Groundwater Recharge and Quality Analysis

https://github.com/katieelliott98/WDA_Final.git

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Contents

1 Rationale and Rearch Questions

Knowing how precipitation affects groundwater levels is important for managing groundwater extraction, especially with climate change and changing rainfall distributions. Also knowing the likely quality of water for a given groundwater depth can help inform decision making. Given the importance of these factors, the focus of this projectn is to understand the lag time between precipitation, stormflow is used as a proxy, and groundwater levels. In reality this is trying to understand the recharge time of the groundwater aquifer. Two different sites will be analysed to see if there is a noticeable difference with different geologies. The first site is in Houserville, PA and is Pennsylvanian aquifer and the second is in Sewickley, PA and is a Valley and Ridge aquifer. The second main question investigated is how water quality of these aquifers has change overtime and how it changes with groundwater level.

The Main Questions Analyzed

1. How is groundwater levels and stormflow changing overtime? Is there seasonality?
2. How does storm flow impact groundwater levels?
3. How is groundwater quality changing overtime? Are chemicals more concentrated at low groundwater levels or high?

2 Dataset Information

All data used in this project is from the USGS. Datasets were picked based on differing geology. First groundwater monitoring stations were selected that had both water level data and water quality data. Then the nearest stream gage with the most complete data was selected. Stream flow was separated with lfstat into baseflow and stormflow. Stormflow in this analysis is a proxy for precipitation because precipitation gage information was hard to find near groundwater monitoring stations.

Table 1. Data Information for Project

Dataset	Variable	Unit	Source
Groundwater Level	Water Level	ft below surface	USGS
Groundwater Quality	pH	Standard Units	USGS
Gage Data	Discharge	ft^3/s	USGS
All	Date	Y-m-d	USGS

3 Exploratory Analysis

A line plot was created with ggplot to get a view of the data. Figure 1 shows data for Houserville, PA, which exhibits very clear seasonal patterns in the groundwater levels, and possibly seasonality for stormflow. Figure 2 demonstrates the data for Sewickley, PA, which has obvious seasonality in stormflow and is not clear on seasonality for groundwater levels. Neither dataset has obvious trends overtime for groundwater nor stormflow. Based on the exploratory analysis a good next step would be a seasonal Mann-Kenall test to see if there is a trend overtime and if there is strong statistical seasonality.

Figure 1. Groundwater levels and Stormflow Over Time
Houserville, PA

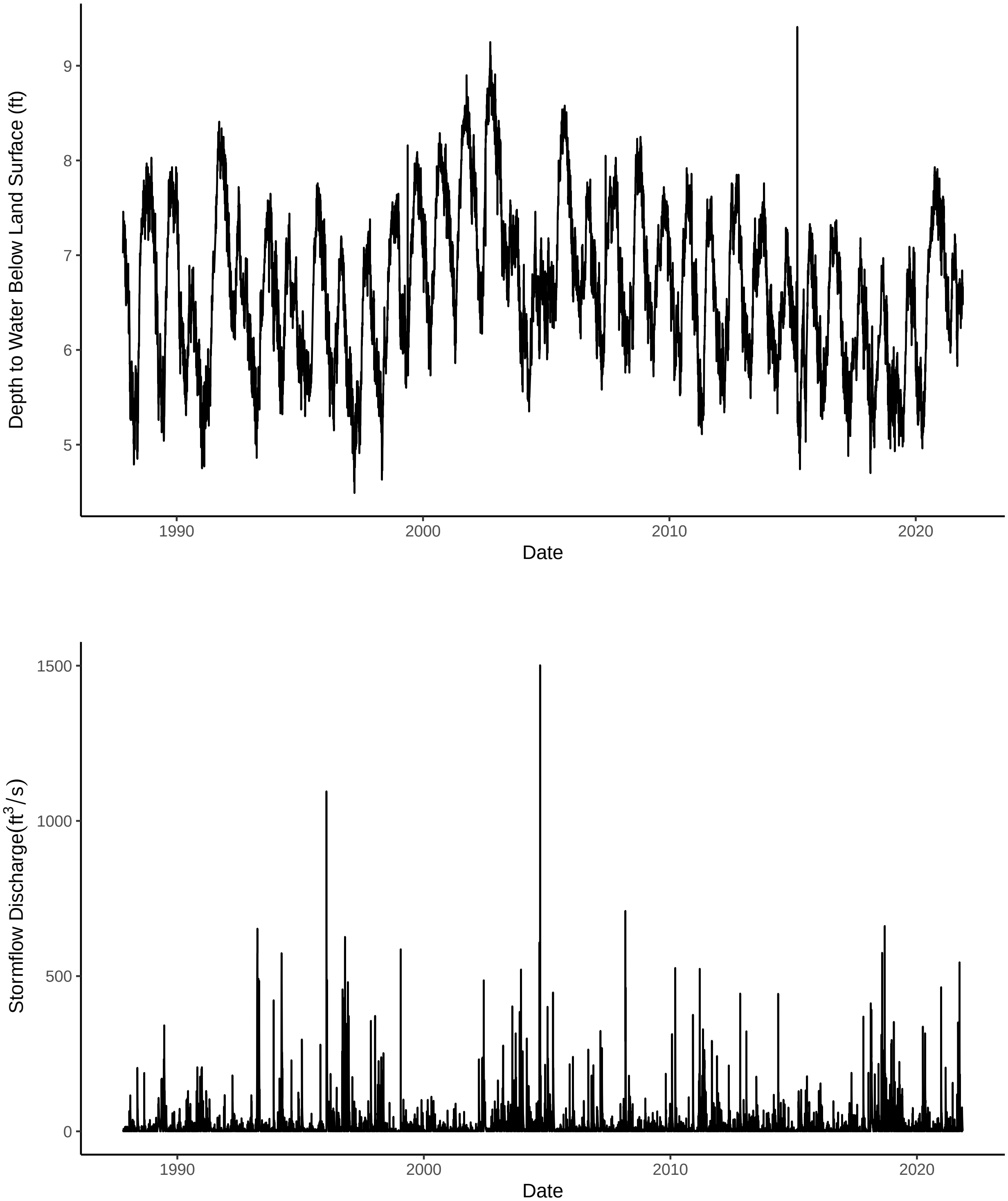
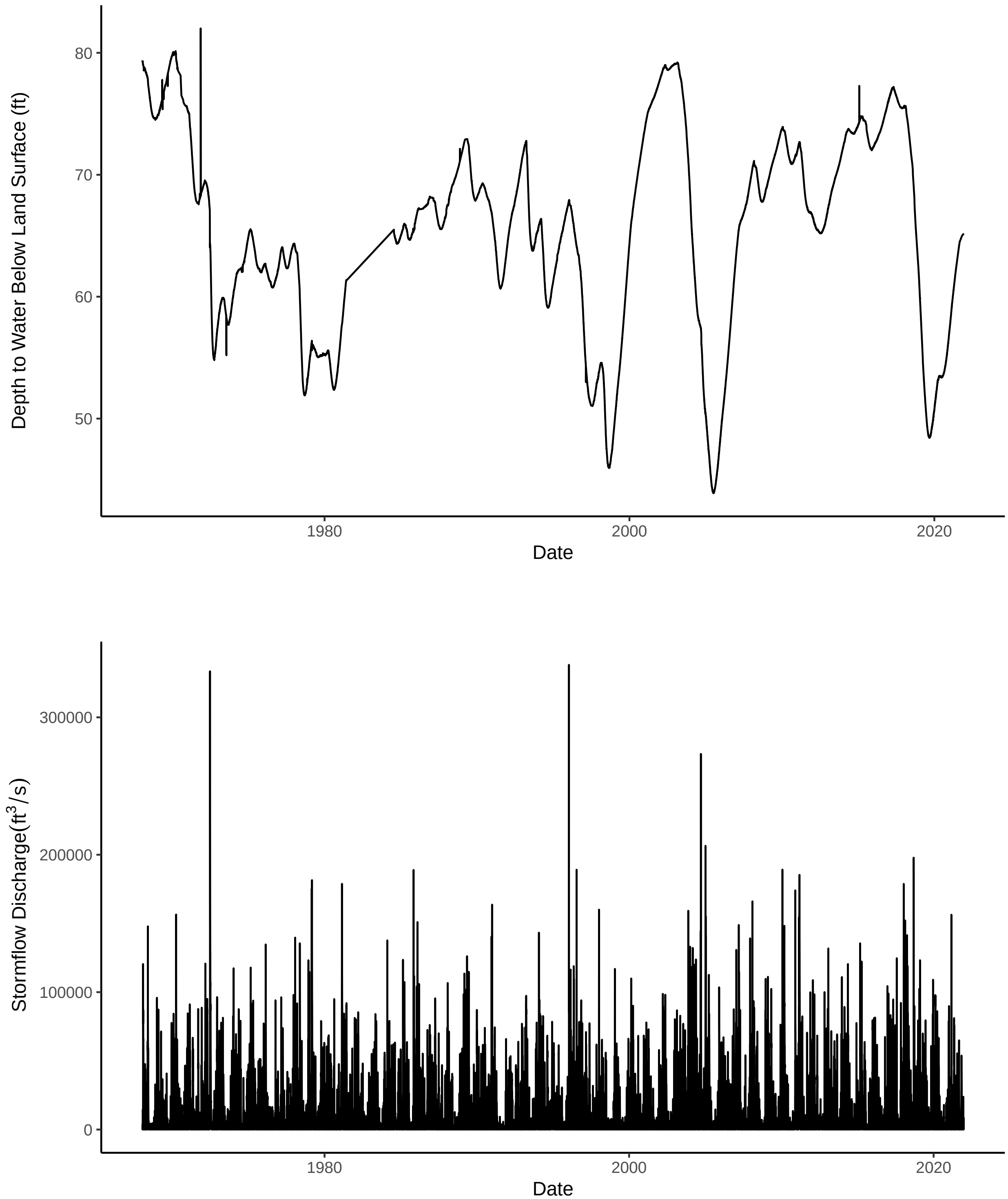


