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Statistical Evaluation of Edwards Aquifer Water Levels, Pumping, and Springflow

prepared for

Clearwater Underground Water Conservation District

prepared by

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Geoscientist's Seal

This report documents the work of the following licensed professional geoscientist's with LBG-Guyton Associates, a licensed professional geoscientist firm in the State of Texas (License No. 50111).

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Executive Summary

The purpose of this study was to determine a methodology for a drought trigger, based on multiple hydrogeologic parameters, to gauge when Clearwater Underground Water Conservation District (CUWCD) is approaching drought conditions. Work involved developing a Salado Creek discharge model with parameters that indicate when flow rate will drop below a reasonable or pre-defined level of discharge. The parameters would allow the District to develop drought triggers that would define when to begin implementing or informing constituents of the need for conservation efforts.

To develop reliable drought triggers, the relationship between Salado Creek discharge and local hydrogeologic parameters must be developed. In this study, we focused on the lower flow conditions for the Salado Creek discharge which is more important when considering drought conditions. In particular, we limited our evaluation to data less than or equal to the median discharge value.

To model discharge from the Salado Creek, a multilinear analysis was performed to define a set of parameters that reasonably models discharge. The most reasonable model developed used daily water level measurements from two wells near the Salado Creek gaging station. The discharge model developed is described by the following equation that allows for prediction of flow at the gaging station:

$$Discharge = 8{,}872 + -61.04 \times SWN\ 5804816\ WL + -8.81 \times SWN\ 5804628\ WL$$

Comparison with measured values indicates that the model under predicts discharge when water levels are deeper (that is, low flow conditions). The under prediction is a limitation of the model that could potentially be addressed in the future with a step function or non-linear model. However, the current model does provide a conservative estimate of discharge as it approaches the desired future condition level of 100 acre-feet per month.

State well number (SWN) 5804816's depth to water level measurement may provide the best option for developing drought triggers as it can have the greatest indication of discharge rates. In addition, while the water levels in SWN 5804816 clearly respond to recharge events, the response is of a lower magnitude and appears to be slower than for SWN 5804628 suggesting it would be more indicative of longer-term aquifer conditions. The more rapid fluctuations in SWN 5804628 make it less applicable for developing drought triggers, though water levels should continue to be monitored for predicting creek discharge.

To evaluate the potential effect of pumping on Salado Creek discharge we conducted a capture analysis using the groundwater flow model (GAM) for the northern segment of the Edwards aquifer. Pumping from the cells closest to the stream cause the greatest reductions in outflow with a maximum reduction in average outflow. Simulation results also indicate that for most of the area to the west of Salado Creek, 50 percent or more, on average, of groundwater pumping originates as captured potential outflow. Quantified capture zones may aid the District in identifying areas where monitoring of the aquifer conditions and groundwater production could be most beneficial in relation to flow in Salado Creek.

1. Introduction

The purpose of this study was to determine a methodology for a drought trigger, based on multiple hydrogeologic parameters, to gauge when Clearwater Underground Water Conservation District (CUWCD) is approaching drought conditions. This trigger would allow the District to begin to implement or inform its constituents of the need for conservation efforts. Having the ability to determine drought conditions is especially important in a karstic aquifer system like the Edwards, where the interactions between the aquifer and surface water conditions can be readily apparent, and the goal is to limit impacts to springflow. This drought trigger methodology is developed through analysis of the relationships between the Salado Creek gauge station discharge rate and local hydrogeologic parameters such as water levels, precipitation rates, and the Palmer Hydrologic Drought Index (PHDI), and was developed through statistical analysis of their relationships. From the Salado Creek discharge model, the parameters that feed that model can be assessed as to when they would cause the Salado Creek springflow rate to drop below a reasonable or pre-defined level of discharge within the creek. These parameters can then be monitored to inform the District if some of the values are approaching or near values that would indicate low discharge within the Salado Creek.

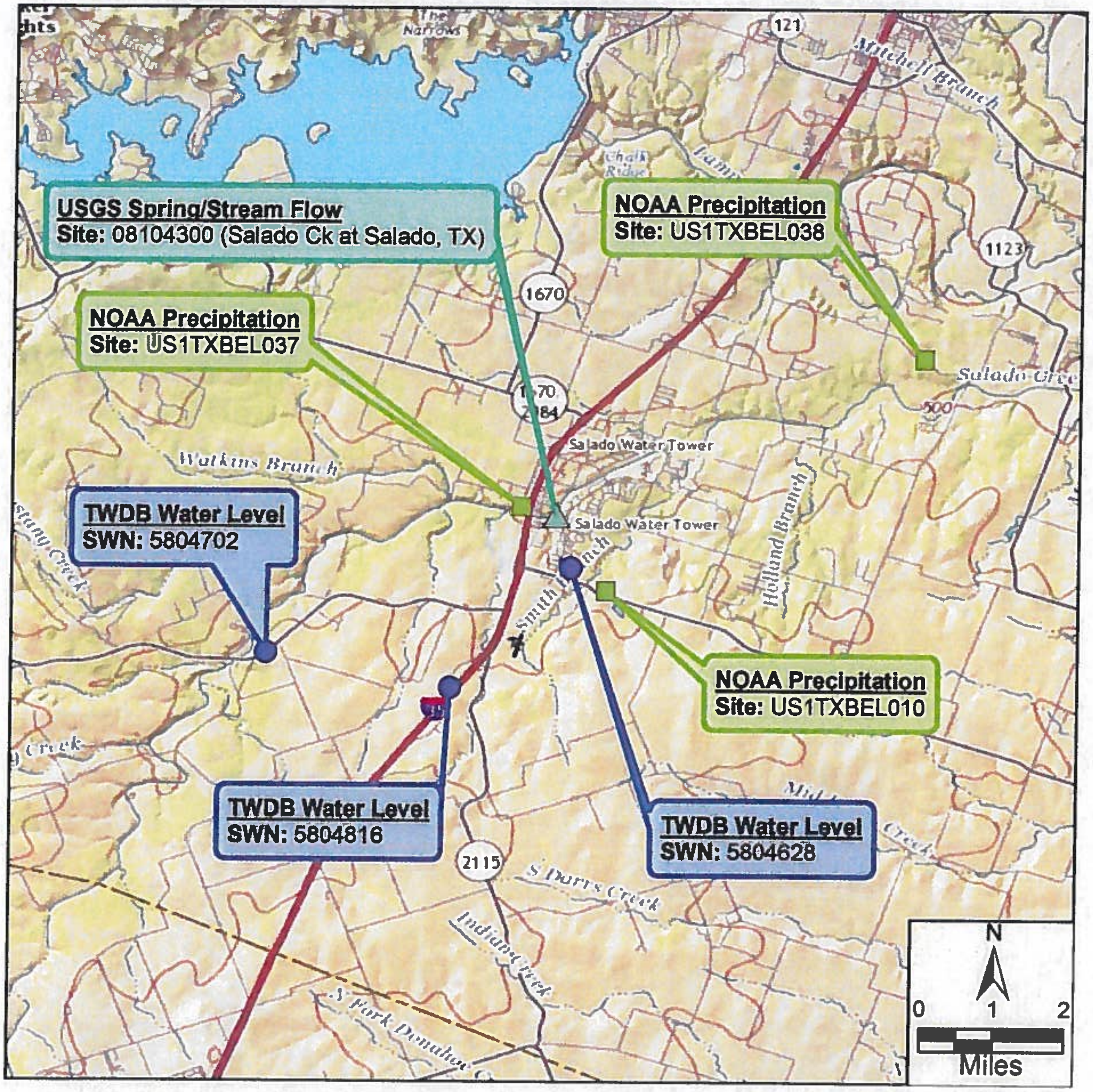
2. Data Acquisition

To develop a reliable drought trigger, the relationship between Salado Creek discharge and local hydrogeologic parameters must be developed. Developing the relationship requires data during the period of record of the Salado Creek gauge station which began on March 3, 2013. For the drought trigger to be useful, the parameters used must be both readily available and have sufficient data to adequately define that relationship. This limited the data to large government institutes that have generally began to house and store data within their websites making access to the data both convenient and reliable. For this study, the process of acquiring the necessary datasets was automated, which made the data gathering process quick and efficient. The initial datasets were limited to the area around Salado Creek. These datasets were evaluated based on how much data was present and if data were still being collected. Once the initial vetting process was performed, seven datasets were collected that ranged over four different hydrogeologic parameters including the Salado Creek gauge data. Table 1 indicates the data types, sources, and available measurement frequency. Figure 1 shows the location where data for each parameter used in this evaluation are collected.

Table 1: Hydrogeologic Parameter Dataset Information.

Data Type	Source	Measurement Rate
Spring/Stream Flow	USGS	15 min
Water Level	TWDB	Hourly
Precipitation	NOAA	Daily
Palmer Hydrological Drought Index	NOAA	Monthly

Figure 1. Location of USGS, TWDB, and NOAA Data Collection Sites.



Data acquired were three water level datasets from the Texas Water Development Board's (TWDB) current water level observation website, three precipitation stations, and the PHDI from the National Oceanic and Atmospheric Administration's (NOAA) daily global historical climatology network. The Salado Creek gauge station data (discharge and water level height) were obtained from the United States Geological Survey's (USGS) water services website. With the data acquired, the next step was evaluating how the data was delivered and what steps needed to be taken to get the data into a reasonable format for analysis.

For this study a daily rate was chosen as the main time interval. The well water-level data were provided in an hourly rate which was averaged over the 24-hour period to provide a single value for each day. The precipitation station data were provided in daily rates, but in units of tenths of millimeter which were converted into feet. The PHDI data is only calculated for the entire month and it was assumed that the monthly rate was the same every day; while this assumption is most likely incorrect, it was necessary to analyze the data at a daily time interval. The PHDI is a unitless value from less than -4 to greater than 4, which indicates dry or wet conditions respectively. The Salado Creek gauge data was provided in 15 minute intervals were averaged into a daily rate. The discharge data was converted from cubic feet per day into acre-feet per month to match the current Edwards aquifer desired future conditions (DFC) for the District of 100 acre-feet per month.

3. Statistical Analysis of Hydrogeologic Parameters

3.1. Statistical Summary of Available Data

The first step in analyzing the data involved preparing a statistical summary. This statistical summary provides insight into the spread of the data and potential concerns or irregularities. Table 2 provides the summary of the obtained data.

Table 2: Summary Statistics for Hydrogeologic Parameters.

Dataset	Minimum	1st Quartile	Median	Mean	3rd Quartile	Maximum	Standard Deviation
Salado Ck Discharge (ac-ft per month)	211	439	946	2,801	2,851	158,963	9,905
Salado Ck Gage Height (ft)	1.36	1.50	1.65	1.79	1.90	5.25	0.47
Water Level 5804702 (ft bgl)	68.95	71.89	72.77	72.58	73.49	79.52	1.20
Water Level 5804816 (ft bgl)	116	122	125	124.1	126	130.6	3.01
Water Level 5804628 (ft bgl)	4.56	61.63	73.49	66.66	79.53	93.21	20.1
Precipitation US1TXBEL010 (ft)	0	0	0	0.08	0	0.69	0.03
Precipitation US1TXBEL037 (ft)	0	0	0	0.01	0	0.35	0.04
Precipitation US1TXBEL038 (ft)	0	0	0	0.01	0	0.40	0.03
Palmer Hydrologic Drought Index	-6	-2.65	-1.27	-0.61	1.01	6.19	2.85

ac-ft = acre-feet; ft = feet; bgl = below ground level

The statistical summary itself consists seven different values; minimum, 1st quartile, median, mean, 3rd quartile, maximum, and standard deviation. The minimum and maximum values are just the smallest and largest values in the data and define the limits of the data. The 1st quartile and 3rd quartile are the values at which data are less than 25% and 75% of the values in the dataset respectively. These two terms can help define where most of the data fall. The median is the middle value in the data and the mean is the sum of the values divided by the total number of values in the dataset. The standard deviation is a measure of how spread out the values are from the mean with larger values indicating a greater spread of values in the dataset.

Looking at Table 2 we can start determine some general information about the data. The Salado Creek gauge station's discharge rates have a large range in values. The larger mean relative to the smaller median and large max suggest that the dataset has some outlier values that are driving the mean to be higher. These outliers are important, as they can cause further analysis to be skewed due to these higher values and may need to be removed as they may not reflect the majority of the data very well. The Salado Creek gauge height data has a smaller range and not as many outliers as indicated by the median and mean values being similar, and the small standard deviation suggesting a smaller spread in data.

Looking at the water levels, both wells 5804702 and 5804816 have uniform spread in data and both datasets do not deviate much from their respective mean value. Well 5804628's water level measurements do have a large spread in the data as indicated by the standard deviation being about 10 times larger than the other wells. The spread in the data could indicate that the well is much more susceptible to recharge and drought conditions or local pumping.

Looking at precipitation data from the three gauging stations, it is apparent that most of the time there is little to no precipitation occurring in this area (75% of the data has zero precipitation). However, there are also times of very large rainfall events as indicated by the maximum values at each station. The PHDI's range is close to zero due to the minimum and maximum values being the same, but having opposite signs (negative and positive). PHDI's data does skew down towards the negative values, or more drought like conditions, as indicated by the median value being negative.

3.2. Data Refinement for Low Flow Conditions Evaluation

To further understand and to visualize the data, each parameter was plotted against time to see how the data changes (see Attachment A). The Salado Creek discharge graph (A.1) helps to reinforce the idea of outliers within the dataset, as is apparent by most the data being below 25,000 acre-feet per month with a few points as many as four times that amount in the dataset. The gauge height (A.2) has fluctuations with time that, as expected, appear to correlate to the same high values seen in the discharge dataset. All three water level data fluctuate with time (A.3-A.5), which could be caused by local pumping or recharge events, although the magnitude of fluctuations varies greatly between the wells. The precipitation data (A.6-A.8) shows almost no rainfall occurred during their respective time with moments of high to moderate rainfall sporadically occurring. The PHDI (A.9) does show some possible cyclic nature which is likely associated with local weather events.

Before moving on to the next phase of analysis it is important to use the information obtained during the summary portion to make any corrections to the data if necessary. In this study, we focused on the lower flow conditions for the Salado Creek discharge data which is more important when considering drought conditions. In particular, we limited our evaluation to data less than or equal to the median discharge value. The median value was chosen as it both encompasses the lower flow rates while also containing half of the original discharge dataset thus providing enough data points to produce a reasonable model while also focusing on the lower discharge rates. Limiting the data to these lower discharge rates had an additional effect of reducing the number of usable data points from the other datasets.

For the models presented in this study to be applicable, all parameters within each model require a corresponding value. For example, if on a particular day only two of three needed parameters are present, then the model cannot use that day to calculated discharge. Due to this limitation, the precipitation data from rain gauge station US1TXBEL037 was removed because there were no corresponding measurements with the lower discharge values. Water level data from SWN 5804702 was removed as well, as post-processing work showed that there was no correlation, or connection, between the water level values and discharge at this well. The updated summary statistics for the lower discharge limited data is shown in Table 3 below.

Table 3: Summary Statistics for Datasets with Correlation to Median and Lower Salado Creek Discharge Measurements.

Dataset	Minimum	1st Quartile	Median	Mean	3rd Quartile	Maximum	Standard Deviation
Salado Ck Discharge (acre-feet per month)	211.16	293.42	439.44	465.57	595.56	946.44*	188.24
Salado Ck Gage Height (ft)	1.36	1.5	1.65	1.79	1.91	5.25	0.47
Water Level 5804816 (ft bgl)	4.56	61.63	73.49	66.67	79.53	93.21	20.14
Water Level 5804628 (ft bgl)	116	121.95	124.98	124.15	125.97	130.62	3.01
Precipitation US1TXBEL010 (ft)	0	0	0	0.01	0	0.69	0.03
Precipitation US1TXBEL038 (ft)	0	0	0	0.01	0	0.4	0.03
Palmer Hydrologic Drought Index	-5.99	-2.65	-1.27	-0.61	1.01	6.19	2.85

*median value from Table 2.

A helpful way to view the data is by overlapping the discharge data with the parameters through time to visually identify if there are any times in which the discharge rate could be explained by one or more of the parameters (see Attachment B). Figure B.1 is of all the water level measurements and discharge, and illustrates how much the water level fluctuates at SWN 5804628 relative to SWN 5804816. Looking at how the water levels compare to the discharge, the relationships between them starts to become apparent. As the depths to water levels becomes smaller (water levels recovering) there tends to be larger discharge rates in the creek and vice-versa.

When looking at the precipitation graph (B.2), there does not appear to be as strong of a connection between the Salado Creek discharge and rainfall. During the low discharge period between 2014 and 2015 there are a few significant rainfall events, but no corresponding increase in discharge. Likewise, during high discharge events, there does not seem to be any correlating rainfall events. Looking at PHDI graph (B.3) there is seems to be a reasonable correlation between discharge values increasing with PHDI values.

3.3. Linear Analysis of Data Correlation

The next step is to determine what basic linear relationship exists between the Salado Creek discharge and the other parameters (see Attachment C). A linear relationship involves fitting a straight line between two datasets to determine how the change in one of the values affects the other and uses that line to extrapolate information out beyond the current dataset. Linear fits were calculated for each parameter and plotted along with the slope, intercept, and R^2 value of each line.

The slope of the line is the rate at which the line increases or decreases when moving along the horizontal axis. The intercept is the value at which the line intercepts the vertical axis when the horizontal axis value is equal to zero. The R^2 value is a metric, between zero and one, that indicates how well two parameters correlate to each other. The closer to one the R^2 value is, the greater the correlation between the parameters; that is, the closer to one the R^2 value, the greater the likelihood that a change in one will be reflected with a change in the other.

Looking at Salado Creek discharge versus Salado Creek gage height (C.1), it would be expected to follow a linear positive trend as discharge and height should both increase and decrease at the same time as the amount of water in the creek increases or decreases. The graph and line do show this correlation with a very high R^2 value of 0.82. For the two water-level datasets, it is expected that the lines will have a negative slope because when water levels decline less water is being discharged to the creek. SWN 5804628 (C.2) has a negative slope and a respectable R^2 value of 0.64, meaning that the line is a good portrayal of more than half of the data, but does not explain all of the discharge occurring. For SWN 5804816 (C.3) it has a negative slope and a R^2 value of 0.67 suggesting a slightly better correlation.

Looking at the two precipitation stations (C.4-C.5), we would expect a positive trend indicating that as precipitation increases then discharge should increase as well. Looking at the graphs, the linear model does show a positive trend, but all the R^2 values are very low, meaning the line has little to no importance. Importantly, the data plotted does not account for a temporal offset between precipitation and discharge. That is, the correlation may improve if precipitation from 10 days ago is compared to discharge. This may be due to a delayed effect between the actual rainfall event and that water reaching the aquifer and discharging into the creek. This delayed effect was considered and analyzes performed, but correlation values did not increase. While precipitation certainly controls the stream and spring flows, a correlation between daily rainfall amounts and discharge could not be obtained; this lack of daily correlation could indicate that it is the long-term volumes of precipitation have a greater effect than daily events.

Graph C.6 represents the PHDI data and is a little different than the rest due to the early assumption that had to be made to create daily rates for the PHDI, which causes the stacked values seen in the PHDI graph. The linear relationship does show what we would expect, a positive slope indicating that lower discharges equate to more drought conditions and higher discharge to more wet conditions. This relationship is not very strong per the R^2 value and may also look different if we had actual daily rates.

3.4. Multilinear Analysis of Data Correlation

From the linear analysis, it is apparent that there is a relationship between discharge and the rest of the parameters, but not one strong enough to explain discharge by itself. To model discharge from the Salado Creek, a multilinear analysis was performed to define a set of parameters that reasonably models discharge. While the previous linear processes looked at all parameters, for the multilinear analysis only the depth to water levels and precipitation data were used. The gauge height was not used because it is directly related to the discharge and the PHDI is not included because it is only updated at the end of the month and cannot be used to calculate recent changes.

The multilinear analysis considers the four datasets and tries to produce an intercept value and coefficients that would produce a simulated discharge value that matches the actual discharge value. The multilinear analysis allows for the discharge to be modeled with hypothetical parameter values to see what the discharge would be like in varying conditions. For the multilinear analysis to work all parameters within the model need to be present for each day, or the model will skip that day, or remove that data point when trying to produce the model. Four different models were chosen to try and simulate discharge rates at Salado Creek. Table 4 summarizes the parameters applied to develop each model.

Table 4. Models Developed to Simulate Salado Creek Discharge Rates.

Model Number	Datasets Applied
1	Water Levels and Actual Precipitation
2	Water Levels
3	Precipitation
4	Water Levels and Average Precipitation

To evaluate how well the model worked the R^2 value can be used again, but more importantly the residuals. The residuals are the difference between the actual discharge value and the modeled value. The smaller the residual the better the model performed in calculating the measured value. To evaluate the model as a whole the root mean square error (RMSE) calculation is generally used. The closer to zero the RMSE, the better the model performed. From the R^2 value and the RMSE (Table 5), we can see how the different models performed in predicting the actual discharge rate. The number of points in each model is also considered, as it is important to have enough values to produce the model. Table 5 provides a summary of the results for each model.

Table 5: Summary of Model Results.

