WR009598. https://doi.org/10.1029/2010WR009598.

Arthington, A.H., Bhaduri, A., Bunn, S.E., Jackson, S.E., Tharme, R.E., Tickner, D., Young, B., Acreman, M., Baker, N., Capon, S., Horne, A.C., Kendy, E., McClain, M.E., Poff, N.L., Richter, B.D., Ward, S., 2018. The Brisbane declaration and global action agenda on environmental flows (2018). Front. Environ. Sci. 6. https://doi.org/10.3389/fenvs.2018.00045.

Band, L.E., Patterson, P., Nemani, R., Running, S.W., 1993. Forest ecosystem processes at the watershed scale: incorporating hillslope hydrology. Agric. For. Meteorol. 63, 93–126. https://doi.org/10.1016/0168-1923(93)90024-C.

Barlow, P.M., Harbaugh, A.W., 2006. USGS directions in MODFLOW development. Groundwater 44, 771–774. https://doi.org/10.1111/j.1745-6584.2006.00260.x.

Barlow, P.M., Leake, S.A., 2012. Streamflow depletion by wells—Understanding and managing the effects of groundwater pumping on streamflow: U.S. Geological Survey Circular 1376, 84 p. (https://pubs.usgs.gov/circ/1376/.).

Bauer, S., Olson, J., Cockrill, A., Van Hattem, M., Miller, L., Tauzer, M., Leppig, G., 2015. Impacts of surface water diversions for marijuana cultivation on aquatic habitat in four northwestern California watersheds. PLoS One 10, e0120016. https://doi.org/10.1371/journal.pone.0120016.

Bogan, M.T., Lytle, D.A., 2011. Severe drought drives novel community trajectories in desert stream pools: drought causes community regime shifts. Freshw. Biol. 56, 2070–2081. https://doi.org/10.1111/j.1365-2427.2011.02638.x.

Butsic, V., Carah, J.K., Baumann, M., Stephens, C., Brenner, J.C., 2018. The emergence of cannabis agriculture frontiers as environmental threats. Environ. Res. Lett. 13, 124017. https://doi.org/10.1088/1748-9326/aaeade.

Butsic, V., Schwab, B., Baumann, M., Brenner, J.C., 2017. Inside the emerald triangle: modeling the placement and size of cannabis production in Humboldt County, CA USA. Ecol. Econ. 142, 70–80.

Carah, J.K., Howard, J.K., Thompson, S.E., Short Gianotti, A.G., Bauer, S.D., Carlson, S. M., Dralle, D.N., Gabriel, M.W., Hulette, L.L., Johnson, B.J., 2015. High time for conservation: adding the environment to the debate on marijuana liberalization. Bioscience 65, 822–829.

Carrer, G.E., Klaus, J., Pfister, L., 2019. Assessing the catchment storage function through a dual-storage concept. Water Resour. Res. 55, 476–494. https://doi.org/10.1029/2018WR022856.

Condon, L.E., Maxwell, R.M., 2014. Feedbacks between managed irrigation and water availability: diagnosing temporal and spatial patterns using an integrated hydrologic model. Water Resour. Res. 50, 2600–2616. https://doi.org/10.1002/2013WR014868.

de Graaf, I.E.M., Gleeson, T., Rens van Beek, L.P.H., Sutanudjaja, E.H., Bierkens, M.F.P., 2019. Environmental flow limits to global groundwater pumping. Nature 574, 90–94. https://doi.org/10.1038/s41586-019-1594-4.

Dillis, C., Biber, E., Bodwitch, H., Butsic, V., Carah, J., Parker-Shames, P., Polson, M., Grantham, T., 2021a. Shifting geographies of legal cannabis production in California. Land Use Policy 105, 105369.

Dillis, C., Butsic, V., Carah, J., Zipper, S.C., Grantham, T., 2021b. Cannabis farms in California rely on wells outside of regulated groundwater basins. Environ. Res. Commun. 3, 075005.

Dillis, C., Butsic, V., Georgakakos, P., Portugal, E., Grantham, T.E., 2023. Water demands of permitted and unpermitted cannabis cultivation in Northern California. Environ. Res. Commun. 5, 025005. https://doi.org/10.1088/2515-7620/acb6d5.

