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Vulnerability of an Endangered Amphibian to Climate-Change Induced Hydrologic Change

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ABSTRACT

Climate change significantly affects precipitation patterns at multiple scales, which influences river and other hydrologic flow regimes. However, the impacts of climate-driven changes to hydrologic regimes on the vulnerability of species associated with riparian areas remain largely unexplored. Not considering the effect of flow alteration compromises the ability to identify and protect critical habitat areas. We developed a species distribution model to predict the distribution of an endangered amphibian (arroyo toad, *Anaxyrus californicus*) under current and future climate-impacted flow scenarios to better understand its vulnerability to altered conditions. The current modeled distribution of the arroyo toad was compared to models that estimated flows altered through stochastic changes in air temperature and precipitation associated with climate change. To analyze vulnerability, we investigated disparities in elevation, range size, range overlap, protected range, and predicted probability of occurrence. The study identified key flow metrics associated with toad habitats, emphasizing a negative relationship with most, aligning with arroyo toad breeding requirements. Vulnerability assessments demonstrated a potential reduction in toad range and shifts in elevational range potentially due to climate-induced flow alterations. Our study underscores the importance of managing altered flow to support freshwater ecosystems, allowing managers to prioritize conservation efforts, protect vulnerable streams, and address problematic areas. However, additional factors like geomorphology and human activities also play significant roles, suggesting the need for diverse management strategies.

1 | Introduction

Anthropogenic climate change poses global challenges, in part due to the reshaping of precipitation patterns across the planet (Madakumbura et al. 2021; Marvel and Bonfils 2013; Zhang et al. 2007). In semi-arid landscapes like Southern California, substantial interannual variations in precipitation are a defining characteristic of the historic precipitation regimes (Dettinger 2011; Mitchell and Blier 1997; Dettinger et al. 2011) and local biota have evolved in the context of these variations (Dettinger 2011; Jennings et al. 2018). However, climate projections suggest a significant shift in these patterns due to increasing temperatures (Berg et al. 2015; Berg and Hall 2015; Duffy et al. 2006; Hayhoe et al. 2004; Pierce et al. 2013) likely leading to rapid swings in extreme events. Longer dry periods and more intense wet seasons are expected to heavily impact river flow regimes (Arnell and Gosling 2013; Döll and Zhang 2010) potentially increasing the frequency and severity of droughts (Diffenbaugh et al. 2015) and altering the timing and intensity of peak flows.

Potential effects of climate-driven flow changes on the vulnerability of stream-dependent endangered species remain relatively underexplored. Consequently, habitat protection primarily centers on criteria such as vegetation community, substrate, and stream gradient, often without substantial consideration of flow. Moreover, flow management amid future alterations associated with climate change is poorly understood (Rogers et al. 2021). Neglecting these factors might compromise the necessary protection for an endangered species, potentially omitting portions of its distributional range from consideration both presently and in the future, and potentially even undermining ongoing conservation efforts. Understanding and addressing climate-related flow alteration is therefore vital for informed decision-making regarding the conservation of vulnerable aquatic and semi-aquatic species (Foden et al. 2019; Jones et al. 2016). In addition, implementing flow management in critical areas could improve the resilience of endangered species habitats (Mathwin et al. 2021; Yackulic et al. 2022) affected by climate change.

The arroyo toad (*Anaxyrus californicus*) is native and endemic to Southern California and listed as endangered under the Federal Endangered Species Act (USFWS 1994; Jennings and Hayes 1994; Sweet 1992). Adults are fully terrestrial; however, the species depends on specific aquatic habitat conditions for breeding and development. They are associated with sandy, generally ephemeral pools with slow-moving, shallow flow in low-gradient streams, often utilizing stream terraces and sand bars (Cunningham 1964; Sweet 1992; Sweet and Sullivan 2005). These conditions are created historically by natural flow regimes with scouring flood events (Jennings and Hayes 1994). Consequently, the toad is highly vulnerable to prolonged drought (Bucciarelli et al. 2020; Fisher et al. 2018; Hitchcock et al. 2022; Miller et al. 2018) that may reduce the presence of suitable pools driven through the different characteristics of the seasonal flow regime, for example, spring recession and summer baseflow to provide habitat, and winter peak flows for scouring events. There is also a relationship between drought and flow and the presence of invasive aquatic species, with a benefit to the toad if there are drought events that cause the local extirpation of these invasive aquatic species (Miller et al. 2012).

Arroyo toads' susceptibility to extended drought and reliance on periodic flooding make them particularly vulnerable to impacts of climate change (Thomson et al. 2016). This vulnerability renders them an ideal model species for evaluating how climate change-driven hydrologic alterations impact a riparian-associated amphibian. Like most threatened or endangered species habitat loss is the toad's greatest threat. The critical habitat designation and toad recovery plan established by the U.S. Fish and Wildlife Service in the 1990s (USFWS 1999, 2011) describe the toad's reliance on natural flooding patterns and the adverse effects of flow modification on toad populations. Previous studies concerning toad habitat have described the influence of direct climate factors, that is, air temperature and precipitation, or have focused on flow modification from specific dam locations or invasive beavers (Hitchcock et al. 2022; Madden-Smith et al. 2003; Richmond et al. 2021). However, these documents do not include the potential threat or impacts of climate change on stream flow.

Assessing the toad's predicted probability of occurrence under current and future scenarios allows for an understanding of its susceptibility to future climate-related flow conditions. Comparing differences in regional-scale distributional predictions between present and future scenarios provides insights into the species' vulnerability, offering a basis to understand how alterations in flow conditions due to climate change might impact its habitat and distribution. These assessments require robust predictive models that can accurately predict toad distribution according to physical drivers. Previous research has modeled the suitability of riparian habitats locally, primarily focusing on landscape, topographic, and recent climatic factors (Treglia et al. 2015, 2018). While that research included remotely sensed variables that can be tied to hydrologic flows (e.g., greenness and wetness indices), directly incorporating metrics related to flow and flow alteration should yield more robust models relating directly to the species' biology. These factors are needed to adequately address the toad's conservation needs and accurately identify critical habitat to inform management decisions, for example, priority protection: omission of specific flow-related variables may ultimately contribute to inaccurate predictions of how toad distribution may shift with changing physical conditions. Therefore, incorporating seasonal flow alteration variables is crucial for ensuring comprehensive and accurate assessments that inform effective long-term conservation strategies.

Species distribution models (SDMs) are crucial tools in assessing climate change impacts on species distribution and have played a significant role in guiding decisions in endangered species conservation (Pearson and Dawson 2003; Guisan et al. 2013). Utilizing environmental variables, SDMs identify key factors influencing habitat suitability and distribution patterns, providing valuable insights for prioritizing protection or restoration efforts in areas undergoing climate-induced habitat changes. Moreover, SDMs can forecast species distributions under varied scenarios, allowing for an understanding of potential range shifts due to climate-induced alterations in flow. Our study aims to expand upon the SDMs developed by Treglia et al. (2015, 2018) by incorporating such variables, resulting in models more directly linked to the species' life history, thus enhancing the model's predictive capacity. Given flow-dependent habitat requirements for toads, we predict that flow will be a more influential predictor of future distribution than land use characteristics.

We developed a broad scale SDM to predict the distribution of arroyo toad and compared changes to the predicted distributional range under current and future climate-related seasonal flow alteration.

Our research questions were: (1) What is the probability of occurrence of arroyo toad under current flow conditions? (2) How much influence does flow (across different seasons) have on arroyo toad relative to other factors? (3) How vulnerable are arroyo toad to future changes in flow, based on changes in distributional range, and (4) Which areas in the region may be most impacted by altered flow in the future?