Figure 2. Groundwater levels and Stormflow Over Time
Sewickley, PA



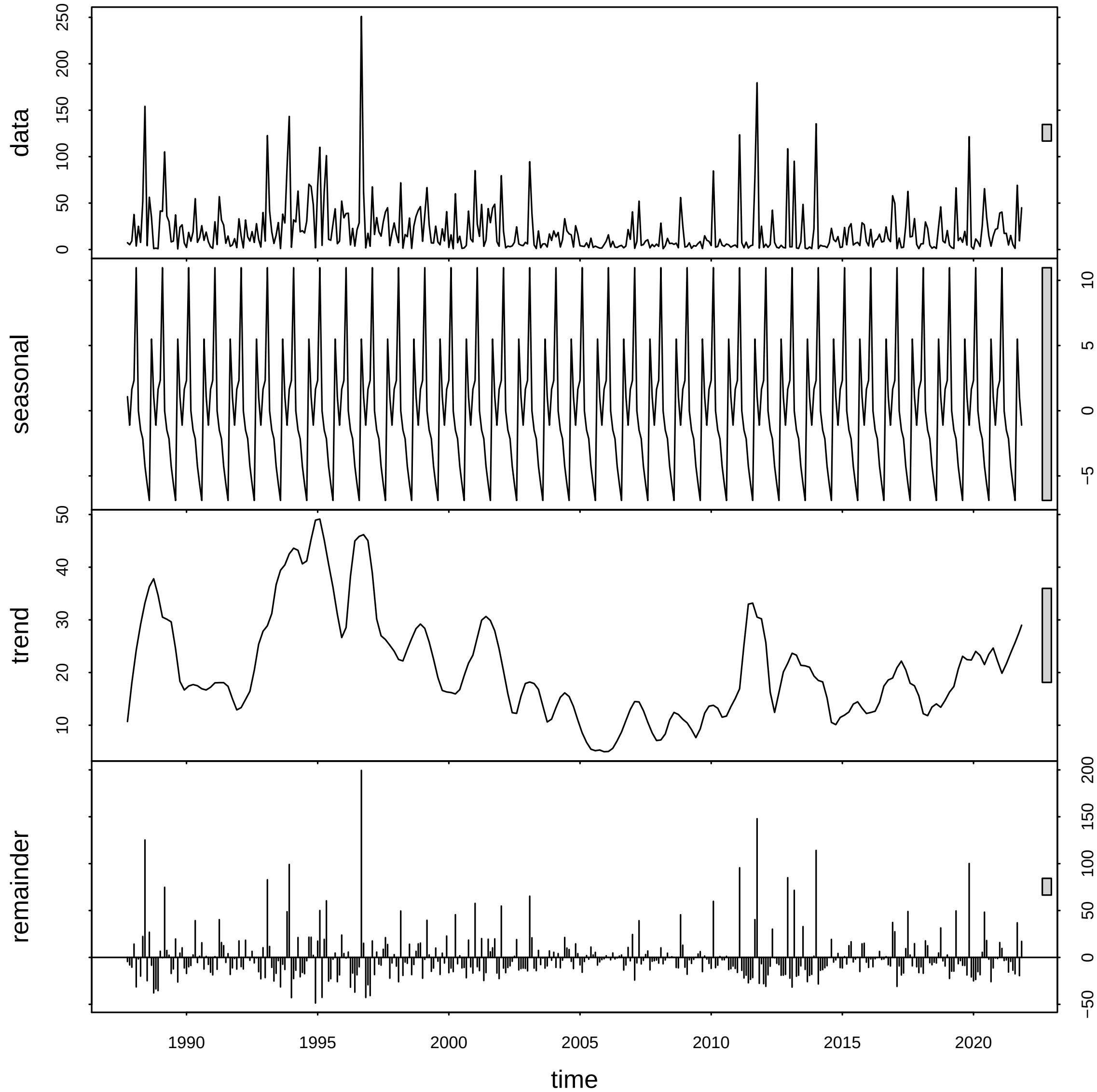
4 Analysis

4.1 Question 1: How is groundwater levels and stormflow changing overtime? Is there seasonality?

Seasonality was analyzed for both groundwater levels and stormflow by first aggregating the datasets into monthly data. Then they were transformed into time series and decomposed. The results of this can be seen in Figures 1234. Then a seasonal Mann-Kendall test was run based on the presence of seasonality. The results of these tests showed the overall trend overtime in both Houserville and Sewickley, PA for their groundwater levels and their stormflow.

4.1.1 Decomposition and Trend Analysis for Houserville, PA: Stormflow

There is a seasonal trend for stormflow in Houserville, PA. So the Mann-Kendall test was run producing a z value of -3.8953 and a p-value of 0.00009809. Meaning that it is statistically significant that stormflow is trending downward over time.



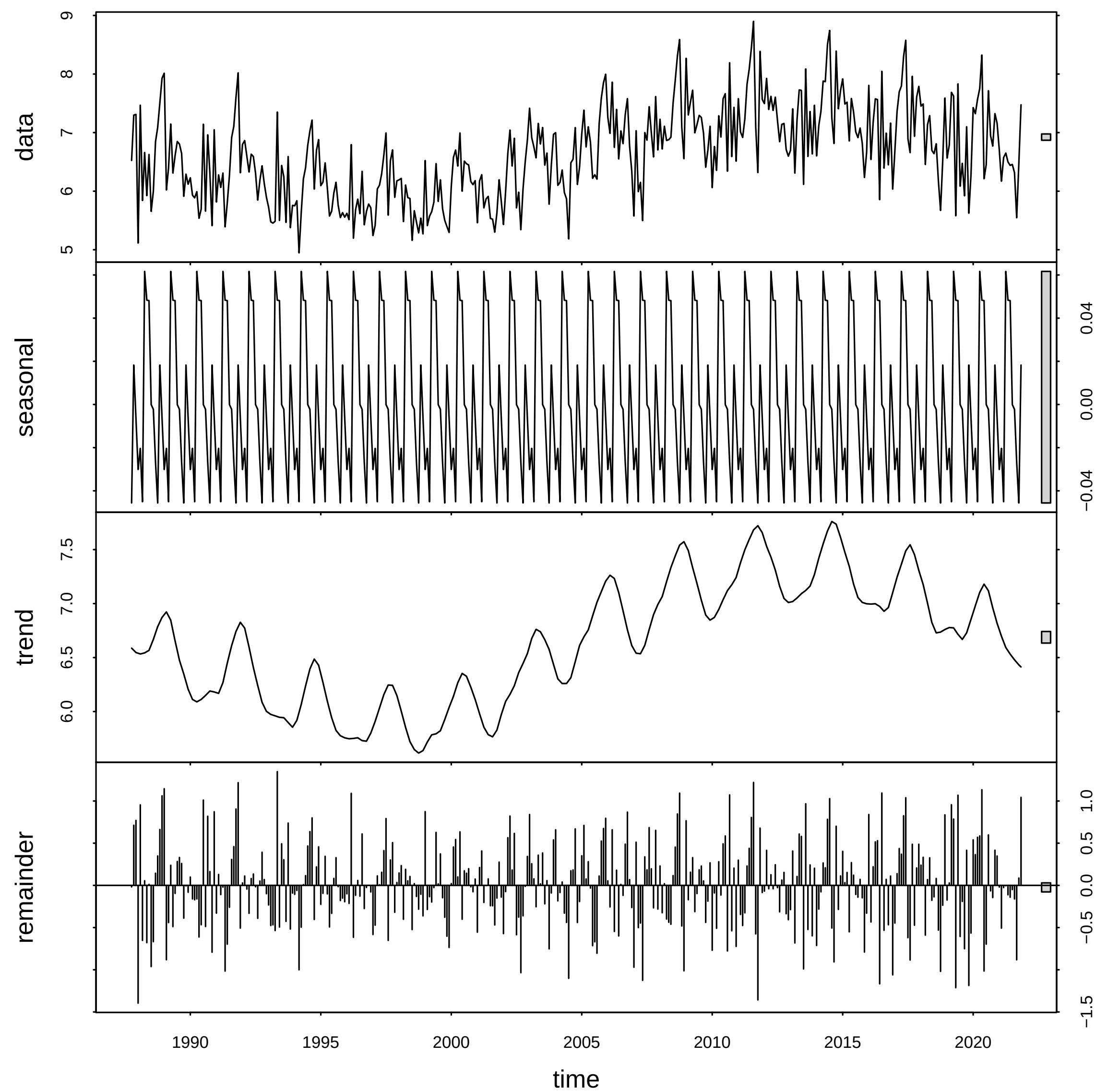

```
##
##  Seasonal Mann-Kendall trend test (Hirsch-Slack test)
##
## data:  penn_gage_ts
## z = -3.8953, p-value = 0.00009809
## alternative hypothesis: true S is not equal to 0
## sample estimates:
##      S  varS
##   -918 55420
```

```
##
##  Seasonal Mann-Kendall trend test (Hirsch-Slack test)
```

```
##
## data: penn_gage_ts
## alternative hypothesis: two.sided
##
## Statistics for individual seasons
##
## H0
##                        S   varS    tau      z  Pr(>|z|)
## Season 1:   S = 0   -41 4550.3 -0.073 -0.593 0.5531961
## Season 2:   S = 0  -137 4550.3 -0.244 -2.016 0.0437870  *
## Season 3:   S = 0   -97 4550.3 -0.173 -1.423 0.1546937
## Season 4:   S = 0  -183 4550.3 -0.326 -2.698 0.0069747 **
## Season 5:   S = 0  -131 4550.3 -0.234 -1.927 0.0539575  .
## Season 6:   S = 0   -93 4550.3 -0.166 -1.364 0.1726152
## Season 7:   S = 0   -29 4550.3 -0.052 -0.415 0.6780801
## Season 8:   S = 0  -171 4550.3 -0.305 -2.520 0.0117303  *
## Season 9:   S = 0   -57 4550.3 -0.102 -0.830 0.4064433
## Season 10:   S = 0   -9 4958.3 -0.015 -0.114 0.9095458
## Season 11:   S = 0   31 4958.3  0.052  0.426 0.6700765
## Season 12:   S = 0   -1 4550.3 -0.002  0.000 1.0000000
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

4.1.2 Decomposition and Trend Analysis for Houserville, PA: Groundwater

There is a seasonal trend for groundwater levels in Houserville, PA. So the Mann-Kendall test was run producing a z value of 9.4939 and a p-value of < 2.2e-16. Meaning that it is statistically significant that distance from the surface to the groundwater level is trending upward over time. This suggests ground water is decreasing over time.



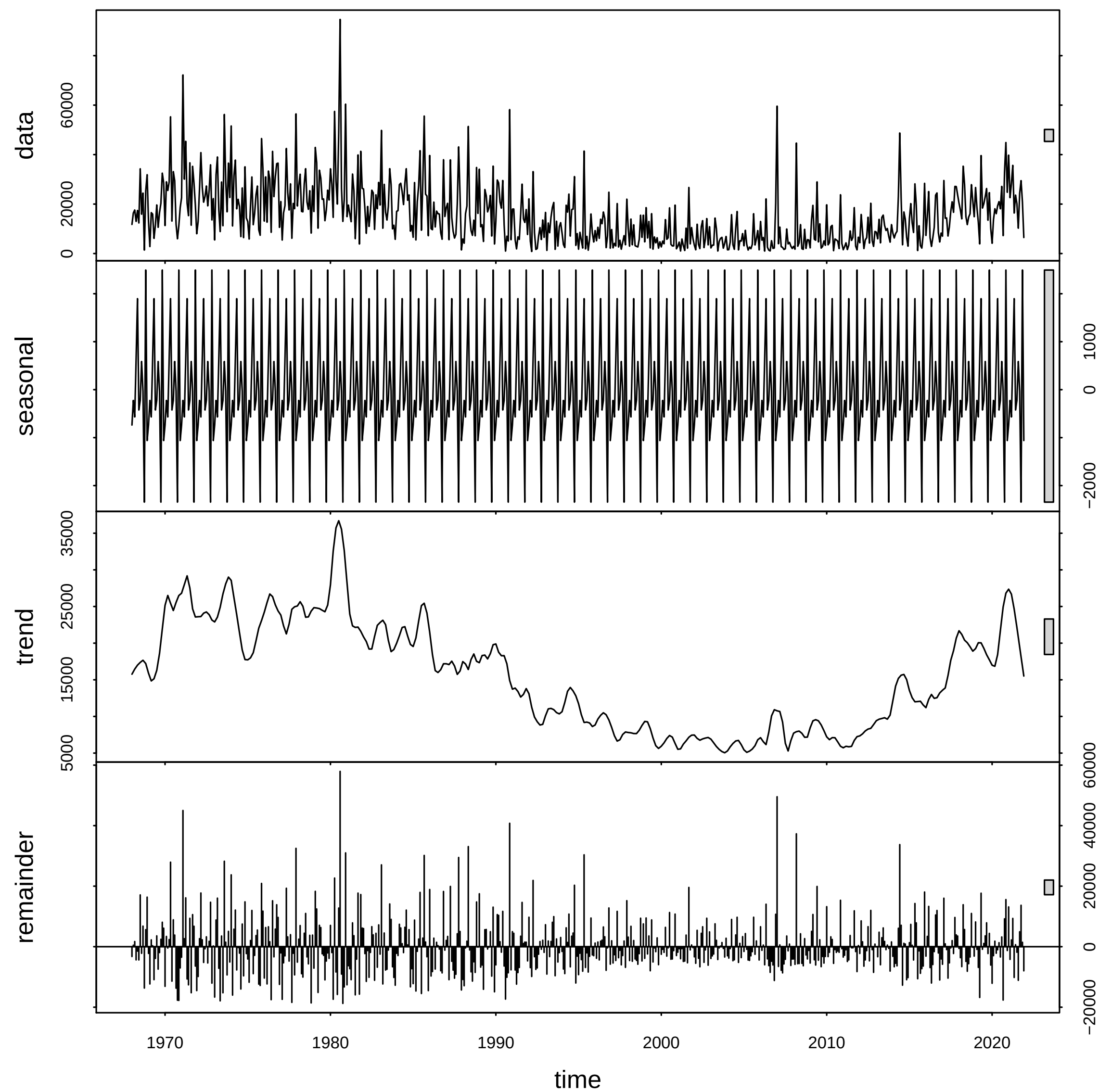

