Synchronization of In-Stream Abiotic Conditions in Pinnacles National Park

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ABSTRACT

Intermittent streams are a sensitive and dynamic ecosystem that constitute approximately 79% of California's stream miles. As climate change is poised to intensify the water cycle and increase weather severity, intermittent stream dynamics are at risk of being disrupted which can cause long term damage to the ecosystem. This study examines the abiotic dynamics of an intermittent stream in Pinnacles National Park, California, during a drier than average year (2022), primarily focusing on dissolved oxygen (DO) concentration and water depth. Applying multivariate autoregressive state space (MARSS) models and wavelet analyses, we investigated spatial and temporal variations of abiotic factors caused by their covariate drivers of air temperature, precipitation, and canopy cover. Despite a dry study period, significant relationships emerged between precipitation, temperature, canopy cover, and the abiotic factors of DO and depth. Temperature exerted a dominant influence on both DO and depth, while precipitation accounted for periods of variability. Canopy cover showed marginal effects. Wavelet analysis revealed periods of synchronization, primarily driven by temperature fluctuations. The study underscores the vulnerability of intermittent streams to climate change and emphasizes the importance of proactive conservation measures to protect these sensitive ecosystems.

KEYWORDS

intermittent streams, climate change, multivariate autoregressive state space (MARSS) models, wavelet analyses, spatial scale interactions

INTRODUCTION

Intermittent streams, or those that experience periods of low to no flows during certain seasons of the year (EPA 2015), account for more than 50% of the world's water systems and play an integral role in the regulation of the world's freshwater (Acuña et al. 2014). Within California, 79% of the 415,764 miles of streams are intermittent. Although they are more frequently found in arid and semi-arid environments, intermittent streams are increasing in abundance globally due to climate change (Döll & Schmied 2012). Like all aquatic ecosystems, the abiotic conditions of intermittent streams—such as water depth, water temperature, and dissolved oxygen (DO)—drive both the biotic structure (species richness and diversity) and ecosystem functioning (stream metabolism and biogeochemical processes) of intermittent stream ecosystems. Given the global intensification of the water cycle by climate change, including predictions of longer, more severe droughts, understanding the scales at which the abiotic conditions of intermittent streams change over time is of increasing importance for management and conservation efforts (Gomez et al. 2017).

Intermittent streams are dynamic ecosystems with four main states: flowing, flow-cessation, drying, and rewetting (Allen et al. 2020). These cycles change hydrological connectivity along streams, leading to variation in abiotic factors at different spatial and temporal scales. The rewetting phase, when precipitation reconnects the stream network, distributes necessary nutrients downstream, spurring a "pulse" of biogeochemical activity (McIntyre et al. 2008, Shumilova et al 2019). Abiotic factors such as dissolved oxygen are directly affected by the rewetting period as the stream disperses the canopy cover's organic litter downstream which will affect the DO concentrations (Doretto et al. 2020). Apart from the biotic effects of rewetting, abiotic factors such stream temperature and soil chemistry are greatly affected during the rewetting phase (Majid et al. 2023). In general, DO concentrations are influenced by environmental drivers such as solar radiation (which is, in turn, affected by the canopy cover of riparian vegetation), water temperature, water depth, nutrients, pH, and salinity (Li et al. 2017, Wilson et al. 2019, Diamond et al. 2023). Abiotic conditions are driven by rewetting events which can be disrupted under drought conditions and can vary greatly year after year due to climate change affecting factors such as precipitation rates and flooding events.

During supra-seasonal droughts, parts of the stream network may stay dry entirely or wetted reaches may be limited by fragmentation. During such droughts, emergence timing, decomposition, and stressed biotic processes are interrupted. Stream synchronization occurs when abiotic factors are the same over the same time but different spaces (Gong et al. 2005). The importance of synchronization lies in the fact that it can be used to inform the effects of drought on abiotic factors (Sarremejane et al. 2021, Gomez et al. 2009). Synchronization can also be used to explore the stability of the tributary by linking the spatial scale interactions along with the river transects in order to provide a more holistic understanding of the overall stream health (Yeakel et al. 2014). By understanding the differences of synchronized conditions across a spatial and temporal scale, the root drivers can explain how climate change is affecting streams at a local level. This study explores the spatial and temporal comparisons of physical conditions of Chalone Creek, Pinnacles National Park, California. Pinnacles National Park has a semi-arid Mediterranean climate, receiving an average of 422 mm of precipitation annually (data from 1948 to 2005). However during the 2021-2022 water year, the park received only 225 mm precipitation, just over half the long-term average. This unusually dry year presents an opportunity to study potential future impacts of climate change-caused drought on intermittent stream ecosystems.

I explored the following questions: (1) How do DO and depth change over time across the stream network; (2) What are drivers (e.g., precipitation, air temperature, and canopy cover) of DO and depth across the network; and (3) How are DO and depth synchronized across the stream network? I aimed to understand the mechanisms in which physical conditions of Chalone Creek changed over the abnormally dry rewetting period. To answer my questions, I used several time series analysis methods including multivariate autoregressive state-space models (MARSS), multivariate wavelets, and wavelet linear models to understand the relationships among the abiotic conditions. First, I hypothesized that as depth increases during the progression of the wet season, DO concentrations will also increase across all sites through the study period. Second, I hypothesized that canopy cover and temperature will have positive relationships with DO and negative relationships with depth. Third, I hypothesized that depth and DO will be synchronized across all sites.

