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

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Key Points:

1. Streamflow depletion from groundwater extraction can be estimated using watershed storage-discharge sensitivity functions.
2. Simulated water withdrawals from headwater catchments reduce streamflow and accelerate stream drying, particularly in dry years.
3. Simulations suggest cannabis irrigation depletes streamflow; however, impacts are likely localized and hard to detect at broad scales.

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 discharge at the start of the dry season is 1mm/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, such as those presented in our case study, could be applied to estimate impacts of groundwater extraction for water use (e.g., for cannabis agriculture) in headwater streams wherever streamflow data are available.

Plain Text Summary:

Nearly all streamflow originates as groundwater draining from hillslopes upstream. Groundwater extraction for agriculture or household use can reduce streamflow by removing this water from the landscape before it emerges into stream channels. While this effect is well-understood,determining groundwater pumping's impact on streamflow is challenging due to uncertainties in water use practices, difficulty measuring underground water movement, and seasonal and yearly environmental water abundance changes. We developed a new method to estimate groundwater pumping's impact on streamflow based on observed streamflow and precipitation, which are easier to measure than groundwater levels. We tested this method in two watersheds in Northern California to understand how water use by cannabis farms, common to the region, could impact streamflow. Our results suggest in dry years, groundwater pumping can de-water streams that typically flow year-round and cause seasonally dry streams to dry sooner. In Elder Creek, a stream with year-round flows, pumping from wells could dry the stream by late summer. In Dry Creek, which naturally dries in summer, pumping could cause drying five weeks earlier. This new method can be used to estimate water use impacts in other small streams and help communities manage their water in ways that limit environmental impacts.

Introduction:

In headwater catchments without snowmelt, groundwater draining from hillslopes is a primary source of streamflow that sustains both the ecological and human communities that inhabit these upland areas (Salve et al. 2012, Lovill et al. 2018). Groundwater extraction from upland catchments has the potential to deplete streamflow, yet quantifying the relationship between hillslope hydrology and streamflow is challenging due to the difficulty of accessing remote, rugged terrain and the complexity of subsurface hillslope hydrology (Rempe and Dietrich 2018). 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 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). Streamflow gauges in headwater catchments, though uncommon (Andrews and Grantham 2024), offer an opportunity to estimate depletion responses in these systems.

Given these challenges, new approaches are needed to assess streamflow depletion risk from water withdrawals in headwater catchments. This is particularly true in regions such as Northern California, USA, where the widespread distribution of small surface water diversions and groundwater extraction in upland watersheds is a growing threat to salmon and other sensitive aquatic species (Grantham et al. 2010, Carah et al. 2015, Dilis et al. 2021). Common 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). 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 2018) and where streams rapidly respond to active hillslope hydrology on the timescale of individual storms. Here we present an alternative approach that takes advantage of storage-discharge functions (Kirchner 2009, Ajami et al. 2011), which describe the relationship between stream discharge and hillslope- or catchment-scale water storage. These functions have been applied to estimate the dynamic storage capacity and groundwater recharge in headwater catchments (Dralle et al. 2018, Dralle et al. 2023a), but their application in assessing streamflow depletion risk from water withdrawals has not yet been explored.

Here, we investigate how groundwater pumping potentially affects streamflow in headwater catchments using storage-discharge functions. We specifically simulate the effects of water withdrawals for cannabis agriculture, which occurs throughout northern California and is concentrated in small, upland watersheds (Butsic et al. 2017). Cannabis cultivation in the region relies heavily on streams and groundwater to meet irrigation needs (Dillis et al. 2020 and 2021). As such, cannabis agriculture has been identified as a threat to stream ecosystems (Bauer et al 2014, Carah et al 2015), but the potential magnitude of diversion impacts on streamflow remain poorly understood. In this study, we take a scenario-based approach to quantify how cannabis cultivation area, irrigation water source (well or surface diversion), irrigation efficiency, water year type, and watershed lithology affect streamflow depletion risk. Our primary goal is to demonstrate how storage-discharge relationships can be used to calculate the impact of groundwater extraction on stream discharge in headwater catchments, which face growing water-use pressures in California and many regions of the world. Additionally we highlight the relative effect of factors that may influence streamflow depletion risk from cannabis agriculture in two well-studied watersheds in California's north coast.