```
##
##  Seasonal Mann-Kendall trend test (Hirsch-Slack test)
##
## data:  penn_aqu_ts
## z = 9.4939, p-value < 2.2e-16
```

```
## alternative hypothesis: true S is not equal to 0
## sample estimates:
##     S  varS
##  2236 55420

##
##  Seasonal Mann-Kendall trend test (Hirsch-Slack test)
##
## data: penn_aqu_ts
## alternative hypothesis: two.sided
##
## Statistics for individual seasons
##
## H0
##                      S   varS   tau     z    Pr(>|z|)
## Season 1:   S = 0  181 4550.3 0.323 2.668  0.00762135  **
## Season 2:   S = 0  223 4550.3 0.398 3.291  0.00099823 ***
## Season 3:   S = 0  267 4550.3 0.476 3.943 0.000080367 ***
## Season 4:   S = 0  291 4550.3 0.519 4.299 0.000017150 ***
## Season 5:   S = 0  257 4550.3 0.458 3.795  0.00014761 ***
## Season 6:   S = 0  235 4550.3 0.419 3.469  0.00052256 ***
## Season 7:   S = 0  127 4550.3 0.226 1.868  0.06177882   .
## Season 8:   S = 0  185 4550.3 0.330 2.728  0.00637781  **
## Season 9:   S = 0   71 4550.3 0.127 1.038  0.29940461
## Season 10:   S = 0 113 4958.3 0.190 1.591  0.11170854
## Season 11:   S = 0 151 4958.3 0.254 2.130  0.03315388   *
## Season 12:   S = 0 135 4550.3 0.241 1.986  0.04698056   *
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

4.1.3 Decomposition and Trend Analysis for Sewickley, PA: Stormflow

There is a seasonal trend for stormflow in Sweickley, PA. So the Mann-Kendall test was run producing a z value of -8.7502 and a p-value of < 2.2 e-16. Meaning that it is statistically significant that stormflow is trending downward over time.



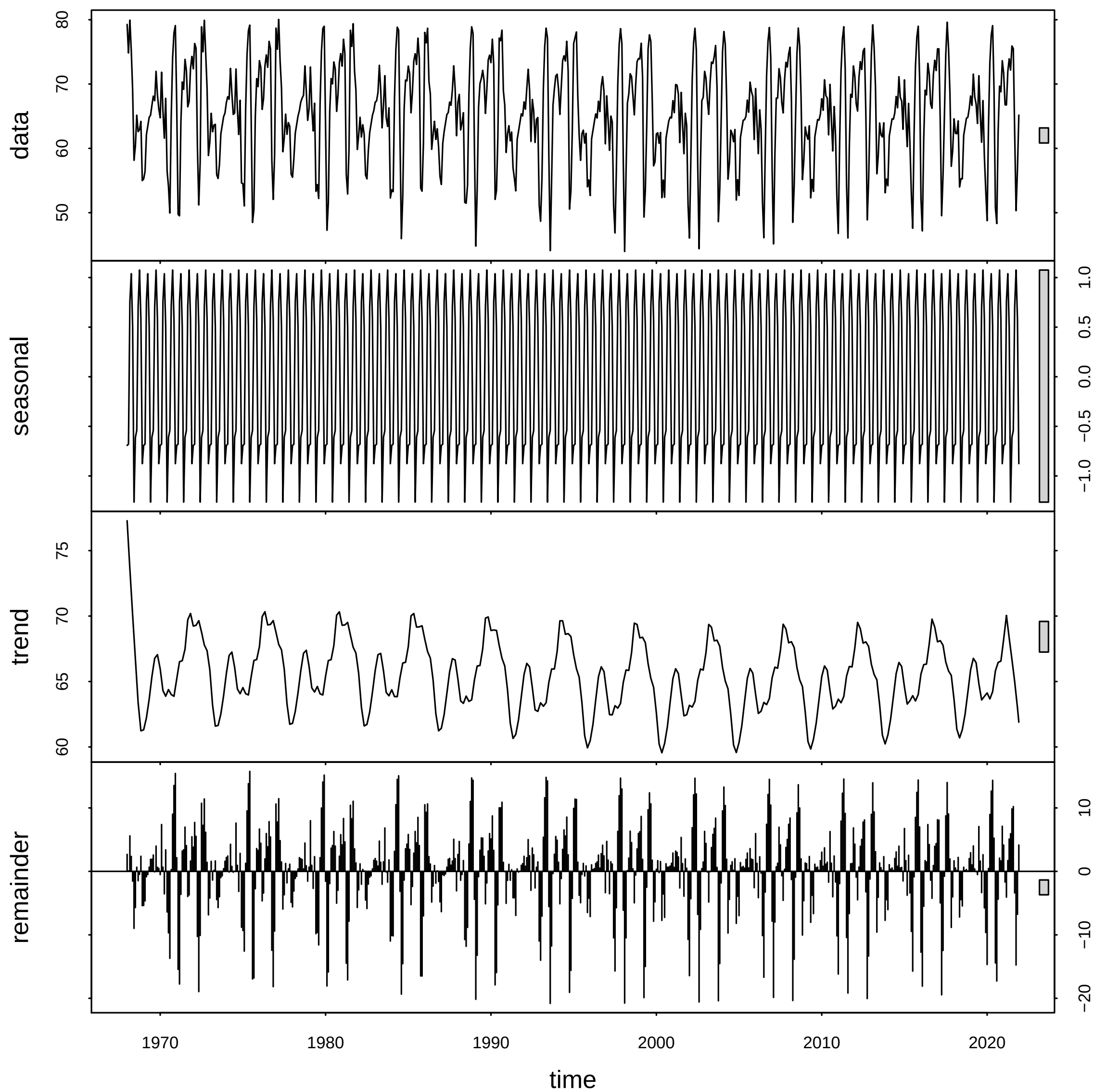

```
##
##  Seasonal Mann-Kendall trend test (Hirsch-Slack test)
##
## data:  vr_gage_ts
## z = -8.7502, p-value < 2.2e-16
## alternative hypothesis: true S is not equal to 0
```

```
## sample estimates:
##      S   varS 
##  -4064 215604 

## 
##  Seasonal Mann-Kendall trend test (Hirsch-Slack test)
## 
## data: vr_gage_ts
## alternative hypothesis: two.sided
## 
## Statistics for individual seasons
## 
## H0
##                       S  varS    tau      z   Pr(>|z|)    
## Season 1:   S = 0  -287 17967 -0.201 -2.134 0.03286940   * 
## Season 2:   S = 0  -291 17967 -0.203 -2.164 0.03050148   * 
## Season 3:   S = 0  -295 17967 -0.206 -2.193 0.02828159   * 
## Season 4:   S = 0  -461 17967 -0.322 -3.432 0.00059962 ***
## Season 5:   S = 0  -317 17967 -0.222 -2.357 0.01839910   * 
## Season 6:   S = 0  -233 17967 -0.163 -1.731 0.08348509   . 
## Season 7:   S = 0  -479 17967 -0.335 -3.566 0.00036237 ***
## Season 8:   S = 0  -323 17967 -0.226 -2.402 0.01629460   * 
## Season 9:   S = 0  -357 17967 -0.249 -2.656 0.00790964  ** 
## Season 10:   S = 0 -249 17967 -0.174 -1.850 0.06428766   . 
## Season 11:   S = 0 -415 17967 -0.290 -3.089 0.00201098  ** 
## Season 12:   S = 0 -357 17967 -0.249 -2.656 0.00790964  ** 
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

4.1.4 Decomposition and Trend Analysis for Sewickley, PA: Groundwater

There is a seasonal trend for groundwater level in Sewickley, PA. So the Mann-Kendall test was run producing a z value of -0.56856 and a p-value of 0.5697. This means that there is no statistically significant trend over time.