Model	R^2	Number of Points	RMSE
1	0.72	348	106
2	0.74	547	95
3	0.01	348	198
4	0.71	348	105

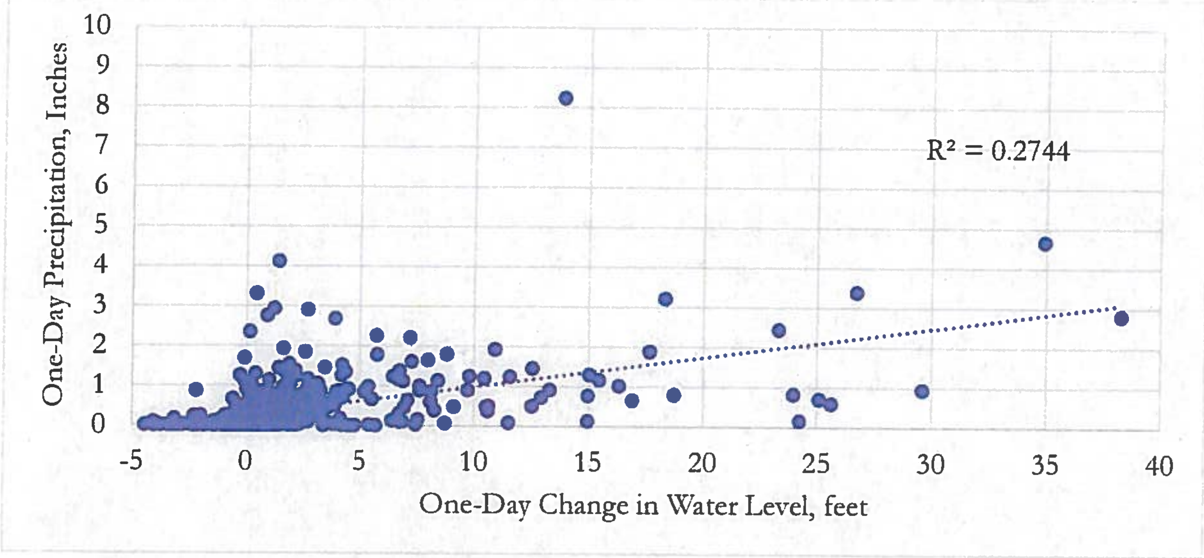
Model 2 has the best R^2 and RMSE values, meaning it does the best job estimating the actual discharge values from the parameters, as well as having the highest number of data points. Model 1 and 4 have reasonable R^2 and RMSE values. Model 3 is the worst model, and does a very poor job estimating the actual discharge values. Attachment E contains charts illustrating the simulated results of each model.

3.5. Multilinear Model Results

From the analyses a few conclusions can be made about the data and their relationship with discharge at the Salado Creek gauge station. First it appears that water levels are the main predictor of discharge. Water levels as predictors are evident in the linear plots having an acceptable correlation with discharge, but furthered in the multilinear models in which they show a high correlation with discharge (Model 2). Second reported daily precipitation is not a good predictor of discharge. The linear graphs show little statistical correlation and when used as the only model parameter (Model 3) it fails to estimate discharge. While intuitively precipitation would be necessary to predict discharge, it appears that the daily precipitation events are not sufficient to show a statistical correlation. However, to further evaluate a statistical correlation, we did look at rainfall events against water levels to see if there are any relationships between them.

The series of graphs in Attachment D show the linear relationship between all wells and precipitation stations. From these graphs we can quickly see that all lines are positive, indicating that water levels recover with increased rain which would be expected if rainfall was quickly being recharge into the Edwards aquifer. While there is a lack of correlation between water levels and rainfall, there is a relatively rapid correlation between rainfall and a change in water levels (see Figure 2). However, the correlation is limited to the same day illustrating the rapid flux that occurs in the local Edwards aquifer.

Figure 2. Change in Water Levels in Well 5804628 versus Area Precipitation. Correlation Shown is for Measurements that Occur on the Same Day.



Of the models developed, Model 3 should not be used due to its inability to match the measured data well, but the rest of the models can all be argued as being useful. Model 1 has good results and uses all of the data, but lacks enough data points across the entire timeline relative to the other models. Model 2 has good model metrics, but only uses water levels which, can be argued, ignores a source of discharge, namely precipitation. Although precipitation alone has been shown not to be a good predictor of discharge, it still explains some of the discharge. Model 4 tries to increase the number of data points by substituting in precipitation values and averaging them, but fails to do so as there were already values present for both precipitation stations for all discharge values. In fact the reason that models 1, 3, and 4 have the same number of points for each model is because precipitation is limiting the number of values that can be used. There are only 348 precipitation points that correspond to recorded discharge values, and thus limits the data to that number.

One of the objectives of this study was to produce an easy and readily available means to determine and predict discharge at Salado Creek. Taking those criteria into consideration, along with the model metrics from Table 5, then model 2 is the optimal choice. It has both the best model metrics, and only relies on the depth to water level data making it less difficult to obtain the necessary data. Going forward Model 2 will be considered the optimal model choice and used to help develop drought triggers.

With Model 2 chosen we can precede with analyzing the models equation and what it means in estimating discharge. The Model 2 equation for calculating discharge rates at Salado Creek is:

$$Discharge = 8{,}872 + -61.04 * SWN\ 5804816\ WL + -8.81 * SWN\ 5804628\ WL$$

Where:

SWN 5804816 WL = Depth to water in feet below ground level at well 5804816
SWN 5804628 WL = Depth to water in feet below ground level at well 5804628
Depth to water entered as positive value

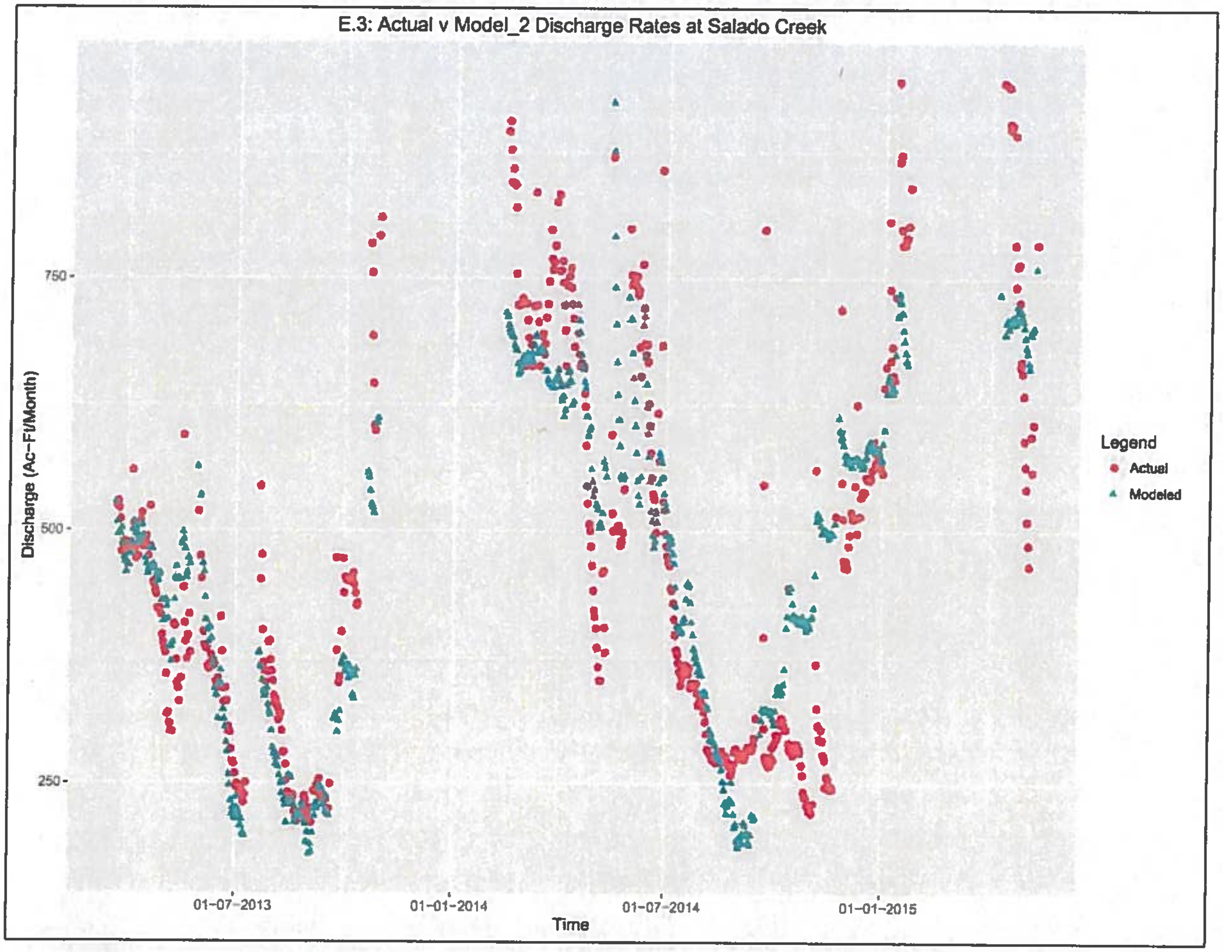
Using this equation, it is possible to now predict possible discharge rates and scenarios, while also understanding how the water levels at these two wells play a role in determining discharge rates. Both coefficients are negative and therefore will lower the intercept value when water levels are below land surface. The rate at which they can do so varies between the two, with the SWN 5804628 water level changes causing minor changes in discharge rates, and SWN 5804816 water level changes causing major changes discharge rates.

While Model 2 is the most reasonable model, it also only explains about 74 percent of the discharge. While this is good for a complex system like the Edwards aquifer, it also means that there can be other factors at work that were not considered, but could help further modeled discharge rates. Once again though, going back to the objective of this study, additional data may be difficult or obscure to obtain, which could make the additional work to obtain that information no longer practical or cost effective.

4. Statistical Model Application

With the discharge model chosen, consideration of drought triggers can be addressed. The first step is to consider the possible simulated discharge limits based on the maximum and minimum values from the two wells. Based on the actual maximum water level depths seen at the two wells, the simulated discharge would be about 80 acre-feet per month and based on the minimum water level depths it would be about at 1,750 acre-feet per month. The maximum water level limit indicates that based on historical water level data the simulated discharge at Salado Creek falls below the current desired future condition of the Edwards aquifer of 100 acre-feet per month (see Figure 3).

Figure 3. Simulated Salado Creek Discharge using Model 2 (also in Attachment E).



As we observe in Figure 3, the actual discharge does not decrease to the same level as predicted by the model. The underpredicting of actual discharge with deeper water levels is a current limitation of the linear model that could potentially be addressed in the future with a step function or non-linear model. However, the current model does provide a conservative estimate of discharge as it approaches DFC levels.

Attachment F contains graphs that were produced to determine how sensitive water level changes are to discharge. These graphs will hold the other well's water level depths at the average water level and then incrementally change the water level of the remaining well between the range of values seen in its dataset. These graphs can show us how sensitive discharge is to each well and which well can give significant information on potential discharge rates. From the graphs, we can see that both wells show discharge decreasing with lower water levels, but do so at different rates.

Looking at the last graph (F.3) with both lines, it becomes apparent how much water level decline reflects discharge relative to SWN 5804816. The steep slope indicates that for every foot lost in water level, there is a loss of 61 acre-feet per month of discharge at the creek. Based on the current water level depth dataset for SWN 5804816 the standard deviation is 3.01 feet, indicating that while even small changes in water level result in relatively large declines in discharge, these changes are not likely to occur. SWN 5804628's water levels will change more overtime (standard deviation of 20.14), but it has smaller effect on the predicted discharge at Salado Creek.

SWN 5804816's depth to water level measurement may provide the best option for developing drought triggers as it can have the greatest indication of discharge rates. In addition, while the water levels in SWN 5804816 clearly respond to recharge events, the response is of a lower magnitude and appears to be slower than for SWN 5804628 suggesting it would be more indicative of longer-term aquifer conditions. The more rapid fluctuations in SWN 5804628 make it less applicable for developing drought triggers, though water levels should continue to be monitored for predicting creek discharge. The trends in water levels from the two wells can be used to forecast the Salado Creek discharge similar to a weather forecast.

It is also important to determine what constitutes a drought based on the discharge rate in the Salado Creek. One possible metric is the current DFC of 100 acre-feet per month of discharge, but that value is already fairly low. That is, if the DFC mark is reached, then drought conditions would most likely already be occurring. Earlier in this study the relationship between the PHDI and discharge was analyzed, and can be used here to help develop the discharge rate in the creek that would indicate drought conditions have started. Looking at the line developed (see C.6 in Attachment C), the point at which the PHDI value becomes zero can be used as the point at which discharge switches from wet to dry conditions. Based on the dataset used for this study, dry conditions are prevalent when the Salado Creek discharge rate is about 475 acre-feet per month.

5. Effect of Pumping on Salado Creek Discharge

To evaluate the potential effect of pumping on Salado Creek discharge we conducted a capture analysis using the groundwater flow model (GAM) for the northern segment of the Edwards aquifer. We used this model because it is the GAM used for evaluating the DFCs for the Edwards aquifer in Bell County which allows for a repeatable comparison with the baseline evaluations. The capture analysis method was selected because the size of the model grid and rapid response of water levels in the aquifer to recharge events makes analysis of impacts to stream and spring flow based on a cone of depression less applicable. The capture analysis is performed by conducting a series of model simulations and evaluating how each simulation affects discharge to the stream; this type of analysis implicitly considers the short-term cone of depression created by pumping by looking specifically at how the drawdown affects outflow to the stream and springs.

In the GAM, there are 2,113 model cells assigned to Bell County that are not associated with a spring or stream. For the capture analysis adding pumping in the amount of 325,851 gallons per day (one acre-foot per day) to the DFC pumping file for one of the 2,113 model cells and ran the model. We then calculated the average flow out of the model to the cells representing Salado Creek and the associated springs. This average flow from the simulation was then compared to the average outflow of 28.8 cubic feet per second to the same model cells for the baseline DFC simulation.

As would be expected, the cells closest to the stream cause the greatest reductions in outflow. The maximum reduction in average outflow due to the added production was about 1.6 percent. There are also ten model cells located in the northwest portion of the model where the pumping results in a slight increase (less than 0.2 percent) in outflow to Salado Creek and the associated springs; these cells are located along the boundary of the model and the added pumping may be causing flow in other cells to go toward Salado Creek rather than to the north. Figure 4 illustrates the added pumping affects outflow to Salado Creek.

Similar to the percent reduction of flow, we also calculated the percent of the added pumping where the source of water was captured potential outflow to Salado Creek and the associated springs. Simulation results indicate that for most of the area to the west of Salado Creek, 50 percent or more, on average, of the added pumping originates as captured potential outflow. The greatest affect appears to occur in the areas upstream of the springs where the creek runs in a more south-to-north direction prior to turning east and under Interstate 35. The areas to the east of the creek appear to have much less of an impact on the potential outflows. Figure 5 illustrates the percent of potential outflow captured by the added pumping.

Using the zones shown on Figure 4 and Figure 5, the District can identify which wells could potentially have the greatest impact on the stream and spring flow. For example, a well completed in the 80 to 90 percent capture zone that is permitted for 100 acre-feet per year would potentially have a greater impact on flow because, over the long-term, 80 to 90 acre-feet of the permitted production may have otherwise discharged to Salado Creek or the associated springs. These zones may also aid the District in identifying areas where monitoring of the aquifer conditions and groundwater production could be most beneficial in relation to flow in Salado Creek.

Figure 4. Simulated Percent Change in Outflow to Salado Creek and Associated Springs (negative values indicate the percent flow was decreased).

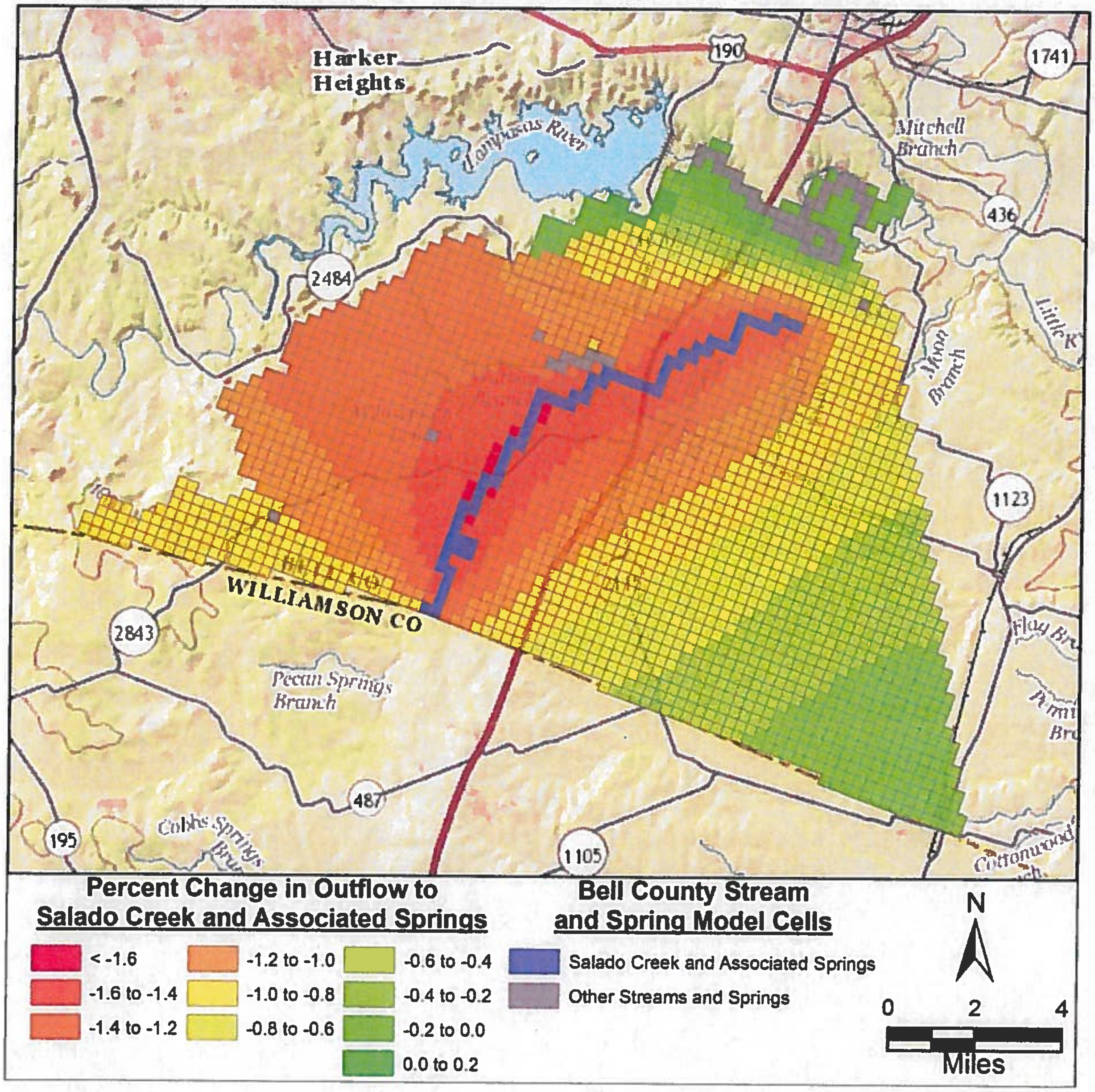
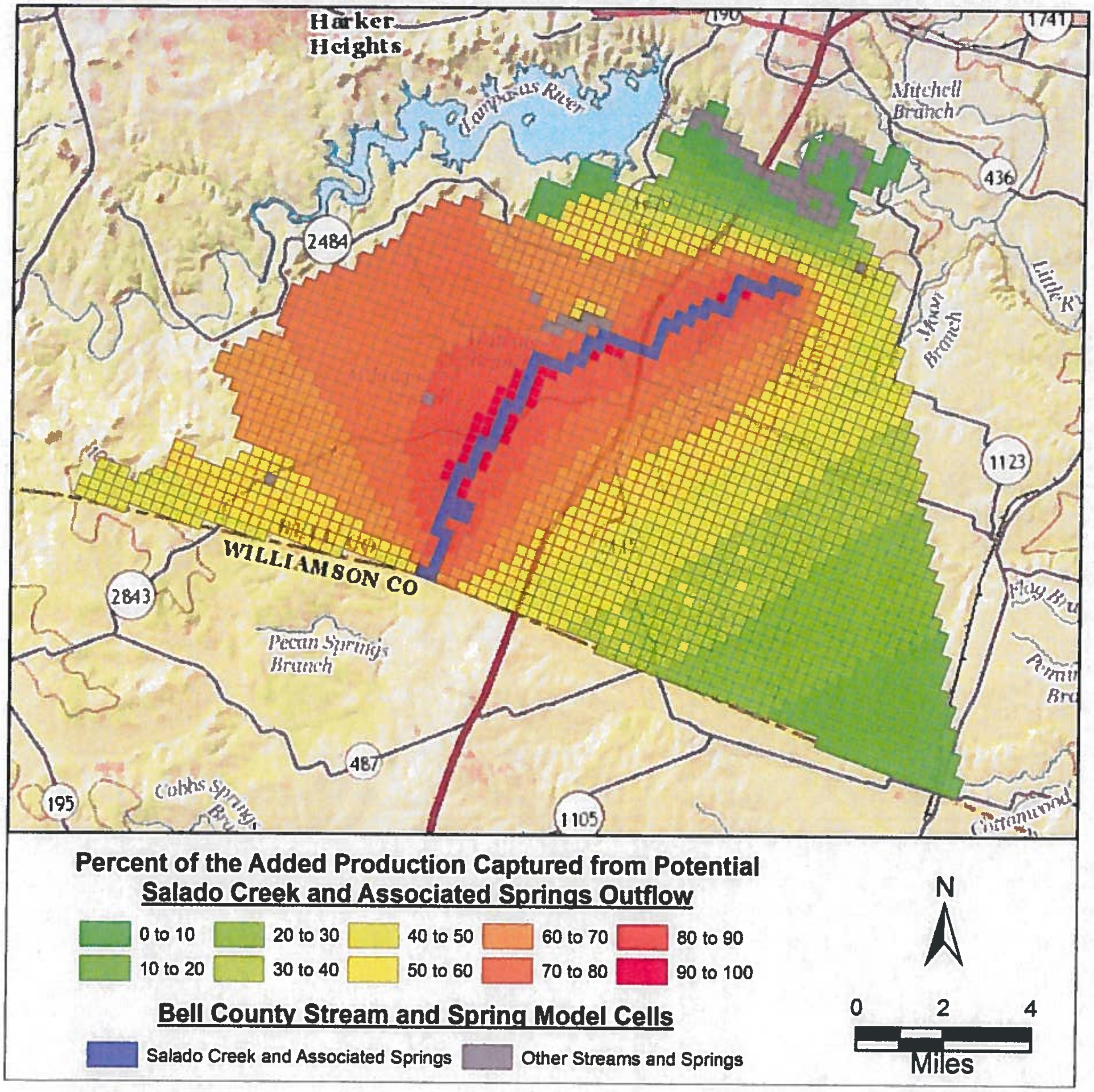


Figure 5. Simulated Percent of Potential Outflow to Salado Creek and Associated Springs Captured by the Added Pumping of 325,851 Gallons per Day (negative values not included).