2 | Methods

We developed a SDM to predict the probability of occurrence of arroyo toad to habitat-related variables describing flow, catchment, and landscape characteristics. The SDM was adapted from Treglia et al. (2015) using updated physical and

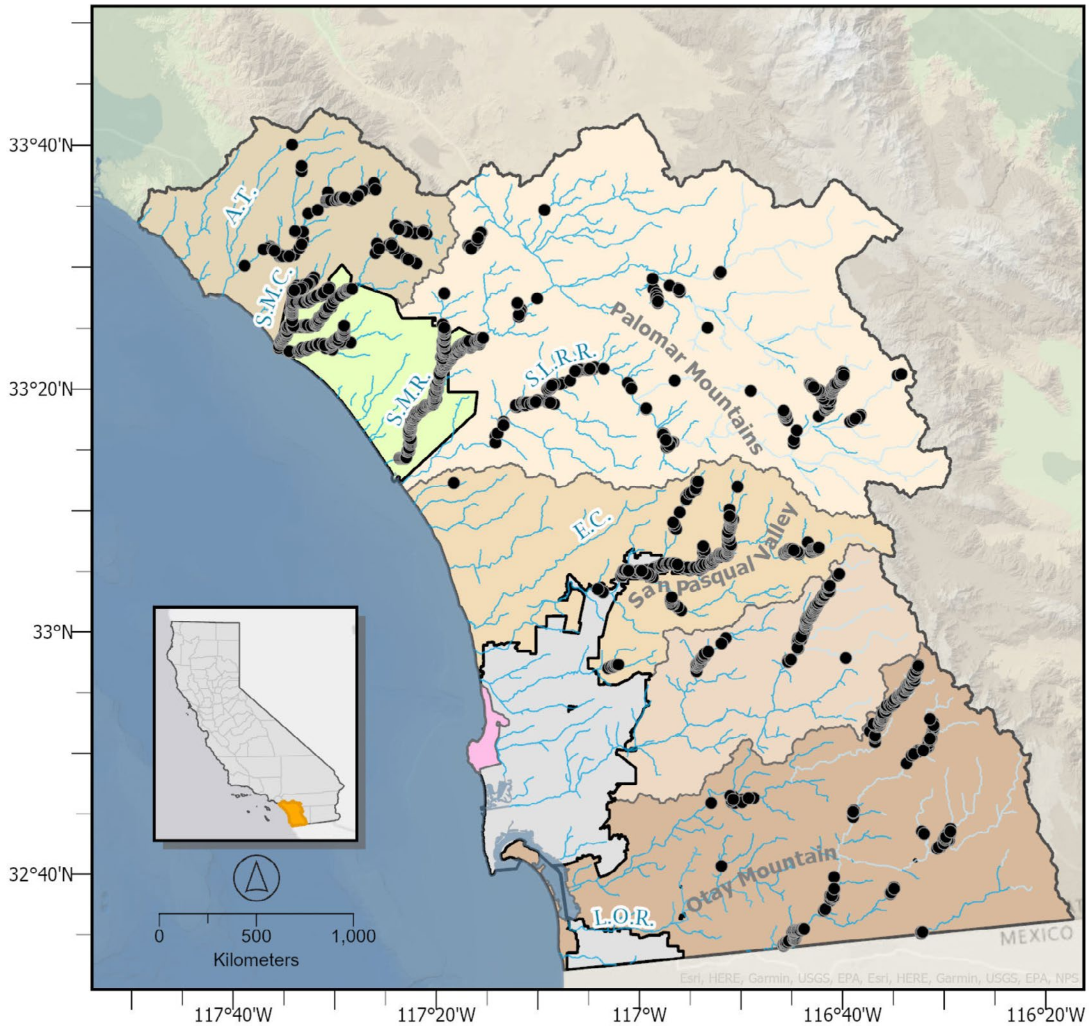

FIGURE 1 | Map of arroyo toad observations in RB9 region between 1990 and 2014 and associated hydroperiod monitoring reference sites. Inset box with location in California. Green polygon is Camp Pendleton, Blue polygon is City of San Diego, Pink polygon is La Jolla. Abbreviated waterbodies: AT; Arroyo Trabuco, EC; Escondido Creek, LOR; Lower Otay River, SLRR; San Luis Rey River, SMC; San Mateo Creek, SMR; Santa Margarita River. Beige polygons represent areas of San Diego county, from North to South: San Juan, Northern San Diego, Central San Diego, Mission Bay and San Diego River, and Southern San Diego. [Color figure can be viewed at wileyonlinelibrary.com]

biological data along with functional flow metrics (FFM), which describe components of the natural flow regime essential for the ecological, geomorphic, or biogeochemical functions that support native aquatic species in California (Yarnell et al. 2015, 2020). We compared arroyo toad predicted distribution under existing and future flow scenarios, driven by changes in air temperature and precipitation. To analyze vulnerability, we investigated disparities in elevation, range size, range overlap, protected range, and predicted probability of occurrence of arroyo toads under current and future climate scenarios.

2.1 | Study Area

We focused on the greater San Diego region as our study area, situated in Southern California (Figure 1). The region supports some of the largest populations of arroyo toads known to be remaining and is thus an important area for the survival of the species. Covering approximately 10,000 km^2 in the southwest corner of California, the region is bordered by the Pacific Ocean to the west, the Elsinore Mountains, and Peninsular Ranges to the north and east, and the United States-Mexico border to the south. It includes most of San Diego County, parts of southwestern Riverside County, and southwestern Orange County (San Diego Water Board 2021). The region supports diverse landscape characteristics encompassing coastal areas, mountain ranges, and semi-arid regions. Continued urbanization has led to increased surface imperviousness and population growth. There are thirteen primary stream systems that originate in the western highlands and flow towards the Pacific Ocean, which range in flow types from perennial to ephemeral, as influenced by the region's variable rainfall distribution and the presence of surface water impoundments.

2.2 | Units of Analysis

The stream network for the region was based on the National Hydrography Dataset (NHD, https://www.usgs.gov/natio nal-hydrography). However, following the model from Treglia et al. (2015) we converted the network into a gridded base layer, with our unit of analysis ($200m^2 \times 200m^2$) as a gridded raster layer ($n = 16{,}023$ focal grid cells, $3204\,km^2$). All spatial analysis and mapping visualizations were created using R packages raster (version 3.6–26, Hijmans 2023), sf (version 1.0–16, Pebesma and Bivand 2023), and ggplot2 (version 3.5–1, Wickham 2016).

2.3 | Species Occurrence Data

Toad occurrence data were collated from several sources (Preston et al. 2022, San Diego Regional Board 2021, GBIF[1]), which supplemented the data from the previously developed model (Treglia et al. 2015). The data were collected through stream surveys mainly consisting of targeted day and nighttime visual and audio encounters and dip net techniques. Occurrences from San Diego Regional Board were collected through eDNA methods (San Diego Water Board 2021b). Despite variations in collection methods, the data were comparable in this context because only the presence of toads was used in model development that will be applied, as opposed to abundance or density.

All life stages associated with toad breeding (egg, tadpole, juvenile, and adult) require the same general habitat conditions; therefore, all were included in the analysis. To be temporally consistent with the physical data, including readily available climatic and streamflow data at the stream reach scale, only occurrence data observed between 1990 and 2014 were retained for analysis. In addition, all observation points outside 50 m of the stream network were removed to reduce spatial error.

2.4 | Physical Data

The focus of this study was to assess the relationship between altered hydrologic regimes and the distribution of the arroyo toad. Nonetheless, several additional habitat characteristics are critical in supporting toad habitat, for example, sandy substrate with a low gradient. We therefore included landscape variables describing soil, topography, and geomorphology. All variables are described in Table 1 (adapted from Treglia et al. 2015) and were updated to match the spatial extent of the current model. Where layers started with 10 m raster data, we used the nearest neighbor resampling method found in ESRI's ArcPro to resample the data to a 200 m raster. Importantly, the Landsat TM remote sensing data (greenness, wetness, and brightness, Table 1) were extracted from multiple days due to cloud cover, combining calculations from September 5th, 23rd, and 30th 2014 to represent the dry season and April 7th, 14th, and 16th 2014 to represent the wet season. All remaining landscape variables were sourced and calculated in the same manner as outlined by Treglia et al. (2015). On occasion, some variable values could not be calculated for certain grid cells; these were removed prior to analysis. While acknowledging that climate, such as air temperature and precipitation, significantly influences toad distribution (Bucciarelli et al. 2020; Miller et al. 2018), we deliberately excluded these variables from our analysis. The rationale behind this decision was that incorporating direct climate measures would increase model complexity, creating difficulties in interpreting the direct impact of flow alteration on toad habitat. Instead, we indirectly incorporated climate influence through climate-derived flow metrics and scenarios.