```
##
##  Seasonal Mann-Kendall trend test (Hirsch-Slack test)
##
## data:  vr_aqu_ts
## z = -0.56856, p-value = 0.5697
## alternative hypothesis: true S is not equal to 0
```

```
## sample estimates:
##      S   varS
##   -265 215603

##
##  Seasonal Mann-Kendall trend test (Hirsch-Slack test)
##
## data: vr_aqu_ts
## alternative hypothesis: two.sided
##
## Statistics for individual seasons
##
## H0
##                       S  varS    tau      z Pr(>|z|)
## Season 1:   S = 0   -31 17967 -0.022 -0.224  0.82290
## Season 2:   S = 0   -43 17967 -0.030 -0.313  0.75402
## Season 3:   S = 0   -11 17967 -0.008 -0.075  0.94053
## Season 4:   S = 0   138 17966  0.096  1.022  0.30673
## Season 5:   S = 0  -101 17967 -0.071 -0.746  0.45564
## Season 6:   S = 0    35 17967  0.024  0.254  0.79976
## Season 7:   S = 0    31 17967  0.022  0.224  0.82290
## Season 8:   S = 0   -21 17967 -0.015 -0.149  0.88139
## Season 9:   S = 0   -51 17967 -0.036 -0.373  0.70913
## Season 10:   S = 0   17 17967  0.012  0.119  0.90499
## Season 11:   S = 0 -215 17967 -0.150 -1.597  0.11037
## Season 12:   S = 0  -13 17967 -0.009 -0.090  0.92866
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

4.2 Question 2: How does stormflow impact groundwater levels?

To understand how stormflow impacts groundwater level the two datasets were combined by date to consildate the information. Stormflow and groundwater were plotting against each other to see if there was any correlation, as seen in Figure 3 and 6. A CCF (cross correlation function) was run to understand what lag leads to the best correlation between the two variables. This test was run for both sites and was run with and without seasonality included to see if there was a difference. The results of the CCF were fairly inconclusive given what researchers know about the relationship between groundwater and precipitation. CCF figures are 4, 5, 7, and 8.

Figure 3. Scatter Plot of Stormflow and Groundwater Depth using Monthly Averages

Houserville, PA

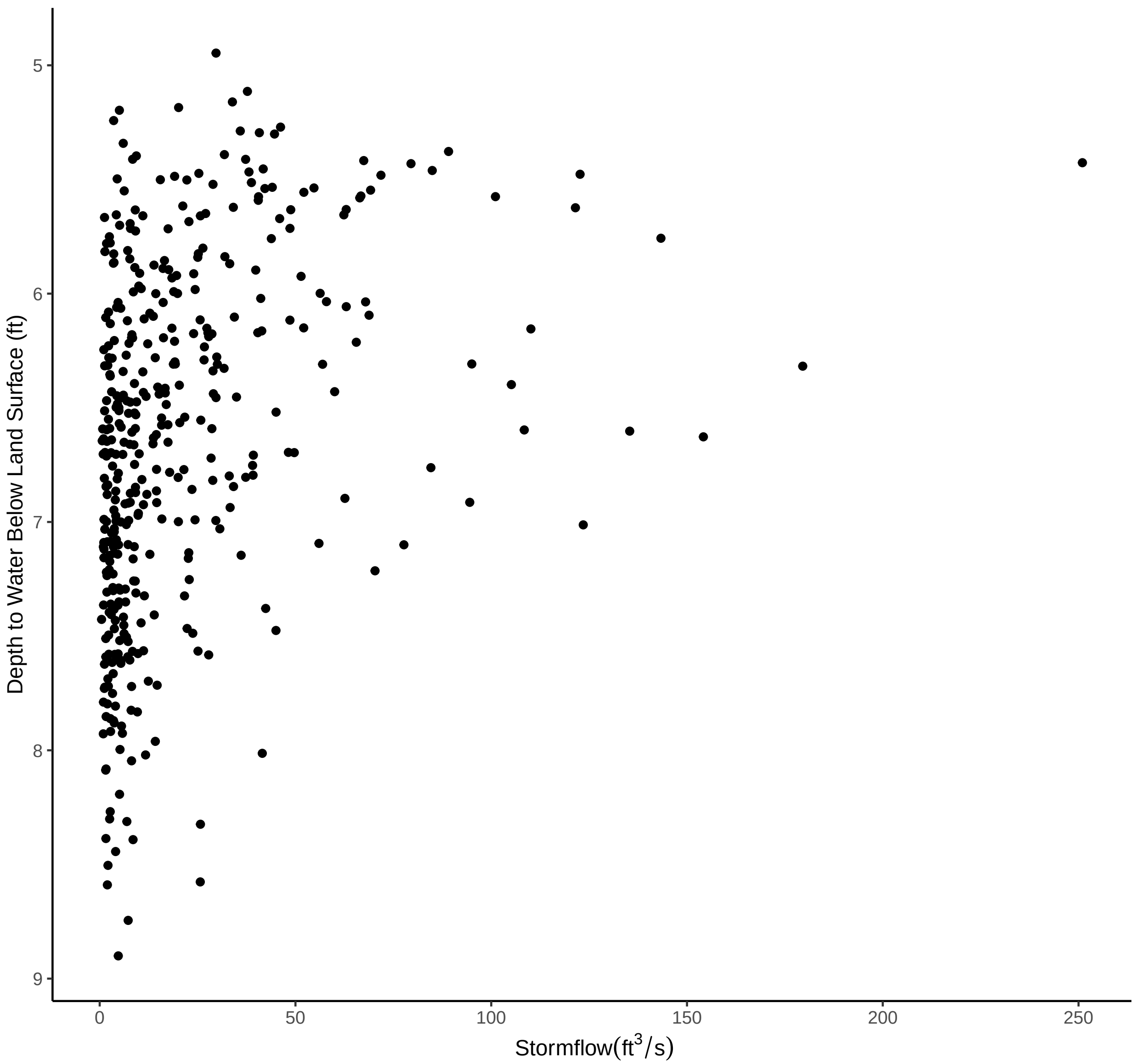


Figure 4. Covarience of Average Stormflow and Groundwater Levels with Seasonality Included (Houserville, PA)

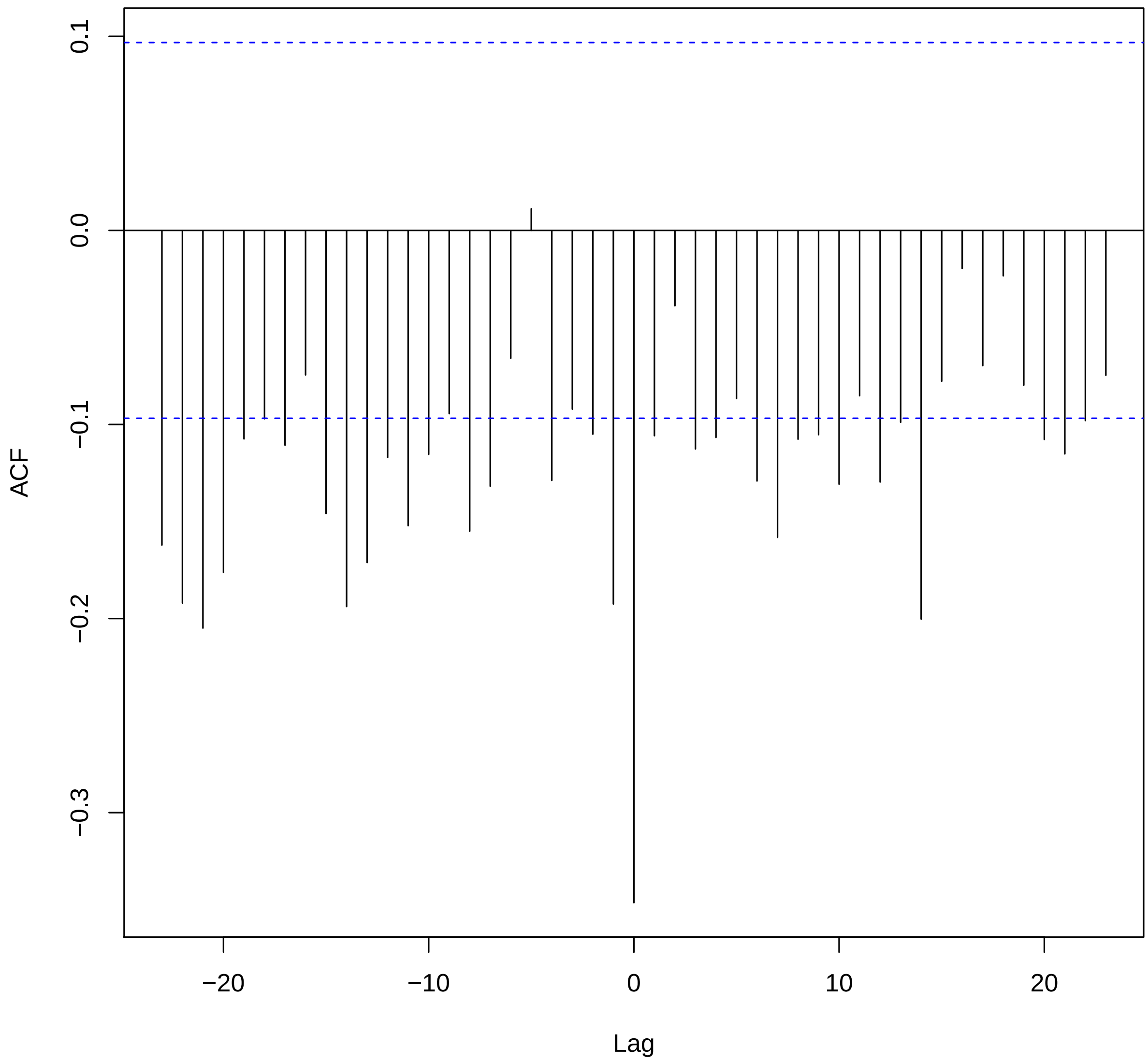


Figure 5. Covarience of Average Stormflow and Groundwater Levels Without Seasonality (Houserville, PA)