6. Conclusions

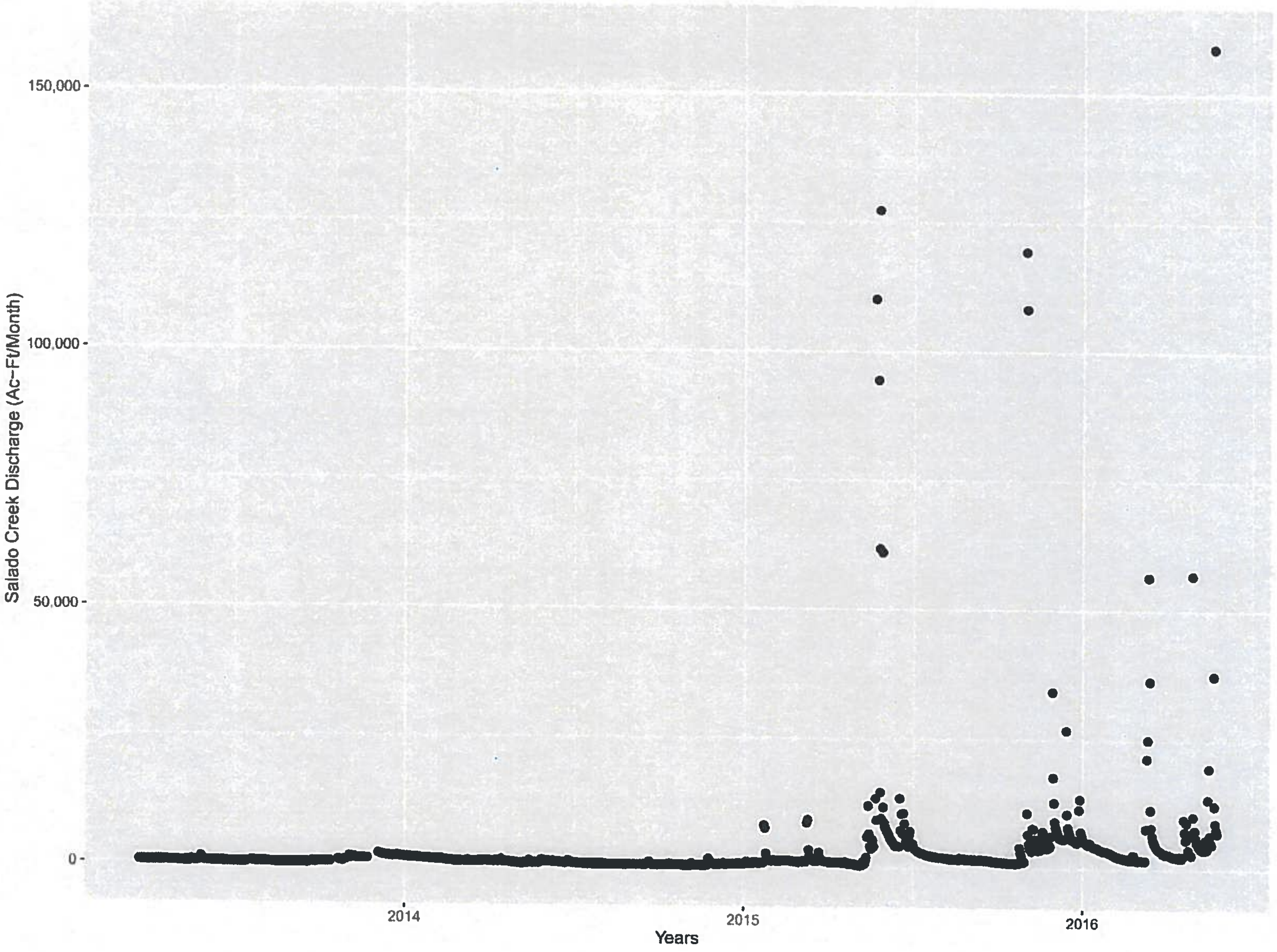
To develop a statistical model to predict low discharge rates at the Salado Creek gauging station, we identified and incorporated six different datasets. Analysis and modeling of the data revealed that the best multilinear model for predicting flow in Salado Creek at the gaging station uses only water level measurements from two local Edwards aquifer wells from which water levels are available on a daily basis. Using the water level measurements from the two monitored state wells, we were able to develop an equation that provides a reasonable prediction of flow in the creek. While we understand that precipitation and drought directly influence flow from the springs and in the creek, we were not able to develop a strong statistical correlation with the available data.

Potential drought triggers that can be developed using the daily water level readings from the two wells used to develop the model of Salado Creek flow. Of the two wells, the well with state well number 5804816 would likely provide the best option as an index well due to smaller changes in water level indicating changes in flow compared to well 5804628. In addition, the water levels in 5804816 appear to respond more slowly to recharge events making it more indicative of long-term conditions.

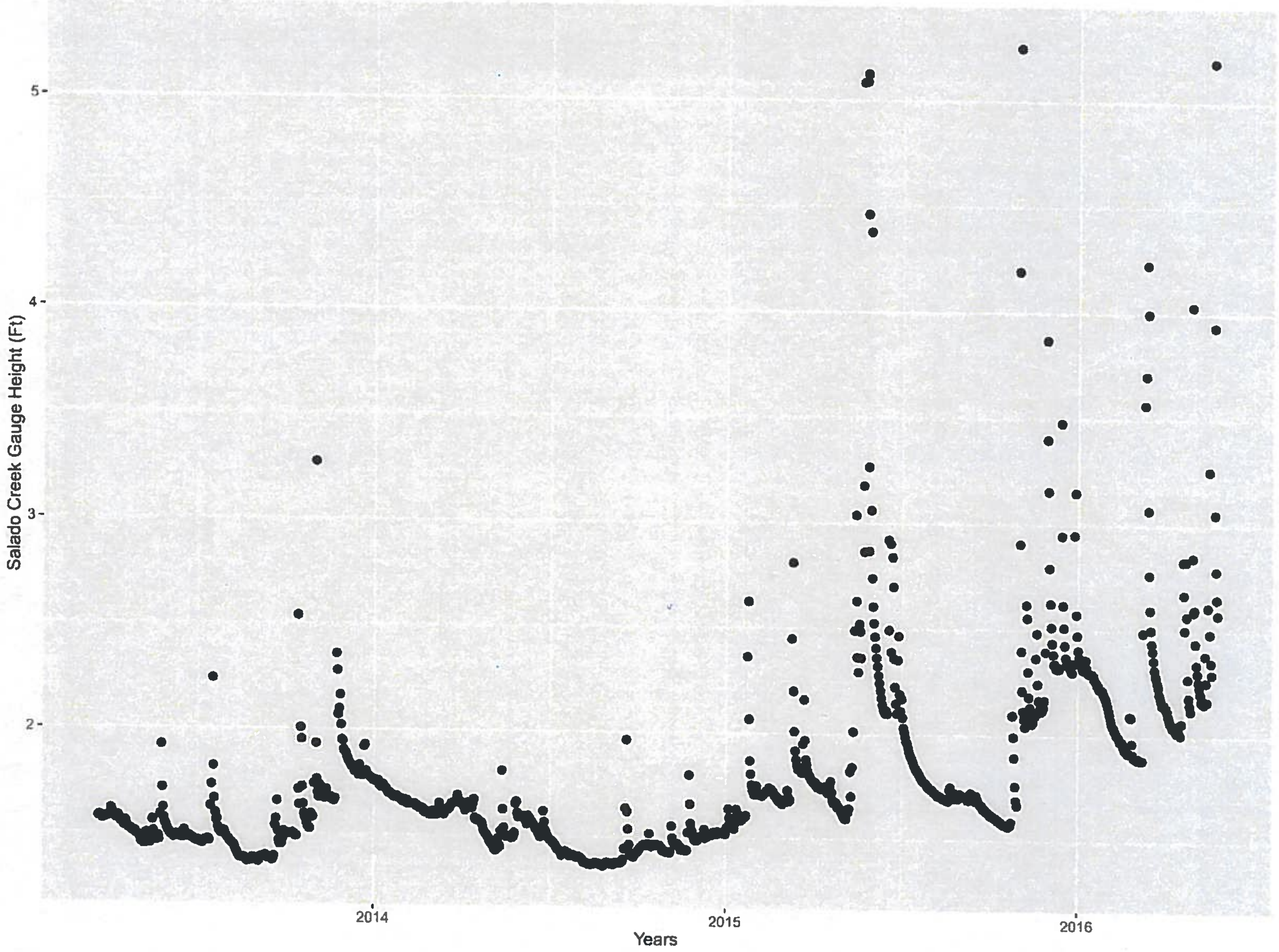
Capture analysis using the GAM indicates that, for the long-term average, more than 50 percent of the groundwater production west of Salado Creek comes from captured potential outflow to Salado Creek and associated springs. Edwards aquifer production to the east of the creek has less of a direct impact with the effects decrease as production moves further downdip. The identified percent capture areas may aid the District in determining the locations most beneficial for monitoring related to Salado Creek flows.

Attachment A – Charts of Hydrogeologic Parameters versus Time

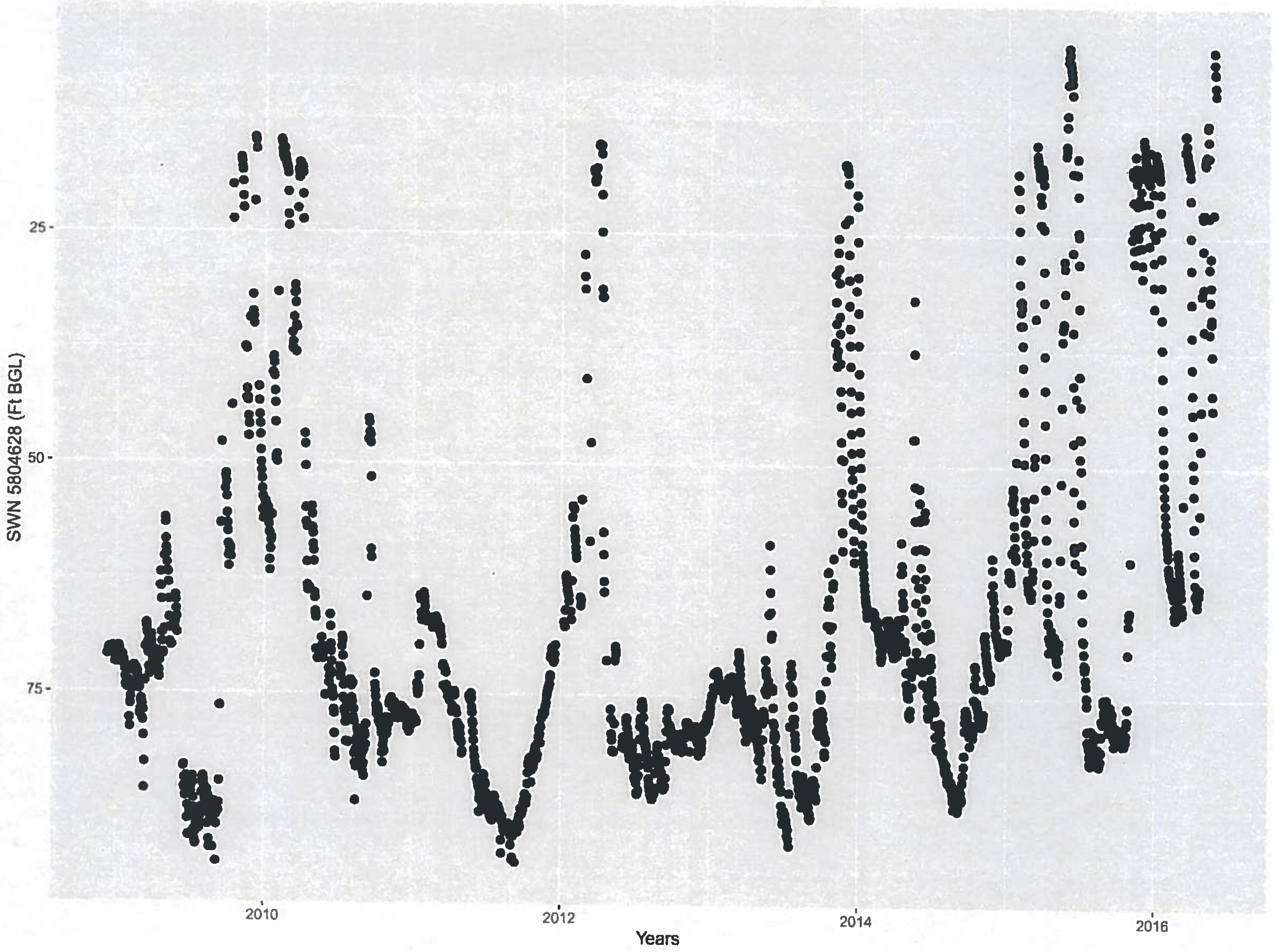
A.1: Salado Creek Discharge (Ac−Ft/Month) vs Time



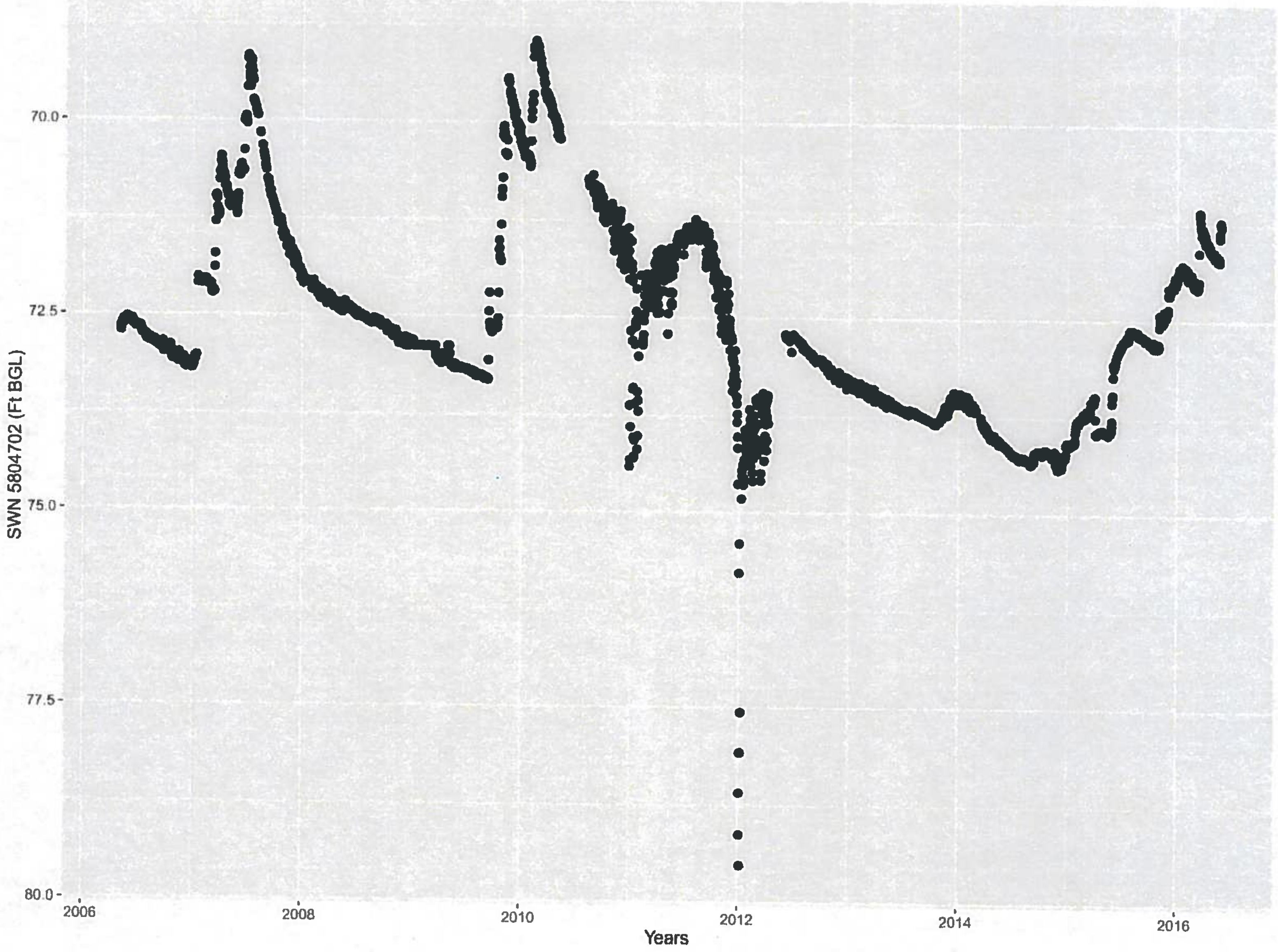
A.2: Salado Creek Gauge Height (Ft) vs Time



