ENVIRONMENTAL RESEARCH
COMMUNICATIONS

PAPER • OPEN ACCESS

Cannabis and residential groundwater pumping impacts on streamflow and ecosystems in Northern California

To cite this article: Samuel C Zipper *et al* 2019 *Environ. Res. Commun.* **1** 125005

Environmental Research Communications

OPEN ACCESS

RECEIVED
30 August 2019

REVISED
24 September 2019

ACCEPTED FOR PUBLICATION
31 October 2019

PUBLISHED
18 November 2019

PAPER

Cannabis and residential groundwater pumping impacts on streamflow and ecosystems in Northern California

Samuel C Zipper[1,2], Jennifer K Carah[3], Christopher Dillis[4], Tom Gleeson[1], Ben Kerr[5], Melissa M Rohde[6], Jeanette K Howard[3] and Julie K H Zimmerman[7]

[1] Department of Civil Engineering, University of Victoria, Victoria BC, Canada
[2] Now at: Kansas Geological Survey, University of Kansas, Lawrence KS, United States of America
[3] The Nature Conservancy, 201 Mission Street, 4th Floor, San Francisco CA, United States of America
[4] California State Water Resources Control Board, North Coast Region, Santa Rosa CA, United States of America
[5] Foundry Spatial Ltd, Victoria BC, Canada
[6] The Nature Conservancy, 877 Cedar Street, Suite 242, Santa Cruz CA, United States of America
[7] The Nature Conservancy, 555 Capitol Mall, Suite 1290, Sacramento CA, United States of America

E-mail: samzipper@ku.edu

Keywords: marijuana, streamflow depletion, irrigation, groundwater, water management, California, residential water use

Supplementary material for this article is available online

Abstract

Cannabis is an emerging agricultural frontier, but due to its quasi-legal status its environmental impacts are poorly understood. Where cannabis is irrigated by groundwater, pumping can lead to streamflow depletion in surrounding streams which may impair other water users or aquatic ecosystems. Here, we investigate the impacts of groundwater pumping for cannabis irrigation at the scale of the watershed, the individual well, and the stream segment, and contextualize by comparing with residential groundwater use. Combining mapped cannabis cultivation and residential structure locations with grower reports of irrigation water sources, we develop distributed estimates of groundwater pumping and associated streamflow depletion caused by cannabis and residential users within the Navarro River Watershed in Northern California (USA). An estimated 73% of cannabis cultivation sites and 92% of residential structures in the watershed rely on groundwater, and groundwater abstraction leads to streamflow depletion during late summer when groundwater is a critical source of baseflow to ecologically important streams. However, streamflow depletion caused by cannabis cultivation is dwarfed by the impacts of residential use, which causes >5 times as much streamflow depletion and is concentrated close to ecologically important stream segments. Focusing on cannabis, a small number of wells (<25%) cause a disproportionate amount of depletion (>50%), and significant predictors for impacts of a well are the annual pumping rate, the distance to the closest stream, and the transmissivity between the well and the stream. Streamflow depletion increases nonlinearly when pumping occurs within 1.2 km of streams, and most cannabis and residential groundwater use is within this critical distance. Given the rapid increase in cannabis cultivation, these results indicate that potential streamflow depletion from groundwater irrigation of cannabis is a current and future concern, and will be superimposed on top of significant depletion already occurring due to residential use in the region studied.

1. Introduction

Cannabis (*Cannabis sativa* L.) cultivation has expanded rapidly in recent years in California and elsewhere, and with unknown impacts on water resources (Bauer *et al* 2015, Stoa 2015, Butsic *et al* 2018). While estimates of cannabis water use are highly uncertain due to a lack of data, previous work has found that cannabis is often cultivated close to sensitive aquatic habitats and irrigation requirements can exceed summer low flows in areas with substantial cultivation (Bauer *et al* 2015, Butsic and Brenner 2016). Accordingly, quantifying the environmental impacts of cannabis irrigation has been identified as a key research priority (Ashworth and Vizuete 2017).

Most previous work on cannabis cultivation has focused on surface water diversions (e.g. Bauer *et al* 2015). However, recent work indicates that in some regions such as Northern California, groundwater is the primary water source for most cultivators and therefore an underappreciated concern (Dillis *et al* 2019a, 2019b, Wilson *et al* 2019). One potential negative impact of groundwater pumping is reduced streamflow ('streamflow depletion') due to the capture of groundwater which otherwise would have discharged into a stream (Barlow *et al* 2018). Since groundwater provides a relatively stable and cool supply of water to streams, it is critical to the survival of aquatic organisms such as rare and endangered anadromous fish (Larsen and Woelfle-Erskine 2018, Greer *et al* 2019).

Here, we ask, *what are the potential impacts of ongoing groundwater pumping for cannabis cultivation in the Navarro River Watershed (California, USA) on streamflow and aquatic ecosystems*? We answer this question using an analytical depletion function, a newly developed tool for estimating streamflow depletion with low data and computational requirements (Zipper *et al* 2019a), to evaluate streamflow depletion caused by groundwater pumping for cannabis cultivation and contextualize this depletion via comparison to pumping for residential groundwater use. Specifically, we ask:

(1) At the watershed scale, how much streamflow depletion is potentially associated with groundwater pumping for cannabis cultivation, and how does it compare with pumping for residential groundwater use?

(2) At the well scale, how does streamflow depletion vary among pumping wells and what are the most important factors driving this variability?

(3) At the stream segment scale, what locations would pumping wells have the greatest negative impact on ecologically important stream segments?

2. Methods

2.1. Study site: Navarro River Watershed, CA

The Navarro River Watershed (816 km^2) is in Mendocino County, California, USA. Streamflow in the Navarro River is highly seasonal, and streamflow in late summer and early fall are dominated by baseflow (figure 1(a)). These cool groundwater inflows are critical for aquatic ecosystems including anadromous fish (section 2.1.2; Spence *et al* 2008, National Marine Fisheries Service 2016). However, there are significant long-term decreasing baseflow trends in August (-0.11 mm $decade^{-1}$), September (-0.11 mm $decade^{-1}$), and October (-0.45 mm $decade^{-1}$) based on the 1951–2018 water years, which coincide with the time of year when baseflow is particularly critical for aquatic ecosystems.

Timberland is the primary (∼70%) land use in the rural Navarro River Watershed, followed by rangeland (∼20%), agriculture (∼5%), and limited residential areas (North Coast Regional Water Quality Control Board 2005). Irrigated agriculture has expanded since the 1960s, and 97% of traditional crop areas (mostly vineyards) use surface water for irrigation (McGourty *et al* 2013). The Navarro River Watershed is in the 'Emerald Triangle' region (Humboldt, Mendocino, and Trinity Counties), an area well known for significant cannabis cultivation. There is growing concern that cannabis cultivation is an expanding environmental stressor in the region (Carah *et al* 2015, Butsic *et al* 2018). While historical cannabis cultivation data are not available for the watershed, widespread but small-scale cultivation in the region began in the late 1960s, with further expansion in the 1980s due to rising prices (Raphael 1985, Corva 2014, Polson 2018). Key statewide legal changes leading to additional expansion in the region occurred in 1996, when Proposition 215 legalized medical cannabis, and 2016, when Proposition 64 legalized recreational cannabis. Recent estimates have found that the area under cultivation in Mendocino and Humboldt counties nearly doubled between 2012 and 2016 (Butsic *et al.* 2018).

2.1.1. Water use

We estimated the spatiotemporal distribution of groundwater use for cannabis cultivation and residential use in the Navarro River Watershed using a combination of existing datasets and new statistical models. These methods are described in detail in the supplemental information is available online at stacks.iop.org/ERC/1/125005/mmedia. Only 3% of traditional agricultural acreage in the watershed is irrigated using groundwater (McGourty *et al* 2013), so this water use was not considered in our analysis.

