THE INFLUENCE OF STEP-POOLS ON WATER CHEMISTRY: SAN JUAN MOUNTAINS, COLORADO

A Thesis

by

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MASTER OF SCIENCE

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ABSTRACT

The number of streams in the United States with poor water quality conditions continues to increase each year. With a spike in the number of streams needing water quality improvements, new ways of stream health remediation are becoming more necessary than ever. A water quality analysis was conducted on step-pool sequences in the San Juan Mountains, Colorado to determine whether or not they have a potential to improve stream health. Six creek sites surrounding the Uncompahgre River were tested for all of the following chemical and physical characteristics. The chemical characteristics tested were: pH, conductivity, total dissolved solids, dissolved oxygen, nutrients (nitrate-nitrogen and phosphate), sulfate, and total iron and the physical characteristics tested were: step-pool depth, width, length, elevation, stream velocity and stream discharge. All of these characteristics were compared and analyzed to determine if step-pool sequences had an impact on the stream water quality in those six creeks. The analysis determined that 1). There was no statistical difference between the water quality in the streams before water passed through the step-pool sequences and after the water had passed through the step-pool sequences, 2). The location of the step-pool sequences on either side of the Uncompahgre River had a significant impact on nitrate-nitrogen, sulfate, total dissolved solids, and conductivity, and 3). There were relationships and patterns between a few of the physical and chemical characteristics within the step-pools. The overall result of the study indicates that though the step-pools may not improve the water quality in streams, relationships exist within the step-pools between the chemical and physical characteristics that should be further examined.

DEDICATION

I dedicate this thesis to my parents, Scott and Julie Ruff, fiancé, Hank deVilleneuve, sister, Elise Ruff, and nephew, Bentley Morgan.

ACKNOWLEDGEMENTS

I would like to thank my committee chair, Dr. Giardino, and my committee members, Dr. Marcantonio, and Dr. Datta for their guidance and support throughout the course of this research.

Thanks also go to my friends and colleagues and the department faculty and staff for making my time at Texas A&M University a great experience.

I would also like to thank my mom for taking her time to come with me to Colorado and help conduct my research. Without you this would not have been possible.

Finally, thanks to my father for his encouragement and to my fiancé for his patience and love.

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NOMENCLATURE

°C	Degrees Celsius
AMD	Acid Mine Drainage
DO	Dissolved oxygen
EPA	Environmental Protection Agency
Fe^{2+}	Ferrous Iron
Fe^{3+}	Ferric Iron
Fe_T	Total iron
ft	Feet
GPS	Global positioning system
m	Meters
m/s	Meters per second
m^3/s	Meters cubed per second
mL	Milliliters
NCBI	North Carolina Biological Index
NO_3-N	Nitrate-nitrogen
PO_4^{3-}	Phosphate
ppm	Parts per million
SO_4^{2-}	Sulfate
TDS	Total dissolved solids
USGS	United States Geological Survey
μS/cm	Micro-Siemen per centimeter

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CHAPTER I

INTRODUCTION AND LITERATURE REVIEW

The National Rivers and Streams Assessment Report 2008-2009 stated that 46 percent of streams in the United States are in “poor” biological condition (EPA, 2016). Nutrient stressors such as high nitrogen and phosphorus concentrations were two of the main contributors (EPA, 2016). In the state of Colorado, USA, of the 59,639 river miles assessed there were 281 river miles affected by nutrients which is < 0.5% of river miles assessed.

One way to combat declining stream health may be to examine the impact of step-pool sequences in mountain streams on the quality of the water and determine the extent of that impact. Step-pool sequences occur in high-gradient mountain streams with alternating steps and pools, creating the appearance of a staircase (Chin, 1999). The steps are most commonly composed of boulders and large rocks, whereas the pools typically contain finer sediments (Wang et al., 2009). Step-pool sequence structures are stable because the boulders in the steps create a tightly interlocked structure (Wang et al., 2009).

A few case studies, in particular, offer the most information on step-pool chemistry and have also examined water quality in some form for mountain streams. O’Dowd and Chin (2016) conducted a study in the Smith River Basin in Northern California determining the differences in biophysical attributes between steps and pools, factors such as dissolved oxygen (DO), pH, and water temperature were also examined between the steps and pools as well as other water quality parameters. O’Dowd and Chin (2016) sampled three different creeks within the basin to determine their chemical and physical properties. These creeks were Eighteen Mile Creek, East Forks Patrick’s Creek, and West Forks Patrick’s Creek respectively. When comparing the physical aspects of the three different creeks, the overall depth of the waters in each creek were much shallower in the steps of the creeks (0.09 ± 0.01 m) compared to pools (0.21 ± 0.01 m), which were almost twice as deep as the steps (O'Dowd and Chin, 2016). O'Dowd and Chin (2016) also found that the water velocity was much faster in the steps (0.50 ± 0.04 m/s) than the pools (0.07 ± 0.04 m/s). Steps have a much higher gradient than the pools, which allows for water to flow quickly over them.

When comparing the physical characteristics between steps and pools in regards to water quality for the three creeks only two categories showed a significant difference between the two, these categories were DO (mg/L) and DO (% saturation). The percentage of DO for the steps was approximately 70%, whereas the percent of DO for the pools was around 61% (O'Dowd and Chin, 2016). All of the other factors such as pH, conductivity, total dissolved solids (TDS) and temperature showed no significant difference between the steps and the pools. pH values were 8.2, TDS concentrations approximately 90 g/L, and the temperature around 13°C (O'Dowd and Chin, 2016).

In regards to what is considered "good" quality water and "poor" quality water these numbers would indicate that the quality of the water in these mountain creeks are relatively good. According to the Environmental Protection Agency (EPA) standard drinking water quality values, pH should be between 6.5 and 8.5 and that TDS should be no more than 500 mg/L (EPA, 2004). DO concentrations should be above 3 mg/L to support most aquatic life with the preference being at least 4 or 5 mg/L to be "good" quality (EPA, 2004). It is also important to note that higher stream temperatures are usually an indication of lower DO concentrations The temperatures in this study were on the lower side so it is reasonable that the concentrations of DO were elevated.

Zhang et al. (2014) conducted a study in the Wenxia River in Zhongxiang City, Hubei province of China and determined the effects of reaerating rivers *via* artificial step-pools and how this process affected the DO and temperature of the mountain streams. Zhang et al. (2014) theorized that by increasing the amount of turbulence in the river using an artificial step-pool system, that it would cause more air entrainment and increase DO concentrations. Measurements were collected at three different locations within the river (plane gravel, plane gravel + boulders and with the same water depth but different bed conditions. With the plane gravel, no matter how much discharge occurred at the point, DO levels were much higher in the morning than in the afternoon. The average change in DO level was 1.636 mg/L after reaeration (Zhang et al. 2014).

In the morning when discharge was low, the DO levels increased more than they did in the afternoon whereas the opposite effect occurred when discharge was vastly increased in the morning and afternoon. Typically, as discharge increases the turbulence from the step-pool will decline and, thus, the amount of entrained air will decline as well and negate the effect of morning atmospheric reaeration (Zhang et al. 2014). The average change for DO was 1.41 mg/L, which is slightly lower than the average for plane gravel (Zhang et al. 2014). The temperature of the river did not fluctuate enough for the Zhang et al. (2014) to go in detail in the study with the values remaining close to a zero degree change. This study is significant to the topic of how step-pools affect certain aspects of water chemistry because it demonstrates that step-pools do increase the DO levels and also that discharge has a significant effect on water chemistry as well.

Hines and Hershey (2011) incorporated a water quality element when studying step-pool sequences in rivers around Greensboro, North Carolina. This study is similar to the other two studies in that it examined the biophysical properties of the rivers. Specifically, the study looked at the ammonium uptake in restored mountain streams and compared it to streams that were unrestored in the same area. One way these streams were restored was adding step-pool sequences. Hines and Hershey (2011) found that the mean instream temperatures were approximately 1.8°C higher than the unrestored sites without step-pools (Hines and Hershey, 2011). They also found that the ammonium concentration levels in the restored streams were typically lower than those that were unrestored and that ammonium uptake was usually higher as well in the restored streams but those patterns were not statistically significant (Hines and Hershey, 2011). Interestingly, the study also found that according to the North Carolina Biological Index (NCBI) there was no statistically significant difference between the water quality of the restored site and the unrestored sites (Hines and Hershey, 2011). In fact, most of the restored sites even received a water quality rating of poor, including the ones with step-pools. This study is significant to the topic because it shows that the water quality of these step-pool sequences need to be evaluated to see what sort of impact they have on overall stream quality and health.

Problem Statement

The work will entitle to investigate whether or not step-pools have an impact on the water quality of mountain streams after the water has passed through a step-pool sequence.

Study Objectives

The primary objective of this study was to determine if step-pool sequences have any impact on mountain stream water quality. If this objective is proven to be true, it can influence future development projects and help with stream remediation for impaired streams. These projects could include developing new areas for stream recreation or planning for the stream water to be the source to irrigate a future park. The results could potentially indicate that by adding step-pools into streams, even if not naturally occurring, step-pools would have a positive effect on the stream for both water quality and vegetation. With clean, fresh water becoming increasingly scarce and highly sought after, any opportunity for current sources to be improved and better utilized will make a considerable difference for future water needs. Implementing step-pool systems in streams could not only help provide more drinking water sources for people, but also help create thriving ecosystems and biodiversity.

The secondary objective was that the results help fill the void where current research is lacking in regards to understanding certain aspects of stream health. When researching this topic that has not been extensively examined previously there was great anticipation that the results would reveal some new information about the subject. The data collected from this research could shed new light on aspects of stream health and quality that have not been considered in the past. Specific objectives of the study were to:

- Measure the physical characteristics of the pools and steps
- Determine the water chemistry of mountain streams in the San Juan Mountains

CHAPTER II

INFLUENCE OF STEP-POOL SEQUENCES ON MOUNTAIN STREAMS: SAN JUAN MOUNTAINS

Synopsis

The number of streams in the United States with poor water quality conditions continues to increase each year. With a spike in the number of streams needing water quality improvements, new ways of stream health remediation are becoming more necessary than ever. A water quality analysis was conducted on step-pool sequences in the San Juan Mountains, Colorado to determine whether or not they have a potential to improve stream health. Six creek sites surrounding the Uncompahgre River were tested for all of the following chemical and physical characteristics. The chemical characteristics tested were: pH, conductivity, total dissolved solids, dissolved oxygen, nutrients (nitrate-nitrogen and phosphate), sulfate, and total iron and the physical characteristics tested were: step-pool depth, width, length, elevation, stream velocity and stream discharge. All of these characteristics were compared and analyzed to determine if step-pool sequences had an impact on the stream water quality in those six creeks. The analysis determined that 1). There was no statistical difference between the water quality in the streams before water passed through the step-pool sequences and after the water had passed through the step-pool sequences, 2). The location of the step-pool sequences on either side of the Uncompahgre River had a significant impact on nitrate-nitrogen, sulfate, total dissolved solids, and conductivity, and 3). There were relationships and patterns between a few of the physical and chemical characteristics within the step-pools. The overall result of the study indicates that

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Introduction

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Methods

Study Area: Site Selection and Descriptions

The study area for this thesis is located in the San Juan Mountains of southwestern Colorado (Figure 1). The San Juan Mountains span approximately 31,000 km^2, with only one quarter of the area residing below 2,400 m in elevation (Cross et al., 1935). The region is split into east and west by the Continental Divide. The west side of the divide, where the study area is located, contains numerous headwaters of the Colorado River that drain to the Gulf of California

(Cross et al., 1935). The sprawling mountains make it an ideal location for locating step-pools. In the area, 6 creeks were selected as step-pool data collection sites.

These creeks are: Oak Creek (Figure 1), Portland Creek (Figure 2), Weehawken Creek (Figure 3), Mineral Creek (Figure 4), Bear Creek (Figure 5), and Red Mountain Creek (Figure 6). Each of these creeks were chosen based on access and sufficient step-pool sequences for data collection. Oak Creek and Portland Creeks are tributaries of the Uncompahgre River, which runs through the town of Ouray, CO. Bear Creek is also a tributary of the Uncompahgre River with its confluence south of Ouray, CO. Weehawken Creek is a tributary of Canyon Creek, which is a tributary of the Uncompahgre River. Red Mountain and Mineral Creeks lie to the south of Ouray (Figure 7). All watersheds are forested and most have hiking trails, camping and camping lodges and fishing.

Figure 1. Oak Creek step-pool sequence

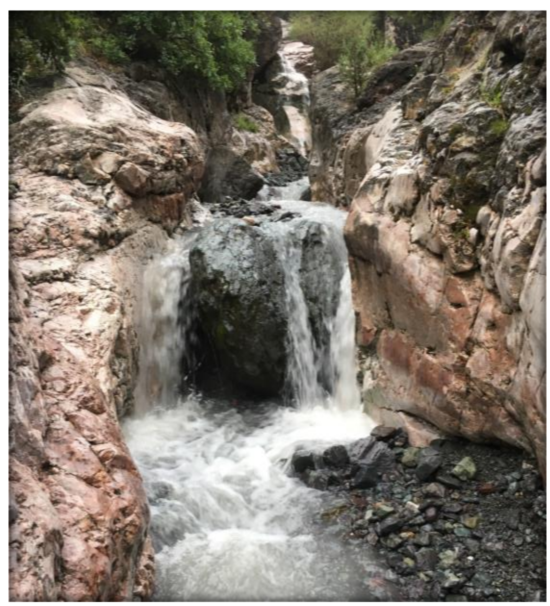

Figure 2. Portland Creek step-pool sequence

Figure 3. Weehawken Creek step-pool sequence

Figure 4. Mineral Creek step-pool sequence

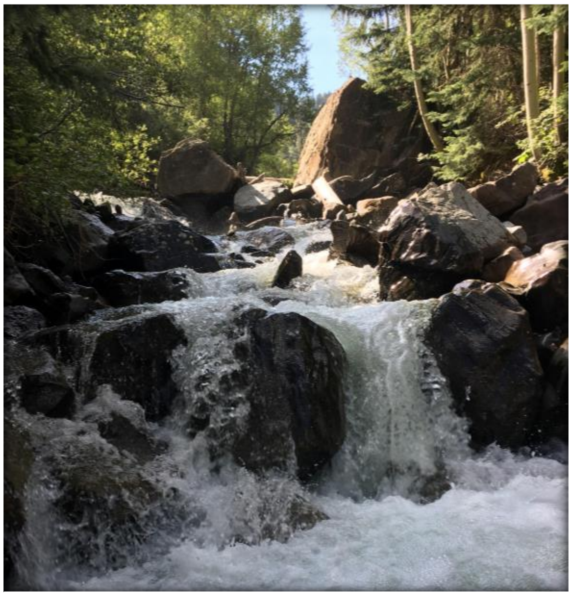

Figure 5. Bear Creek step-pool sequence

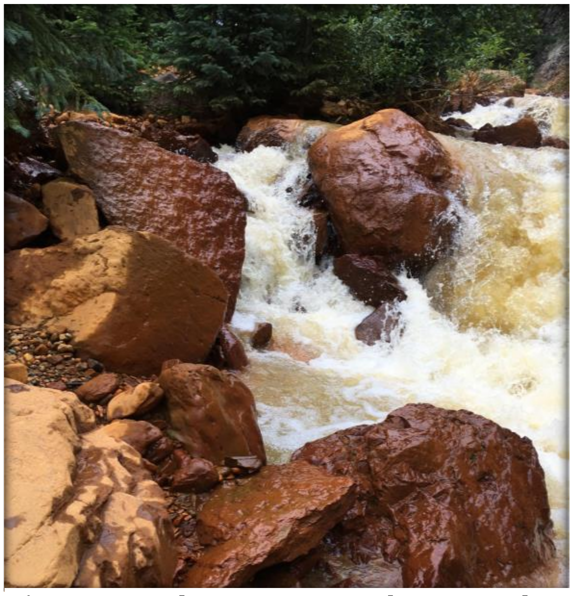

Figure 6. Red Mountain Creek step-pool sequence

Figure 7. San Juan Mountains, Colorado study area including all study sites: Oak Creek, Portland Creek, Weehawken Creek, Bear Creek, Red Mountain Creek, and Mineral Creek.

The geology of the region and thus the watersheds studied varies. Ouray was built in a glacial valley with the primary geology consisting of Precambrian quartzites and slates along with volcanic rocks (Blair, 1996). Nearby, the Bear Creek and Weehawken Creek watersheds share similar geology to the creeks in Ouray. The Red Mountain Creek and Mineral Creek watersheds differ from those close to Ouray because the rocks are red-brown and orange as a result of the presence of iron oxides. The other rock types in the region include breccias, pyroclasts of rhyolite, and quartz (Blair, 1996). In the 1880's, the Red Mountain Mining District was the second largest producer of silver in the United States (Runkel et al., 2005). When mining ceased in the 1900's, Red Mountain Creek became susceptible to acid mine drainage (AMD) (Runkel et al., 2005). AMD occurs when iron disulfide minerals (iron pyrite FeS_2) are exposed to air and water in mines and then the oxidized minerals runoff into nearby water bodies (Nordstrom and Alpers, 1999). For the Red Mountain Creek region, Runkel et al. (2005) found pH values in the creek as low as 2.9 (Runkel et al., 2005) in a 2002 United States Geological Survey (USGS) study. The headwaters of Mineral Creek are in Tertiary volcanic and silicic rocks. These rocks come from the caldera that Mineral Creek runs through. Church et al. (2007) found that Mineral Creek contributed 43 percent of the iron in the Animas River Basin. The presence of iron disulfides in multiple regions in the study area infers that the creeks are likely to have high TDSs, iron and sulfate concentrations as well as low pH. None of the creeks in the study are on Colorado's 303 (d) list for impaired waters (CDPHE, 2016).

Chemical Water Quality and Physical Testing

All six streams were used for water quality and physical testing. Within each stream at least three step-pools were examined as well as sections of the water above and below the step-pool sequences. Figure 8 summarizes every physical and chemical test that was conducted at each of the six creeks used in the study. Each of the tests were used on the stream sequences above and below the step-pool sequences, as well as the step-pools themselves.

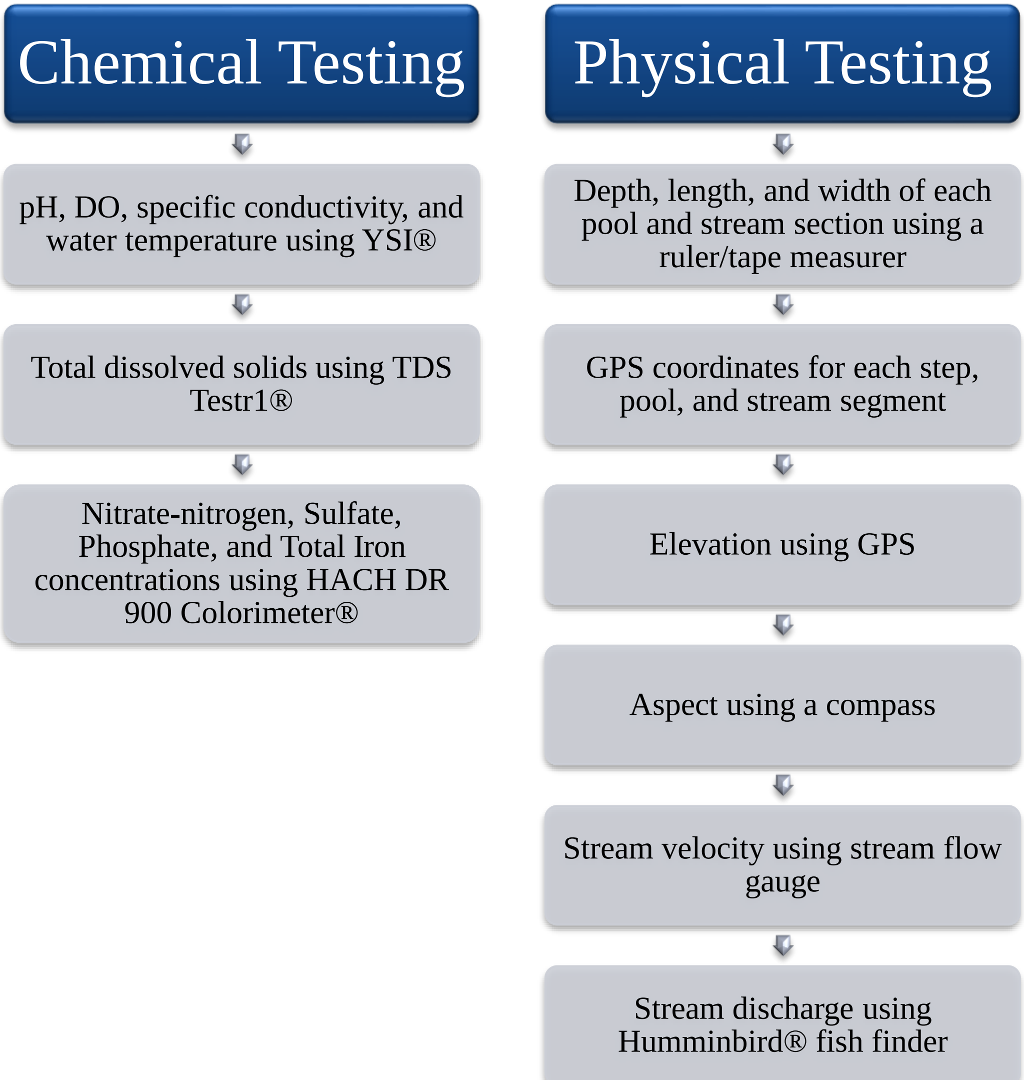

Figure 8. Summary of chemical and physical testing for step-pool and stream sequences within each examined creek.

Beginning with the section of each stream above the step-pool sequences, depth, length, and width were measured for each pool, step, and stream section. These depths and measurements were determined using a meter stick in the deepest part of the stream section (beginning and end) and each pool. The length and width of each step pool and stream section were then measured with a measuring tape. The distance between each pool and stream sections were measured using a measuring tape in order to approximate the distance of the entire step pool sequence within each creek. After recording the distances between each pool and stream section the average velocity of the stream was recorded using a velocity gauge. The end of the rod stuck down 1/3 of the depth of the deepest part of the stream.

Chemical water quality characteristics such as pH, conductivity, temperature, and DO in each portion of the step-pool sequence and stream were examined using an YSI® meter. Before use, the YSI was calibrated for both pH and DO to give accurate readings. The calibrated probes were placed in the stream sections and step-pools to determine all four measurements. Dissolved oxygen was recorded for both percent saturation and mg/L and between each use the YSI® probes was rinsed with distilled water to prevent false readings. A separate meter, TDSTestr1®, was used to examine total dissolved solids (TDS) in parts per million (ppm). The tip of the tester probe was rinsed with distilled water before being placed in each section of the stream.

A GPS unit was used to collect latitude, longitude, and elevation data for all step-pools and stream sections. This information was recorded using waypoints on the GPS unit. The top and bottom of each step-pool, as well as the stream sections above and below the step-pool sequences were recorded also as waypoints using the GPS. Along with position and elevation, the aspect of each step-pool and stream section was determined. Measuring the aspect of the step-pools and stream sections conveys which direction they are facing relative to north. To calculate the aspect, a compass was held against the body and the square end of the compass aimed down slope.

To test for nutrients nitrate-nitrogen and phosphate (NO_3-N and PO_4^{3-}), sulfate (SO_4^{2-}) and total iron (Fe_T) in the streams, a HACH DR 900 Colorimeter® was used. Nitrate-nitrogen is the amount of nitrogen in a nitrate ion. Before examining a stream or step-pool sample, a reagent blank was measured in the HACH DR 900 Colorimeter® and subtracted and from the stream sample results. For every portion of the study site, samples containing reagents for each of the four ions tested and the vials were cleaned with distilled water before proceeding to the next section of the system. To make testing for ions as efficient as possible, YSI® and TDSTestr1® data were collected simultaneously.

To test for NO_3-N, HACH DR 900 Colorimeter® program *355 N, Nitrate HR PP* was used. The sample cell was filled with 10 mL of stream water using a graduated cylinder. The nitrate powder pillow reagent was added to the sample and a one-minute timer was set to give the reagent time to react. While the timer was active the sample cell was shaken to help catalyze the reaction. The 10 mL blank sample of distilled water was prepared and when the second timer was completed the outside was cleaned and inserted into the cell holder. The prepared sample was also cleaned and within one minute of the timer expiring inserted into the sample holder and covered with the HACH DR 900 Colorimeter® cap to ensure no light exposure when the measurement was being read.

The program used to test for PO_4^{3-} is *490 P React PP*. The sample cell was filled with 10 mL of the stream sample and then the PO_4^{3-} powder pillow reagent was added to the cell. After shaking the sample cell for thirty seconds a two-minute reaction timer was set and the blank sample prepared again. When the timer expired the blank was inserted and the HACH DR 900 Colorimeter® zeroed. Once the instrument was zeroed the prepared sample was inserted into the cell holder, covered, and measured. A similar procedure was used to test for SO_4^{2-} and Fe_T. The program used for SO_4^{2-} is *680 Sulfate* and a five-minute instrument timer was set and the sample was kept still/undisturbed during that time. For Fe_T, the *265 Iron FerroVer* program was used and after the Fe_T reagent powder was added the sample was swirled to mix and a three-minute timer was set. Both SO_4^{2-} and Fe_T were measured in the same manner as PO_4^{3-} and NO_3-N once their respective timers were completed.

The last measurement taken in each creek after all other chemical and physical aspects were examined and recorded was a stream profile using a Humminbird® fish finder. The Humminbird® was connected to a 12 V battery and placed inside a bag to keep it dry while recording in the stream. To get the fish finder to record data, an SD card was used and inserted into the machine, so that it could later be exported and interpreted. The stream profile was captured for each creek (except for Bear Creek due to safety concerns) using the Humminbird® in snap shot and recording view. Waypoints were created at the top of the step-pool sequence when the fish finder was placed in the creek and while the probe was recording data it was dragged along the surface of the creek down the entire length of the sequence to capture the sonar view of the stream profile for calculating discharge.

Results

The Mann-Whitney U-Test ($\alpha = 0.05$) was used to determine if the water quality from above the step-pool sequences and below the step-pool sequences were statistically different. This included: pH, DO, TDS, conductivity, water temperature, nutrients (NO_3-N and PO_4^{3-}), SO_4^{2-} and Fe_T. A single-factor ANOVA analyses ($\alpha = 0.05$) was performed comparing the streams discharging into the eastern and western sides of the Uncompahgre River to determine if there was a statistical difference between chemical and physical characteristics of each side. Stream discharge for each creek was calculated by multiplying the average velocity, the creek width, and the average depth calculated from the Humminbird® sonar data. The discharge data was used in the ANOVA analyses. Length, width, depth, and elevation of the step-pools were compared to the chemical characteristics using a regression model to see if there were any patterns in water quality. The chemical characteristics were also compared with each other in a regression analyses. Tables of the data collected for each parameter for each creek are summarized in Appendix A.

Mann Whitney U-Test Between Upstream and Downstream Water Quality

All nine water quality characteristics were tested and none yielded a significant result. Temperature (°C) was the only characteristic that was close to being considered significant. Box plots for each characteristic were created as a visual representation of the differences between the upstream and downstream values (Appendix B).

Single-Factor ANOVA Analyses between Eastern and Western Discharging Creeks

As previously stated, the purpose of the single-factor ANOVA analysis was to determine if there were statistical differences between characteristics of creeks discharging from the east and west into the Uncompahgre River. The results of this test yielded four characteristics that had a statistical difference between the eastern and western creeks. These characteristics were: NO_3-N, SO_4^{2-}, conductivity, and TDS. Tables 1-4 show the results of the ANOVA analyses.

Table 1. NO_3-N ANOVA analyses

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	71.51845	1	71.51845	6.144377	0.019244	4.182964
Within Groups	337.5501	29	11.63966			
Total	409.0685	30				

Table 2. SO_4^{2-} ANOVA analyses

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	1610.035	1	1610.035	8.405023	0.007876	4.259677
Within Groups	4597.35	24	191.5563			
Total	6207.385	25				

Table 3. Conductivity ANOVA analyses

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	131671.2	1	131671.2	19.9917	0.00011	4.182964
Within Groups	191002.5	29	6586.292			
Total	322673.6	30				

Table 4. TDS ANOVA analyses

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	102773.3	1	102773.3	17.40013	0.000251	4.182964
Within Groups	171287.5	29	5906.466			
Total	274060.8	30				

Regression Analyses for Water Quality and Physical Characteristics

For the regression analysis, 90 graphs were created comparing all physical characteristics with the chemical characteristics as well as all the chemical characteristics with each other. When doing the analyses, only the step-pool data (not the upstream or downstream values) were used in the comparisons.

The following 13 graphs were chosen for having the most impactful visual groupings for specific characteristic combinations and/or because there were multiple creeks that showed strong relationships (either positive or negative with an R^2 value greater than 0.9) between the characteristics. The Red Mountain Creek data values were plotted separately in these sections in order to eliminate outliers because there is evidence of AMD influencing the water quality. The remaining graphs can be found in Appendix C.

Chemical vs. Physical Characteristics

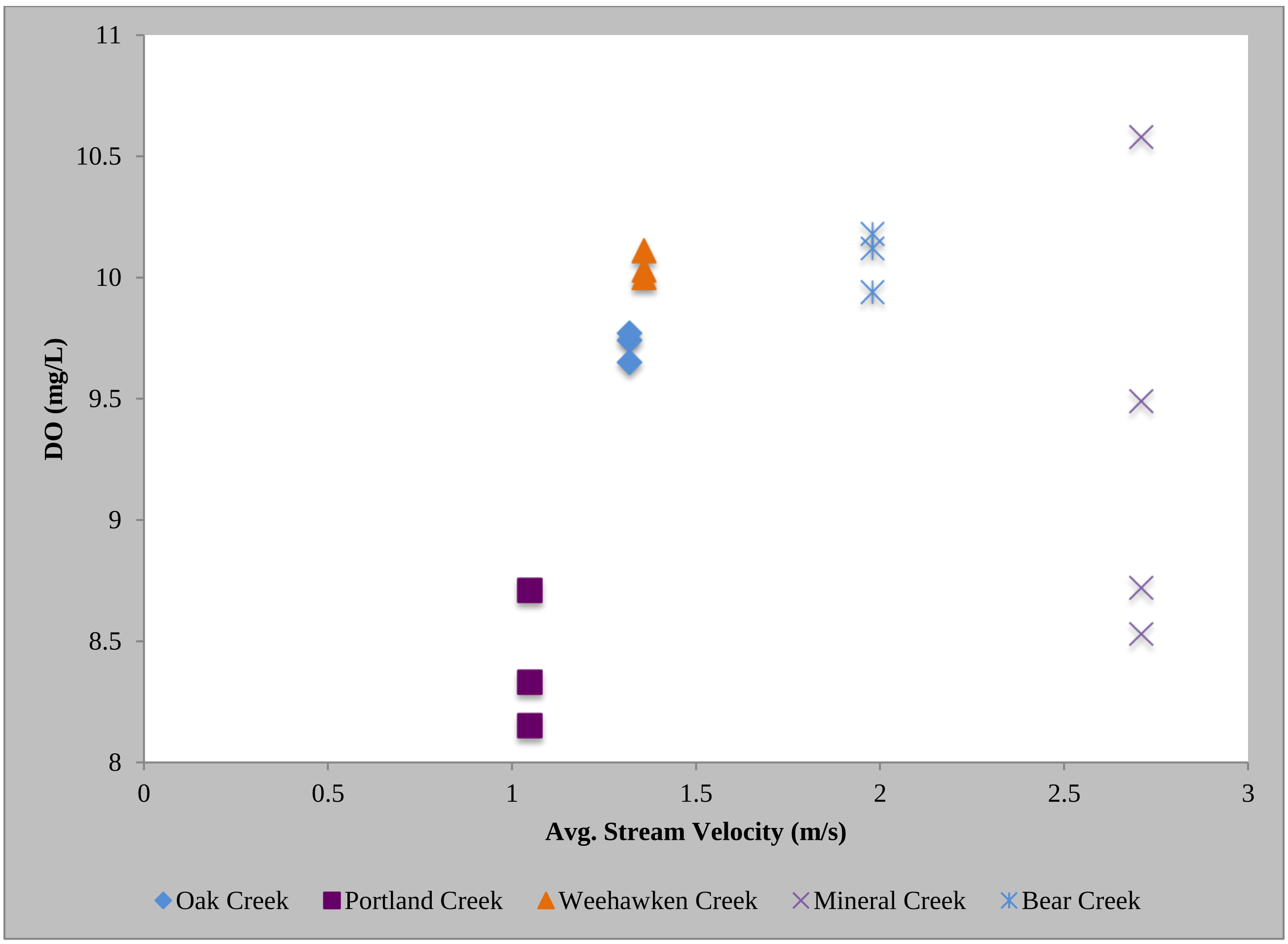

Figure 9. Step-pool dissolved oxygen concentrations compared to average stream velocity

When comparing DO concentrations to average stream velocity, the resulting pattern indicates that the greater the stream velocity, the higher the DO concentration is (Figure 9). Positive and negative relationships were ignored for this graph because the average stream velocity was the same value for each step-pool. The following figure (Figure 10) depicts the values for Red Mountain Creek.

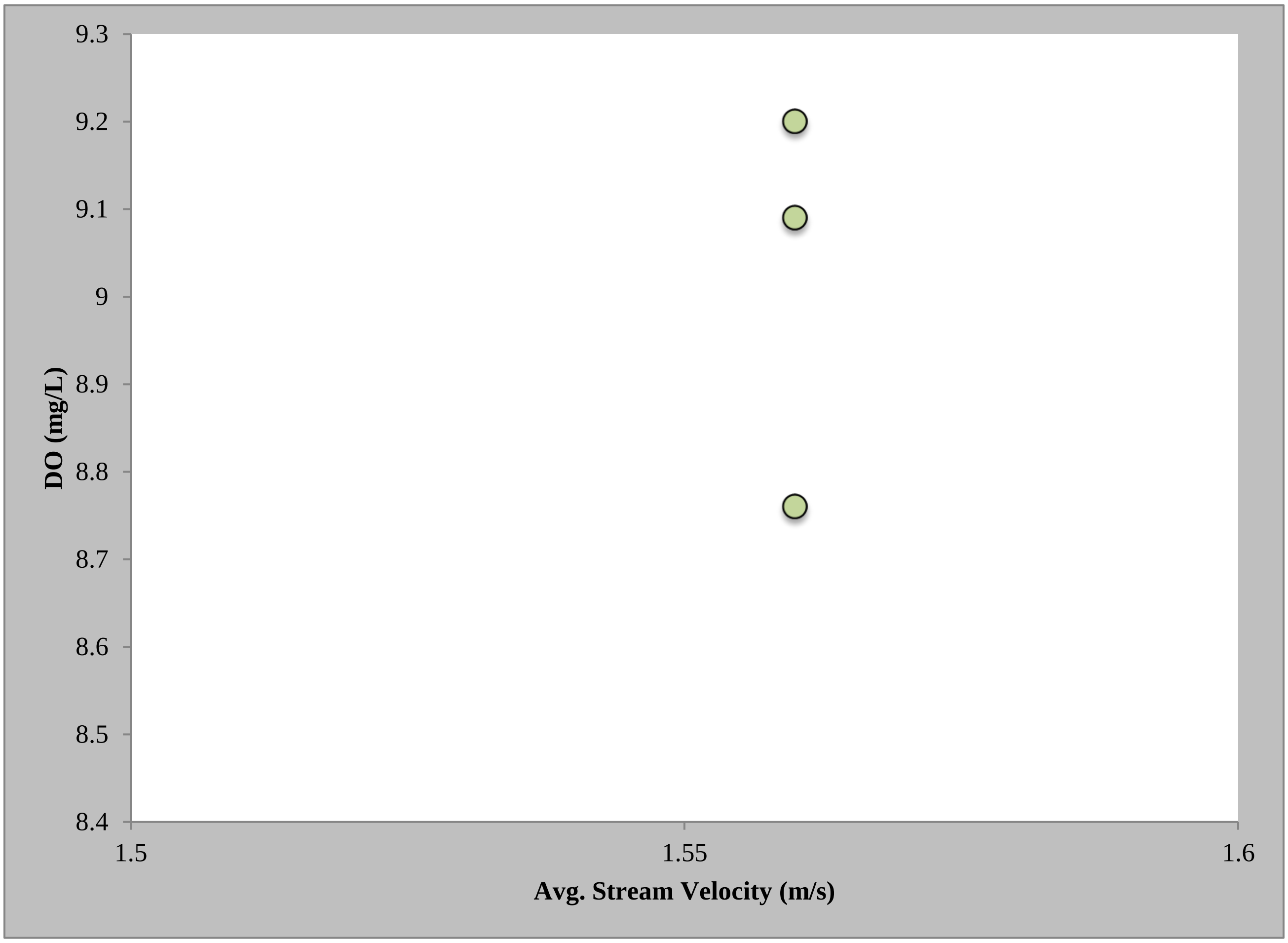

Figure 10. Red Mountain Creek step-pool dissolved oxygen concentration compared to average stream velocity

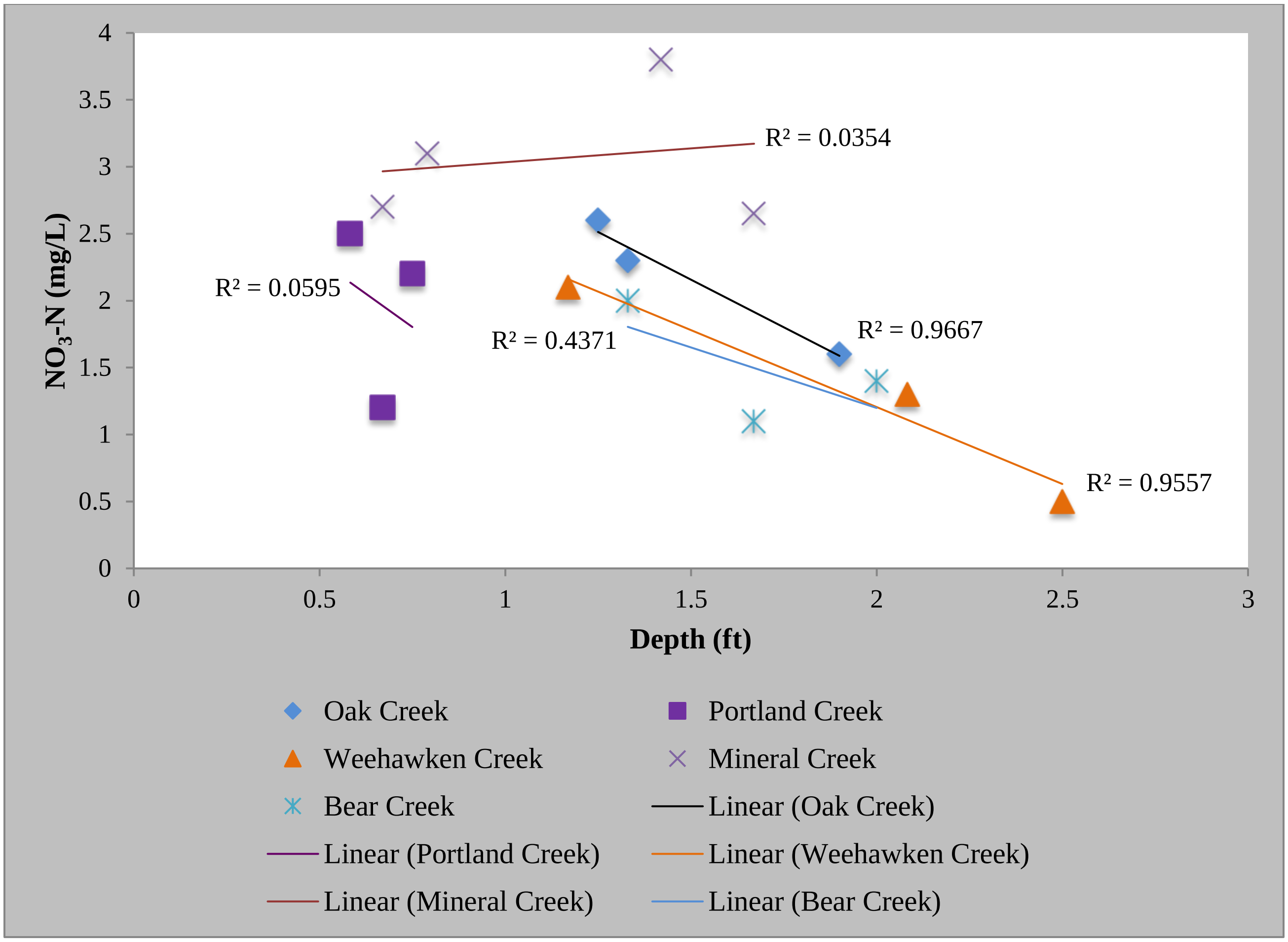

Figure 11. Step-pool nitrate-nitrogen concentrations compared to step-pool depth

The comparison of NO_3-N concentration and step-pool depth demonstrated a visual pattern in which as the depth of the step-pools increase the NO_3-N concentrations are decreasing (Figure 11). There were two creeks (Oak Creek and Weehawken Creek) that show a strong relationship (negative) between NO_3-N concentration and depth. However, the Red Mountain Creek data (Figure 12) shows a strong positive relationship.

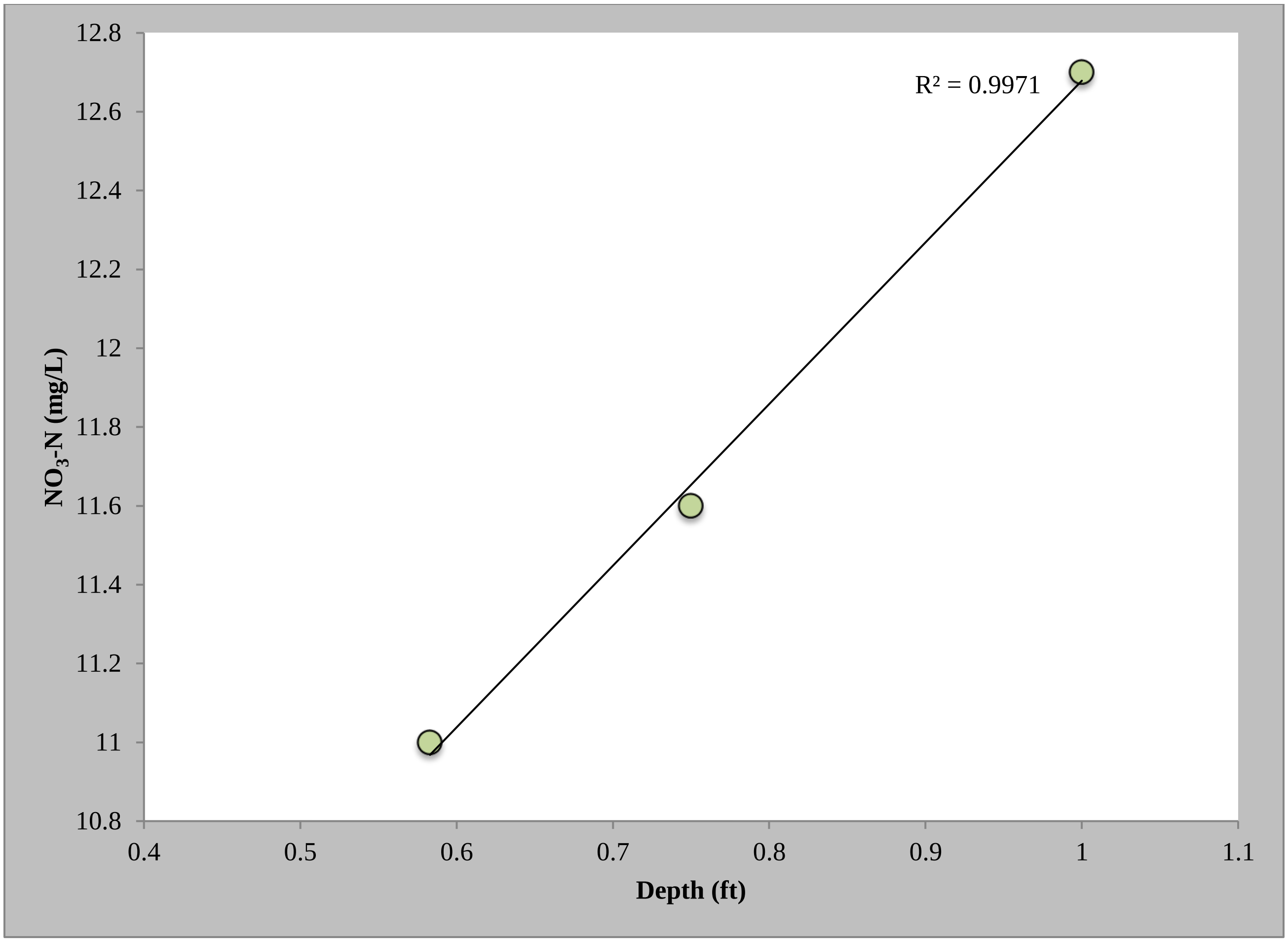

Figure 12. Red Mountain Creek step-pool nitrate-nitrogen concentration compared to step-pool depth

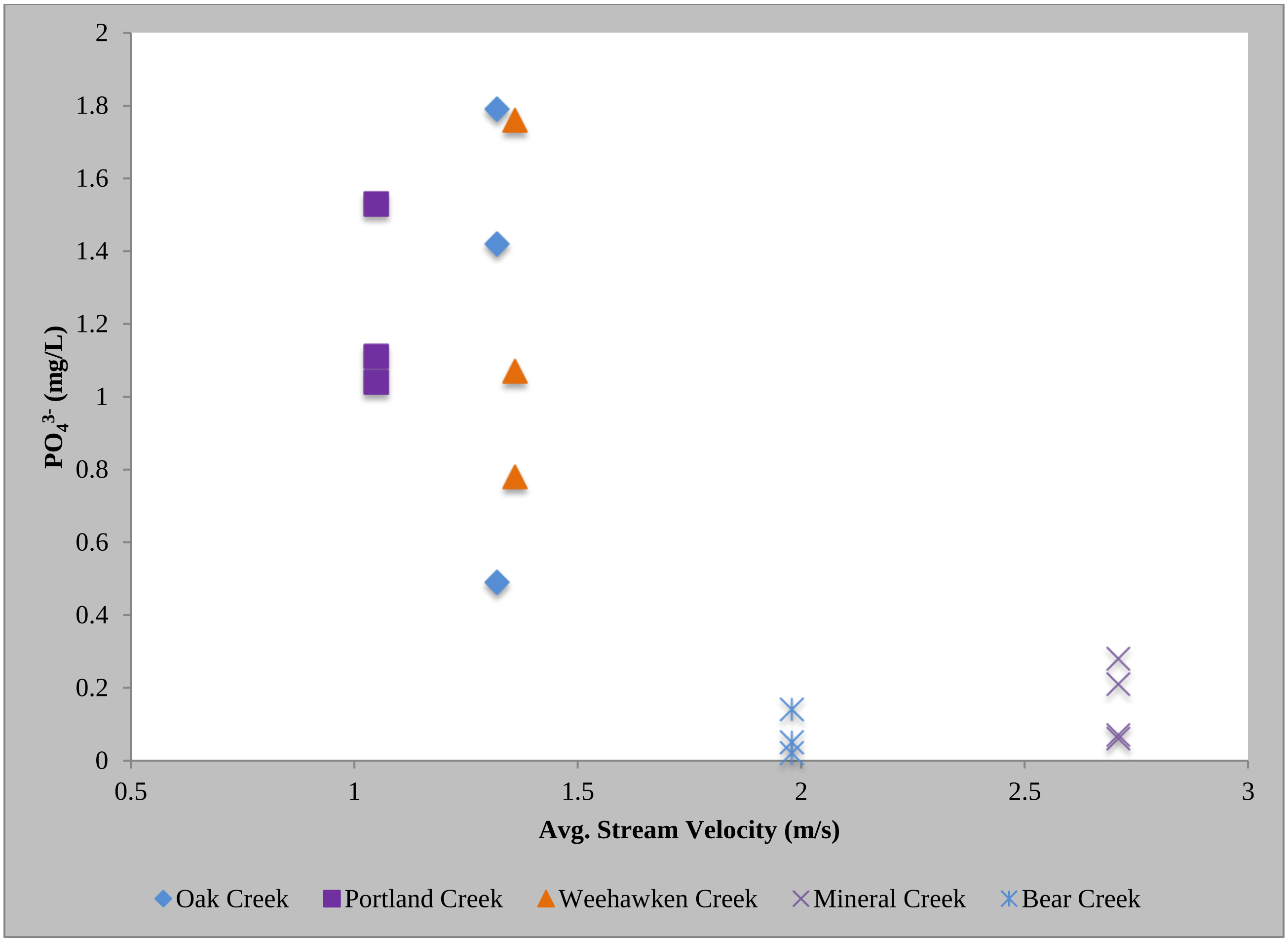

Figure 13. Step-pool phosphate concentrations compared to average stream velocity

There was only one PO_4^{3-} and physical comparison that showed a clear visual pattern, which was the comparison of PO_4^{3-} and average stream velocity. In Figure 13, as PO_4^{3-} concentrations are decreasing, average stream velocity values are typically increasing. Only Oak Creek showed a strong relationship (positive) between the two characteristics. Another observation that can be made is that the creeks with larger differences in the PO_4^{3-} concentrations also had higher overall PO_4^{3-} concentration values. There were no strong positive or negative relationships because the stream velocity is the same for all the step-pools. The following figure (Figure 14) depicts the Red Mountain Creek data.