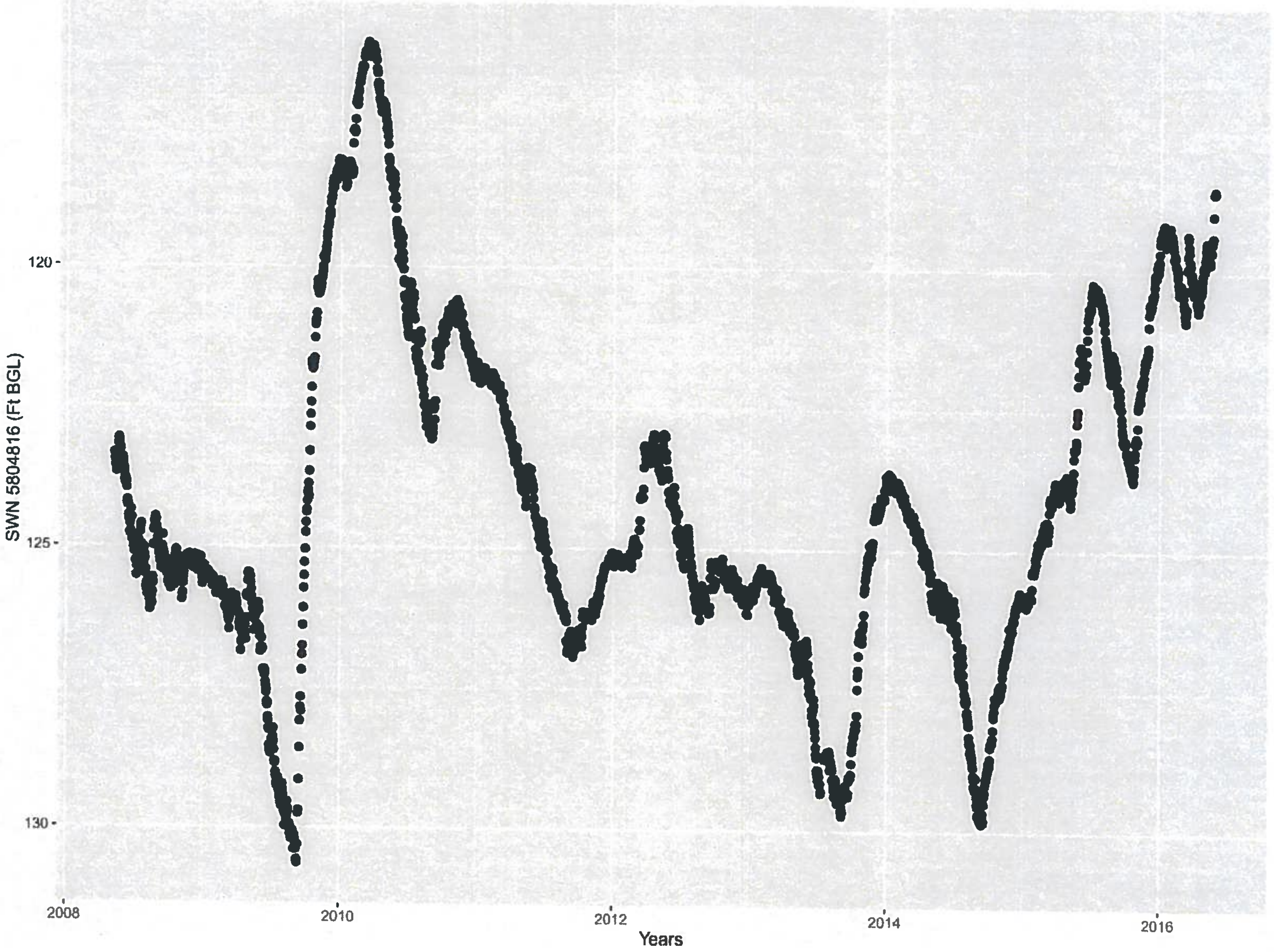
A.3: SWN 5804628 (Ft BGL) vs Time



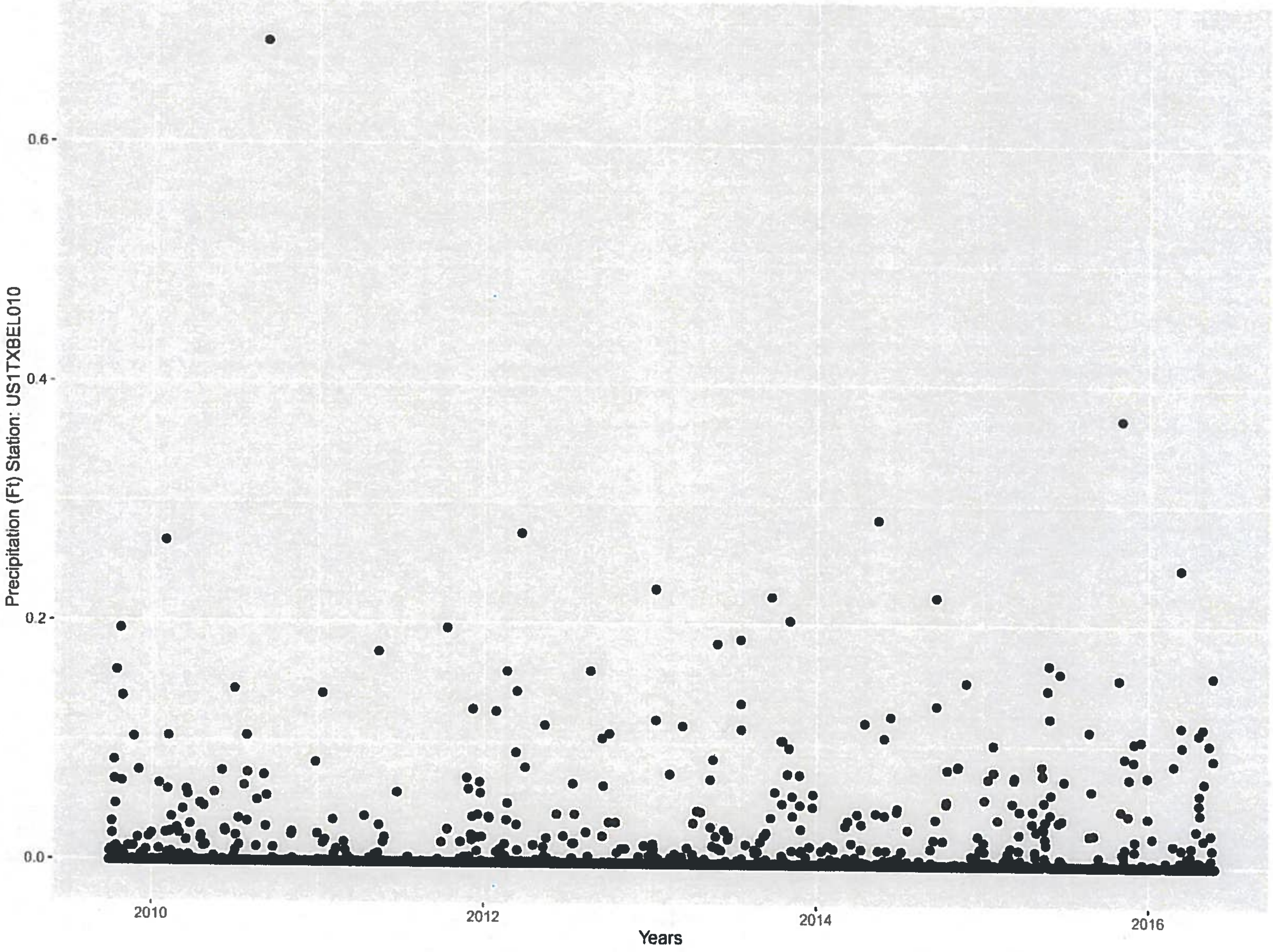
A.4: SWN 5804702 (Ft BGL) vs Time



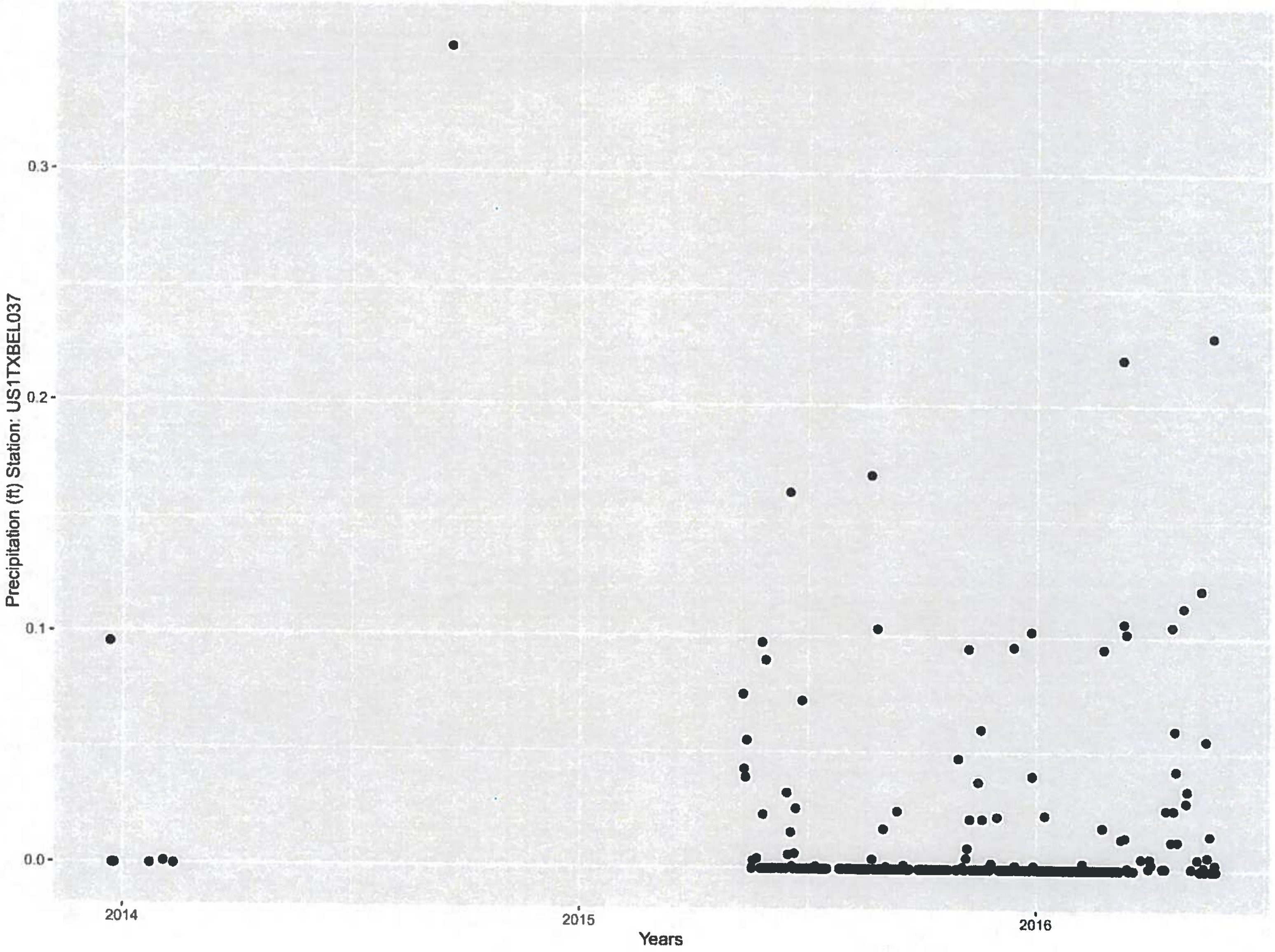
A.5: SWN 5804816 (Ft BGL) vs Time



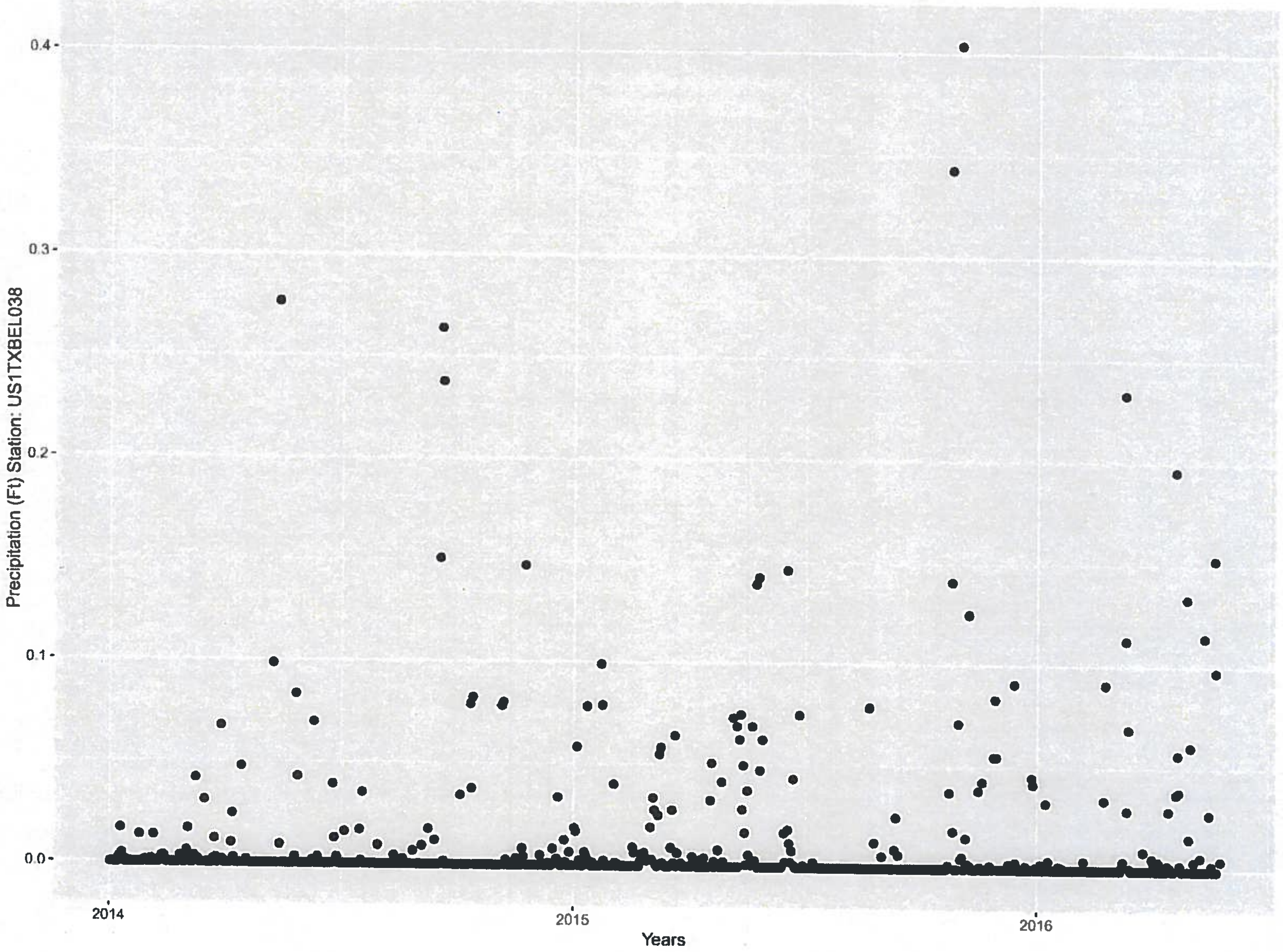
A.6: Precipitation (Ft) Station: US1TXBEL010 vs Time