Cannabis cultivation locations were identified from high-resolution aerial imagery in a previously mapped dataset (Butsic and Brenner 2016, Butsic *et al* 2018). Based on data from annual grower reports received through the North Coast Regional Water Quality Control Board (NCRWQCB), we developed two statistical models to predict locations and amount of groundwater withdrawals for cannabis cultivation. These models (described in detail in the supplemental information) include a random forest model using site physical, hydrological, and infrastructure characteristics to determine which cultivation locations used groundwater for irrigation and a multiple linear regression model using cultivated area and growing conditions to predict the monthly amount of

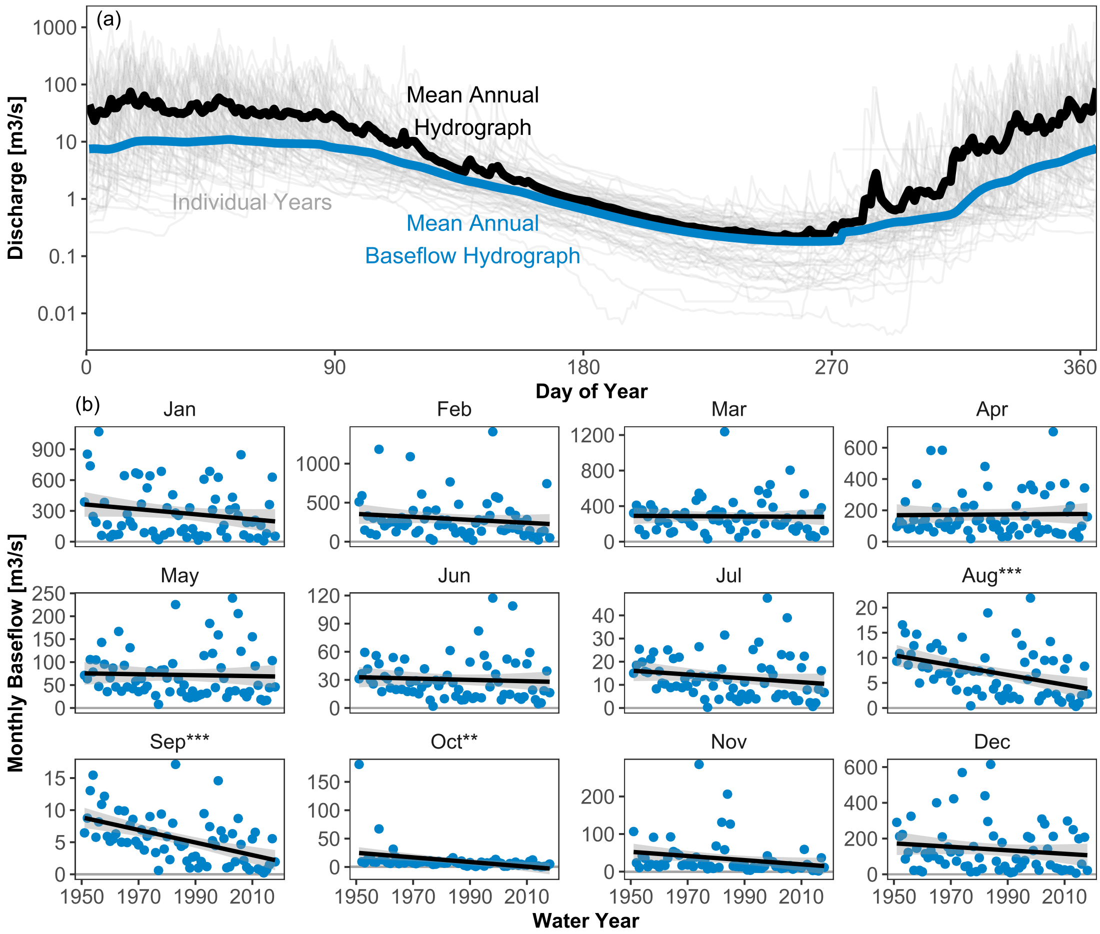

Figure 1. (a) Daily discharge (gray lines), mean daily discharge (black line), and mean daily baseflow (blue line) for the Navarro River (USGS gauge 11468000) for 1951–2018 water years, modified from Zipper *et al* (2018). (b) Mean monthly baseflow for 1951–2018 water years, with linear trend line in black. Linear trends are significant in starred months (** indicates $p < 0.01$; *** indicates $p < 0.001$). Note that *y*-axes differ between panels. Baseflow separation using (Nathan and McMahon 1990) digital filter.

irrigation applied at each site. After applying these models to the 411 parcels containing mapped cultivation sites, we predicted 302 parcels (73%) would use groundwater which is consistent with regional-scale estimates (Dillis *et al* 2019a). We used these pumping estimates as a representative monthly pumping schedule, which we then repeated for the full 50-year period of analysis.

To contextualize cannabis impacts, we also estimated the amount and impacts of residential groundwater use (i.e., homes with wells) using mapped residential structure locations (The Nature Conservancy, unpublished data) as described in the Supplemental Information. We screened out known points of surface water diversions from the California electronic Water Rights Information Management System (CA State Water Resources Control Board 2019 a), and estimate 1314 of 1423 residential structures (92%) in the Navarro River Watershed are groundwater-supplied, which is consistent with regional Resource Conservation District staff estimates that the overwhelming majority of residences use groundwater (personal comm., Linda MacElwee, Mendocino County Resource Conservation District). We estimated monthly water use for each property based on per capita water use data (CA State Water Resources Control Board 2019b) and average household size estimates (Mendocino County Water Agency 2010). Reported per capita water use spanned June 2014-February 2019, so we average monthly household water use across all years to generate a representative monthly pumping schedule, which we then repeated for the full 50-year period of analysis.

2.1.2. Stream ecological value

To identify streams with high ecological value, we used intrinsic habitat potential estimates for coho salmon (*Oncorhynchus kisutch*) in Northern California from Agrawal *et al* (2005). We selected coho salmon as the species of interest due to their high sensitivity to stream temperature conditions during late summer low flows (Welsh *et al* 2001), which are strongly dependent on groundwater inflow (Spence *et al* 2008, Gleeson and Richter 2018), and their status as an endangered species at state and federal levels (National Marine Fisheries Service 2012). The intrinsic habitat potential represents the likelihood (0–1) that a stream segment will have suitable habitat for a given species based on the channel gradient, valley width, and discharge. Following regionally-developed

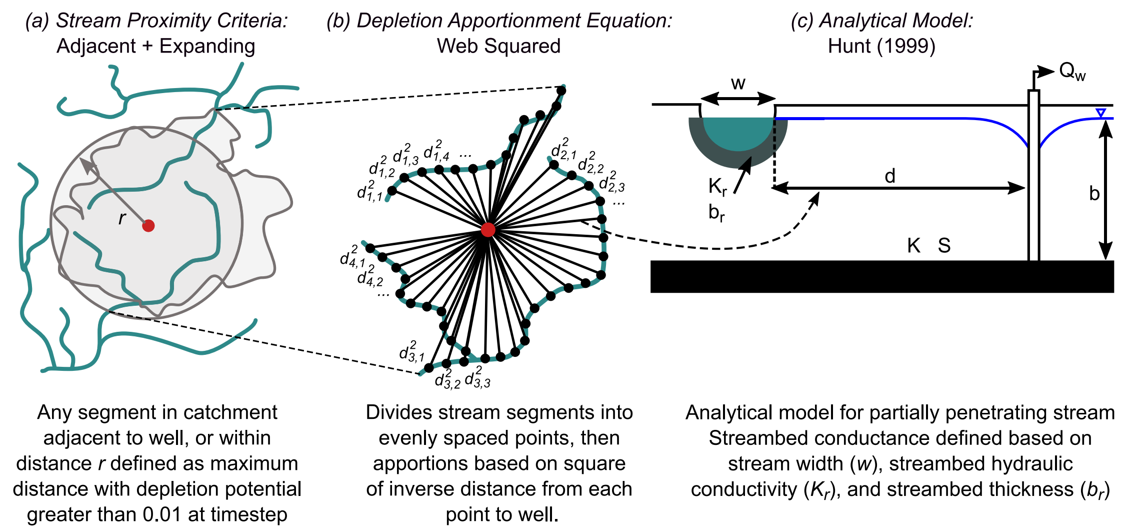

Figure 2. Diagram showing components of analytical depletion function: (a) stream proximity criteria, (b) depletion apportionment equations, and (c) analytical model.

standards (National Marine Fisheries Service 2016), we used a threshold of $\geqslant 0.7$ to indicate high quality habitat potential (figure 4). We aggregated the raw stream segment estimates of intrinsic habitat potential (NOAA; mean segment length = 85–126 m depending on species) to match segments in the US National Hydrography Dataset (NHD; mean segment length = 1560 m) with any NHD segment containing a high potential NOAA segment classified as high potential.

2.2. Calculating streamflow depletion

2.2.1. Analytical depletion function overview

We used an analytical depletion function (figure 2) to estimate the quantity and timing of streamflow depletion from cannabis and residential groundwater use. Analytical depletion functions, developed in Zipper *et al* 2019a, combine: (i) stream proximity criteria, which determine the stream segments that may be affected by a well; (ii) a depletion apportionment equation, which calculates the relative proportion of total streamflow depletion occurring in each stream segment meeting the proximity criteria; and (iii) an analytical model, which estimates the total streamflow depletion for each stream segment which is then scaled using the depletion apportionment results. The output of an analytical depletion function is the streamflow depletion in each stream segment in response to a given well.