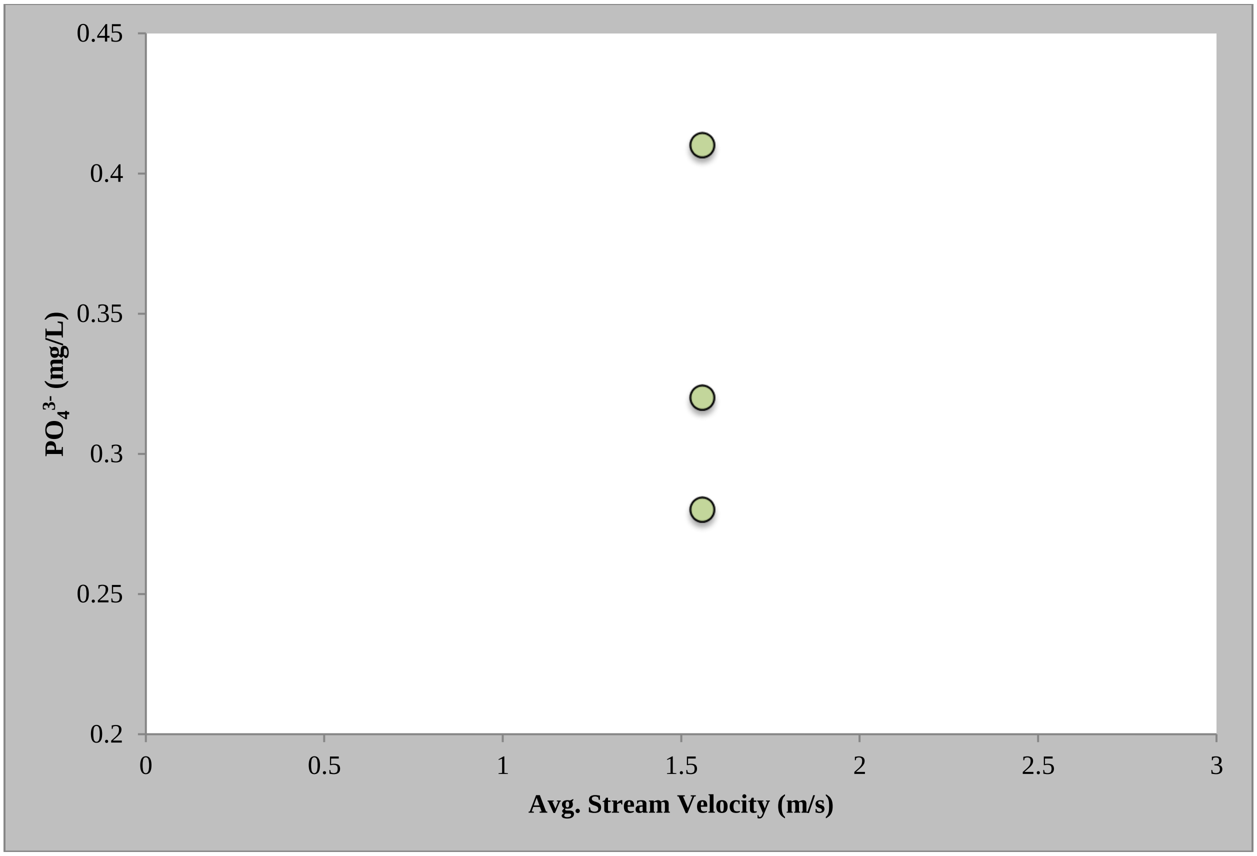

Figure 14. Red Mountain Creek step-pool phosphate concentrations compared to average stream velocity

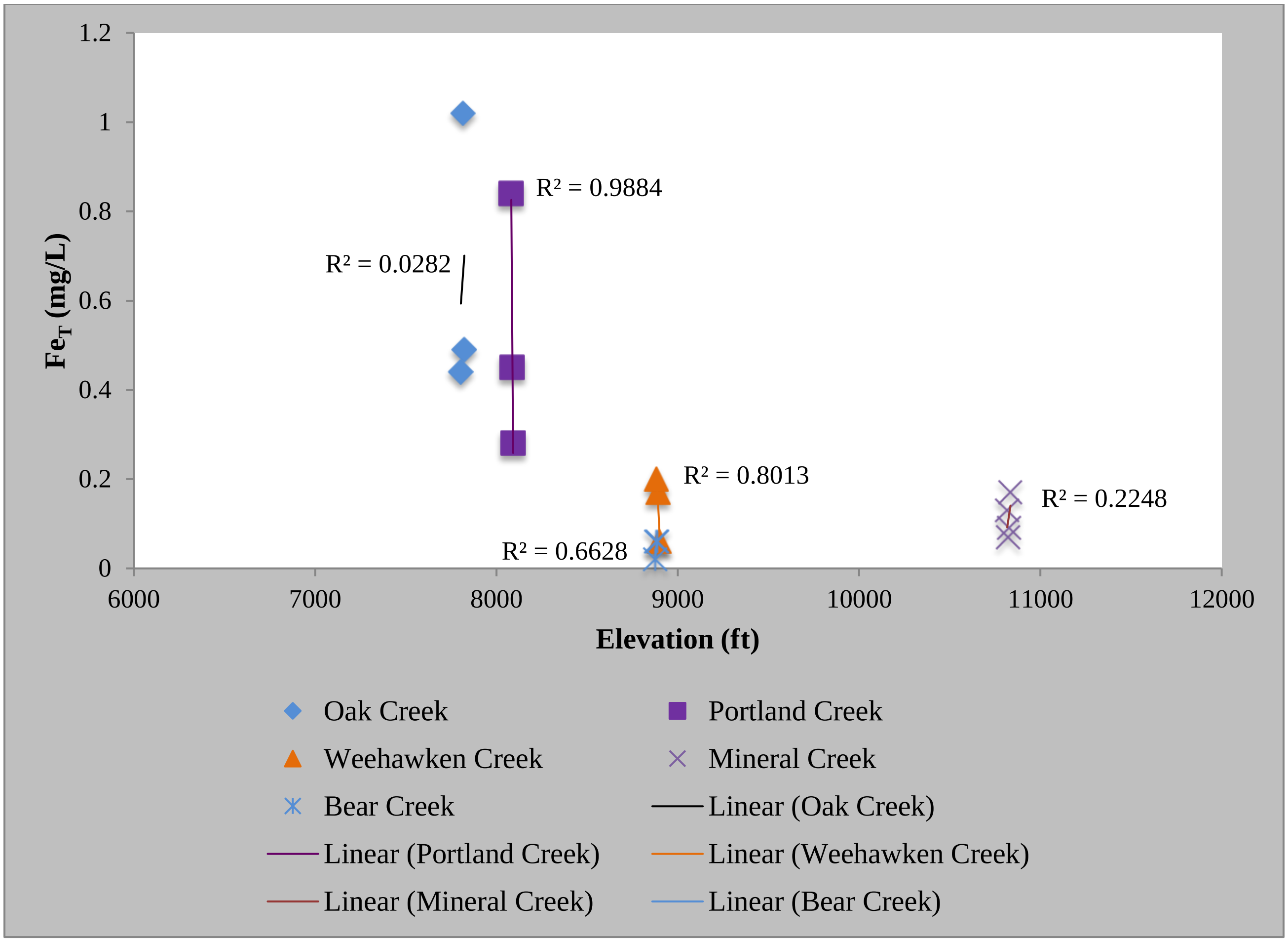

Figure 15. Step-pool total iron concentrations compared to step-pool elevation

For Fe_T concentration versus elevation, the general trend appears to be as the elevation increases the Fe_T concentrations are decreasing (Figure 12). Only Portland Creek data points showed a strong relationship (negative) during the regression analysis. There is no Red Mountain Creek data for Fe_T because the Fe_T concentrations were too high for the HACH DR 900 Colorimeter® to record. The HACH DR 900 Colorimeter® has can only record up to a maximum of 3.0 mg/L for Fe_T.

Chemical Characteristics vs. Chemical Characteristics

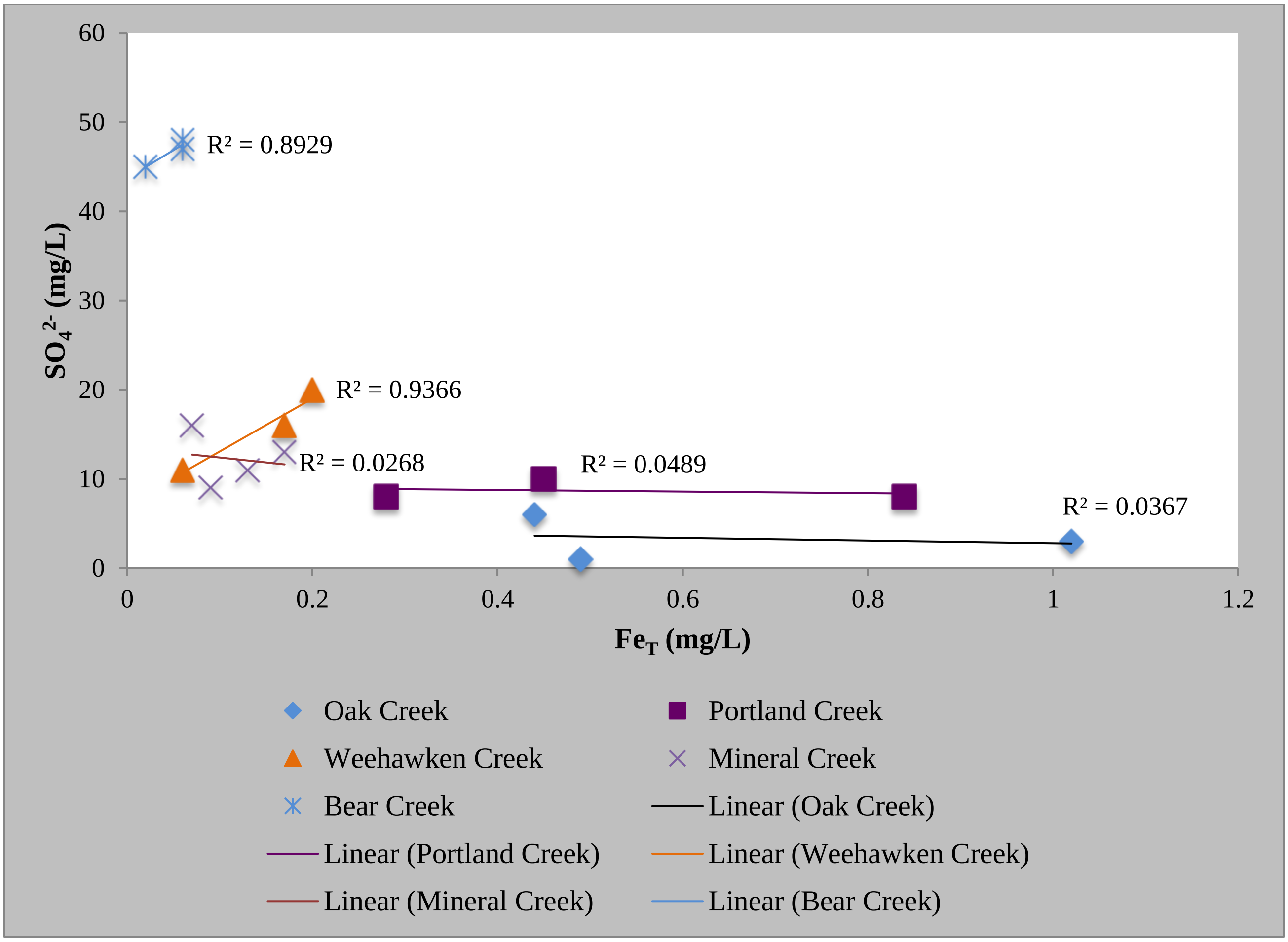

Figure 16. Step-pool sulfate concentrations compared to step-pool total iron concentrations

This comparison of SO_4^{2-} and Fe_T has an overall negative relationship between SO_4^{2-} and Fe_T. Both Portland Creek and Oak Creek show a similar pattern of having the highest Fe_T concentrations while also having most of the lowest SO_4^{2-} concentrations (Figure 16). Red Mountain Creek was not included because both the SO_4^{2-} values and the Fe_T values were too high for HACH DR 900 Colorimeter® to record. The maximum value that the HACH DR 900 Colorimeter® can record for sulfate is 70 mg/L.

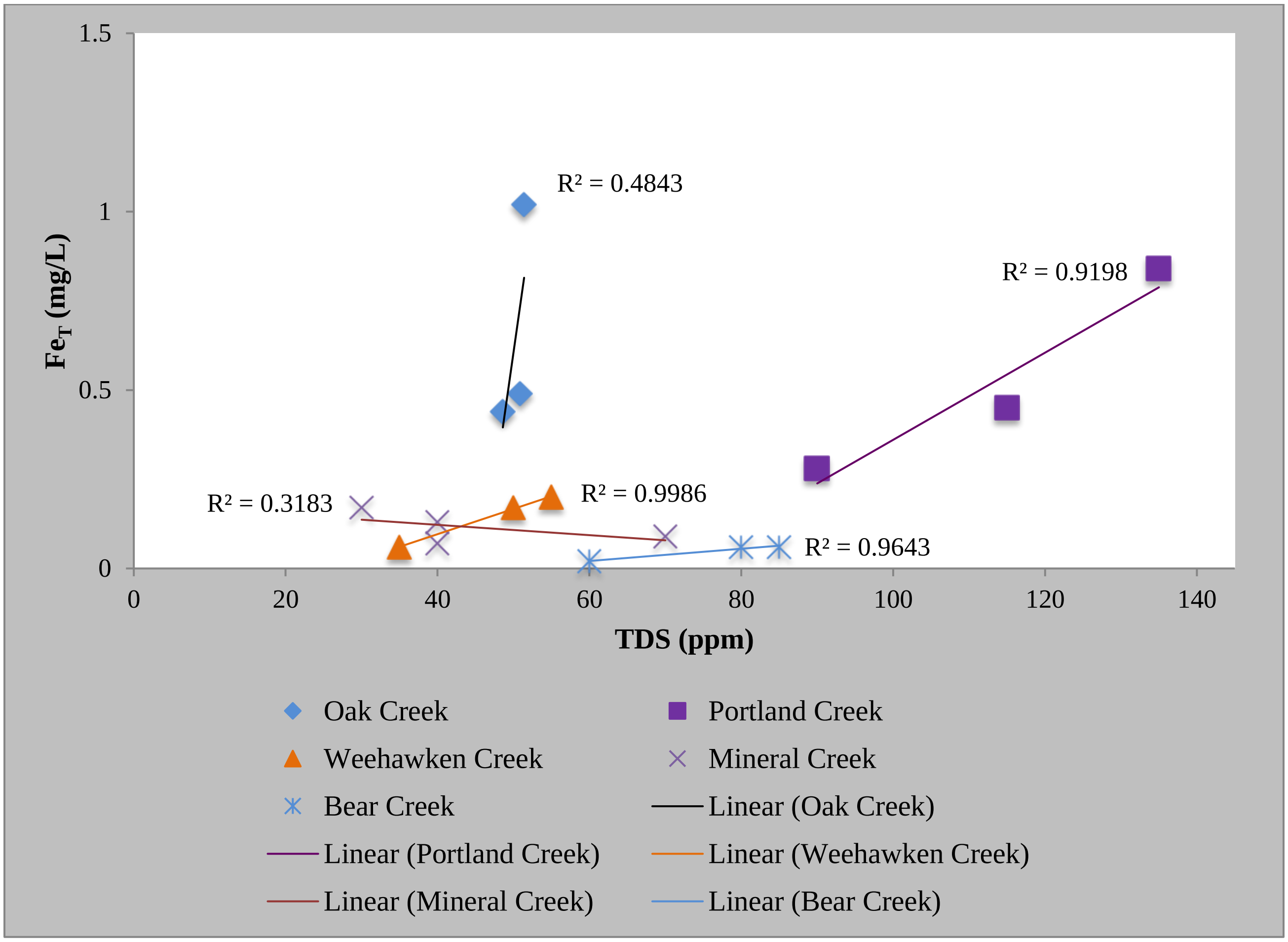

Figure 17. Step-pool total iron concentrations compared to step-pool total dissolved solids concentrations

Figure 17 is one of the few graphs that had more than two creeks showing strong relationships during a comparison. The graph comparing Fe_T with TDS depicts a strong positive relationship in which Fe_T and TDS are both increasing with one another. The three creeks that show strong relationships are Portland Creek, Weehawken Creek, and Bear Creek. Red

Mountain Creek data points were not included because the instrument could not record the high Fe_T values.

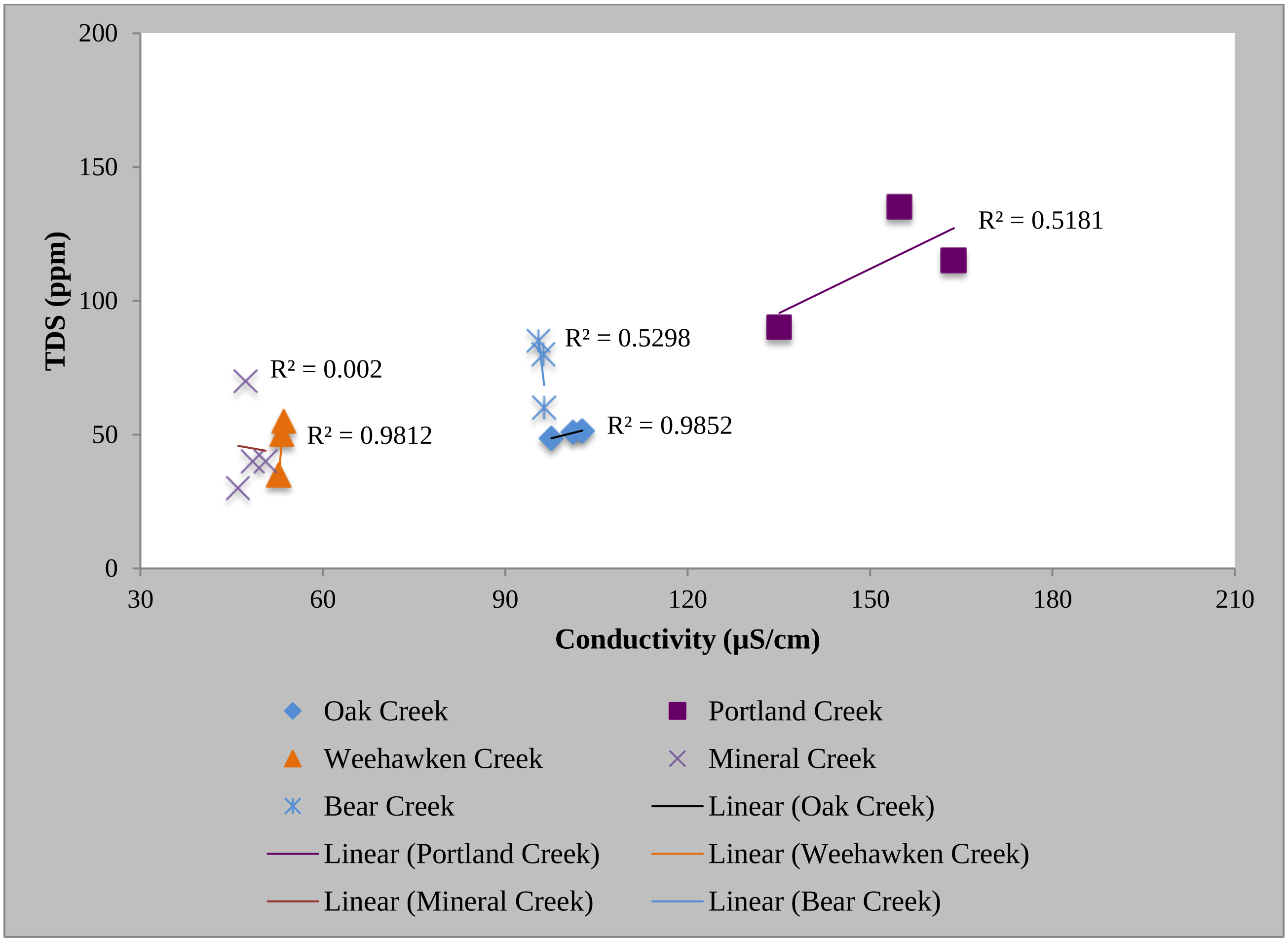

Figure 18. Step-pool total dissolved solids concentrations compared to step-pool conductivity

Figure 18 depicts a clear positive relationship between TDS and conductivity. In this figure, TDS is increasing as conductivity is increasing. There were also two creeks (Weehawken Creek and Oak Creek) that had strong positive relationships, which helps support this assumption. The Red Mountain Creek data (Figure 19) shows a positive relationship.

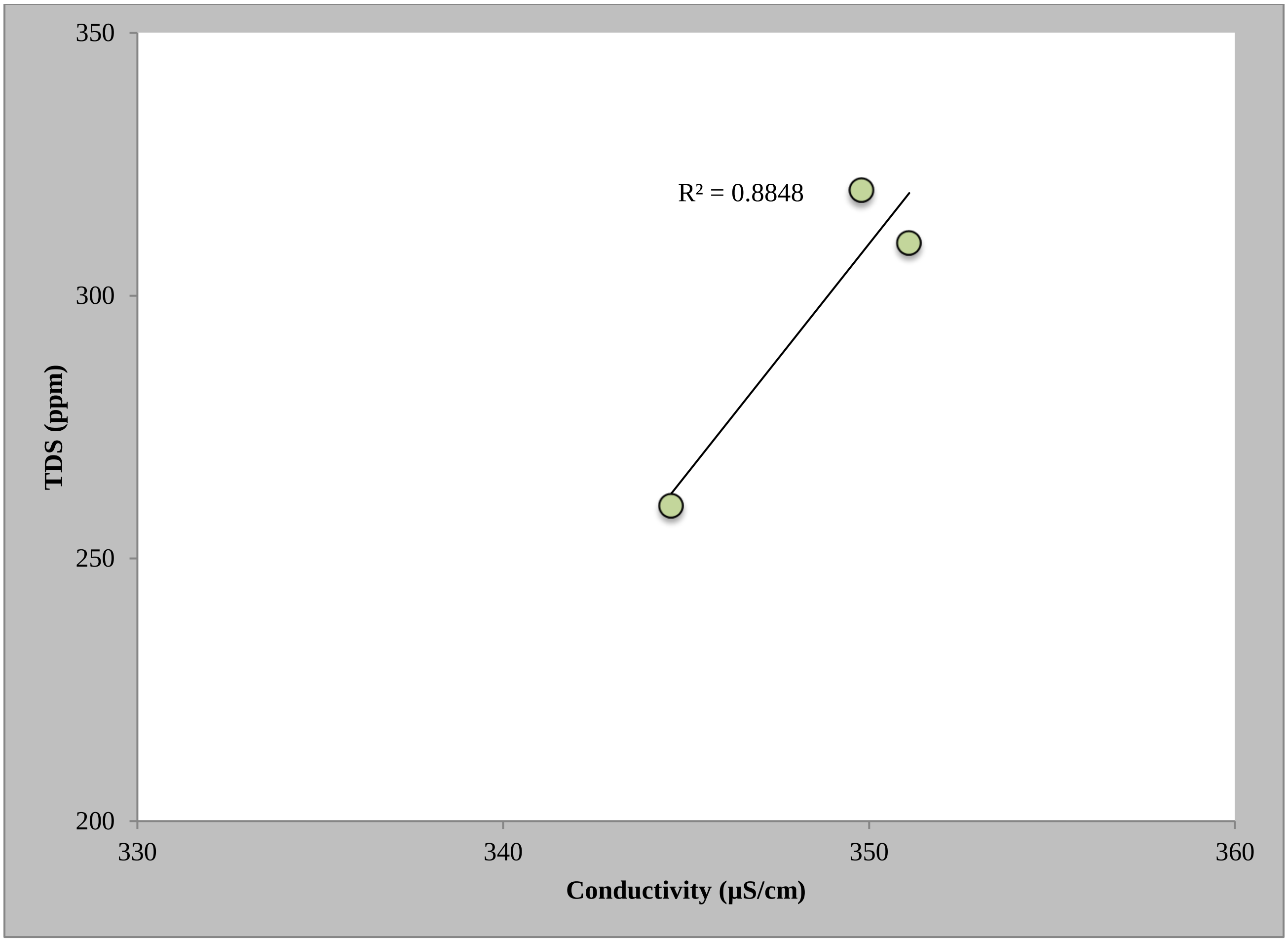

Figure 19. Red Mountain Creek step-pool total dissolved solids concentrations compared to step-pool conductivity

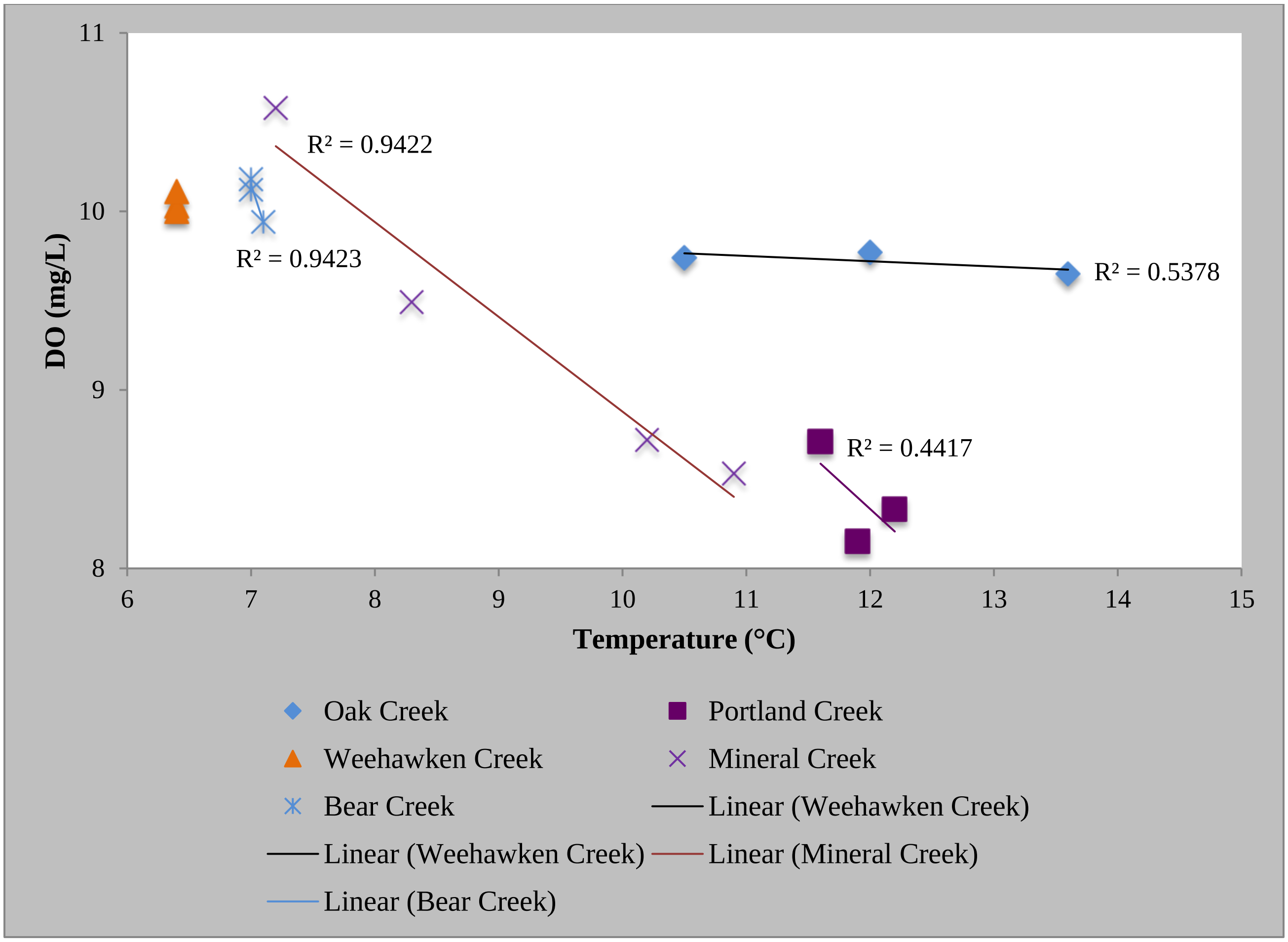

Figure 20. Step-pool dissolved oxygen concentrations compared to step-pool temperatures

The final chemical characteristic versus chemical characteristic comparison that shows a pattern is the DO concentration of step-pools versus step-pool temperature. Figure 20 shows a pattern of increasing pool temperature leading to decreasing DO concentration. There were two creeks that had strong relationships and both were negative. These creeks were Bear Creek and Mineral Creek. The R^2 value for Weehawken Creek temperature is not shown because the temperature for all three step-pools in the sequence was the same. Red Mountain Creek data (Figure 21) shows a positive relationship.

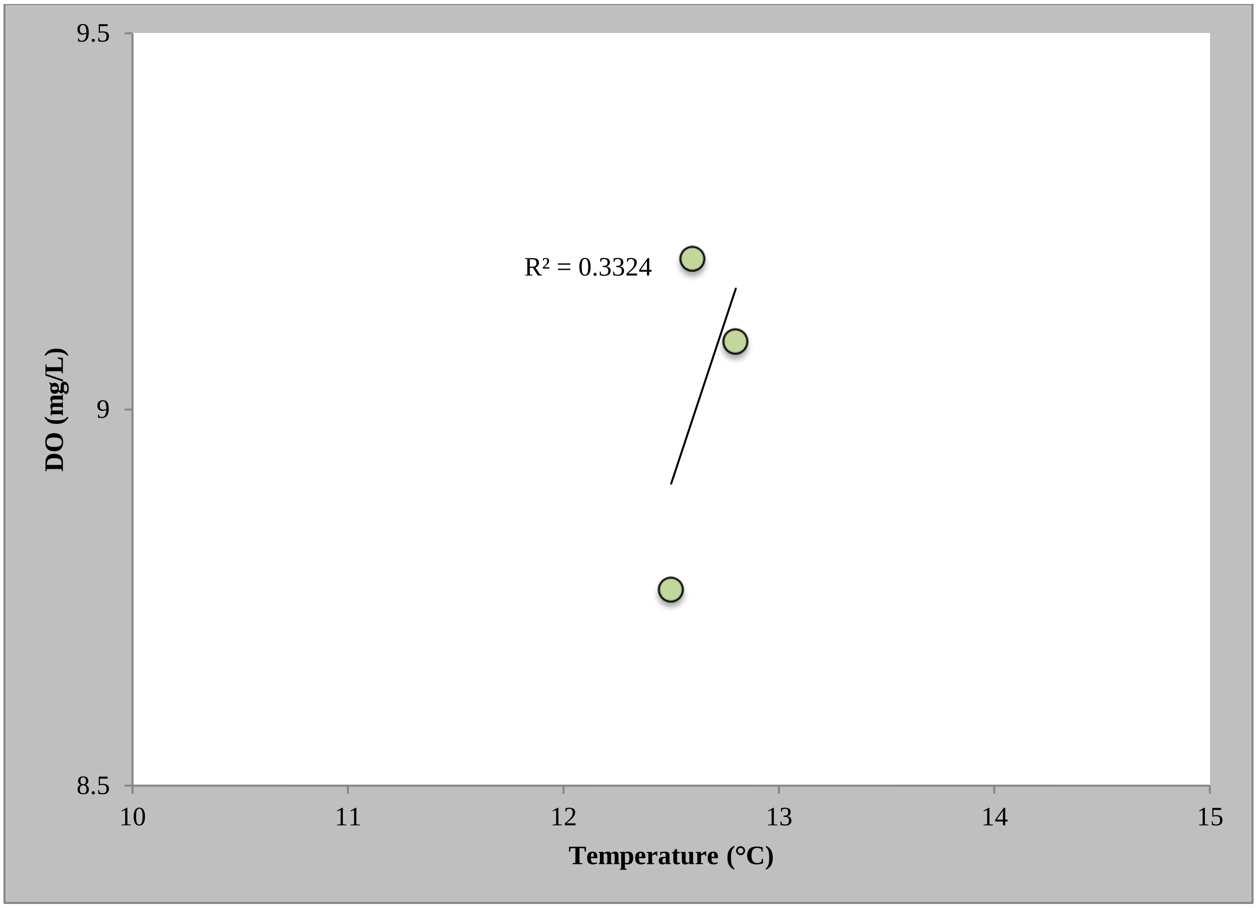

Figure 21. Red Mountain Creek step-pool dissolved oxygen concentrations compared to step-pool temperatures

Discussion

Improvement of Stream Water Quality as Water Moves Through the Step-pool System

The findings of the Mann Whitney-U Test indicate that there is no statistical difference between the quality of the stream water before flowing through the step-pool sequence and after the water has passed through the sequence. The assumption can be made that the step-pool sequences do not have a direct impact on the improvement of stream water quality. In fact, many of the tables in Appendix A show that the data points after the step-pool sequences frequently had higher water quality characteristic values than those before the step-pool sequence.

The Influence of Location on Step-Pool Water Quality

The first-order ANOVA test was conducted to determine if the streams draining into the Uncompahgre River from the west have different water quality characteristic values than those draining from the east. The findings of the ANOVA indicated that four characteristics did show a difference between the water quality data values. These characteristics were NO_3-N, SO_4^{2-}, conductivity, and TDS (Tables 1-4). As previously stated, step-pool sequences do not seem to have a direct influence on the stream water quality data, which indicates that there are other factors influencing the water quality in the region. When comparing the east side of the Uncompahgre to the west, there are some differences in land use/cover.

Land use/cover in the Ouray area can primarily be divided into three groups: developed, historic mining districts and forested areas. Figure 22 depicts all the historic mining districts in the Ouray area. A notable difference between the land use/cover where the creek sites are located on the eastern side of the Uncompahgre compared to the western side is that the eastern side has more creek sites in historic mining districts (Ouray County, 2015). Both Red Mountain Creek and Portland Creek are in historic districts (Red Mountain district and the Ouray district) compared to just Oak Creek (Ouray district) being located in a historic mining district on the western side of the Uncompahgre. The fact that a majority of the creeks on the eastern side of the river are located in these historic mining districts could be the reason that TDS, conductivity, and SO_4^{2-} concentrations are higher on the eastern side. Mining operations can cause increases in the concentrations of TDS, conductivity, and SO_4^{2-} from weathering and oxidation of exposed iron pyrite. NO_3-N concentrations may be higher on the eastern side of the Uncompahgre River because residents of the Ouray area use more fertilizers on their lawns on that live on that side of the river.

Relationships in Stream Water Quality Data for Step-Pools

As anticipated, there were many patterns and relationships between the characteristics in the step-pool sequences, both physical and chemical. Out of the 90 regression graphs generated for the comparison, only 13 (including the separate Red Mountain Creek graphs) were considered for further analysis due to the presence of strong relationships. Although most of the graphs in Appendix C depicted interesting relationships and patterns, they were not as strong as the relationships chosen for further analysis.

The first relationship analyzed was DO compared to average stream velocity. The general trend that can be seen in the graph is positive, with DO concentrations increasing in the step-pools as the stream velocity increases (Figure 9). Streams without step-pool sequences demonstrate the same pattern. When the stream water is moving quickly, it becomes aerated by turbulence as it moves over rocks, which creates oxygen bubbles that dissolve into the water (Murphey, 2007). Because the step-pool streams create a lot of turbulence when the water falls from the steps to the pools the process helps further oxygenate those pools. The faster the water is falling from the steps, from increasing stream velocity, the more turbulence in the pools as well as higher DO concentrations.

The Red Mountain Creek data in Figure 10 shows the DO concentrations being lower than Weehawken and Oak Creek concentrations, even though it has a higher average stream velocity. This can be explained by the precipitation of ferric iron (Fe^{3+}) from either AMD or weathering of iron rich soils in the area. When ferrous iron (Fe^{2+}) is exposed to oxygen in surface water it is oxidized into Fe^{3+}. The Fe^{3+} then precipitates as Fe^{3+} oxyhydroxides also known as iron floc, the orange precipitate commonly found in streams affected by AMD (Hustwit et. al, 1992). The oxidation process of forming the iron floc consumes oxygen, thus lowering DO levels in streams. Red Mountain Creek will comparatively have lower DO even it is moving more quickly because it is likely using up some of that oxygen to oxidize Fe^{3+}.

The next chemical and physical characteristic comparison had two creeks (Weehawken and Oak Creek) with strong negative relationships (Figure 11). The comparison was between NO_3-N and step-pool depth and yielded an overall negative trend with NO_3-N decreasing with the increase of step-pool depth. There is not an obvious explanation for this relationship in the step-pools. This could be a result of how the NO_3-N concentrations were sampled in field. The sample was collected as close to the bottom of the step-pools as possible. When the pools are less deep, the sample is taken closer to the surface than the deeper pools. It is possible that the majority of the NO_3-N concentrations are closer to the surface and do not reach deeper areas before continuing down the stream. Red Mountain Creek showed a strong positive relationship between the two characteristics (Figure 12). A reason for the relationship being positive could be that there is more aquatic plants in the deeper step-pools, which is causing an increase in NO3-N, but it is difficult to determine definitively with a limited data set.

Another average stream flow comparison that depicted a strong visual pattern was the comparison with PO_4^{3-} (Figure 13). The overall trend of the graph is negative, with average stream flow increasing as PO_4^{3-} concentration decreases. Previous research has found that phosphorus levels increased as water velocity increased, which is the opposite of the relationship seen in the creeks with step-pool sequences (House et. al, 1995). One explanation as to why PO_4^{3-} is decreasing as average stream velocity increases in step-pools could be that when the stream water is moving more quickly, it is more difficult for the PO_4^{3-} to settle at the bottom of the pools where the sample was collected. This could cause the concentrations at the bottom of the pools to be lower when stream velocity is higher. If the Red Mountain Creek data points (Figure 14) were added to Figure 13 it would fit in with the overall trend of the other creeks.

The final chemical and physical characteristic comparison that stood out during the analysis was Fe_T concentration in the step-pools compared to step-pool elevation. The graph depicts and overall negative trend with Fe_T concentration decreasing with increasing elevation (Figure 15). The most probable explanation for this relationship is that weathering and stormwater runoff are transporting Fe_T particles from higher elevations to lower elevations through gravity. As the runoff is traveling from the higher elevations to the lower elevations it is collecting more Fe_T particles and the accumulation of all of the particles is creating high concentrations in the step-pools in the lower creeks.

The second part of the regression analysis was the chemical versus chemical characteristic analysis. The first relationship to discuss is the comparison between Fe_T and SO_4^{2-}. Weehawken Creek is the only creek to have a strong relationship, which is positive, but the remaining creeks show an overall negative trend between the characteristics (Figure 16). Usually the two characteristics are most commonly linked in literature when AMD is occurring because both can come from the oxidation of iron pyrite. Location of the step-pools may be the cause of this negative relationship. Portland Creek and Oakland Creek are the closest creeks to town both have the lowest sulfate concentrations compared to Fe_T. this could be because the soils near the town contain clay and iron has a common relationship with clay. Iron can be an essential ion in clay mineral structure or adhered to the outside of the mineral as an oxide (Carroll, 1958).

The chemical versus chemical relationship that had the most strong relationships, positive or negative, out of any other was the comparison of Fe_T and TDS. Weehawken, Bear, and Portland Creek all showed strong positive relationships along with an overall positive trend in which Fe_T and TDS are both increasing simultaneously in the step-pools (Figure 17). One explanation for the strong positive relationship between TDS and Fe_T is that weathering is a major source for both characteristics in the study area. The most common source of TDS is the weathering of sedimentary rocks, which are common in the Ouray area (Miller, 2002). When weathering is occurring both TDS and Fe_T are likely running off into the step-pools at the same time creating the positive relationship.

The next comparison of TDS and conductivity yielded an overall positive relationship with two creeks (Oak and Weehawken) having strong positive relationships (Figure 18). The relationship between TDS and conductivity has been well documented in literature regarding stream water quality. Conductivity is the water's capability to pass electrical flow using ions in the water (Conductivity, Salinity & Total Dissolved Solids, 2016). The more ions that are present, the higher the stream water conductivity will be. Total dissolved solids are a summation of all ion particles smaller than 2 microns (Conductivity, Salinity & Total Dissolved Solids, 2016). Based on the definitions of both characteristics, the assumption can be made that conductivity is increasing when TDS are increasing because the amount of ions are increasing in the step-pools. The Red Mountain Creek graph (Figure 19) showed a positive trend between the two characteristics but the values for TDS and conductivity are much higher than the other creeks. Sulfate is a common ion in TDS, and with SO_4^{2-} concentrations elevated from AMD it explains why TDS and conductivity were so high in Red Mountain Creek. Something important to note from this analysis is that even with the presence of a step-pool sequence, the stream water still shows the same pattern regarding TDS and conductivity as streams without step-pool sequences.

The final chemical versus chemical analysis was a comparison between DO and temperature. The overall trend depicted in Figure 20 was negative with temperature increasing as DO decreases. There were two creeks with strong negative relationships, Bear Creek and Mineral Creek. Temperature and DO are another example of a thoroughly researched pairing in regards to stream chemistry. The solubility of oxygen in water decreases as the temperature of the water increases (Dissolved Oxygen, 2016). This means that the relationship between the two characteristics should usually be negative. Interestingly, Red Mountain Creek was the only creek to show a positive relationship between the two characteristics (Figure 21). Most likely with more data points the relationship would be similar to the other creeks, considering the relationship only has an R^2 value of 0.3324. Again, it is important to note that overall the creeks have similar stream water chemistry as those without step-pool sequences.

Future Research Considerations

Analyzing additional water quality characteristics could shed more light on the question of the impact of step-pool sequences on stream health. The characteristics that should be considered for future research are salinity, turbidity, and cations such as calcium, magnesium, sodium, and potassium. Another factor to consider for future research would be seasonality. All of the data was collected in the summer and there may be a difference in step-pool sequence impact on stream water quality based on which season the testing is conducted in.