Methods:

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. The most straightforward approach to using storage-discharge functions was well-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:

$$dS/dt \;=\; P \;-\; Q \;-\; E \qquad (2)$$

Where P = precipitation and E = evapotranspiration

Kirchner (2009) introduced an additional representation of f, the catchment sensitivity function:

$$g(Q) \;=\; f'(f^{-1}(Q)) \;=\; dQ/dS \;=\; \frac{dQ/dt}{dS/dt} \;=\; \frac{dQ/dt}{P-Q-E} \qquad (3)$$

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. 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 3 simplifies as:

$$g(Q) \;=\; dQ/dS \;\approx\; -\frac{dQ/dt}{Q} \text{ when } P, E \;\ll\; Q \qquad (4)$$

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 et al. 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. Klaus 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:

$$g(Q) = dQ/dS_{gw} = \frac{dQ/dt}{R - Q - E_{gw}} \quad (5)$$

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.

This formulation acknowledges that storage changes inferred through flow analysis only concern the subsurface saturated reservoir that generates flow.

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 decreasing over the course of the 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.

$$ln(g(Q)) = ln((-dQ/dt)/Q) \qquad (6)$$

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 (figure 2). For more detail see Dralle et al. 2023a and accompanying code.

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, re-writing mass balance as:

$$dQ/dt = g(Q)(R - U - E_{gw} - Q) \tag{7}$$

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), Equation 7 can be simplified as:

$$dQ/dt = -g(Q)(U + Q) \tag{8}$$

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.

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

Study area (geographic setting, watershed characteristics, hydrology - as represented by the models)

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 Fransiscan Coastal Belt and Dry Creek in the Central Belt Melange. 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. 2017, Rempe et al. 2018, Lovil et al 2017, Hahm et al 2019, Dralle et al 2019, 2023a, 2023b). 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. Storage-discharge sensitivity functions have been calculated for both streams in previous work (Dralle et al 2018, 2023a) using the methods described above.

Elder Creek

Elder Creek (16.9 km²) 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 2000mm/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 2018, Dralle et al. 2023b). Coastal Belt landscapes tend to support mixed-conifer and conifer forests.

Dry Creek

Dry Creek (3.5 km²) flows through Franciscan Coastal Belt Melange. This Melange is a mixture of larger bedrock blocks of varying size and lithology suspended in a clay-like argillite matrix. Melange landscape weathering profiles are thin, with a much smaller dynamic storage capacity (200mm) compared to that of Coastal Belt hillslopes. Dry Creek receives mean annual rainfall of roughly 1800mm. 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 melange landscapes cannot support perennial summer flow; Dry Creek discharge usually ceases within 2 months of the final storm of the wet season. Melange 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 melange matrix (Hahm et al. 2019).

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 parameters to create hypothetical scenarios that represent the wide range of potential impacts streams might experience on the landscape (Table 1). 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).

Initial flow

Initial flow values represent the discharge (mm/day) at the start of the spring irrigation season in May, 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.

Farm water-use

We define farm water-use as the area-normalized volume of cannabis farm irrigation demand. 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 (figure S2). Using water-use estimates from farms without storage (N = 7115), we area-normalized monthly-water use estimates (mm/day). 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 (Figure S2). Monthly water demand estimates were used to interpolate daily values.

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. (2018). We calculated the total coverage of cannabis farms relative to the area of watersheds at multiple scales, including hydrologic unit code (HUC) 12 watersheds, reported in the USGS 2019 National Hydrography Dataset (Figure 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.