Based on previous work comparing analytical depletion functions for the region (Zipper *et al* 2019a), we used the 'Adjacent + Expanding' stream proximity criteria (figure 2(a)), the web squared depletion apportionment equation (figure 2(b); equation S1; Zipper *et al* 2018), and the Hunt (1999) model (equation S2). To simulate monthly pumping schedules developed in section 2.1, we used the superposition approach described in Jenkins (1968). This analytical depletion function was tested against 49 other analytical depletion functions and found to produce the most accurate estimates of depletion for the Navarro River Watershed across a number of performance criteria (Zipper *et al* 2019a). Analytical depletion functions were implemented using the streamDepletr package (Zipper 2019) for R, and described in detail in the Supplemental Information and Zipper *et al* 2019a.

2.2.2. Analytical depletion function inputs

Analytical depletion functions require input data describing stream network geometry , the well, and hydrostratigraphic conditions. See the Supplemental Information for a detailed description of these inputs.

For inputs describing the stream network geometry, we used the National Hydrography Dataset to map stream locations, and an empirical relationship between drainage area and stream width developed in Zipper *et al* 2019a. The total extent of our domain included the Navarro River Watershed and adjacent watersheds (figure S2) so that wells could have impacts beyond the watershed borders.

For inputs describing the well, we used the spatial locations and pumping schedules for cannabis cultivation and residential structures described in section 2.1. Well screen depths were not reported in the NCRWQCB reports used to model well locations and pumping rates, so we used the screened interval for the closest Well Completion Report from the California Department of Water Resources (https://dwr.maps.arcgis.com/apps/webappviewer/index.html). For the synthetic wells used to map the sensitivity of streams to pumping throughout the watershed (section 2.3; figure S2), we defined the screen length as the mean of production wells in the well completion report database and set the top of the screen at the estimated water table elevation.

Though detailed measurements of inputs describing hydrostratigraphy are not available from within the Navarro River Watershed, we synthesize data from nearby watersheds in the same regional geological setting to inform our study. In the nearby Elder Creek watershed, Dralle *et al* (2018) describe thin soils overlying a fractured and saturated bedrock system driving hillslope hydrology in the region, and in lowland portions of the domain mapped unconsolidated sedimentary aquifers are present along the Navarro River and coastal areas (CA Department of Water Resources (2016)). Accordingly, we adopt a two-layer conceptual model in which fractured bedrock is overlain by unconsolidated sediment of variable thickness corresponding to the bedrock depth (Hengl *et al* 2014, 2017; figure S2). In hillslopes, this top layer is thin and effectively ignored in our streamflow depletion calculations because the top layer is above the water table and therefore not considered in our calculations of effective transmissivity (see below). In low-lying areas along the Navarro River and coast, the top layer is thicker (up to ∼35 m) and represents the alluvial aquifer. We define the top layer's hydraulic conductivity as 4.5×10^{-3} m s^{-1} based on pumping tests from the alluvium around the Russian River (Su *et al* 2007), a value which is also consistent with surficial soil estimates of hydraulic conductivity from Dralle *et al* (2018). Complete hydrostratigraphic properties for each of these layers are defined in table S2.

To calculate effective transmissivity and effective storativity, we averaged transmissivity and storativity between each well location and the closest point to that well on each stream segment, meaning that these inputs are unique for each well-stream combination (equations S5–S7). We followed Reeves *et al* (2009) to estimate streambed conductance (equation S3) using the hydraulic properties of the aquifer at the location of each stream segment. In this approach, streambed conductance is a lumped empirical parameter accounting for various aspects of the real world which are not addressed in analytical models including streambed properties, anisotropy, and stream-aquifer geometry (Kollet and Zlotnik 2003, Glose *et al* 2019). Groundwater recharge is not a necessary consideration for this study because recharge does not affect either the distribution or magnitude of streamflow depletion unless the pumping itself leads to a change in recharge, which we assume is not the case here (Bredehoeft *et al* 1982, Feinstein *et al* 2016).

2.3. Quantifying watershed-, well- and stream-scale impacts

For watershed-scale impacts, we used the analytical depletion function to estimate monthly cannabis and residential streamflow depletion in the first, 10th, and 50th year after the onset of pumping in each of the mapped groundwater withdrawal locations for cannabis cultivation and residential use. Streamflow depletion is challenging to quantify (Barlow and Leake 2012) and no known measurements exist within the watershed for validation. Furthermore, since we do not know the year at which pumping began for each withdrawal point, we are not intending to reproduce historical or project future streamflow depletion patterns, but rather evaluate the magnitude of streamflow depletion for different pumping timescales caused by current groundwater use. The output of the analytical depletion function was the streamflow depletion caused by each well in each stream segment within our domain, which we compared to average baseflow over the past 20 water years separated using the Nathan and McMahon (1990) digital filter to evaluate impacts relative to current hydrologic conditions.

For well-scale impacts, we evaluated whether some cannabis cultivation parcels contributed disproportionately to depletion by ranking the total depletion caused by each well across all stream segments in September after 1, 10, and 50 years of pumping. We then quantified the factors which drove impacts at the well-scale using R^2 partitioning (Lindeman *et al* 1979) as implemented in the relaimpo package for R (Grömping 2006). Specifically, for each year tested (1, 10, 50 years), we built a multiple linear regression model predicting a well's total capture fraction as a function of annual water use, distance to closest stream segment, effective transmissivity between the well and the closest stream segment, streambed conductance of the closest stream segment, and the depth to bedrock at the well. We then used ANOVA to identify significant predictors ($p < 0.05$) of depletion at each timestep and evaluated the relative contribution of each significant predictor to the total R^2. We used a 1000-sample bootstrapping approach to generate mean and confidence intervals for the relative importance of each significant predictor variable.

For stream segment-scale impacts, we focused on streams with high ecological value (section 2.1.2). Following Feinstein *et al* (2016), we designed a grid of synthetic pumping wells at 1 km spacing ($n = 787$; figure S2) which we tested one-at-a-time using the mean monthly pumping schedule from all cannabis cultivation sites to simulate the impacts of pumping for 1, 10, and 50 years. These synthetic wells are meant to test pumping impacts on streamflow in a systematic manner throughout the entire domain and do not necessarily represent locations where pumping is currently occurring. We then summed the impacts from each well on streams of high ecological value and interpolated results to 150m resolution using inverse distance weighted interpolation as implemented in the gstat package for R (Gräler *et al* 2016) to map the spatial distribution of potential impacts

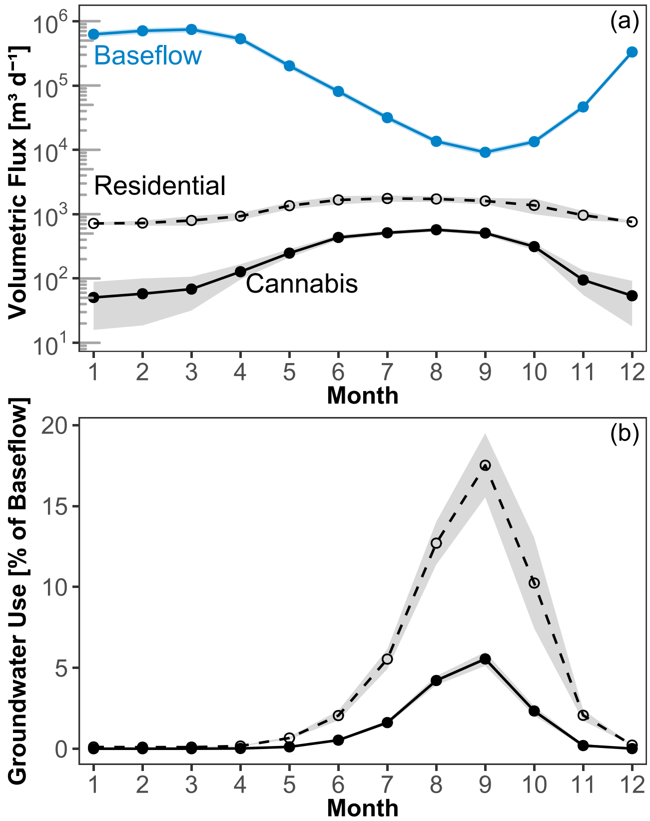

Figure 3. Estimated monthly cannabis and residential groundwater use, shown (a) as a volume and (b) as a percentage of mean monthly baseflow (1999–2018 water years). Shaded ribbon show +/−1 standard deviation of estimated water use.

on high ecological value streams. To determine the distance from a stream at which effects are greatest, we created buffers of 100–3000 m at an interval of 100 m around each high-value stream segment. Within each of these buffers, we averaged the values within this distance of the stream from the interpolated rasters. To identify the distance at which impacts of pumping begin to increase non-linearly, we identify the maximum of the second derivative of a smoothed relationship between depletion from high potential streams and buffer distance surrounding each high-potential stream.