Conclusion

Step-pool systems do not have any direct impact on improving water quality for the characteristics that were examined. There were relationships between some of the characteristics that may indicate that even though the step-pools themselves do not necessarily improve water quality they could still have an influence on the quality of water with further analysis. These relationships include: DO and average stream velocity, NO_3-N and depth, PO_4^{3-} and average stream velocity, Fe_T and elevation, SO_4^{2-} and Fe_T, Fe_T and TDS, TDS and conductivity, and DO and temperature. The location of the step-pool systems seems to have the strongest influence on the quality of the water in the streams. With the data collected in this study, it would most likely not be beneficial to create artificial step-pool sequences to improve water quality for future development projects, such as developing new areas for stream recreation, or to improve stream health in impaired streams.

CHAPTER III

CONCLUSIONS

The water quality testing conducted in this study provides qualitative analyses on the impact of step-pool sequences regarding stream health. The assumption of this study was that step-pool sequences in mountain streams would have a positive influence on stream water quality. A Mann Whitney-U Test was conducted to determine whether or not the quality of the stream water before entering a step-pool sequence was statistically different than the water quality after it had passed through the sequence. The results of the test concluded that the stream water quality before the step-pool sequence was no better nor worse than the water quality after the sequence.

After establishing that the step-pool sequences did not have a direct impact on the quality of the water in the stream, a first-order ANOVA test was conducted to determine if there was a statistical difference between the creeks discharging from the east of the Uncompahgre River and the creeks discharging from the west of the Uncompahgre River. The test yielded a result of four different characteristics being statistically significant: TDS, conductivity, NO_3-N, and SO_4^{2-}. The main difference between the locations of these creeks was the land use/cover where the data points were collected. Creeks that were on the eastern side of the Uncompahgre River had higher concentrations which was most likely caused by a majority of the creeks being located in historic mining districts. These results led to the assumption that the location of step-pool sequences has a large impact on the water quality.

The final statistical analysis that was conducted was a regression analysis of physical versus chemical characteristics and chemical versus chemical characteristics. The results of the regression analysis indicate that there are clear relationships and patterns between the characteristics in the step-pools. The most notable relationships were: DO and average stream velocity, NO_3-N and depth, PO_4^{3-} and average stream velocity, Fe_T and elevation, SO_4^{2-} and Fe_T, Fe_T and TDS, TDS and conductivity, and DO and temperature. Most of these relationships yielded similar results to those in streams without step-pool sequences, while others may have been influenced by factors such as AMD and the way the samples were taken in the field.

The overall conclusion of this study is that while step-pools do not directly improve the quality of water in streams, they may still influence the quality of water in the step-pools without necessarily improving it. Testing other factors such as turbidity, cations such as calcium, magnesium, sodium and potassium, and seasonality may further fill in gaps about the influence of step-pool sequences on water quality that this study did not address. Based on the data collected in this study, the assumption can be made that it most likely would not be beneficial to create artificial step-pool sequences to improve water quality for future development projects, such as new areas for stream recreation, or to improve stream health in impaired streams.

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APPENDIX A

Table 5. Data collected at Oak Creek

Location in Step-Pool Sequence	Characteristic	Value
Before step-pools	Elevation (ft)	7,832
Before step-pools	DO (%)	85.6
Before step-pools	DO (mg/L)	9.65
Before step-pools	Width (ft)	7.75
Before step-pools	Depth (ft)	0.5
Before step-pools	Aspect	138°SE
Before step-pools	Temperature (°C)	9.3
Before step-pools	pH	7.83
Before step-pools	Conductivity (µS/cm)	104.3
Before step-pools	TDS (ppm)	52.5
Before step-pools	Nitrate-nitrogen (mg/L)	0.6
Before step-pools	Phosphate (mg/L)	0.35
Before step-pools	Sulfate (mg/L)	3
Before step-pools	Total Iron (mg/L)	0.39
Step-pool 1	Elevation of pool (ft)	7,823
Step-pool 1	Elevation of step (ft)	7,828
Step-pool 1	DO (%)	92.9
Step-pool 1	DO (mg/L)	9.74
Step-pool 1	Height of step (ft)	4.5
Step-pool 1	Width of step (ft)	9.5

Table 5. Continued

Location in Step-Pool Sequence	Characteristic	Value
Step-pool 1	Length of pool (ft)	8.67
Step-pool 1	Width of pool (ft)	3.083
Step-pool 1	Depth of pool (ft)	1.33
Step-pool 1	Aspect	141°SE
Step-pool 1	Temperature (°C)	10.5
Step-pool 1	pH	5.57
Step-pool 1	Conductivity (µS/cm)	101.2
Step-pool 1	TDS (ppm)	50.9
Step-pool 1	Nitrate-nitrogen (mg/L)	2.3
Step-pool 1	Phosphate (mg/L)	1.79
Step-pool 1	Sulfate (mg/L)	1
Step-pool 1	Total Iron (mg/L)	0.49
Step-pool 2	Elevation of pool (ft)	7,815
Step-pool 2	Elevation of step (ft)	7,819
Step-pool 2	DO (%)	90.5
Step-pool 2	DO (mg/L)	9.77
Step-pool 2	Height of step (ft)	3.25
Step-pool 2	Width of step (ft)	2.33
Step-pool 2	Length of pool (ft)	7.583
Step-pool 2	Width of pool (ft)	5.17
Step-pool 2	Depth of pool (ft)	1.25

Table 5. Continued

Location in Step-Pool Sequence	Characteristic	Value
Step-pool 2	Aspect	121°SE
Step-pool 2	Temperature (°C)	12
Step-pool 2	pH	6.31
Step-pool 2	Conductivity (μS/cm)	102.7
Step-pool 2	TDS (ppm)	51.4
Step-pool 2	Nitrate-nitrogen (mg/L)	2.6
Step-pool 2	Phosphate (mg/L)	1.42
Step-pool 2	Sulfate (mg/L)	3
Step-pool 2	Total Iron (mg/L)	1.02
Step-pool 3	Elevation of Pool (ft)	7,804
Step-pool 3	Elevation of step (ft)	7,809
Step-pool 3	DO (%)	91.7
Step-pool 3	DO (mg/L)	9.65
Step-pool 3	Height of step (ft)	4.17
Step-pool 3	Width of step (ft)	7
Step-pool 3	Length of pool (ft)	7.8
Step-pool 3	Width of pool (ft)	9.8
Step-pool 3	Depth of pool (ft)	1.9
Step-pool 3	Aspect	162°SE
Step-pool 3	Temperature (°C)	13.6
Step-pool 3	pH	6.45

Table 5. Continued

Location in Step-Pool Sequence	Characteristic	Value
Step-pool 3	Conductivity (µS/cm)	97.6
Step-pool 3	TDS (ppm)	48.6
Step-pool 3	Nitrate-nitrogen (mg/L)	1.6
Step-pool 3	Phosphate (mg/L)	0.49
Step-pool 3	Sulfate (mg/L)	6
Step-pool 3	Total Iron (mg/L)	0.44
After step-pools	Elevation (ft)	7,799
After step-pools	DO (%)	80.4
After step-pools	DO (mg/L)	9.2
After step-pools	Width (ft)	9.67
After step-pools	Depth (ft)	1
After step-pools	Aspect	143°SE
After step-pools	Temperature (°C)	9.4
After step-pools	pH	7.65
After step-pools	Conductivity (µS/cm)	108.8
After step-pools	TDS (ppm)	53.8
After step-pools	Nitrate nitrogen (mg/L)	0.7
After step-pools	Phosphate (mg/L)	0.26
After step-pools	Sulfate (mg/L)	3
After step-pools	Total Iron (mg/L)	0.23

Table 6. Data collected at Portland Creek

Location in Step-Pool Sequence	Characteristic	Value
Before step-pools	Elevation (ft)	8,098
Before step-pools	DO (%)	84.6
Before step-pools	DO (mg/L)	9.25
Before step-pools	Width (ft)	5
Before step-pools	Depth (ft)	4.5
Before step-pools	Aspect	314°NW
Before step-pools	Temperature (°C)	11.3
Before step-pools	pH	8.13
Before step-pools	Conductivity (µS/cm)	137.8
Before step-pools	TDS (ppm)	65
Before step-pools	Nitrate-nitrogen (mg/L)	1.7
Before step-pools	Phosphate (mg/L)	1.02
Before step-pools	Sulfate (mg/L)	4
Before step-pools	Total Iron (mg/L)	0.22
Step-pool 1	Elevation of pool (ft)	8,092
Step-pool 1	Elevation of step (ft)	8,096
Step-pool 1	DO (%)	75.1
Step-pool 1	DO (mg/L)	8.15
Step-pool 1	Height of step (ft)	4.25
Step-pool 1	Width of step (ft)	4.33
Step-pool 1	Length of pool (ft)	4.25

Table 6. Continued

Location in Step-Pool Sequence	Characteristic	Value
Step-pool 1	Width of pool (ft)	5.5
Step-pool 1	Depth of pool (ft)	0.583
Step-pool 1	Aspect	300°NW
Step-pool 1	Temperature (°C)	11.9
Step-pool 1	pH	7.01
Step-pool 1	Conductivity (µS/cm)	135.1
Step-pool 1	TDS (ppm)	90
Step-pool 1	Nitrate-nitrogen (mg/L)	2.5
Step-pool 1	Phosphate (mg/L)	1.53
Step-pool 1	Sulfate (mg/L)	8
Step-pool 1	Total Iron (mg/L)	0.28
Step-pool 2	Elevation of pool (ft)	8,088
Step-pool 2	Elevation of step (ft)	8,089
Step-pool 2	DO (%)	77.4
Step-pool 2	DO (mg/L)	8.33
Step-pool 2	Height of step (ft)	0.583
Step-pool 2	Width of step (ft)	3.167
Step-pool 2	Length of pool (ft)	1.083
Step-pool 2	Width of pool (ft)	5
Step-pool 2	Depth of pool (ft)	0.67
Step-pool 2	Aspect	320°NW

Table 6. Continued

Location in Step-Pool Sequence	Characteristic	Value
Step-pool 2	Temperature (°C)	12.2
Step-pool 2	pH	7.46
Step-pool 2	Conductivity (µS/cm)	163.8
Step-pool 2	TDS (ppm)	115
Step-pool 2	Nitrate-nitrogen (mg/L)	1.2
Step-pool 2	Phosphate (mg/L)	1.11
Step-pool 2	Sulfate (mg/L)	10
Step-pool 2	Total Iron (mg/L)	0.45
Step-pool 3	Elevation of Pool (ft)	8,082
Step-pool 3	Elevation of step (ft)	8,087
Step-pool 3	DO (%)	80.4
Step-pool 3	DO (mg/L)	8.71
Step-pool 3	Height of step (ft)	4.75
Step-pool 3	Width of step (ft)	2.5
Step-pool 3	Length of pool (ft)	6.17
Step-pool 3	Width of pool (ft)	3.33
Step-pool 3	Depth of pool (ft)	0.75
Step-pool 3	Aspect	306°NW
Step-pool 3	Temperature (°C)	11.6
Step-pool 3	pH	7.66
Step-pool 3	Conductivity (µS/cm)	154.9

Table 6. Continued

Location in Step-Pool Sequence	Characteristic	Value
Step-pool 3	TDS (ppm)	135
Step-pool 3	Nitrate-nitrogen (mg/L)	2.2
Step-pool 3	Phosphate (mg/L)	1.04
Step-pool 3	Sulfate (mg/L)	8
Step-pool 3	Total Iron (mg/L)	0.84
After step-pools	Elevation (ft)	8,079
After step-pools	DO (%)	83.6
After step-pools	DO (mg/L)	9.03
After step-pools	Width (ft)	5.42
After step-pools	Depth (ft)	4.42
After step-pools	Aspect	276°NW
After step-pools	Temperature (°C)	11.8
After step-pools	pH	8.18
After step-pools	Conductivity (µS/cm)	138.9
After step-pools	TDS (ppm)	130
After step-pools	Nitrate-nitrogen (mg/L)	1.8
After step-pools	Phosphate (mg/L)	1.22
After step-pools	Sulfate (mg/L)	4
After step-pools	Total Iron (mg/L)	0.72

Table 7. Data collected at Weehawken Creek

Location in Step-Pool Sequence	Characteristic	Value
Before step-pools	Elevation (ft)	8,910
Before step-pools	DO (%)	81.4
Before step-pools	DO (mg/L)	10.1
Before step-pools	Width (ft)	9
Before step-pools	Depth (ft)	0.75
Before step-pools	Aspect	80°NE
Before step-pools	Temperature (°C)	6.1
Before step-pools	pH	6.91
Before step-pools	Conductivity (µS/cm)	53.2
Before step-pools	TDS (ppm)	30
Before step-pools	Nitrate-nitrogen (mg/L)	1.1
Before step-pools	Phosphate (mg/L)	1.56
Before step-pools	Sulfate (mg/L)	19
Before step-pools	Total Iron (mg/L)	0.1
Step-pool 1	Elevation of pool (ft)	8,899
Step-pool 1	Elevation of step (ft)	8,903
Step-pool 1	DO (%)	81.5
Step-pool 1	DO (mg/L)	10.03
Step-pool 1	Height of step (ft)	3.25
Step-pool 1	Width of step (ft)	4.67
Step-pool 1	Length of pool (ft)	5.33

Table 7. Continued

Location in Step-Pool Sequence	Characteristic	Value
Step-pool 1	Width of pool (ft)	9.17
Step-pool 1	Depth of pool (ft)	2.5
Step-pool 1	Aspect	46°NE
Step-pool 1	Temperature (°C)	6.4
Step-pool 1	pH	7.18
Step-pool 1	Conductivity (μS/cm)	52.8
Step-pool 1	TDS (ppm)	35
Step-pool 1	Nitrate-nitrogen (mg/L)	0.5
Step-pool 1	Phosphate (mg/L)	1.76
Step-pool 1	Sulfate (mg/L)	11
Step-pool 1	Total Iron (mg/L)	0.06
Step-pool 2	Elevation of pool (ft)	8,893
Step-pool 2	Elevation of step (ft)	8,896
Step-pool 2	DO (%)	81.7
Step-pool 2	DO (mg/L)	10
Step-pool 2	Height of step (ft)	2.75
Step-pool 2	Width of step (ft)	5.17
Step-pool 2	Length of pool (ft)	4.17
Step-pool 2	Width of pool (ft)	5.67
Step-pool 2	Depth of pool (ft)	2.083
Step-pool 2	Aspect	77°NE

Table 7. Continued

Location in Step-Pool Sequence	Characteristic	Value
Step-pool 2	Temperature (°C)	6.4
Step-pool 2	pH	7.06
Step-pool 2	Conductivity (µS/cm)	53.3
Step-pool 2	TDS (ppm)	50
Step-pool 2	Nitrate-nitrogen (mg/L)	1.3
Step-pool 2	Phosphate (mg/L)	0.78
Step-pool 2	Sulfate (mg/L)	16
Step-pool 2	Total Iron (mg/L)	0.17
Step-pool 3	Elevation of Pool (ft)	8,883
Step-pool 3	Elevation of step (ft)	8,889
Step-pool 3	DO (%)	82.6
Step-pool 3	DO (mg/L)	10.11
Step-pool 3	Height of step (ft)	6.083
Step-pool 3	Width of step (ft)	7.42
Step-pool 3	Length of pool (ft)	6.17
Step-pool 3	Width of pool (ft)	17.25
Step-pool 3	Depth of pool (ft)	1.17
Step-pool 3	Aspect	84°NE
Step-pool 3	Temperature (°C)	6.4
Step-pool 3	pH	7.3
Step-pool 3	Conductivity (µS/cm)	53.6

Table 7. Continued

Location in Step-Pool Sequence	Characteristic	Value
Step-pool 3	TDS (ppm)	55
Step-pool 3	Nitrate-nitrogen (mg/L)	2.1
Step-pool 3	Phosphate (mg/L)	1.07
Step-pool 3	Sulfate (mg/L)	20
Step-pool 3	Total Iron (mg/L)	0.2
After step-pools	Elevation (ft)	8,881
After step-pools	DO (%)	82.6
After step-pools	DO (mg/L)	10.06
After step-pools	Width (ft)	7.25
After step-pools	Depth (ft)	1
After step-pools	Aspect	92°SE
After step-pools	Temperature (°C)	7
After step-pools	pH	6.79
After step-pools	Conductivity (µS/cm)	54.5
After step-pools	TDS (ppm)	45
After step-pools	Nitrate-nitrogen (mg/L)	1.1
After step-pools	Phosphate (mg/L)	0.98
After step-pools	Sulfate (mg/L)	13
After step-pools	Total Iron (mg/L)	0.05

Table 8. Data collected at Mineral Creek

Location in Step-Pool Sequence	Characteristic	Value
Before step-pools	Elevation (ft)	10,843
Before step-pools	DO (%)	80.4
Before step-pools	DO (mg/L)	9.88
Before step-pools	Width (ft)	8.17
Before step-pools	Depth (ft)	8.42
Before step-pools	Aspect	125°SE
Before step-pools	Temperature (°C)	6.4
Before step-pools	pH	6.04
Before step-pools	Conductivity (µS/cm)	45.1
Before step-pools	TDS (ppm)	40
Before step-pools	Nitrate-nitrogen (mg/L)	3.8
Before step-pools	Phosphate (mg/L)	0.27
Before step-pools	Sulfate (mg/L)	12
Before step-pools	Total Iron (mg/L)	0.06
Step-pool 1	Elevation of pool (ft)	10,835
Step-pool 1	Elevation of step (ft)	10,840
Step-pool 1	DO (%)	85.4
Step-pool 1	DO (mg/L)	10.58
Step-pool 1	Height of step (ft)	4.5
Step-pool 1	Width of step (ft)	2.75
Step-pool 1	Length of pool (ft)	3.583

Table 8. Continued

Location in Step-Pool Sequence	Characteristic	Value
Step-pool 1	Width of pool (ft)	3.33
Step-pool 1	Depth of pool (ft)	0.79
Step-pool 1	Aspect	112°SE
Step-pool 1	Temperature (°C)	7.2
Step-pool 1	pH	6.22
Step-pool 1	Conductivity (µS/cm)	46.1
Step-pool 1	TDS (ppm)	30
Step-pool 1	Nitrate-nitrogen (mg/L)	3.1
Step-pool 1	Phosphate (mg/L)	0.28
Step-pool 1	Sulfate (mg/L)	13
Step-pool 1	Total Iron (mg/L)	0.17
Step-pool 2	Elevation of pool (ft)	10,828
Step-pool 2	Elevation of step (ft)	10,834
Step-pool 2	DO (%)	80.9
Step-pool 2	DO (mg/L)	9.49
Step-pool 2	Height of step (ft)	5.67
Step-pool 2	Width of step (ft)	4.67
Step-pool 2	Length of pool (ft)	5.083
Step-pool 2	Width of pool (ft)	3.75
Step-pool 2	Depth of pool (ft)	0.67
Step-pool 2	Aspect	140°SE

Table 8. Continued

Location in Step-Pool Sequence	Characteristic	Value
Step-pool 2	Temperature (°C)	8.3
Step-pool 2	pH	6.5
Step-pool 2	Conductivity (µS/cm)	47.3
Step-pool 2	TDS (ppm)	70
Step-pool 2	Nitrate-nitrogen (mg/L)	2.7
Step-pool 2	Phosphate (mg/L)	0.06
Step-pool 2	Sulfate (mg/L)	9
Step-pool 2	Total Iron (mg/L)	0.09
Step-pool 3	Elevation of Pool (ft)	10,822
Step-pool 3	Elevation of step (ft)	10,827
Step-pool 3	DO (%)	77.7
Step-pool 3	DO (mg/L)	8.72
Step-pool 3	Height of step (ft)	4.17
Step-pool 3	Width of step (ft)	5.25
Step-pool 3	Length of pool (ft)	3.5
Step-pool 3	Width of pool (ft)	4.583
Step-pool 3	Depth of pool (ft)	1.67
Step-pool 3	Aspect	143°SE
Step-pool 3	Temperature (°C)	10.2
Step-pool 3	pH	6.48
Step-pool 3	Conductivity (µS/cm)	48.5

Table 8. Continued

Location in Step-Pool Sequence	Characteristic	Value
Step-pool 3	TDS (ppm)	40
Step-pool 3	Nitrate-nitrogen (mg/L)	2.65
Step-pool 3	Phosphate (mg/L)	0.07
Step-pool 3	Sulfate (mg/L)	16
Step-pool 3	Total Iron (mg/L)	0.07
Step-pool 4	Elevation of pool (ft)	10,817
Step-pool 4	Elevation of step (ft)	10,820
Step-pool 4	DO (%)	77.2
Step-pool 4	DO (mg/L)	8.53
Step-pool 4	Height of step (ft)	2.04
Step-pool 4	Width of step (ft)	3.75
Step-pool 4	Length of pool (ft)	3.42
Step-pool 4	Width of pool (ft)	2.33
Step-pool 4	Depth of pool (ft)	1.42
Step-pool 4	Aspect	112°SE
Step-pool 4	Temperature (°C)	10.9
Step-pool 4	pH	6.48
Step-pool 4	Conductivity (µS/cm)	50.6
Step-pool 4	TDS (ppm)	40
Step-pool 4	Nitrate-nitrogen (mg/L)	3.8
Step-pool 4	Phosphate (mg/L)	0.21

Table 8. Continued

Location in Step-Pool Sequence	Characteristic	Value
Step-pool 4	Sulfate (mg/L)	11
Step-pool 4	Total Iron (mg/L)	0.13
After step-pools	Elevation (ft)	10815
After step-pools	DO (%)	75.4
After step-pools	DO (mg/L)	8.1
After step-pools	Width (ft)	11.42
After step-pools	Depth (ft)	0.33
After step-pools	Aspect	101°SE
After step-pools	Temperature (°C)	12.2
After step-pools	pH	6.04
After step-pools	Conductivity (µS/cm)	52.3
After step-pools	TDS (ppm)	35
After step-pools	Nitrate-nitrogen (mg/L)	1.1
After step-pools	Phosphate (mg/L)	0.12
After step-pools	Sulfate (mg/L)	14
After step-pools	Total Iron (mg/L)	0.14

Table 9. Data collected at Bear Creek

Location in Step-Pool Sequence	Characteristic	Value
Before step-pools	Elevation (ft)	8,893
Before step-pools	DO (%)	81.5
Before step-pools	DO (mg/L)	9.96
Before step-pools	Width (ft)	8.583
Before step-pools	Depth (ft)	1.83
Before step-pools	Aspect	292°NW
Before step-pools	Temperature (°C)	6.7
Before step-pools	pH	7.3
Before step-pools	Conductivity (µS/cm)	96.2
Before step-pools	TDS (ppm)	80
Before step-pools	Nitrate-nitrogen (mg/L)	1.9
Before step-pools	Phosphate (mg/L)	0.06
Before step-pools	Sulfate (mg/L)	43
Before step-pools	Total Iron (mg/L)	0.19
Step-pool 1	Elevation of pool (ft)	8,889
Step-pool 1	Elevation of step (ft)	8,891
Step-pool 1	DO (%)	82.2
Step-pool 1	DO (mg/L)	9.94
Step-pool 1	Height of step (ft)	4.25
Step-pool 1	Width of step (ft)	4.67
Step-pool 1	Length of pool (ft)	6.17

Table 9. Continued

Location in Step-Pool Sequence	Characteristic	Value
Step-pool 1	Width of pool (ft)	5.25
Step-pool 1	Depth of pool (ft)	1.67
Step-pool 1	Aspect	306°NW
Step-pool 1	Temperature (°C)	7.1
Step-pool 1	pH	7.14
Step-pool 1	Conductivity (µS/cm)	96.3
Step-pool 1	TDS (ppm)	80
Step-pool 1	Nitrate-nitrogen (mg/L)	1.1
Step-pool 1	Phosphate (mg/L)	0.05
Step-pool 1	Sulfate (mg/L)	47
Step-pool 1	Total Iron (mg/L)	0.06
Step-pool 2	Elevation of pool (ft)	8,882
Step-pool 2	Elevation of step (ft)	8,886
Step-pool 2	DO (%)	83.3
Step-pool 2	DO (mg/L)	10.12
Step-pool 2	Height of step (ft)	3.17
Step-pool 2	Width of step (ft)	2.75
Step-pool 2	Length of pool (ft)	3.75
Step-pool 2	Width of pool (ft)	2
Step-pool 2	Depth of pool (ft)	1.33
Step-pool 2	Aspect	288°NW

Table 9. Continued

Location in Step-Pool Sequence	Characteristic	Value
Step-pool 2	Temperature (°C)	7
Step-pool 2	pH	7.3
Step-pool 2	Conductivity (µS/cm)	95.5
Step-pool 2	TDS (ppm)	85
Step-pool 2	Nitrate-nitrogen (mg/L)	2
Step-pool 2	Phosphate (mg/L)	0.14
Step-pool 2	Sulfate (mg/L)	48
Step-pool 2	Total Iron (mg/L)	0.06
Step-pool 3	Elevation of Pool (ft)	8,877
Step-pool 3	Elevation of step (ft)	8,880
Step-pool 3	DO (%)	83.6
Step-pool 3	DO (mg/L)	10.18
Step-pool 3	Height of step (ft)	3
Step-pool 3	Width of step (ft)	7.17
Step-pool 3	Length of pool (ft)	4.083
Step-pool 3	Width of pool (ft)	10.17
Step-pool 3	Depth of pool (ft)	2
Step-pool 3	Aspect	302°NW
Step-pool 3	Temperature (°C)	7
Step-pool 3	pH	7.28
Step-pool 3	Conductivity (µS/cm)	96.4

Table 9. Continued

Location in Step-Pool Sequence	Characteristic	Value
Step-pool 3	TDS (ppm)	60
Step-pool 3	Nitrate-nitrogen (mg/L)	1.4
Step-pool 3	Phosphate (mg/L)	0.02
Step-pool 3	Sulfate (mg/L)	45
Step-pool 3	Total Iron (mg/L)	0.02
After step-pools	Elevation (ft)	8,875
After step-pools	DO (%)	82.8
After step-pools	DO (mg/L)	10.04
After step-pools	Width (ft)	9
After step-pools	Depth (ft)	1
After step-pools	Aspect	290°NW
After step-pools	Temperature (°C)	7
After step-pools	pH	7.35
After step-pools	Conductivity (µS/cm)	96.7
After step-pools	TDS (ppm)	40
After step-pools	Nitrate-nitrogen (mg/L)	2
After step-pools	Phosphate (mg/L)	0.05
After step-pools	Sulfate (mg/L)	51
After step-pools	Total Iron (mg/L)	0.09

Table 10. Data collected at Red Mountain Creek

Location in Step-Pool Sequence	Characteristic	Value
Before step-pools	Elevation (ft)	9,679
Before step-pools	DO (%)	85.3
Before step-pools	DO (mg/L)	9.17
Before step-pools	Width (ft)	8.17
Before step-pools	Depth (ft)	2
Before step-pools	Aspect	358°NW
Before step-pools	Temperature (°C)	11.7
Before step-pools	pH	4.04
Before step-pools	Conductivity (µS/cm)	343.7
Before step-pools	TDS (ppm)	320
Before step-pools	Nitrate-nitrogen (mg/L)	12.8
Before step-pools	Phosphate (mg/L)	0.17
Before step-pools	Sulfate (mg/L)	>70
Before step-pools	Total Iron (mg/L)	>3.00
Step-pool 1	Elevation of pool (ft)	9,676
Step-pool 1	Elevation of step (ft)	9,678
Step-pool 1	DO (%)	83.8
Step-pool 1	DO (mg/L)	8.76
Step-pool 1	Height of step (ft)	1.25
Step-pool 1	Width of step (ft)	1.583
Step-pool 1	Length of pool (ft)	2.25

Table 10. Continued

Location in Step-Pool Sequence	Characteristic	Value
Step-pool 1	Width of pool (ft)	3.083
Step-pool 1	Depth of pool (ft)	0.75
Step-pool 1	Aspect	332°NW
Step-pool 1	Temperature (°C)	12.5
Step-pool 1	pH	3.8
Step-pool 1	Conductivity (µS/cm)	349.8
Step-pool 1	TDS (ppm)	320
Step-pool 1	Nitrate-nitrogen (mg/L)	11.6
Step-pool 1	Phosphate (mg/L)	0.32
Step-pool 1	Sulfate (mg/L)	>70
Step-pool 1	Total Iron (mg/L)	>3.00
Step-pool 2	Elevation of pool (ft)	9,670
Step-pool 2	Elevation of step (ft)	9,673
Step-pool 2	DO (%)	86.3
Step-pool 2	DO (mg/L)	9.2
Step-pool 2	Height of step (ft)	2.083
Step-pool 2	Width of step (ft)	3.42
Step-pool 2	Length of pool (ft)	5.583
Step-pool 2	Width of pool (ft)	2.25
Step-pool 2	Depth of pool (ft)	1
Step-pool 2	Aspect	332°NW

Table 10. Continued

Location in Step-Pool Sequence	Characteristic	Value
Step-pool 2	Temperature (°C)	12.6
Step-pool 2	pH	3.66
Step-pool 2	Conductivity (µS/cm)	351.1
Step-pool 2	TDS (ppm)	310
Step-pool 2	Nitrate-nitrogen (mg/L)	12.7
Step-pool 2	Phosphate (mg/L)	0.28
Step-pool 2	Sulfate (mg/L)	>70
Step-pool 2	Total Iron (mg/L)	>3.00
Step-pool 3	Elevation of Pool (ft)	9,664
Step-pool 3	Elevation of step (ft)	9,669
Step-pool 3	DO (%)	85.5
Step-pool 3	DO (mg/L)	9.09
Step-pool 3	Height of step (ft)	5.083
Step-pool 3	Width of step (ft)	4.5
Step-pool 3	Length of pool (ft)	7.33
Step-pool 3	Width of pool (ft)	7.25
Step-pool 3	Depth of pool (ft)	0.583
Step-pool 3	Aspect	358°NW
Step-pool 3	Temperature (°C)	12.8
Step-pool 3	pH	3.54
Step-pool 3	Conductivity (µS/cm)	344.6

Table 10. Continued

Location in Step-Pool Sequence	Characteristic	Value
Step-pool 3	TDS (ppm)	260
Step-pool 3	Nitrate-nitrogen (mg/L)	11
Step-pool 3	Phosphate (mg/L)	0.41
Step-pool 3	Sulfate (mg/L)	>70
Step-pool 3	Total Iron (mg/L)	>3.00
After step-pools	Elevation (ft)	9663
After step-pools	DO (%)	84.8
After step-pools	DO (mg/L)	8.83
After step-pools	Width (ft)	15.17
After step-pools	Depth (ft)	1.25
After step-pools	Aspect	348°NW
After step-pools	Temperature (°C)	13.43
After step-pools	pH	3.55
After step-pools	Conductivity (µS/cm)	360.3
After step-pools	TDS (ppm)	320
After step-pools	Nitrate-nitrogen (mg/L)	8.8
After step-pools	Phosphate (mg/L)	0.25
After step-pools	Sulfate (mg/L)	>70
After step-pools	Total Iron (mg/L)	>3.00

Table 11. Average Creek Velocity and Discharge

Creek Name	Average Creek Discharge (m^3/s)	Average Creek Velocity (m/s)
Oak	1.041	1.32
Portland	1.034	1.05
Weehawken	1.833	1.36
Mineral	1.245	2.71
Bear	2.017	1.98
Red Mountain	1.163	1.56

APPENDIX B

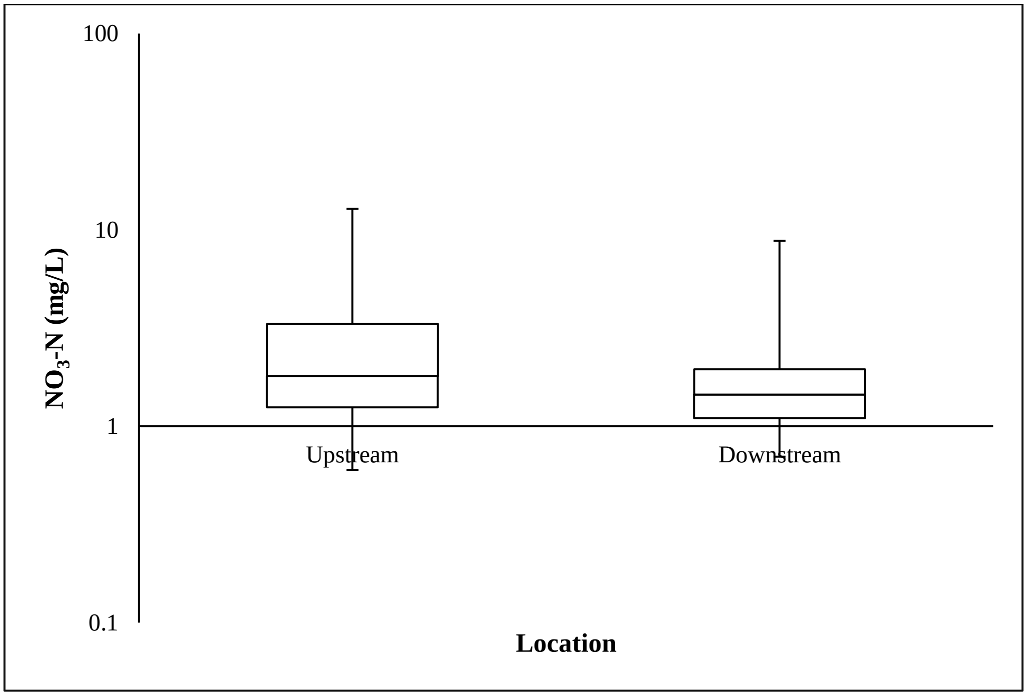

Figure 22. Box plot of upstream and downstream nitrate-nitrogen concentrations

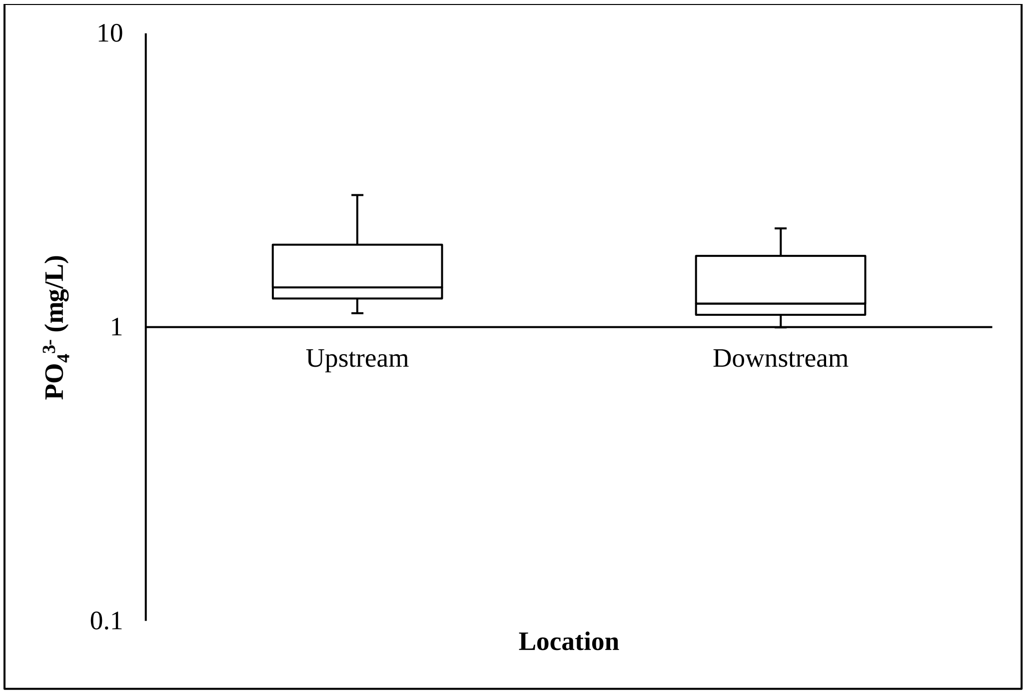

Figure 23. Box plot of upstream and downstream phosphate concentrations

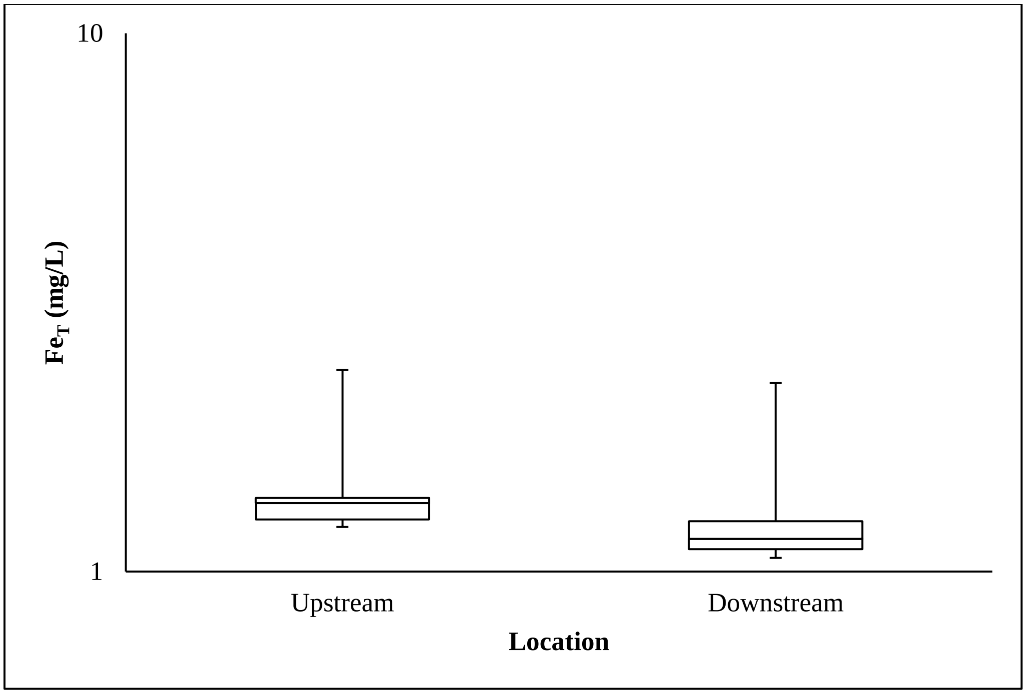

Figure 24. Box plot of upstream and downstream total iron concentrations

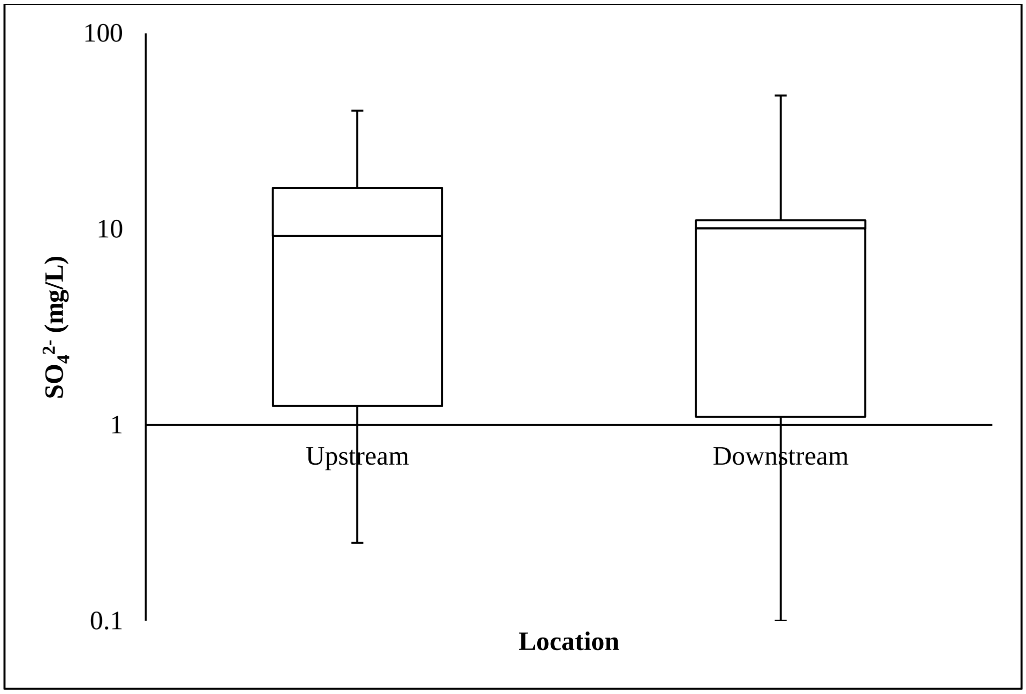

Figure 25. Box plot of upstream and downstream sulfate concentrations

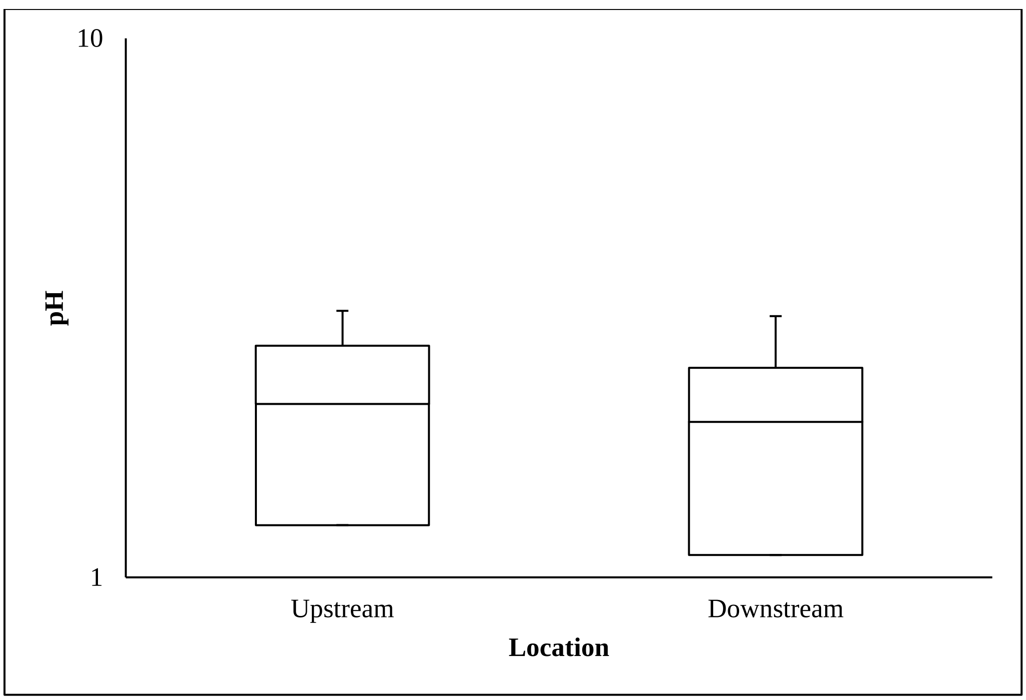

Figure 26. Box plot of upstream and downstream pH concentrations

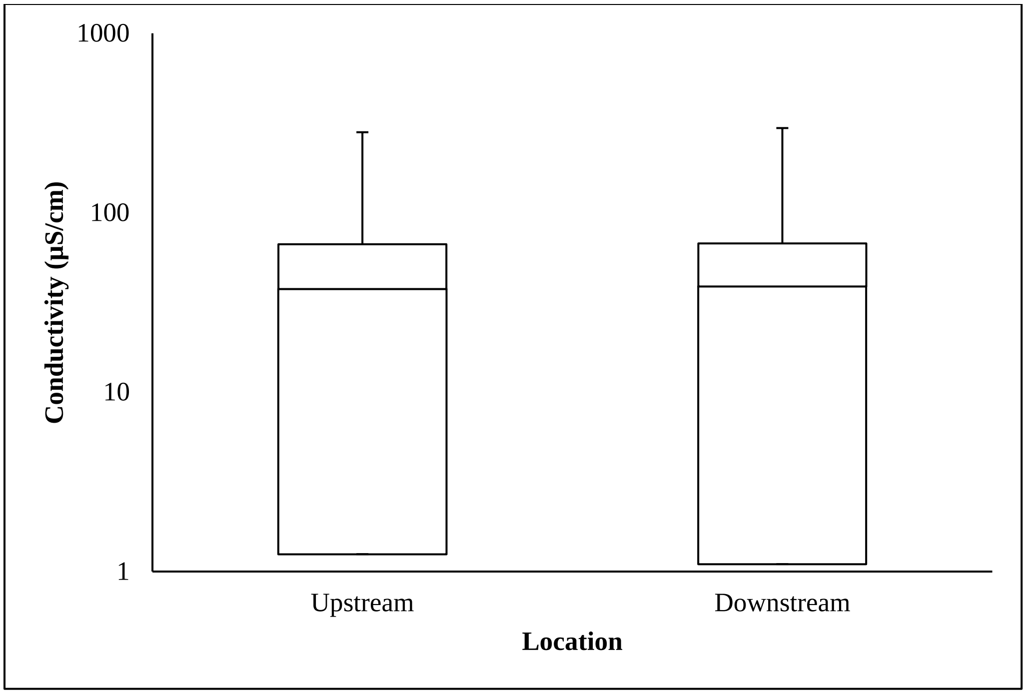

Figure 27. Box plot of upstream and downstream conductivity concentrations

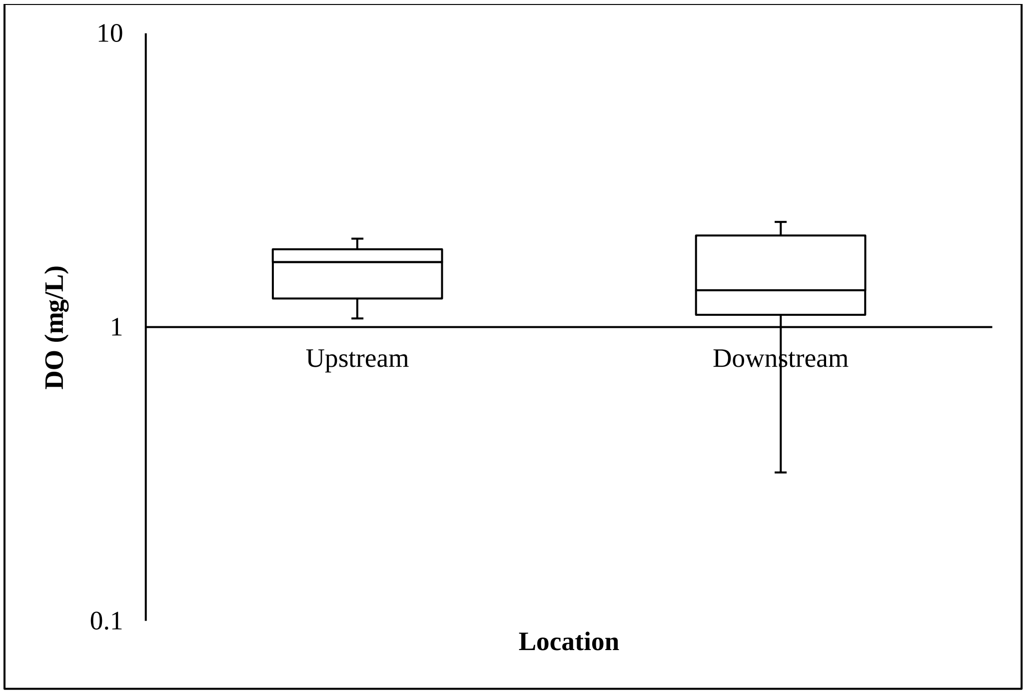

Figure 28. Box plot of upstream and downstream dissolved oxygen concentrations

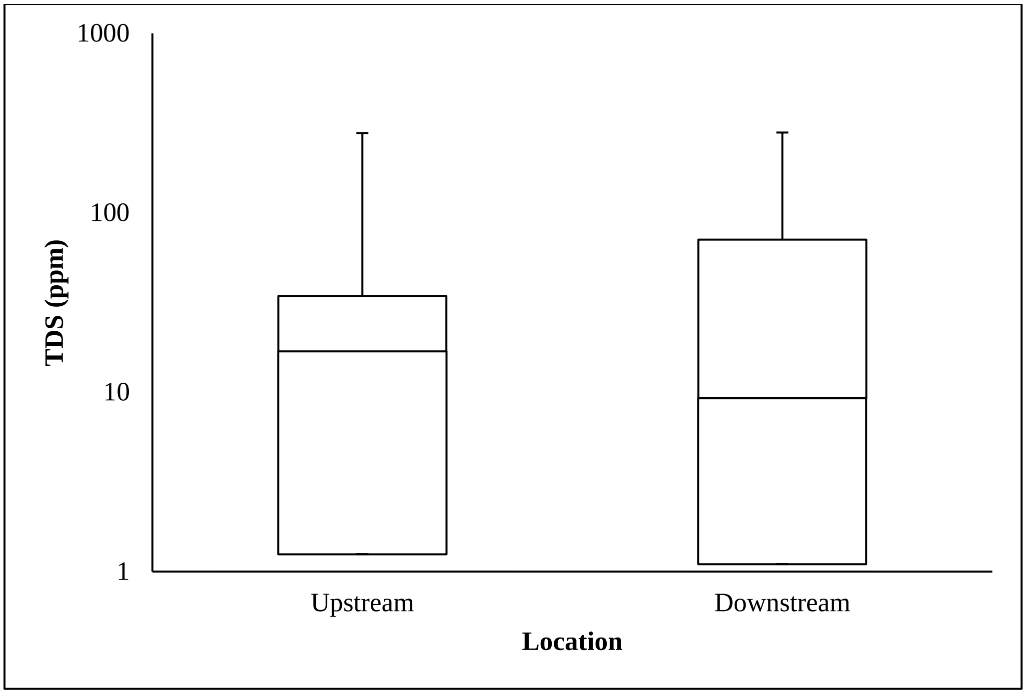

Figure 29. Box plot of upstream and downstream total dissolved solids concentrations

