

Nitrogen Concentration Responses to Drought in Sagehen Creek, California

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ABSTRACT

Nitrogen is a limiting nutrient in freshwater systems. Relative concentrations of nitrogen species can determine the productivity of local and downstream ecosystems. In this study, I explored how total nitrogen concentrations and combined nitrate and nitrite concentrations responded to drought conditions in an upland creek. To do this, I compared the temporal variability of nitrogen concentrations during drought years and in years with adequate precipitation levels. I performed an analysis of covariance to determine if data grouped by drought and non-drought conditions were significantly different. While total nitrogen concentrations did not significantly change between drought years and non-drought years, I found nitrate and nitrite concentration trends to be significantly altered during drought conditions. Specifically, I observed an increase in the variability in nitrogen concentrations, with maximum concentrations reaching as high as double the maximum of nitrate and nitrite during non-drought years. To determine dominant predictors of nitrate and nitrite concentrations, I performed multivariable linear regression. The results indicated that gage height and water temperature were significant predictor variables of nitrate and nitrite concentrations in the system. Contrary to established literature, I found that elevated nitrate and nitrite concentrations occurred in cold water temperatures and low flow conditions. This finding suggests that inhibited microbial denitrification coupled with decreased flow and disrupted stream connectivity could result in elevated nitrate and nitrite concentrations. As the occurrence and severity of droughts could increase, low flow conditions may become more frequent, thereby disturbing stream nutrient dynamics and ecosystem productivity.

KEYWORDS

nitrogen cycling, water quality, multivariable regression, solute chemistry, freshwater ecology

INTRODUCTION

Solute nutrients are vital components for primary productivity in freshwater ecosystems (Hecky and Kilham 1988, Elser et al. 2007). Nitrogen is essential for the health of freshwater streams. Nitrogen-dependent algae are primary producers in stream ecosystems upon which species of higher trophic levels depend on for nourishment. Sudden changes in nitrogen availability can dramatically alter the stability and productivity of stream ecosystems. A lack of biologically available nitrogen could result in relocation or extinction of plant and fish species (Smith 1984). Excess nitrogen could result in eutrophication, hypoxia, disruption of plant and soil dynamics, soil acidification, and increase nitrous oxide emissions (Rhyther J.H. & Dunstan 1971), (Fenn et al. 1998). The loss of biological activity in freshwater ecosystems could create a demand for stream ecosystem restoration management to ensure stability. The health of a stream's ecosystem ultimately depends on mechanisms regulated by precipitation, temperature, and groundwater chemistry such as sufficient lateral transport of nitrogen in soils, groundwater to surface water ratios, and regular upstream flow conditions (Fenn et al. 1998). Droughts decrease precipitation levels, and alter these mechanisms. With this in mind, the nature and occurrences of California droughts must be considered when discussing changes in nitrogen concentrations and freshwater ecosystem productivity.

Droughts cause a decrease in precipitation levels. This results in a series of changes that can alter the chemical and ecological stability of freshwater ecosystems. Nitrogen concentrations in an upland creek are determined by several factors. Stream connectivity and flow rates are fundamental components of freshwater hydrology (Lake 2003). During dry periods, nitrogen stocks in soils located within watersheds can increase due to buildup of litter-fall (Jackson et. al 1988). At average precipitation levels, inorganic nitrogen is physically trans-located by leaching. Without adequate precipitation, trans-location is limited, and excess nitrogen accumulates in soils. This excess nitrogen is released into streams upon a major precipitation event, and elevated nitrogen levels are expected. Plants and microbial organisms sequester nitrogen through metabolic processes (Jackson et. al 1988). During a drought, nitrogen sequestration and overall plant productivity decreases due to decreased soil moisture and decreased species richness (Peñuelas et al. 2007). Decreased translocation can lead to excess nitrogen in soils, which can result in a pulse in nitrogen in aquatic systems following a significant precipitation event. By altering mechanisms

necessary for physical and metabolic nitrogen processing, nitrogen cycling in streams becomes disrupted, and ecosystem dynamics are altered.