2.4.1 | Functional Flow Metrics

To incorporate flow, we used FFM as predictors in the SDM. These metrics describe various seasonal components of the annual hydrograph (Yarnell et al. 2015, 2020) and form the foundation of the California Environmental Flows Framework (CEFF; Stein et al. 2021; Taniguchi-Quan et al. 2022), which is the basis of most flow management in California. Altogether, there are 24 individual metrics that describe various aspects of streamflow across five functional flow components (Peak flows, dry-season baseflow, wet-season baseflow, fall pulse flows, and spring recession flow) identified for California streams. FFM describing magnitude ($n = 9$, Table 1) of flow were available for 2116 NHD reaches in the San Diego region, excluding small upper tributaries with watersheds less than ~$1\,km^2$ to prevent overextrapolation (1990–2014, Taniguchi-Quan et al. 2022). In brief, random forest (RF) algorithms were used to predict change in functional flow magnitude from reference to current conditions (i.e., delta (Δ) FFM) for NHD river segments. The algorithm establishes the relationship of climate data and natural and human-impacted catchment descriptors to the change in FFM from the expected reference condition (Grantham et al. 2022). The RF models were built using 429 USGS gage data from across California to ensure sufficient training data and applied to NHD stream segments in the San Diego region. For more details on the input data and hydrologic modeling approach, see Supporting Information S2. We used the delta (Δ) FFM as a measure of flow alteration to evaluate its impacts on toad distribution. Given the habitat requirements of the toads, fall pulse flows together with peak flows are expected to play a critical role in scouring and reshaping habitats, while spring recession will be critical for exposing suitable habitat in spring. Similarly, dry season baseflows are likely essential in maintaining adequate flows during the breeding season. To spatially align these metrics from NHD reach scale to the landscape variables in 200 m gridded format, they were converted to a gridded raster layer in ARCGIS Esri Inc. (2022). ArcGIS Pro (Version 3.0).[2] This resulted in repeated FFM values for every grid located in the same reach. Due to discrepancies in spatial resolution, several reaches could not be spatially matched to all physical data inputs. Therefore, the model was built with 1865 NHD reaches (n cells = 16,023).

2.4.2 | Climate-Induced Flow Alteration Predictions

A climate change vulnerability assessment was conducted to evaluate how potential changes in precipitation and air temperature may affect FFM and arroyo toad distributions. This assessment was comprised of developing future climate change scenarios for input into the toad SDM.

To develop the future scenarios, we conducted a climate stress test for every stream reach (Fowler et al. 2024) where we imposed perturbations to the historical monthly timeseries (1950–2014, PRISM Climate Group, Oregon State University, https://prism.oregonstate.edu) used as input into the hydrologic RF models. The range of changes used in the stress test was bracketed from

TABLE 1 | All variables applied in the random forest model, with names and abbreviations (if applicable), description, and source.

Name (Abbreviation)	Description	Value used	Source
Soil data			
% Clay; % sand; % silt; soil water storage capacity	Weighted average of values per soil type across all soil layers, obtained from 1:250,000 scale soil data	Average, weighted by area of each soil type per analysis grid	Derived from STATSGO2 Soil Data, produced by the Natural Resources Conservation Service, U.S. Dept. of Agriculture[a]
Topography and geomorphology			
Elevation along stream segment	Estimated as lowest elevation	Calculated value per analysis grid	Calculated value per 10 m National Elevation Dataset (NED, Gesch 2007)[b]
% Stream slope	Estimated within each analysis grid cell using GIS data for elevation and streams	Value per analysis grid	Derived from 10 m NED overlaid on 1:24,000 National Hydrologic Dataset[c]
Multiresolution index of valley bottom flatness (MRVBF)	Measure of how flat and wide a valley is	Maximum value per analysis grid	Derived from 10 m NED using flatness (MRVBF) valley is. Analysis grid methodology described by Gallant and Dowling (2003)
Vector ruggedness measure (VRM03 and VRM18)	Measure of how rugged terrain is, based on, analysis windows of 3 and 18 grids from 10 m NED	Minimum values per analysis grid	Derived from 10 m NED using methodology described by Sappington et al. (2007)
Catchment area	Total area draining into a given analysis grid	Maximum value per analysis grid	Derived from sink-filled 10 m NED using methodology described by (Gruber and Peckham 2009)
Remotely sensed data			
Brightness (Med, Var); greenness (Med, Var); wetness (Med, Var)	Indices of "brightness," "greenness," and "wetness" for April 7th, 14th, and 16th and September 5th, 23rd, and 30th 2014	Median (Med) and Variance (Var) within analysis grid	Derived from Landsat TM imagery[d] using the Tasseled Cap Transformation (Crist and Cicone 1984) for Landsat data (NASA Landsat Program 2010)
Functional flow metrics			
Dry season baseflow, peak flow (10, 5-, and 2-year floods), spring recession, fall pulse, largest annual storm (Q99), winter baseflow (low and median) magnitude metrics	Median magnitude of flow alteration (change from reference expectations) from 1990 to 2014	Majority value per analysis grid	(Taniguchi-Quan et al. 2022)

Abbreviations: GIS, graphical information system; Med, median; MRVBF, multiresolution index of valley bottom flatness; NED, national elevation dataset; Q99, largest annual storm; Var, variance; VRM, vector ruggedness measure.
[a]Available from: http://soildatamart.nrcs.usda.gov/.
[b]Available from: https://apps.nationalmap.gov/viewer/.
[c]Available from: https://www.usgs.gov/national-hydrography/national-hydrography-dataset.
[d]Available from: https://www.usgs.gov/landsat-missions/landsat-data-access.

TABLE 2 | Future scenario names, description, and change values imposed on the historical climate timeseries.

Scenario	Change in P (%)	Change in T (C)	Change in P wet (%)	Change in P dry (%)
Baseline	0	0		
Wetter	20	0		
Drier	−20	0		
Hotter	0	+2		
Amplified extremes: Wet wetter, dry drier	0	0	20	−20
Large changes, drier/hotter	−20	+2		
Small changes, drier/hotter	−10	+1		
Large changes, wetter/hotter	20	+2		
Small changes, wetter/hotter	10	+1		
Large changes, amplified extremes/hotter	0	+2	20	−20
Small changes, amplified extremes/hotter	0	+1	10	−10

Note: For change in P 20%, for example, we added 20% precipitation to all monthly values in the historical timeseries.
Abbreviations: DRY, July to September; P, monthly precipitation; T, monthly mean air temperature; WET, December to February.

future climate change projections in the region from Cal-Adapt's database of Localized Constructed Analogs (LOCA) downscaled global climate models (GCM) at RCP 8.5 (https://cal-adapt.org/tools/annual-averages/): CanESM2 (which represents an average), CCSM4 (a warmer/drier model), CNRM-CM5 (cooler/wetter), and MIROC5 (most different from the others). From these GCMs, the percent change in the mean monthly climate from the baseline historical period of 1950–2014 to a future period of 2035–2100 was used to bracket the range of changes used in the stress test. For the climate stress test, we evaluated 3 climate stressors: (1) changes in monthly precipitation, (2) changes in monthly average temperature, and (3) amplified precipitation extremes where wet months get wetter and dry months get drier. For the first stressor, changes in monthly precipitation (+20% to −20%) were applied to all monthly precipitation values in the historical timeseries, and all summary statistics based on monthly precipitation used as input into the hydrologic models were updated. For the second stressor, changes in mean monthly temperature were applied as an absolute change, 0°C to +2°C, and all summary statistics based on monthly temperature were updated. To assess the scenarios of amplified precipitation extremes, monthly precipitation from the wet months of December to February was up to 20% wetter and from the dry months of July to September was up to 20% drier.