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. 2019a). 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 Equation 8 (with U=0 in the solver for surface water diversions) through the growing season with the solve_ivp function from Python's SciPy package. 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 Equation 8 accounts for water used by cannabis agriculture that is removed from the dynamic storage that contributes to streamflow (Figure 1). See section "Assessing changes in discharge from groundwater pumping" for details of how groundwater extraction was incorporated into storage-discharge functions.

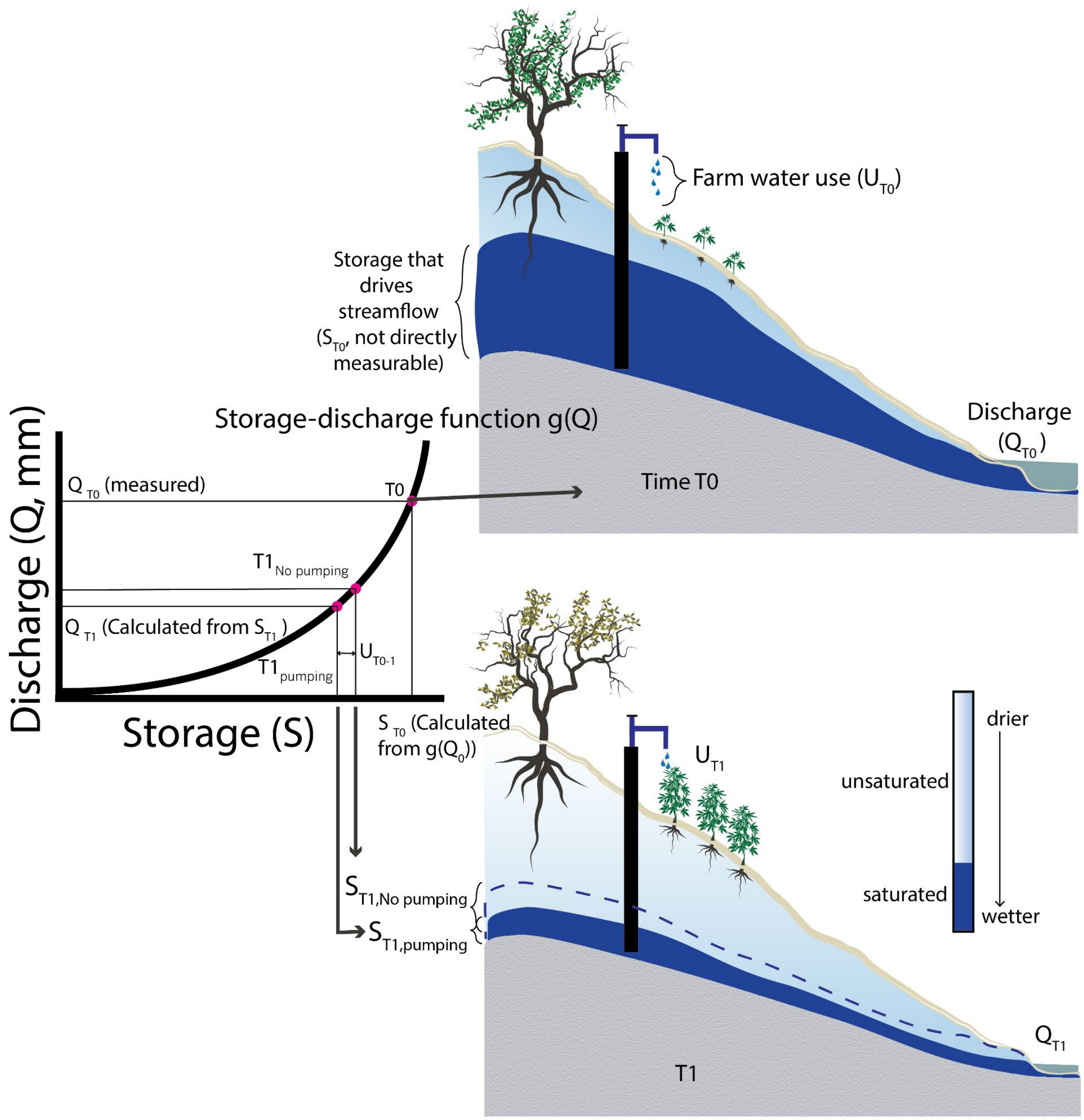

Figure 1. Representation of the storage-discharge relationship within a hillslope at two timepoints (T0 and T1). At time T1, the dashed blue line represents where the saturated zone would be if there were no groundwater pumping on the hillslope.