Studies have been focused on the effects on drought conditions on nitrogen availability in flowing freshwater systems, although the number of these types of studies is limited (Lake 2003). To understand the effects of drought on nitrogen availability in freshwater streams, analyses of past hydro-chemical data must be conducted. To create a more comprehensive model of Earth's freshwater nutrient supply systems, more research on the effects of drought on nitrogen levels needs to be conducted.

The objective of this research was to answer the question "How does drought affect the amount of nitrogen in freshwater aquatic systems". The purpose was to statistically describe and model the patterns of nitrogen concentrations during years that experienced drought conditions. The spatial relationship between precipitation and nitrogen availability was examined and analyzed using a time-series based multivariable regression model. I hypothesized that both inorganic and organic nitrogen concentrations during drought periods would change significantly in comparison with years with adequate precipitation.

METHODS

Study Site

Sagehen Creek is located in the northeastern Sierra Nevada about 20 miles north of Lake Tahoe. It is a tributary to the Truckee River in Nevada County, California (Markstrom et al., 2012). The drainage basin spans 27 km², and elevations range from approximately 1,600 meters to 2,600 meters (Markstrom et al., 2012). Air temperatures vary greatly throughout the basin, and are highly dependent on elevations. Average annual precipitation at lower elevations is about 86 centimeters (Markstrom et al., 2012). Most precipitation is stored in snowpack and is released in mid-late spring. Vegetation in the Segehen Creek Basin is primarily coniferous. The geology of the bedrock within the Sagehen Creek Basin consists mostly of granitic and volcanic rock (Markstrom et al., 2012).