Although multiple combinations of changes in the three stressors can be evaluated, for the sake of simplicity, we selected the baseline (i.e., no change) and extreme scenarios (Table 2, Supporting Information S1, Table S1) for comparative analysis. The scaled monthly climate data were then compared to monthly precipitation and air temperature data used to train the hydrologic RF model to avoid over-extrapolation. Because the hydrologic RF model leverages gages across the state of California, there were spatial analogs in the training dataset outside of the San Diego region that experienced similar climatic conditions as the future scenarios being evaluated. However, at some reaches where the hotter scenarios exceeded temperatures from the training dataset, monthly air temperature was capped at the maximum monthly air temperature from the training dataset. Annual delta FFMs were predicted using the hydrologic RF model and projected monthly climate data, and the median delta FFM was taken for each scenario and stream reach from the reprojected years of 1990 to 2014.

2.4.3 | Critical Habitat and Protected Land

The designated critical habitat allocated for the arroyo toad was obtained as a Geographic Information System (GIS) layer from the California Department of Fish and Wildlife Biogeographic Information and Observation System (USFWS 2011). Protected land encompasses open space lands that have been protected for open space uses through fee ownerships and was obtained from the California Protected Land Areas Database (CPAD, www.calands.org, June 2023). In addition, Camp Pendleton,[3] a military base located on U.S. federal land, was added to the protected land area as the base is required to monitor and protect endangered species that occur on the base, including the arroyo toad population.

2.4.4 | SDMs

Our SDM was developed using a classification RF approach. RF is a machine learning algorithm that uses a decision tree process that, as applied in SDM work, classifies sites into a probability of achieving a binary outcome (i.e., presence, absence) by relating species occurrence or observation data to associated physical conditions in geographical space, and has been broadly used in this realm (Breiman 2001; Evans et al. 2011; Evans and

Cushman 2009; Oliveira et al. 2012). The model was built with 967 presence (occurrence) points and 977 absence points, which was a combination of both true absences and pseudo absence (or background) points. The pseudo absence points were calculated through a spatially explicit method based on kernel density surfaces (Fitzpatrick et al. 2013; Phillips et al. 2009) of the 200 m gridded stream network. To avoid bias within the model, we aimed to include approximately the same number of pseudo absence points (combined with true absence points) as observation points ($n = 967$, Barbet-Massin et al. 2012). The RF model was built with only grids containing a presence or absence ($n = 1944$) together with the corresponding physical data. All RF development was conducted using the randomForest package (Liaw and Wiener 2002) in R version 4.2.3 (R Core Team 2023).

2.4.5 | Multicollinearity and Model Criteria

Although RF models can deal with correlated variables in general, to avoid challenges with interpretation (Strobl et al. 2008; Toloşi and Lengauer 2011) we assessed the physical data for multicollinearity, removing any variables with a variance inflation factor (VIF) above 5 (James et al. 2013). Six variables were removed from the model due to multicollinearity: 5-year peak flow, Percent Silt, Wetness Median (April), Brightness Variance (April), Brightness Median (Sept) Greenness Median (Sept). The remaining variables were included in the model with the following criteria: 10001 trees, 2 variables randomly sampled at each split, and a minimum node size of 5. The criteria were selected from pre-tuning the model and taking values that resulted in the highest model performance.

2.4.6 | Validation and Variable Importance

A classification RF includes an internal validation process, which calculates a misclassification rate (out-of-bag error, OOB) by training the model on a subset of the data at each tree and testing the predictions on the remaining data. To supplement this process, we validated the model by randomly dividing the input data into training and testing datasets in an 80/20 split. Through 10-fold cross validation, we derived four additional validation metrics describing how well the training data predicts the testing data: (1) Receiver operator curve (ROC) a threshold-independent measure of model performance with values > 0.8 considered as high performance (Swets 1988; Thuiller et al. 2005), (2a) sensitivity, and (2b) specificity measures that describe how well the model predicts toad presence and absence, respectively, with values ranging between 0 and 1 and a value of 0.5 being no better than random, and (3) true skills statistic (TSS), a combination of sensitivity and specificity that ranges from -1 to 1 with a value of > 0.6 considered as useful to excellent model performance. The OOB error rate from the internal validation process is expressed as a percentage; we converted the error rate to an accuracy rate by subtracting the difference from 100; therefore, higher values indicate higher accuracy.

To understand the individual influence of each physical variable, variable importance was extracted from the model and calculated as the mean decrease in accuracy if the variable were to be removed. We scaled the variable importance values and report as relative importance (%). Finally, using partial dependence plots, we determined the relationship between flow alteration and probability of occurrence for each FFM, reporting both the direction (positive or negative) and general guidance for flow management to support arroyo toads.

2.4.7 | Predicted Suitability

To ensure robust results and to minimize error, we ran the RF model ten times, which involved calculating a different set of pseudo absences and a different random data split for each model run (Cutler et al. 2007; Treglia et al. 2015). Each of the ten models were used to predict probability of occurrence separately across the region. The predicted probabilities, relative importance, validation, and accuracy measures were averaged across all models. To convert the probability of occurrence to binary presence/absence, we determined a probability threshold by maximizing the sensitivity and specificity (Liu et al. 2005, 2013) for each model run. This 0.535 threshold was then averaged across all models and applied in the final prediction. Validation metrics are reported as mean ± standard deviation. The predicted suitability was mapped together with designated critical habitat and protected land. Predicted occurrences of the arroyo toad within a 50 m buffer of designated critical habitat and protected land areas were counted and converted to percentage. We predicted probabilities of toad occurrence for all the chosen climate scenarios, which were averaged across all 10 models.

2.5 | Analysis of Vulnerability

We assessed the vulnerability of arroyo toad distribution to seasonal flow alteration by evaluating changes in its predicted distributional range under each climate scenario, comparing baseline and future scenarios across multiple parameters. To identify alterations in the toad's distribution, comparisons were made regarding the following metrics:

1. Range size: Determined as the number of grid cells indicating a predicted presence for each scenario.
2. Range overlap: Quantified as the percentage of grid cells portraying a predicted presence shared by both baseline and individual future scenarios.
3. Range elevation: Defined as the difference in elevation of predicted presences between current and future conditions, calculated by averaging elevation values from Table 1 across all grid cells that indicated a predicted presence. Statistical *t*-tests, after log transformation of parameters to meet normality assumptions, were employed to assess differences in mean elevation between current and future predicted presences of arroyo toad.
4. Protected range: Computed by tallying binary presence predictions within designated critical habitat and protected land, presented as a percentage.
5. Change in predicted probability: Calculated by contrasting the probability of occurrence in each future scenario with predictions from the baseline condition. Categories were established based on probability shifts: increased (more than

0.05), decreased (more than 0.05), or remained unchanged (i.e., no more or less than a 0.05 change) from baseline. The value 0.05 was chosen as it was ecologically meaningful and useful for management, it being well above the typical variation (0.023 median standard deviation) of the dataset, making it useful for comparison between scenarios.

Predicted probabilities were transformed into binary presence/absence using a consistent probability threshold as described for the current predicted suitability. These measures collectively portray the arroyo toad's vulnerability concerning deviations from baseline predictions. Additionally, the assessment of changes in predicted probabilities highlights geographical regions most vulnerable to alterations in flow.

TABLE 3 | Mean validation metric of 10 models ± standard deviation, with values denoting high performance.

Validation metric	Value	High performance values[a]
Out of bag error (−100) (%)	84.8 ± 0.55	Higher = better accuracy
Receiver operator curve	0.91 ± 0.006	> 0.8
Sensitivity	0.85 ± 0.01	> 0.5
Specificity	0.83 ± 0.01	> 0.5
True skills statistic	0.68 ± 0.02	> 0.6

[a]See methods section for associated justification and references.