METHODS

Study site

My colleagues and I conducted the experiment in Chalone Creek, Pinnacles National Park (Pinnacles), California, United States (Figure 1), an intermittent stream where approximately 90% of the network dries for part of the year. Precipitation in this system primarily falls within the months of December to March, and the onset of rains typically rewets intermittent sites in the network that then flow until June. Chalone Creek presents an excellent opportunity to explore the impacts of drought on streams because the stream spans a large gradient of intermittency (~15-100% flow permanence), making it an ideal location to test hypotheses regarding flow regimes.

Data collection

Rose Mohammadi, a graduate student in the Ruhi Lab at the University of California, Berkeley, primarily collected the following data, with my assistance. To study patterns of succession and abiotic dynamics within Chalone Creek, ten sites were selected, spanning both the Bear Gulch and the Sandy Creek tributaries along with the mainstem during spring 2022. Chalone Creek did not fully reconnect during the winter rewetting period, causing sites located on the same tributary to experience partial reconnection following December and January rains.

We measured dissolved oxygen (using the HOBO U26 Dissolved Oxygen logger, Onset), pool depth, and water temperature (using the HOBO Water Level Data Logger, Onset) at 10-minute intervals from February 22nd ,2022 to April 5th, 2022 . To understand the effects of light availability of the canopy cover at each site, we affixed one light-level logger to a control tile at each site (using the HOBO Pendant MX Temperature/Light Data Logger, Onset) to record throughout the experiment duration. Precipitation data, along with hourly relative humidity and solar radiation measurements, were obtained from the Western Regional Climate Center website (wrcc.dri.edu).

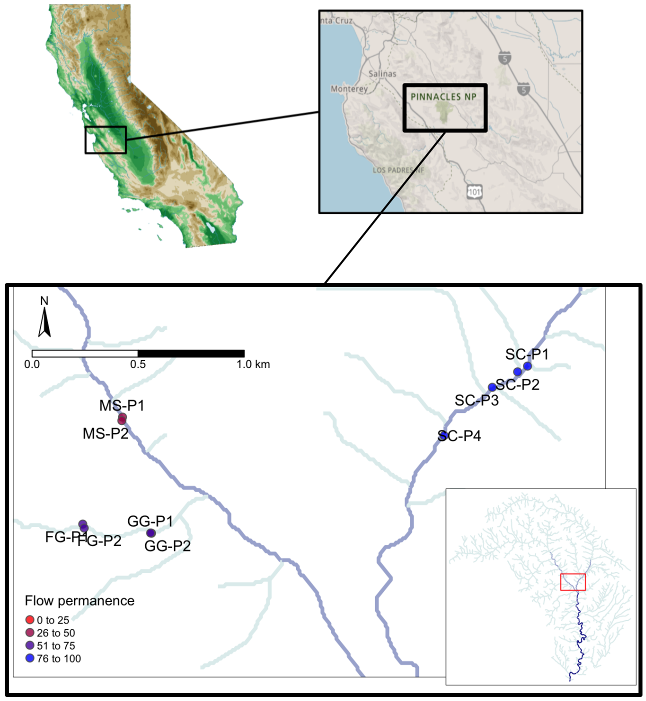

Figure 1. Relative location of Pinnacles National Park. Map of Chalone Creek in Pinnacles National Park. The study sites are indicated by circles with flow permanence being illustrated through the term of the study period.

Analysis

Data cleaning and visualization

We inspected and cleaned the data, removing any null values. Missing data values were interpolated using a Kalman filter. All time series were then z-scored before running the models. Z-scoring the data places it into the context of standard deviations from the mean which can allow us to find and understand trends within the data by limiting bias (Colan 2013). To visualize temporal patterns in the time domain, we used the "ggplot2" package to plot the DO and depth time series data for each of the 10 study sites. All analyses were conducted in R (v4.3.1; R Core Team 2023).

MARSS modeling

We used multivariate autoregressive state-space (MARSS) models to explore how DO concentrations and depth changed over time, their spatial structure, and the influence of different environmental drivers (temperature, precipitation, and canopy cover). MARSS models are the state-space extension of multivariate autoregressive (MAR) models, which leverage theory about temporal correlation patterns to parse out the influence of environmental drivers and species interactions (Ives et al. 2003). The primary advantage of MARSS models lies in their ability to incorporate observation error in the model which allows for inferences to remain unaltered (Knape & de Valpine, 2012). MARSS models take the following equations:

1) $X_t=BX_{t-1}+U+Cc_t+W_t$, where W_t~MVN $(0,Q)$ (Process Model)
2) $Y_t=ZX_t+V_t$, where V_t~MVN $(0,R)$ (Observation Model)

Equation 1 illustrates the process or state model and Equation 2 illustrates the observation process. Equation 1 is used to model the dynamic relationship within the variables of the system, specifically focusing on temporal interactions. In Equation 1, the *B* matrix shows interactions and density dependent effects at a specified site, and the *U* matrix is used to show trends in the growth rate. The *B* matrix was set to "identity" because there were no interactions. The *C* matrix shows the estimated effects of each covariate on each state. I Equation 2, Y_t is the observed data of each abiotic factor (DO and depth), or site-specific time series per. *Z* is a matrix that connects the observations to the states X_t. W_t and V_t are both error values for state and observation models, with Wt consisting of a multivariate normal distribution with a mean of 0 and covariance depending on the *Q* matrix. V_t consists of a multivariate normal distribution with a mean of 0 but unlike W_t, the covariance depends on the *R* matrix. We specified *Q* as "diagonal and equal," meaning all sites have the same process error variance. We also specified *R* as "diagonal and equal," setting the sites to have the same observation error variance. Models were fitted using the package "MARSS" (Holmes et al., 2014).