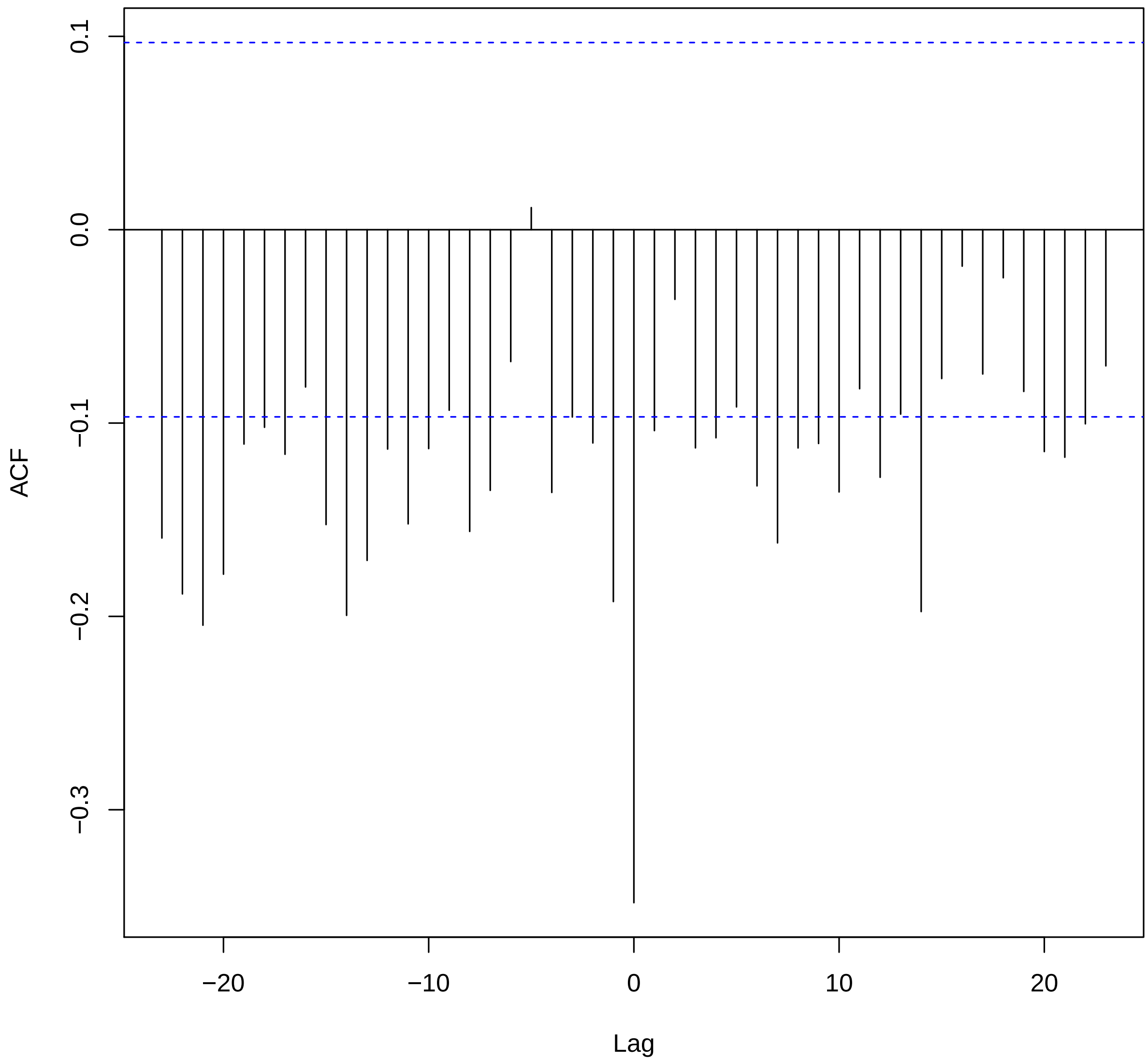


Figure 6. Scatter Plot of Stormflow and Groundwater Depth using Monthly Averages
Sewickley, PA

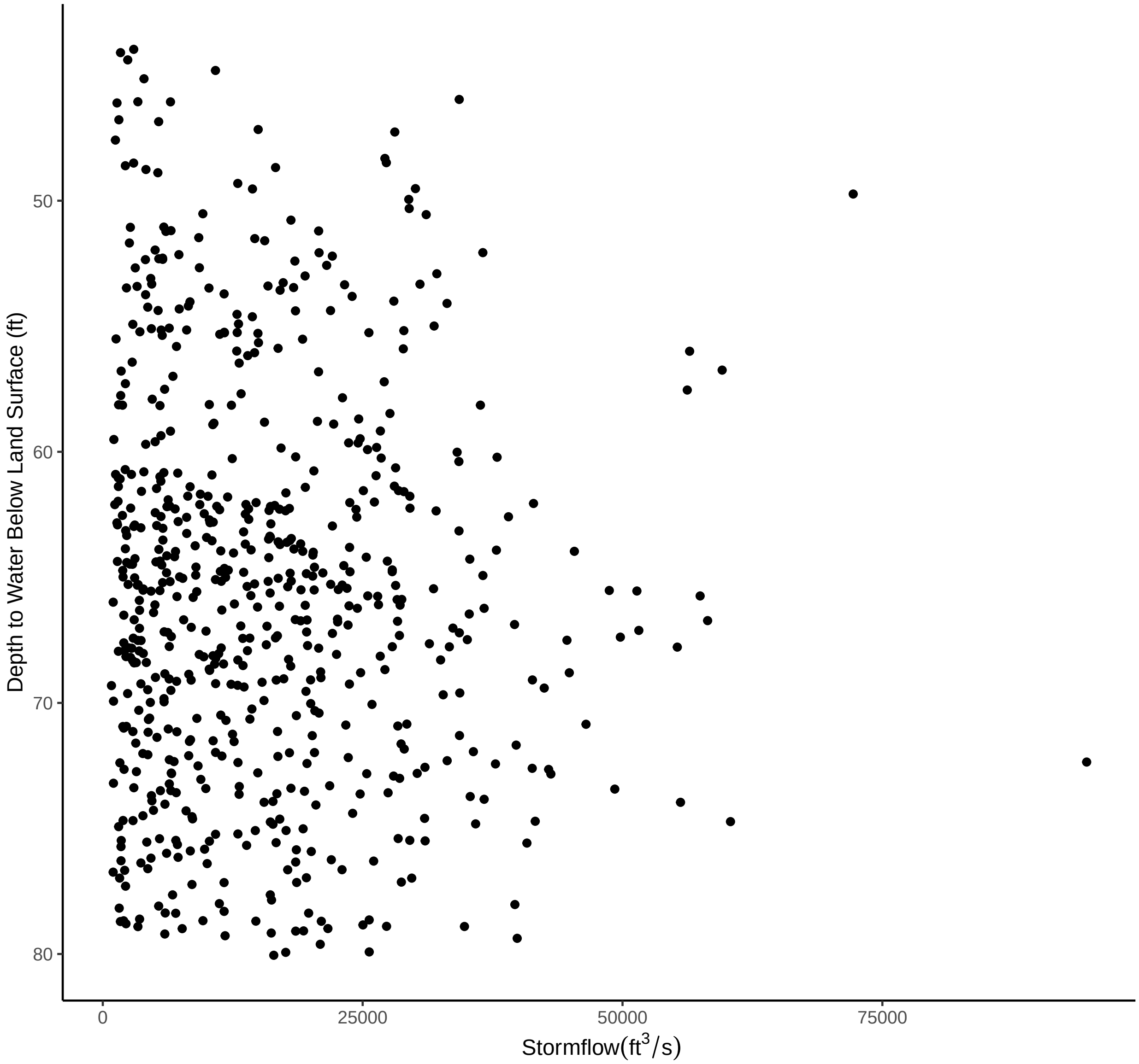


Figure 7. Covarience of Average Stormflow and Groundwater Levels with Seasonality Included (Sewickley, PA)