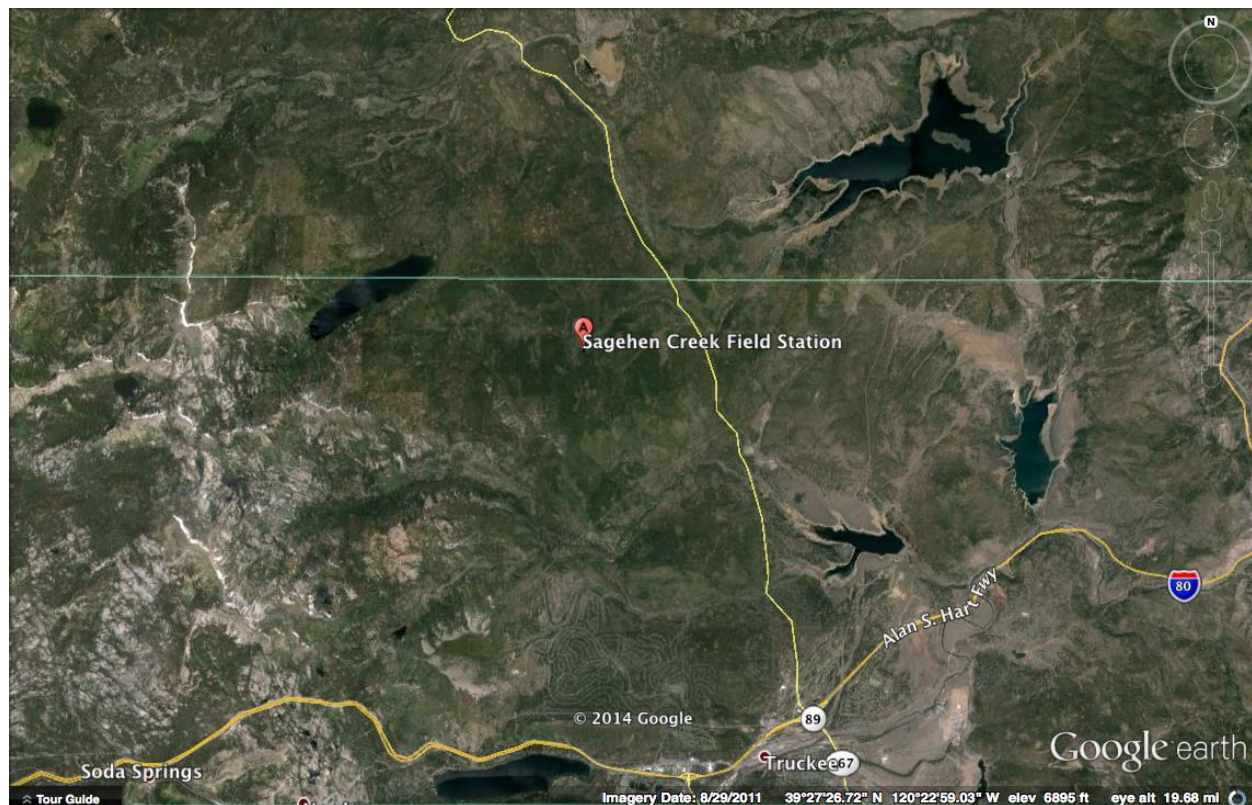


Figure 1: Location of the Sagehen Creek Field Station (USGS site number 10343500)

Data Collection

To characterize geological, meteorological, and hydrological conditions of the Sagehen Creek basin, I obtained data from various survey efforts. From the United States Geological Survey's (USGS) Hydrologic Benchmark Network, I acquired gage height (ft), water temperature (C°), nitrate + nitrite concentration (NN) (mg/L), and total nitrogen concentration (TN) (mg/L). I obtained total precipitation data (cm/month) from the National Atmospheric Deposition Program (NADP). I used data collected from the USGS and the NADP between June 2004 and March 2015.

Data analysis

Analysis of covariance

To establish supportive evidence of the alternative hypothesis of a significant difference between longterm trends in nitrogen concentrations (TN) and combined nitrate and nitrite (NN) concentrations between drought years and non-drought years, I ran an ANCOVA using MATLAB R2014A (Appendix). I created a dummy variable to separate drought years and non-drought years. I classified drought years as years that received less than 10 cm below the average annual precipitation for the Sagehen Creek basin (85 cm). P-values < 0.05 were considered statistically significant.

Significance of Predictor Variables and Multivariable regression model

To determine which variables were the most significant predictor variables in predicting nitrate and nitrite concentrations, I used multivariable linear regression in MATLAB R2014A (Appendix). To model total nitrogen in the study site, I created a multivariable regression model using significant predictor variables and their respective β coefficients in MATLAB R2014A (Appendix).

RESULTS

Analysis of covariance

While combined nitrate and nitrite concentrations in Sagehen Creek were found to relatively constant from 2004-2015 during non-drought years, NN concentrations increased during drought years (Figure 2). There was a significant difference between the trend line slopes between drought years and non-drought years. ($p = 0.0189$) (Table 1). From 2004-2015, I found that there was no significant difference between total nitrogen concentrations during drought years and non-drought years ($p = 0.1793$) (Figure 3, Table 2).