We constructed a set of candidate models to test different hypotheses around the *Z* matrix and whether observations were spatially structured by pool, site, or at the watershed scale (Figure 3). We estimated *U* (trends over the study period) and *C* (covariate effects: air temperature, precipitation, and canopy cover). The three models for DO and depth were ranked by Akaike Information Criterion corrected for small sample sizes (AICc). The best model was fit using the maximum likelihood estimation along with a Kalman estimation for maximization of estimation of the joint probability distribution over the abiotic variables for each time series. We bootstrapped the coefficients of the models to a 95% confidence interval and ran tests for autocorrelation and normality (ACF) on the residuals of the model.

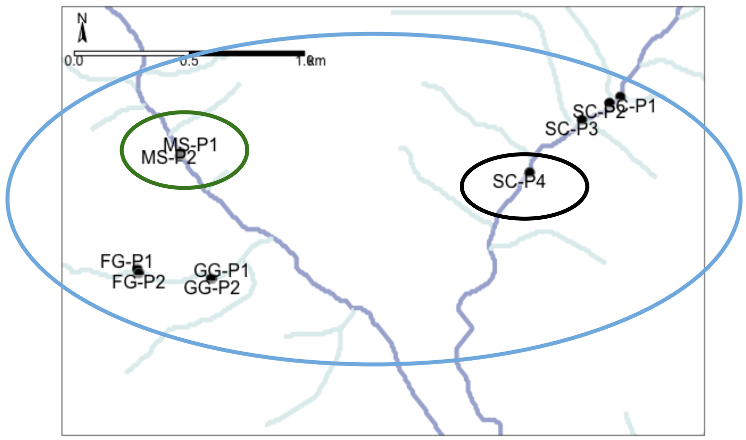

Figure 2. Visual guide of the hypotheses tested. This map tests different Z matrix structures, observing relationships at the pool(black), site(green), and watershed level(blue).

Wavelet transform analyses of abiotic factors

To visualize synchrony in DO and depth across timescales and time, we use the wavelet phasor mean field. Wavelet spectral analyses take multivariate data and express it in a three dimensional space with the following planes: time (x), frequency (y), and power (z). Power is defined as the magnitude of the variance in the series. We computed the wavelet phasor mean field using the "wmpf" function in the "wsyn" package (v1.0.4; Reuman et al. 2021) and plotted the wavelet spectra for both DO and depth. We also computed the wavelet power, or strength of phase synchrony, across timescale for the entire DO and depth time series.

We also used linear models for wavelet transforms to determine the contributions and interactions of environmental covariates to DO and depth synchrony. We followed Sheppard et al. (2019) to compute the fractions of synchrony explained by precipitation, temperature, and canopy cover.

RESULTS

Trends

From plotting the data, overall DO concentrations appeared to be slightly decreasing over the course of the study (Figure 4). The decreases in dissolved oxygen are also expected as there is less organic matter such as leaf litter within the streams due to the fact that new leaves are being formed on trees. Plots also showed that increased at some sites and decreased across others (Figure 5).

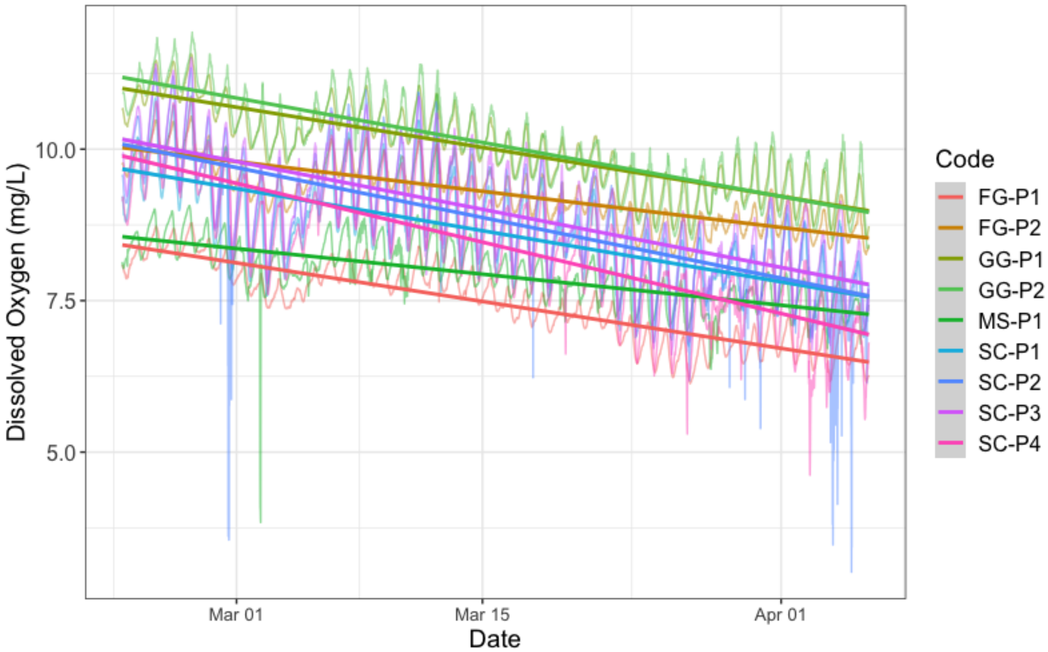

Figure 3. Graph of changes in dissolved oxygen over the course of the study period. Data was graphed from Feb to April in Pinnacles National Park at each of the selected sites and trend lines were added to highlight trends over time.