Table 1. Parameter levels used to generate synthetic hydrographs and streamflow depletion scenarios.

Model parameter	Levels
Initial flow (mm/day)	0.1, 0.5, 1, 5, 10
Water source	Surface diversion, groundwater extraction
Areal coverage of cannabis on landscape (percent farm area relative to catchment area)	0.01, 0.05, 0.1, 0.5, 1, 5, 10
Farm water-use efficiency	Percentiles of monthly farm water use presented in Dillis et al. (2023) percentiles were 0.5, 0.75, 0.9, 0.95
Stream type	Elder Creek (Coastal Belt), Dry Creek (Melange)

Responses of streamflow and categorizing depletion

For each scenario, we calculated the percent reduction in total summer discharge and number of zero-flow days predicted to occur. These response variables were chosen for their ecological significance to fish and other species dependent upon streamflow. 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.

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. All code and data can be found in the GIThub repository available on Zenodo [DOI: 10.5281/zenodo.14902190](https://doi.org/10.5281/zenodo.14902190)

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 (Figure 2, Figure 3, Figure 4 , Figure 5). Initial flow had the greatest impact on summer discharge followed by extraction source, farm use efficiency, and finally areal coverage of cannabis (Figure 5A). The number of zero-flow days was most strongly influenced by water source, followed by areal coverage, use efficiency, and initial flow (Figure 5B). Below, we highlight specific scenarios that illustrate the effects of each parameter, which are summarized graphically (Figure 3 & Figure 4) and in effect-size calculation (Figure 5).