Dillis, C., Grantham, T., McIntee, C., McFadin, B., Grady, K., 2019. Watering the emerald triangle: irrigation sources used by cannabis cultivators in Northern California. Calif. Agric. 73, 146–153.

Dillis, C., McIntee, C., Butsic, V., Le, L., Grady, K., Grantham, T., 2020. Water storage and irrigation practices for cannabis drive seasonal patterns of water extraction and use in Northern California. J. Environ. Manage. 272, 110955.

Dillis, C., McIntee, C., Grantham, T., Butsic, V., Le, L., Grady, K., 2019b. Water storage and irrigation practices associated with cannabis production drive seasonal patterns of water extraction and use in Northern California watersheds. bioRxiv 618934.

Doble, R.C., Crosbie, R.S., 2017. Review: current and emerging methods for catchment-scale modelling of recharge and evapotranspiration from shallow groundwater. Hydrgeol. J. 25, 3–23. https://doi.org/10.1007/s10040-016-1470-3.

Dralle, D.N., Hahm, W.J., Rempe, D.M., Karst, N.J., Thompson, S.E., Dietrich, W.E., 2018. Quantification of the seasonal hillslope water storage that does not drive streamflow. Hydrol. Process. 32, 1978–1992. https://doi.org/10.1002/hyp.11627.

Dralle, David N., Hahm, W.J., Rempe, D., 2023a. Inferring hillslope groundwater recharge ratios from the storage-discharge relation.

Dralle, D.N., Rossi, G., Georgakakos, P., Hahm, W.J., Rempe, D.M., Blanchard, M., Power, M.E., Dietrich, W.E., Carlson, S.M., 2023b. The salmonid and the subsurface: hillslope storage capacity determines the quality and distribution of fish habitat. Ecosphere 14, e4436. https://doi.org/10.1002/ecs2.4436.

Dralle, D.N., Georgakakos, P.B., 2025. *cannabit: Scenario-based modeling of streamflow depletion from cannabis agriculture* [Dataset], [Software]. Zenodo. https://doi.org/10.5281/zenodo.14902190.

Fan, Y., Clark, M., Lawrence, D.M., Swenson, S., Band, L.E., Brantley, S.L., Brooks, P.D., Dietrich, W.E., Flores, A., Grant, G., Kirchner, J.W., Mackay, D.S., McDonnell, J.J., Milly, P.C.D., Sullivan, P.L., Tague, C., Ajami, H., Chaney, N., Hartmann, A., Hazenberg, P., McNamara, J., Pelletier, J., Perket, J., Rouholahnejad-Freund, E., Wagener, T., Zeng, X., Beighley, E., Buzan, J., Huang, M., Livneh, B., Mohanty, B.P., Nijssen, B., Safeeq, M., Shen, C., Van Verseveld, W., Volk, J., Yamazaki, D., 2019. Hillslope hydrology in global change research and earth system modeling. Water Resour. Res. 55, 1737–1772. https://doi.org/10.1029/2018WR023903.

Fienen, M.N., Bradbury, K.R., Kniffin, M., Barlow, P.M., 2018. Depletion mapping and constrained optimization to support managing groundwater extraction. Groundwater 56, 18–31. https://doi.org/10.1111/gwat.12536.

Hahm, W.J., Dietrich, W.E., Dawson, T.E., 2018. Controls on the distribution and resilience of *Quercus garryana*: ecophysiological evidence of oak's water-limitation tolerance. Ecosphere 9, e02218. https://doi.org/10.1002/ecs2.2218.

Hahm, W.J., Dralle, D.N., Rempe, D.M., Bryk, A.B., Thompson, S.E., Dawson, T.E., Dietrich, W.E., 2019. Low subsurface water storage capacity relative to annual rainfall decouples mediterranean plant productivity and water use from rainfall variability. Geophys. Res. Lett. 46, 6544–6553. https://doi.org/10.1029/2019GL083294.