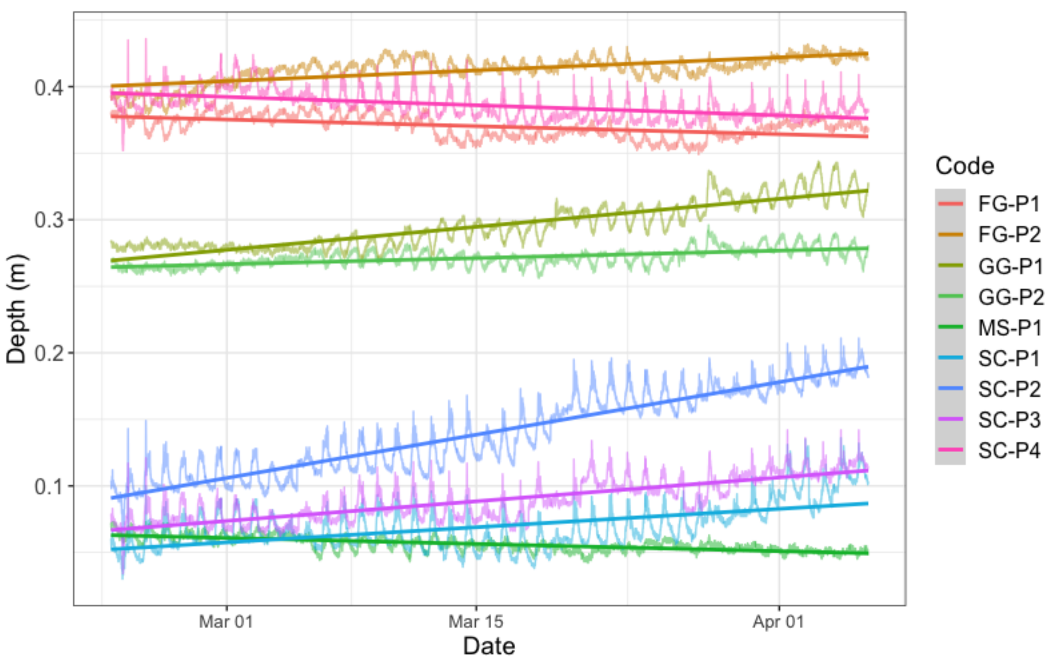

Figure 4. Graph of changes in depth over the course of the study period. Data was graphed from Feb to April in Pinnacles National Park at the selected sites and trend lines were added to highlight trends over time.

Spatial structure and covariate effects

The top-ranked model for both the DO and depth data included the pool-specific Z matrix (Table 1). When comparing the AICc values of these models, they were thousands of values lower than the next competitive model meaning that we can understand interactions better when observing trends that occur between the covariates and pool specific data. Across all pools, there were no significant (the confidence intervals include zero) trends (U) in DO nor depth (Figure 5A, Figure 7A). However, there were significant covariate effects (C matrix) of precipitation, temperature, and canopy cover on DO (Figure 5B-D). Precipitation had significant positive effects on DO at 8 of the 9 sites (Figure 5B). Conversely, temperature and canopy cover had significant negative effects on DO at 8 and 6 of the sites, respectively (Figure 5C-D). Precipitation similarly had a significantly positive effect on depth at most sites (Figure 10B). Temperature had a positive effect on depth at 2 sites and a negative effect on depth at 4 sites (Figure 7C). Canopy cover also both positively and negatively affected depth (Figure 7D).

Table 1. MARSS models ranked by AICc values. The lower the AICc, the better quality the MARSS model will be at representing the interactions between covariates and abiotic factors.

Dissolved Oxygen

Z	Q	AIC	AICc
Pool	Diagonal and Equal	-9660.58	-9660.08
Site	Diagonal and Equal	-2651.71	-2651.54
Watershed	Diagonal and Equal	5252.17	5252.22

Depth

Z	Q	AIC	AICc
Pool	Diagonal and Equal	-84316.27	-84315.80
Site	Diagonal and Equal	-56547.95	-56547.78
Watershed	Diagonal and Equal	-53548.74	-53548.69

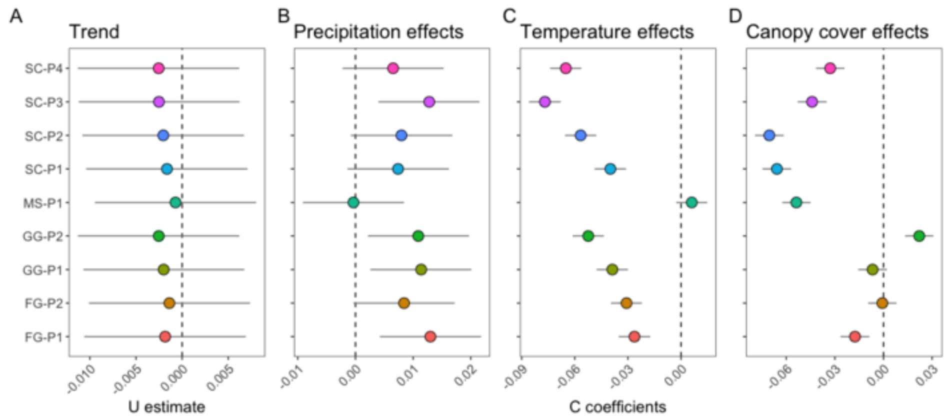

Figure 5. Trend and covariate effects on DO estimated by the top-ranked MARSS model. Effects obtained by bootstrapping. (A) Trend estimates (*U* matrix) for DO concentrations across the 9 sites. (B-D) Covariate effects on DO concentrations where estimates with the 95% confidence interval above or below 0 (dotted line) represent significant drivers of DO.