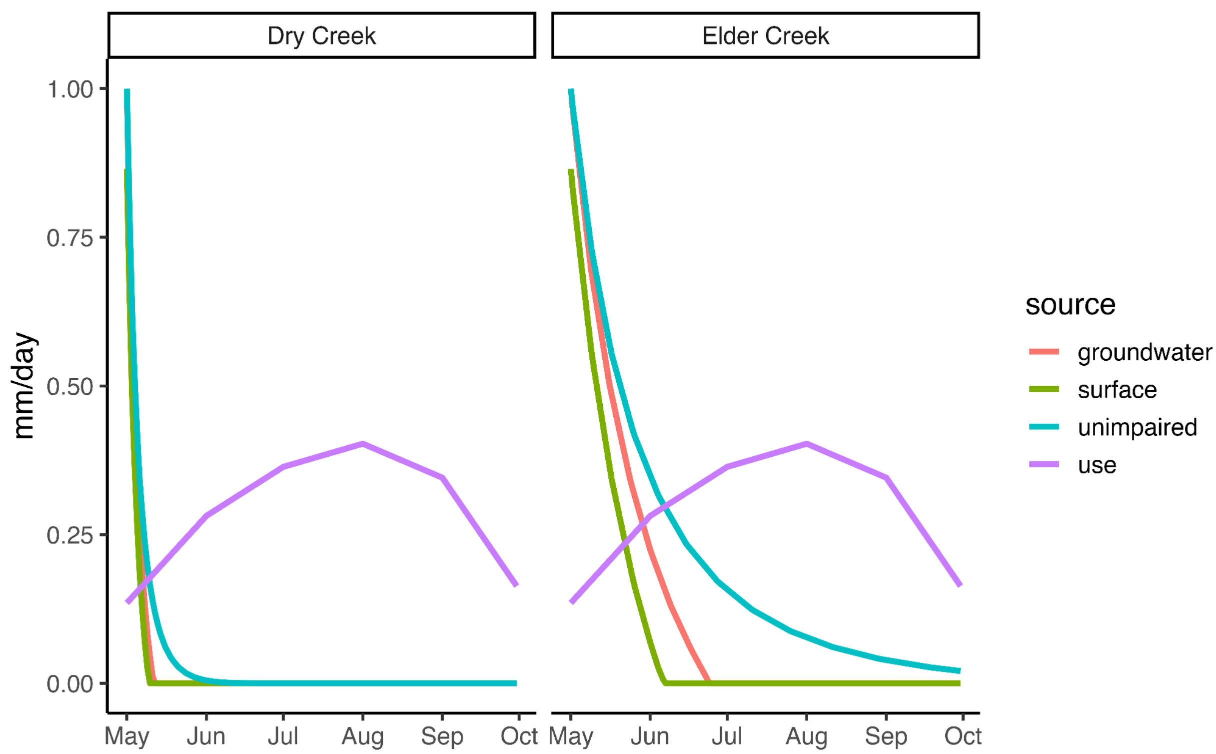

Figure 2: Example curves from modeled scenarios with lines for measured discharge (Q, blue), modeled unimpaired discharge using storage-discharge sensitivity function (dashed orange), Impaired hydrograph resulting from surface water withdrawal (red), modeled impaired hydrograph resulting from groundwater pumping (green), 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.

Table 2. 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

Water source

Using g(Q) (equation 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 (Figure 2). Water extraction from wells also resulted in less streamflow depletion over the course of the summer (Figure 2, Figure 3A, Figure 4) and fewer zero flow days (Figure 3B). There were also significant differences in the responses of the two study watersheds to water extraction. In Elder Creek (with median water use, initial discharge of 10mm/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 2). When all diversions were from groundwater, Dry Creek had a 1.35% decrease in summer flow and 123 zero-flow days (Table 2).

Initial flow

Initial flow greatly impacted the amount of summer discharge (Figure 4) and number of zero-flow days in both of our study streams, but had a greater impact on Elder Creek than Dry Creek (Figure 5B). Initial flow also modulated the sensitivity of the streams to flow depletion from cannabis irrigation (Figure 5). 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 0.5mm/day and 10mm/day initial flow in Elder

Creek’s summer discharge was 19.4% (3.66 mm decrease from unipaired) and 2.6% (3.67 mm decrease from unipaired), respectively. Dry Creek’s total summer discharge decreased 13.0% (0.39 mm decrease from unipaired) when initial discharge was 0.5mm/day, but only a 1.7% (0.59 mm decrease from unimpaired) with 10mm/day of initial discharge (Tabel 1). 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 10mm/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, Tabel 1).

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 10mm/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 2).

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 2).