Hahm, W.J., Dralle, D.N., Sanders, M., Bryk, A.B., Fauria, K.E., Huang, M.H., Hudson-Rasmussen, B., Nelson, M.D., Pedrazas, M.A., Schmidt, L., Whiting, J., Dietrich, W.E., Rempe, D.M., 2022. Bedrock vadose zone storage dynamics under extreme drought: consequences for plant water availability, recharge, and runoff. Water Resour. Res. 58, e2021WR031781. https://doi.org/10.1029/2021WR031781.

Hahm, W.J., Rempe, D.M., Dralle, D.N., Dawson, T.E., Dietrich, W.E., 2020. Oak transpiration drawn from the weathered bedrock vadose zone in the summer dry season. Water Resour. Res. 56, e2020WR027419. https://doi.org/10.1029/2020WR027419.

Hansen, M.C., Potapov, P.V., Moore, R., Hancher, M., Turubanova, S.A., Tyukavina, A., Thau, D., Stehman, S.V., Goetz, S.J., Loveland, T.R., Kommareddy, A., Egorov, A., Chini, L., Justice, C.O., Townshend, J.R.G., 2013. High-resolution global maps of 21st-century forest cover change. Science 342, 850–853. https://doi.org/10.1126/science.1244693.

Jasechko, S., Perrone, D., 2021. Global groundwater wells at risk of running dry. Science 372, 418–421. https://doi.org/10.1126/science.abc2755.

Jasechko, S., Seybold, H., Perrone, D., Fan, Y., Shamsudduha, M., Taylor, R.G., Fallatah, O., Kirchner, J.W., 2024. Rapid groundwater decline and some cases of recovery in aquifers globally. Nature 625, 715–721. https://doi.org/10.1038/s41586-023-06879-8.

Jayko, A.S., Blake Jr, M.C., 1989. Deformation of the Eastern Franciscan belt, northern California. J. Struct. Geol. 11, 375–390.

Kirchner, J.W., 2009. Catchments as simple dynamical systems: catchment characterization, rainfall-runoff modeling, and doing hydrology backward. Water Resour. Res. 45, 2008WR006912. https://doi.org/10.1029/2008WR006912.

Kollet, S.J., Zlotnik, V.A., 2003. Stream depletion predictions using pumping test data from a heterogeneous stream–aquifer system (a case study from the Great Plains, USA). Journal of Hydrology, Recent Advances in Aquifer Hydraulics and Their Applications to Aquifer and Vadose Zone Characterization, Remediation, and Dewatering 281, 96–114. https://doi.org/10.1016/S0022-1694(03)00203-8.

Konikow, L.F., Leake, S.A., 2014. Depletion and capture: revisiting "the source of water derived from wells. Groundwater 52, 100–111. https://doi.org/10.1111/gwat.12204.

Lees, M., Knight, R., 2024. Quantification of record-breaking subsidence in California's San Joaquin Valley. Commun. Earth Environ. 5. https://doi.org/10.1038/s43247-024-01778-w.

Link, P., Simonin, K., Maness, H., Oshun, J., Dawson, T., Fung, I., 2014. Species differences in the seasonality of evergreen tree transpiration in a Mediterranean climate: analysis of multiyear, half-hourly sap flow observations. Water Resour. Res. 50, 1869–1894. https://doi.org/10.1002/2013WR014023.

Liu, P.-W., Famiglietti, J.S., Purdy, A.J., Adams, K.H., McEvoy, A.L., Reager, J.T., Bindlish, R., Wiese, D.N., David, C.H., Rodell, M., 2022. Groundwater depletion in California's Central Valley accelerates during megadrought. Nat. Commun. 13, 7825. https://doi.org/10.1038/s41467-022-35582-x.

Lovill, S.M., Hahm, W.J., Dietrich, W.E., 2018. Drainage from the critical zone: lithologic controls on the persistence and spatial extent of wetted channels during the summer dry season. Water Resour. Res. 54, 5702–5726. https://doi.org/10.1029/2017WR021903.

Nyholm, T., Christensen, S., Rasmussen, K.R., 2002. Flow depletion in a small stream caused by ground water abstraction from wells. Groundwater 40, 425–437. https://doi.org/10.1111/j.1745-6584.2002.tb02521.x.