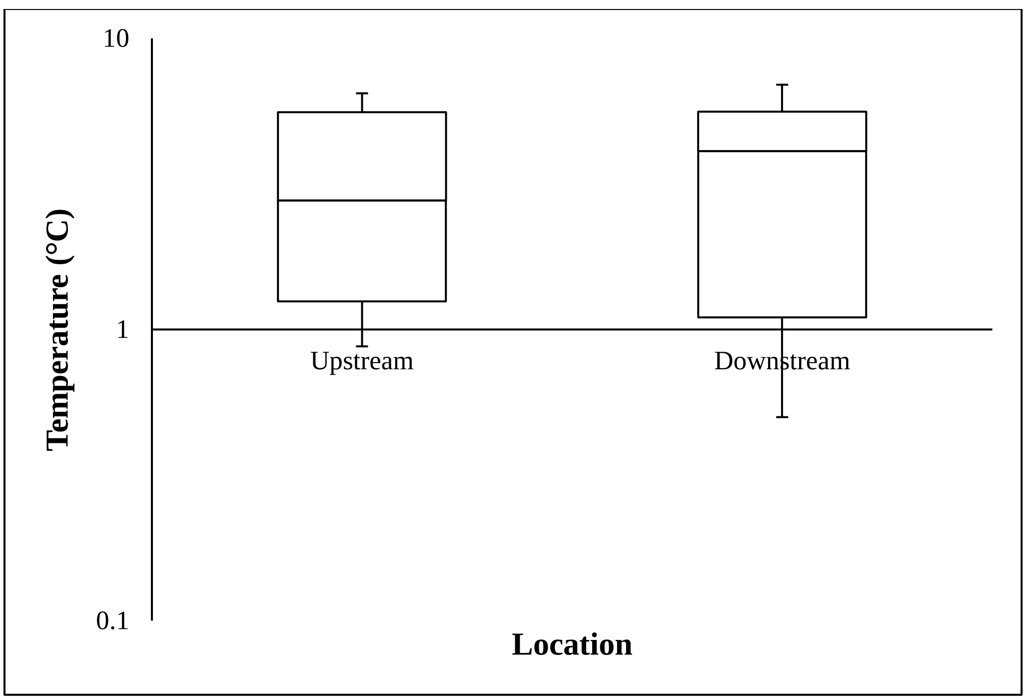

Figure 30. Box plot of upstream and downstream total dissolved solids concentrations

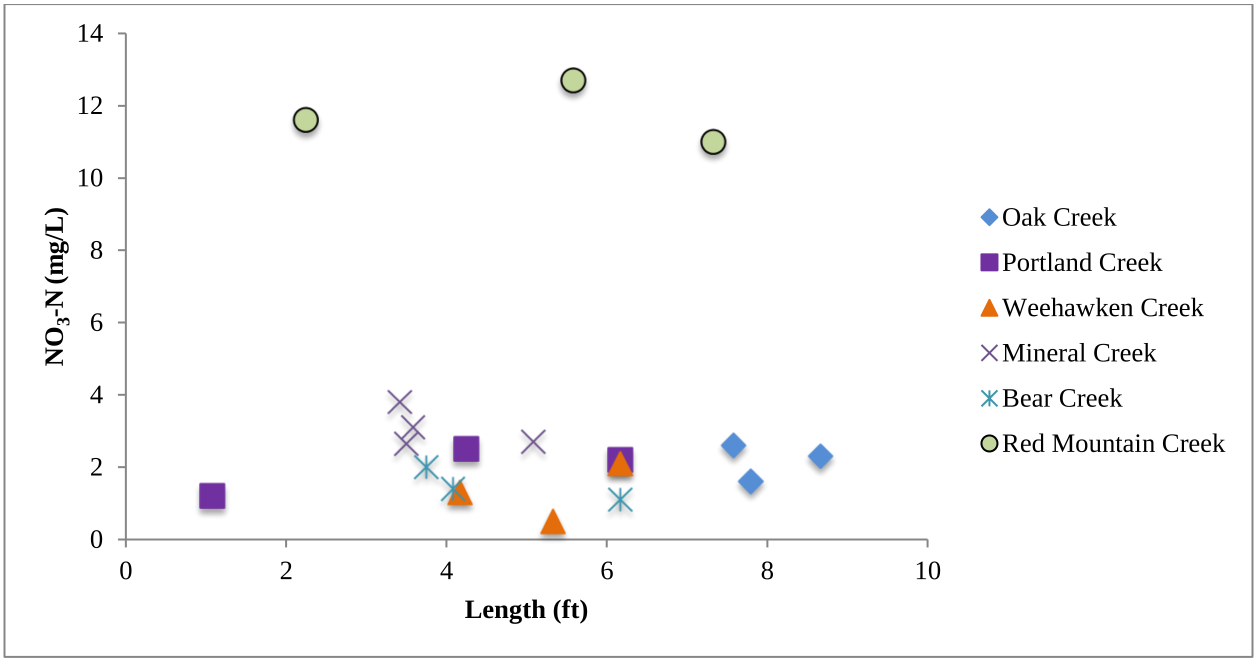

Figure 31. Step-pool nitrate-nitrogen concentrations compared to step-pool length

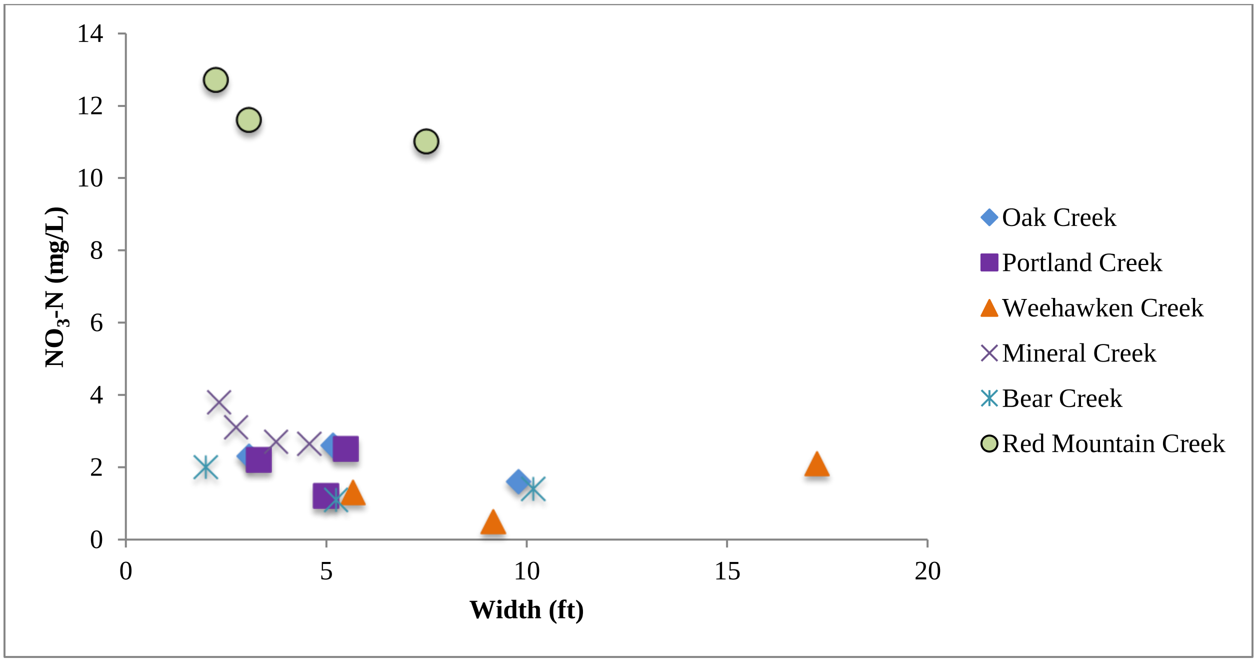

Figure 32. Step-pool nitrate-nitrogen concentrations compared to step-pool width

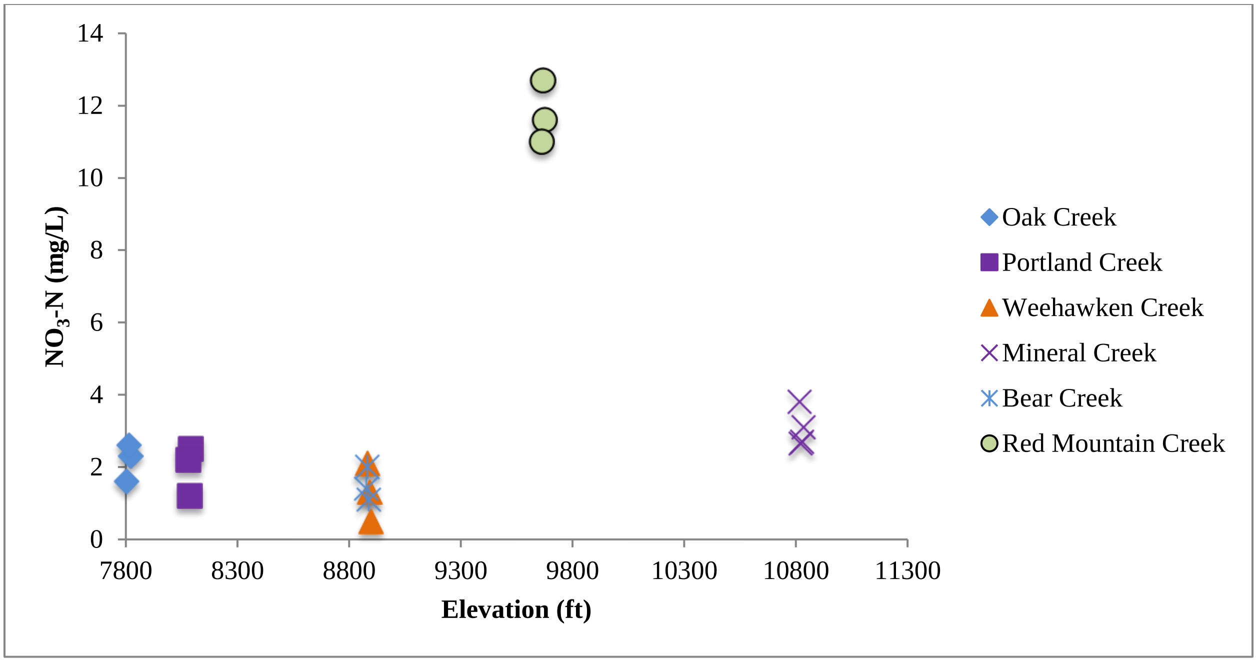

Figure 33. Step-pool nitrate-nitrogen concentrations compared to step-pool elevation

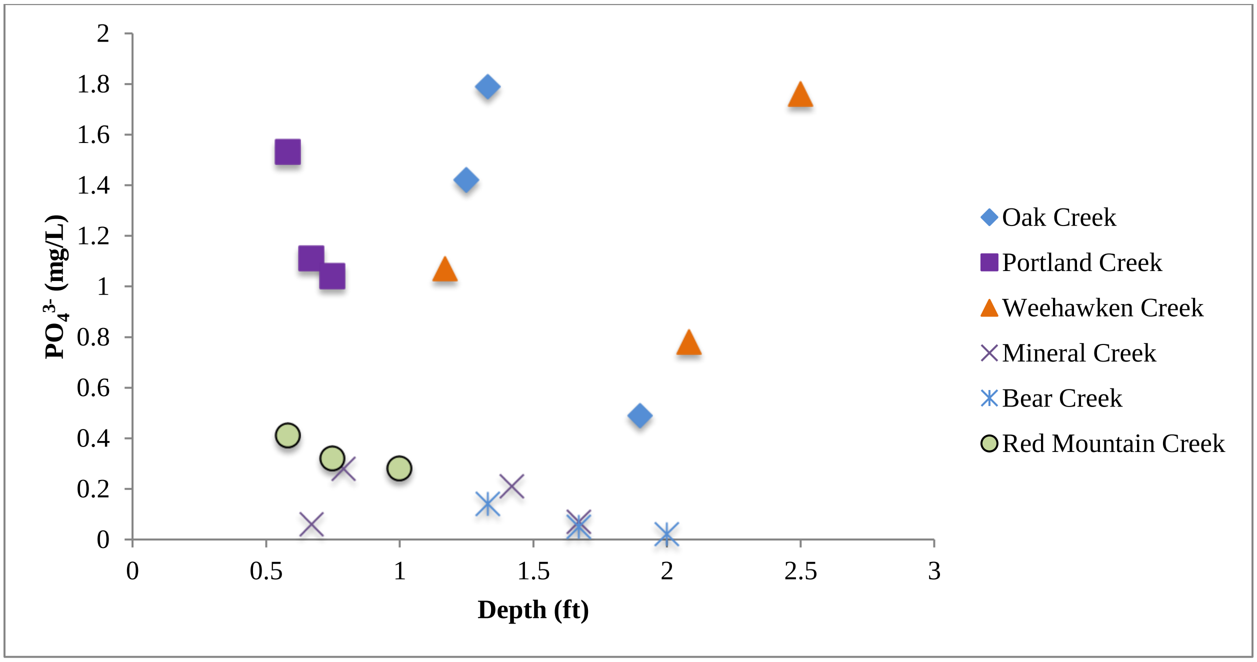

Figure 34. Step-pool phosphate concentrations compared to step-pool depth

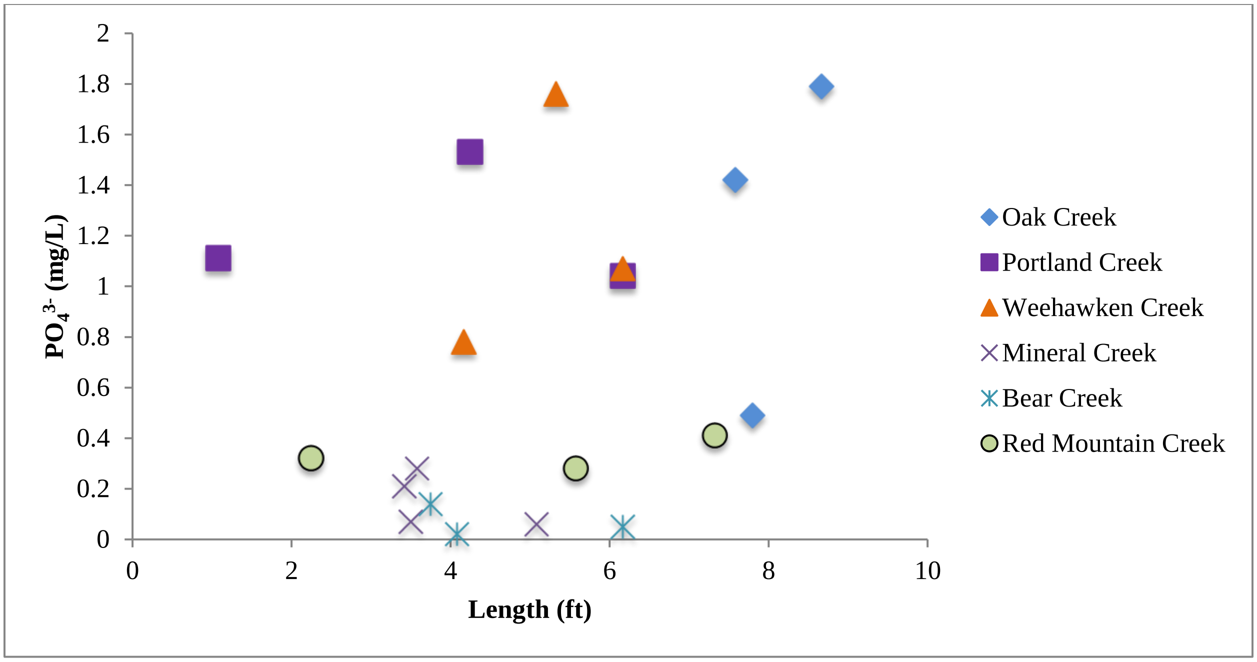

Figure 35. Step-pool phosphate concentrations compared to step-pool length

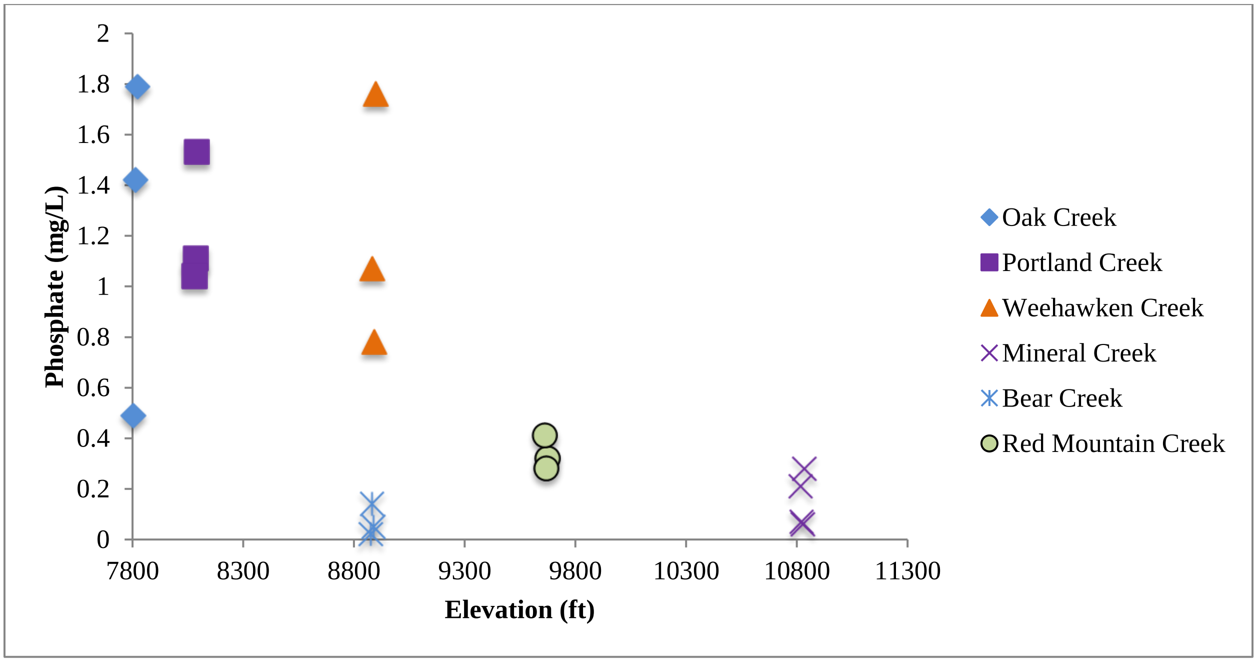

Figure 36. Step-pool phosphate concentrations compared to step-pool elevation

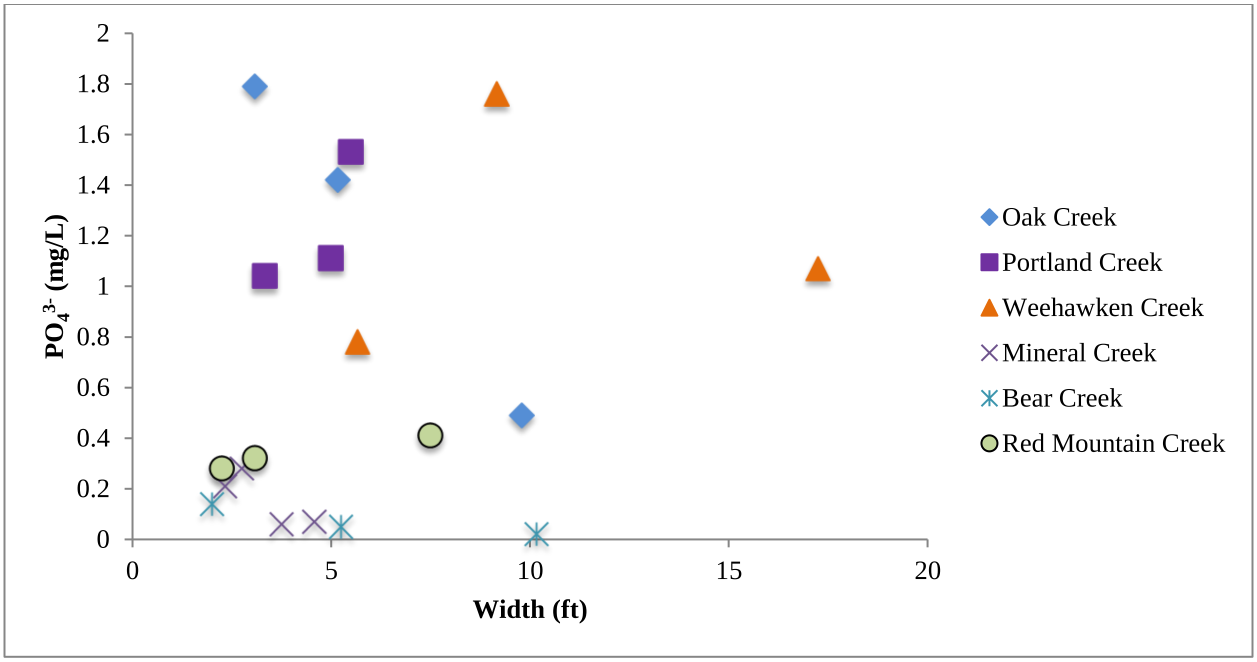

Figure 37. Step-pool phosphate concentrations compared to step-pool width

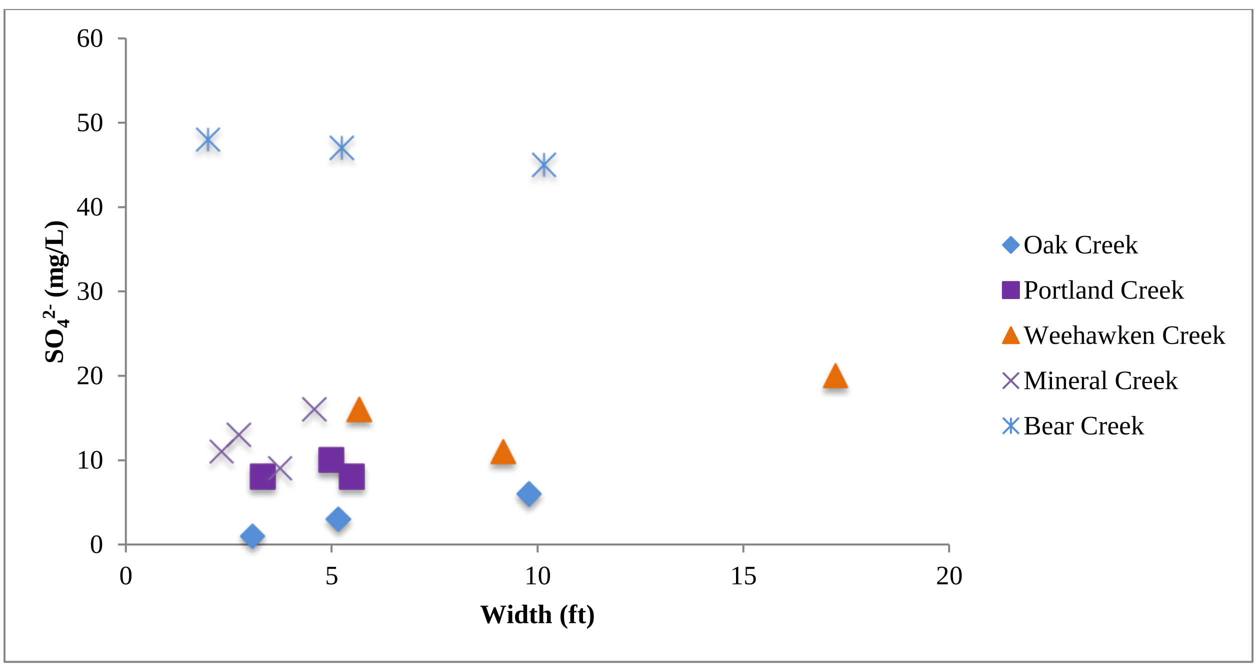

Figure 38. Step-pool sulfate concentrations compared to step-pool width

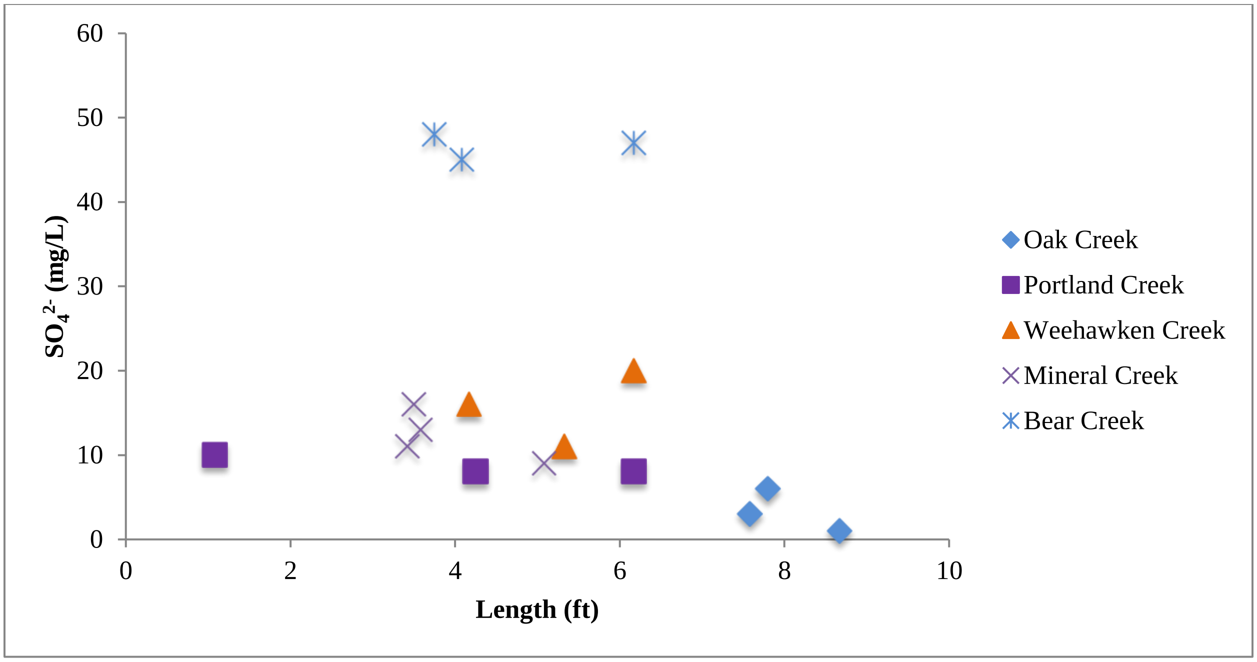

Figure 39. Step-pool sulfate concentrations compared to step-pool length

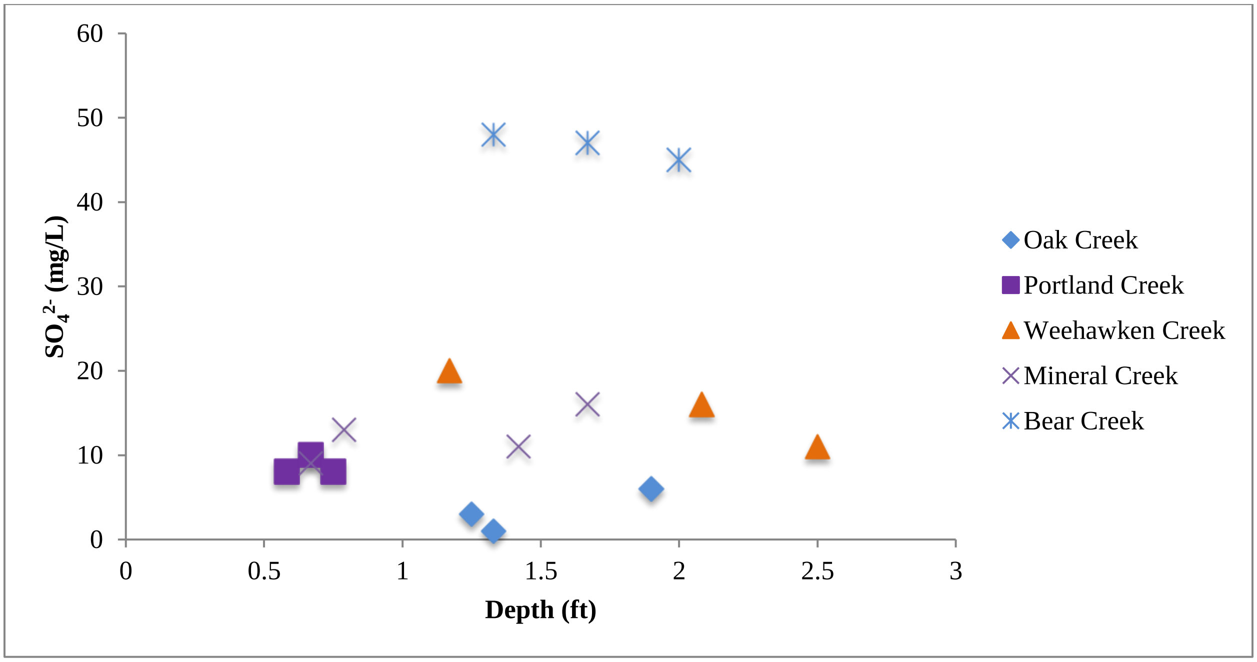

Figure 40. Step-pool sulfate concentrations compared to step-pool depth

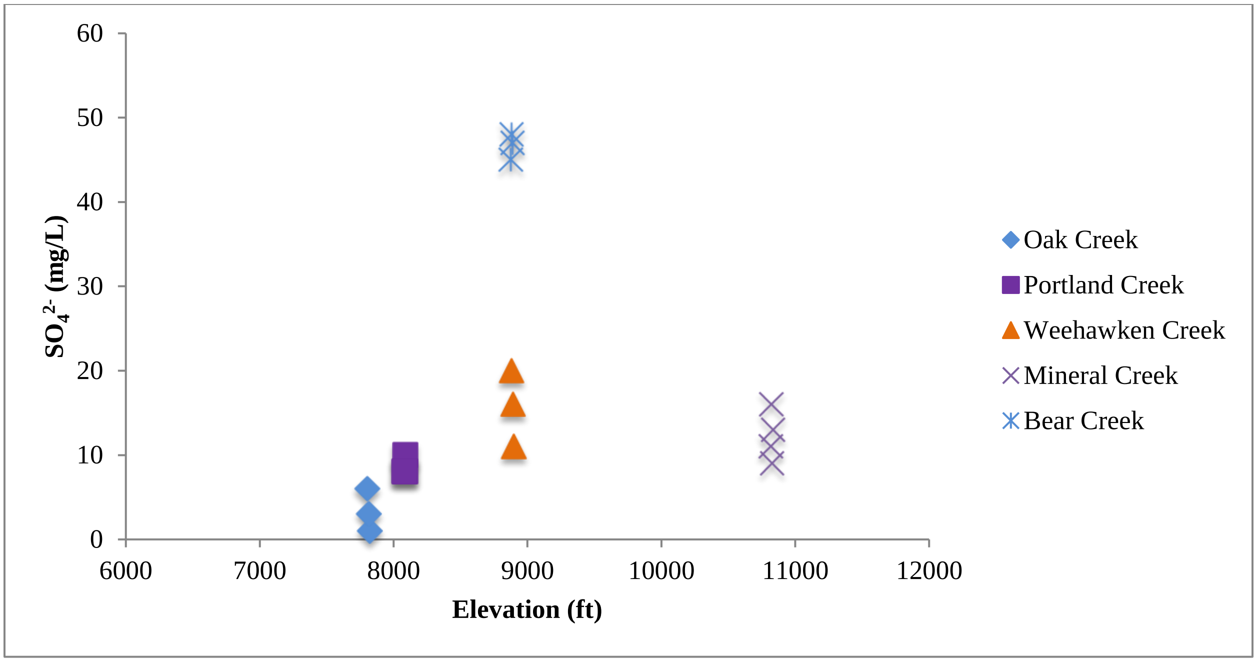

Figure 41. Step-pool sulfate concentrations compared to step-pool elevation

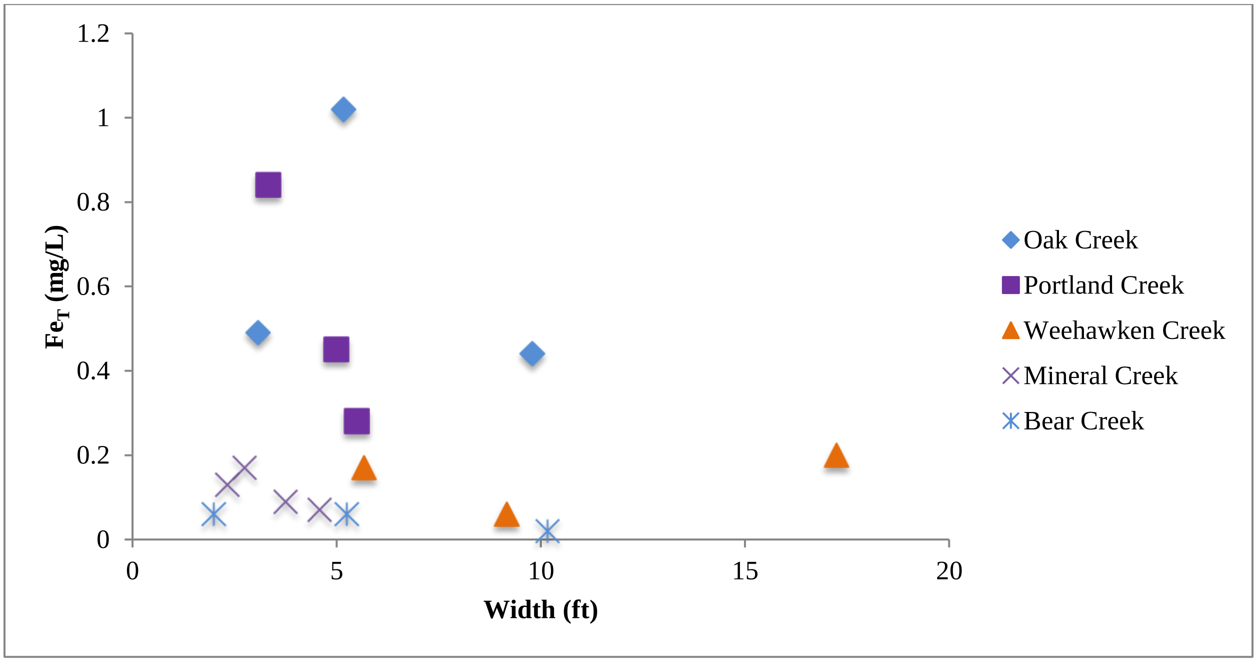

Figure 42. Step-pool total iron concentrations compared to step-pool width

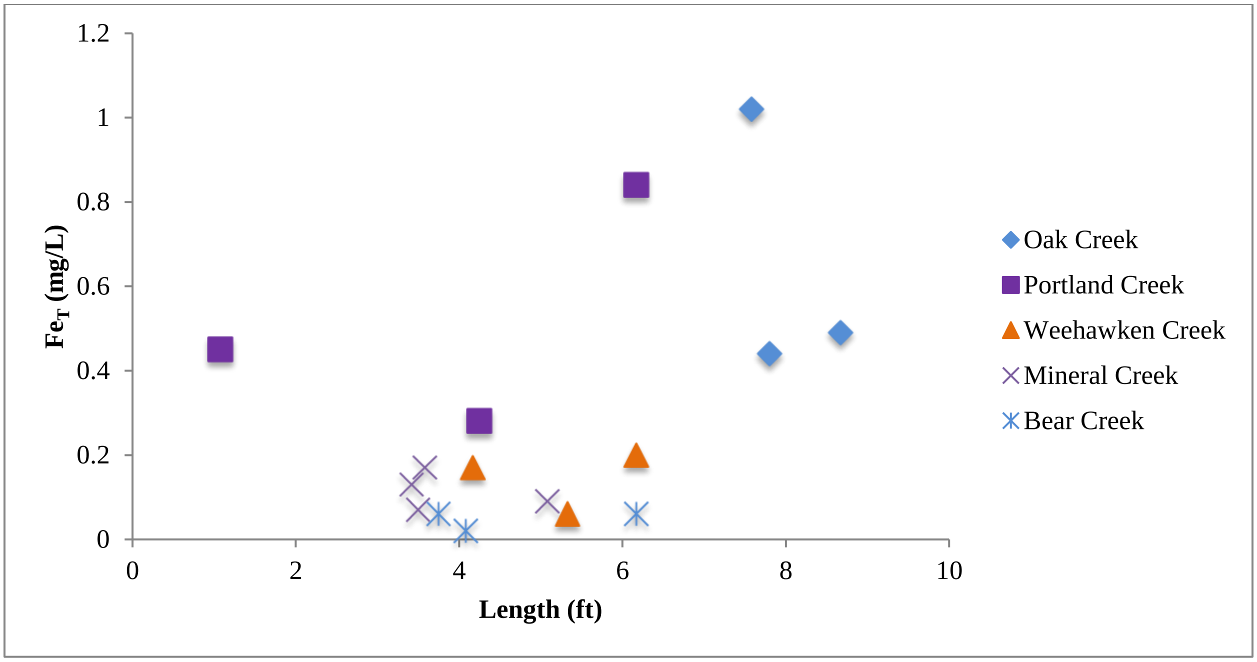

Figure 43. Step-pool total iron concentrations compared to step-pool length

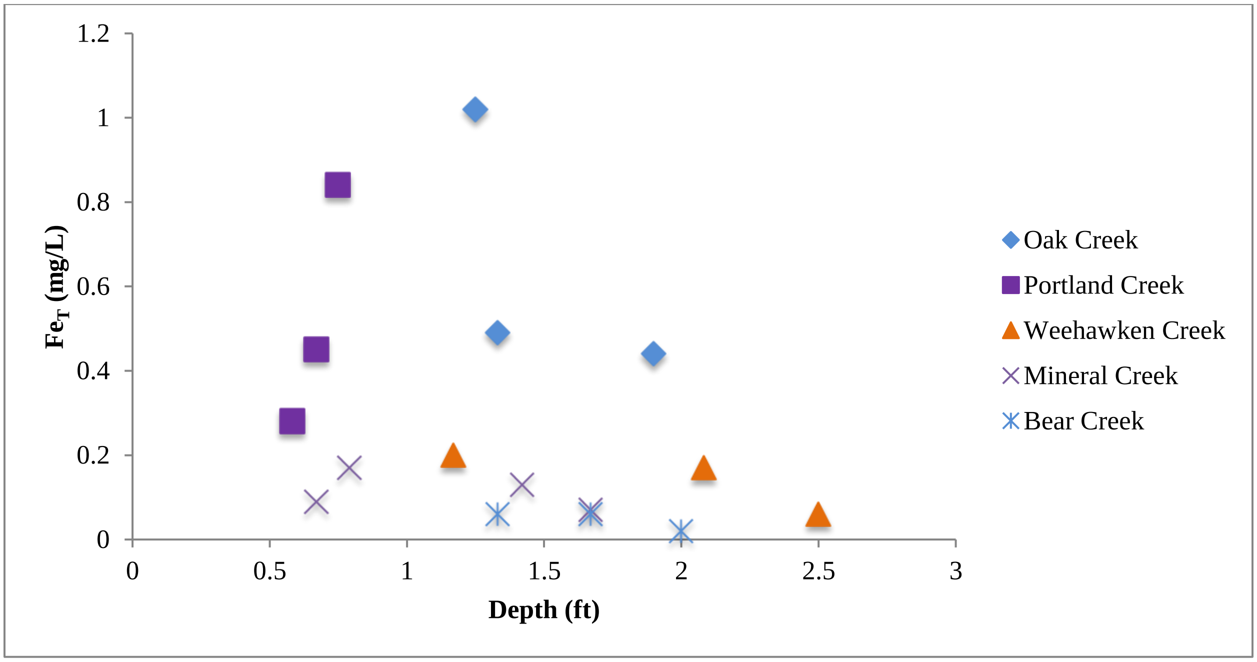

Figure 44. Step-pool total iron concentrations compared to step-pool depth

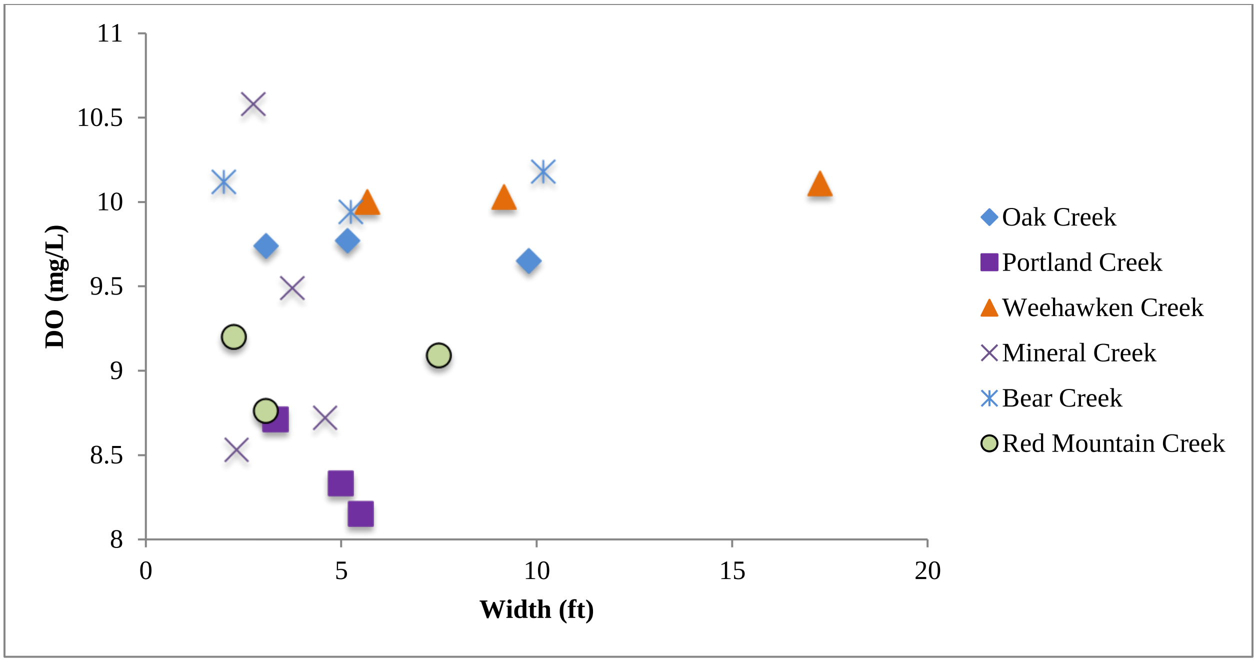

Figure 45. Step-pool dissolved oxygen concentrations compared to step-pool width

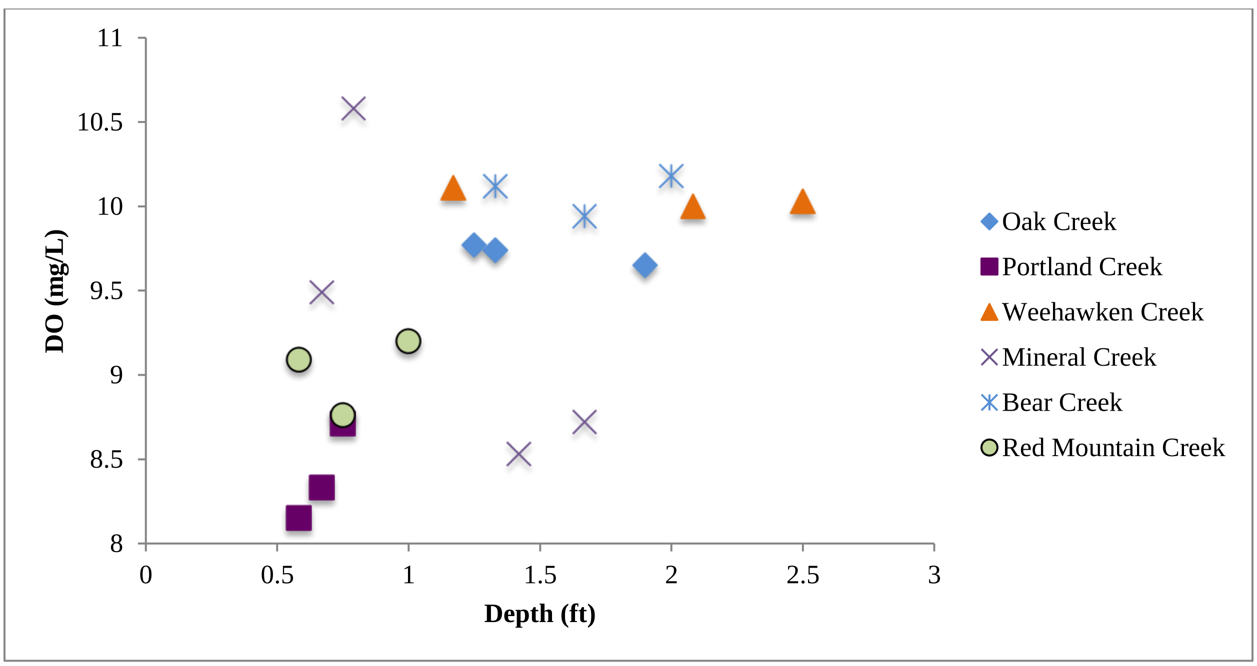

Figure 46. Step-pool dissolved oxygen concentrations compared to step-pool depth

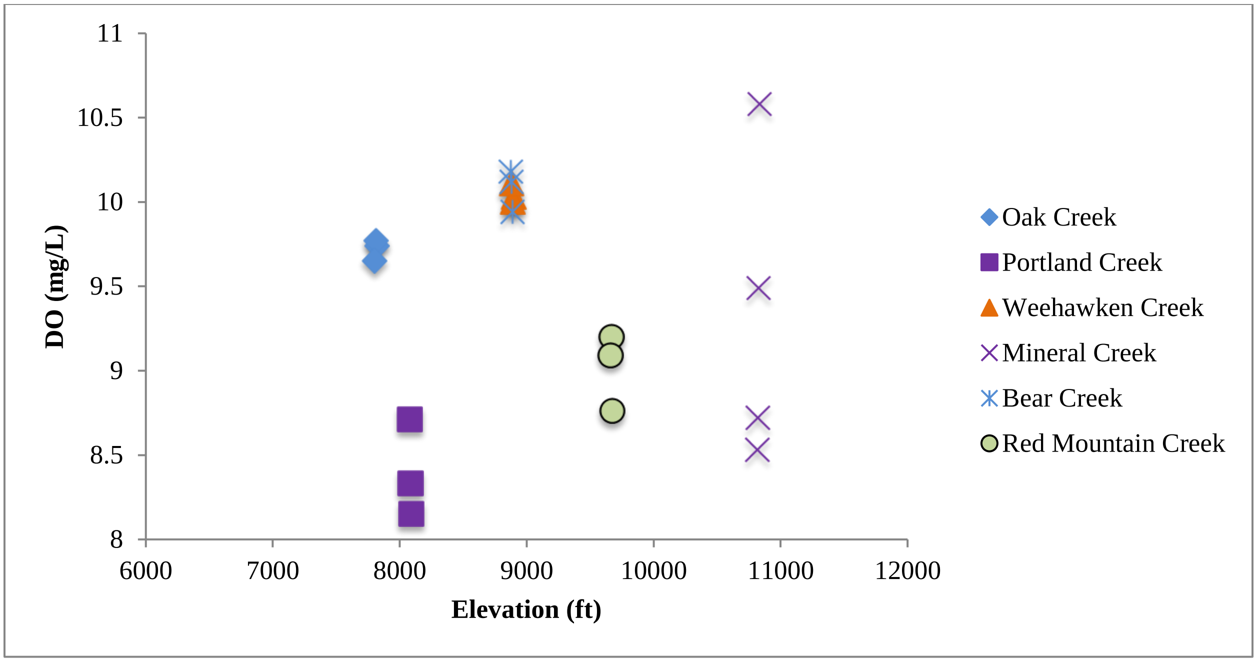

Figure 47. Step-pool dissolved oxygen concentrations compared to step-pool elevation