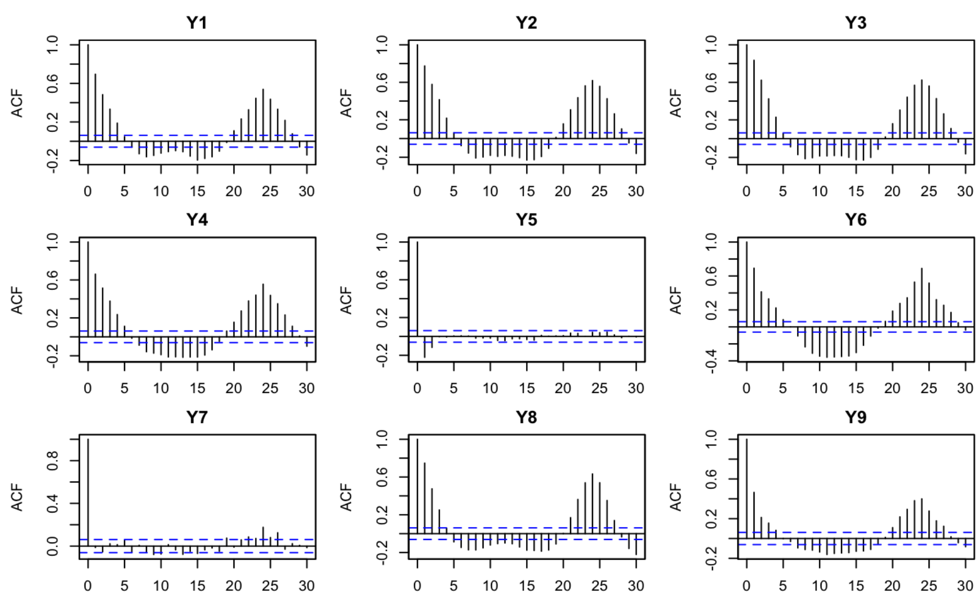

Figure 6. ACF confidence intervals for dissolved oxygen. The blue dotted lines represent the 95% confidence interval for the autocorrelation graphs and if the lines are greater than the blue dotted lines then there is high autocorrelation.

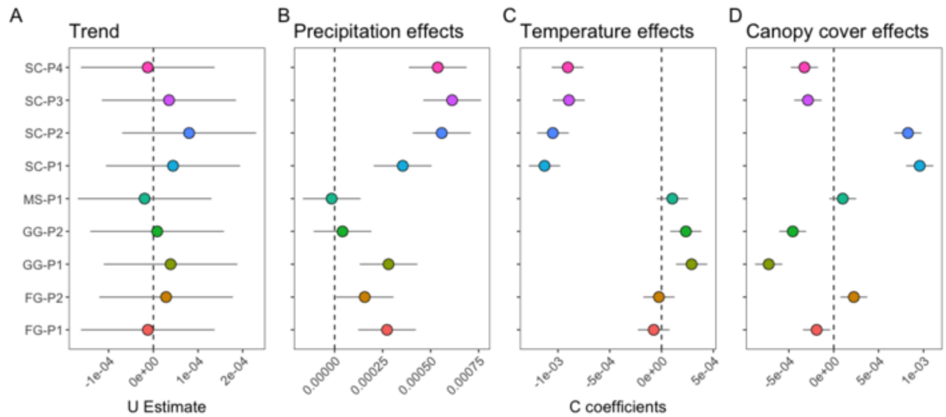

Figure 7. Trend and covariate effects on depth estimated by the top-ranked MARSS model. Effects obtained by bootstrapping. (A) Trend estimates (*U* matrix) for DO concentrations across the 9 sites. (B-D) Covariate effects on DO concentrations where estimates with the 95% confidence interval above or below 0 (dotted line) represent significant drivers of DO.

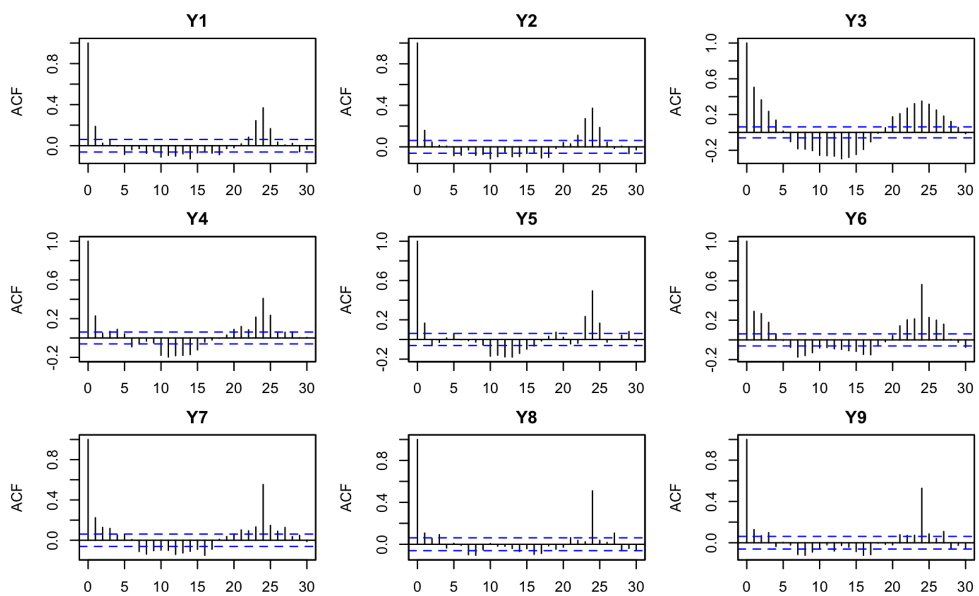

Figure 8. ACF confidence intervals for depth. The blue dotted lines represent the 95% confidence interval for the autocorrelation graphs and if the lines are greater than the blue dotted lines then there is high autocorrelation.