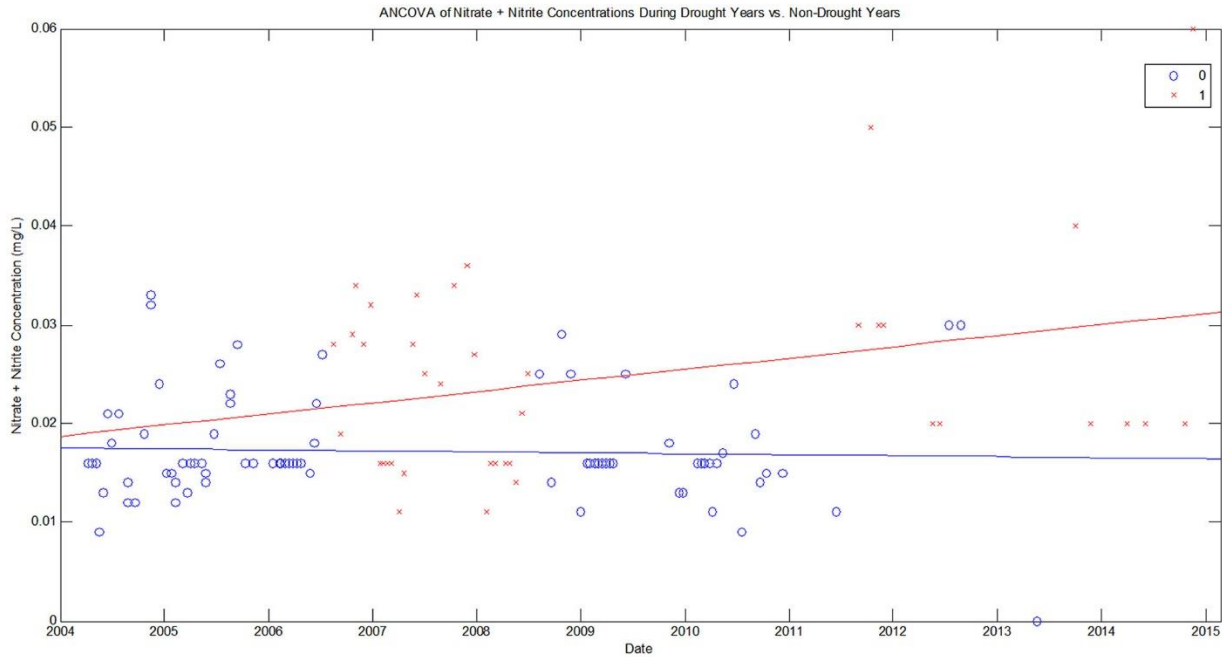


Figure 2: Analysis of covariance of nitrate and nitrite concentrations from 2004-2015 comparing drought years to non-drought years. The blue circles (0) and blue trend line indicate concentrations during non-drought years. The red x's (1) and red trend line indicate concentrations during drought years.

Table 1: Analysis of covariance of nitrate and nitrite concentrations during drought years and non-drought years.

ANOVA Results

Source	d.f.	F	P-value (Prob>F)
Dummy	1	-0.02	1
Year	1	1.84	0.1772
Dummy x Year	1	5.66	0.0189