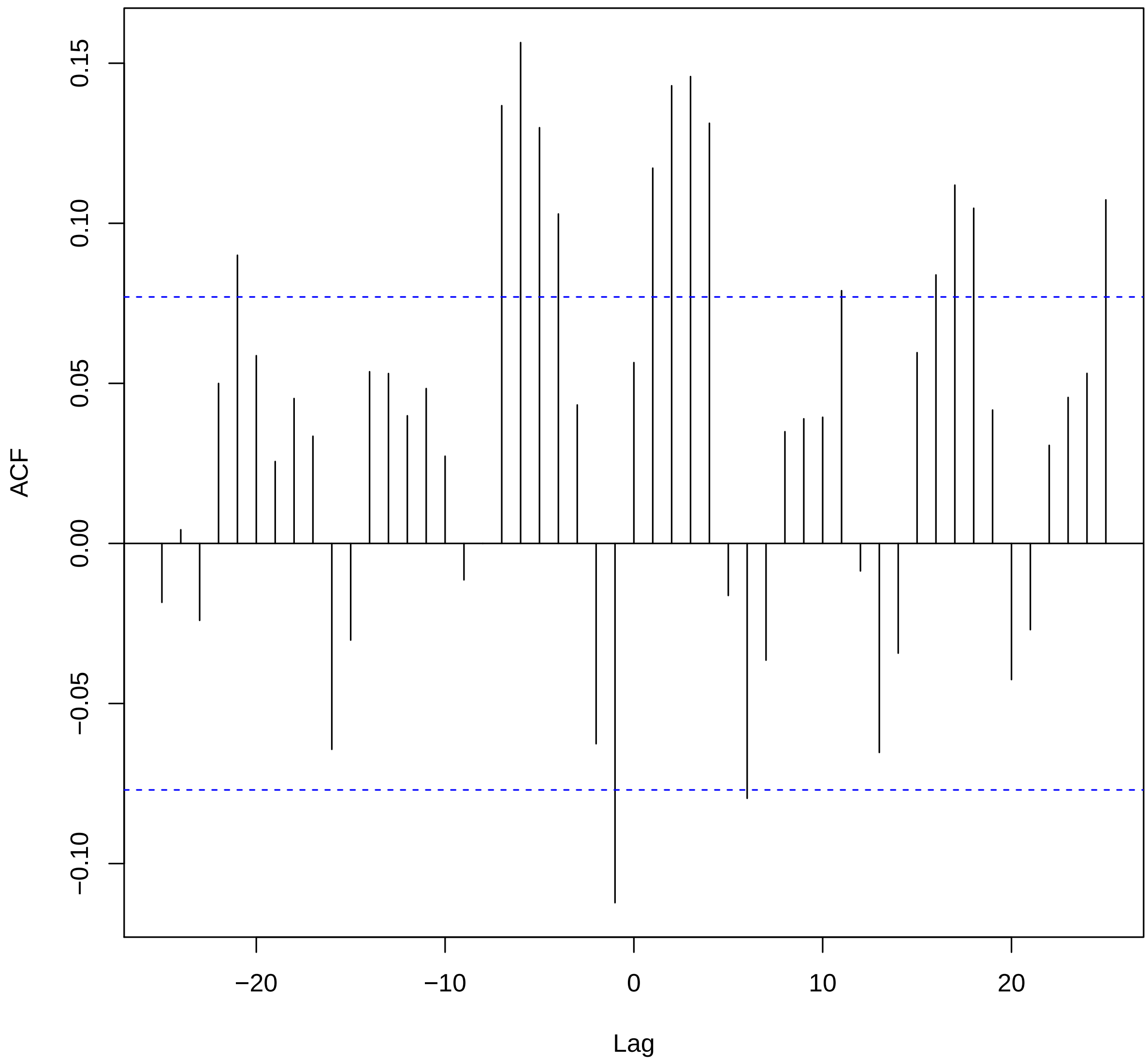
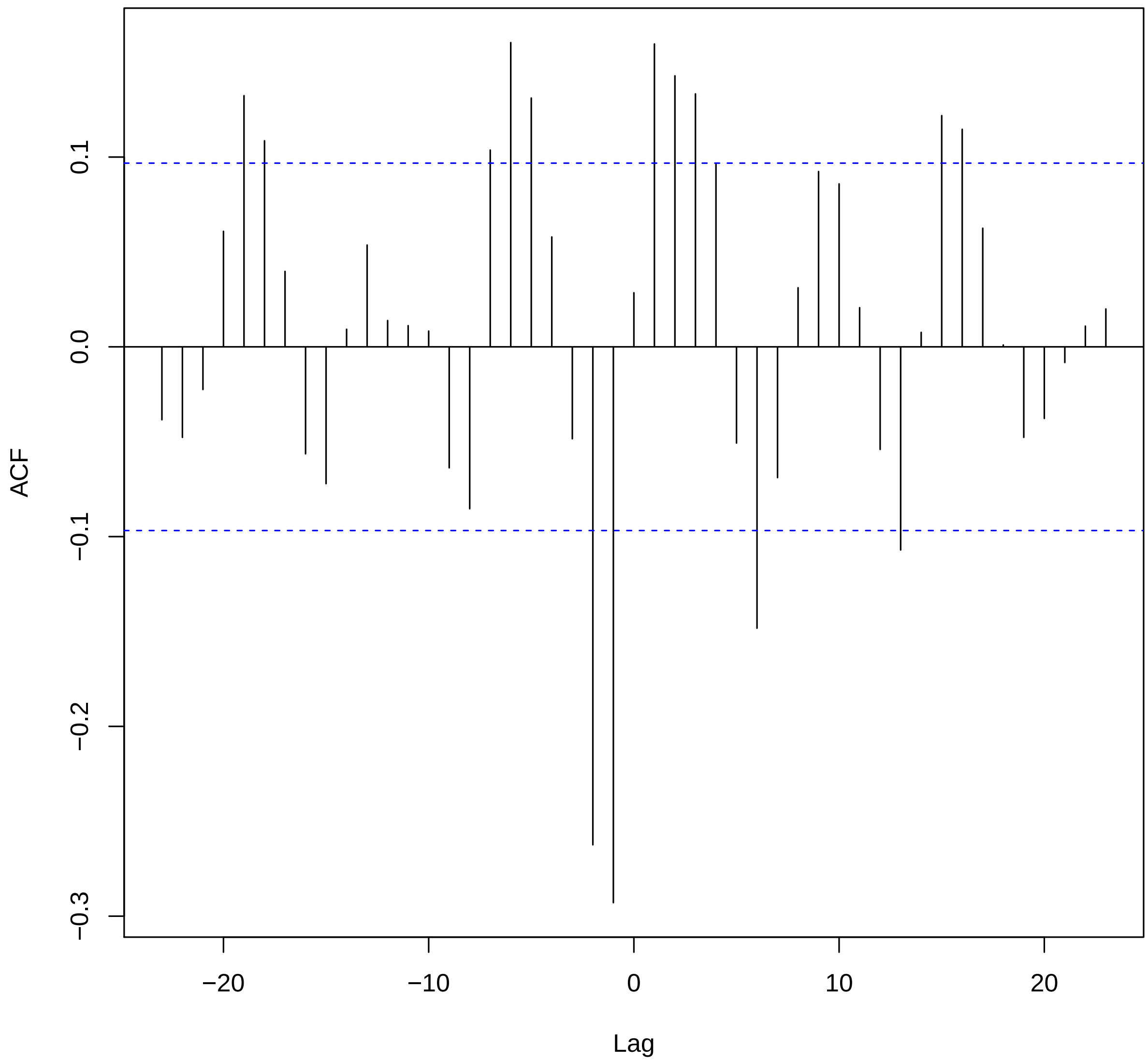


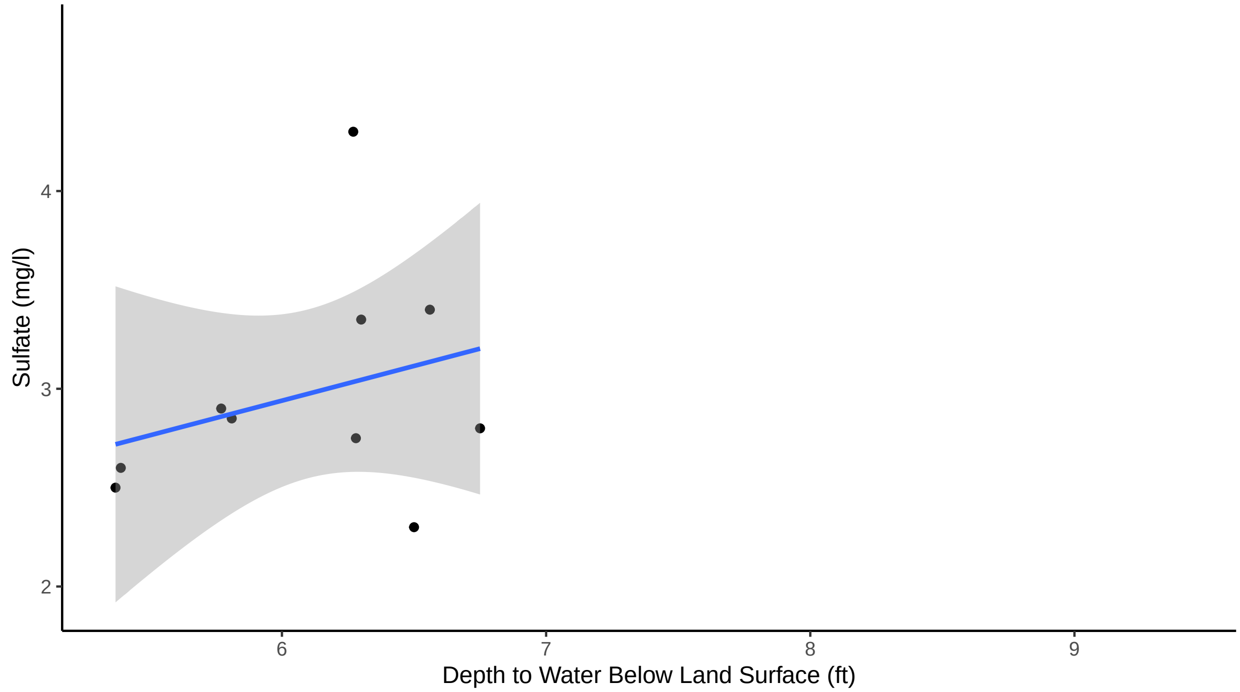
Figure 8. Covarience of Average Stormflow and Groundwater Levels Without Seasonality (Sewickley, PA)

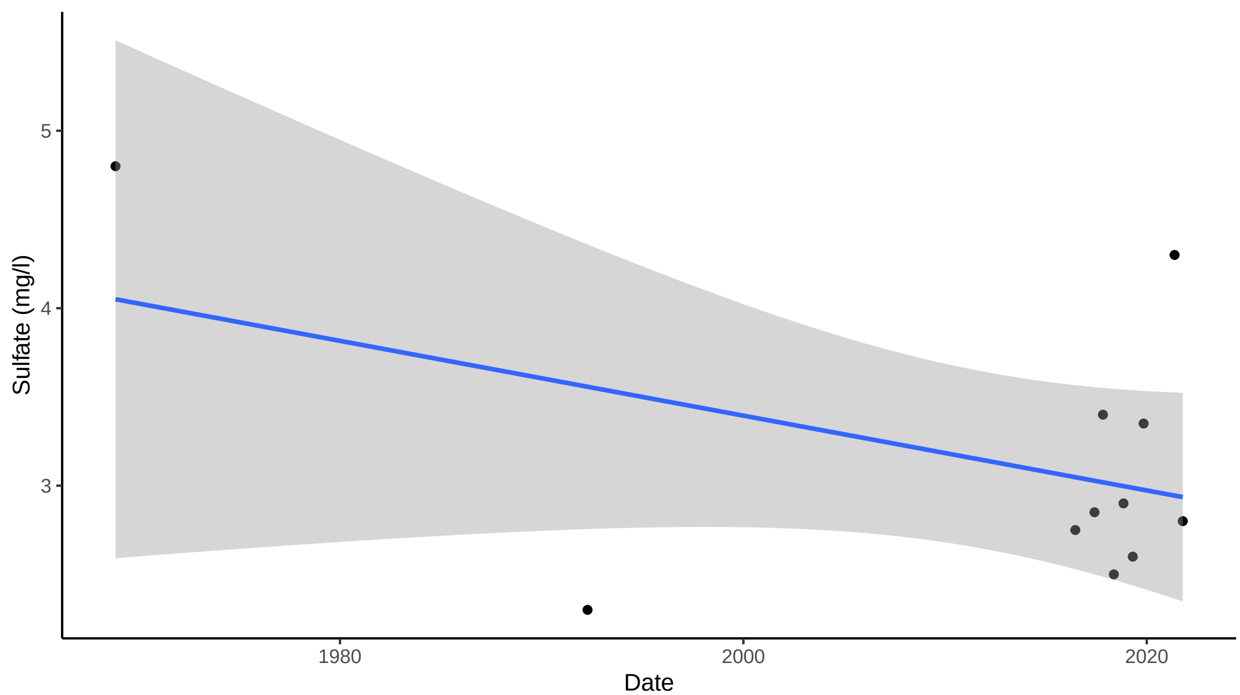


4.3 Question 3: How is groundwater quality changing overtime? Are chemicals more concentrated at low groundwater levels or high?