To understand the role of flow alteration to changes in the toad's distributional range, we conducted a comparative analysis of the values of each FFM corresponding to the predicted range. Statistical *t*-tests were performed (as above) to determine the differences in FFM values between the baseline and each flow scenario. It is important to clarify that this assessment was not conducted as a measure of vulnerability. Instead, its primary purpose was to understand the role of flow alteration in driving changes in the toad's distributional range.

3 | Results

3.1 | Model Performance and Validation

Overall, the RF model performed well for all validation metrics (Table 3). These results indicate that the model had high predictive power according to the performance criteria set.

3.2 | Variable Importance

The relative importance of all variables is illustrated in Figure 2. From the most important 10 variables, 7 described hydrological alteration (FFM), with Fall Pulse flow being the most important overall. These results indicate that the flow alteration metrics are highly influential in the distribution of arroyo toads. Additionally, elevation together with percent sand and clay was the most important landscape variable, underscoring the importance of predominant substrate and physical conditions on the distribution of arroyo toads. All FFM, except for the variable magnitude of largest annual storm, showed a negative relationship with probability of occurrence (Table 4).

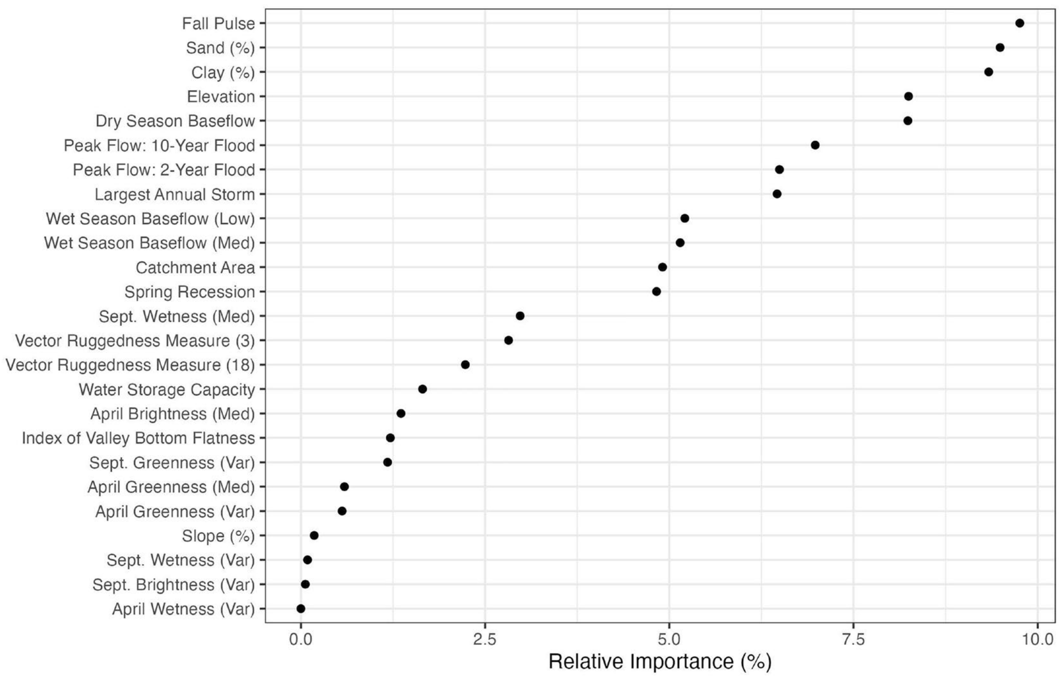

FIGURE 2 | Mean relative importance of each individual metric calculated from 10 random forest models as the mean decrease in accuracy, converted to relative importance.

TABLE 4 | Flow alteration relationship and direction that tends to increase probability for arroyo toad sorted by relative importance of flow metrics based on partial dependence plots.

Functional flow metric	General guidance for arroyo toad	Direction of relationship (+/−)	Relative importance (%)
Fall pulse flow: Magnitude	Reduction tends to increase probability	−	10
Dry-season baseflow: Magnitude	Reduction tends to increase probability	−	8
Peak flow: Magnitude (10-year flood)	Reduction tends to increase probability	−	7
Peak flow: Magnitude (2-year flood)	Reduction tends to increase probability	−	6
Peak flow: Magnitude of largest storm (q99)	Increase tends to increase probability (variable)	+/−	6
Spring recession flow: Magnitude	Reduction tends to increase probability	−	5
Wet-season baseflow: Magnitude	Reduction tends to increase probability	−	5
Wet-season: Median magnitude	Reduction tends to increase probability	−	5

Note: Peak flow (10-year flood), spring recession, and dry-season baseflow magnitudes are the most influential flow metrics for arroyo toad. Increase and decrease are in relation to baseline condition, that is, 0 delta.

3.3 | Predicted Suitability

The mean probability of arroyo toad occurrence across all ten models is shown in Figure 3a. High probabilities are mostly evident in low gradient and more natural locations such as San Mateo Creek and Santa Margarita River in the Camp Pendleton area, as well as San Luis Rey River. These areas correspond to the toad observations in Figure 1. Occasionally, areas with zero or very few observations are predicted as high probability, for example, Lower Otay River and less developed sections of Arroyo Trabuco.

The binary threshold, established at 0.535 by optimizing sensitivity and specificity, was applied to convert probabilistic predictions into outcomes of presence (1) and absence (0). The analysis revealed a total range size of 2234 grids (447 km^2) indicating presence across the current period of 1990 to 2014. Within this range, 1174 grids (235 km^2), constituting ~53% of occurrences, were situated within the confines of designated critical habitat, whereas 1060 grids (212 km^2, ~47%) lay outside these specified critical habitat areas Figure 3c. Furthermore, 1232 grids (246 km^2, ~55%) were predicted on protected land, whereas 1002 grids (200 km^2, ~45%) were predicted outside of protected land (Figure 3b). A total of 541 grids (108 km^2, ~24%) were predicted to occur in both critical habitat and protected land.

3.4 | Analysis of Vulnerability

All model scenarios predicted similar or reduced range sizes compared to the baseline ($n = 2234$, 447 km^2) projections (Table 5). The hotter scenario ($n = 697$, 139 km^2) as well as scenarios simulating large perturbations ($n = 421–842$, 84–168 km^2) yielded the smallest predicted range sizes. In contrast, the drier and amplified extremes scenarios yielded the largest and the most similar range size compared to the baseline projection ($n = 2298$ and 2256, respectively, 459 and 451 km^2). The hotter scenario as well as scenarios simulating large perturbations predicted the smallest overlap with baseline projections, mirroring the results from range size (Table 5). Conversely, the drier scenario and scenarios related to amplified extremes exhibited the largest predicted overlap with the baseline (94.45% and 95.93%, respectively).

The majority of modeled scenarios predicted toad occurrences at higher elevations compared to the baseline projection (Table 5). Only the wetter scenario predicted toad occurrences in significantly lower elevations (mean = 227.93 ± 5.97, $p = < 0.001$). The predictions through drier, amplified extremes and wetter/hotter (small changes) scenarios did not show significantly different elevations from baseline (Table 5). All other scenarios predicted toads in significantly higher elevations, with the scenario simulating the hotter scenario yielding predictions in the highest elevations (mean = 413.42 ± 15.84, $p = 0.01$).