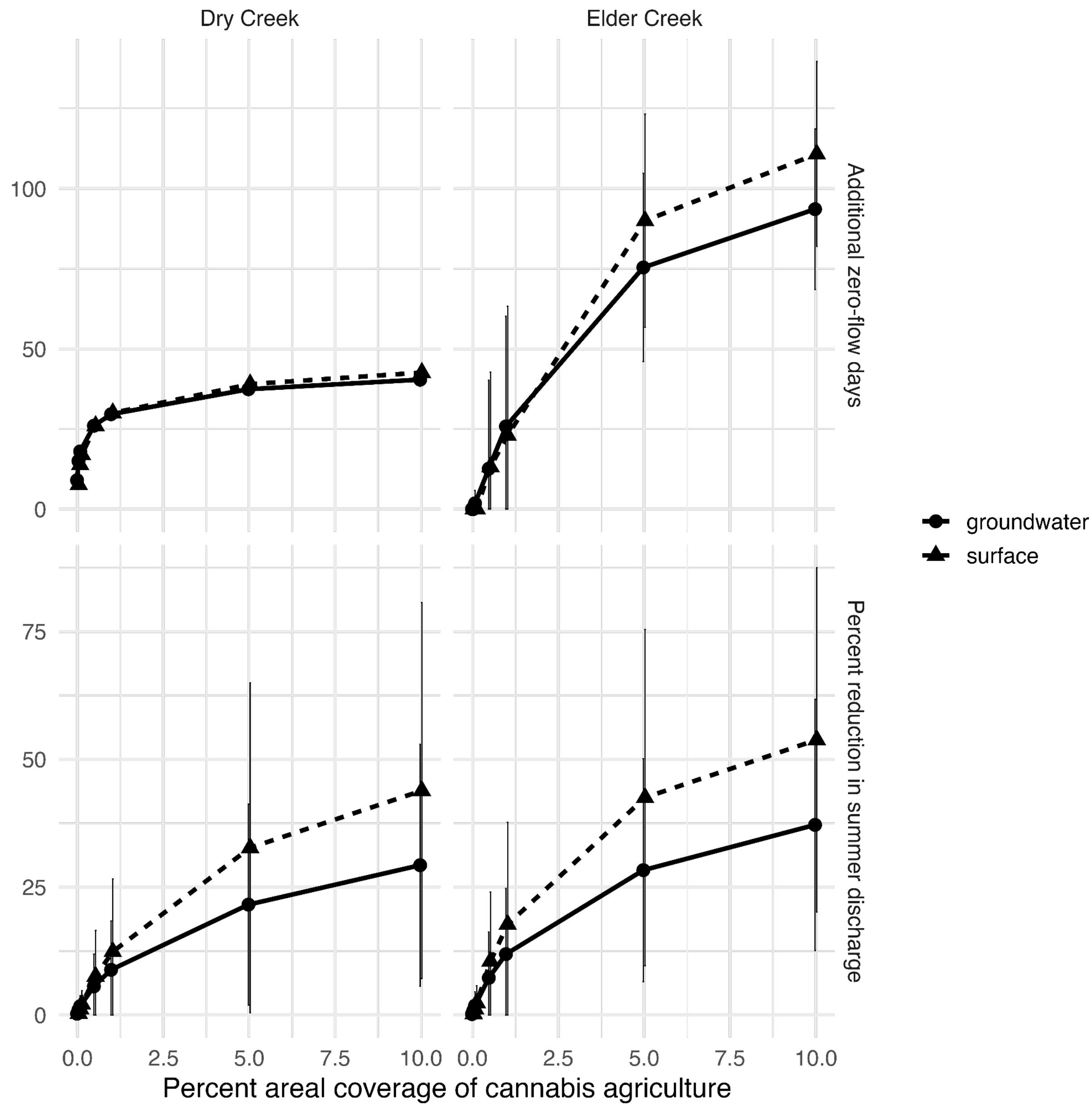

Figure 3: Summaries of number of additional days of no flow (top row) and reduction in summer discharge (bottom row) for median farm water use. Dashed lines represent surface water withdrawals, solid lines groundwater withdrawals. Dry Creek is shown on the left panels and Elder Creek on the right. Error bars show standard deviation around estimates.