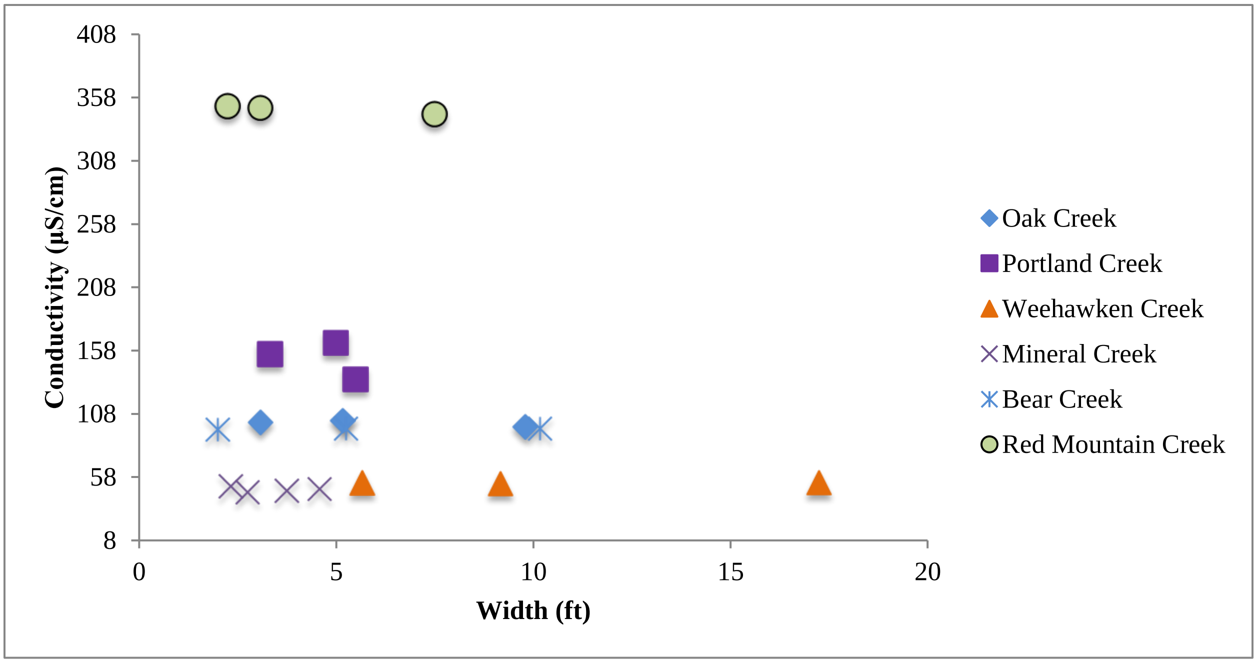

Figure 48. Step-pool conductivity compared to step-pool width

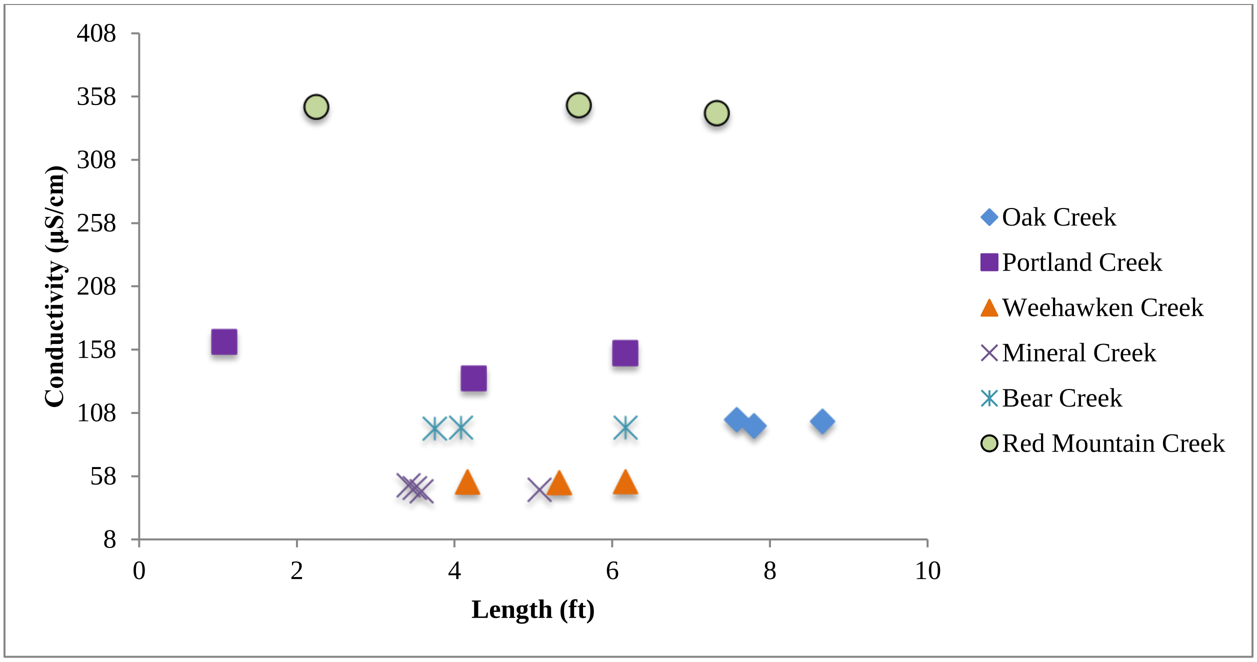

Figure 49. Step-pool conductivity compared to step-pool length

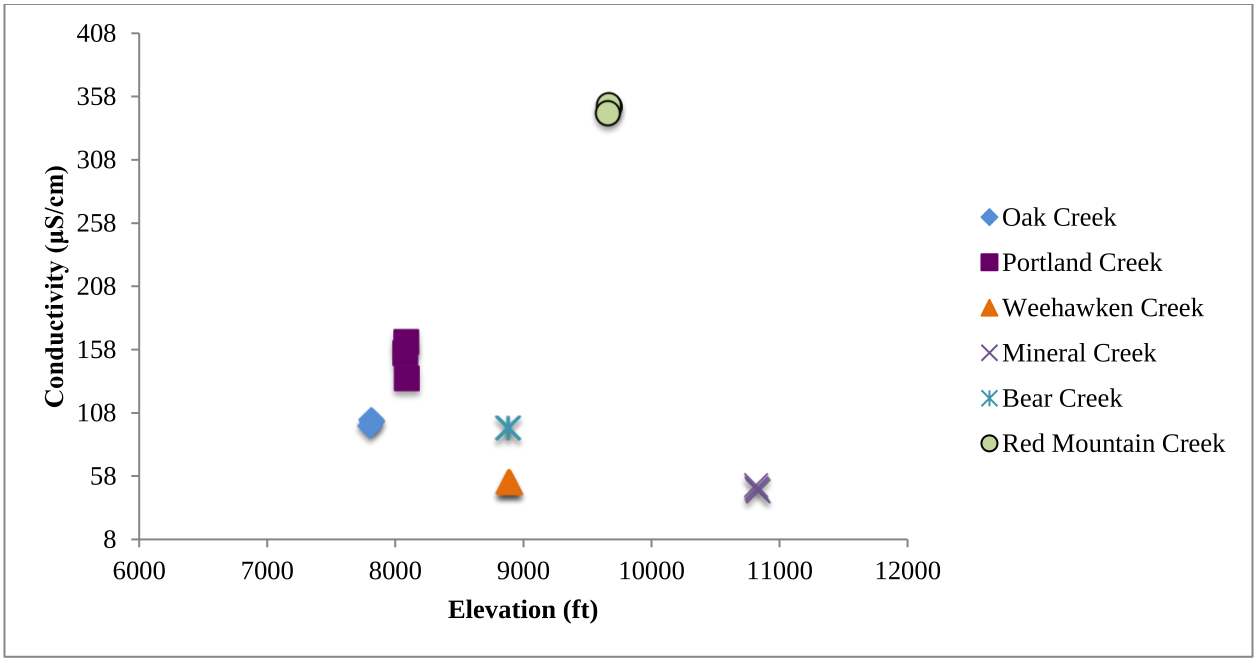

Figure 50. Step-pool conductivity compared to step-pool elevation

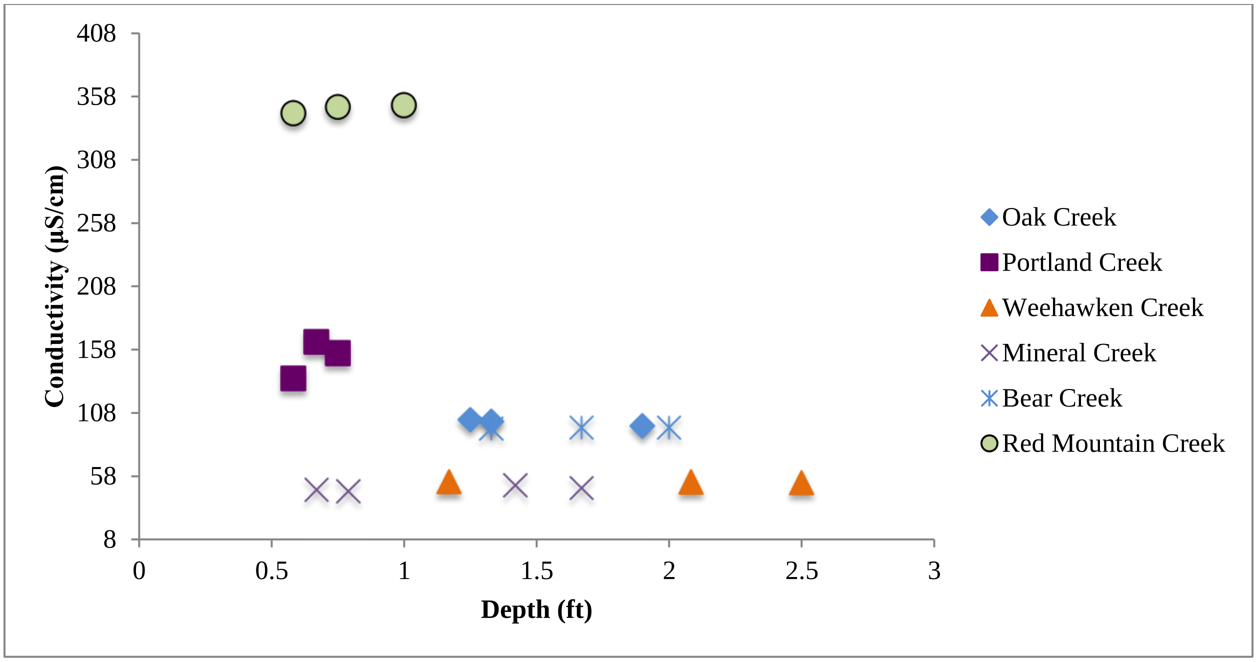

Figure 51. Step-pool conductivity compared to step-pool depth

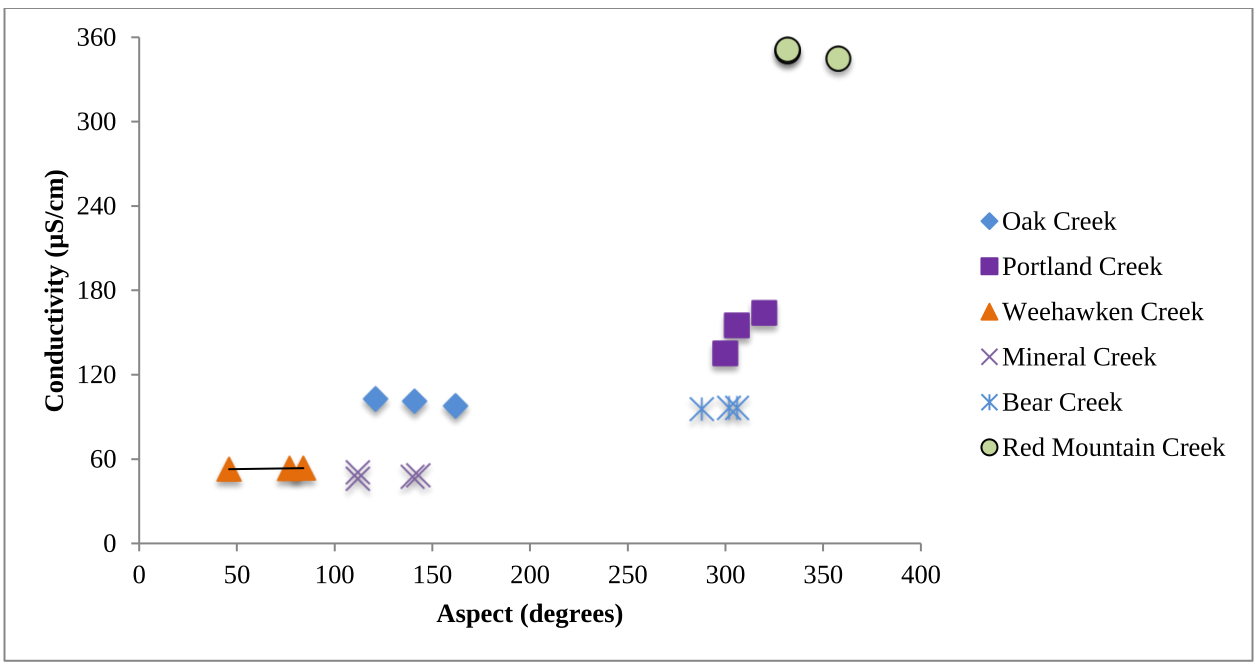

Figure 52. Step-pool conductivity compared to step-pool aspect

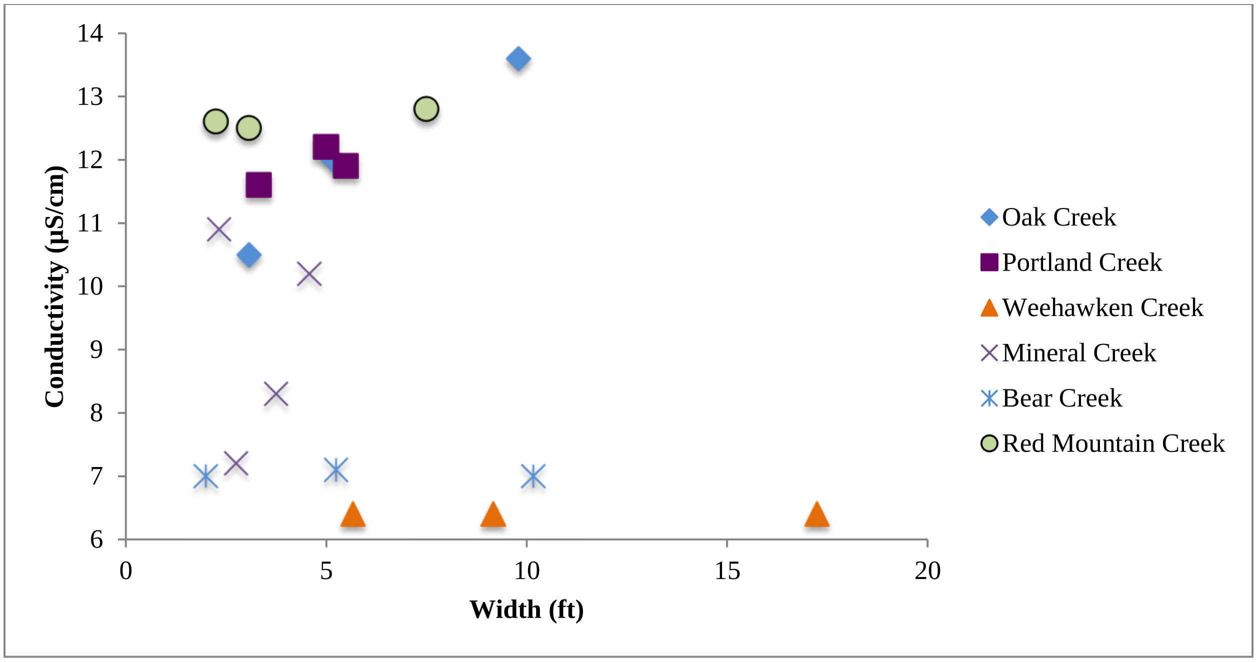

Figure 53. Step-pool temperature compared to step-pool width

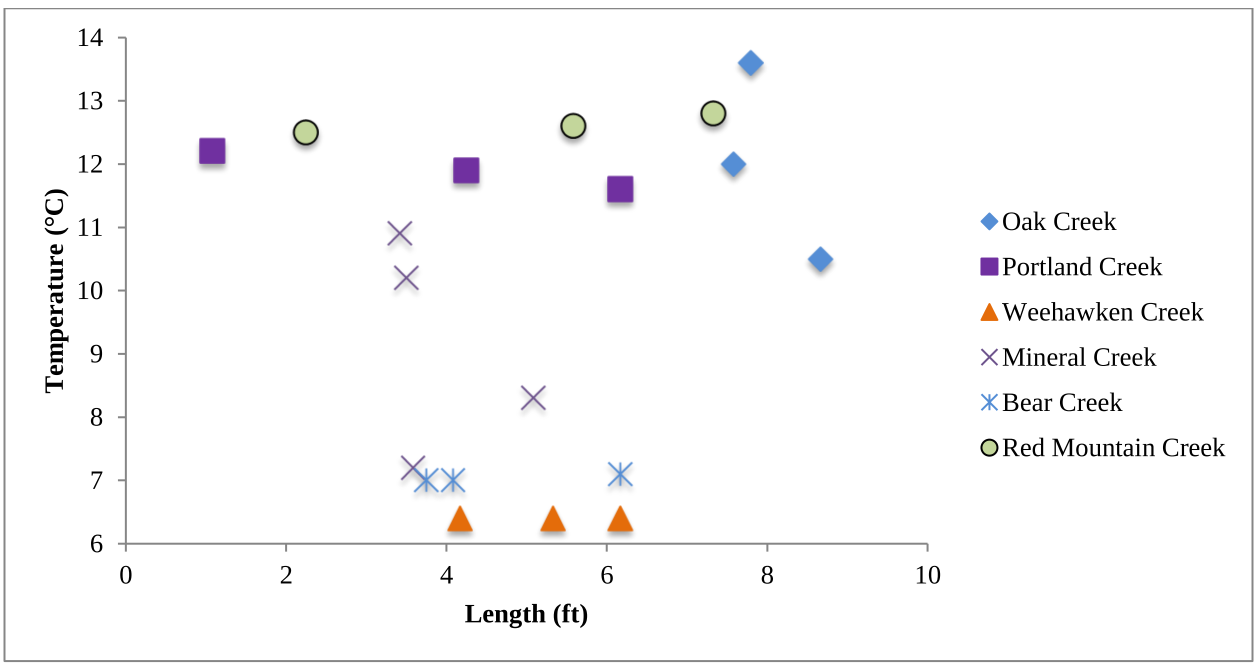

Figure 54. Step-pool temperature compared to step-pool length

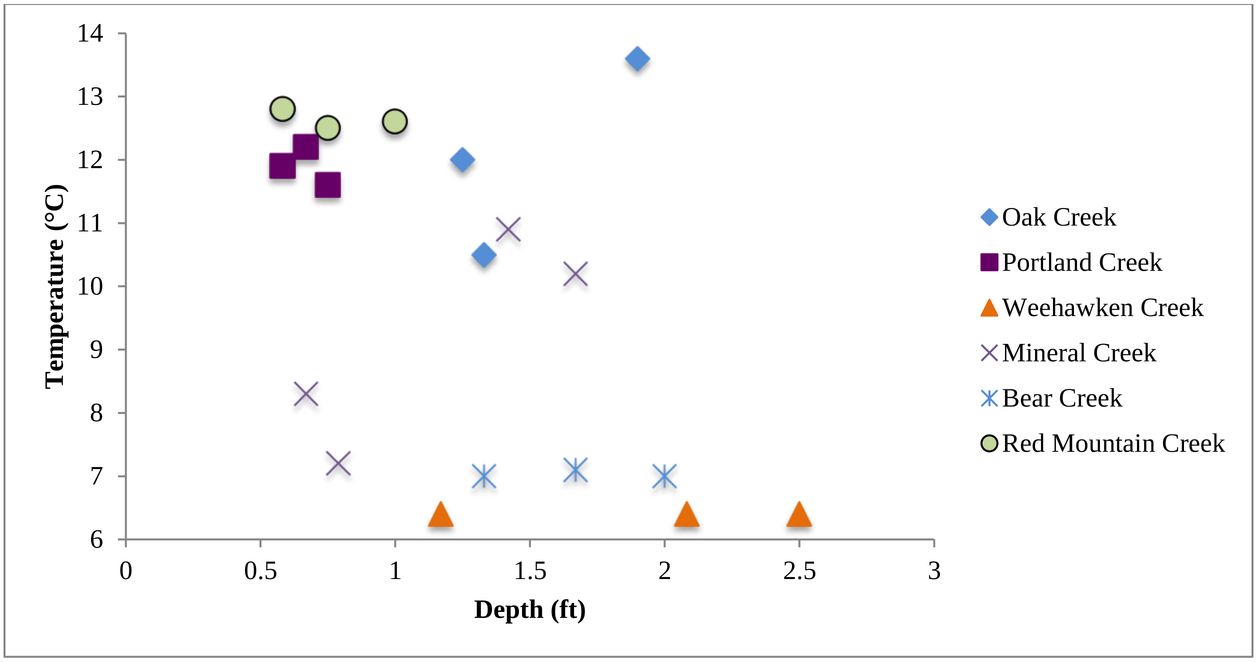

Figure 55. Step-pool temperature compared to step-pool depth

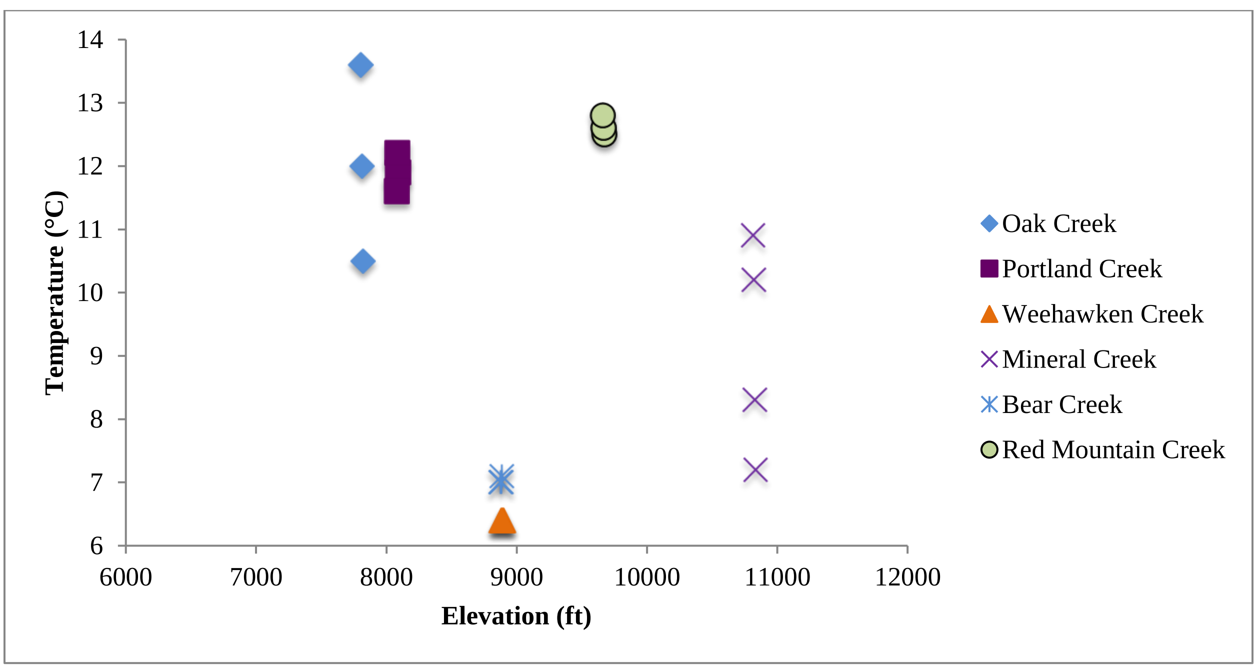

Figure 56. Step-pool temperature compared to step-pool elevation

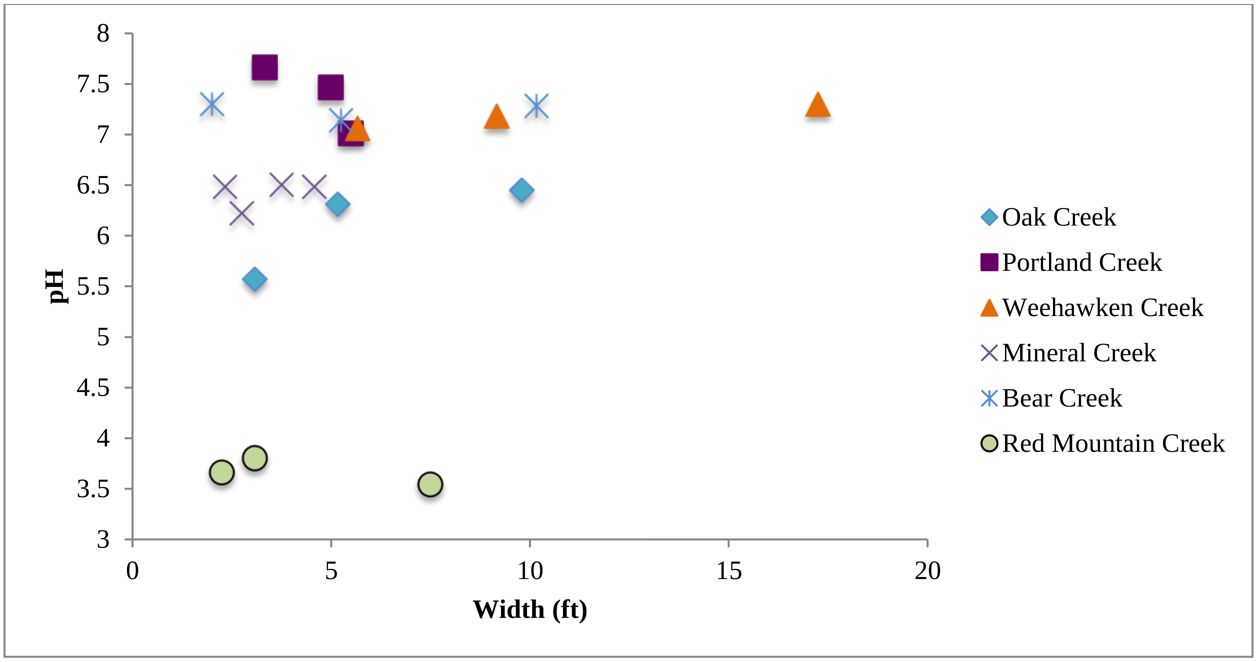

Figure 57. Step-pool pH compared to step-pool width

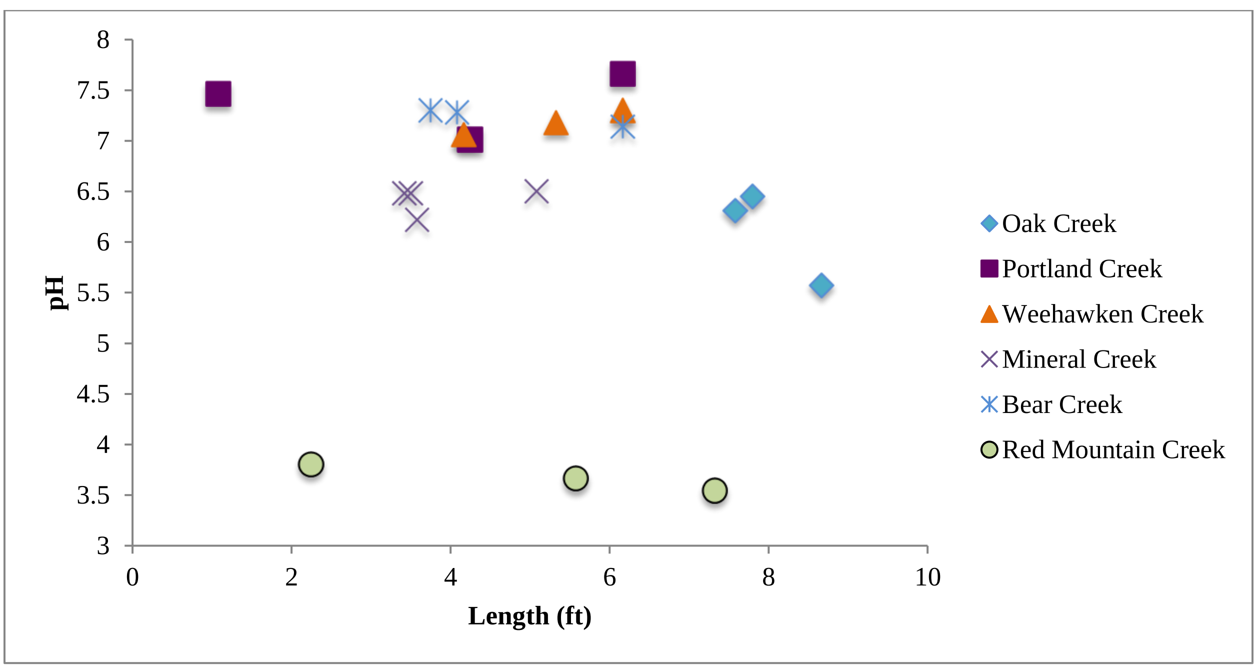

Figure 58. Step-pool pH compared to step-pool length

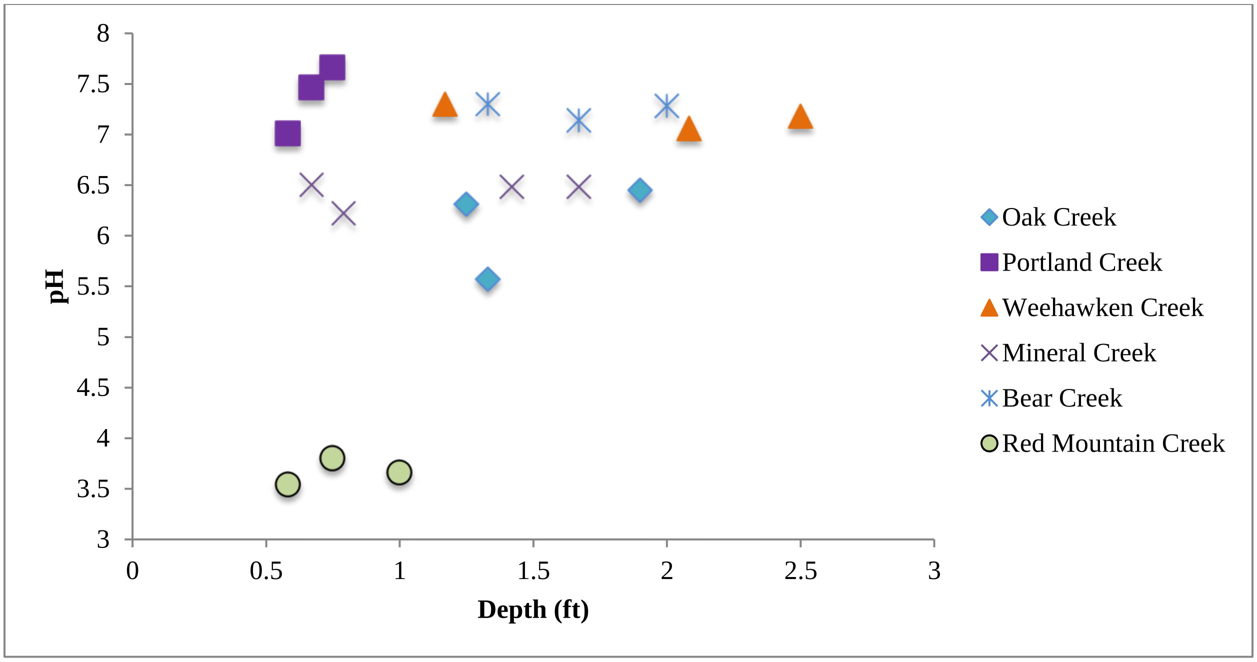

Figure 59. Step-pool pH compared to step-pool depth

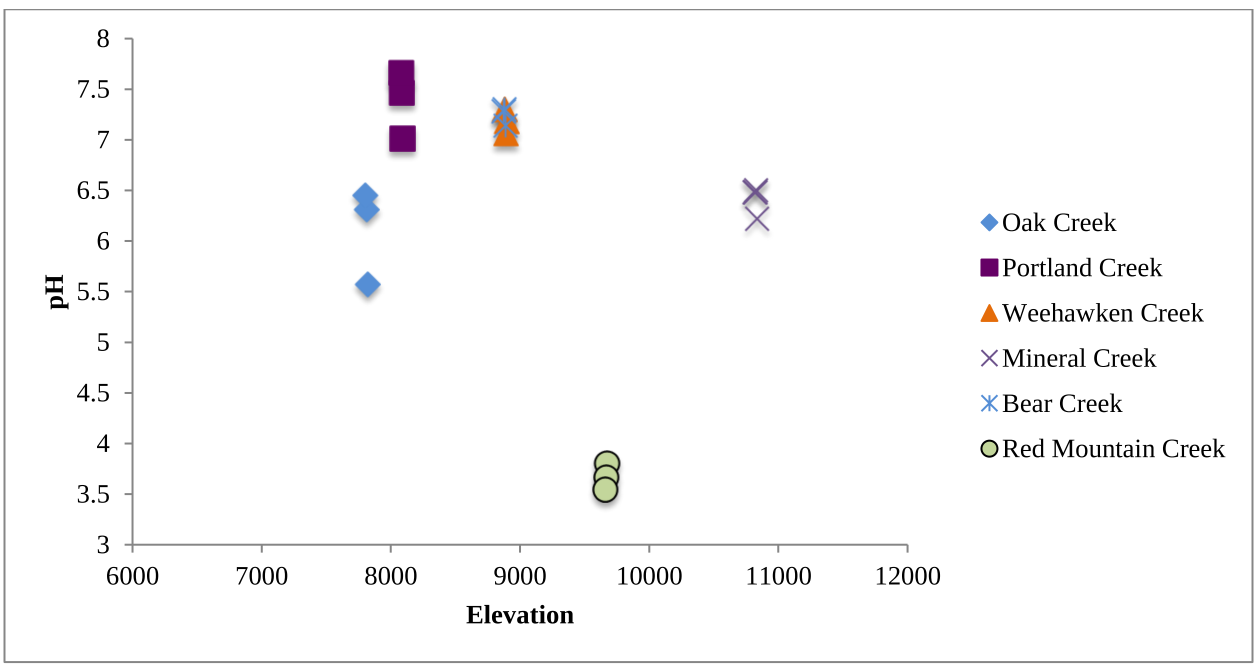

Figure 60. Step-pool pH compared to step-pool elevation

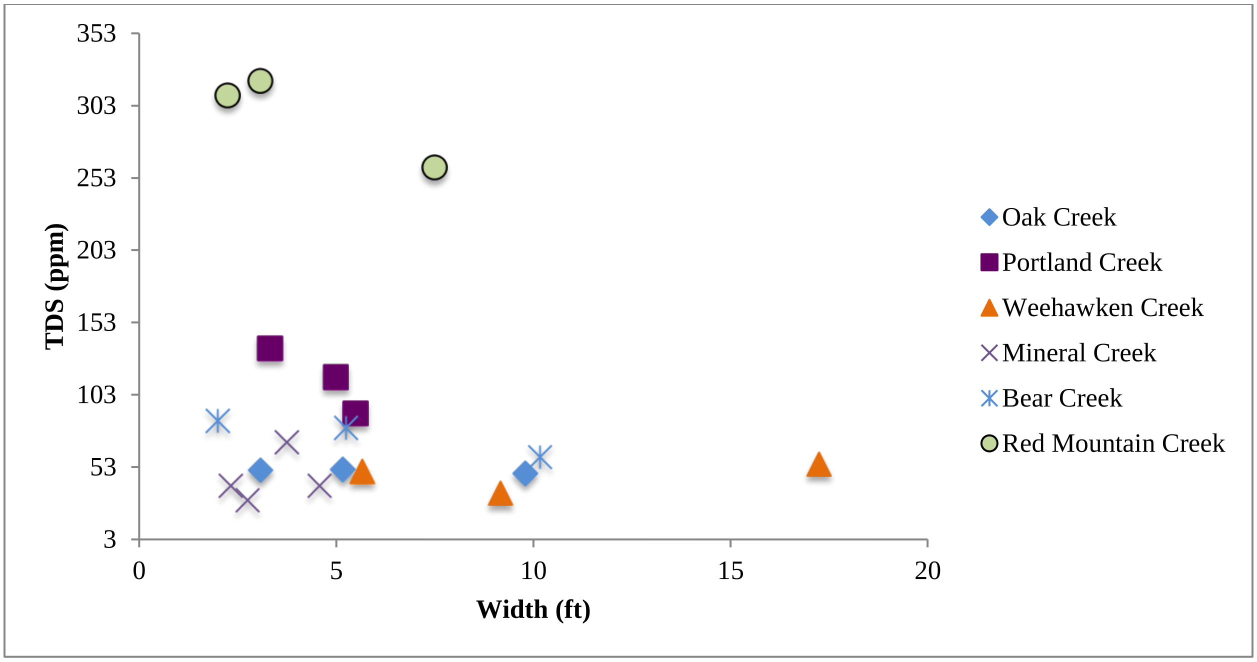

Figure 61. Step-pool total dissolved solids compared to step-pool width

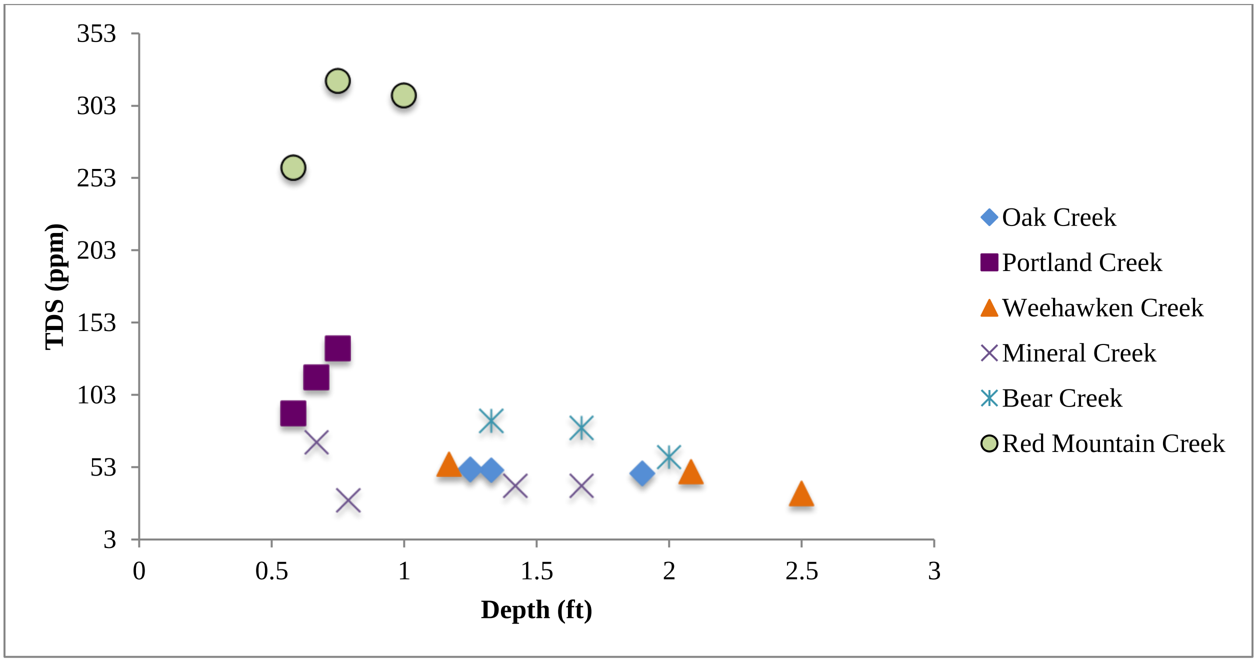

Figure 62. Step-pool total dissolved solids compared to step-pool depth

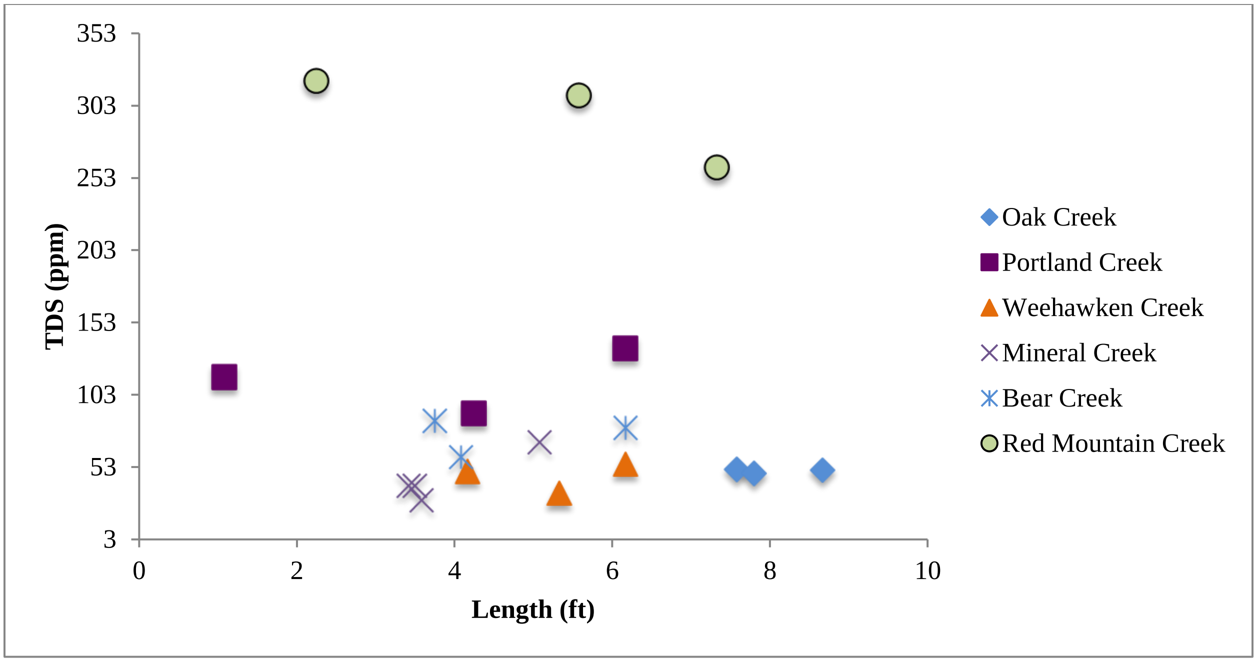

Figure 63. Step-pool total dissolved solids compared to step-pool length

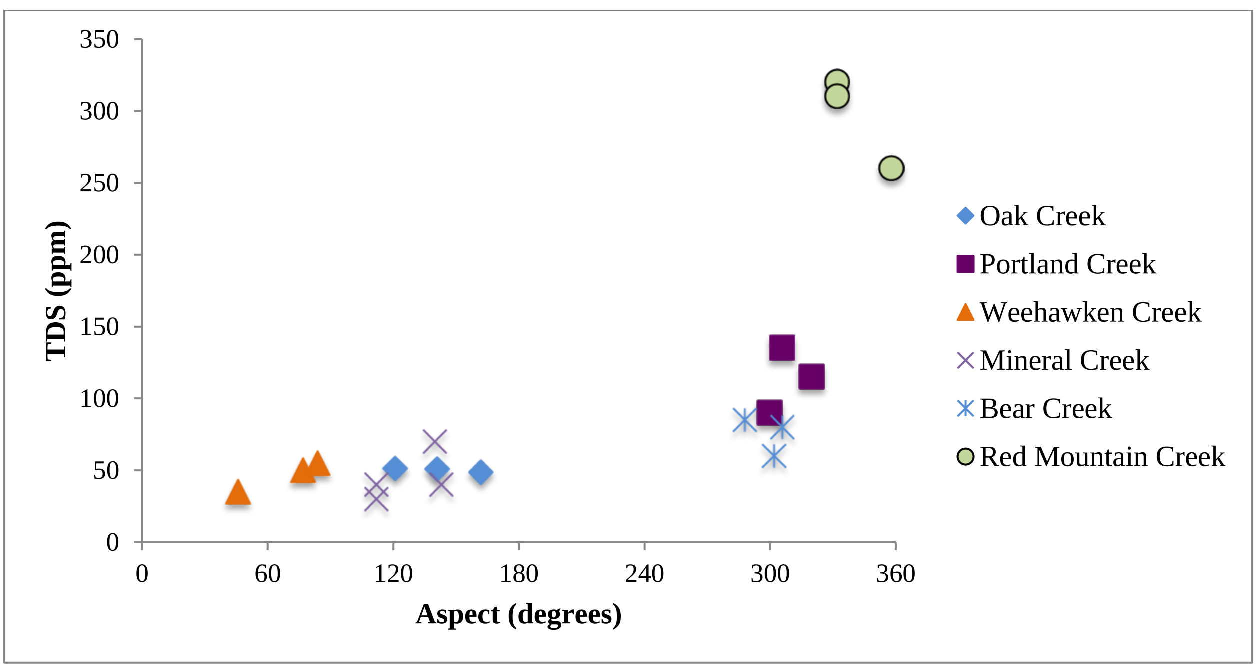

Figure 64. Step-pool total dissolved solids compared to step-pool aspect