3. Results and discussion

3.1. Cannabis and residential groundwater use

Both cannabis and residential properties use substantial amounts of groundwater with strong seasonality in estimated groundwater abstraction. Groundwater use for cannabis production within the Navarro River Watershed is minimal in the wet winter months and peaks in August at 572 $m^3 d^{-1}$ (figure 3(a)), and estimated annual abstractions total 92,945 m^3. Residential groundwater use has a similar seasonal pattern but a much greater magnitude, peaking in July at 1753 $m^3 d^{-1}$ (figure 3(a)). The lowest residential water use month (January) has greater groundwater withdrawals than the highest cannabis water use month, and total annual abstractions for residential use (437,786 m^3) are 4.7 times greater than abstractions for cannabis. As a percentage of baseflow, both cannabis and residential groundwater use is highest in September at 5.5% and 17.5% of mean monthly baseflow, respectively (figure 3(b)). This is the month where baseflow is lowest, affected by a significant decreasing trend, and most important for salmon habitat (figure 1).

The larger groundwater use by residential properties is driven by two factors which vary seasonally. In the summer, overall residential use is higher than cannabis use even though cannabis has a higher per-well abstraction rate because there are more residential pumping locations in the watershed than groundwater-irrigated cannabis cultivation sites (1314 residential structures compared to 302 cannabis parcels using groundwater). If the number of cannabis parcels increased to match the number of residential structures, groundwater abstraction for cannabis would exceed residential use for June-September. In the winter, residential water use is greater than that of cannabis because cannabis water use is negligible outside of the summer growing season, while residential properties have ongoing water use during the winter months due to

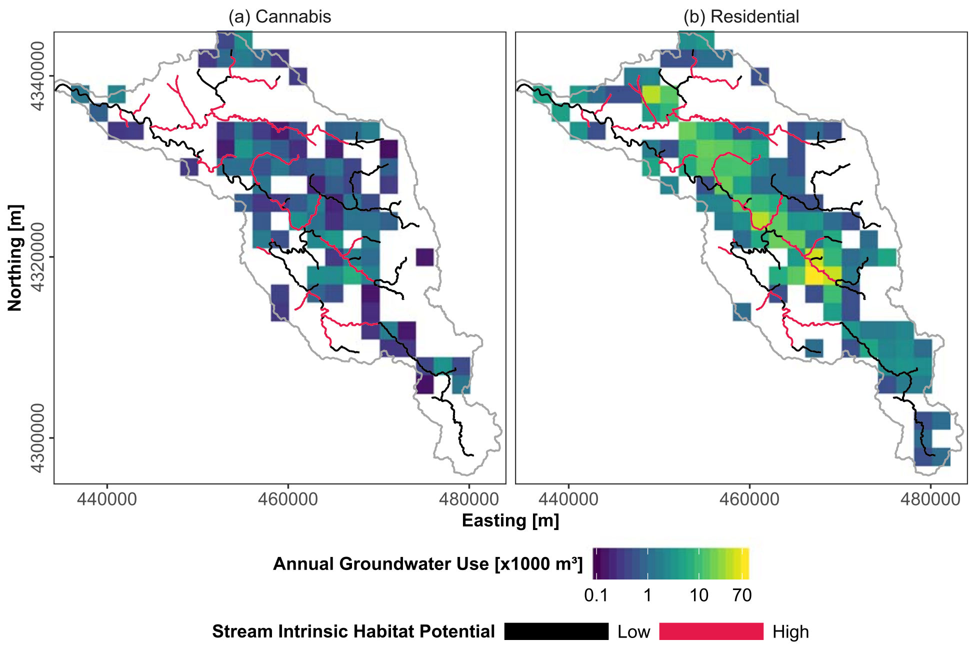

Figure 4. Map of intrinsic habitat potential for coho salmon within the Navarro River Watershed, with estimated annual (a) cannabis and (b) residential groundwater use (aggregated from points to 2km resolution to protect individual privacy). White areas within the watershed boundary have no estimated groundwater use. Habitat potential for steelhead salmon are shown in figures S3–S5.

climate-insensitive indoor water requirements such as cooking and cleaning (Gato *et al* 2007, Breyer *et al* 2012, Zipper *et al* 2017).

Spatially, residential groundwater use is more clustered along the river than cannabis groundwater use, including many streams with high salmonid habitat potential (figure 4). The spatial distribution of residential use corresponds with the locations of most of the towns in the flatlands along the Navarro River (e.g., Boonville, Philo, Navarro). Cannabis cultivation is much more diffuse within the watershed, primarily concentrated in the middle reaches of the watershed (figure 4(a); Butsic *et al* 2017, Butsic *et al* 2018).

3.2. Watershed scale impacts

Streamflow depletion associated with both cannabis and residential groundwater use (figure 5) follows a similar seasonal pattern to water withdrawals (figure 3), with a slight time lag due to the delay between groundwater pumping and streamflow depletion. Streamflow depletion associated with cannabis production is largest in September both volumetrically (figure 5(a); 93, 139, and 176 $m^3 d^{-1}$ after 1, 10, and 50 years of pumping respectively) and as a percentage of monthly baseflow (figure 5(b); 1.0%, 1.5%, and 1.9% after 1, 10, and 50 years of pumping respectively) over our entire study period. This is offset from the month of peak water use, which is August (figure 3(a)). Peak monthly streamflow depletion associated with residential groundwater use is substantially larger than that of cannabis (figure 5(a)), at 485 $m^3 d^{-1}$ after 1 year (5.2x greater than cannabis), 700 $m^3 d^{-1}$ after 10 years (5.0× greater), and 854 $m^3 d^{-1}$ after 50 years (4.9x greater). Like cannabis, the impacts are largest relative to baseflow in September (5.3% after 1 year, 7.6% after 10 years, and 9.3% after 50 years) which is when baseflow is lowest and the primary component of streamflow (figure 5(b)). These impacts approach the presumptive standard of 10% of monthly baseflow which is suggested to sustain aquatic ecosystems (Gleeson and Richter 2018).

The degree to which streamflow depletion caused by cannabis or residential pumping may affect aquatic ecosystems is a function of the streamflow in a given year, which is driven by interannual weather variability. For example, in a dry or average year, reductions in flow caused by groundwater pumping are occurring during a time in which flow is already below the state aquatic baseflow standard (figures 6(a)–(b)), which is defined by the California Cannabis Cultivation Policy as median August flow over the period of record (CA State Water Resources Control Board 2017). In contrast, during a wet year, streamflow remains greater than the aquatic baseflow standard even when potential pumping impacts are considered (figure 6(c)). During the period of record, there were five years (1951, 1996, 1997, 2003, and 2011) in which baseflow would have dropped below the aquatic baseflow standard if additional pumping equal to the present rates occurred for one year prior, indicating that managing the impacts of streamflow depletion may be most critical when flow is near aquatic ecosystem thresholds.

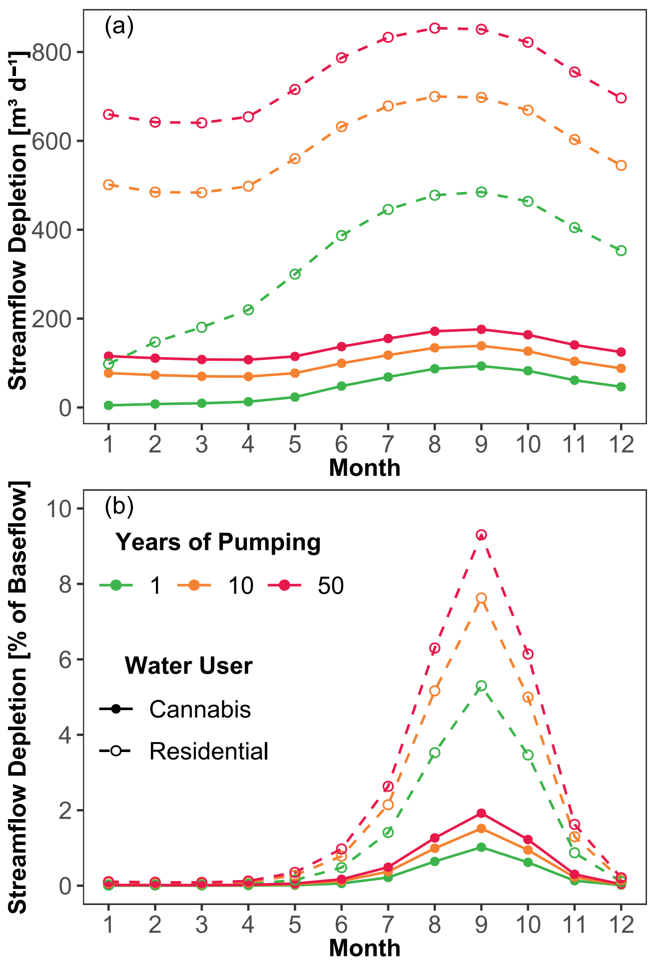

Figure 5. Streamflow depletion (within the Navarro River Watershed only) caused by groundwater pumping for cannabis cultivation and residential use after 1, 10, and 50 years of pumping, expressed (a) volumetrically and (b) as a percentage of mean monthly baseflow (1999–2018 water years).