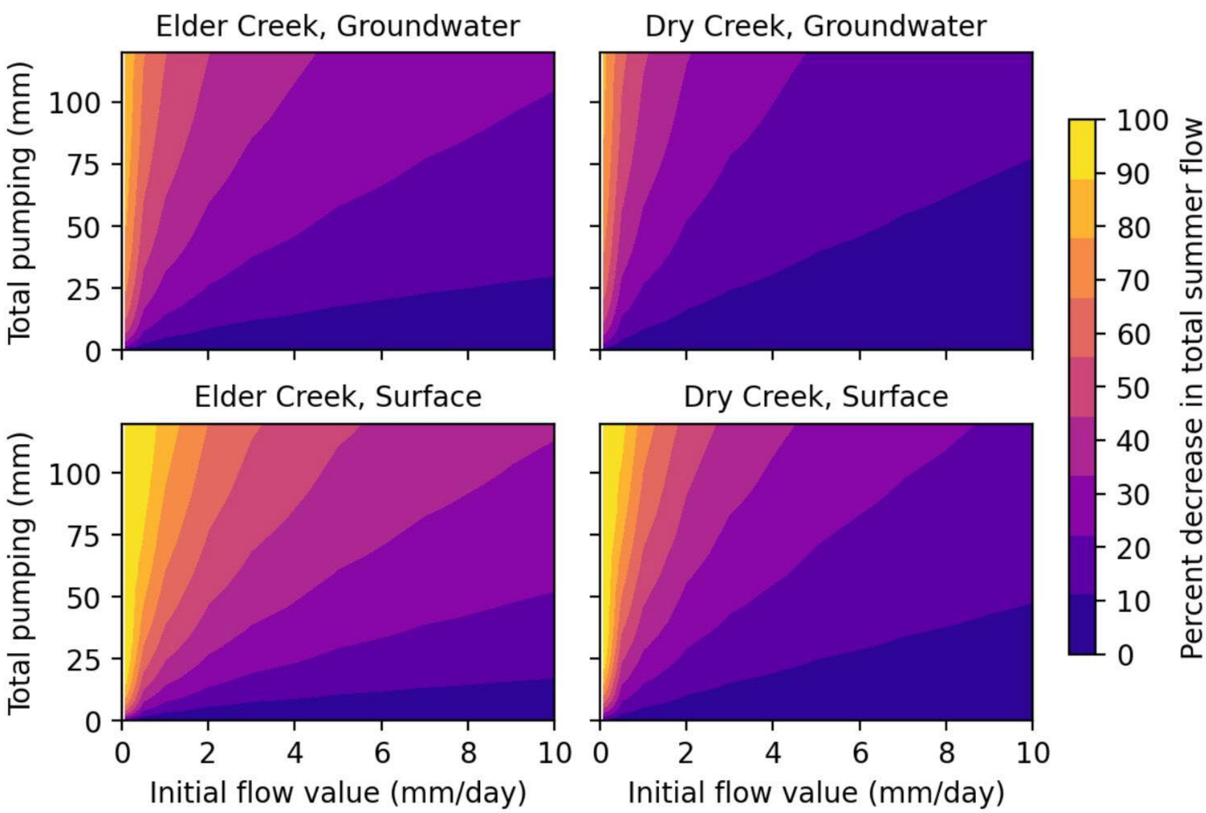

Figure 4: Heatmaps showing the proportional reduction in summer flow resulting from combinations of different initial discharges that represent water year type and a composite water use axis (areal coverage x pumping rate). Cooler colors represent lower reductions in summer flow compared to warmer colors.