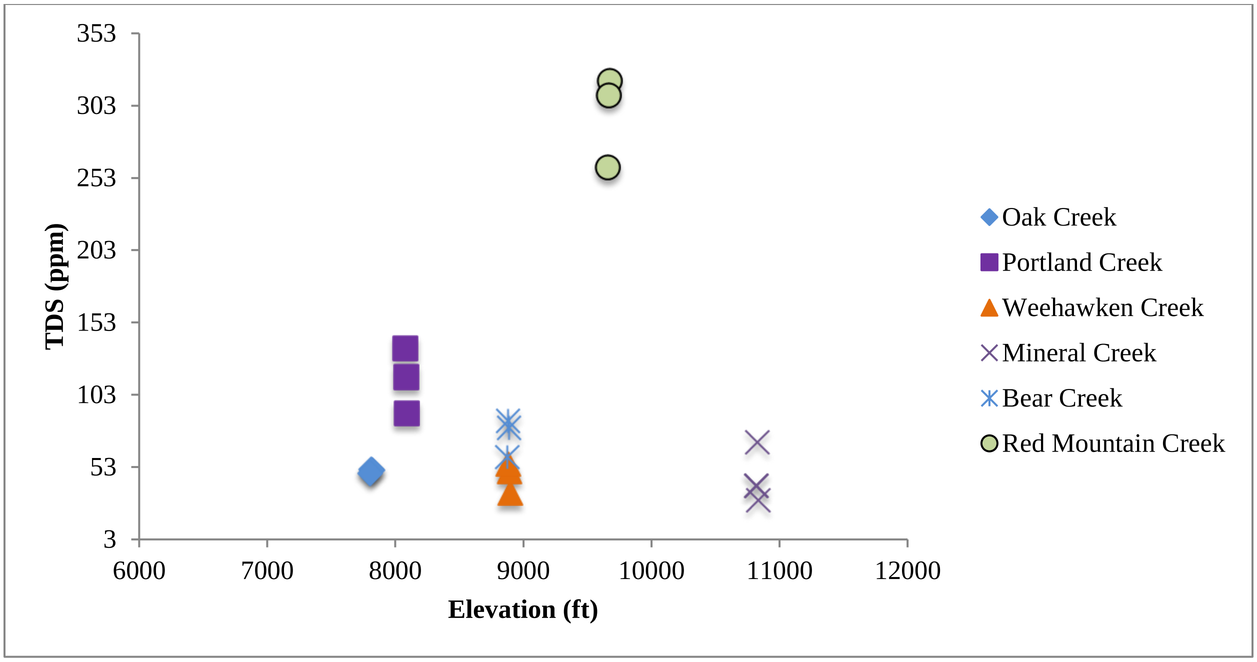

Figure 65. Step-pool total dissolved solids compared to step-pool elevation

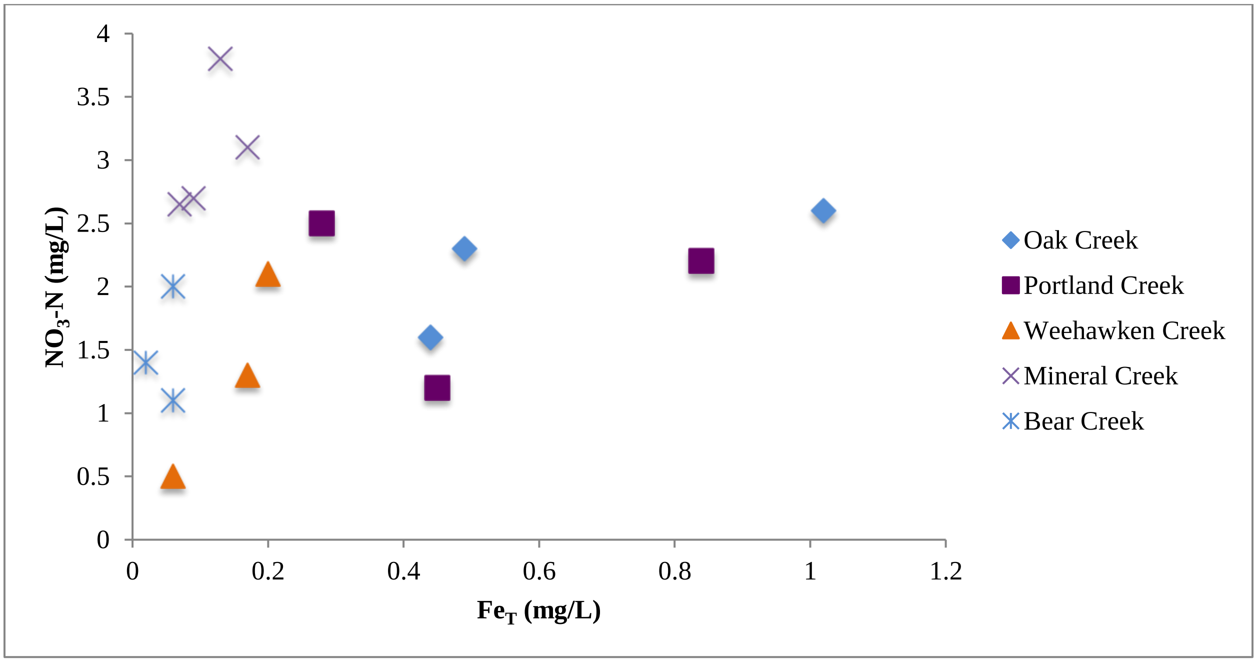

Figure 66. Step-pool nitrate-nitrogen concentrations compared to step-pool total iron concentrations

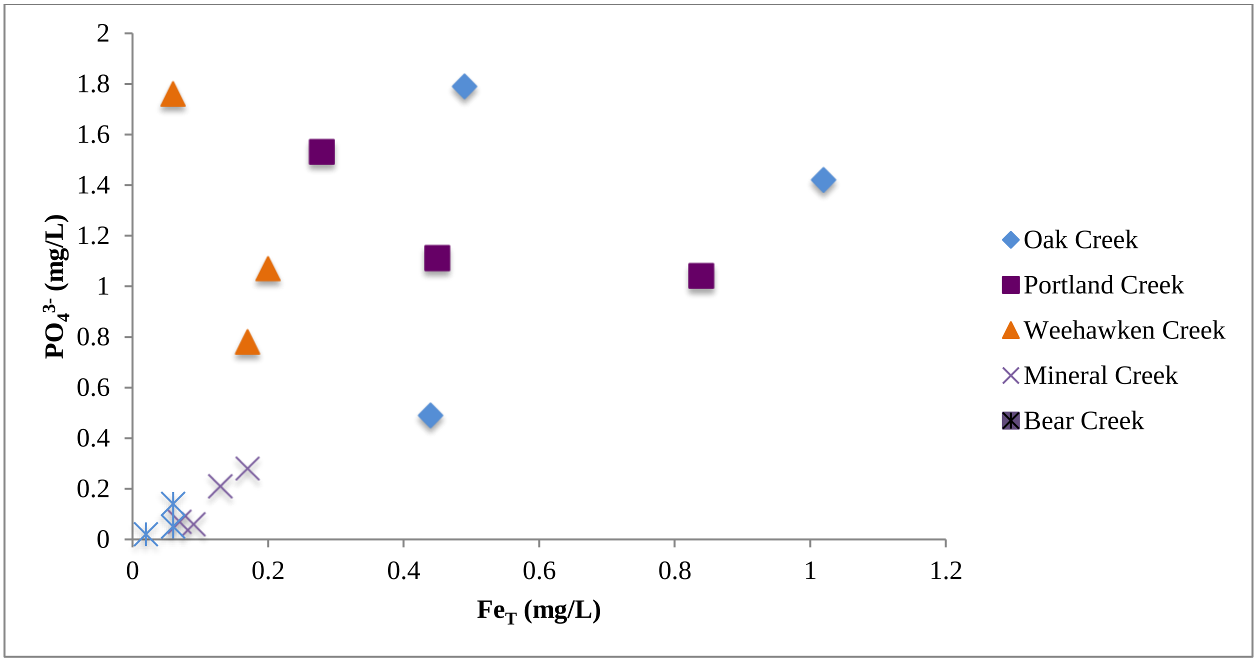

Figure 67. Step-pool phosphate concentrations compared to step-pool total iron concentrations

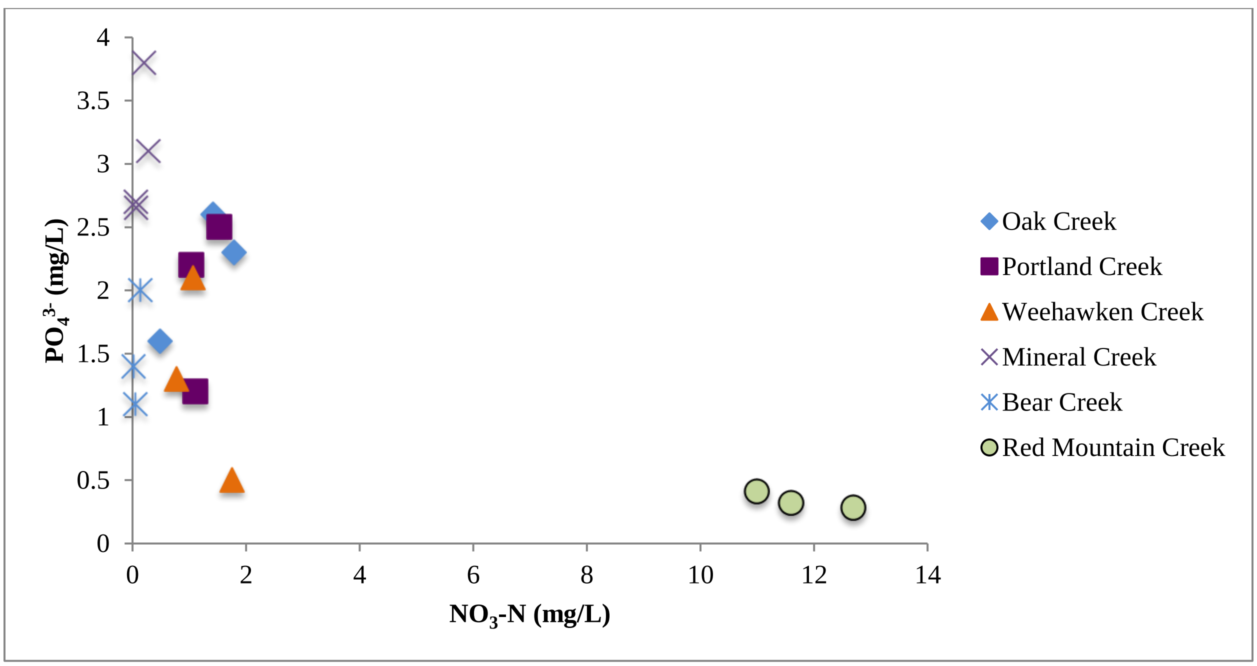

Figure 68. Step-pool phosphate concentrations compared to step-pool nitrate-nitrogen concentrations

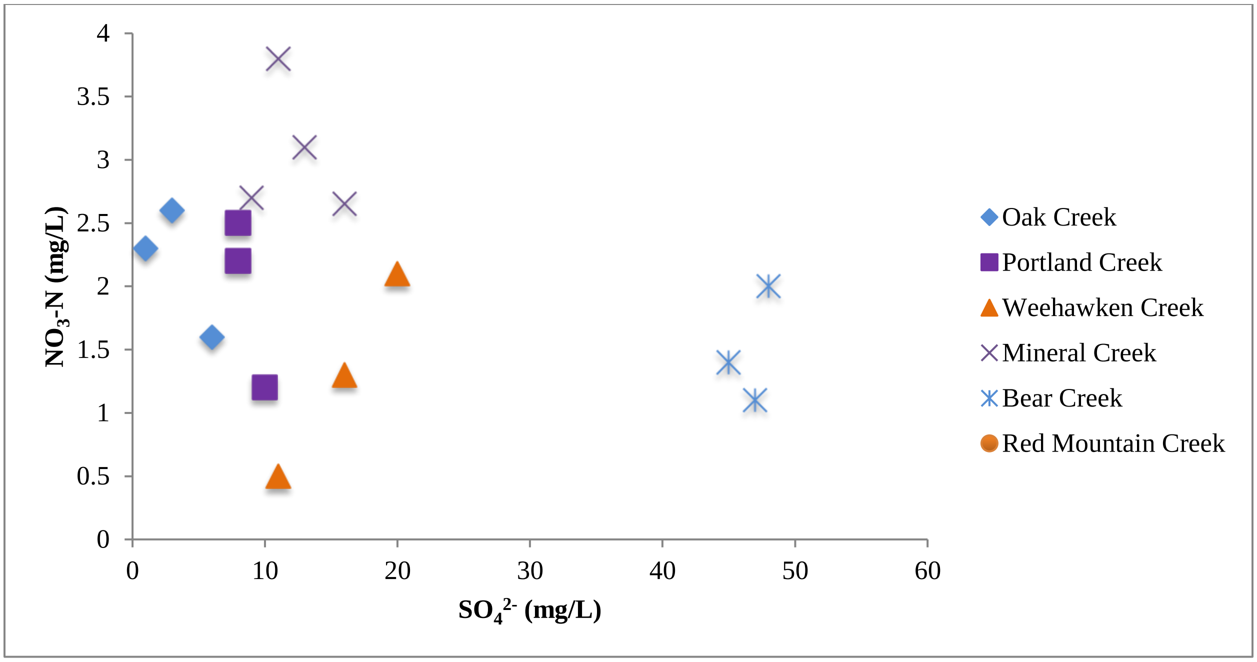

Figure 69. Step-pool nitrate-nitrogen concentrations compared to step-pool sulfate concentrations

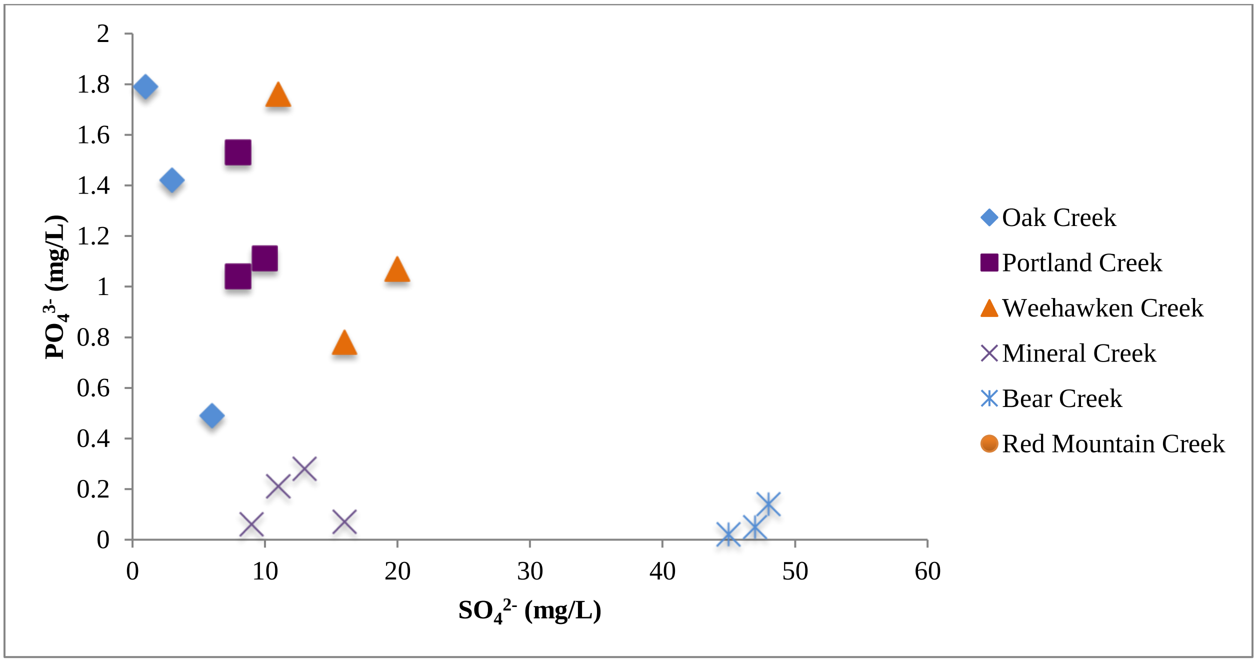

Figure 70. Step-pool phosphate concentrations compared to step-pool sulfate concentrations

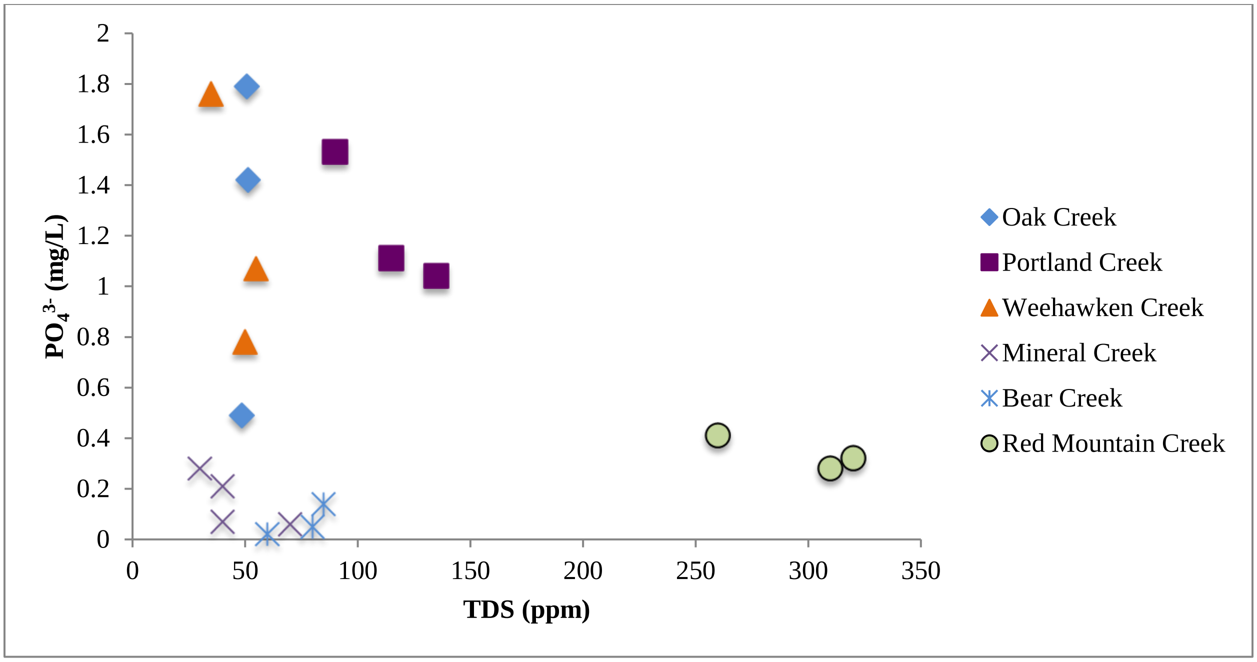

Figure 71. Step-pool phosphate concentrations compared to step-pool total dissolved solids

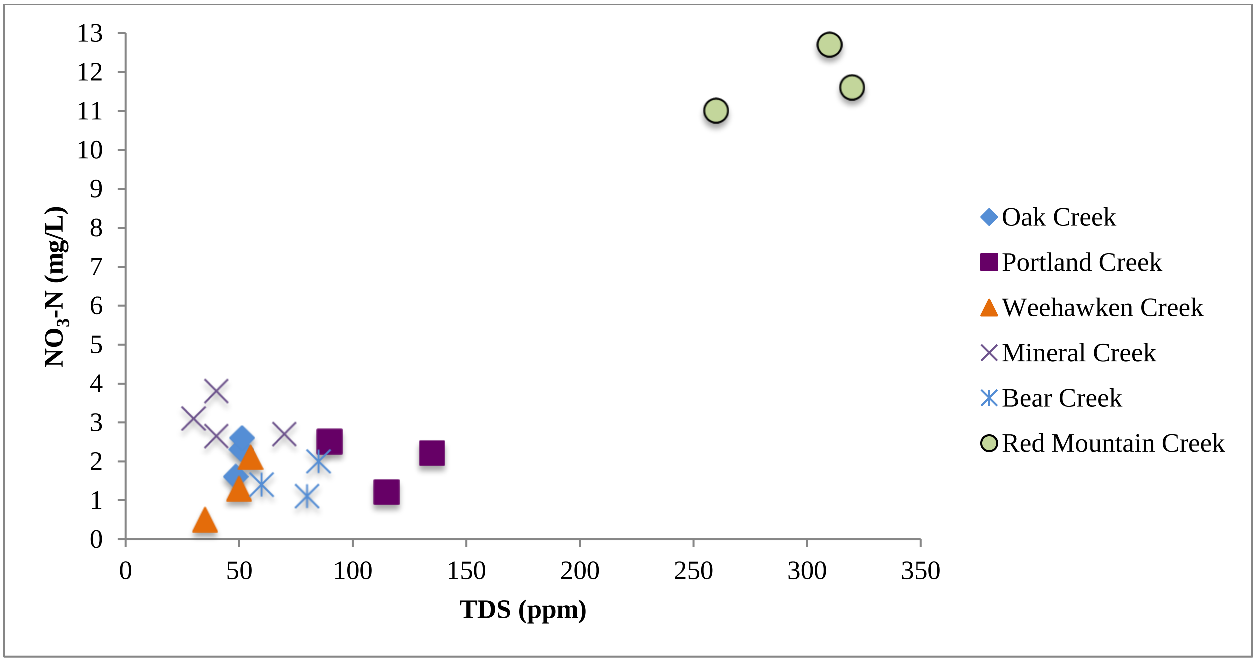

Figure 72. Step-pool nitrate-nitrogen concentrations compared to step-pool total dissolved solids

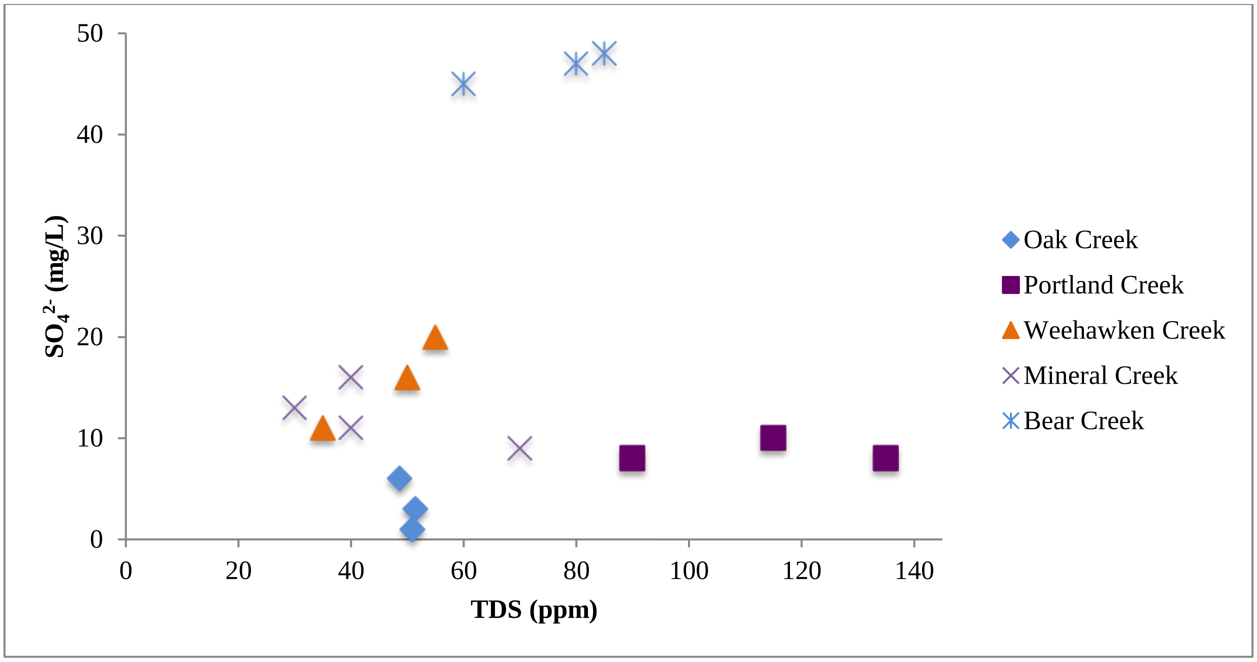

Figure 73. Step-pool sulfate concentrations compared to step-pool total dissolved solids

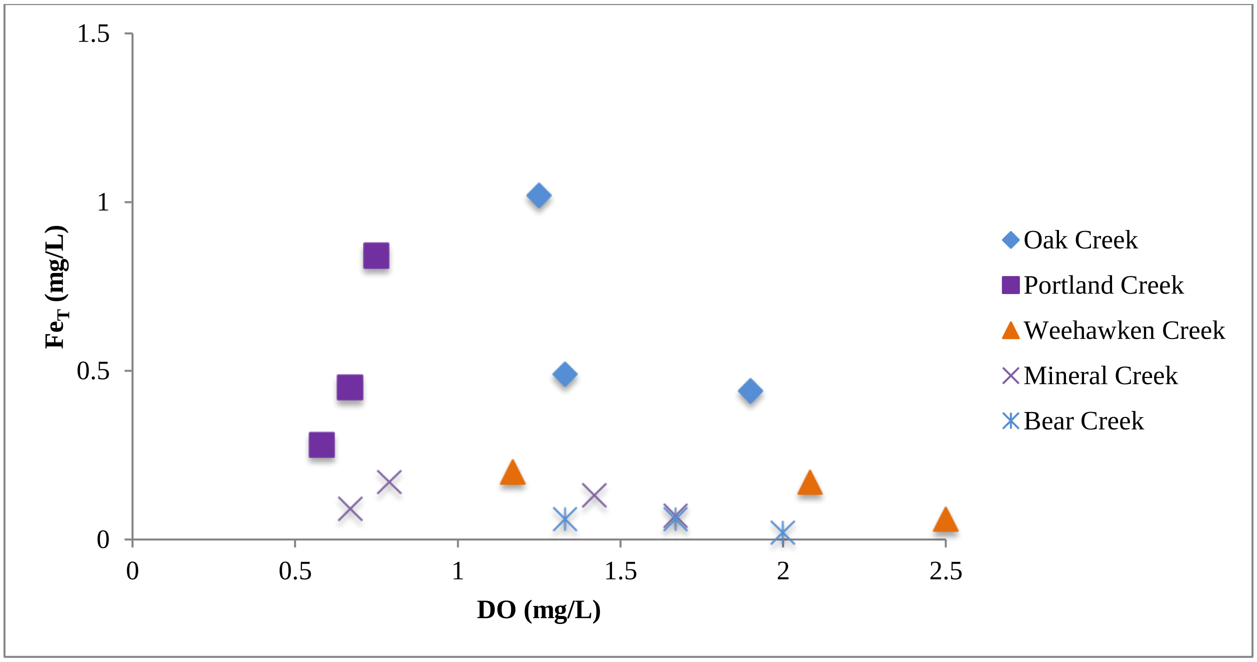

Figure 74. Step-pool total iron concentrations compared to step-pool dissolved oxygen

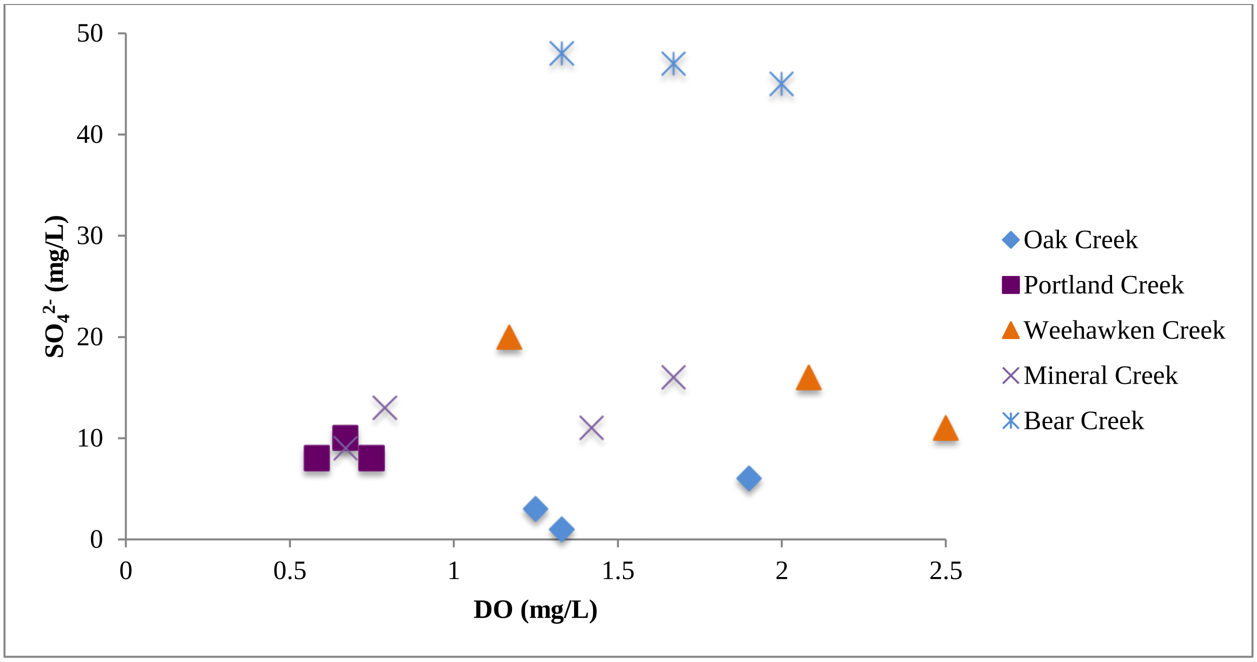

Figure 75. Step-pool sulfate concentrations compared to step-pool dissolved oxygen

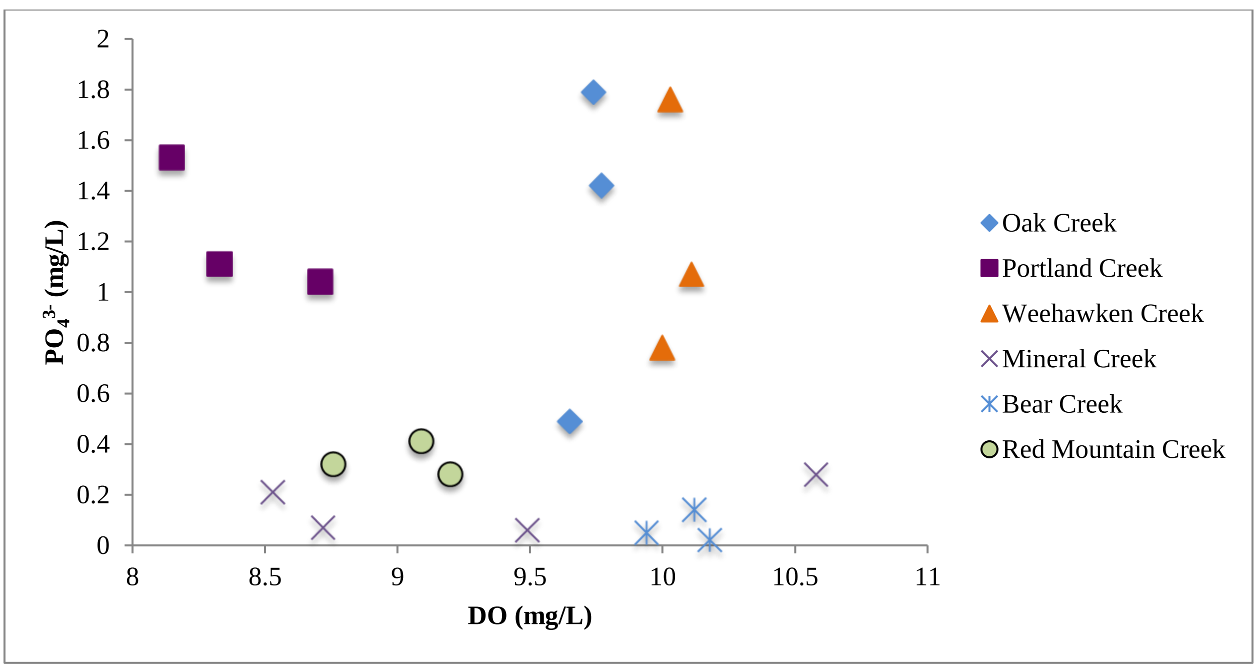

Figure 76. Step-pool phosphate concentrations compared to step-pool dissolved oxygen

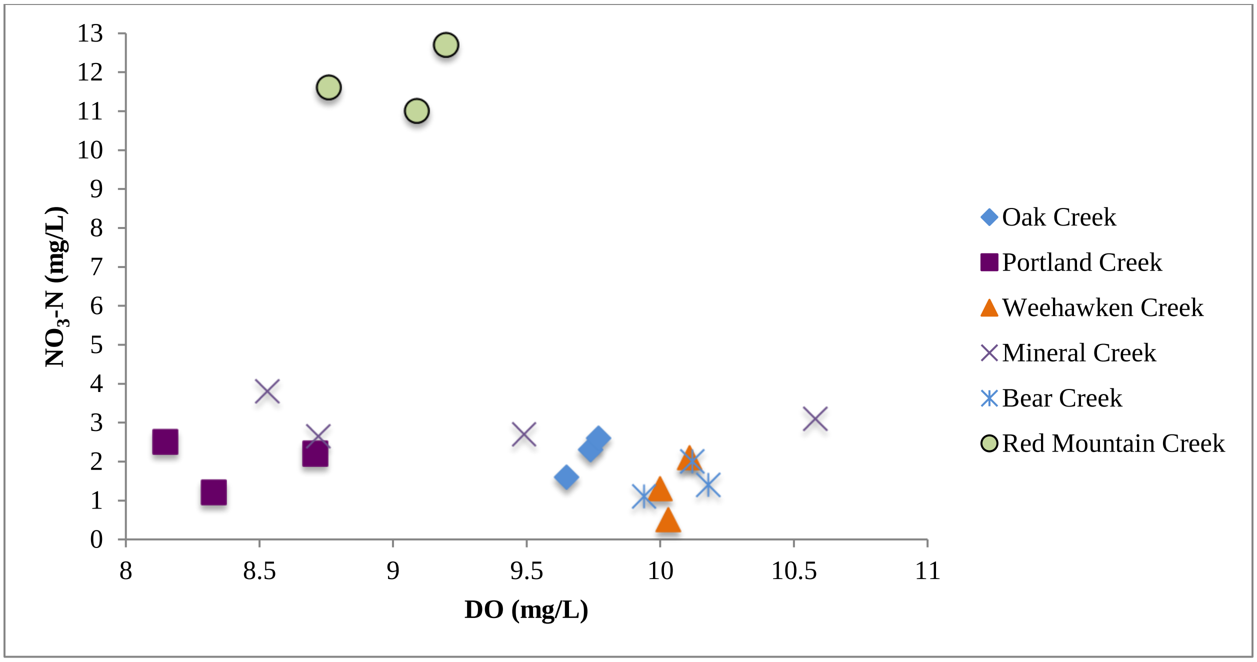

Figure 77. Step-pool nitrate-nitrogen concentrations compared to step-pool dissolved oxygen