Wavelets analysis

I used the multivariate wavelet phasor mean field to discern periods of synchronization across sampling locations within the dissolved oxygen (DO) and depth time series. The wavelet analysis indicated strong synchrony in dissolved oxygen at the 150-200 time scales, corresponding approximately to a daily cycle (Figure 9). The depth wavelet showed a much weaker daily signal, but a significant synchronizing event around timestep 800 (Figure 10). The wavelet linear model indicated that synchronization of DO across sites can primarily be attributed to temperature (75%), with precipitation (8%) and canopy cover (6%) playing lesser roles (Table 2). Similarly, synchrony in depth was primarily explained by temperature (72%), with precipitation (19%) and canopy cover (3%) being less important.

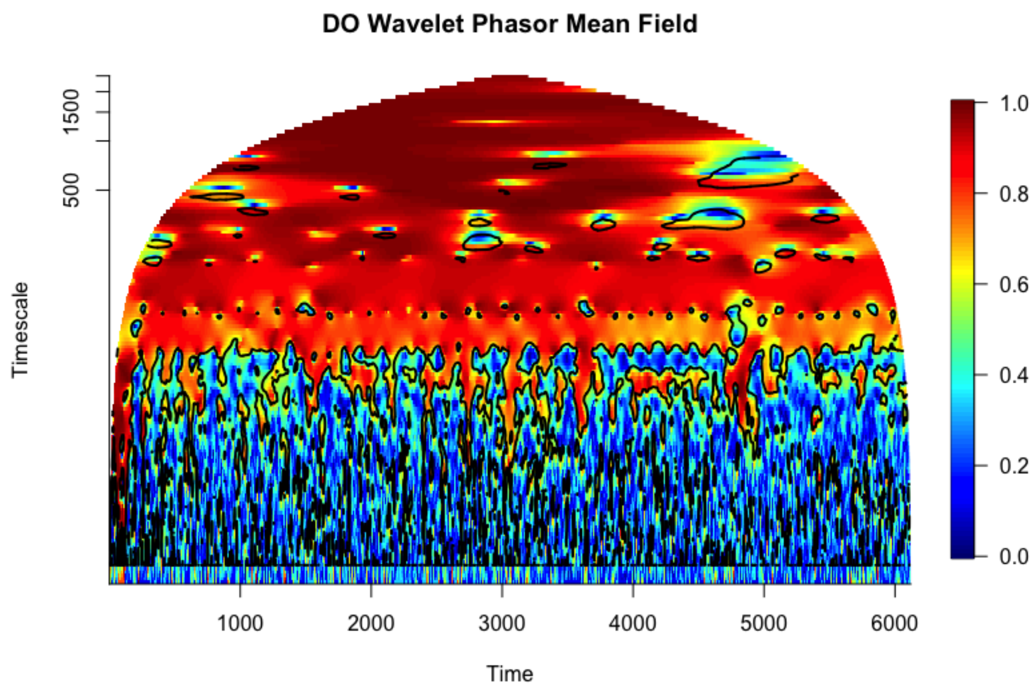

Figure 9. Wavelet of correlation between dissolved oxygen along all sites over time. The dark band of red at the 150 time scale corresponds to diel synchronization of dissolved oxygen across all of the sites.

Table 2. Synchronization of dissolved oxygen explained by the covariate effects. Data was processed using coherence wavelets to understand the percentage of synchrony that could be explained by the abiotic factors and their roles in the total synchrony explained.