Critical habitat (n cells = 2, 846) and protected land (n cells = 7077) overlapped by 1361 cells (15.9%). This overlap represents 47.8% of the critical habitat area and 19.2% of the protected land area. The baseline scenario predicted ~53% of toad occurrence within the boundaries of designated critical habitat and ~55% within the boundaries of protected land (Table 5). The proportion of toad occurrences predicted varied

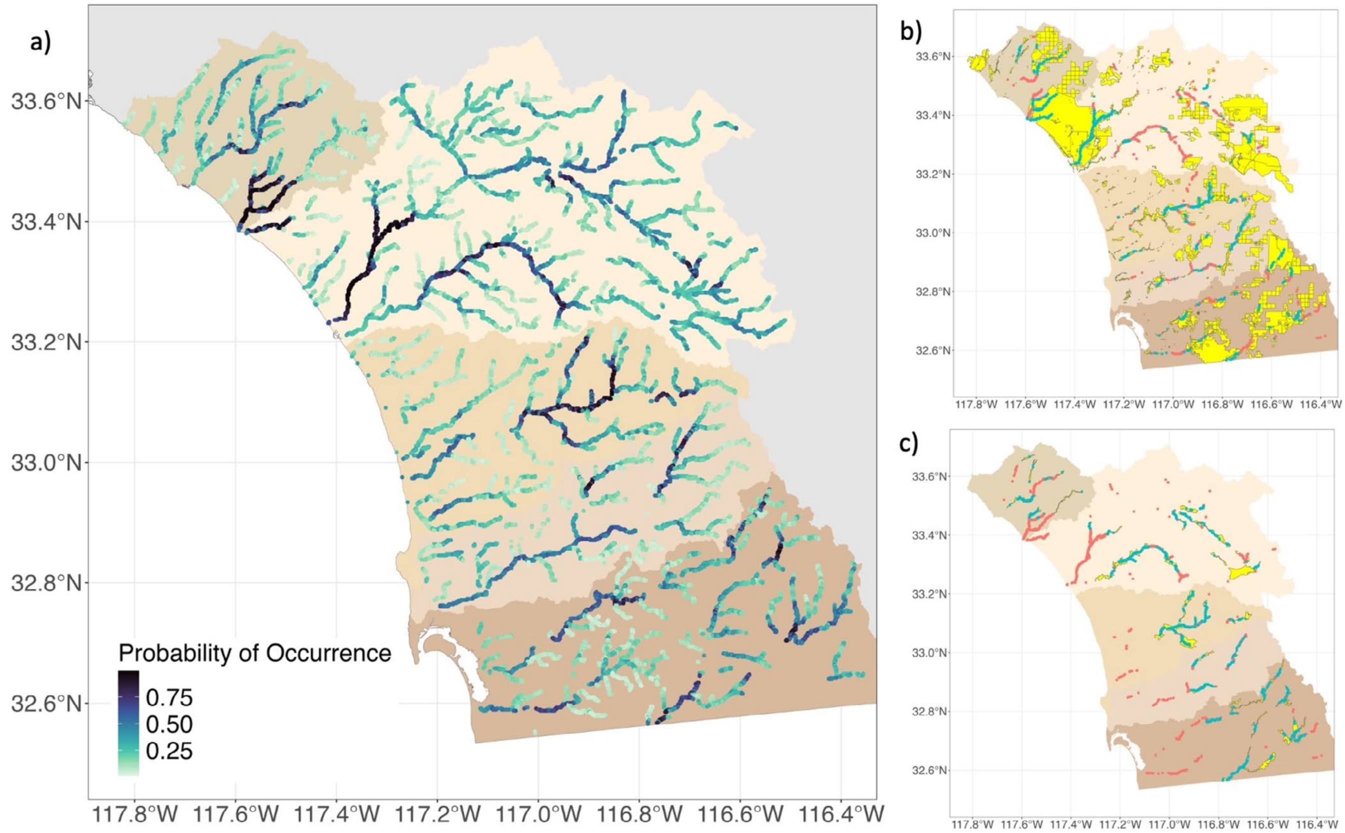

FIGURE 3 | Arroyo toad predicted suitability under current conditions in San Diego region (a) mean probability of occurrence, (b) within protected land, (c) within critical habitat. Blue dots = within boundary, red dots = not within boundary. Beige polygons represent areas of San Diego county, from North to South: San Juan, Northern San Diego, Central San Diego, Mission Bay and San Diego River, and Southern San Diego. [Color figure can be viewed at wileyonlinelibrary.com]

among future scenarios from ~42% to ~58% within critical habitat, and from ~55% to ~70% within protected land. Under the drier scenario, the proportion of predicted occurrences as well as the number of occurrences were the most similar to baseline within critical habitat and protected land. Generally, 50%–60% of presences were predicted on critical habitat for most scenarios, a pattern mirrored on protected land. One exception was the proportion of toad occurrences predicted by the wetter/hotter (large changes) scenario, which predicted the lowest proportion on critical habitat and the highest on protected land. However, this scenario predicted the lowest range size overall ($n = 421$).

Change in predicted probability of occurrence was most evident under the hotter scenarios and all large perturbation scenarios, especially in cases when probability of occurrence was predicted to reduce (Figure 4). Reduced predicted probability of occurrence under these scenarios was similarly distributed, including in more coastal areas such as the urbanized areas near the City of San Diego and the Otay mountains close to the USA-Mexico border. Additionally, reduced probability of occurrence tended to be close to areas of high probability predicted under current conditions (Figure 3) and known occurrences (Figure 1), such as Camp Pendleton, San Mateo Canyon, and San Pasqual Valley. Reduced probability of occurrence was predicted in Escondido Creek; however, this area was predicted with low probability and no recorded toad observations (Figure 1). Increased probability of occurrence tended to be in the Palomar Mountain region, more coastal areas of San Luis Rey, and mountain regions close to the border. These patterns were similarly reflected under scenarios simulating small changes, although to a comparatively lesser degree (Figure 4). The drier, wetter, and amplified extremes scenarios predicted minimal change in probability, displaying small, isolated areas (see Supporting Information S1, Figure S1).

3.4.1 | Future Flow Conditions

Overall, FFM for all scenarios showed that flow augmentation was associated with toad occurrence, except for peak flows (10- and 2-year, largest annual storm, Figure 5), which exhibited depletion associated with toad occurrence. The predicted toad range under the baseline scenario indicates very low flow alteration, aligning with our expectations (Figure 5). Occurrences of toads, as predicted under the wetter, drier, and amplified extremes scenario, most closely mirrored the altered flow patterns to those predicted in the baseline scenario (Figure 5, Table 5, Supporting Information S1, Table S2); however, some FFM were significantly different from baseline. This observation underscores a notable similarity in functional flows between these scenarios, mirrored by their similar range sizes and high range overlap. Notably, predictions for toad occurrences under all other scenarios indicated significantly augmented (i.e., higher than baseline, positive delta) flows across the non-peak FFM, coupled with an increase in elevation. Scenarios simulating

TABLE 5 | Summary statistics and tests of difference of arroyo toad predicted presence: Mean ± standard error of elevation, T statistic (T), degrees of freedom (DF), and *p* value (*p*) of *t* tests assessing the differences in elevation, range size (*n*) under each future scenario, and range overlap of each scenario with baseline.

Scenario	Mean	T	DF	*p*	Range size	Range overlap	Critical habitat	POB	Protected land	POB
Baseline	296.39 ± 6.73				2234		52.55 (1174)		55.15 (1232)	—
Wetter	227.93 ± 5.97	0.48	1324.49	< 0.001	1908	81.83	49.74 (949)	80.83	54.93 (1048)	85.06
Drier	299.13 ± 6.75	1.25	1274.06	0.74	2298	94.45	51.31 (1179)	100.43	53.96 (1240)	100.65
Hotter	413.42 ± 15.84	8.59	1188.88	0.01	697	29.23	55.81 (389)	33.13	62.55 (436)	35.39
Amplified extremes	304.54 ± 6.86	0.86	1314.93	0.54	2256	95.93	51.95 (1172)	99.83	54.26 (1224)	99.35
Small changes, drier/hotter	343.88 ± 8.86	4.60	1303.55	< 0.001	1596	65.94	56.64 (904)	77.00	55.33 (883)	71.67
Large changes, drier/hotter	372.76 ± 13.71	8.97	1229.99	0.08	842	34.96	58.19 (490)	41.74	56.06 (472)	38.31
Small changes, wetter/hotter	311.86 ± 9.47	4.13	1287.81	0.64	1325	55.82	58.11 (770)	65.59	56.75 (752)	61.04
Large changes, wetter/hotter	314.05 ± 19.57	8.74	1171.70	< 0.001	421	18.71	41.81 (176)	14.99	70.31 (296)	24.03
Small changes, amplified extremes/hotter	336.91 ± 9.15	4.80	1306.80	0.01	1522	63.61	56.83 (865)	73.68	56.37 (858)	69.64
Large changes, amplified extremes/hotter	409.01 ± 15.61	8.91	1222.84	0.01	696	29.10	53.01 (369)	31.43	61.49 (428)	34.74

Note: Proportion (%, number of occurrences in brackets) of arroyo toad presences predicted within designated critical habitat and protected land under baseline and future scenarios, with proportion of baseline predicted occurrences (POB) predicted by each climate scenario.