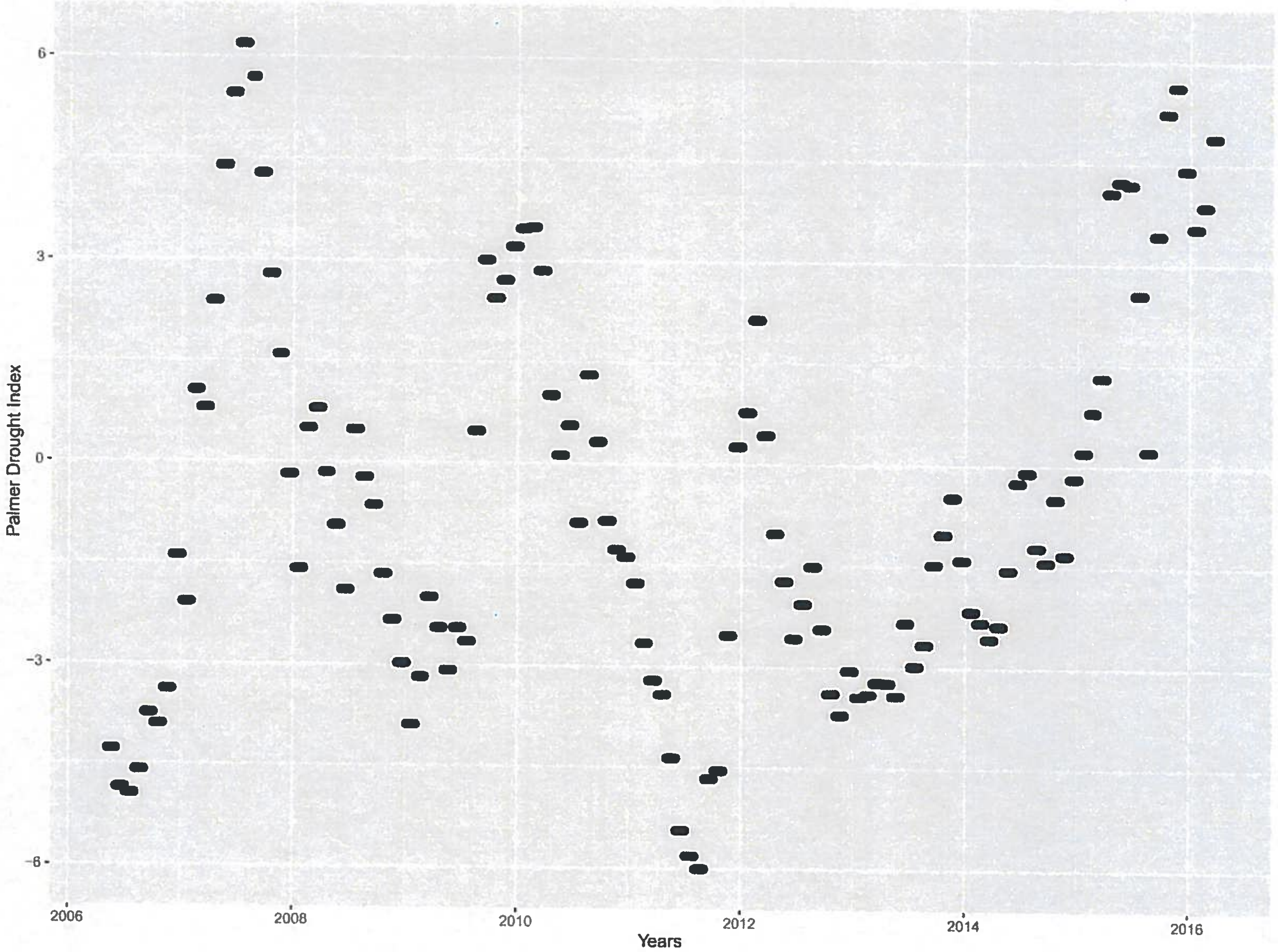


A.7: Precipitation (ft) Station: US1TXBEL037 vs Time



A.8: Precipitation (Ft) Station: US1TXBEL038 vs Time

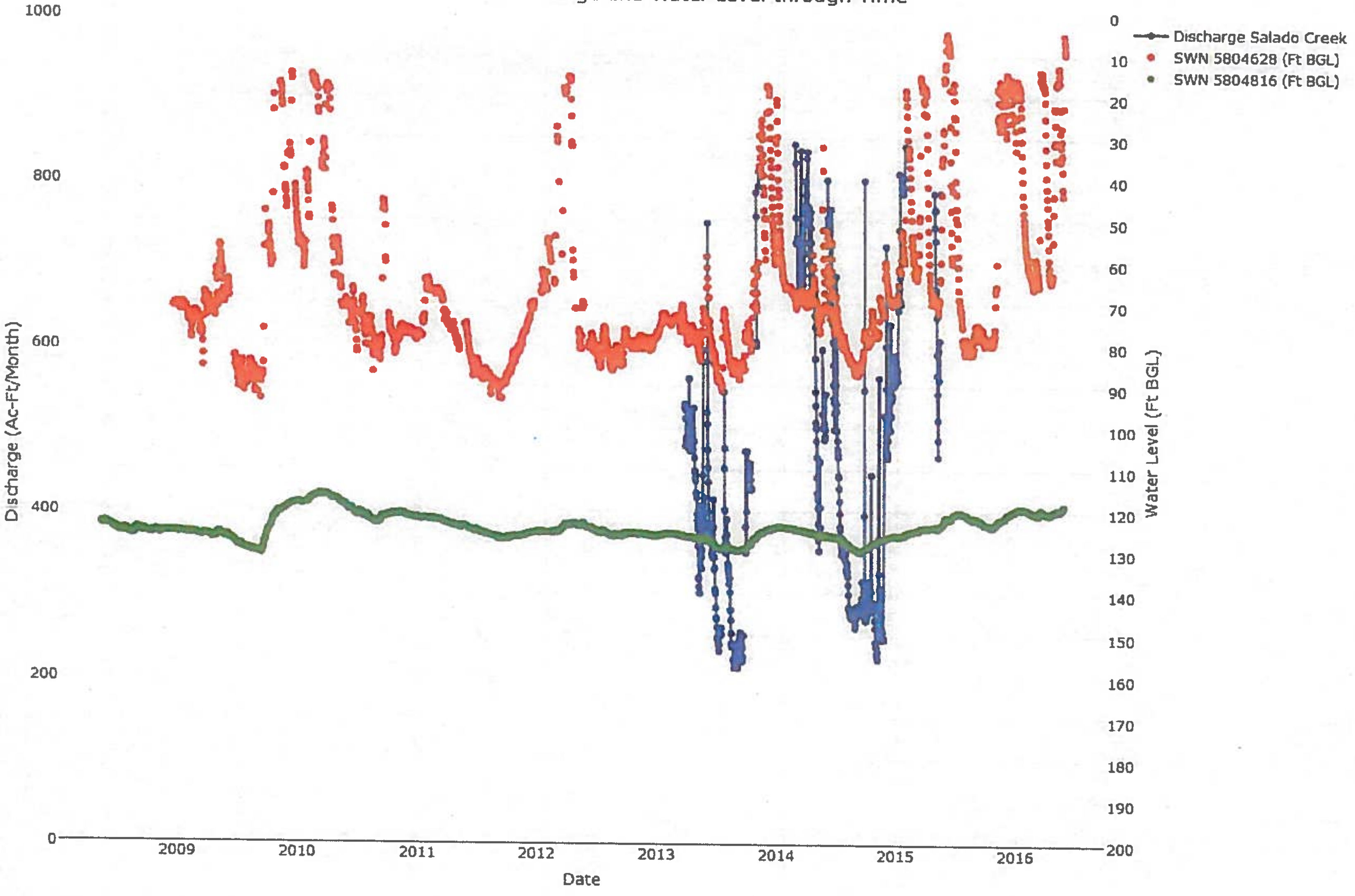




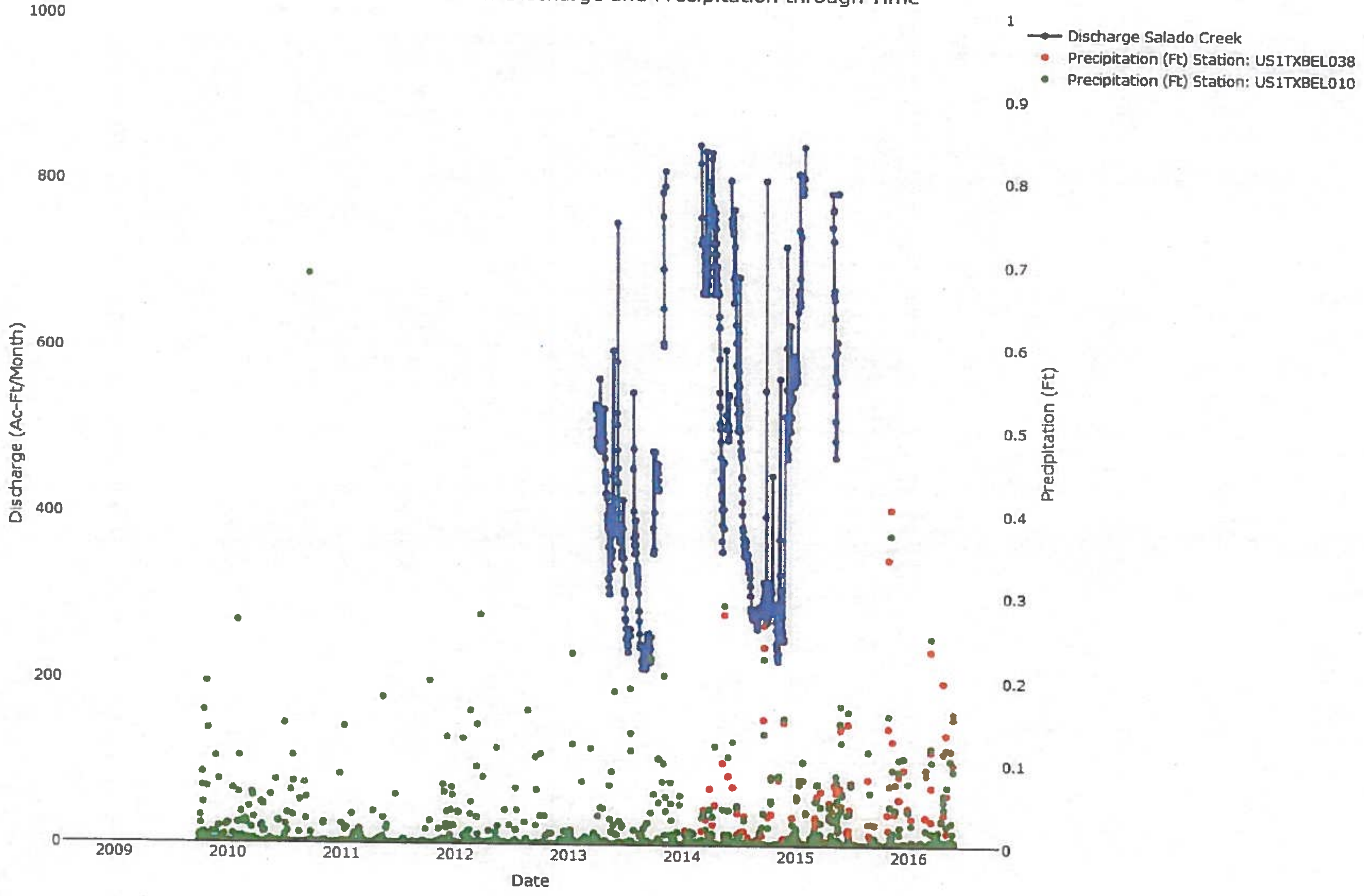
A.9: Palmer Drought Index vs Time

Attachment B – Charts of Discharge with other Hydrogeologic Parameters versus Time

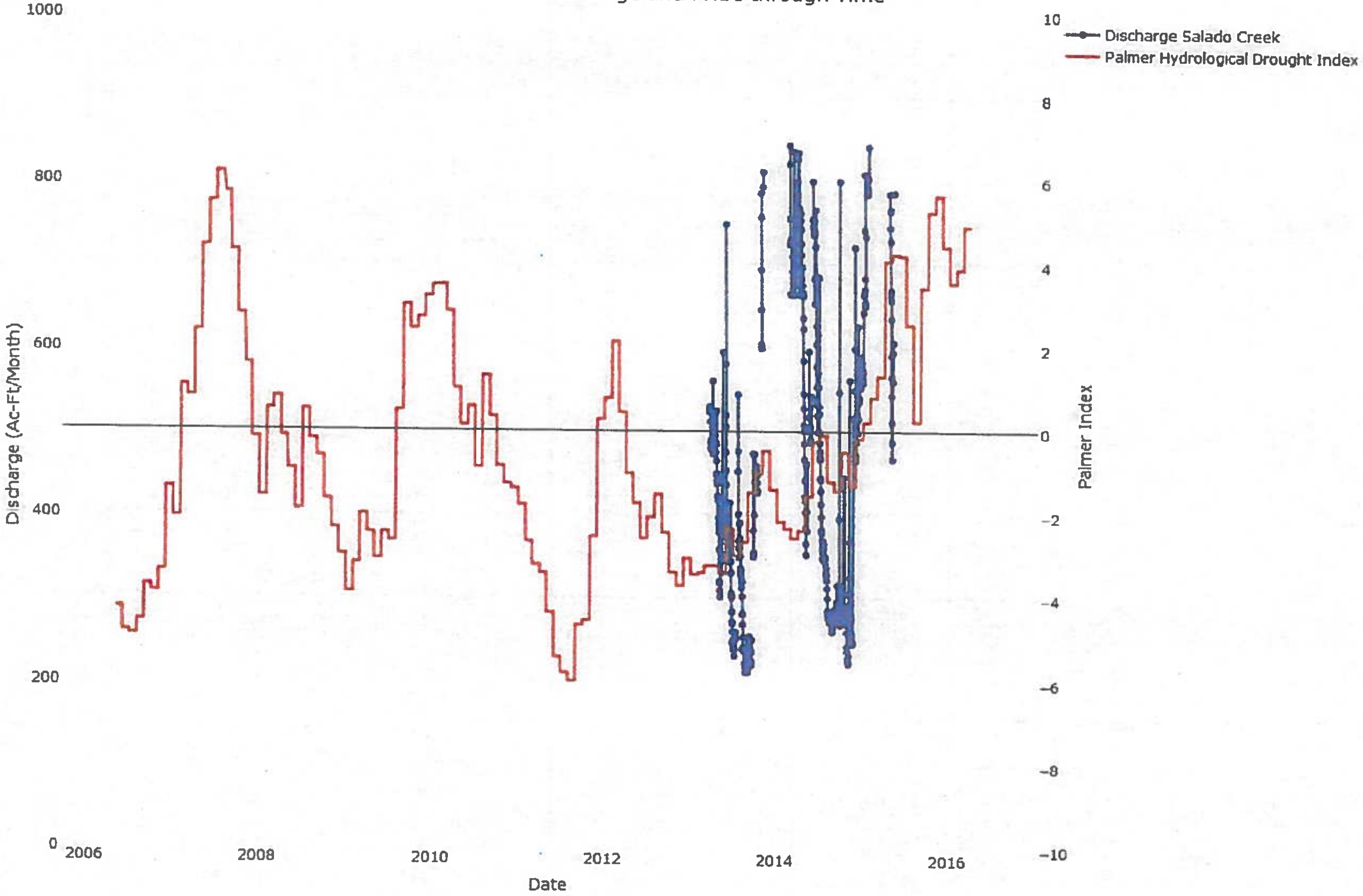
B.1: Discharge and Water Level through Time



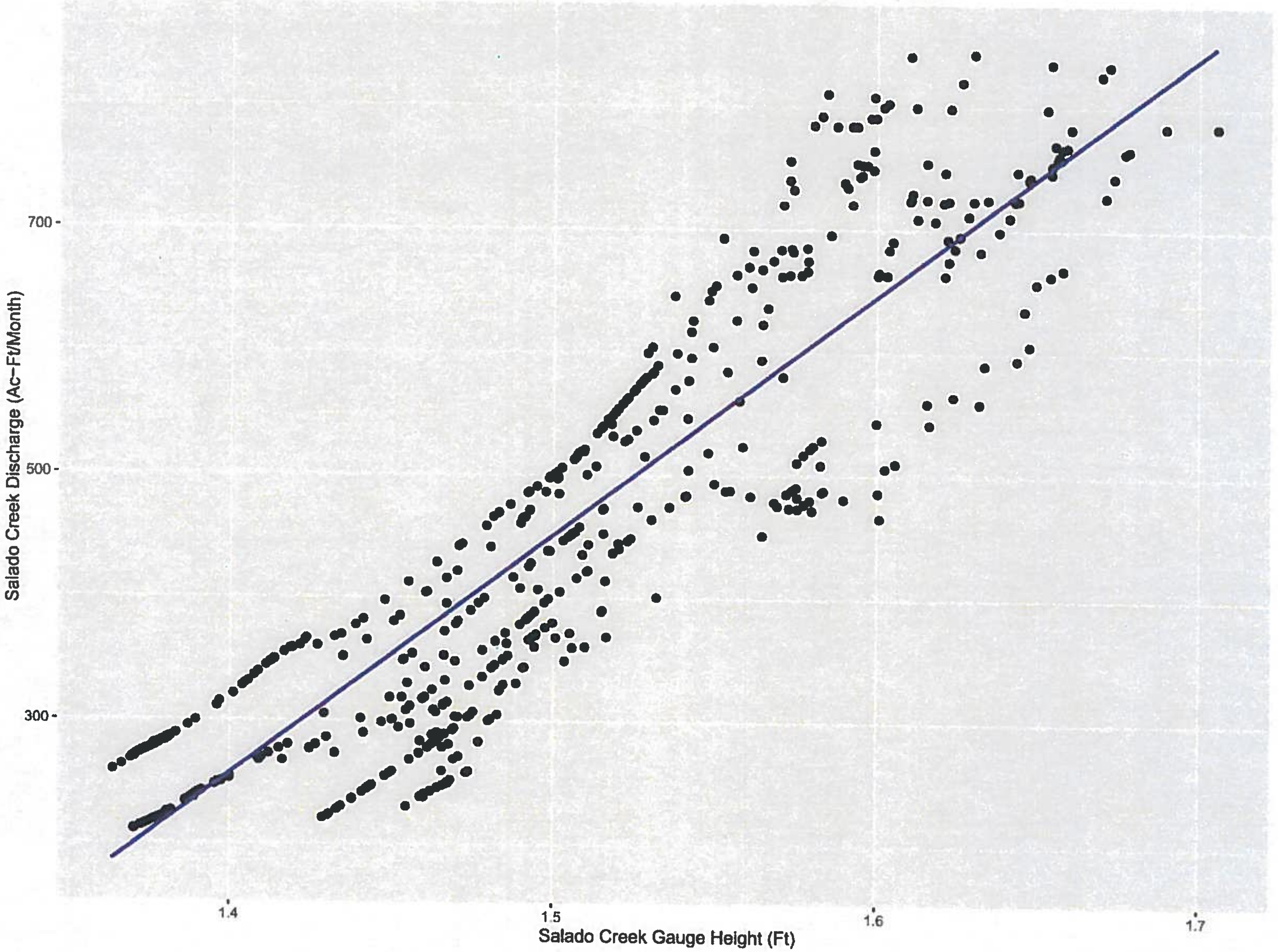
B.2: Discharge and Precipitation through Time



B.3: Discharge and PHDI through Time

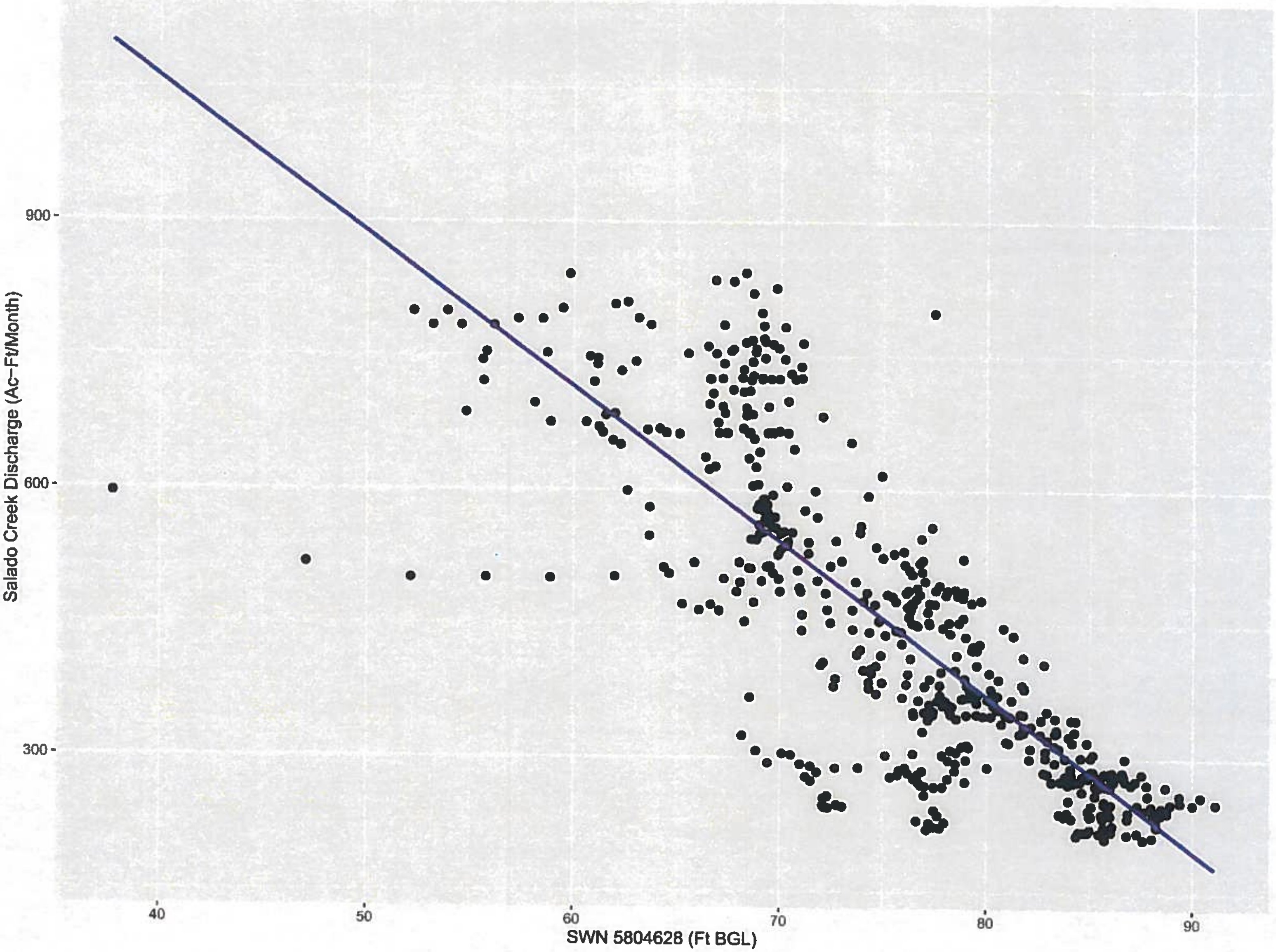


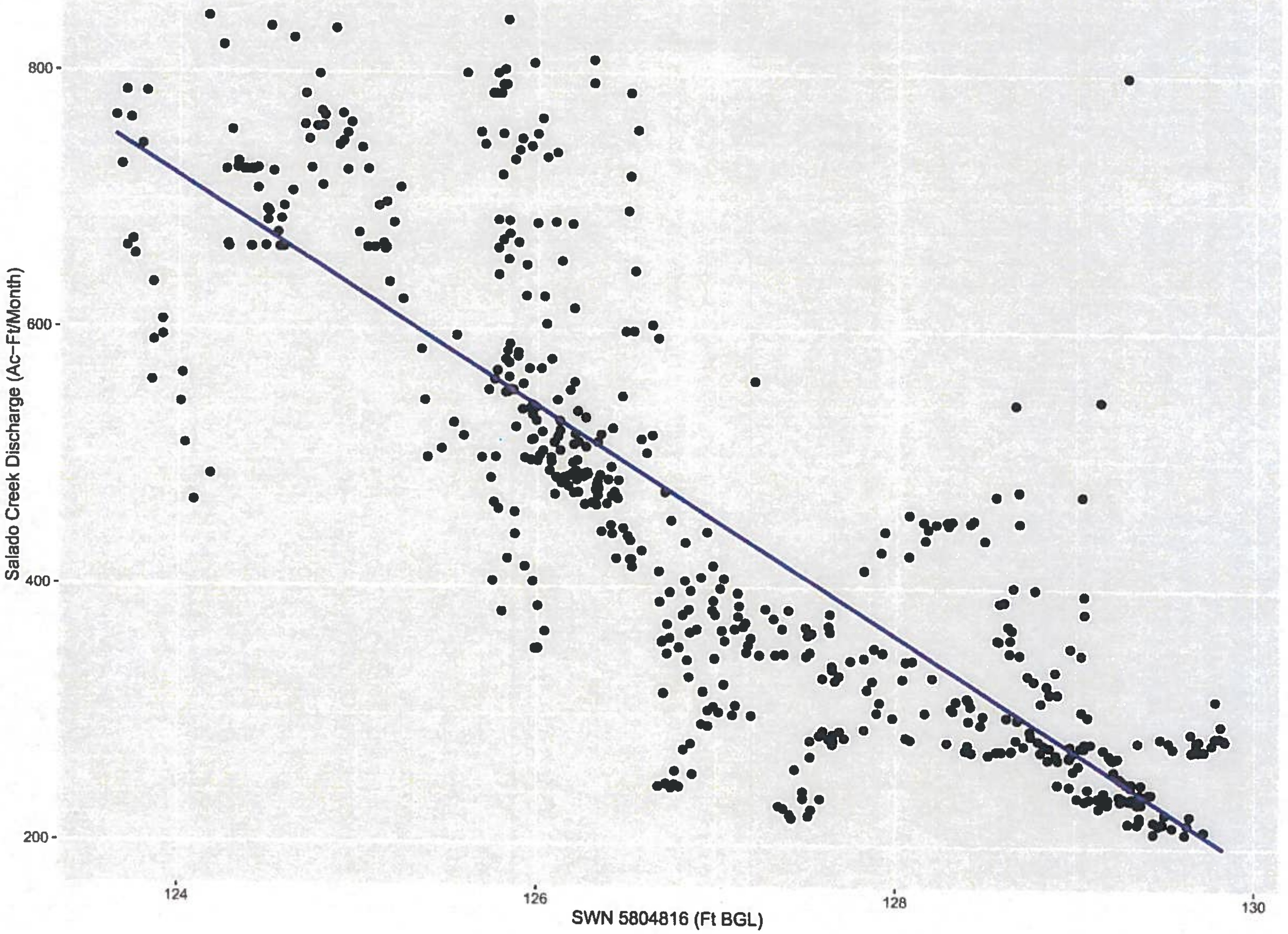
Attachment C – Cross-Plots of Salado Creek Discharge and Hydrogeologic Parameters



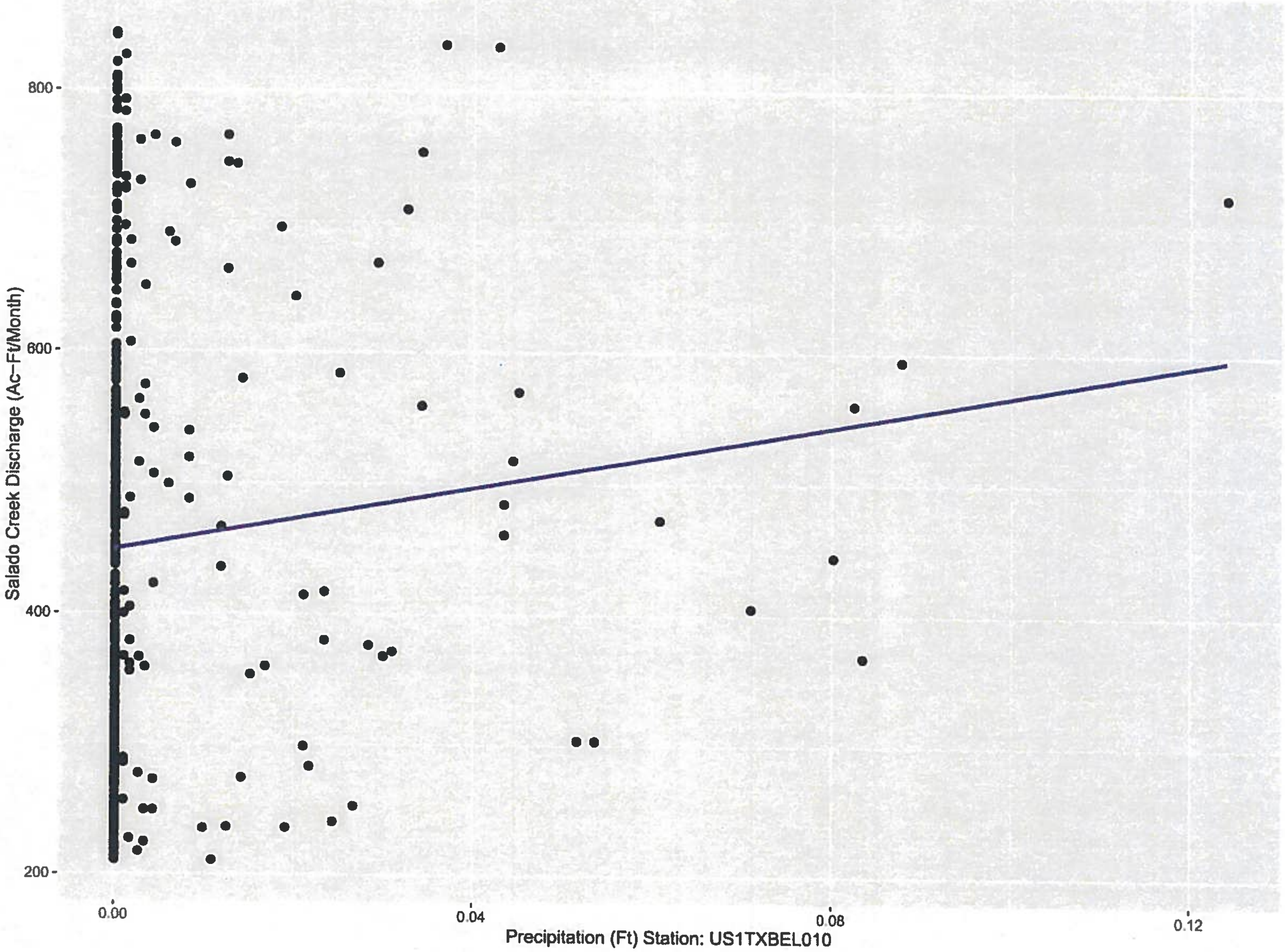
C.1: Adj R2 = 0.81702 Intercept = −2463.9 Slope = 1943.4