Sync Explained	Precipitation	Temperature	Canopy Cover
65%	8%	75%	6%

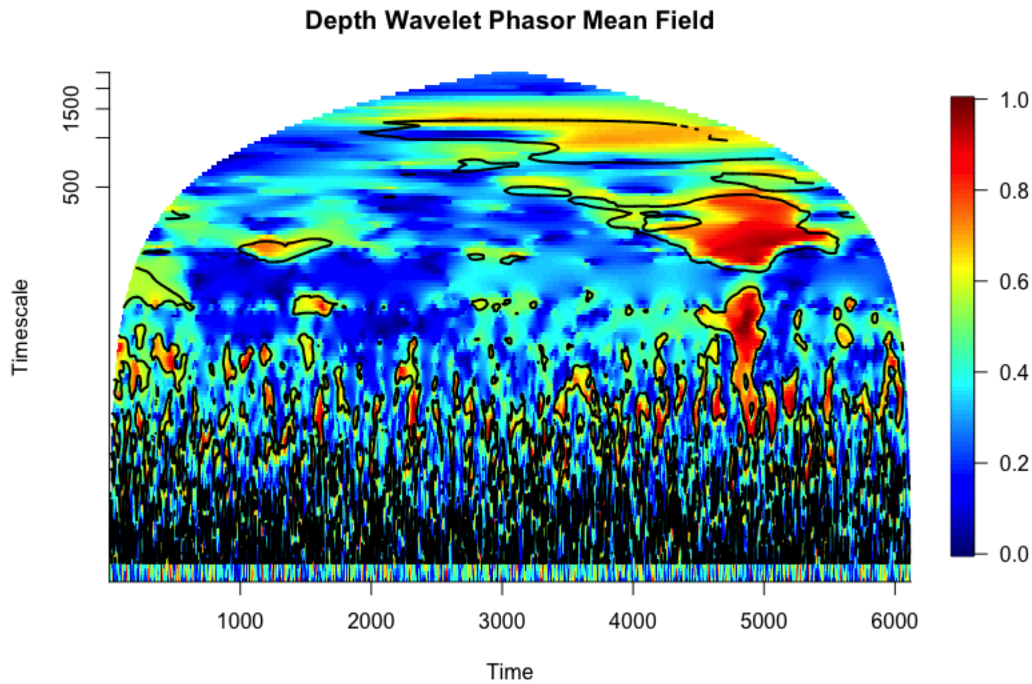

Figure 9. Wavelet of correlation between depth along all sites over time. The dark band of red at the 4900 time scale corresponds to a large precipitation event which drove synchronization of depth across all of the sites.

Table 3. Synchronization of depth explained by the covariate effects. Data was processed using coherence wavelets to understand the percentage of synchrony that could be explained by the abiotic factors and their roles in the total synchrony explained.

Sync Explained	Precipitation	Temperature	Canopy Cover
67%	19%	72%	3%

DISCUSSION

In this study, we used time series data of important abiotic stream conditions, DO and depth, and a novel combination of time-series methods (multivariate autoregressive state-space models, multivariate wavelets, and wavelet linear models) to understand spatiotemporal variation in environmental conditions in an intermittent stream system. We found that abiotic conditions are spatially structured across individual pools and that temperature, precipitation, and canopy cover are drivers of DO and depth fluctuations. Climate change plays an important role in determining the actions of abiotic factors that occur in sensitive ecosystems such as those found within Pinnacles National Park. Over the course of the study, the abiotic factors changed from their initial values in February. These results are in line with the literature associated with changes in abiotic factors. Canopy cover was shown to affect the factors marginally when observing the entire time series of abiotic factors across all of the sites studied. Across dissolved oxygen and depth, there are significant periods of coherence across the time series, with depth observing multiple notable periods of synchronization. The results aim to close the gap in understanding the spatial and temporal relationships amongst abiotic factors in intermittent streams.

Trends

The visual *GGPlot* graphs of the raw dissolved oxygen and depth data indicated that there were trends over time, however when applying the MARSS models, these trends were not found to be significant. The results indicate that in using the MARSS models, the pool specific model was the best for understanding sites that are the most important when contextualizing time series from multiple sites. The *Z* matrix controlled the spatial correlation between pools, sites, and the watershed and it was unexpected that the pool based *Z* was the best model even though there was flow between certain pools. Observing pool specific variability is important as it allows for biota to have more options for survival during stressful periods. These results are corroborated because as drivers such as precipitation and temperature change over time, nutrients and organic matter cascade down the stream system which in turn will lead to direct changes to the overall downstream dissolved oxygen (Vannote et al 1980, Doretto et al 2020, Zhong et al 2021). The trends that are found within the covariate data for precipitation align with the overall trend of the increasing rates of volatility within the rainy season in California. As climate change exacerbates the annual variability of precipitation, expected rates of precipitation can be shifted later within the year which can cause a cascading effect on abiotic and biotic factors that rely on precipitation as indications to begin certain processes (Gasith et al 1999, Swain et al. 2018, Pathak et al 2018). Over the period of the study dissolved oxygen and depth had positive relationships with precipitation which can be attributed to the precipitation observing the role as a synchronizer for watershed level abiotic factors. The reason for this is because the initial rewetting precipitation event should occur at the same time as flow reconnection, therefore discharging organic matter downstream and in turn changing the rates of dissolved oxygen within the sites (Yarnell et al. 2015, Shumilova et al 2019). The negative trends within air temperature can be attributed to the simple fact that due to the shifting of precipitation rates, temperature rates followed in their decline because the precipitation events were shifted (Figure 10).