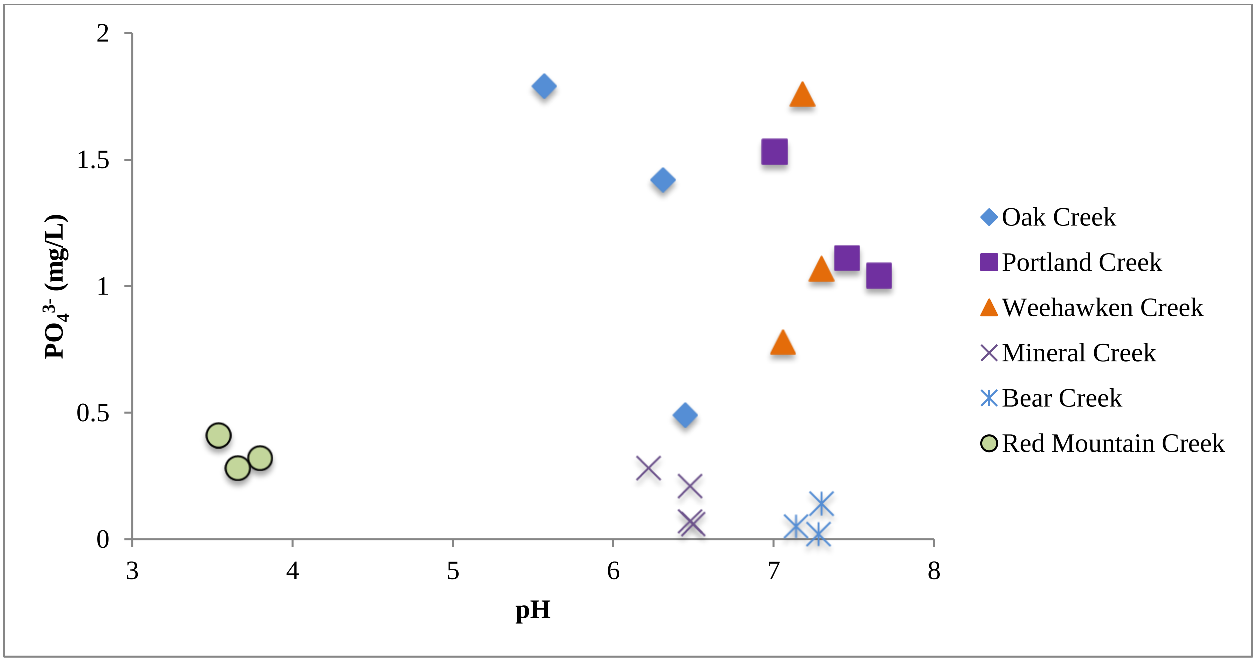

Figure 78. Step-pool phosphate concentrations compared to step-pool pH

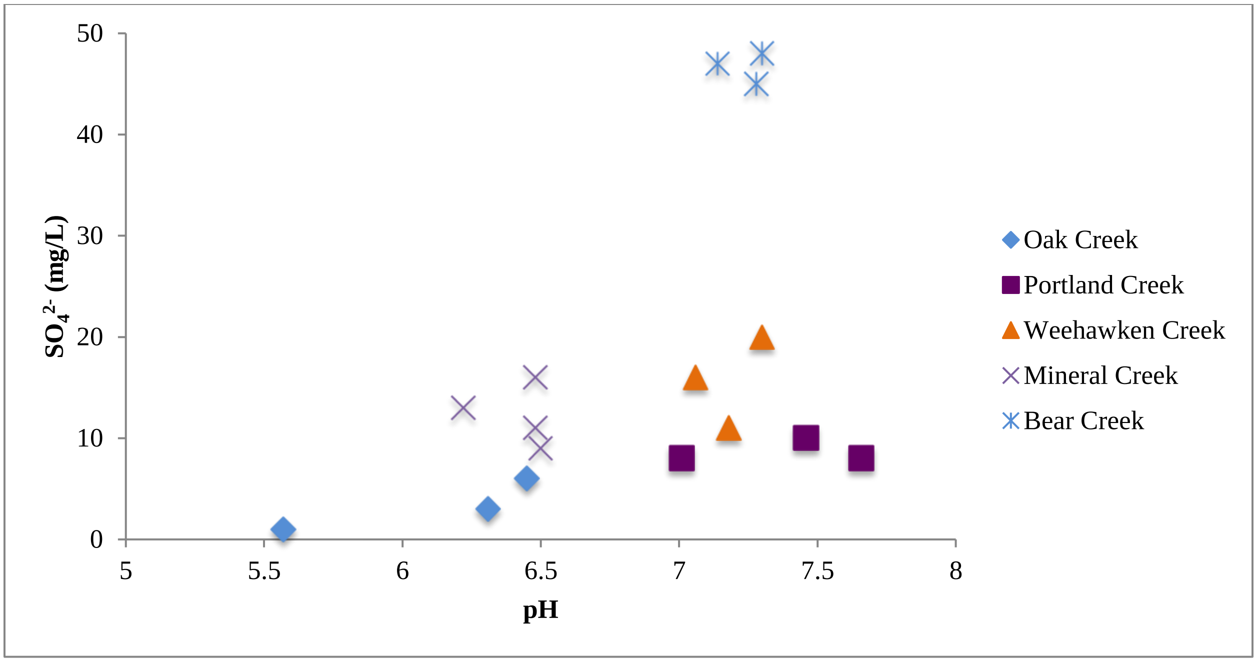

Figure 79. Step-pool sulfate concentrations compared to step-pool pH

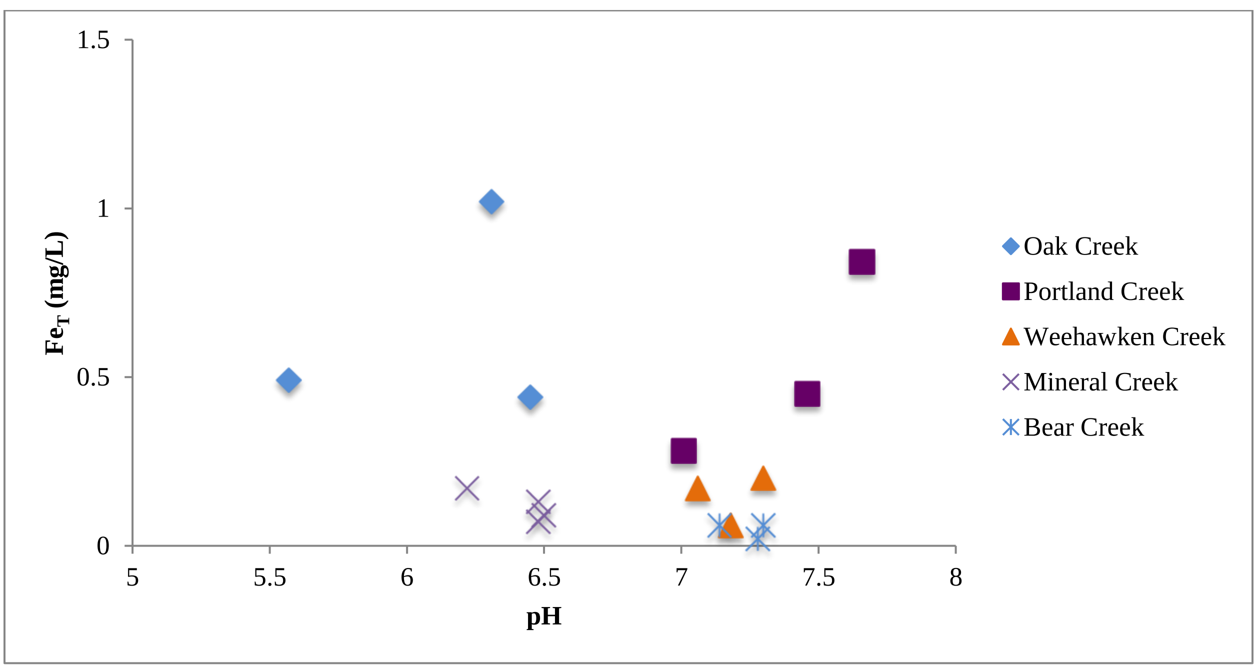

Figure 80. Step-pool total iron concentrations compared to step-pool pH

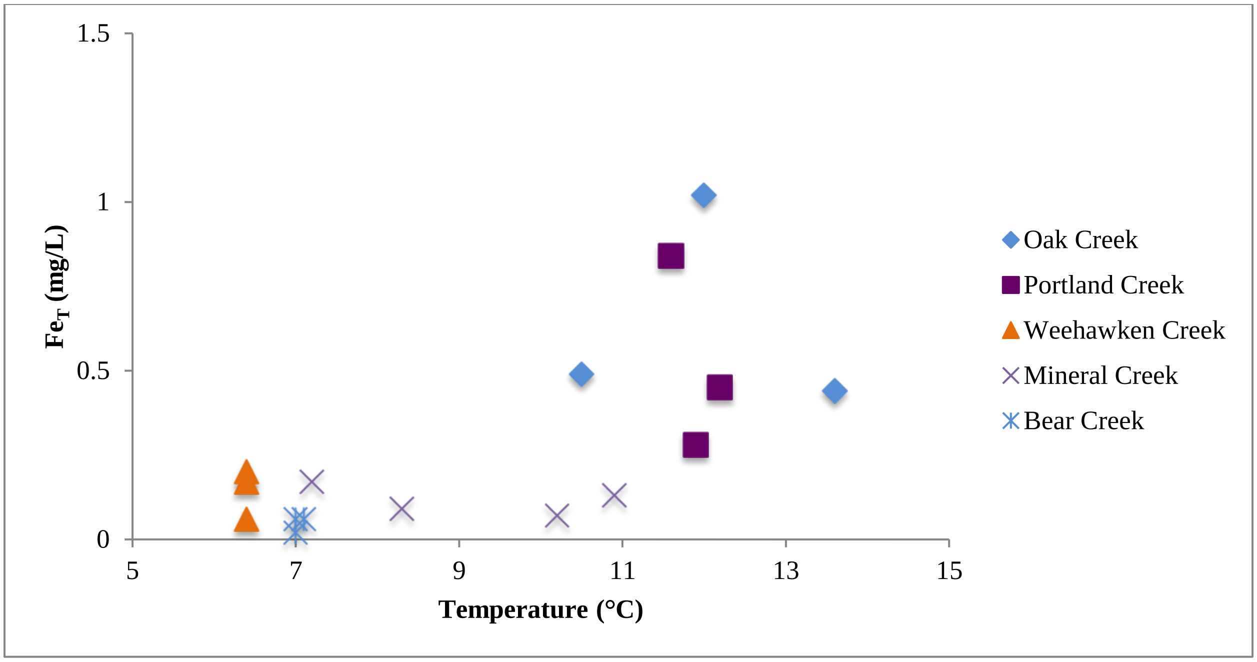

Figure 81. Step-pool total iron concentrations compared to step-pool temperature

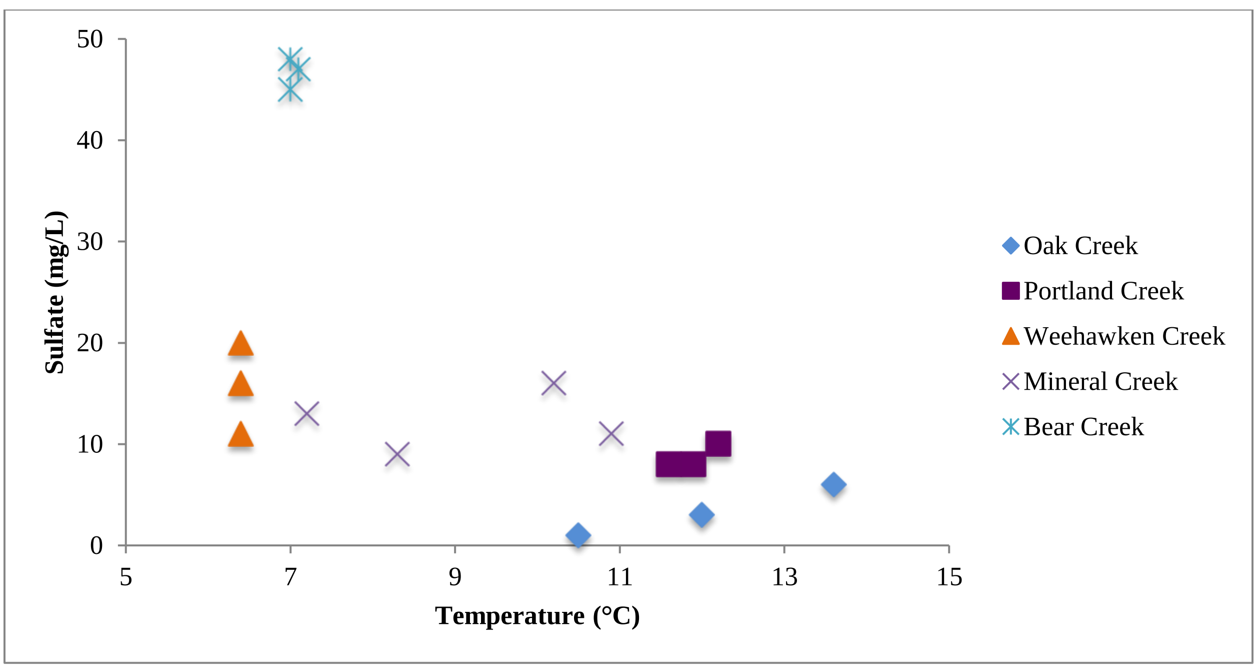

Figure 82. Step-pool sulfate concentrations compared to step-pool temperature

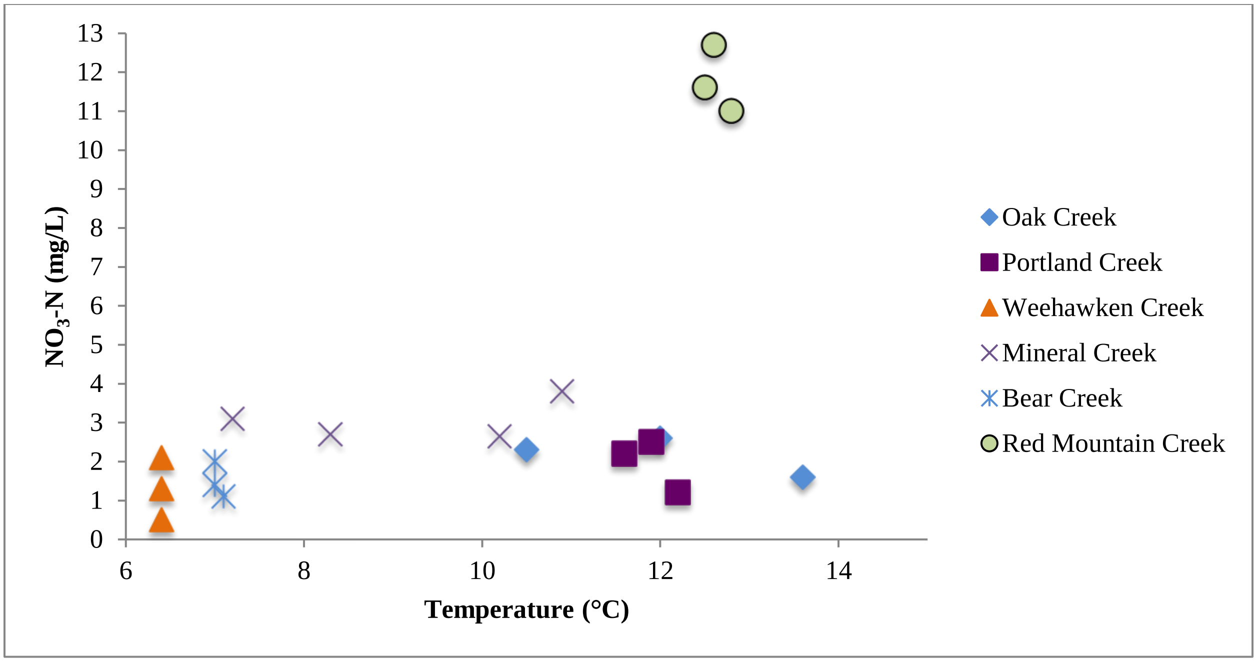

Figure 83. Step-pool nitrate-nitrogen concentrations compared to step-pool temperature

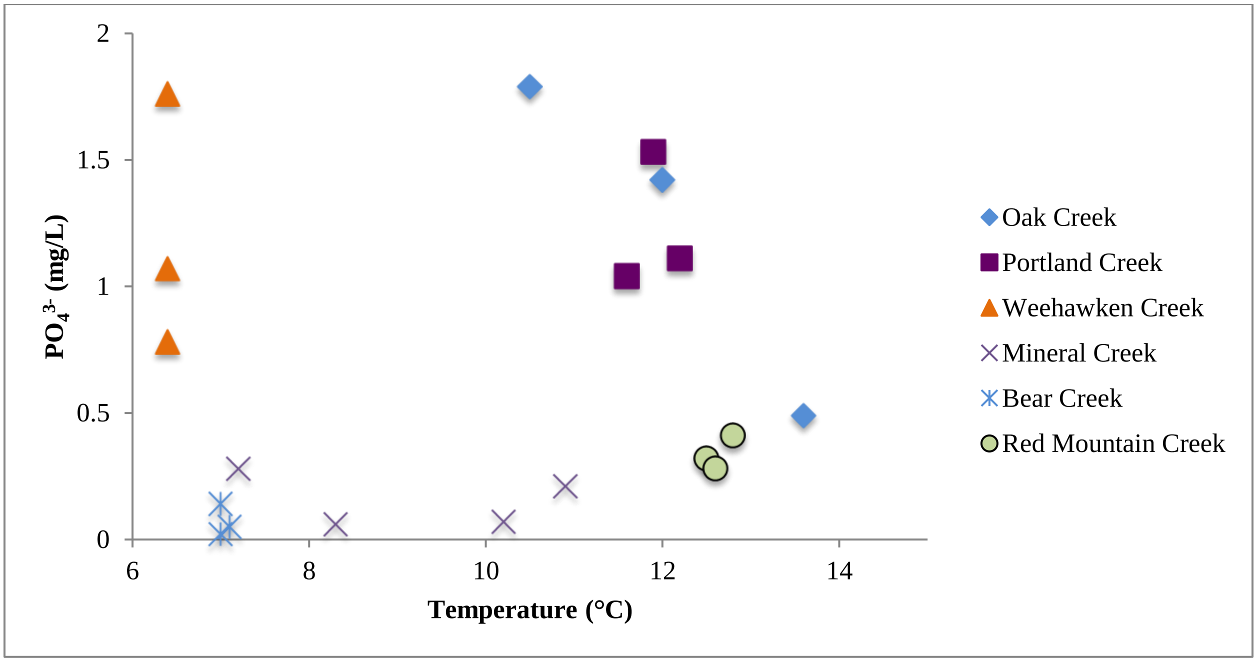

Figure 84. Step-pool phosphate concentrations compared to step-pool temperature

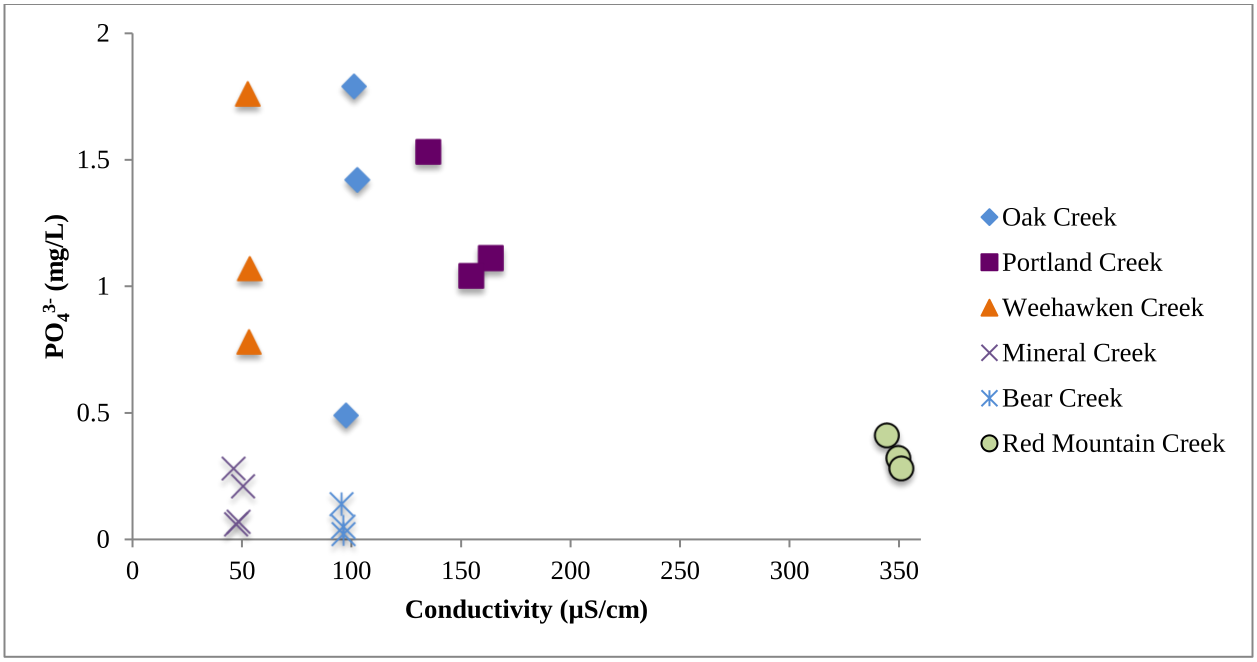

Figure 85. Step-pool phosphate concentrations compared to step-pool conductivity

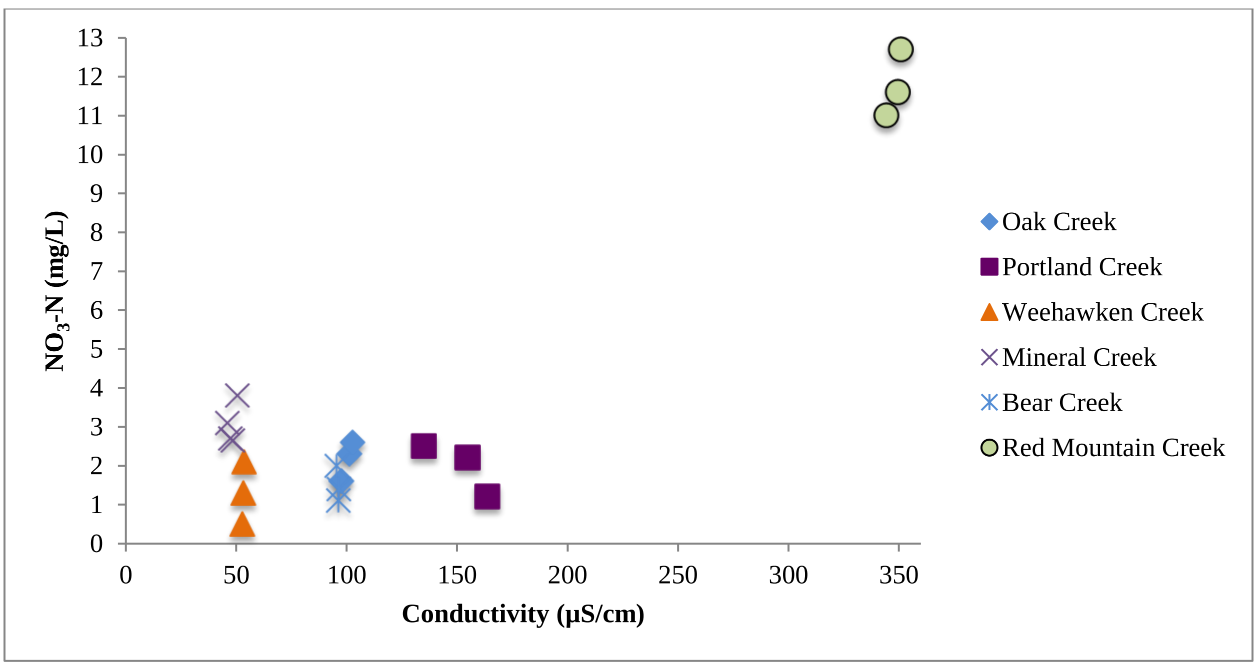

Figure 86. Step-pool nitrate-nitrogen concentrations compared to step-pool conductivity