C.2: Adj R2 = 0.63684 Intercept = 1752.9 Slope = −17.294

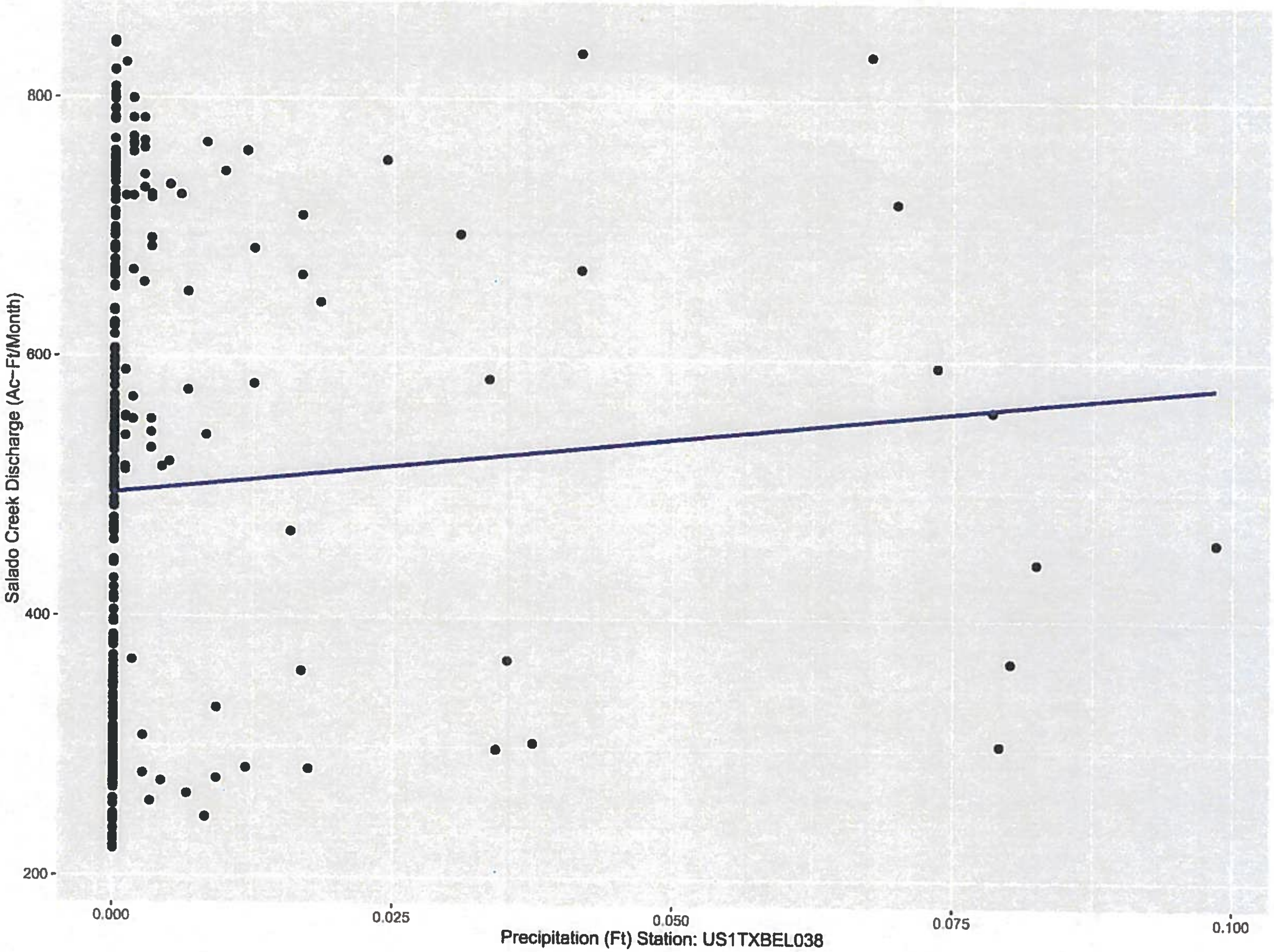




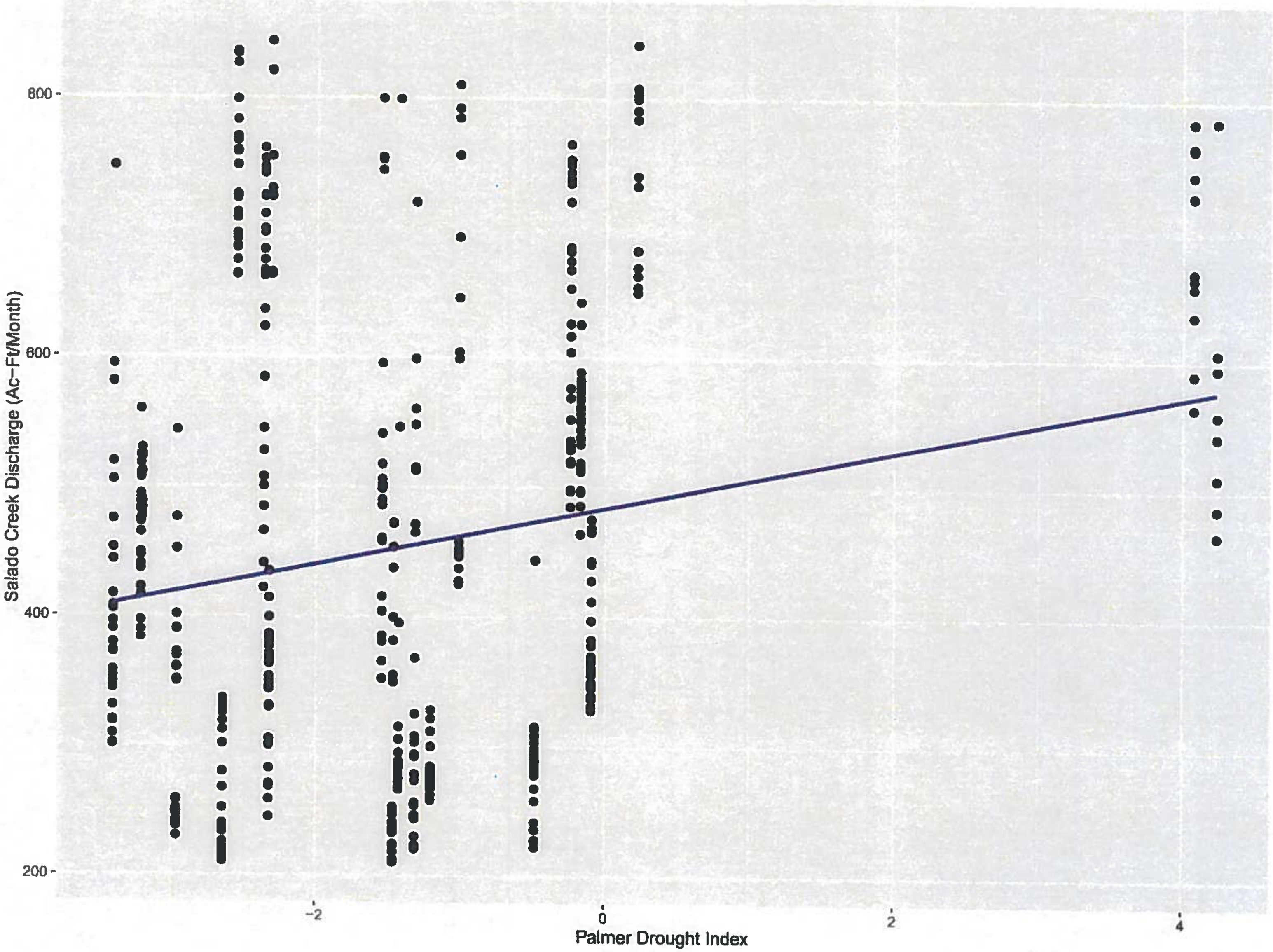
C.3: Adj R2 = 0.6674 Intercept = 11767 Slope = −89.095



C.4: Adj R2 = 0.0048304 Intercept = 448.64 Slope = 1189.3



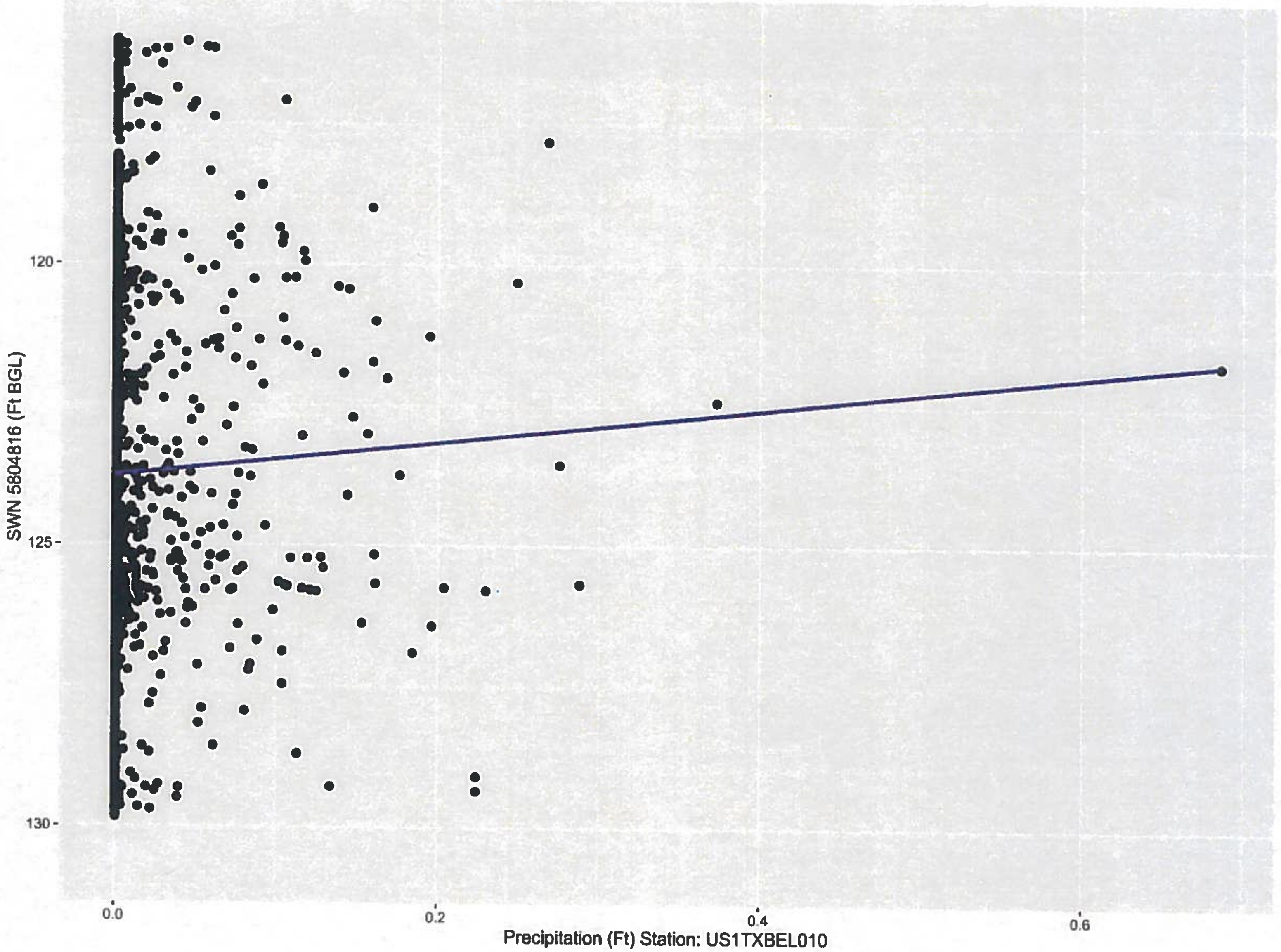
C.5: Adj R2 = 0.00073328 Intercept = 495.39 Slope = 855.59



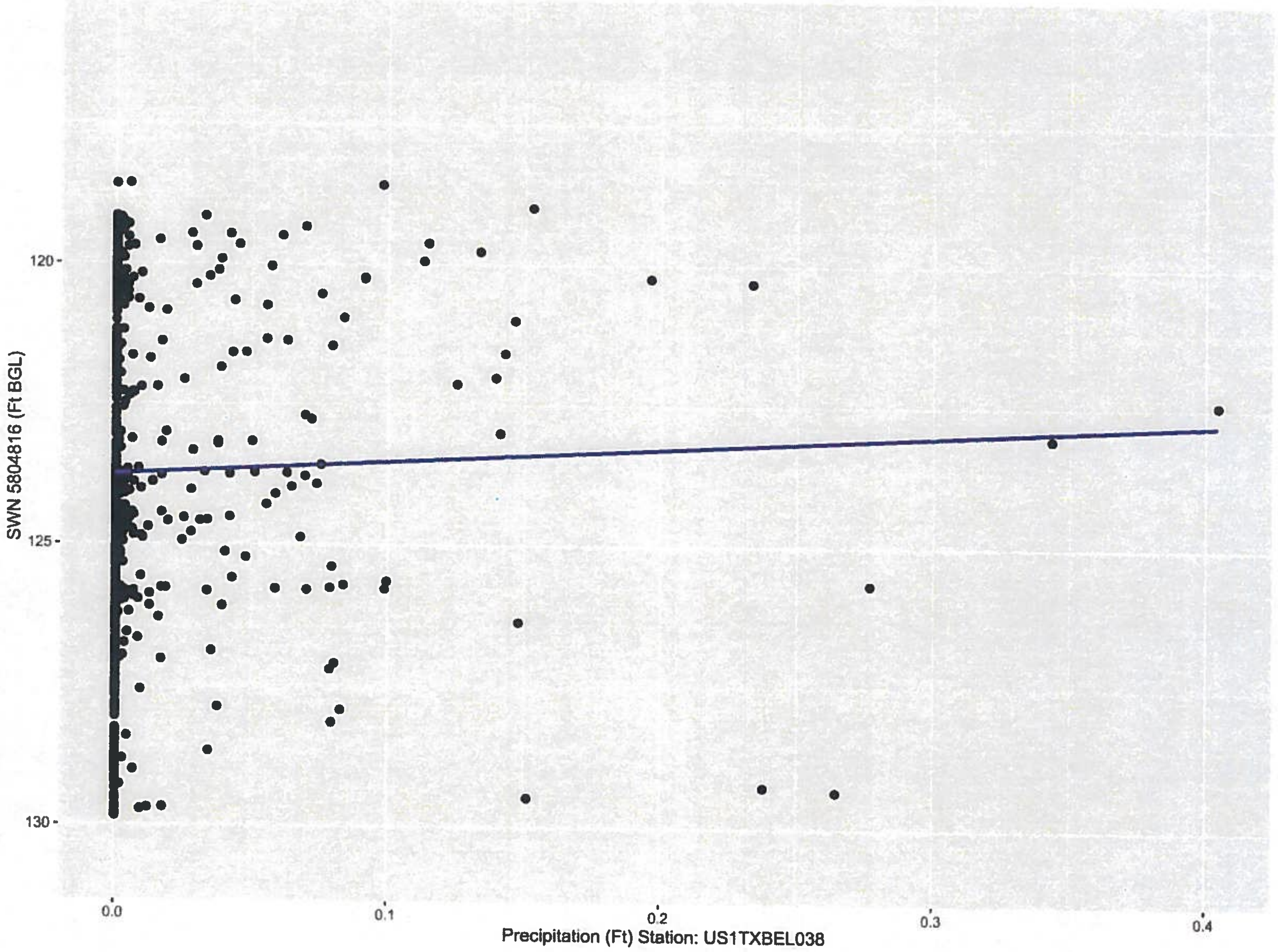
C.6: Adj R2 = 0.034569 Intercept = 484.2 Slope = 21.893

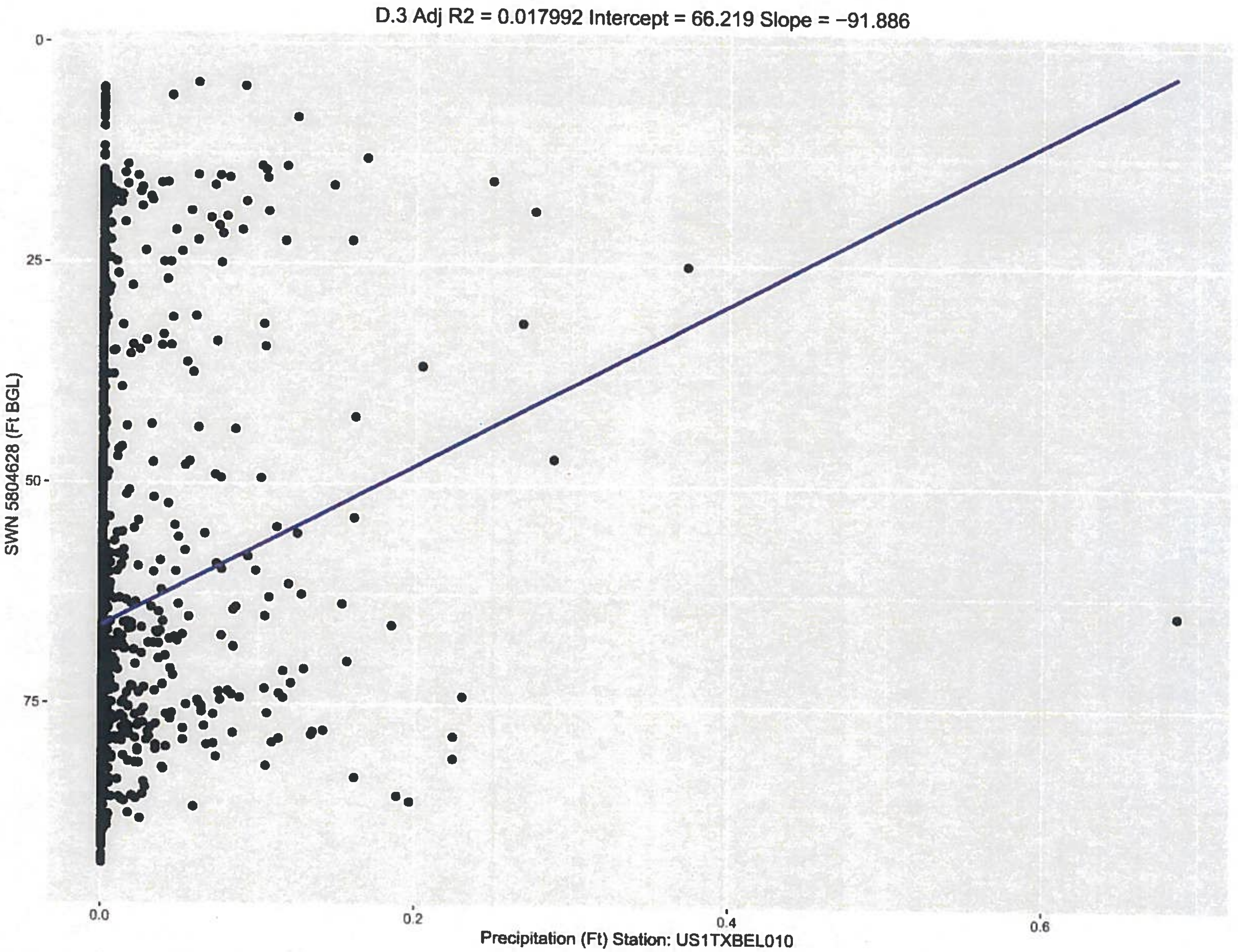
Attachment D – Charts of Precipitation versus Water Levels in Wells