Obedzinski, M., Nossaman Pierce, S., Horton, G.E., Deitch, M.J., 2018. Effects of flow-related variables on oversummer survival of juvenile coho salmon in intermittent streams. Trans. Am. Fish. Soc. 147, 588–605. https://doi.org/10.1002/tafs.10057.

Rempe, D.M., Dietrich, W.E., 2018. Direct observations of rock moisture, a hidden component of the hydrologic cycle. PNAS 115, 2664–2669. https://doi.org/10.1073/pnas.1800141115.

Rossi, G.J., Power, M.E., Carlson, S.M., Grantham, T.E., 2022. Seasonal growth potential of *Oncorhynchus mykiss* in streams with contrasting prey phenology and streamflow. Ecosphere 13, e4211.

Rusjan, S., Mikoš, M., 2015. A catchment as a simple dynamical system: characterization by the streamflow component approach. J. Hydrol. 527, 794–808. https://doi.org/10.1016/j.jhydrol.2015.05.050.

Teuling, A.J., Lehner, I., Kirchner, J.W., Seneviratne, S.I., 2010. Catchments as simple dynamical systems: experience from a Swiss prealpine catchment. Water Resour. Res. 46. https://doi.org/10.1029/2009WR008777.

Welch, L.A., Allen, D.M., 2014. Hydraulic conductivity characteristics in mountains and implications for conceptualizing bedrock groundwater flow. Hydrogeology 22, 1003–1026. https://doi.org/10.1007/s10040-014-1121-5.

Werner, A.D., Bakker, M., Post, V.E.A., Vandenbohede, A., Lu, C., Ataie-Ashtiani, B., Simmons, C.T., Barry, D.A., 2013. Seawater intrusion processes, investigation and

management: Recent advances and future challenges. Advances in Water Resources, 35th Year Anniversary Issue 51, 3–26. https://doi.org/10.1016/j.advwatres.2012.03.004.

Wigington, P., Ebersole, J., Colvin, M., Leibowitz, S., Miller, B., Hansen, B., Lavigne, H., White, D., Baker, J., Church, M., Brooks, J., Cairns, M., Compton, J., 2006. Coho salmon dependence on intermittent streams. Front. Ecol. Environ. 4, 513–518. https://doi.org/10.1890/1540-9295(2006)4%255B513:CSDOIS%255D2.0.CO;2.

Woolfenden, L.R., Nishikawa, T., 2014. Simulation of groundwater and surface-water resources of the Santa Rosa Plain watershed, Sonoma County, California (No. 2014–5052), Scientific Investigations Report. U.S. Geological Survey. https://doi.org/10.3133/sir20145052.

Zipper, S., Gambill, I., Schmitt, M., Kouba, C., Scantlebury, L., Harter, T., Murphy, N.P., 2026. Lagged streamflow depletion due to pumping-induced stream drying: incorporation into analytical streamflow depletion estimation methods. J. Hydrol. 667, 134909. https://doi.org/10.1016/j.jhydrol.2026.134909.

Zipper, S.C., Carah, J.K., Dillis, C., Gleeson, T., Kerr, B., Rohde, M.M., Howard, J.K., Zimmerman, J.K., 2019a. Cannabis and residential groundwater pumping impacts on streamflow and ecosystems in Northern California. Environ. Res. Commun. 1, 125005. https://doi.org/10.1088/2515-7620/ab534d.

Zipper, S.C., Farmer, W.H., Brookfield, A., Ajami, H., Reeves, H.W., Wardropper, C., Hammond, J.C., Gleeson, T., Deines, J.M., 2022. Quantifying streamflow depletion from groundwater pumping: a practical review of past and emerging approaches for water management. Am. Water Resour. Assoc. 58, 289–312. https://doi.org/10.1111/1752-1688.12998.

Zipper, S.C., Gleeson, T., Kerr, B., Howard, J.K., Rohde, M.M., Carah, J., Zimmerman, J., 2019b. Rapid and accurate estimates of streamflow depletion caused by groundwater pumping using analytical depletion functions. Water Resour. Res. 55, 5807–5829. https://doi.org/10.1029/2018WR024403.