Since historical data about the onset of pumping is not available, we are not able to attribute either long-term trends in baseflow (figure 1) or specific exceedance events (figure 6) to historical cannabis cultivation activities, residential development, or other factors such as climate change. However, our results show that a sizeable portion of impacts occur shortly after the onset of pumping. For example, 52.8% and 56.8% of long-term (50 year) depletion in September is already present the year pumping begins for cannabis and residential use, respectively (figure 5). Since the recovery from depletion occurs as an inverse of the timescale of depletion impacts (Jenkins 1968, Barlow and Leake 2012), this indicates that the hydrological system is highly sensitive to potential new pumping impacts, but also may recover quickly if pumping is reduced or halted in certain areas.

3.3. Well scale impacts

Our well-scale assessment of cannabis impacts indicates that a relatively small number of wells have a disproportionate impact on overall watershed-scale depletion. After 1 year of pumping, 50% of the depletion in the Navarro River Watershed can be attributed to only 32 wells (10.6% of estimated groundwater pumping wells in the Navarro; figure 7(a)). After 10 and 50 years, the number of wells causing 50% of depletion increases to 53 (17.5%) and 72 (23.8%), respectively (figure 7(a)). In year 1, only ~50% of well locations have any appreciable depletion (figure 7(a)). These results lend support to targeted conservation measures and the importance of well location, as removing or reducing pumping rates from a small subset of wells could have outsize environmental benefits, particularly at short timescales (e.g., within a single year).

Water use, distance from the well to the closest stream, and the effective transmissivity between a well and the closest stream are the primary predictors of the amount of depletion caused by a well, while streambed conductance and depth to bedrock at the well were not significant predictors. The relative importance of predictors changes through time, indicating shifting drivers of variability in capture fraction at different timescales. The predictive skill of water use increases through time, which is partially counteracted by a decrease

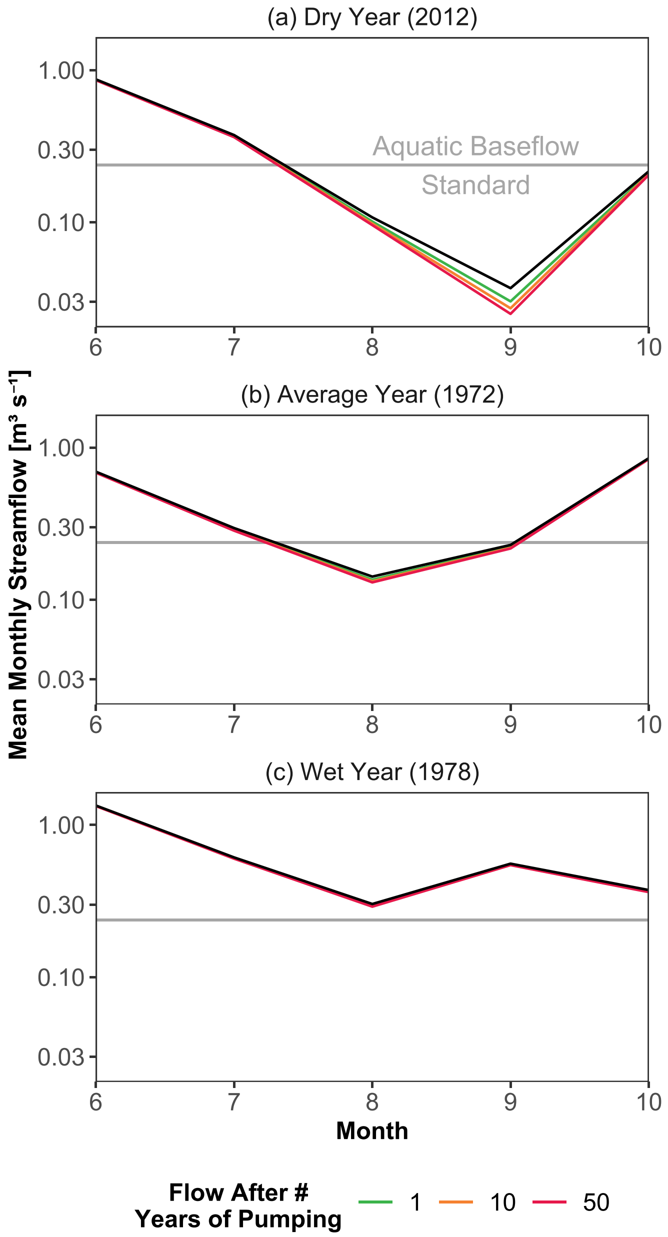

Figure 6. Measured streamflow (black line) and streamflow remaining after 1, 10, and 50 years of depletion (colored lines) from combined cannabis and residential pumping, shown relative to monthly flow in (a) a dry year, 2012, (b) an average year, 1972, and (c) a wet year, 1978. The gray horizontal lines shows the aquatic baseflow standard for the Navarro River from the California Cannabis Cultivation Policy, which is defined as the median August flow over the period of record (CA State Water Resources Control Board 2017). Note log-scale on y-axis.

in the predictive power of transmissivity. The decrease in the importance of transmissivity through time is indicative of the system coming to a new dynamic equilibrium of the source of water to the wells, which is relatively insensitive to hydrogeological properties (Zipper *et al* 2019a, Barlow and Leake 2012). While our conceptual model assumed two homogeneous layers, the decreasing importance of transmissivity through time would likely be true even with heterogeneous hydrostratigraphy because the decreasing predictive power of transmissivity results from the transition from groundwater depletion to streamflow depletion as the primary source of water to wells (Barlow and Leake 2012). In contrast, distance to the closest stream has relatively steady predictive skill in all years, indicating that this may be a consistently useful predictor across all timescales.

3.4. Stream segment scale impacts

Due to the large importance of the well-stream distance (section 3.3), pumping close to stream segments with high habitat potential has the largest potential negative environmental impacts. All else being equal, streamflow depletion would have larger negative impacts in smaller stream segments with lower flow. Portions of the landscape with strong effects on high potential stream segments include much of the middle reaches of the

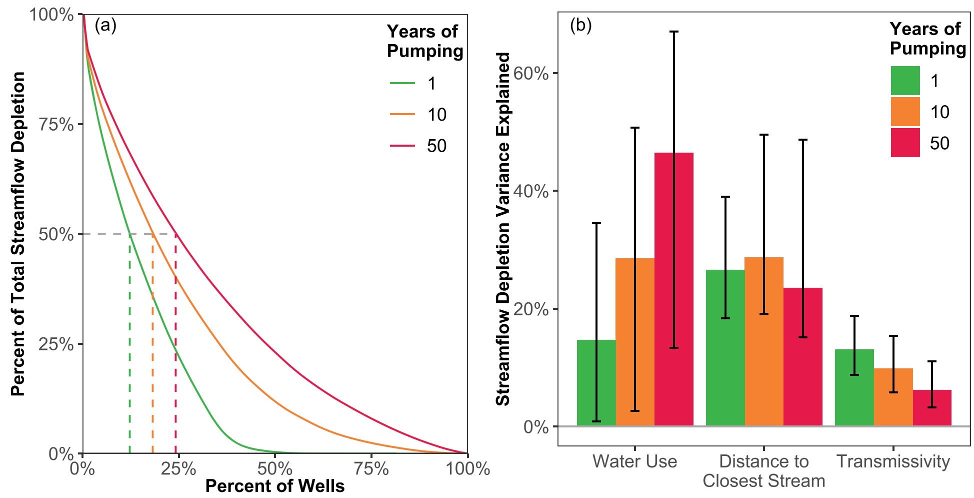

Figure 7. (a) Cumulative distribution functions of the total streamflow depletion accounted for as a function of the percentage of total groundwater pumping wells in September of year 1, 10, and 50 of pumping scenarios. Dashed lines annotate the percent of wells accounting for 50% of the total streamflow depletion at each time interval. (b) Relative importance of significant predictors for predicting cumulative streamflow depletion caused by a well across all stream segments in September of year 1, 10, and 50. Water use is annual estimated pumping rate for that well [$m^3\ yr^{-1}$] and transmissivity is the bulk transmissivity between the well and the closest stream [$m^2\ d^{-1}$]. Bars show mean and errorbars show 95% confidence interval from 1000-sample bootstrap.