Estimated Slopes of Trend Lines

Group	Slope Estimate
Non-Drought	-2.6200e-07
Drought	3.0576e-06

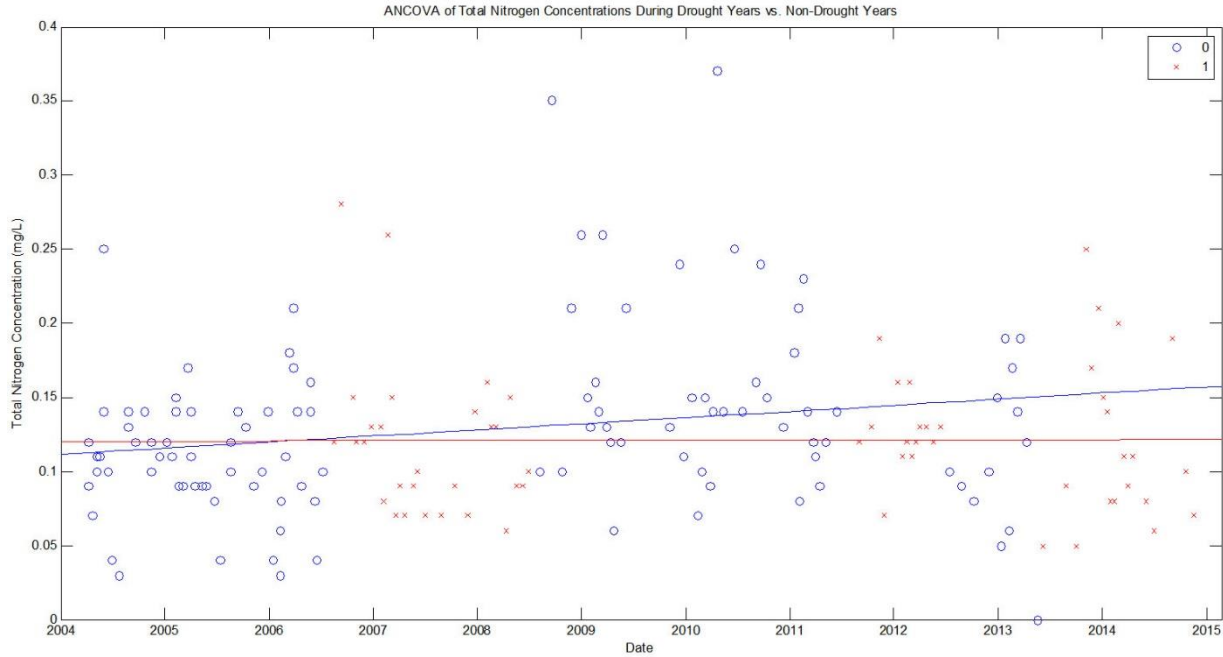


Figure 3: Analysis of covariance of total nitrogen concentrations from 2004-2015 comparing drought years to non-drought years. The blue circles (0) and blue trend line indicate concentrations during non-drought years. The red x's (1) and red trend line indicate concentrations during drought years.

Table 2: Analysis of covariance of total nitrogen concentrations during drought years and non-drought years.

ANOVA Results of Total Nitrogen Concentrations

Source	d.f.	F	P-value (Prob>F)
Dummy	1	-0	1
Year	1	3.42	0.0662
Dummy x Year	1	1.82	0.1793

Estimated Slopes of Trend Lines

Group	Slope Estimate
Non-Drought	1.1155×10^{-05}
Drought	-2.2960×10^{-07}

Multivariable regression and model

I identified two variables that predicted nitrate and nitrite concentrations in Sagehen Creek. Multiple regression analysis revealed that gage height and water temperature were significant contributors to total nitrogen concentrations at the Sagehen Creek field station (Table 1). Gage height had the highest predictive strength with a p-value of 4.7886×10^{-05} , and a β coefficient of -0.0063 (Table 3, Figure 4) The R^2 value for the multiple regression model was 0.1399 (Eq. 1)

Table 2: Multivariable linear regression of significant predictors of total nitrogen concentrations

Predictor Variable	β Estimate	P-value
Intercept	0.0315	1.7386×10^{-18}
Gage Height	-0.0063	4.7886×10^{-05}
Water Temperature	-4.6895×10^{-04}	0.0016