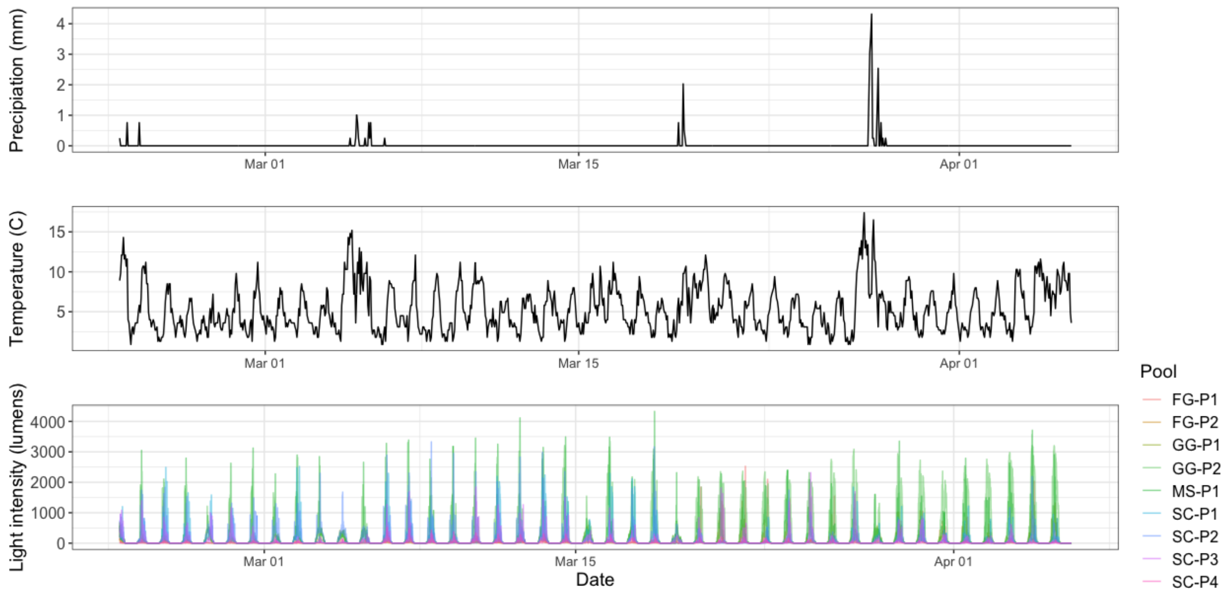

Figure 10. Covariate variables of precipitation, air temperature, and light intensity. This graph visualizes the periods in which the raw data of the covariate variables experience similar trends over time.

Canopy cover and abiotic factors

There are periods where there is a correlation between canopy cover and the abiotic factors of dissolved oxygen, temperature, and depth, however the timescales for when there is coherence is only for a brief period of time across the 1020 time steps. Correlation between canopy cover and dissolved oxygen and temperature both peak in significance around the 300-400 time steps which corresponds to biweekly correlation between these variables. Temperature has been shown to be significantly correlated with changes in canopy cover due to the fact that with an overhead, the understory will have increased temperatures with no overhead and decreased temperatures with overhead (Dugdale et al 2018, Johnson and Almlöf. 2016, Beschta 1997). Dissolved oxygen has significant correlation with canopy cover at the biweekly time scale, indicating that dissolved oxygen can be explained due in part, the rates of canopy cover across the 10 sites. Across the rest of the time series, dissolved oxygen is not significantly correlated with dissolved oxygen which places this result within the scope of literature that shows that interactions between dissolved oxygen and canopy cover are typically inversely related (Seger et al 2014, Alberts et al 2017, Souza et al 2017). The result for the interactions between depth and canopy cover is negligible because unless the site is located at either extreme of completely covered or completely exposed, the intermediate depth variable will not be significantly affected (Lennox et al 2011, Lowrance 2000).

Synchrony of abiotic factors and drivers

The use of wavelet phasor mean fields allows for synchronization across sites to be understood in a visual manner. In order for a time series of dissolved oxygen to show significance in variability, it must be a large enough time series to observe these minute changes (Coulibaly and Burn 2004). The results of dissolved oxygen synchronization showed that there is a strong band of correlation across the 200 time step which is at the weekly time period. Dissolved oxygen across sites can be explained by the fact that the covariate effects are occurring the strongest during the weekly period (Rajwa-Kuligiewicz et al 2016, Diamond et al 2023). The wavelet of depth indicates more instances of synchronization along with larger periods of synchronization across the 10 sites. The synchronicity of depth can be explained by the precipitation events that occurred during the scope of the time series (Figure 10). Given that there was no major rewetting event during the time series, the synchronization of depth can be explained by a combination of both temperature and precipitation (Cauvy-Frauni´e et al 2014, Cazelles et al 2008, Yeakel et al 2014). The lack of synchrony can also be attributed to sites being fed by groundwater effluent which is highly variable due to the position of the water table, causing for there to be limited synchrony. The percentage of synchronization explained by temperature was much larger than the other two covariates, indicating the large role that temperature plays in intermittent stream systems. Precipitation is always important for intermittent streams as it provides the rewetting event that is needed to pulse nutrients through the system, but it is still secondary to temperature. Lastly, canopy cover did not play as large of a role as expected and this can be attributed to the mediterranean climate of Pinnacles National Park that maintains a relatively similar temperature across the park which consequently reduces the role that canopy cover can have on altering both dissolved oxygen and depth. As global temperatures rise due to climate change, the role that air temperature plays in intermittent streams is exacerbated as it can cause for both dissolved oxygen and depth data to experience anomalies that alter the stream metabolism (Quiros et al. 1988, Harvey et al. 2011).

Limitations and future directions

This study was limited by several factors that impeded the overall goals of this study. The main limitation was that during the time period that this study was conducted (February 22nd, 2022 through April 5th, 2022) there was no major rewetting event within Pinnacles National Park. The lack of a rewetting event limited the stream metabolism by not allowing for dissolved oxygen concentrations to flow through the stream, instead the dissolved oxygen in this study was only concentrated for the monthly period. The lack of a rewetting event also contributed to the lack of depth synchronization, otherwise we might assume that a consistent rain event would lead to increases in depth across all 10 sites, as was the case on March 27th . Another limitation of this study is the overall size of the time series. By having a larger time series over the course of several years rather than over one season, the sensitivity of temperature could be highlighted more in order to show the differences between the data shown during the “dry” season of this study as opposed to a very “wet” year.

Broader implications

As climate change intensifies globally, sensitive ecosystems such as those found in Pinnacles National Park will experience more severe weather such as within 2022. The unprecedented volatility of weather can lead to issues in creating management plans for the future because it will be difficult to create long term plans that account for the extreme changes between seasons such as prolonged droughts and variability of precipitation. Intermittent streams experiencing disruptions to their ecological equilibrium and stream metabolism can cause irreparable damage to these sensitive ecosystems. Conservation efforts need to be allocated to mitigating global warming as it is shown that temperatures play a primary role in driving both dissolved oxygen and depth.

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