Navarro River (figures 8(a)–(c)) which is coincident with locations where significant groundwater use occurs for residential structures (figure 4(b)) and, to a lesser degree, cannabis cultivation (figure 4(a)). While the portion of the landscape where pumping harms high potential streams expands through time, across the entire study period there is a nonlinear increase in depletion caused by wells within 1.2 km of a stream segment (figures 8(d)–(f); S6), indicating that a distance of 1.2 km of high potential stream segments may be a critical threshold for management for both short-term and long-term sustainability, especially near headwater streams. Wells which are screened in alluvial materials tend to have the largest impact on high-potential streams (figures 8(d)–(f)), indicating that the magnitude and timing of these impacts may be sensitive to estimates of alluvial hydrostratigraphic properties. Since the alluvial sediment is thickest in low-lying areas along the stream valleys (figure S2), this likely contributes to the nonlinear increase in streamflow depletion for wells within 1.2 km of the stream.

3.5. Management implications

Our results show that there is likely significant streamflow depletion in streams with high habitat potential caused by both cannabis and residential groundwater use in the Navarro River Watershed, with shifting drivers of impacts and implications through time. Over half of the long-term streamflow depletion manifests within a single year of the start of our pumping simulations (figure 5), and impacts at short timescales is most strongly influenced by the proximity of a well to a stream (figure 7) with nonlinearly increasing impacts within a distance of 1.2 km (figure 8). Over long timescales, the primary driver of impacts for a given well is the annual water use (figure 7), though impacts still increase nonlinearly within 1.2 km regardless of pumping rate (figure S6). While the exact timing and quantity of streamflow depletion may vary locally with refined estimates of hydrostratigraphic properties or more precise pumping schedules, our results broadly show the relative importance of cannabis and residential groundwater use within a year and across decades.

This suggests that the area within 1.2 km of the stream network is a critical management area (figure 9). Overall, 233 of the 302 parcels (77%) predicted to use groundwater for cannabis cultivation are within 1.2 km of a stream segment, and these parcels are more frequently close to stream segments with high habitat potential than not (figure 9(b)). Residential groundwater use is also frequently close to streams, with 89% of residential groundwater use within 1.2 km of any stream and 67% of residential groundwater use near a high habitat potential stream (figure 9(c)). While our results focused primarily on cannabis, our approach could be used to quantify impacts of groundwater withdrawals for other reasons. As cannabis cultivation expands in the region, its impacts will be an additional stress on top of ongoing residential groundwater use and direct surface water withdrawals for traditional agriculture. Total surface water withdrawals for traditional agriculture within the Navarro River Watershed were estimated in 2009 as approximately $2 \times 10^6\ m^3\ yr^{-1}$ (McGourty *et al* 2013), which exceeds combined cannabis and residential groundwater abstractions estimated here by a factor of 4.

More broadly, we find that analytical depletion functions are a useful tool for screening-level assessments of groundwater pumping impacts on streams. The ongoing legalization of cannabis will require new and revised

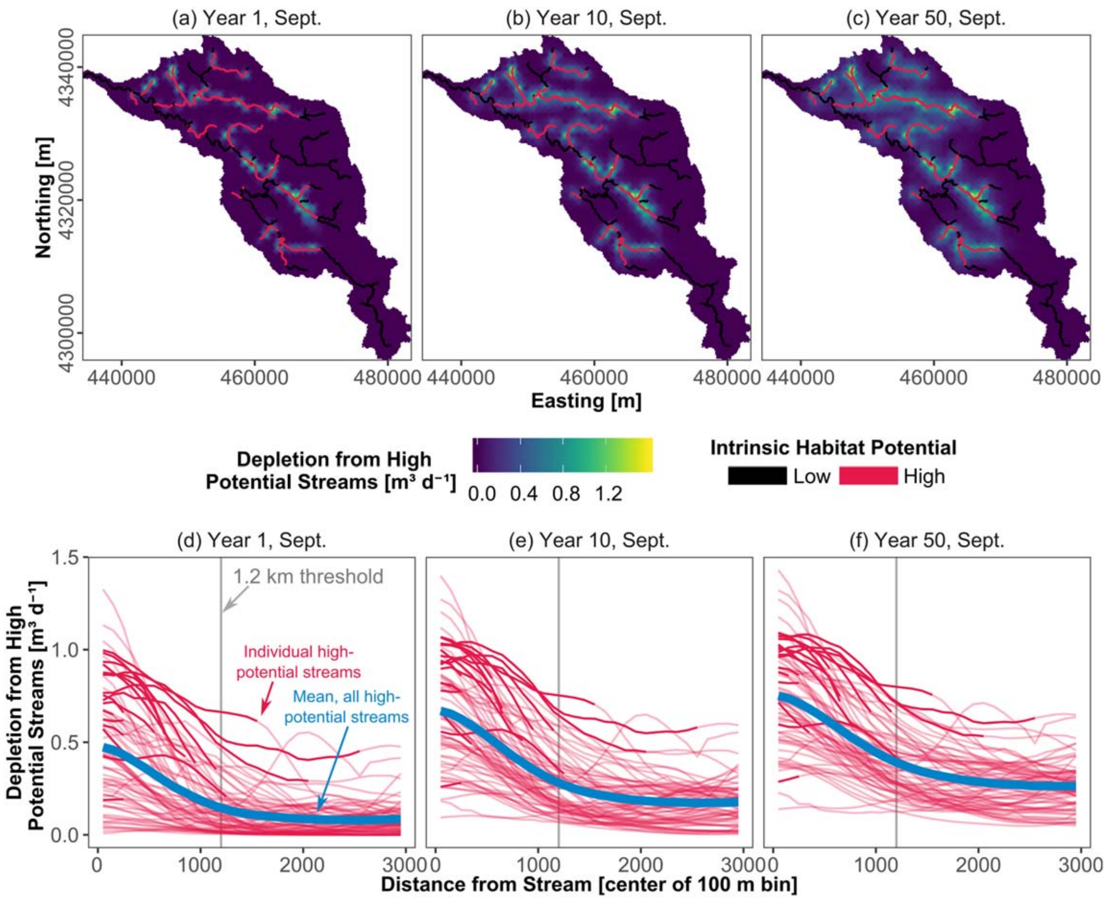

Figure 8 (a)–(c) Volumetric streamflow depletion that would occur from stream segments with high intrinsic habitat potential after 1, 10, and 50 years of pumping for an average cannabis cultivation site at different locations on the landscape. (d)–(f) Mean streamflow depletion from high intrinsic habitat potential streams as a function of distance from the stream; each red line corresponds to a high potential stream segment, and the blue line is the mean of all high potential segments. Dark red lines indicate distances in which wells are screened all or partly in alluvial materials. The vertical gray line indicates the critical 1.2 km distance within which impacts increase nonlinearly (section 3.4).

regulations to protect water and other environmental resources; in the USA, these protections will likely manifest at the local level due to a lack of federal regulation (Owley 2017, Short Gianotti *et al* 2017). Given the paucity of subsurface data available in most watersheds, the rapidity with which cannabis production is expanding (Butsic *et al* 2018), and the local scope at which cannabis is likely to be managed (Owley 2017), it is essential to provide accurate decision support resources with minimal time, data, and computational requirements. We show that analytical depletion functions can identify areas of potential concern for groundwater pumping (e.g., figures 8, 9) which could be used to flag groundwater withdrawal locations for further investigation or targeted conservation measures. Due to the low computational requirements relative to numerical models, analytical approaches are well-suited for integration into decision support tools (Reeves *et al* 2009, Huggins *et al* 2018, Colorado Alluvial Water Accounting System), and analytical depletion functions help overcome many of the limitations identified previously for standalone analytical models such as the inability to simulate multiple and/or sinuous streams.