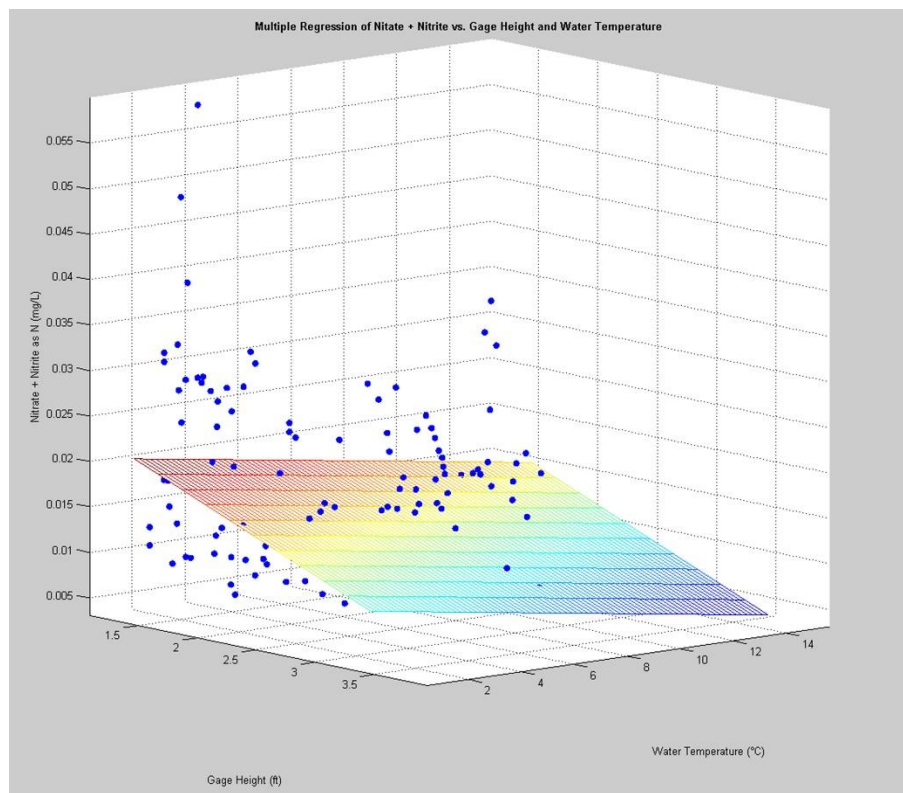


Figure 2: Multiple linear regression scatter modeling gage height and water temperature vs. nitrate and nitrite concentrations. A best fit plane is included (Eq. 1).

$$NN = 0.0315 - 0.0063 \times (\text{Gage height}) - 4.6895 \times 10^{-4} \times (\text{Water Temperature}) \quad (1)$$

DISCUSSION

Nitrogen concentrations in freshwater systems are important indicators of the state of aquatic ecology and water quality. Because nitrogen concentrations are not always directly monitored, it is useful to model nitrogen concentrations in creeks and streams, as these waterways serve as health indicators for local and downstream aquatic systems. In this study, I determined that nitrate and nitrite concentrations increased significantly in Sagehen Creek during drought years. While the multivariable regression model was only able to predict total nitrogen within a limited range of accuracy ($R^2=0.1399$), analytical techniques identified correlations between gage height, water temperature, and nitrate and nitrite concentrations. With the use of this model, the overall health of Sagehen Creek can be gauged and appropriate management and restoration practices can be implemented. My findings in this study imply that nitrate and nitrite concentrations are correlated with drought conditions, which, in light of forecasted continuation of drought conditions in California, could have negative ecological implications. While the complexity of natural systems limits the effectiveness of simple models in predicting total nitrogen levels, analytic techniques can reveal long-term trends and important biogeochemical factors.

Analysis of covariance

Combined nitrate and nitrite concentration patterns were significantly different during years with drought compared to non-drought years ($p = 0.0189$). Years that experienced drought conditions experienced an increase in nitrate and nitrite concentrations. These periods of elevated NN concentrations were during cold and dry periods of the year. Interestingly, this finding challenges other studies performed in other locations (Walling & Foster 1977), (Baldwin et al. 2005). According to other research, a pulse in NN is expected after the first substantial precipitation event in late fall. (Walling & Foster 1977). I found that NN concentrations were highest in January and February, at low gage heights and low water temperatures. Under drought conditions, decreased riparian species richness can result in decreased nitrate and nitrate sequestration (Peñuelas et al. 2007). This could reduce the abundance of denitrifying microbial communities in the system (Zak et al. 2003). In cold and dry conditions, microbial denitrification can be slowed or halted during cold periods due to low temperatures (Nedwell, 1999). Reduced microbial activity can limit the removal of nitrate and nitrite by reducing inorganic nitrogen to

nitrogen gas (Stanford et al. 1975). This mechanism coupled with limited hydrologic flow in drought years could cause a buildup of nitrate and nitrite in Sagehen Creek. I observed low flow patterns in the data during drought years. This observation suggests that low flow could contribute to elevated NN concentrations. Prolonged droughts could result in a more extreme reduction in flow and could increase nitrate and nitrite concentrations in the system (Lake 2003). Long-term total nitrogen concentration patterns did not change between drought years and years that experienced adequate precipitation ($p = 0.1793$). This finding suggests that drought conditions in this region may not have a significant effect on the total nitrogen concentrations in this type of system.

Multivariable regression analysis and model

To predict NN concentration in Sagehen Creek, I identified significant contributive variables. Gage height was the most significant predictor of NN concentration in Sagehen Creek ($p = 4.79 \times 10^{-05}$). With a one unit (ft.) decrease in gage height, NN concentration is expected to rise by about 0.006 mg/L. Water temperature was another significant predictor variable for NN in the study system ($p = 0.0016$). For a one unit decrease in water temperature (C°), NN concentration is expected to increase by 4.69×10^{-04} mg/L. By performing a multiple regression analysis, I was able to develop the predictive multivariable regression model.