D. 1 Adj R2 = 0.00044926 Intercept = 123.76 Slope = −2.9722

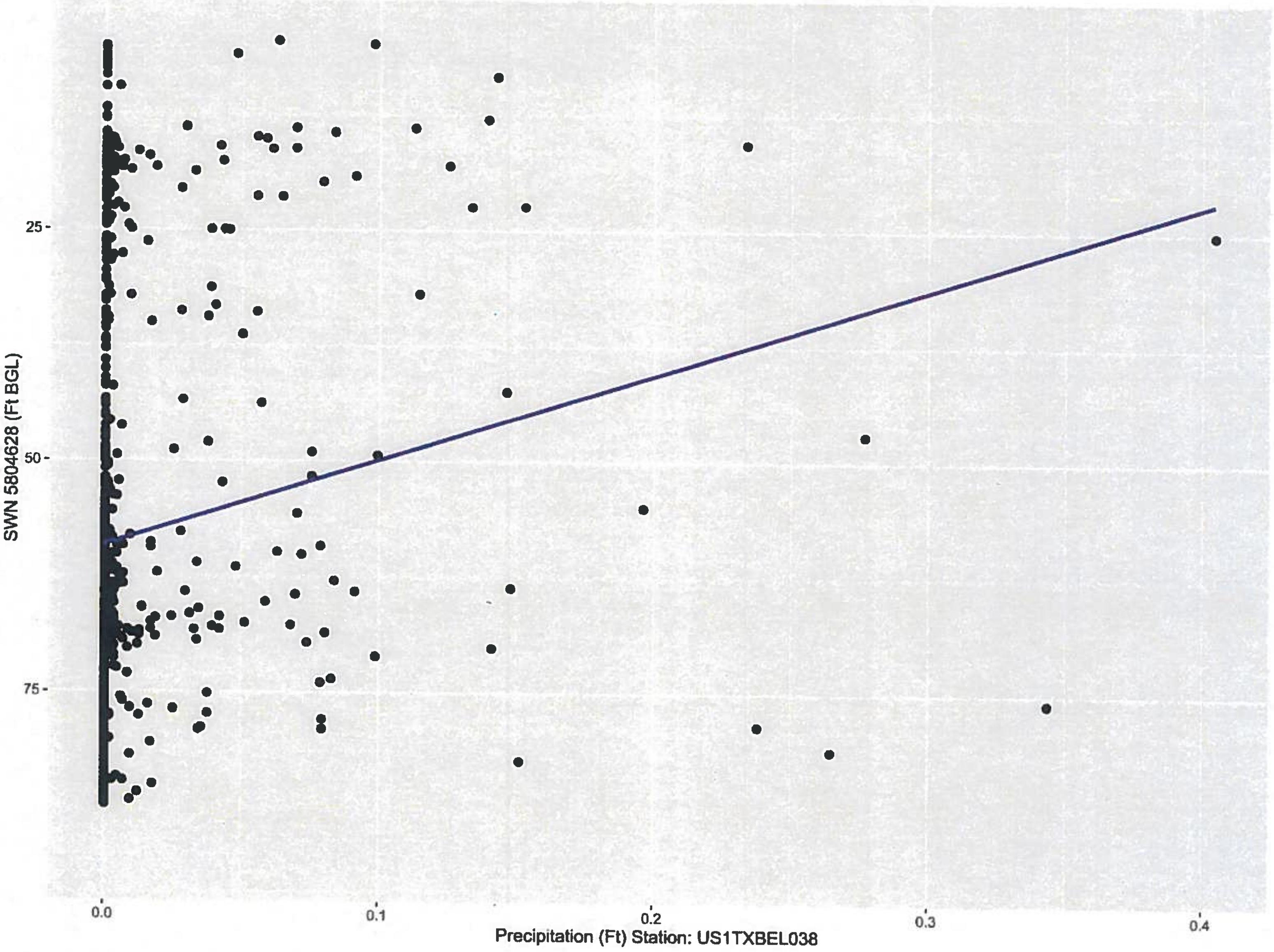


D. 2 Adj R2 = −0.00038035 Intercept = 123.75 Slope = −2.3984

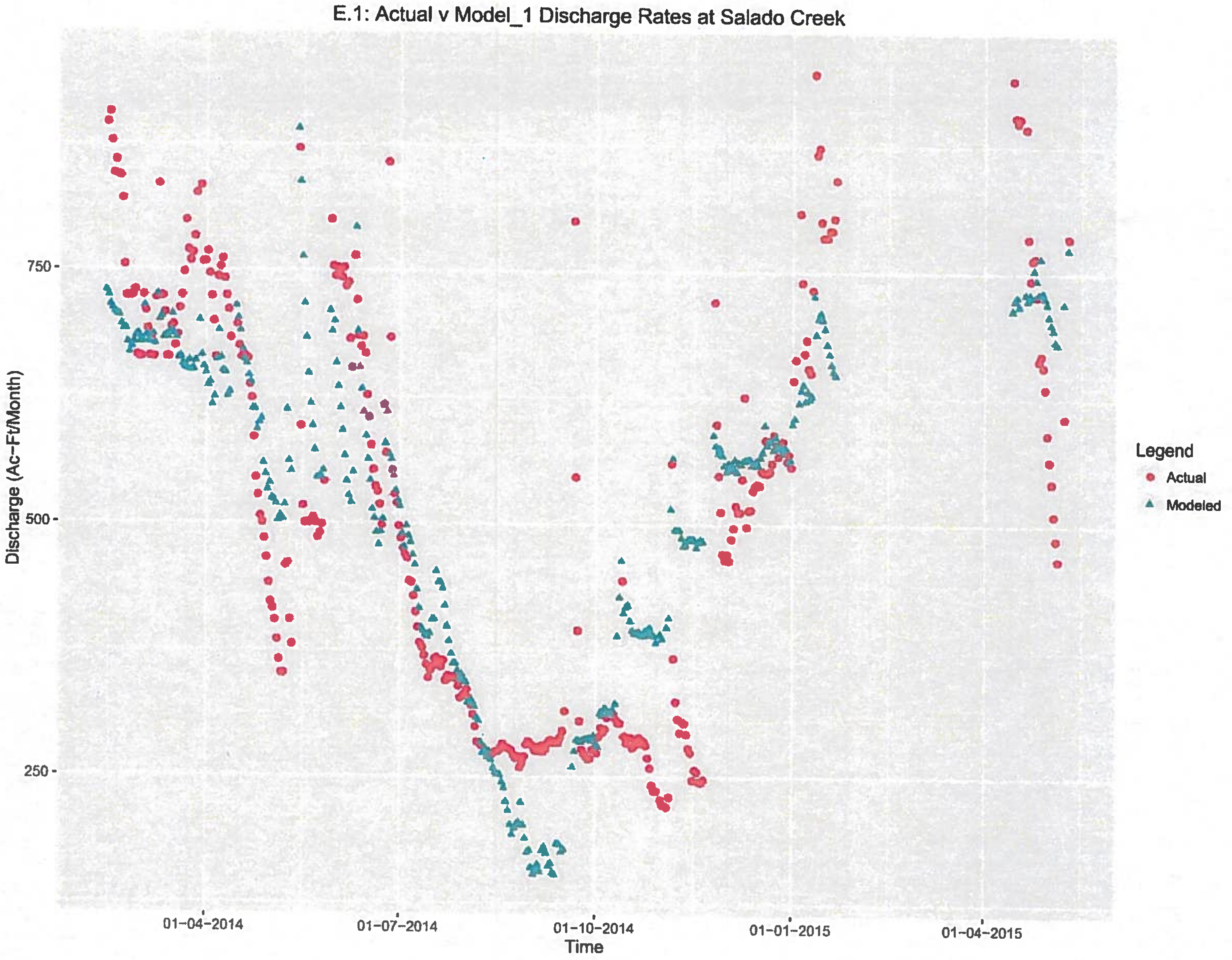



D.3 Adj R2 = 0.017992 Intercept = 66.219 Slope = −91.886

D.4 Adj R2 = 0.01802 Intercept = 59.109 Slope = −92.395

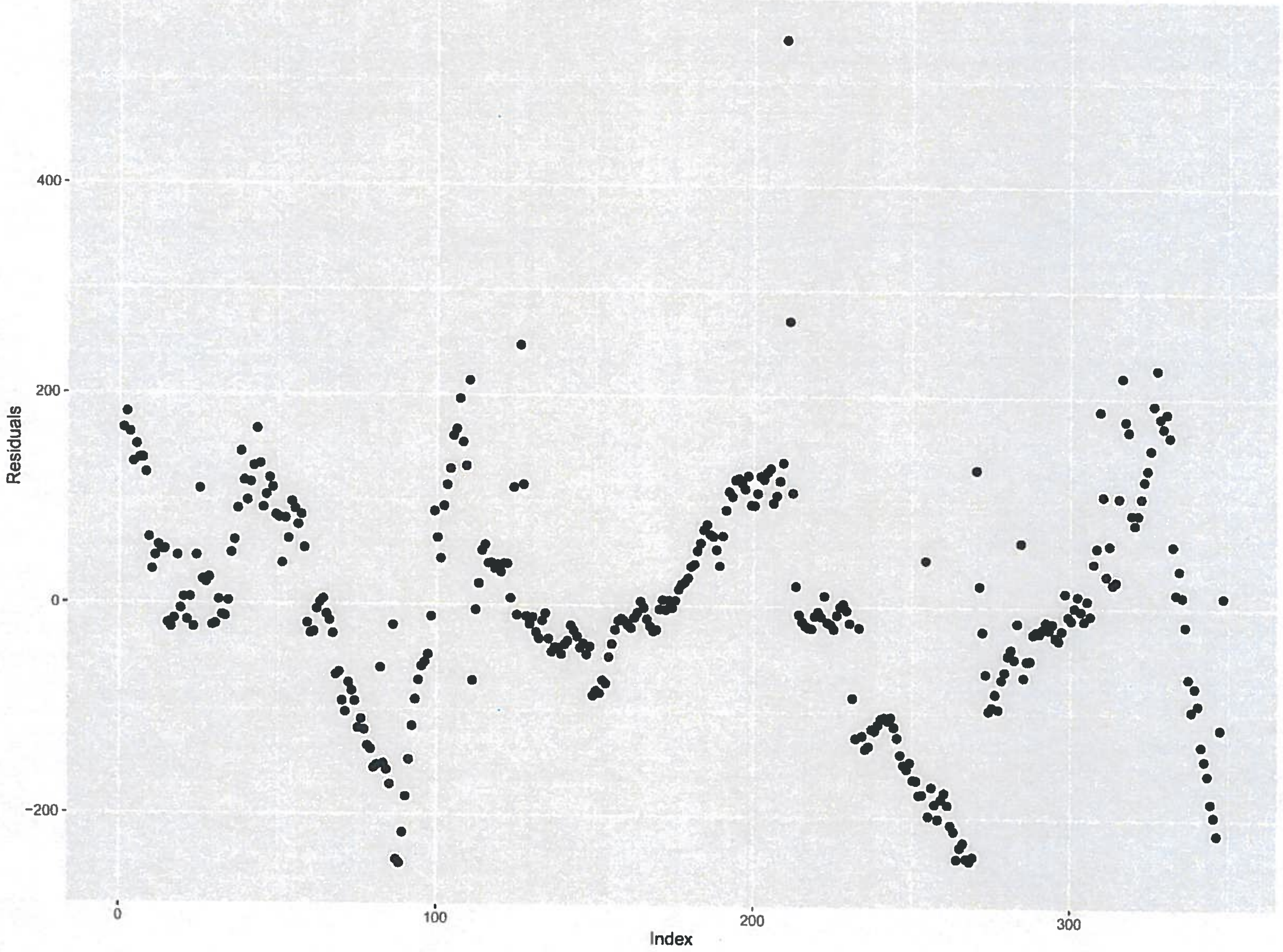


Attachment E – Results of the Four Potential Multilinear Models

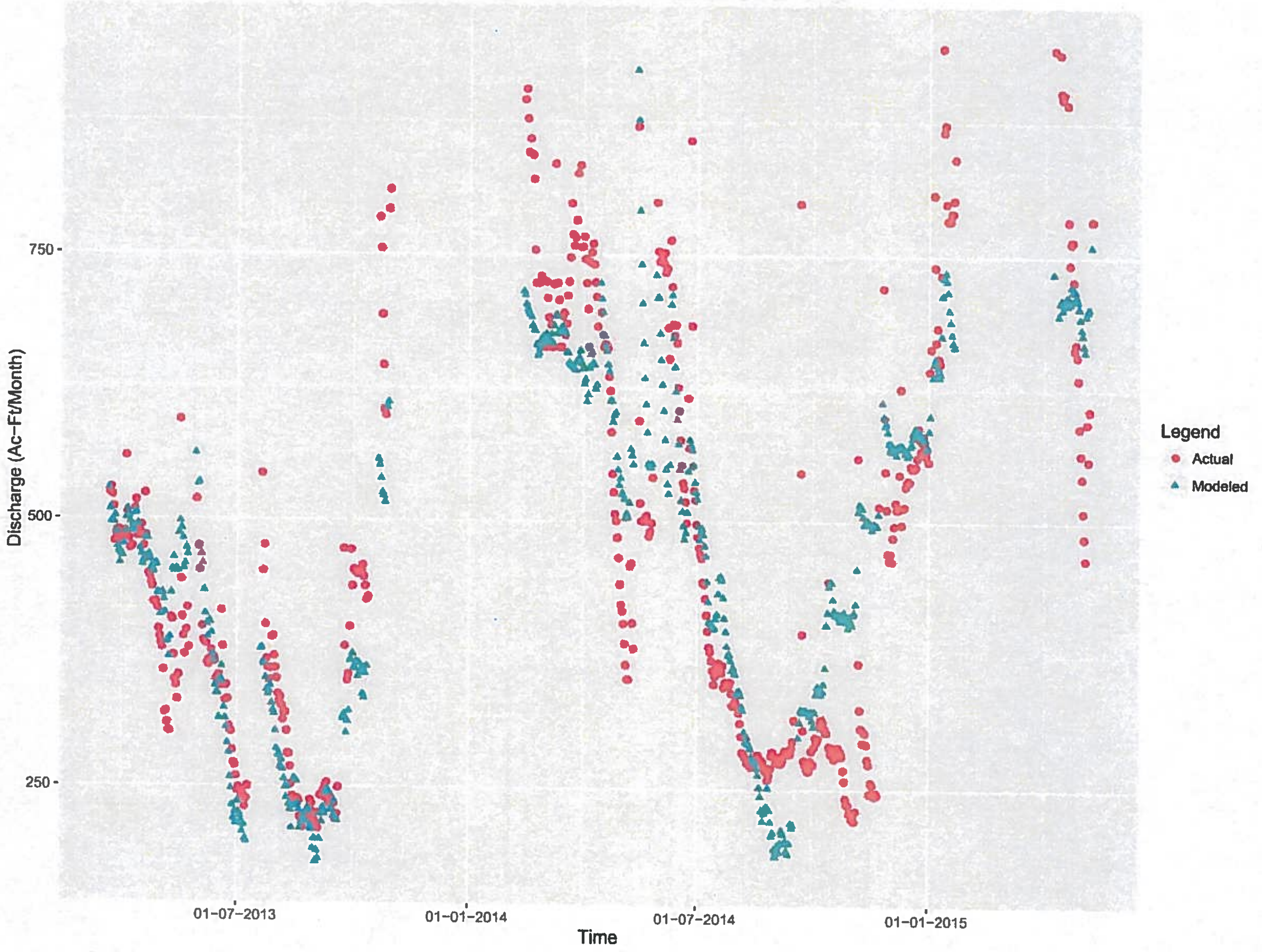


E.1: Actual v Model_1 Discharge Rates at Salado Creek

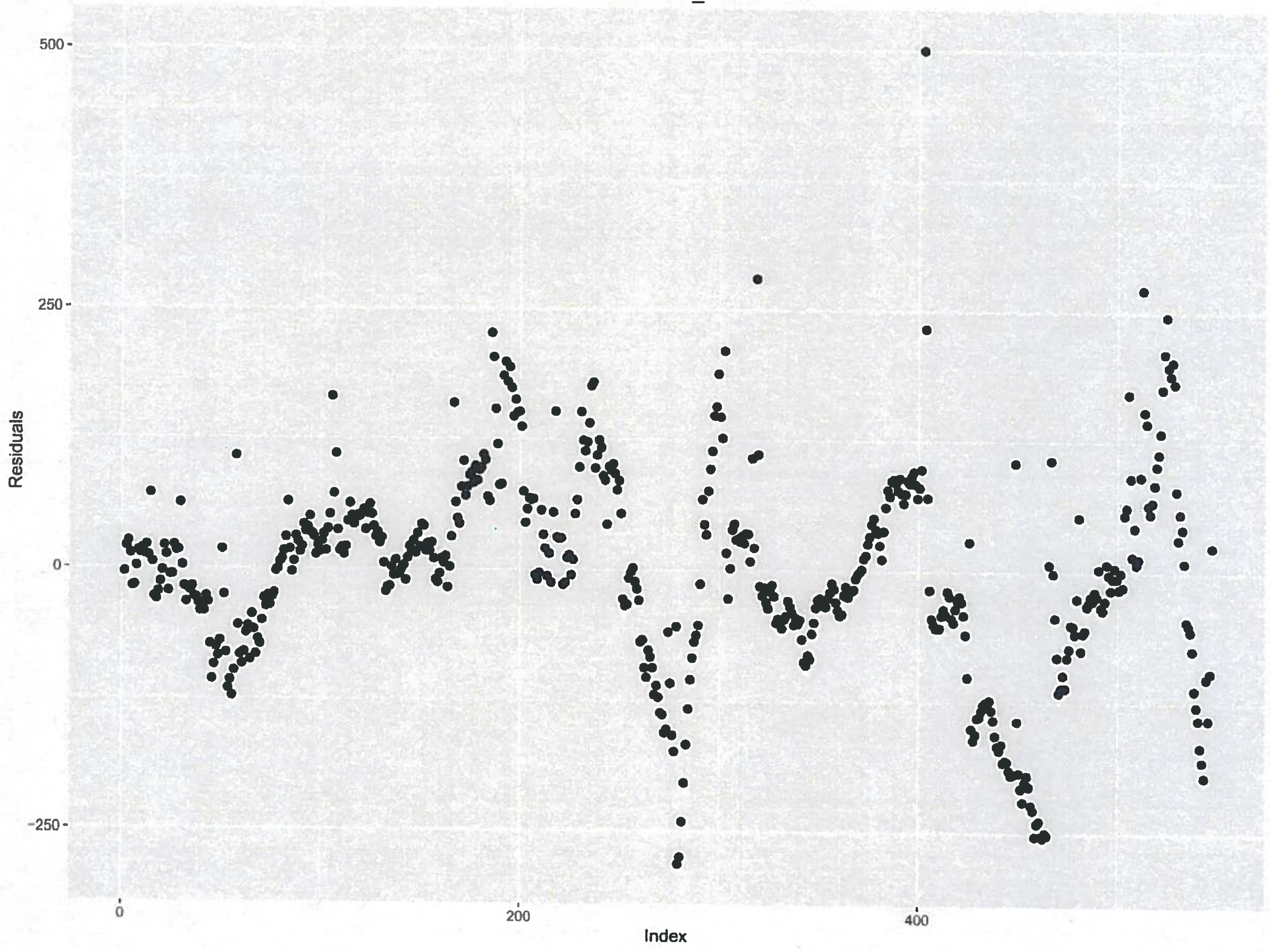
E.2: Plot of Model_1 Residuals

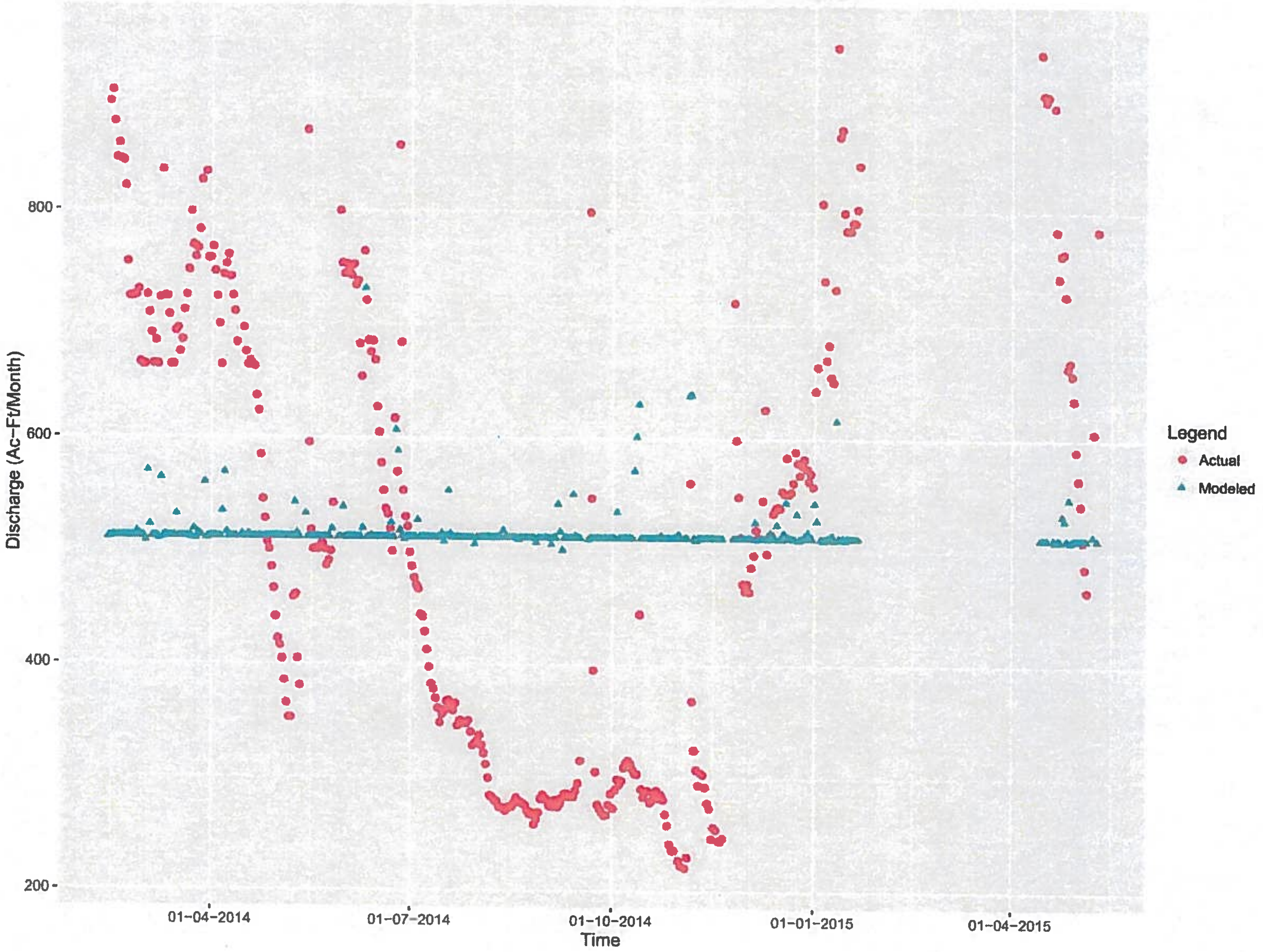