FIGURE 4 | Change in predicted probability of arroyo toad occurrence from baseline scenario to most the future climate scenarios with the most impact in the San Diego region. Change is denoted by any difference of 0.05 or more. See Figure S1 for change in predictions under scenarios Wetter, Drier and Amplified extremes. [Color figure can be viewed at wileyonlinelibrary.com]

large changes, as well as the hotter scenario, showed the greatest differences in FFM from baseline (Figure 5, Supporting Information S1, Table S2), which highlights the spatial differences in predictions reflected in smaller range sizes and range overlap. In other words, about 70% of predicted presences, which do not overlap with the baseline, have significantly augmented FFM and occur at higher elevations.

4 | Discussion

4.1 | Current Suitability and Influence of Flow Alteration

Our study shows that climate-related flow alteration is likely to affect arroyo toad habitat and its future distribution. From our 16,023 grids, 2234 (13.9%) were predicted as suitable habitat under current conditions, which is similar to the ~14% findings of Treglia et al. (2015). Approximately half of the predicted occurrences were contained within protected land or within designated critical habitat. Under current conditions, the presence of toads was predicted in low-gradient and less developed environments, expanding on the observed range of observations. However, certain areas without documented occurrences were also predicted as suitable habitat. This discrepancy might stem from inadequate sampling efforts in these regions, highlighting the need for targeted surveys. Alternatively, it may result from specific area-related factors inhibiting toad reproduction, such as urbanization with associated channelization and perennialization of streams or the presence of invasive species (Riley et al. 2005).

Substrate, elevation, and variables describing seasonal flow components were highly influential in driving toad distribution. The key FFMs for arroyo toad habitat are fall pulse flow magnitude, peak flows (largest annual storm, 10-year and 2-year flood), and

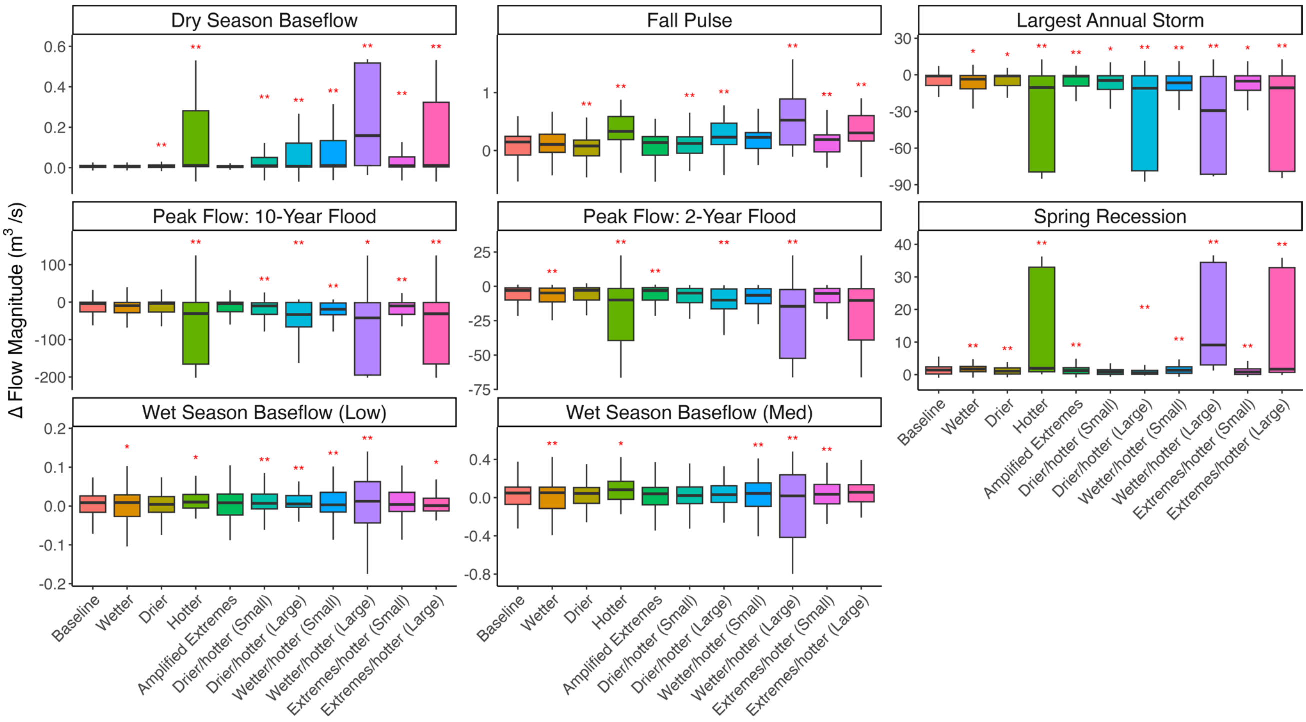

FIGURE 5 | Values of delta functional flow metrics (ΔFFM) for predicted presence grid cells where presence was predicted for each scenario. Boxes represent interquartile range; horizontal bar is the median. Stars indicate significance <0.01**, <0.05*. Note that for ease of visualization outliers (i.e., values outside the box and whisker limits) have been removed from the plot. See Figure S2 in Supporting Information S1 for full figure with outliers. [Color figure can be viewed at wileyonlinelibrary.com]

dry season baseflow magnitude. However, wet season flows as well as the spring recession start magnitude were also influential. These align with the documented requirements of arroyo toads' breeding habitat (Cunningham 1964; Sweet 1992; Sweet and Sullivan 2005) and the interplay between the landscape and stream characteristics determined to be important for amphibians (Ficetola et al. 2011). Fall pulse flows prepare the riverscape by clearing sediment and reconnecting floodplain habitat. Peak flows provide periodic flooding to reshape stream channels, and consistent baseflow maintains low flows during the breeding season. Moreover, the timing of gradual reduction of water levels during the spring recession flows exposes suitable shallow habitats along stream edges. This coincides with the arroyo toad breeding season and provides critical habitat for eggs and tadpoles.

4.2 | Vulnerability of Arroyo Toad

The predicted outcomes across future scenarios consistently indicate a reduction in range size and shifting geographical and elevational positioning of the toad's predicted distribution. In general, estimated ranges located within critical habitat show reductions, some to as much as 18% of baseline estimates. These findings align with previous research (Zhu et al. 2021), which estimated that under future climate change, many species, especially ones of high conservation priority, may have less than 15% of their current range within protected areas. Notably, in future scenarios where the toad's predicted range on protected land was reduced, the proportion of predicted presences (i.e., the percentage of presences predicted within protected land compared to outside) was higher than predicted under baseline conditions. This result could indicate that protected land can act as a buffer against the impacts of climate change on toad habitat. San Mateo Canyon and San Pasqual Valley are highly important areas for the toad under current climate; however, they seem to be particularly vulnerable to flow alteration as shown by the reduced probability of occurrence under warmer climates.

The scenarios with the largest temperature increases predict a greater impact on toad distribution compared to those involving only changes in precipitation. These scenarios (i.e., hotter scenario and scenarios with large changes) predict the smallest range sizes and are accompanied by considerably altered flows related to toad occurrence. Moreover, they display the lowest overlap with the baseline projections and the smallest proportion of toad distribution within critical habitat compared to other scenarios analyzed.