While the multivariable linear regression model only accounted for about 14% of the variability in NN concentration, it is a useful tool for attaining an estimation of NN concentration in Sagehen Creek. The stochastic nature of hydrologic systems deems them difficult to represent in a model. Despite the difficulty in creating a predictive model for NN concentration in Sagehen Creek, outputs from the model are not without value. Estimations of NN concentrations can be used as indicators to determine overall long-term health trends in unmonitored stretches of Sagehen Creek during. Specifically, the model could be useful in determining nitrate and nitrite concentrations in Sagehen Creek during periods with extreme water temperatures and gage heights. The model helps identify important variables to consider when monitoring NN concentration, and it can help generate hypotheses about future NN concentrations and drought dynamics.

Limitations and future directions

The results of this study provide an insightful look into how drought could affect nitrate and nitrite concentrations in Sagehen Creek. The model developed in this study could be used to predict NN concentrations in other headwater streams with similar environmental characteristics as Sagehen Creek. During the process of conducting this research, I encountered several limiting factors that could have significant impacts on the results. Sagehen Creek Field Station is relatively close to the headwaters of the system. That is, although there were significant changes in NN dynamics during drought years, overall NN concentrations were low in comparison to those of a downstream reach where there are more opportunities for NN inputs. Such low concentrations can affect the accuracy of detection instruments (Reiger et al. 2008). To increase detection accuracy, it would be beneficial for future studies to perform this analysis on a downstream reach where NN concentrations are higher on average.

Rapid changes in temperature, precipitation patterns, and soil characteristics and dynamics contribute to the difficulty of predicting solute concentrations in hydrological systems. Variability in hydrological characteristics between reaches of aquatic systems can change rapidly (Dent & Grimm 1999). This suggests that there could have been pulses or drops in NN concentrations that were not accounted for in the data. Future studies could focus on a system that has more frequently sampled data.

Variables used in the multivariable regression model could display multicollinearity. For example, changes in gage height could influence changes in water temperature. Although this would not affect the output of the multivariate linear regression model, it would influence the degree to which gage height and water temperature contribute to NN concentrations in Sagehen Creek (Friedman & Wall 2005). Variables that were not tested in this study such as groundwater NN concentration, soil permeability, and seasonal effects could serve as significant predictor variables for NN concentrations. The lack of data recording important factors such as rainfall to snowfall ratio made it difficult to identify the amount of time it took for a precipitation event to affect nitrate and nitrite concentrations in the system.

Broader implications

The findings of this study could have substantial implications in water quality studies, management of rivers, streams, and reservoirs, as well as in the fishing industry. Headwater creeks such as Sagehen Creek serve as tributaries to larger systems that supply water to reservoirs. With increased NN concentrations in Sagehen Creek, NN there could be an excess of NN downstream. Downstream excess NN could, in turn, increase algae and plant growth. Increased algal and plant growth could result in hypoxia and downstream species relocation (Smith 1984). Additionally, increased NN concentrations could subsequently increase the need for water treatment methods.

With elevated NN concentrations during drought conditions, river and stream restoration management techniques could be introduced to restore overall health to Sagehen Creek and other systems. Increasing flow rates by creating channels would decrease the residence times of solutes. To increase sequestration, riparian plant varieties that are adapted to cold temperatures could be introduced to the system.

Fish communities rely on stable solute chemistry in their habitats. A change in solute chemistry can relocate a species and can cause local extinction (Smith 1984). Such events can have devastating effects ecologically as well as economically as fish species provide ecosystem services to the system (Holmlund & Hammer 1999).

While the findings of this study have suggested that modeling stochastic systems such as stream solute concentrations in a flowing freshwater system provides a general estimation at best, they have also provided significant evidence that NN concentrations in Sagehen Creek increased during drought years. The modeling exercise in this study was not able to fully capture the variability in NN concentrations. The results from this exercise emphasizes the difficulties and complexities involved in modeling natural systems such as Sagehen Creek. However, the trend of increased NN concentrations during drought conditions has ecological, societal, and economic implications. The expected increase in the frequency and severity of droughts due to climate change suggests that water quality in natural systems should continue to be the subject of future studies to ensure ecological and economic stability. This study as well as future studies will provide the tools necessary to become better equipped to anticipate potential problems in the future.