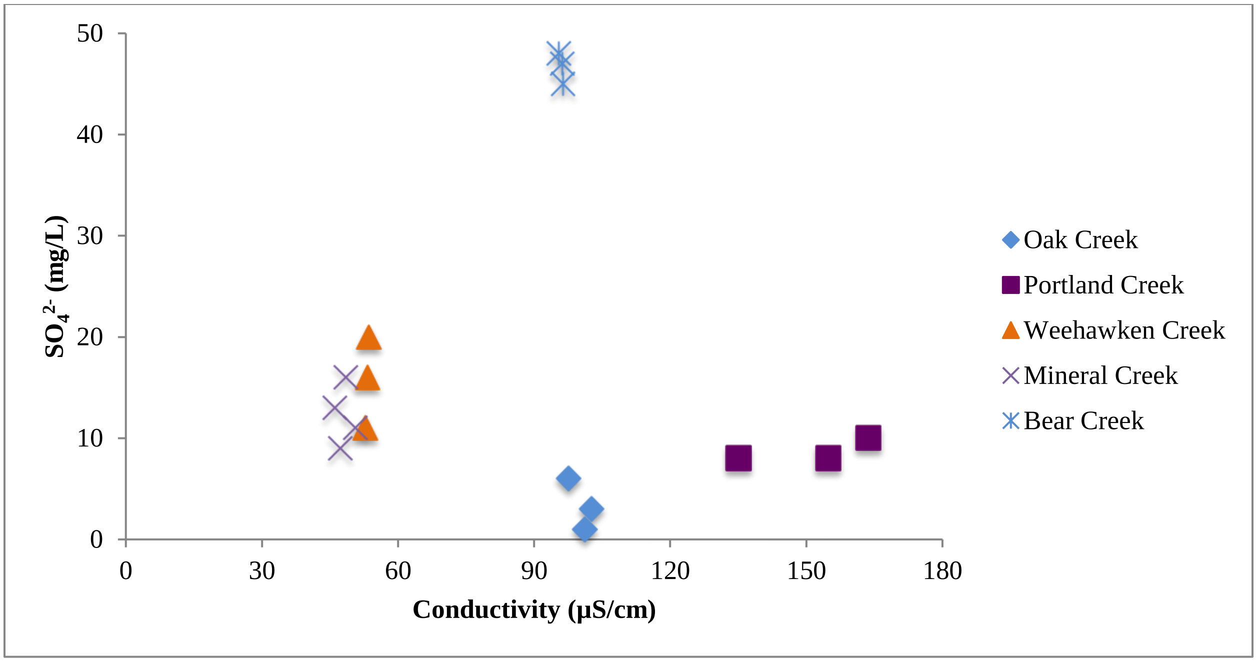

Figure 87. Step-pool sulfate concentrations compared to step-pool conductivity

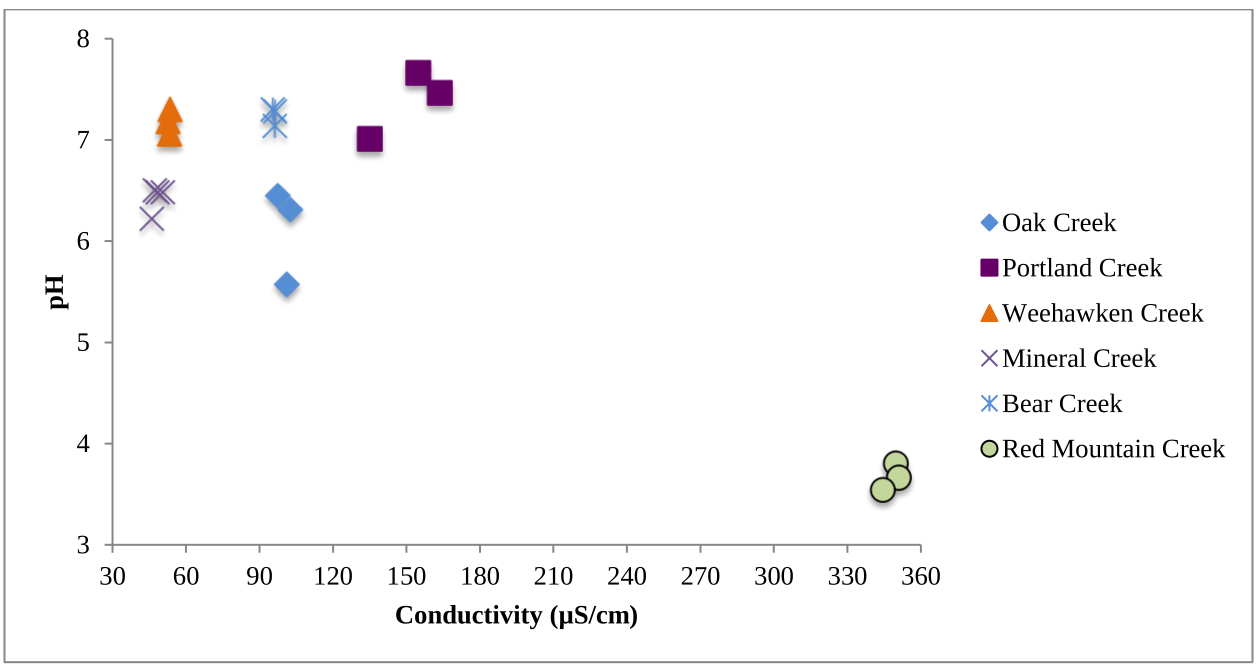

Figure 88. Step-pool pH compared to step-pool conductivity

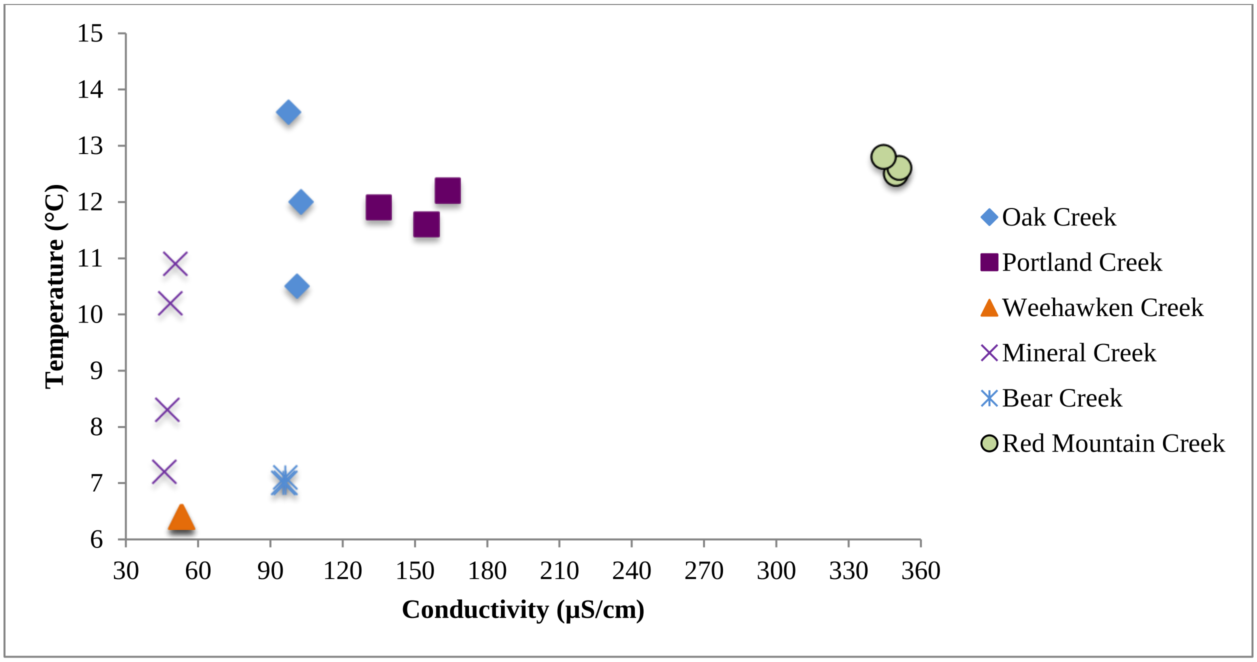

Figure 89. Step-pool temperature compared to step-pool conductivity

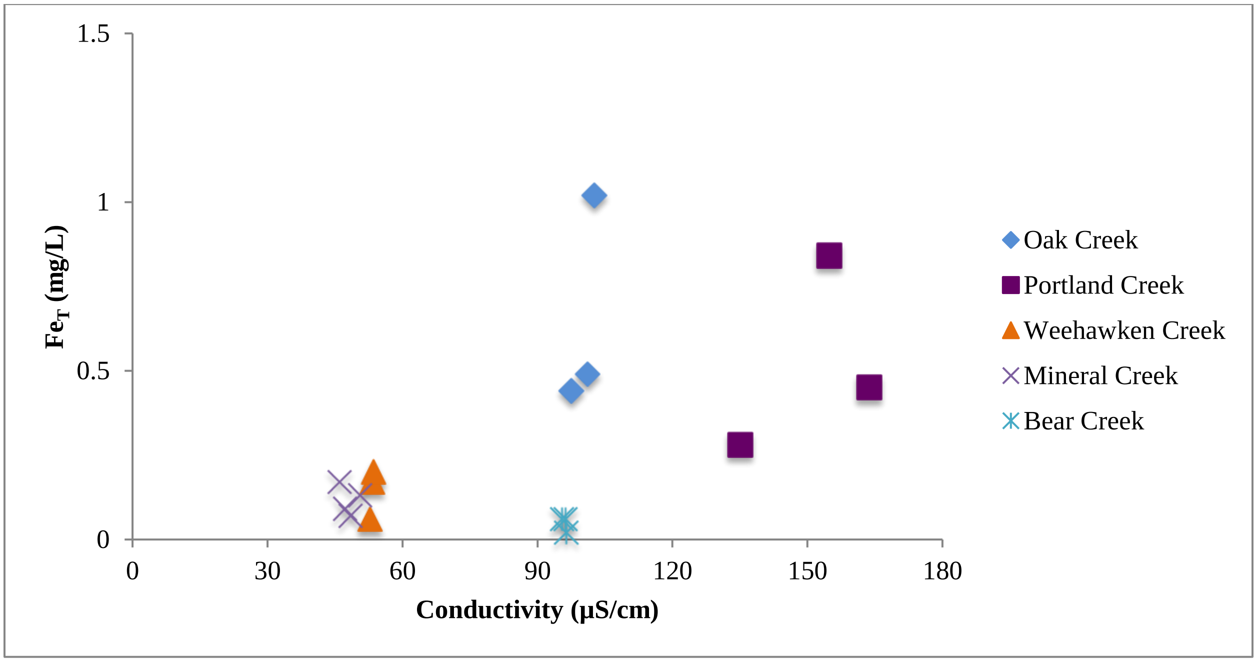

Figure 90. Step-pool total iron compared to step-pool conductivity

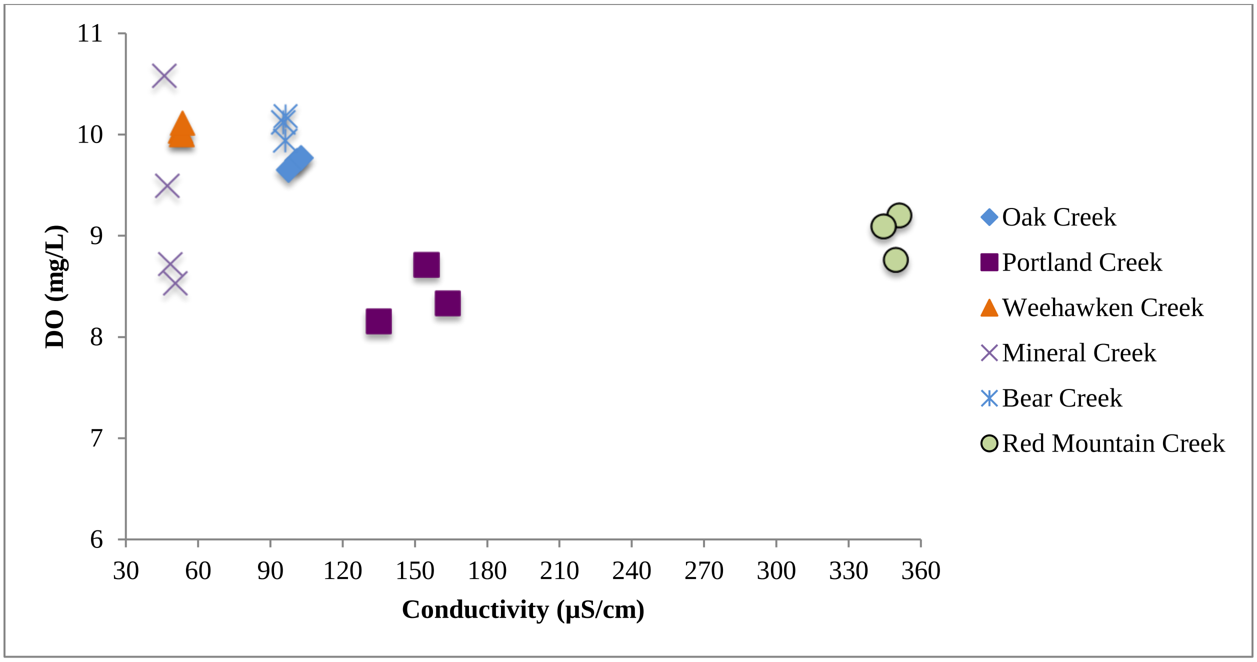

Figure 91. Step-pool dissolved oxygen compared to step-pool conductivity

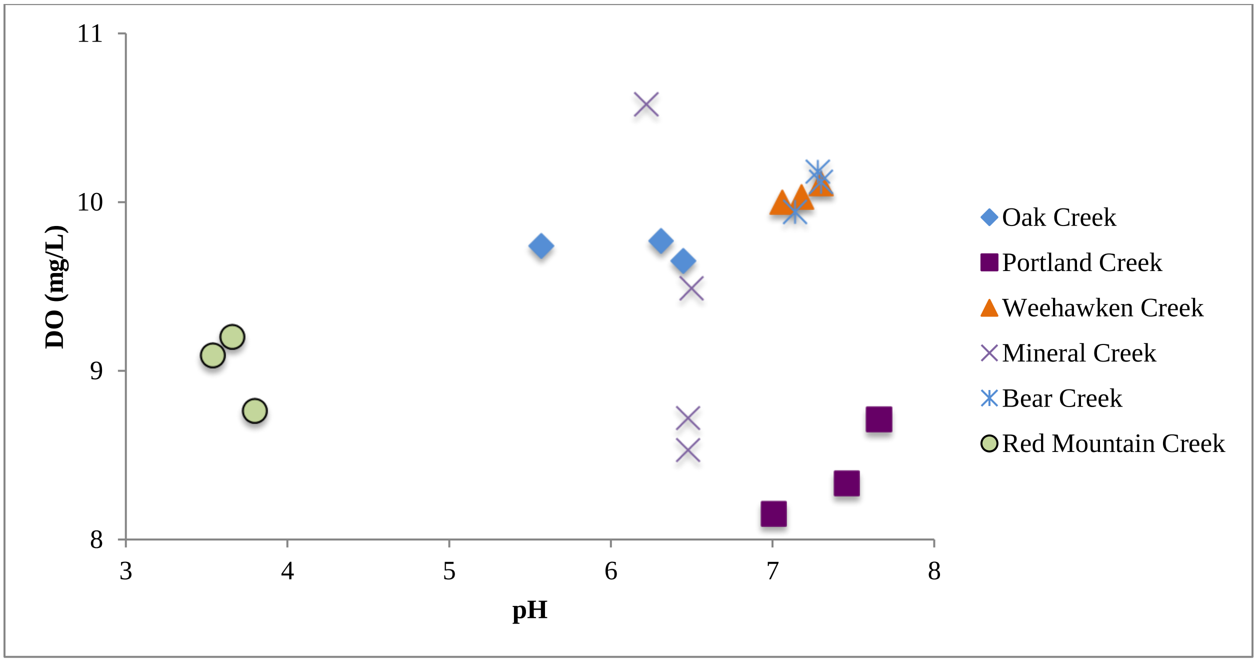

Figure 92. Step-pool dissolved oxygen compared to step-pool pH

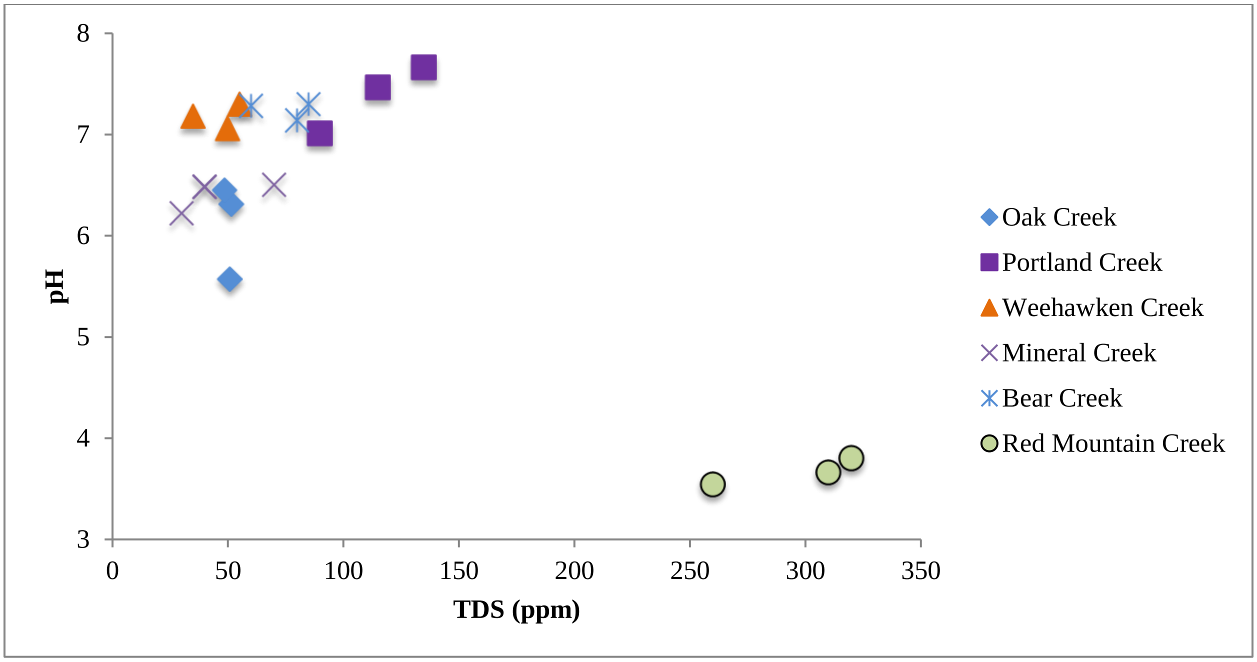

Figure 93. Step-pool pH compared to step-pool total dissolved solids

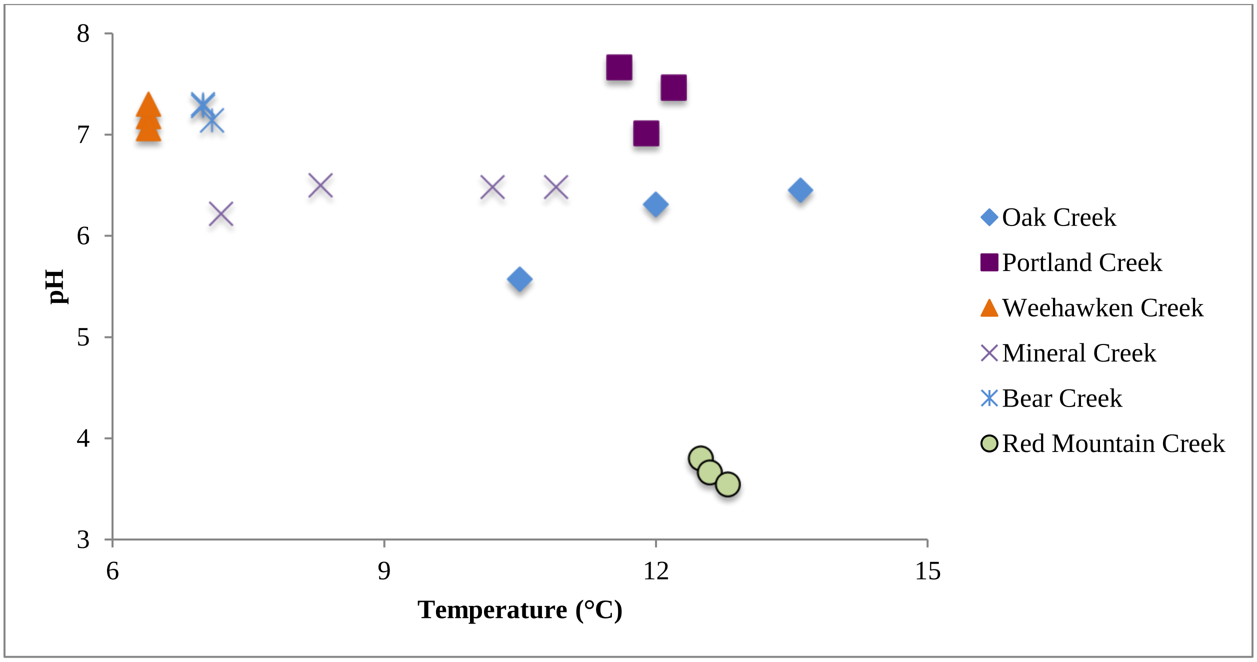

Figure 94. Step-pool pH compared to step-pool temperature

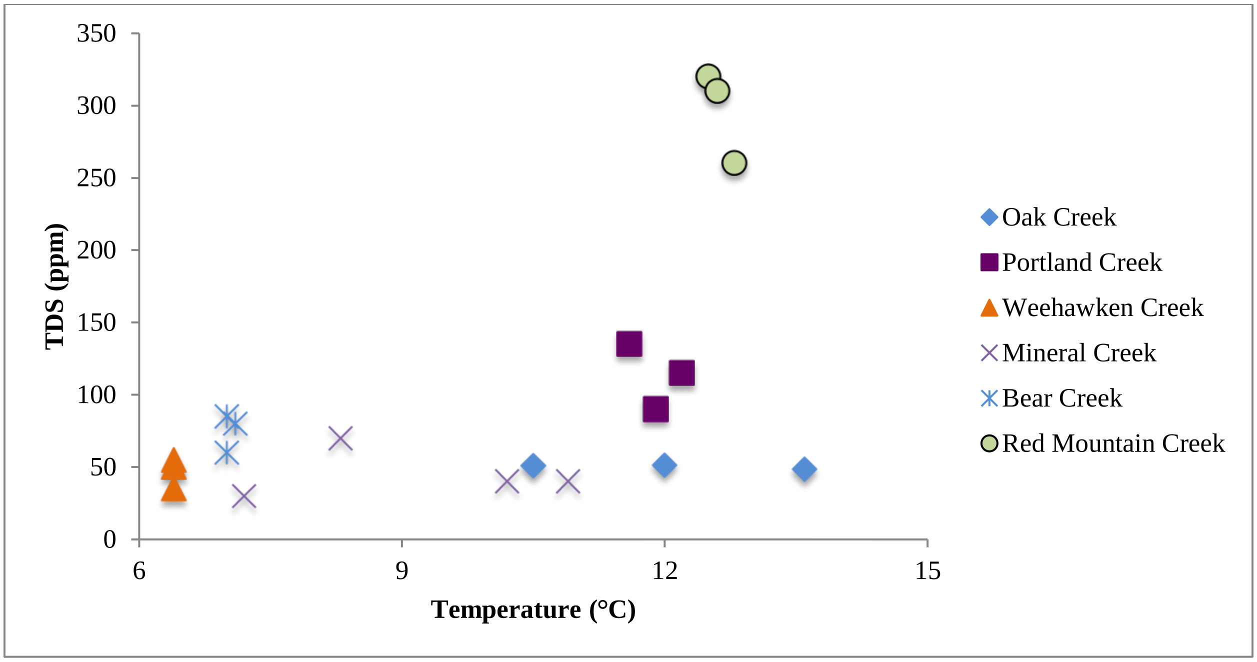

Figure 95. Step-pool total dissolved solids compared to step-pool temperature

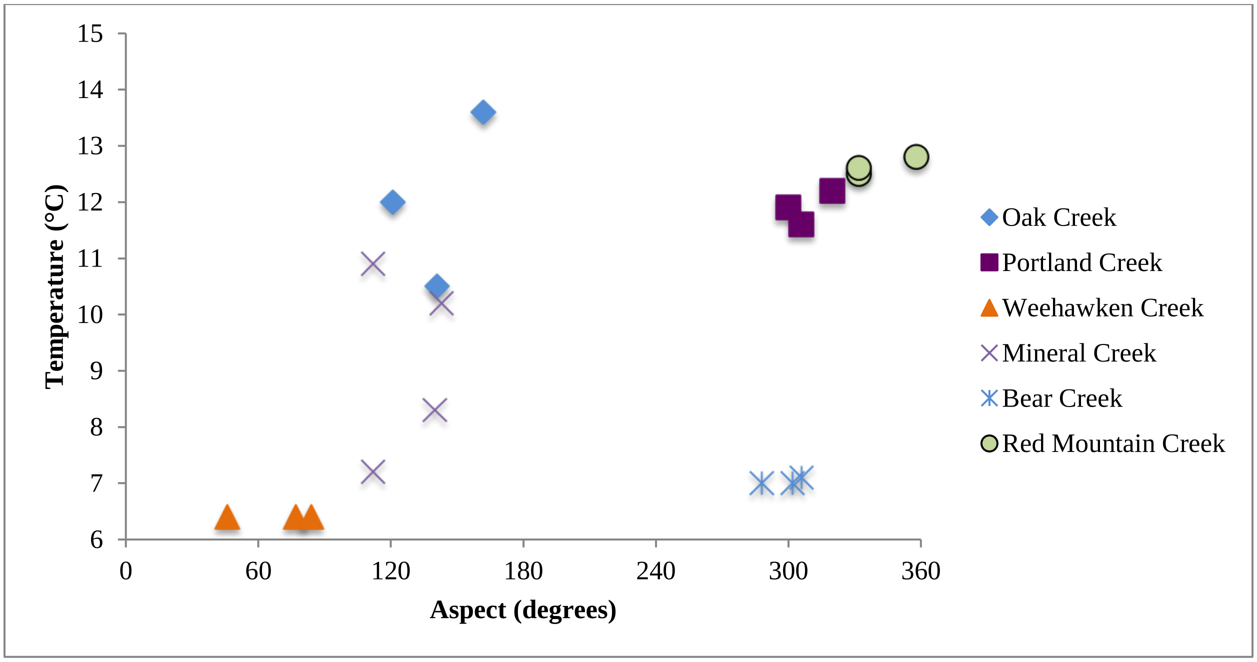

Figure 96. Step-pool temperature compared to step-pool aspect

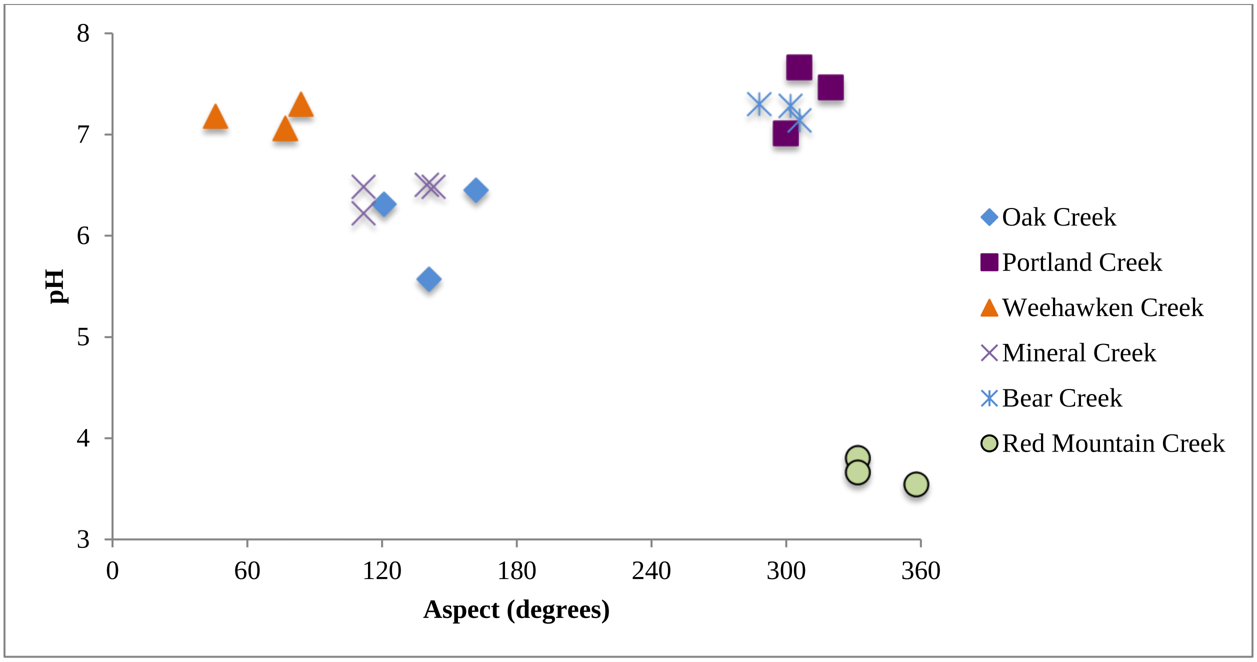

Figure 97. Step-pool pH compared to step-pool aspect

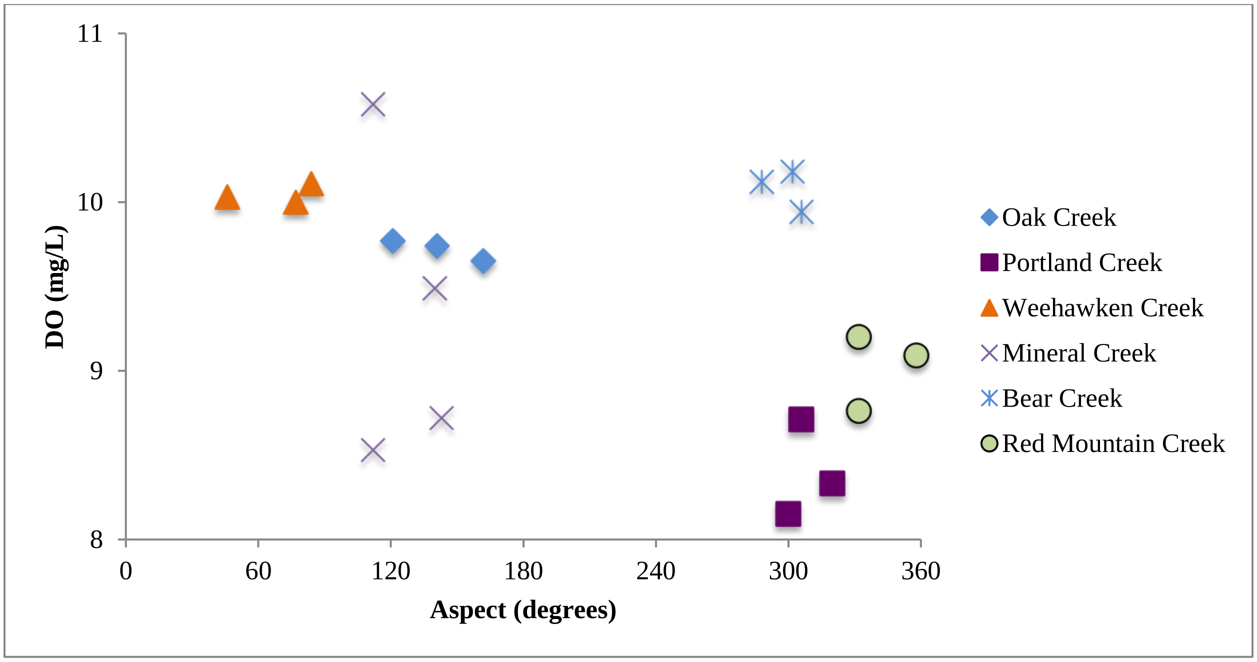

Figure 98. Step-pool dissolved oxygen compared to step-pool aspect

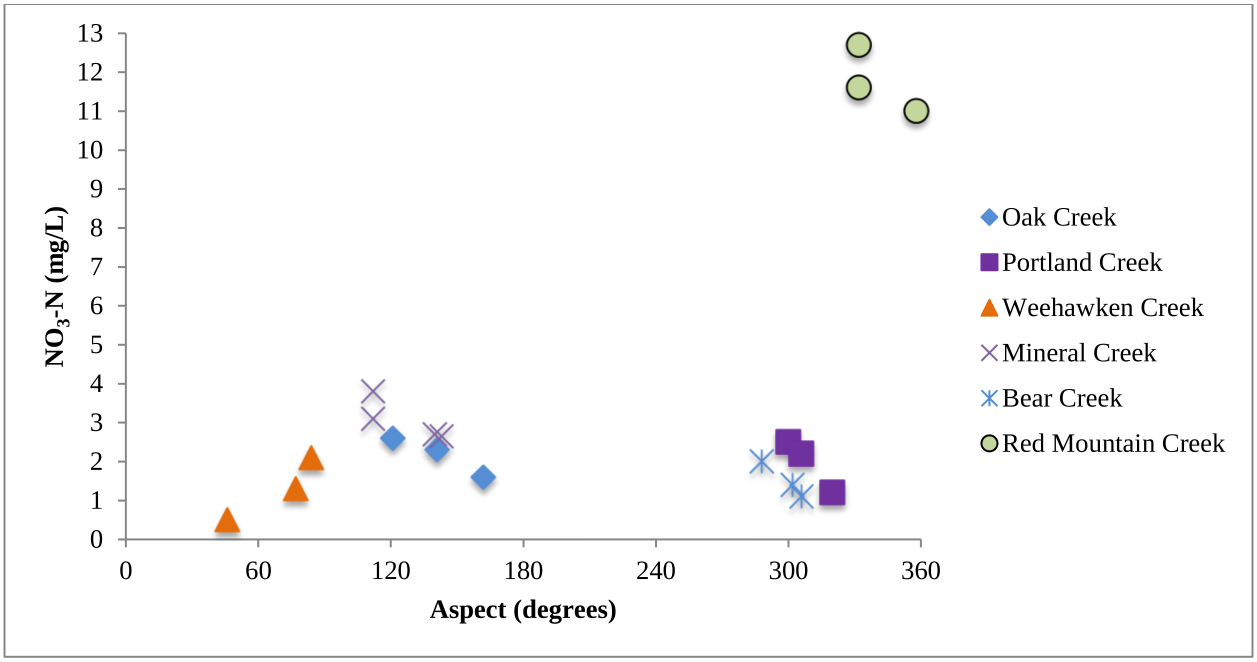

Figure 99. Step-pool nitrate-nitrogen concentrations compared to step-pool aspect

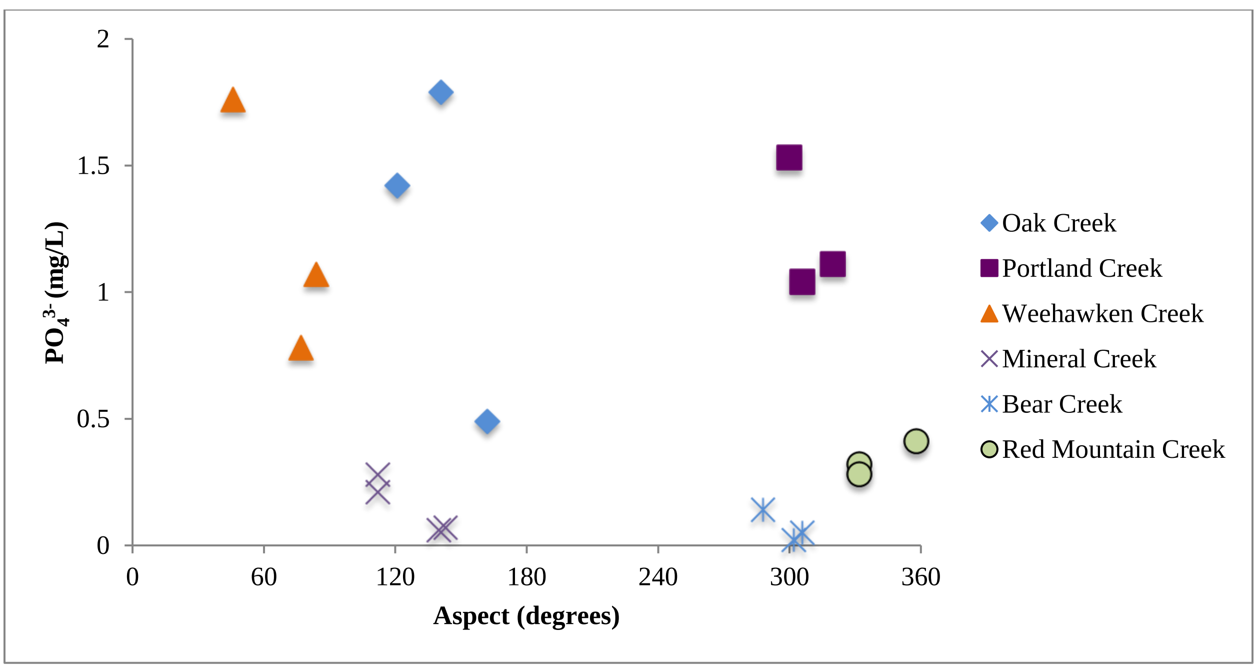

Figure 100. Step-pool phosphate concentrations compared to step-pool aspect

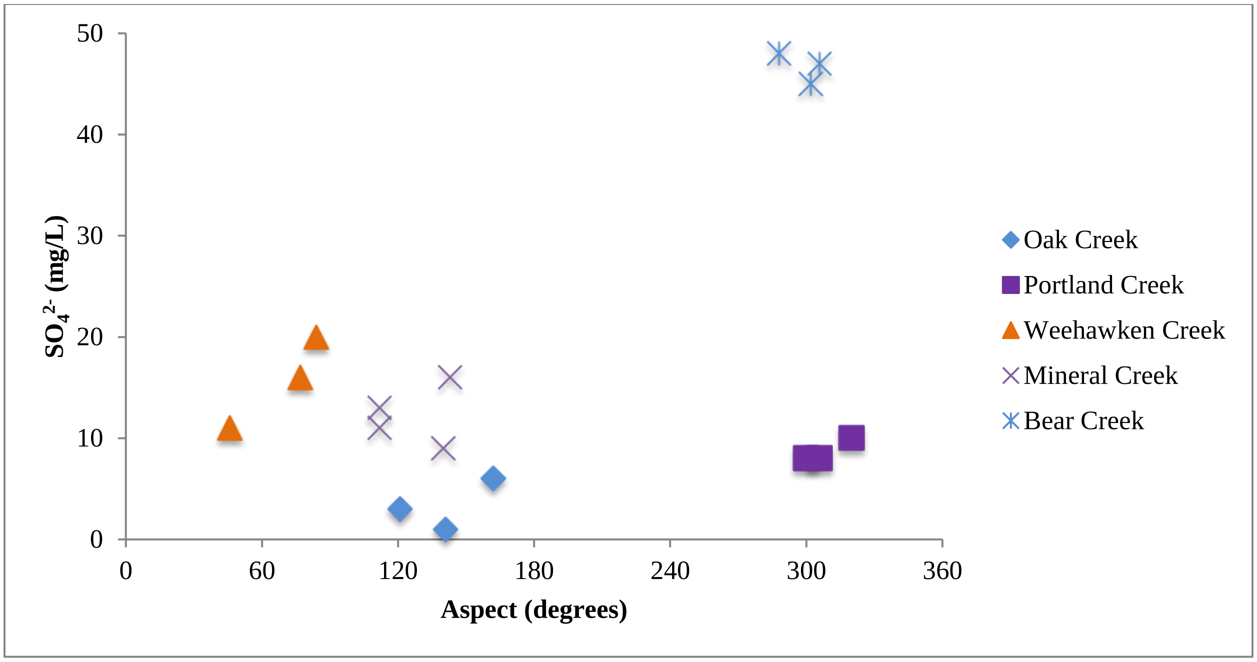

Figure 101. Step-pool sulfate concentrations compared to step-pool aspect

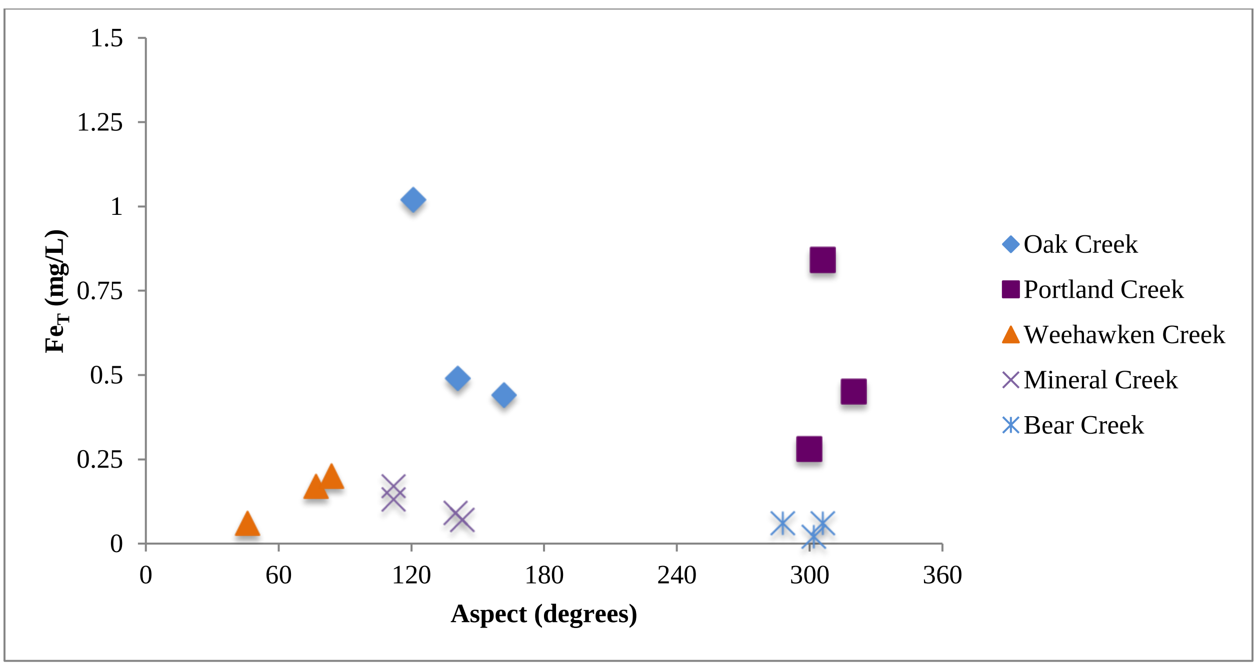

Figure 102. Step-pool total iron concentrations compared to step-pool aspect

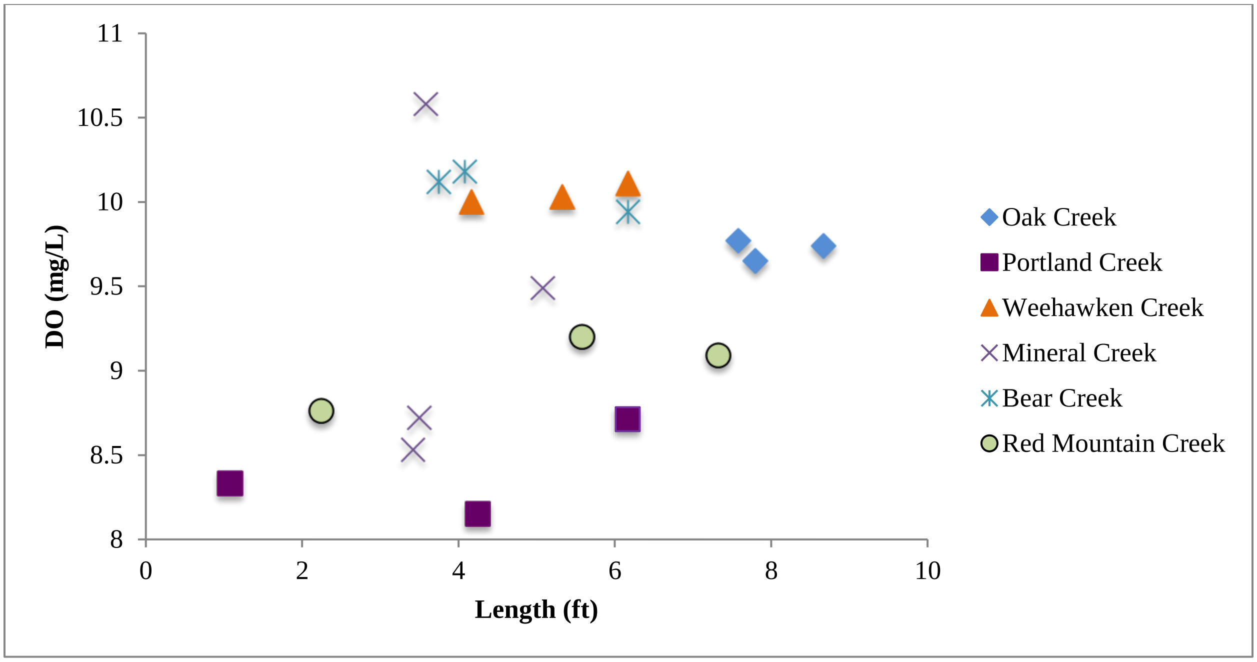

Figure 103. Step-pool dissolved oxygen compared to step-pool length

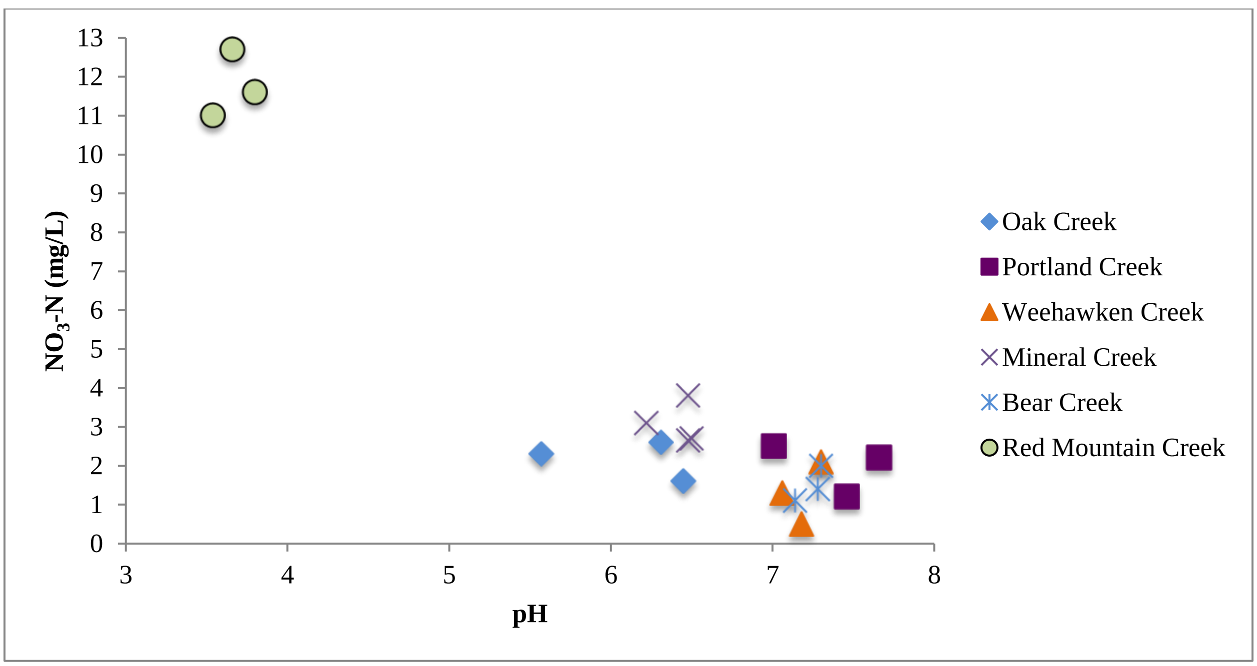

Figure 104. Step-pool nitrate-nitrogen concentrations compared to step-pool pH

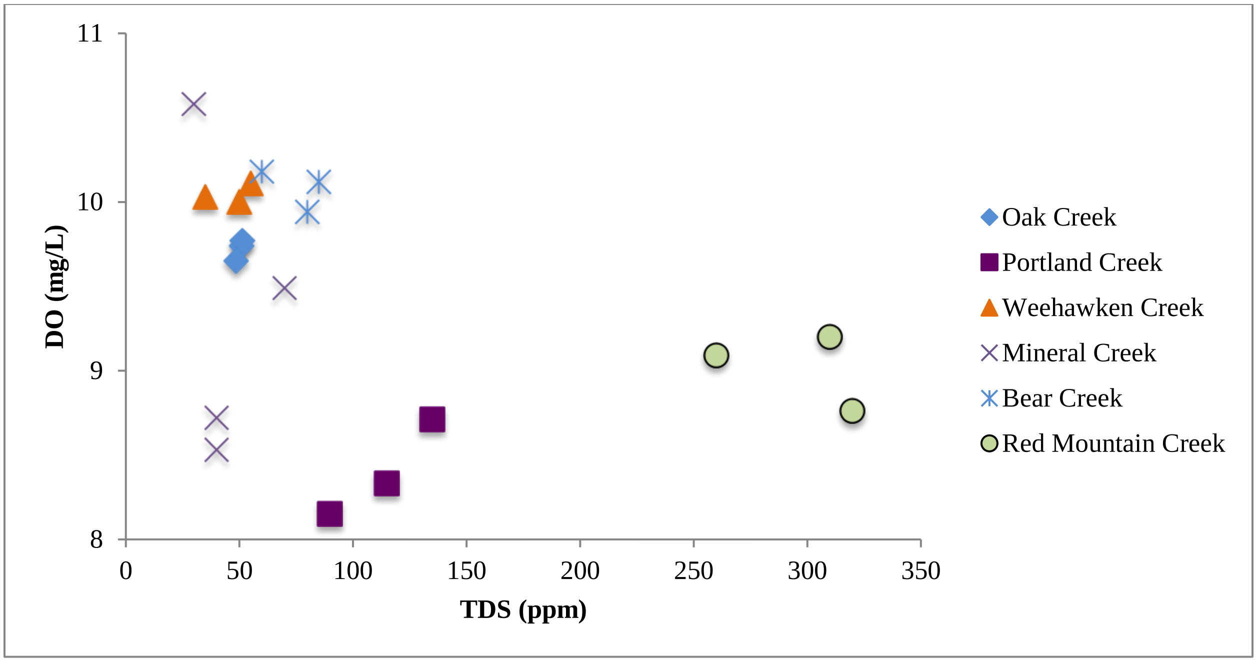

Figure 105. Step-pool dissolved oxygen compared to step-pool total dissolved solids

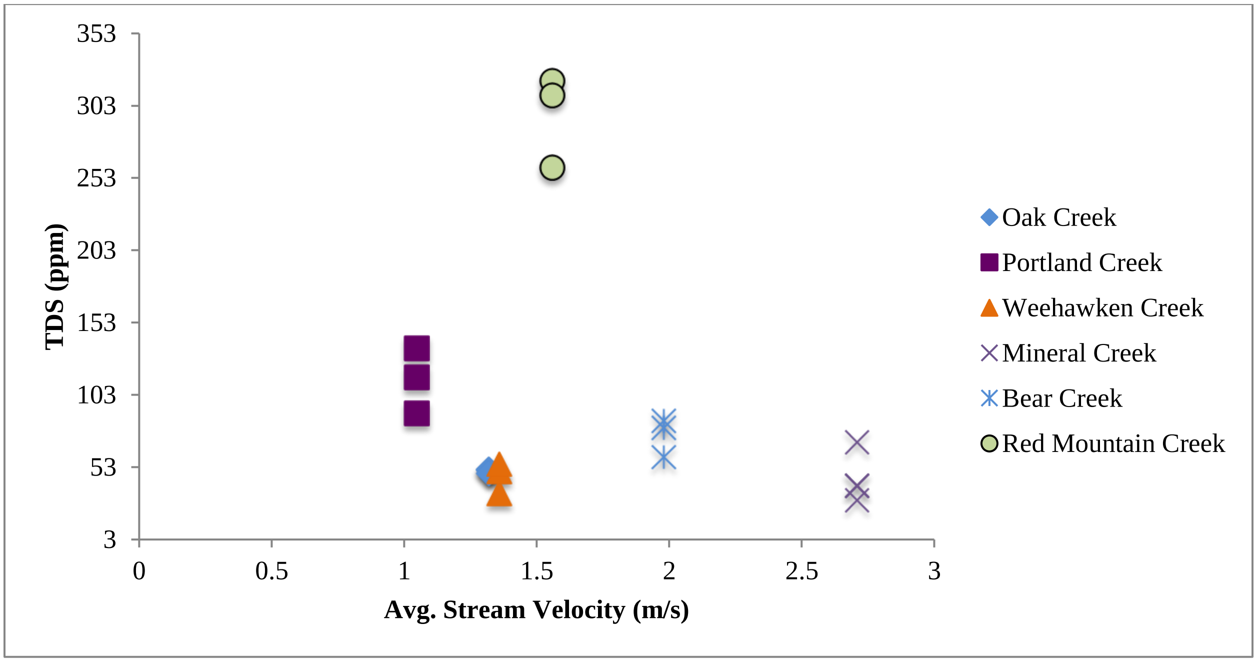

Figure 106. Step-pool total dissolved solids compared to average stream velocity

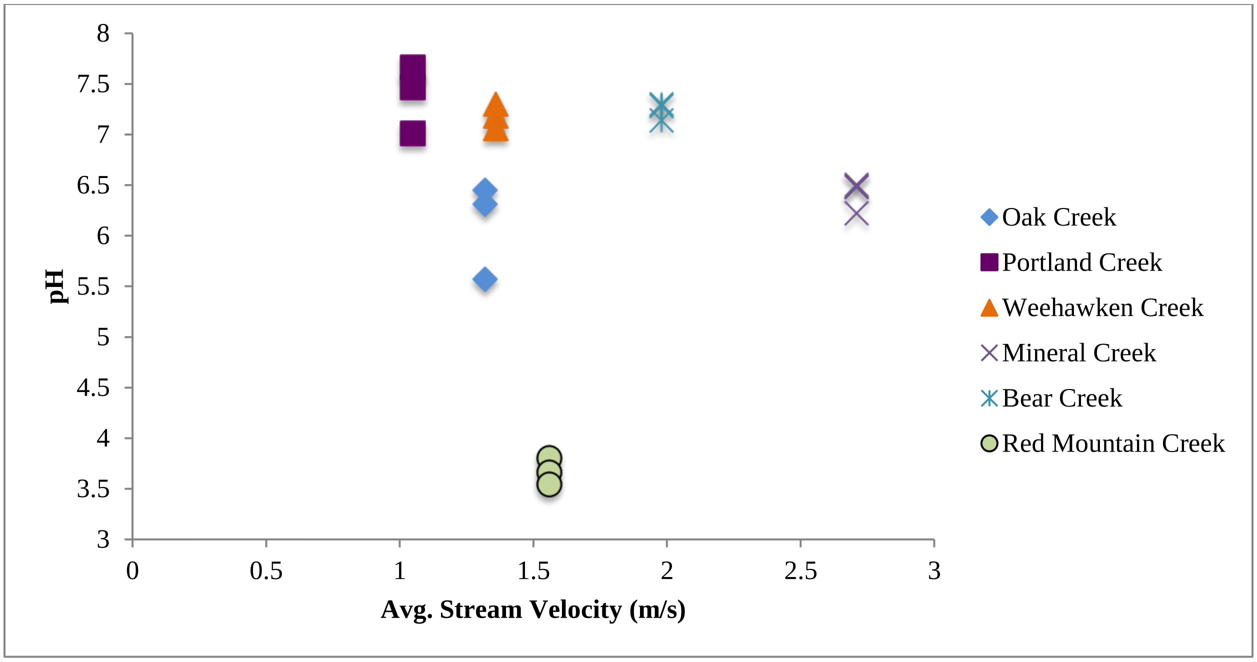

Figure 107. Step-pool pH compared to average stream velocity

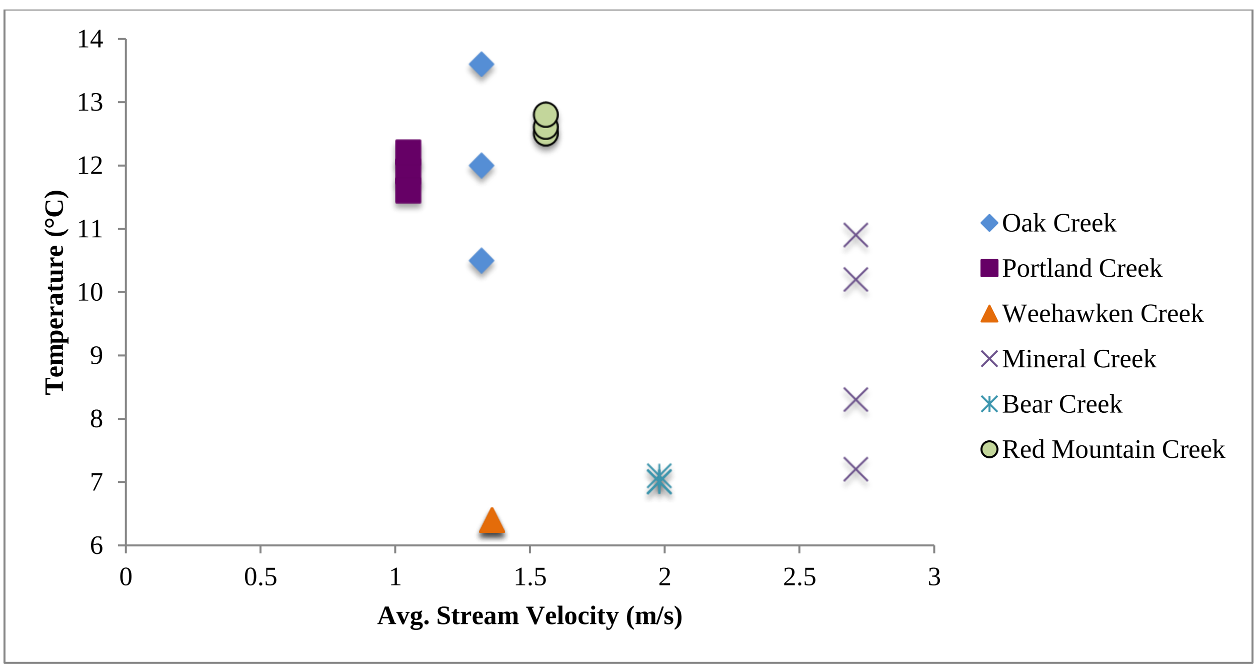

Figure 108. Step-pool temperature compared to average stream velocity

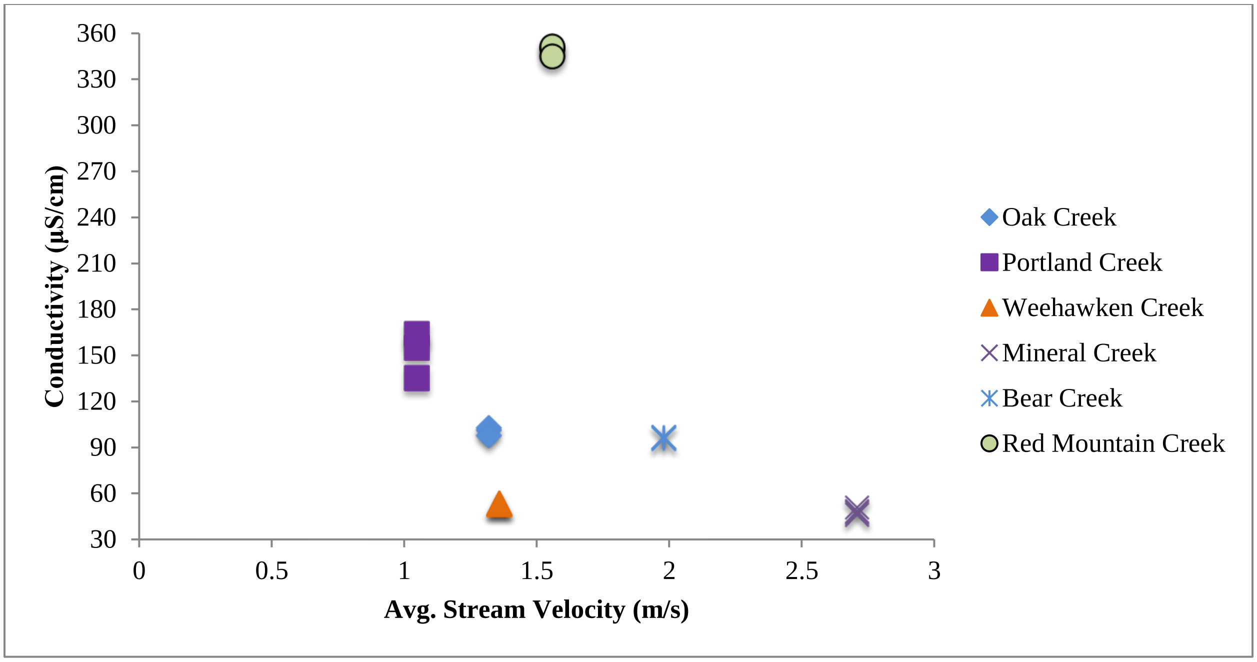

Figure 109. Step-pool conductivity compared to average stream velocity

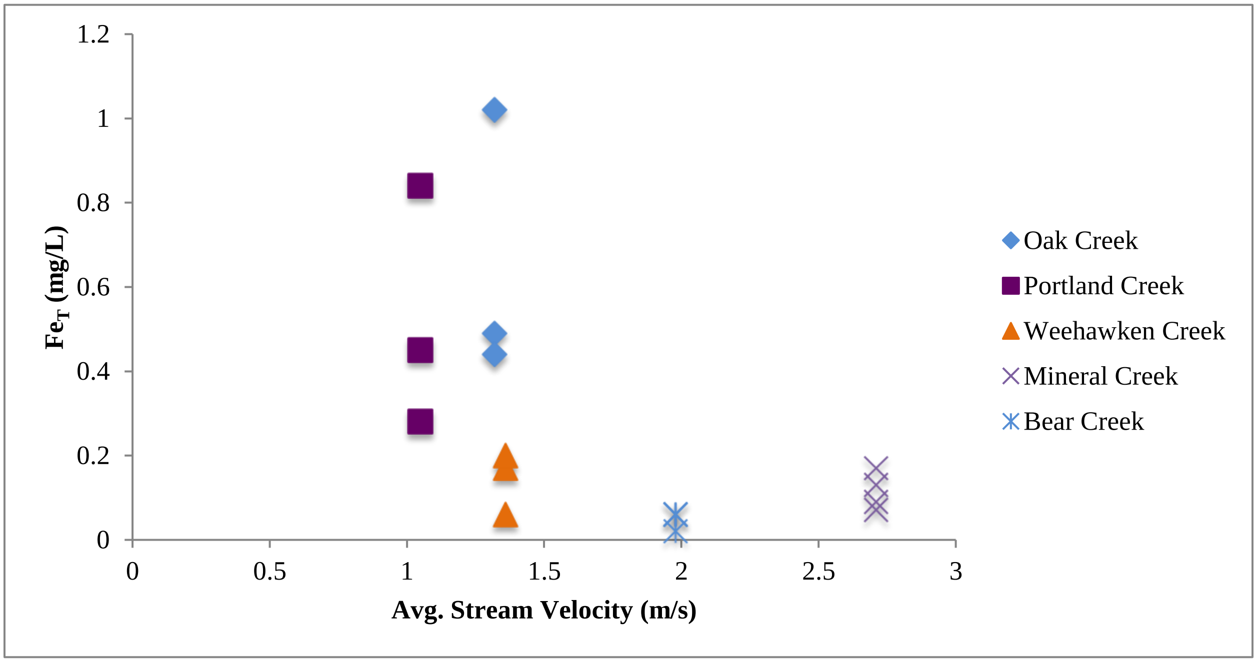

Figure 110. Step-pool total iron compared to average stream velocity

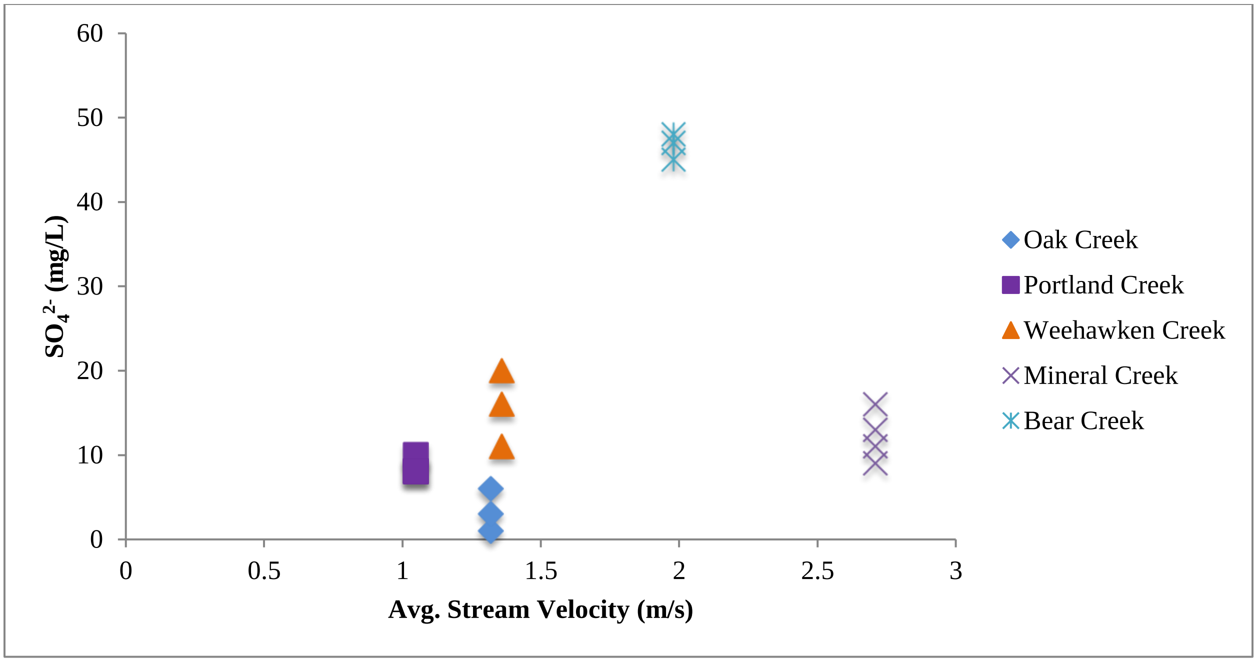

Figure 111. Step-pool sulfate compared to average stream velocity

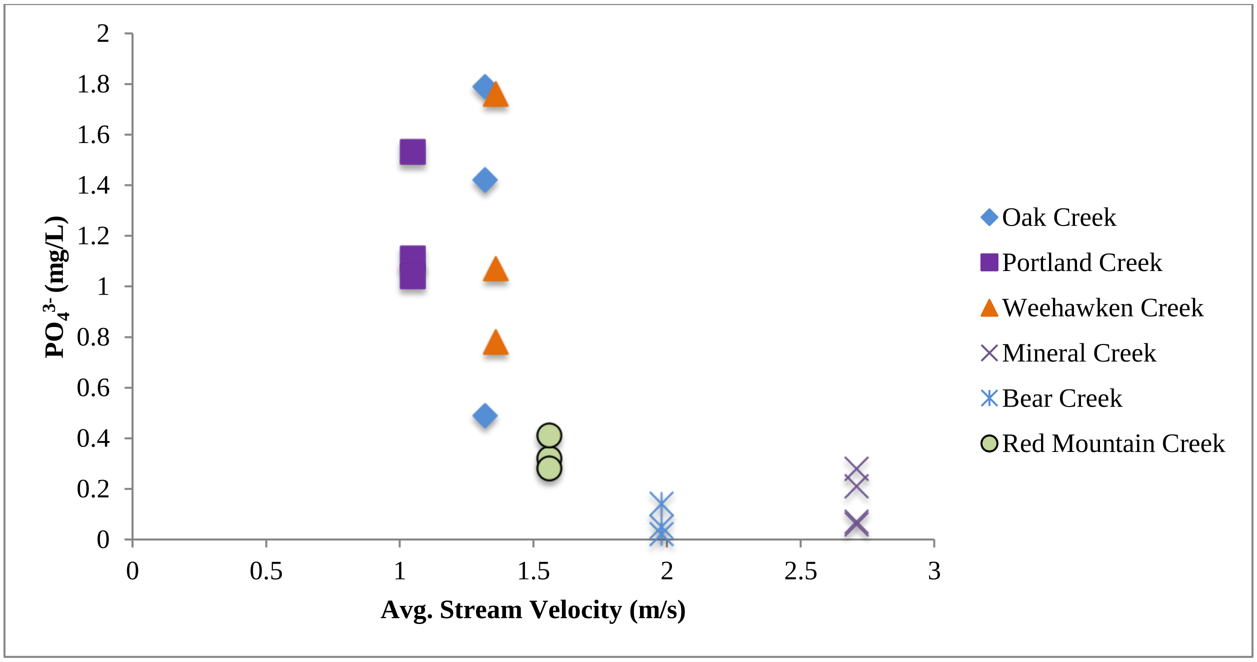

Figure 112. Step-pool phosphate compared to average stream velocity

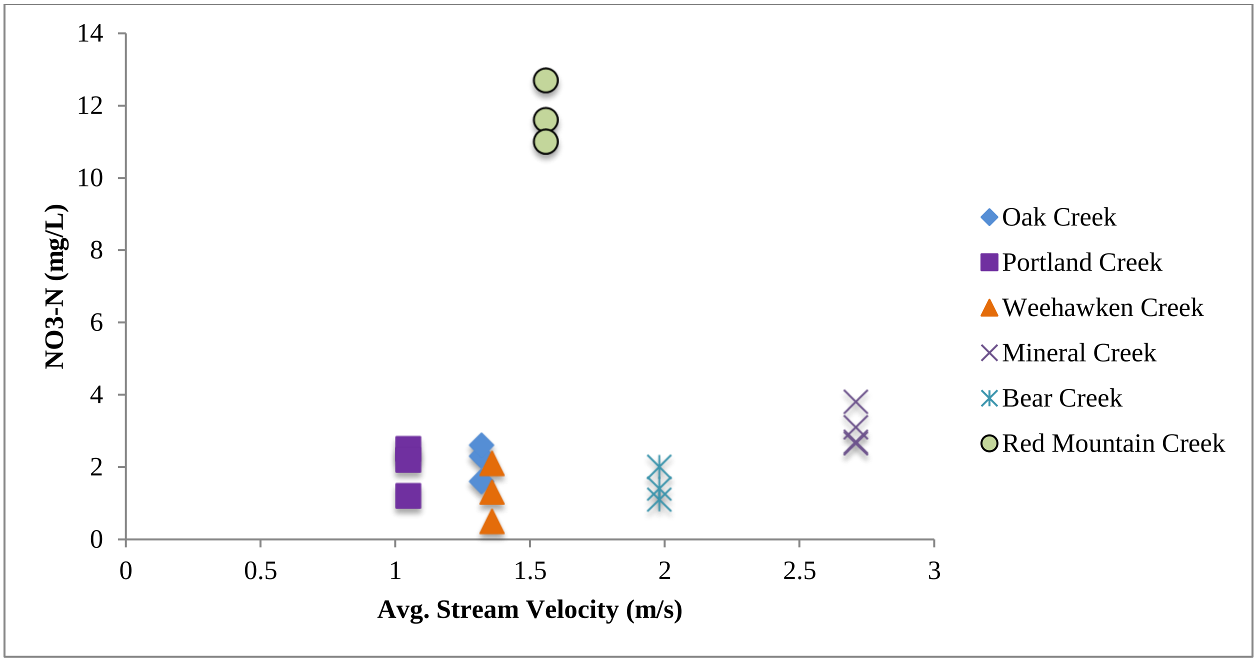

Figure 113. Step-pool nitrate-nitrogen compared to average stream velocity