Lastly, water quality was analyzed with visual plots and linear regression. Two of the many available water quality variables were chosen for analysis: sulfate concentrations and pH. Figures 9 and 10 show how sulfate changes over time and with groundwater depth for Houserville and Sewickley, PA, respectively. Figure 11 and 12 show how pH changes over time and with groundwater depth for Houserville and Sewickley, PA, respectively. Then a linear regression was also run for sulfate concentration and pH in relation to groundwater level and time for both sites to test for statistical significance.

Figure 9. Sulfate Concentration Variations with Water Level and Time
Houserville, PA

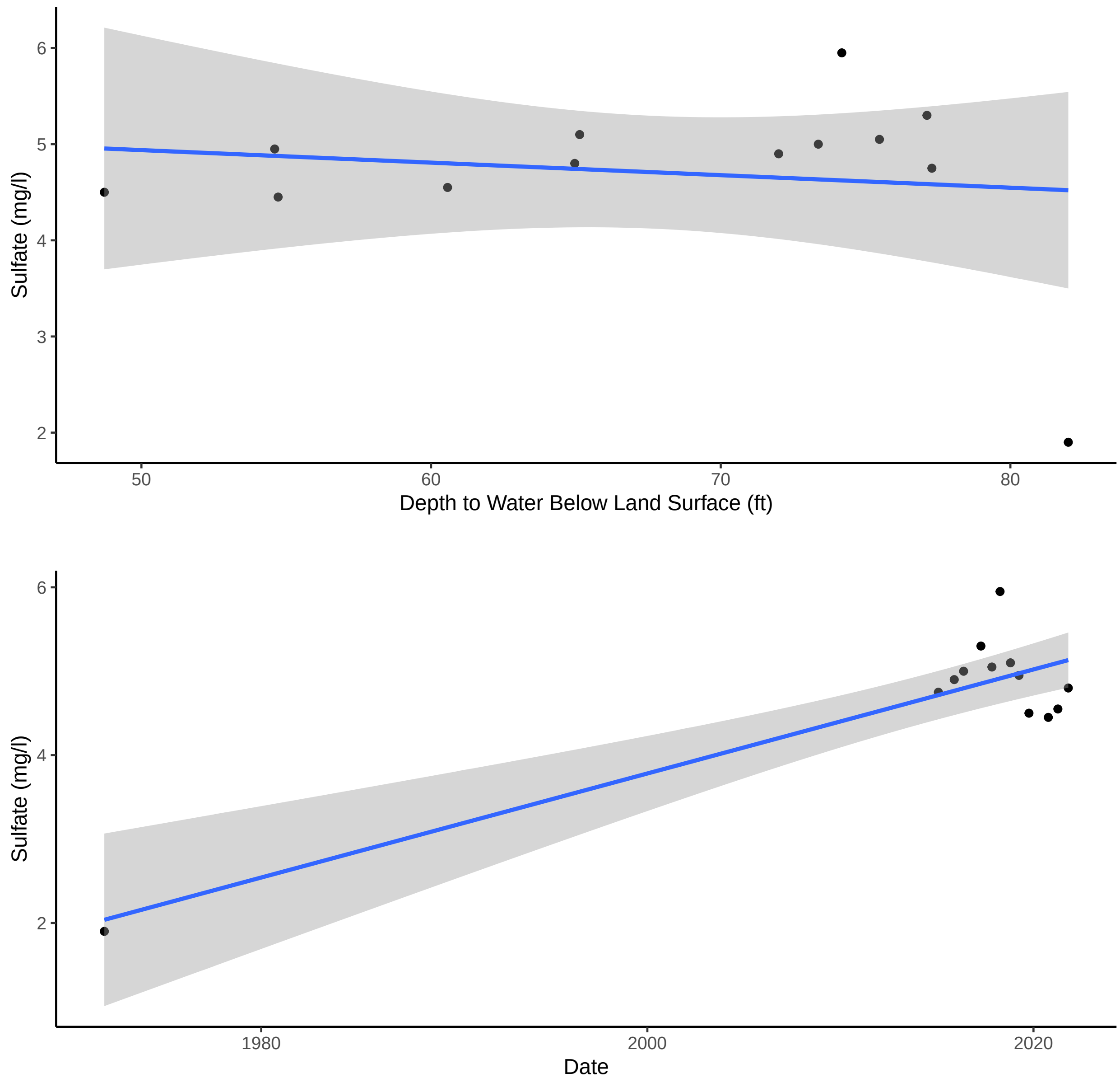




```
##
## Call:
## lm(formula = Sulfate ~ Water_Level, data = groundwater_level_qual_penn)
##
## Residuals:
##      Min       1Q   Median       3Q      Max
## -0.81530 -0.27084 -0.07462  0.20793  1.26537
##
## Coefficients:
##             Estimate Std. Error t value Pr(>|t|)
## (Intercept)   0.8354     2.4556   0.340    0.742
## Water_Level   0.3508     0.4014   0.874    0.408
##
## Residual standard error: 0.5852 on 8 degrees of freedom
##   (6 observations deleted due to missingness)
## Multiple R-squared:  0.08713,    Adjusted R-squared:  -0.02698
## F-statistic: 0.7635 on 1 and 8 DF,  p-value: 0.4077
```

```
##
## Call:
## lm(formula = Sulfate ~ Date, data = groundwater_level_qual_penn)
##
## Residuals:
##     Min      1Q  Median      3Q     Max
## -1.2573 -0.3427 -0.1354  0.3774  1.3560
##
## Coefficients:
##                Estimate  Std. Error t value Pr(>|t|)
## (Intercept)  4.02657793  0.63001574   6.391 0.000127 ***
## Date        -0.00005769  0.00003844  -1.501 0.167624
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Residual standard error: 0.732 on 9 degrees of freedom
##   (5 observations deleted due to missingness)
## Multiple R-squared:  0.2002, Adjusted R-squared:  0.1113
## F-statistic: 2.253 on 1 and 9 DF,  p-value: 0.1676
```

Figure 10. Sulfate Concentration Variations with Water Level and Time

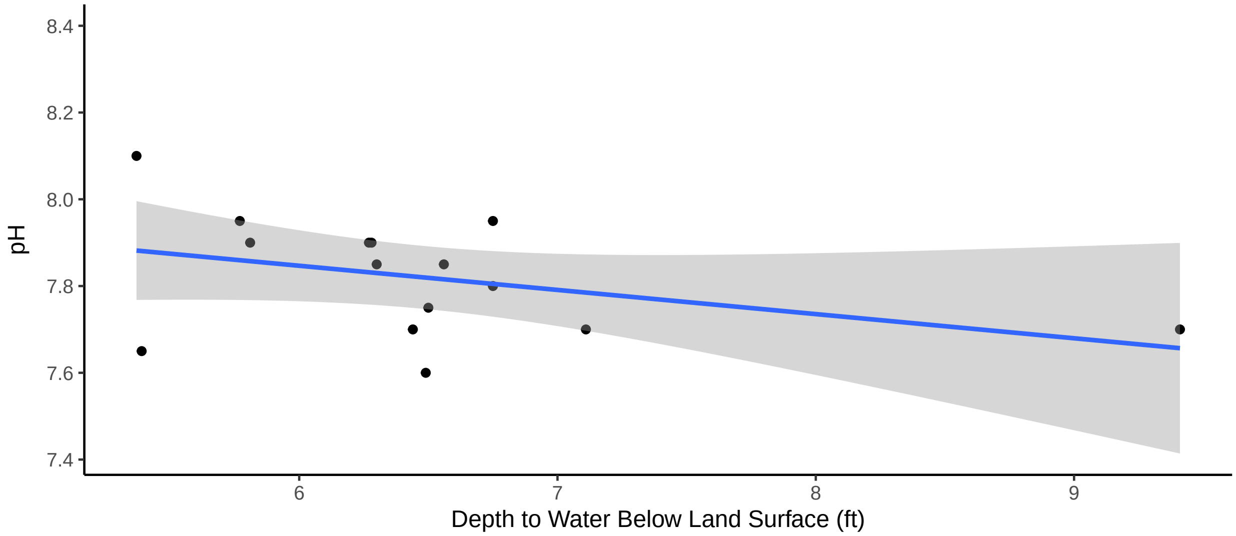


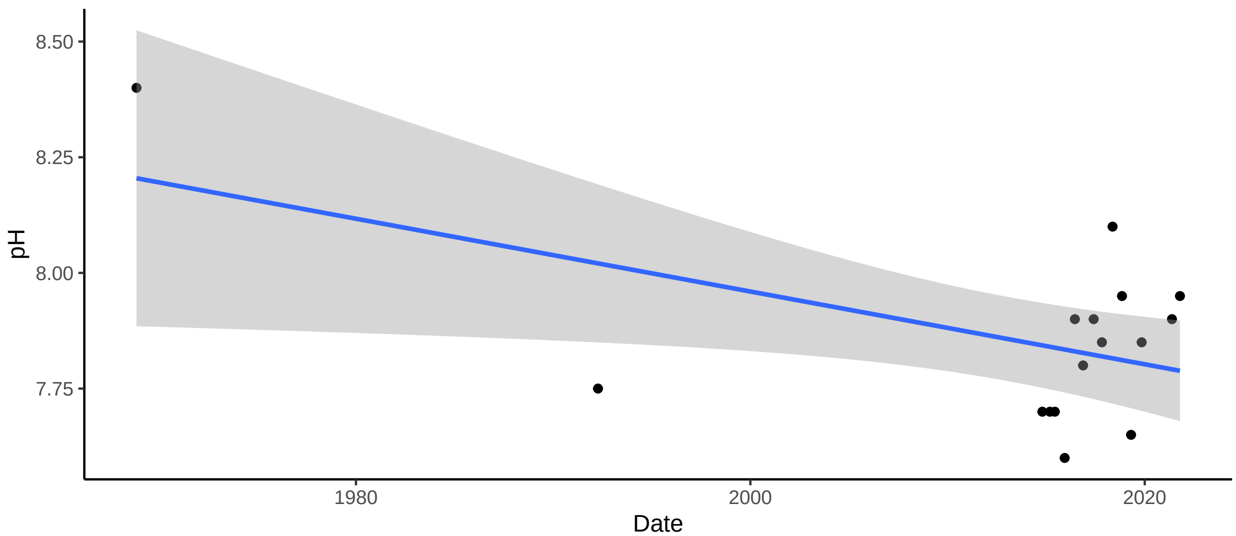
```
##
## Call:
## lm(formula = Sulfate ~ Water_Level, data = groundwater_level_qual_vr)
##
## Residuals:
##     Min      1Q  Median      3Q     Max
## -2.6214 -0.2507  0.1673  0.3662  1.3267
##
## Coefficients:
##             Estimate Std. Error t value Pr(>|t|)
## (Intercept)  5.59012    1.82107    3.07   0.0107 *
## Water_Level -0.01303    0.02661   -0.49   0.6339
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Residual standard error: 0.9607 on 11 degrees of freedom
##   (3 observations deleted due to missingness)
## Multiple R-squared:  0.02135,    Adjusted R-squared:  -0.06762
## F-statistic: 0.2399 on 1 and 11 DF,  p-value: 0.6339
```

```
##
## Call:
## lm(formula = Sulfate ~ Date, data = groundwater_level_qual_vr)
##
## Residuals:
##      Min       1Q   Median       3Q      Max
## -0.61873 -0.33288  0.03428  0.16236  1.03622
##
## Coefficients:
##              Estimate Std. Error t value  Pr(>|t|)
## (Intercept) 1.9216772  0.4858293   3.955   0.00225 **
## Date        0.0001697  0.0000285   5.955 0.0000952 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Residual standard error: 0.4725 on 11 degrees of freedom
##   (3 observations deleted due to missingness)
## Multiple R-squared:  0.7633, Adjusted R-squared:  0.7417
## F-statistic: 35.47 on 1 and 11 DF,  p-value: 0.00009519
```