4. Conclusions

In this study, we evaluate and contextualize the potential impacts of cannabis groundwater use at the watershed, well, and stream segment scales in the Navarro River Watershed (California, USA). We find that cannabis pumping has an important impact on streamflow during the dry season but is dwarfed by streamflow depletion caused by residential groundwater use which is 5x greater. However, cannabis pumping can be considered a new and expanding source of groundwater depletion which will further deplete summer baseflow already stressed by residential water use and traditional agriculture. At the well scale, we find that a small number of wells contribute disproportionately to streamflow depletion, particularly over short timescales; and that relatively easy-to-obtain input data (annual water use and distance to stream) are the primary factors related to pumping impacts on streamflow, with increasing importance of water use through time. Subsurface properties such as transmissivity are most important shortly after

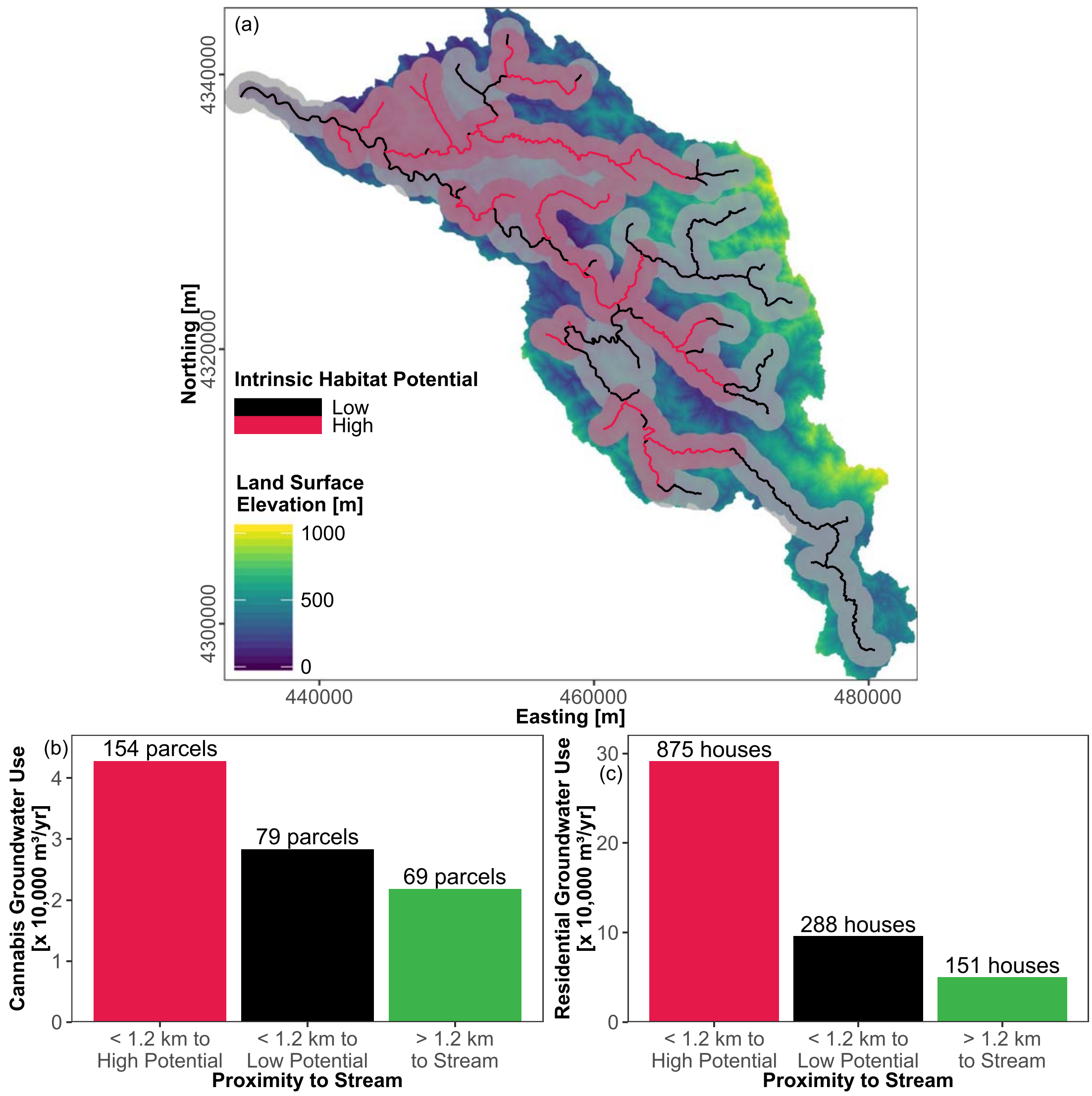

Figure 9. (a) Map showing areas within 1.2 km of stream segments with high intrinsic habitat potential (red line with red buffer) and low intrinsic habitat potential (black line with gray buffer), which was identified as a critical distance threshold for pumping impacts (figure 8, figure S6). (b), (c) Estimated annual groundwater pumping for (b) cannabis irrigation and (c) residential use occurring within 1.2 km of a high potential stream segment, within 1.2 km of a low potential stream segment, and further than 1.2 km from a stream. Note that (b) and (c) have different y-axes.

the onset of pumping and decrease in importance through time. We also show that pumping within a threshold of 1.2 km of sensitive stream segments has a disproportionately high impact, particularly at short (annual to decadal) timescales. Overall, these results indicate that the emerging cannabis agricultural frontier is likely to increase stress on both surface water and groundwater resources and groundwater-dependent ecosystems, particularly in areas already stressed by other groundwater users.

Acknowledgments and Data

The authors were supported by funding from the National Sciences and Engineering Research Council (Canada) to the University of Victoria and Foundry Spatial, and the S D Bechtel, Jr Foundation and Angela Nomellini and Ken Olivier to The Nature Conservancy. We thank Van Butsic and the Cannabis Research Center for sharing the cannabis location data used in this analysis. Data and code are available via the Open Science Framework (http://doi.org/10.17605/OSF.IO/AW4D7). Sensitive data including cannabis cultivation sites, residential structure data, and survey data are not publicly available for privacy protection (Zipper et al 2019b); please contact the authors with questions related to these data. All analyses were performed using R 3.6.0 (R Core Team 2019) and graphics were made using ggplot2 (Wickham 2009) and InkScape (The Inkscape Team 2015).

ORCID iDs

Samuel C Zipper https://orcid.org/0000-0002-8735-5757
Tom Gleeson https://orcid.org/0000-0001-9493-7707

References

Agrawal A, Schick R S, Bjorkstedt E P, Szerlong R G, Goslin M N, Spence B C, Williams T H and Burnett K M 2005 Predicting the potential for historical coho, chinook and steelhead habitat in northern California *NOAA Technical Memorandum NMFS* 1–25

Ashworth K and Vizuete W 2017 High time to assess the environmental impacts of Cannabis Cultivation *Environ. Sci. Technol.* **51** 2531–3

Barlow P M and Leake S A 2012 *Streamflow Depletion by Wells–Understanding and Managing the Effects of Groundwater Pumping on Streamflow* (Reston VA: US Geological Survey)

Barlow P M, Leake S A and Fienen M N 2018 Capture versus capture zones: clarifying terminology related to sources of Water to Wells *Groundwater* **56** 694–704

Bauer S, Olson J, Cockrill A, Hattem M, van, Miller L, Tauzer M and Leppig G 2015 Impacts of surface water diversions for marijuana cultivation on aquatic habitat in four northwestern california watersheds *PLoS One* **10** e0120016

Bredehoeft J D, Papadopulos S S and Cooper H H 1982 Groundwater: the water budget myth *Scientific Basis of Water Resource Management* (Washington, D.C.: National Research Council) vol 51, pp 51–7 Online (https://nap.edu/read/19530/chapter/7)

Breyer B, Chang H and Parandvash G H 2012 Land-use, temperature, and single-family residential water use patterns in Portland, Oregon and Phoenix, Arizona *Appl. Geogr.* **35** 142–51

Butsic V and Brenner J C 2016 Cannabis (Cannabis sativa or C. indica) agriculture and the environment: a systematic, spatially-explicit survey and potential impacts *Environ. Res. Lett.* **11** 044023

Butsic V, Carah J K, Baumann M, Stephens C and Brenner J C 2018 The emergence of cannabis agriculture frontiers as environmental threats *Environ. Res. Lett.* **13** 124017

Butsic V, Schwab B, Baumann M and 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

CA Department of Water Resources 2016 *Bulletin 118, Interim Update 2016* Online (https://water.ca.gov/Programs/Groundwater-Management/Bulletin-118)