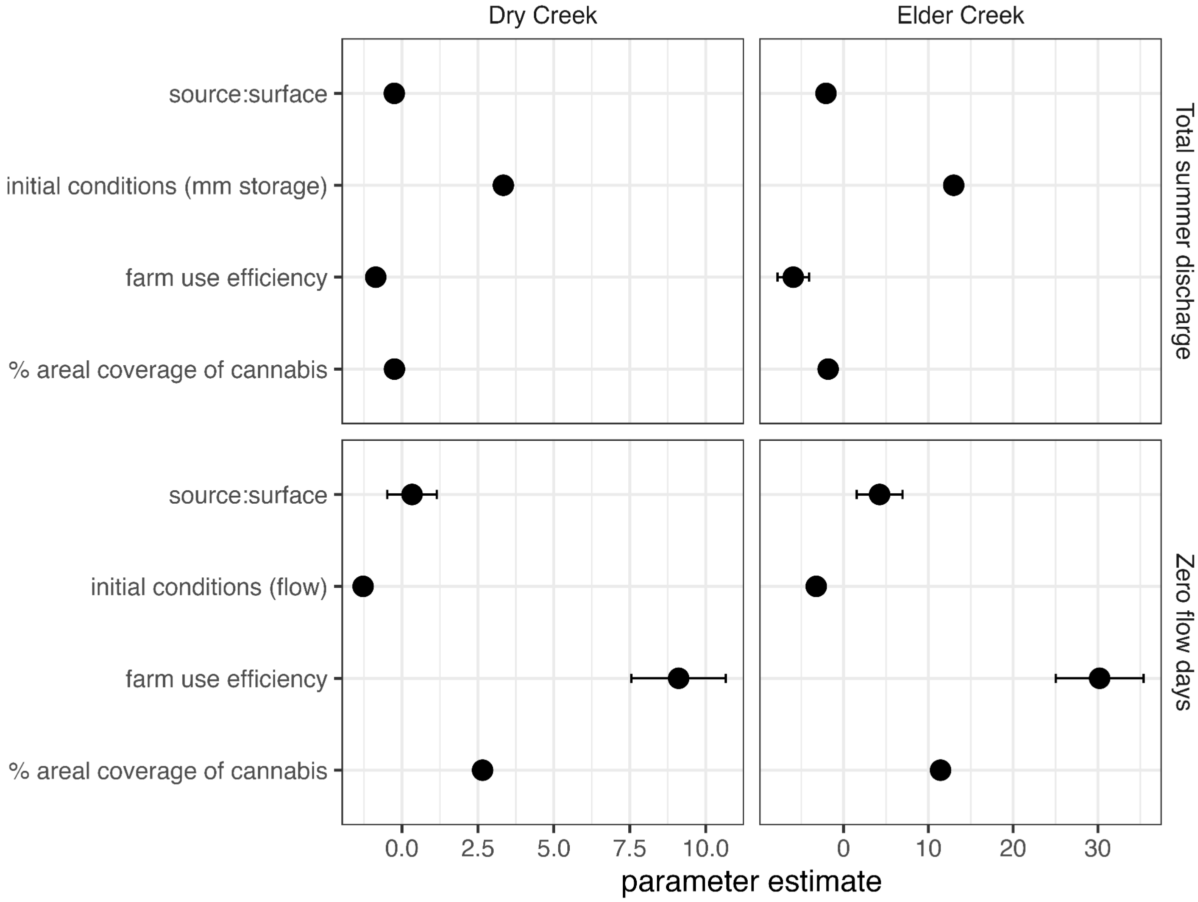

Figure 5: Effect size plots for each of our parameters of interest that were included in the modeled scenarios, note the difference in scale of x-axis between streams. Effect sizes are parameters estimates extracted from Linear models with A. total Summer discharge, and B. number of days with zero surface for both our study streams. Error bars are standard error.

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.

2023). 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. 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 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 data inputs and the resulting inferences must be scaled appropriately. Storage-discharge relationships are most relevant for *catchment*-scale assessments. In particular, 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 at smaller scales (Butsic et al. 2019). In addition, wells are often positioned immediately adjacent to water sources. Particularly in melange landscapes (such as the Dry Creek watershed), sandstone blocks are often associated with perennial water sources that provide unique local habitats for aquatic and terrestrial species. Extraction from these sources could have an outsized impact on the organisms that rely on these wet refuges in otherwise dry landscapes. Wells positioned close to stream channels may approach surface water extraction. In other circumstances, the spatial configuration of diversions could buffer impacts. 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 should prevent complete stream dewatering. Additionally, our analysis does not consider the case of groundwater pumping locally lowering the water table below the stream channel, reversing head gradients and resulting in losing stream conditions. 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, on scales smaller than the catchment level, future studies are needed to understand how storage-discharge methods can be used to explore how 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 (Figure 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%, Figure 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.

In our study streams, 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 (Figures 2, 3, 4, 5). 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 2, Figure 3, 4), 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. 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. Melange 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 melange 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 1, Figure 3, 4). 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 x extraction rate). While the impacts on intermittent melange 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 (Figure 2, 3, 4, 5). 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).

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, but the same approach could be used to investigate the impacts of any human activity that extracts groundwater from the landscape in similar mountainous regions of the world.

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