E.3: Actual v Model_2 Discharge Rates at Salado Creek



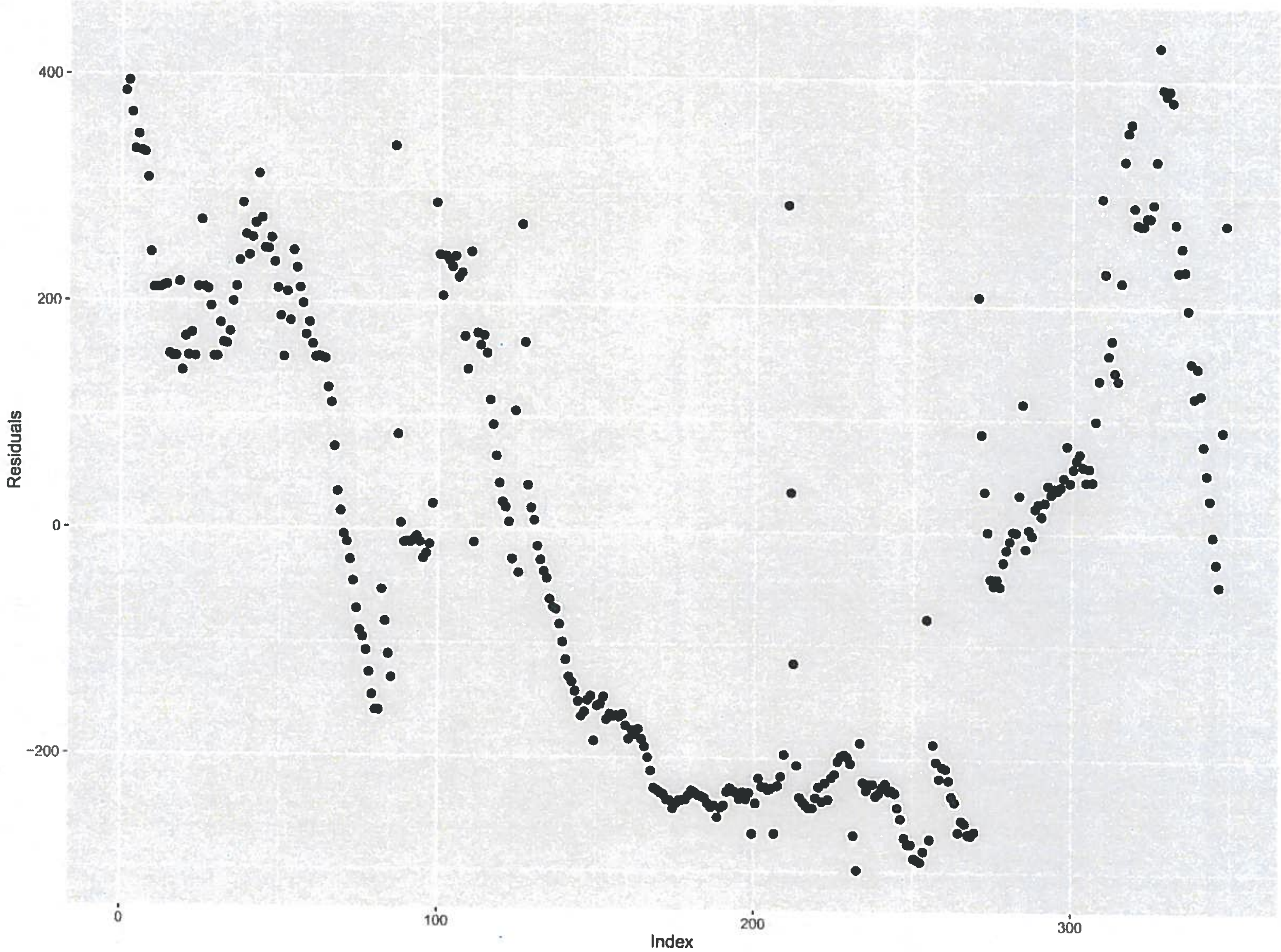
E.4: Plot of Model_2 Residuals

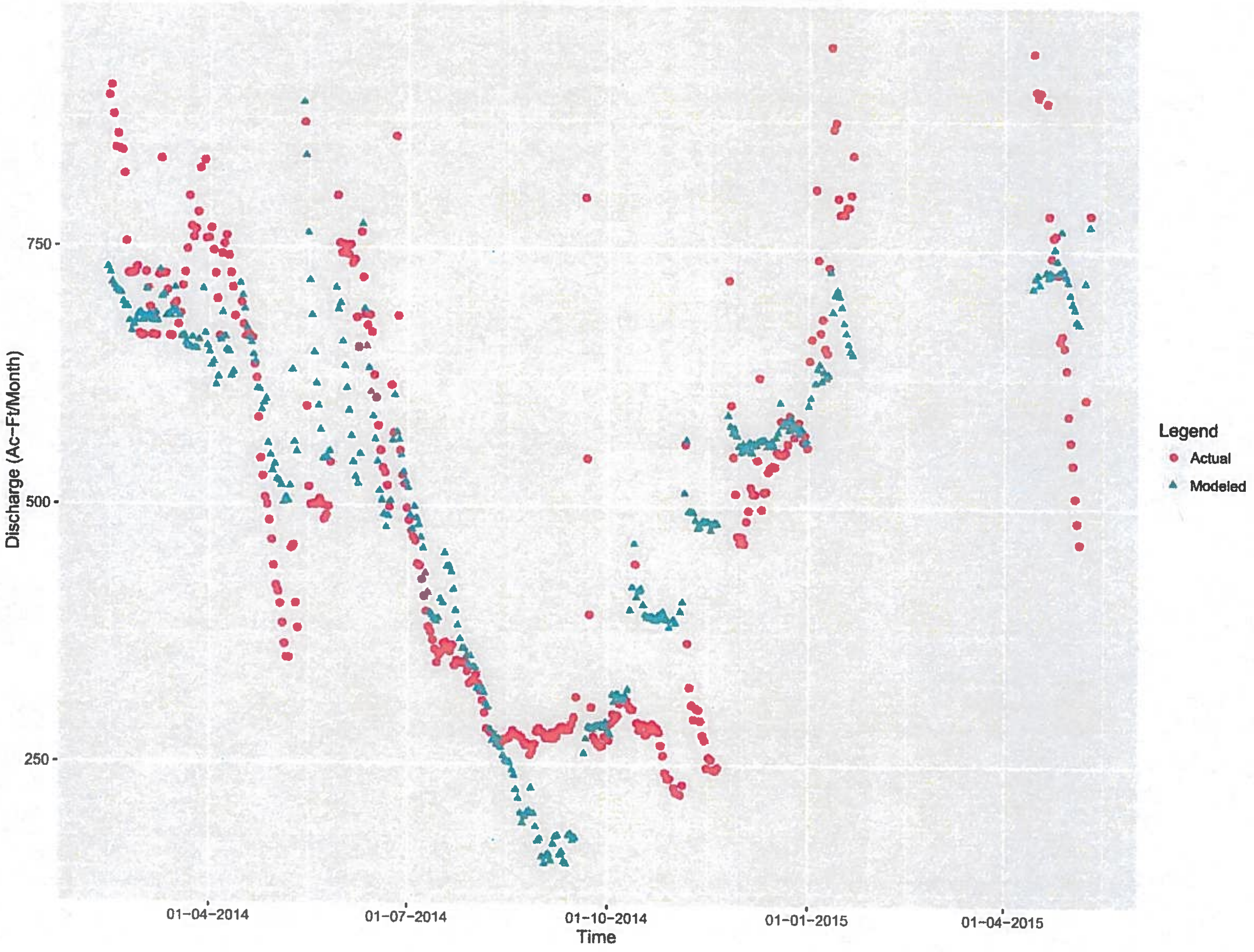




E.5: Actual v Model_3 Discharge Rates at Salado Creek

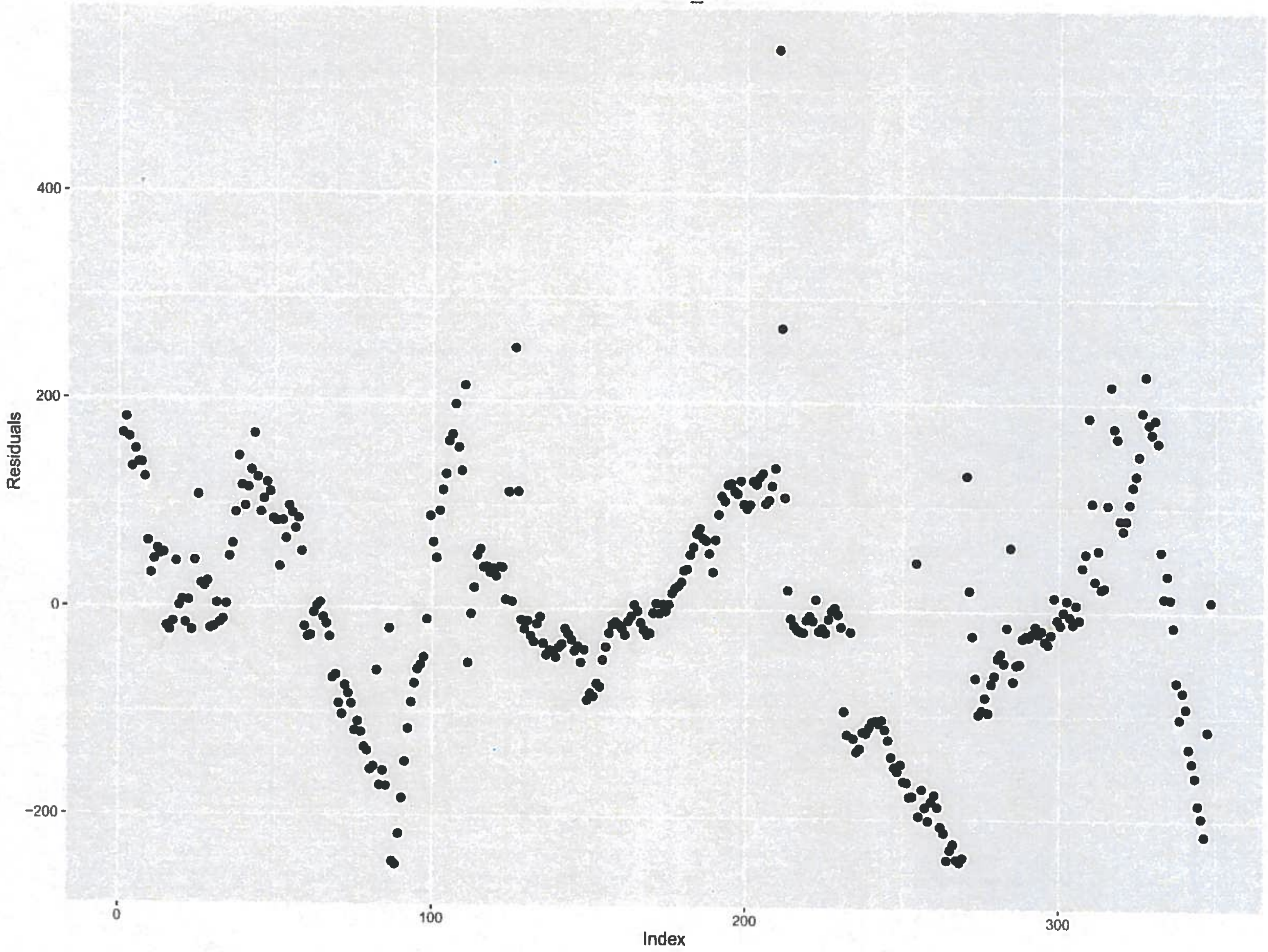
E.6: Plot of Model_3 Residuals





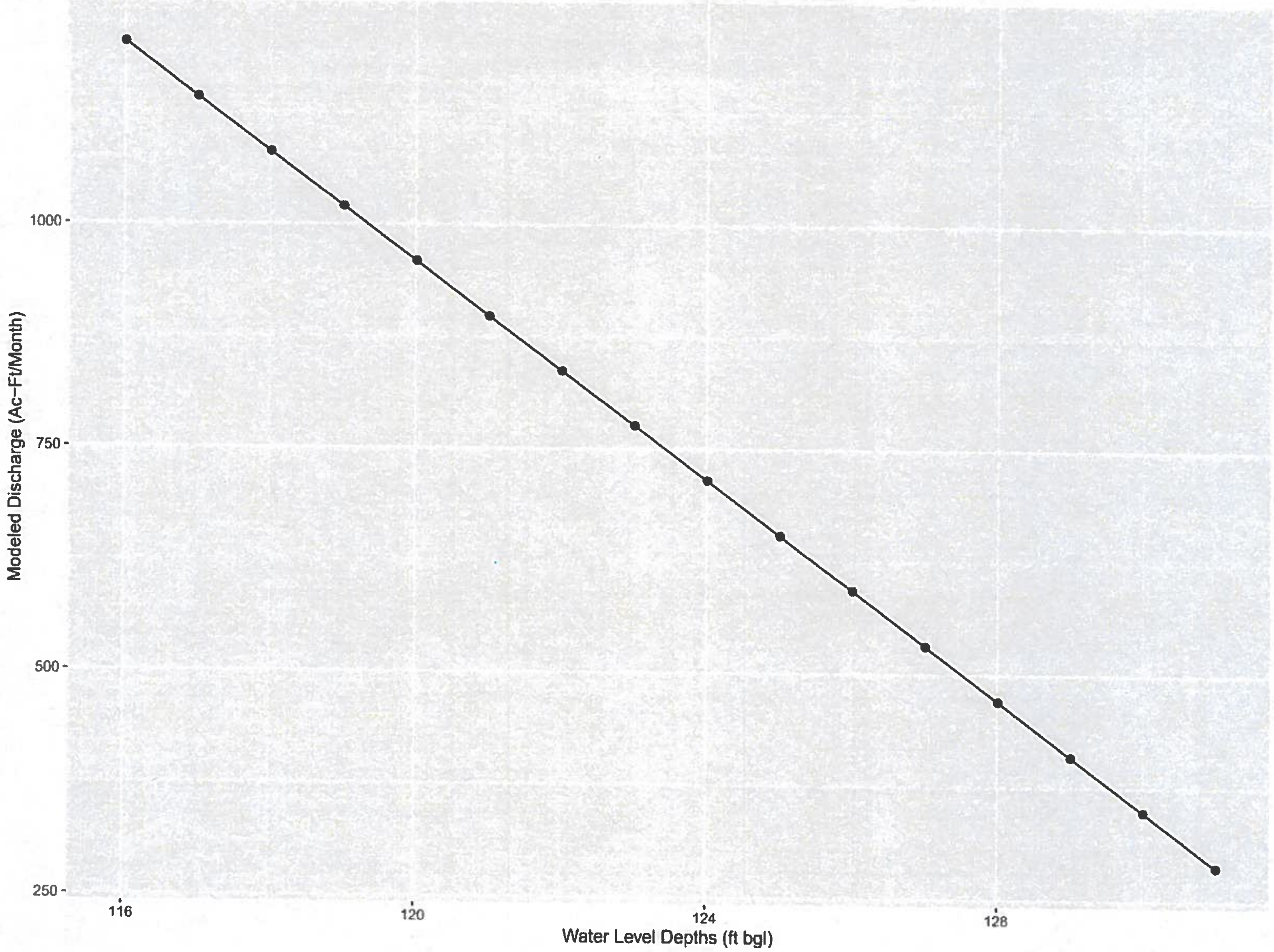
E.7: Actual v Model_4 Discharge Rates at Salado Creek

E.8: Plot of Model_4 Residuals

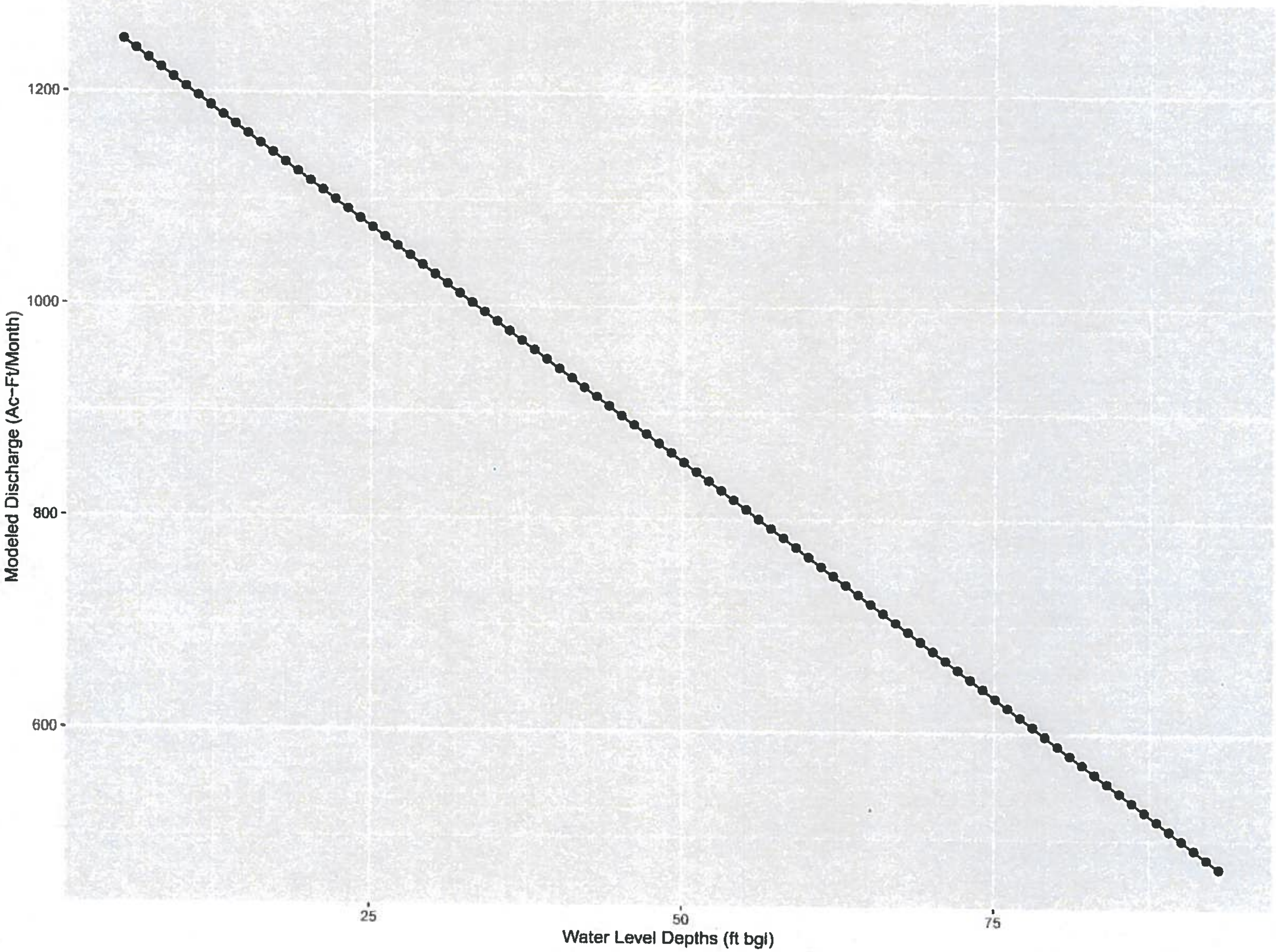


Attachment F – Multilinear Model 2 Stress Test Results

F.1: Stress Test of Modeled Discharge Rate:SWN 5804816



F.2: Stress Test of Modeled Discharge Rate:SWN 5804628



F.3: Stress Test of Modeled Discharge Rate