Figure 11. pH Level Variations with Water Level and Time

Houserville, PA



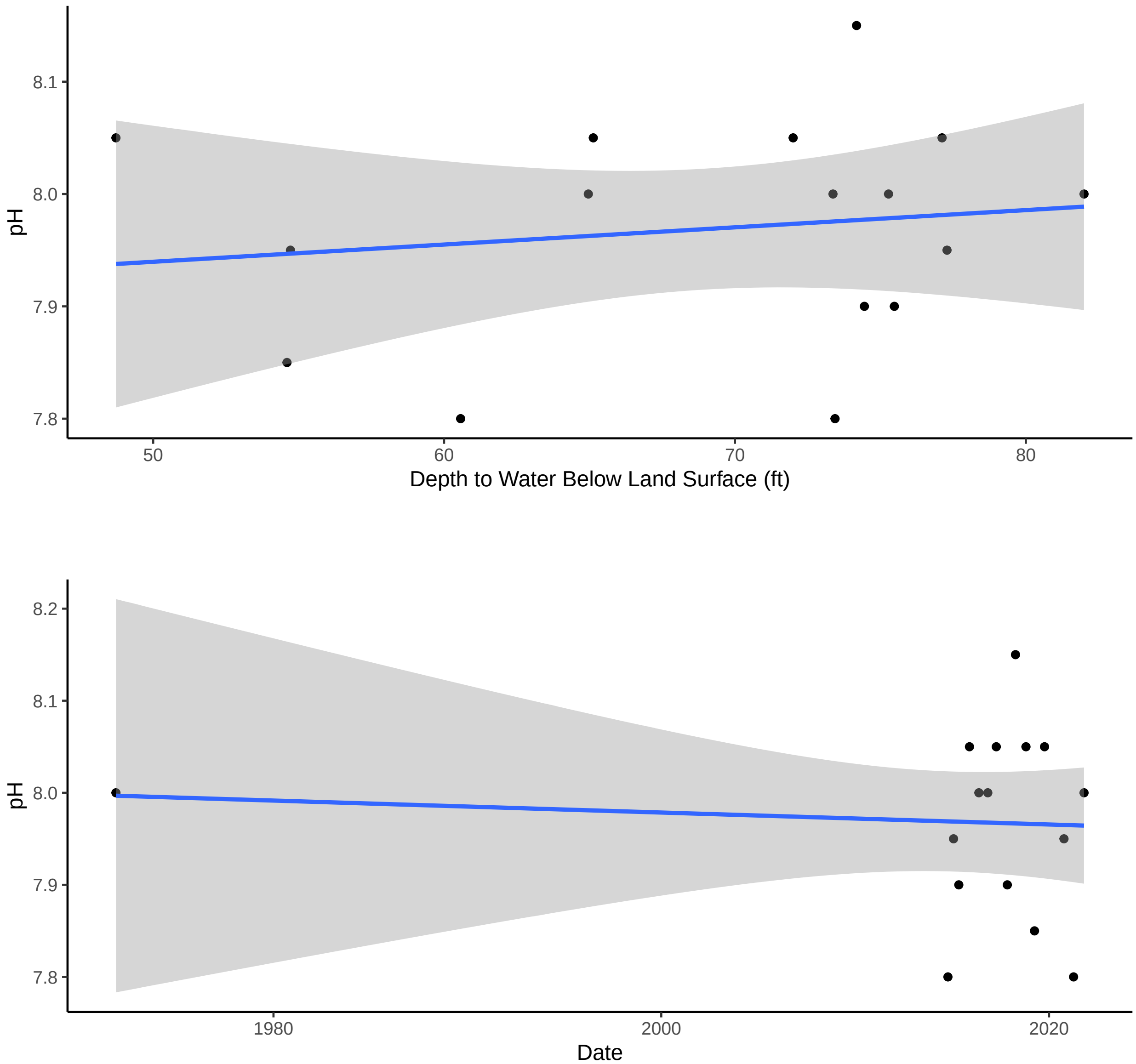


```
##
## Call:
## lm(formula = pH ~ Water_Level, data = groundwater_level_qual_penn)
##
## Residuals:
##      Min       1Q   Median       3Q      Max
## -0.23073 -0.07689  0.03446  0.06858  0.21815
##
## Coefficients:
##             Estimate Std. Error t value Pr(>|t|)
## (Intercept)  8.18106    0.23950  34.159  4.1e-14 ***
## Water_Level -0.05572    0.03659  -1.523    0.152
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Residual standard error: 0.13 on 13 degrees of freedom
##   (1 observation deleted due to missingness)
## Multiple R-squared:  0.1513, Adjusted R-squared:  0.08606
## F-statistic: 2.318 on 1 and 13 DF,  p-value: 0.1518
```

```
##
## Call:
## lm(formula = pH ~ Date, data = groundwater_level_qual_penn)
##
## Residuals:
##      Min       1Q   Median       3Q      Max
## -0.27054 -0.14106  0.03836  0.11589  0.28468
##
## Coefficients:
##                 Estimate   Std. Error t value Pr(>|t|)
## (Intercept)  8.195709415  0.145612916  56.284   <2e-16 ***
## Date        -0.000021532  0.000008836  -2.437   0.0288 *
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Residual standard error: 0.1697 on 14 degrees of freedom
## Multiple R-squared:  0.2979, Adjusted R-squared:  0.2477
## F-statistic: 5.939 on 1 and 14 DF,  p-value: 0.02875
```

Figure 12. pH Level Variations with Water Level and Time

Sewickley, PA



```
##
## Call:
## lm(formula = pH ~ Water_Level, data = groundwater_level_qual_vr)
##
## Residuals:
##      Min       1Q   Median       3Q      Max
## -0.17562 -0.07757  0.01640  0.07070  0.17324
##
## Coefficients:
##             Estimate Std. Error t value Pr(>|t|)
## (Intercept) 7.863025   0.185749  42.332 3.54e-16 ***
## Water_Level 0.001533   0.002669   0.574    0.575
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Residual standard error: 0.1004 on 14 degrees of freedom
## Multiple R-squared:  0.02303,    Adjusted R-squared:  -0.04676
## F-statistic:  0.33 on 1 and 14 DF,  p-value: 0.5748
```

```
##
## Call:
## lm(formula = pH ~ Date, data = groundwater_level_qual_vr)
##
## Residuals:
##      Min       1Q   Median       3Q      Max
## -0.16894 -0.06736  0.01763  0.08201  0.18332
##
## Coefficients:
##                 Estimate   Std. Error t value Pr(>|t|)
## (Intercept)  7.998048905  0.103590613  77.208   <2e-16 ***
## Date        -0.000001780  0.000006101  -0.292    0.775
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Residual standard error: 0.1012 on 14 degrees of freedom
## Multiple R-squared:  0.00604,    Adjusted R-squared:  -0.06496
## F-statistic: 0.08507 on 1 and 14 DF,  p-value: 0.7748
```

5 Summary and Conclusions

5.1 Question 1

From the analysis, stormflow and groundwater have seasonal trends in both Houserville and Sewickley, PA. Given this, a seasonal Mann-Kendall test was run to understand how these variables were changing over time. In Houserville, stormflow was showing statistical significance for decreasing over time, while groundwater levels were also decreasing overtime. In Sewickley, stormflow was showing statistical significance for decreasing over time, while groundwater levels showed no statistical significance in trend over time.

5.2 Question 2

Precipitation or in the case of this analysis stormflow should be an indicator of groundwater levels because groundwater is recharged by precipitation. In this analysis because groundwater levels are measured as distance from the ground surface to the water level, the larger the water level value the less ground water there is. As a result the relationship for this data is the less stormwater or precipitation there is the greater the distance is to the water level. When looking at lag times in Houserville both with and without seasonality there was statistically significant and most dominant lag was at 0, -21 months. This means that according to the analysis ground water could be affected by rainfall within the month or take around 21 months to affect groundwater levels. For Sewickley there was statistically significant and most dominant lag at -2 months. This means it takes stormflow or precip around 2 months to affect groundwater levels. Positively correlated lag was not considered because that relationship does not line up scientifically. There is also the possibility that lag could be seasonal. For example, it could be that as the land is wetter it takes less time for groundwater to be affected by precipitation.

5.3 Question 3

Lastly, although must of the data was concentrated on recent samples the most statistically significant finding was that sulfate concentrations are higher in Sewickley now than before. There is also some evidence in both Houserville and Sewickley that sulfate concentrations increase as depth to water below the surface increases. This may suggest that sulfates are not being flushed out of the system with the water. Most of the analysis of groundwater quality were statistically insignificant. More consistent data sampling would be needed to form conclusions.

6 References

https://cida.usgs.gov/ngwmn/index.jsp

U.S. Geological Survey, 2016, National Water Information System data available on the World Wide Web (USGS Water Data for the Nation).