Altered flow patterns linked to toad occurrence under the hotter scenario were notable, particularly concerning flow metrics like annual storm, spring recession, and dry season baseflow. Similarly, under scenarios representing large changes—encompassing both increased precipitation and temperature—there were substantial alterations in all influential flow metrics associated with toad occurrence. The altered flows at higher elevations where toads were predicted seemed to sustain toad habitat, albeit in far smaller range sizes. Nevertheless, the substantial elevation increase to areas of more similar flow patterns suggests that toads are able to find refuge from climate change in higher elevations (Tiberti et al. 2021). Predicted toad distribution in some areas shifted towards the coast to more urbanized areas.

However, urban development in coastal San Diego occurred before the arroyo toad's distribution could be clearly identified, making the range shift potentially unsuitable.

In contrast, the wetter, drier, and amplified extremes scenarios indicated a less pronounced change in the range size compared to other scenarios, demonstrating the largest range sizes and overlap with the baseline projection. This implies a relatively lower impact on the toad's distributional range. Although the significant elevation decrease under the wetter scenario to areas of more similar flow patterns suggests that toads may also be able to find refuge to climate change in lower elevations; however, this would need further investigation.

4.3 | Management Implications

From a management perspective, directing attention towards the impact of and mitigation of altered flow is pivotal in preserving the integrity of freshwater ecosystems. Altered hydrologic regimes have been identified as the biggest risk factor associated with poor biological condition in southern California Streams as measured by benthic macroinvertebrate and algal indices (Mazor 2015). This study concurs, demonstrating that flow alteration metrics are highly influential in the distribution of vertebrates as well, in this case, the arroyo toad. Comprehensive understanding of flow regime patterns and the most influential factors related to those patterns enables managers to, for example, issue permits for flow-related projects compatible with biological integrity goals, prioritize specific areas for conservation or restoration efforts, and pinpoint problematic areas or projects that might drive hydrological changes. This study illustrates that FFM can increase managers' ability to robustly protect streams for threatened and endangered species. Flow metrics thus can be used to quantitatively estimate whether natural or artificial changes to hydrology would pose risks or benefits to specific wildlife that depend on streams. Flow management recommendations have been made for a number of systems (Cartwright et al. 2017; Irving et al. 2022; Maloney et al. 2021; Mazor et al. 2018; Rogers et al. 2021; Stein et al. 2017) including the potential to benefit amphibian conservation, especially in areas vulnerable to climate change (Mathwin et al. 2021).

Our study highlights the potential impact of climate change on flow alteration, thereby affecting stream species. However, climate is just one of several factors influencing flow alteration. Altered geomorphology, substrate composition, extralimital beaver presence, and human activities such as effluent discharges, flow diversions, and dam releases also play significant roles. Implementing strategies to manage other factors, such as restoring and stabilizing banks and sand/gravel bars and regulating dam operations and effluent releases (Thomson et al. 2016), could help mitigate the adverse effects of climate change on vulnerable stream species. In the context of this study, following the general flow direction guidance (Table 5) can help implement these strategies.

In addition to establishing a connection between flow alteration and the distributional range of the toad, our study identifies areas that could potentially be inhabited by the species both presently and in the future. Many of these areas are not designated as critical habitat or protected land, suggesting the need for consideration in identifying new or alternative areas for conservation (such as the San Diego County—North County Habitat Conservation Plan) or management efforts. Furthermore, the model identifies areas where no toads have been observed, yet habitat is deemed suitable. These areas could benefit from additional survey efforts that may either discover toad presence, identify restoration actions needed for successful toad reoccupation, or uncover additional factors that make the habitat unsuitable.

The selection of the toad as a model species in this study proved effective for several reasons. First, as an endemic species with specific habitat requirements, the toad serves as an excellent indicator of climate change vulnerability (Manes et al. 2021). Its presence can indicate the well-being of habitat, and toads can potentially act as an umbrella species (Hitchcock et al. 2022), whereby conserving toad habitat benefits other species and promotes biodiversity. Second, the toad's legal protection has garnered significant public interest, enhancing stewardship not only for the species itself but also for the ecosystems it inhabits. This charismatic species thus plays a crucial role in fostering conservation efforts and raising awareness about the importance of preserving its habitat. Given that amphibians are among the most vulnerable taxa to climate change worldwide (Foden et al. 2013), effective conservation efforts hold the promise of yielding outcomes that surpass the mere sum of their parts.

4.4 | Benefits of the Approach

The SDM approach described in this paper offers several benefits. First, it leverages broad-scale, openly available physical data, making it highly accessible and applicable across diverse regions and systems. Moreover, its adaptability, facilitated by its reliance on open-source data, makes it one of the most readily available tools for such analyses. The approach is particularly advantageous for identifying potential habitat for species like the arroyo toad. Additionally, while not establishing causal relationships, the model provides valuable insights into the impacts of flow alteration on habitat suitability.

4.4.1 | Limitations/Future Research

The models employed in this study were highly effective in identifying habitat and assessing the potential influence of flow alteration on toad distribution. However, for the development of specific conservation strategies, future studies should delve into site-specific factors and consider long-term effects. For instance, temporal analysis of flow alteration impact, such as through population viability analysis (PVA), would be beneficial in determining species range (Fordham et al. 2013) particularly in scenarios where drought durations exceed the life cycle of the species (Fisher et al. 2018). In addition, we were not able to capture dispersal limitations of the toad in our study, a factor that will be essential in predicting species distributions under future conditions (Lee-Yaw et al. 2022). Dispersal factors could be applied in combination with SDMs or included as part of a PVA temporal analysis. Furthermore, biotic interactions, including those with predators and invasive species such as bullfrogs

(Bucciarelli et al. 2020; Miller et al. 2012), are key considerations as they can significantly impact species distribution and persistence (Heikkinen et al. 2007; Lynn et al. 2019; Pearson and Dawson 2003; Pletterbauer et al. 2016).

Future research could target different threatened and endangered species of concern. For example, San Mateo Creek (an area of high toad probability of occurrence in this study) is also critical habitat for the state and federally endangered southern steelhead (*Oncorhynchus mykiss*). It would be highly beneficial to determine whether the flow metrics that protect the arroyo toad are also adequate for protecting steelhead, or if additional considerations are needed. Research could also focus on species of particular importance to tribal communities, aiding current efforts by the regional water boards to designate water bodies that support tribal, cultural, and subsistence uses.

In terms of the modelled flow data applied in this study, the spatial resolution excluded small tributaries $<1\text{km}^2$. While this was a limitation driven by data availability, the small tributaries could be essential areas of toad breeding or for population expansion at higher elevations in future climate scenarios. Increasing the spatial resolution may also increase the accuracy of the SDM as well as refine the identified areas of toad presence. In addition, flow metrics describing the timing, duration, and frequency of flow events are likely as important to toad breeding habitat as the magnitude of flow. In the context of this study, the data were not available; however, future efforts Could consider these aspects. Coupling future climate-induced flow scenarios with planned watershed management scenarios would also provide valuable insights into the impacts on threatened and endangered species.

5 | Conclusion

This study underscores the considerable impact of climate-related flow alteration on the habitat suitability, hence distribution of the arroyo toad. We have shown that while a substantial portion of the current suitable habitat is within protected areas, future climate change could lead to a notable reduction in the toad's range. Increases in temperature, more than changes in precipitation alone, potentially pose the greatest threat, leading to shifts into areas that are climatically suitable however, may be unsuitable for toads due to factors such as urban development. However, protected areas and higher elevations may serve to buffer the impacts of climate change. It is therefore crucial to emphasize the importance of flow management, alongside addressing other stressors such as invasive species and urbanization. With proactive and targeted management efforts, there is potential to support the arroyo toad's habitat in the face of a changing climate.

Acknowledgments

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Data Availability Statement

The data that support the findings of this study are openly available in Irving_et_al_arroyo_toad at https://github.com/ksirving/Irving_et_al_arroyo_toad.

Endnotes

[1] Available from: https://www.gbif.org/.

[2] Available from: Esri Inc. https://www.esri.com/en-us/arcgis/products/arcgis-pro/overview.

[3] https://catalog.data.gov/dataset/military-installations-ranges-and-training-areas.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.