Carah J K *et al* 2015 High time for conservation: adding the environment to the debate on marijuana liberalization *BioScience* **65** 822–9

CA State Water Resources Control Board 2017 *Cannabis Cultivation Policy: Principles and guidelines for cannabis cultivation* (https://waterboards.ca.gov/board_decisions/adopted_orders/resolutions/2017/final_cannabis_policy_with_att_a.pdf)

CA State Water Resources Control Board 2019a *California Electronic Water Rights Information Management System* (https://waterboards.ca.gov/waterrights/water_issues/programs/ewrims/)

CA State Water Resources Control Board 2019b *Urban Water Supplier Monitoring Reports* Online: (https://drinc.ca.gov/drinc/)

Corva D 2014 Requiem for a CAMP: The life and death of a domestic US drug war institution *International Journal of Drug Policy* **25** 71–80

Dillis C, Grantham T E, McIntee C, McFadin B and Grady K 2019a Watering the Emerald Triangle: Irrigation sources used by cannabis cultivation in Northern California *California Agriculture* **73** 146–53

Dillis C, McIntee C, Grantham T E, Butsic V, Le L and 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 (https://doi.org/10.1101/618934)

Dralle D N, Hahm W J, Rempe D M, Karst N J, Thompson S E and Dietrich W E 2018 Quantification of the seasonal hillslope water storage that does not drive streamflow *Hydrol. Processes* **32** 1978–92

Feinstein D T, Fienen M N, Reeves H W and Langevin C D 2016 A Semi-Structured MODFLOW-USG Model to Evaluate Local Water Sources to Wells for Decision Support *Groundwater* **54** 532–44

Gato S, Jayasuriya N and Roberts P 2007 Temperature and rainfall thresholds for base use urban water demand modelling *J. Hydrol.* **337** 364–76

Gleeson T and Richter B 2018 How much groundwater can we pump and protect environmental flows through time ? Presumptive standards for conjunctive management of aquifers and rivers *River Res Applic* **34** 83–92

Glose T J, Lowry C S and Hausner M B 2019 Vertically integrated hydraulic conductivity: a new parameter for groundwater-surface water *Analysis Groundwater* **57** 727–36

Gräler B, Pebesma E and Heuvelink G 2016 Spatio-temporal interpolation using gstat *The R Journal* **8** 204–18

Greer G, Carlson S and Thompson S 2019 Evaluating definitions of salmonid thermal refugia using *in situ* measurements in the Eel River *Northern California Ecohydrology* **12** e2101

Grömping U 2006 Relative Importance for Linear Regression in R: The Package relaimpo *Journal of Statistical Software* **17** 1–27

Hengl T *et al* 2017 SoilGrids250m: global gridded soil information based on machine learning *PLoS One* **12** e0169748

Hengl T *et al* 2014 SoilGrids1km—Global Soil Information Based on Automated Mapping *PLoS One* **9** e105992

Huggins X, Gleeson T, Eckstrand H and Kerr B 2018 Streamflow Depletion Modeling: Methods for an Adaptable and Conjunctive Water Management Decision Support Tool *JAWRA Journal of the American Water Resources Association* **54** 1024–38

Hunt B 1999 Unsteady Stream Depletion from Ground Water Pumping *Ground Water* **37** 98–102

Jenkins C T 1968 Techniques for Computing Rate and Volume of Stream Depletion by Wells *Ground Water* **6** 37–46

Kollet S J and 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) *J. Hydrol.* **281** 96–114

Larsen L G and Woelfle-Erskine C 2018 Groundwater is key to salmonid persistence and recruitment in intermittent Mediterranean-climate streams *Water Resour. Res.* **54** 8909–30

Lindeman R H, Merenda P F and Gold R Z 1979 *Introduction to Bivariate and Multivariate Analysis* (Glenview, Ill: Scott Foresman & Co)

McGourty G, Lewis D J, Harper J, Elkins R, Metz J, Nosera J, Papper P and Sanford R 2013 Meeting irrigated agriculture water needs in the Navarro River Watershed (Ukiah, California: University of California Cooperative Extension Mendocino County) Online (http://cemendocino.ucanr.edu/files/166809.pdf)

Mendocino County Water Agency 2010 *Water Supply Assessment for the Ukiah Valley Area Plan* (California: Ukiah)

Nathan R J and McMahon T A 1990 Evaluation of automated techniques for base flow and recession analyses *Water Resour. Res.* **26** 1465–73

National Marine Fisheries Service 2012 *Final Recovery Plan for Central California Coast coho salmon Evolutionarily Significant Unit* (Santa Rosa, CA: National Marine Fisheries Service, West Coast Region)

National Marine Fisheries Service 2016 *Coastal Multispecies Recovery Plan* (Santa Rosa, CA: National Marine Fisheries Service, West Coast Region)

North Coast Regional Water Quality Control Board 2005 *Watershed Planning chapter* (CA: Santa Rosa) Online (https://waterboards.ca.gov/northcoast/water_issues/programs/wpc/wpc.pdf)

Owley J 2017 *Unforeseen Land Uses: The Effect of Marijuana Legalization on Land Conservation Programs* (Rochester, NY: Social Science Research Network) Online (https://papers.ssrn.com/abstract=3025416)

Polson M 2018 *Marketing Marijuana: Prohibition, Medicalisation and the Commodity. Economy, Crime and Wrong in a Neoliberal Era* ed J Carrier (New York: Berghahn Books)

Raphel R 1985 Cash crop: An American dream *Ridge Times Press*

R Core Team 2019 *R: A Language and Environment for Statistical Computing* (Vienna: Austria: R Foundation for Statistical Computing) Online (https://R-project.org/)

Reeves H W, Hamilton D A, Seelbach P W and Asher A J 2009 *Ground-water-withdrawal component of the Michigan water-withdrawal screening tool* (Reston VA: U.S. Geological Survey) Online (https://pubs.usgs.gov/sir/2009/5003/)

Short Gianotti A G, Harrower J, Baird G and Sepaniak S 2017 The quasi-legal challenge: assessing and governing the environmental impacts of cannabis cultivation in the North Coastal Basin of California *Land Use Policy* **61** 126–34

Spence B C, Bjorkstedt E P, Garza J C, Smith J J, Hankin D G, Fuller D, Jones W E, Macedo R, Williams T H and Mora E 2008 *A framework for assessing the viability of threatened and endangered salmon and steelhead in the North-Central California Coast Recovery Domain* (California, USA: US Department of Commerce, National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Southwest Fisheries Science Center Santa Cruz)

Stoa R B 2015 Weed and Water Law: Regulating Legal Marijuana *Hastings L.J.* **67** 565–622

Su G W, Jasperse J, Seymour D, Constantz J and Zhou Q 2007 Analysis of pumping-induced unsaturated regions beneath a perennial river *Water Resour. Res.* 43W08421 Online (https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2006WR005389)

The Inkscape Team 2015 *Inkscape* Online (https://inkscape.org/en/)

Welsh H H, Hodgson G R, Harvey B C and Roche M F 2001 Distribution of juvenile coho salmon in relation to water temperatures in tributaries of the Mattole River, California *North American Journal of Fisheries Management* **21** 464–70

Wickham H 2009 *ggplot2: Elegant Graphics for Data Analysis* (New York: Springer) Online (http://ggplot2.org)

Wilson H, Bodwitch H, Carah J K, Daane K, Getz C, Grantham T E and Butsic V 2019 First known survey of cannabis production practices in California *California Agriculture* **73** 119–27

Zipper S C 2019 *streamDepletr: Estimate Streamflow Depletion Due to Groundwater Pumping* Online: (https://CRAN.R-project.org/package=streamDepletr)

Zipper S C, Dallemagne T, Gleeson T, Boerman T C and Hartmann A 2018 Groundwater pumping impacts on real stream networks: testing the performance of simple management tools *Water Resour. Res.* **54** 5471–86

Zipper S C, Gleeson T, Kerr B, Howard J K, Rohde M M, Carah J and Zimmerman J 2019a Rapid and accurate estimates of streamflow depletion caused by groundwater pumping using analytical depletion functions *Water Resour. Res.* **55** 5807–29

Zipper S C, Helm Smith K, Breyer B, Qiu J, Kung A and Herrmann D 2017 Socio-environmental drought response in a mixed urban-agricultural setting: synthesizing biophysical and governance responses in the Platte River Watershed, Nebraska, USA *Ecology and Society* **22** Online (https://ecologyandsociety.org/vol22/iss4/art39/)

Zipper S C *et al* 2019b Balancing Open Science and Data Privacy in the Water Sciences *Water Resour. Res.* **55** 5202–11