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APPENDIX

MATLAB Code:

```

%% Import Excel Dates + Nitrogen Time Series Scatter

T;
datecol = 1;
T(:,datecol) = T(:,datecol) + datenum('30-Dec-1899');
plot(T,TN);
xlabel('Time');
ylabel('Gage Height (ft)');
zlabel('Total Nitrogen');

%% N+N Multiple Regression (Gage, Dummy, and N)
x1 = Gageh;
x2 = watert;
y1 = NN;
y2 = TN;
x1(x1==0) = nan;
x2(x2==0) = nan;
NNadj = y1;
NNadj(NNadj==0.0100) = nan;
NNadj(NNadj==0.0080) = nan;
X = [ones(size(x1)) x1 x2];
X2 = [x1 x2];
X3 = [X3 dummy];
b = regress(y1,X3);
b;
b2 = regress(y1,X);
scatter3(x1,dummy,y1,'filled');
hold on;
x1fit = min(x1):0.2:max(x1);
dummyfit = 0:0.2:1;
[X1FIT,dummyFIT] = meshgrid(x1fit,dummyfit);
YFITD = b(1) + b(2)*X1FIT + b(3)*dummyFIT;
mesh(X1FIT,dummyFIT,YFITD);
xlabel('Gage Height (ft)');
ylabel('Drought = 1 (Precipitation < 10cm below average)');
zlabel('Nitrate + Nitrite as N (mg/L)');
t2 = title('Multiple Linear Regression of Nitrate + Nitrite vs. Gage Height
and Drought Variable');
set(t2,'FontWeight','bold');
%% Plot NN vs. dummy
plot(dummy,NN,'*k');
%% Linear Regression of NN vs. Dummy

p = polyfit(dummy,NN,1);
p;
yfit = p(1)*dummy + p(2);
yresid = NN - yfit;
SSresid = sum(yresid.^2);
SStotal = (length(NN)-1)*var(NN);
rsq = 1 - SSresid/SStotal;

```

```

rsq;

%% N+N Multiple Regression Plot
scatter3(x1,x2,y1, 'filled', 'b')
hold on
x1fit = min(x1):0.2:max(x1);
x2fit = min(x2):0.2:max(x2);
[X1FIT,X2FIT] = meshgrid(x1fit,x2fit);
YFIT = b2(1) + b2(2)*X1FIT + b2(3)*X2FIT;
mesh(X1FIT,X2FIT,YFIT);
xlabel('Gage Height (ft)');
ylabel('Water Temperature (°C)');
zlabel('Nitrate + Nitrite as N (mg/L)');
t = title('Multiple Linear Regression of Nitrate + Nitrite vs. Gage Height and
Water Temperature');
set(t, 'FontWeight', 'bold');
view(50,10);
%% Rsquared of Model
[bstat,bint,r,rint,stats] = regress(X,y1);
%% Multicollinearity Test
collinearity = collintest(X2);

%% TN Mult Regression
bTN = regress(y2,X);
bTN;
scatter3(x1,x2,y2, 'filled');
%% TN Mult Regression Scatter
scatter3(x1,x2,y2, 'filled', 'b')
hold on
x1fit = min(x1):0.2:max(x1);
x2fit = min(x2):0.2:max(x2);
[X1FIT,X2FIT] = meshgrid(x1fit,x2fit);
YFIT2 = b2(1) + b2(2)*X1FIT + b2(3)*X2FIT;
mesh(X1FIT,X2FIT,YFIT2);
xlabel('Gage Height');
ylabel('Water Temperature');
zlabel('Total Nitrogen');
view(50,10);
%% Total Nitrogen vs. Nitrate + Nitrite plot
scatter(y1,y2);

%% N+N ANCOVA
ANCOVA = aoctool(T,NNadj,dummy);

%% Total N ANCOVA
ANCOVA = aoctool(T,TN,dummy);

```