EFFECTS OF DRAWDOWN ON WATER QUALITY AND TEMPERATURE IN DUKE UNIVERSITY'S CHILLER POND

by

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ABSTRACT

The Duke Pond (or chiller pond) collects runoff from 20% of the Duke University campus and serves as a water source to the adjacent evaporative cooling plant. Due to frequent water withdrawals from the chiller plant, the water levels are expected to fluctuate anywhere from one to four feet daily (1.22 m). This project aims to (1) calculate a water budget for the pond, (2) determine the effects of fluctuating water levels on various water quality parameters, (3) assess whether the pond is compliant with state water quality standards, and (4) determine whether the stream temperature is significantly different at the inflow versus the outflow to the pond. An additional goal was to develop a GIS tool that estimates the annual sediment yield from the Duke pond's watershed using the Universal Soil Loss Equation (USLE).

After the pond stabilized I found that dissolved oxygen, pH, temperature, and specific conductance decrease with increasing water levels in the pond. The temperature is not significantly different at the outflow compared to the inflow stream. For the majority of the 8-month sampling period, dissolved oxygen and pH remain compliant with the state standards. Chlorophyll-a had one occurrence where it exceeded the standard. The USLE tool accurately delineates the watershed for the pond and calculates an annual sediment loss of 168.2 lb/ac/yr.

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EXECUTIVE SUMMARY

The Duke Pond (or chiller pond) was constructed in 2015 to supply water to the Duke Chilled Water System plant #2, to be used for evaporative cooling for the campus buildings. It collects stormwater runoff from approximately 20% of the campus. The Duke University Wetland Center was contracted to perform monitoring activities as required by the state of North Carolina. Due to frequent withdrawals by the chiller plant, Duke Facilities Management (FMD) needed to know how fluctuating water levels affect water quality in the pond. Additionally, I determined whether the existence of the pond significantly changes the temperature of the outflowing stream and determined the feasibility of using the Universal Soil Loss Equation to model sediment loss in this highly urbanized watershed.

Water quality data collection was via a multi-parameter sonde suspended at a fixed point at the surface of the pond taking measurements in 15-minute intervals of dissolved oxygen, pH, temperature, and specific conductance. Flow meters at the inflow and outflow streams were used in determining the water budget. Water level data, and monthly depth-integrated samples all were collected from June 2015 to January 2016. To model sediment, I created a tool in ArcMap 10.3 that takes a user-specified point, delineates the upstream contributing area, and uses USLE to calculate annual soil loss in that area in lb/ac/year.

I found that increasing water level results in a decrease in dissolved oxygen, pH, temperature, and specific conductance. The stream temperature is not significantly different at the outflow compared to that at the inflow. The pond's dissolved oxygen concentrations, pH, and chlorophyll-a concentrations remain compliant with the state water quality standards for the majority of the sampling period. There was one chlorophyll-a violation in September 2015 that I believe is attributed to a large storm producing heavy sediment runoff from an upstream construction site. This sudden influx of sediment brought with it nutrients that augmented algal blooms.

The USLE GIS tool produced a watershed very similar to that determined by FMD and determined the annual soil loss to equal 168.2 lb/ac/yr. With a full year of sediment input data, the tool can be validated for its accuracy at predicting annual sediment yield. A comparison of annual sediment yield for watersheds of similar size and land use gave inconclusive results in determining accuracy.

Since we now know that water level affects dissolved oxygen, pH, temperature, and specific conductance, future directions for FMD are to determine if a water level threshold exists at which a specific water level leads to adverse water quality. Then, they will be able to utilize the dam at the outflow structure to ensure that this level is not exceeded. This will be an important step if they would like aquatic life to flourish in the pond, adding to its recreational value. Finally, further flow and nutrient sampling will be needed now that the pond is stabilized to create a nutrient budget to determine the fate of nitrogen and phosphorus in the pond, and to eventually determine the pond's eligibility for nutrient credits.

Introduction

Duke University is the largest potable water consumer in the City of Durham, its use totaling 645 million gallons in 2006. The Duke Chilled Water System plant #2 (or chiller plant) accounts for 30% of this use, totaling approximately 1 million gallons per day (Caldwell, 2013). In order to reduce the amount of potable water consumed for non-potable uses, Duke Facilities Management (FMD), along with the State of North Carolina and Duke University Wetland Center (DUWC) implemented a reclamation pond project that will collect runoff from 20% of Duke's campus (Caldwell, 2013). The water collected in this pond is used to cool the chiller plant facility to offset the purchase of potable municipal water.

The pond was built on top of an existing streambed, therefore FMD is required by the state of North Carolina to perform water quality monitoring for five years post-construction. In addition to the state-required monitoring, FMD is also interested in the effects that fluctuating water levels have on various water quality parameters and on the temperature of the pond, as a result of water withdrawals from the chiller plant.

Withdrawals affect pond stratification, a process by which, during the summer months the top layer of water contains high levels of dissolved oxygen and the lower section contains low levels. Typically, urban ponds exhibit mixed conditions for the most part, but it is possible for an urban pond to become stratified (Mcenroe, 2013). Pollutant transformation occurs best when a pond is stratified (Wong, et al., 1999). Frequent water withdrawals from the chiller plant may disrupt this stratification process. The question that arises is how these fluctuating water levels affect the occurrence of pond stratification and water chemistry. The water level in the pond at a given time will depend on the runoff inputs and the water consumption by the chiller plant. If the outputs exceed the inputs, the water level in the pond will drop. It is expected that the water level will fluctuate by as much as 1.22 meters based on the hydrology and water withdrawals from the chiller plant.

My objectives are to determine how changing water levels and withdrawals from the chiller plant affect water quality and temperature in the pond and how the pond's existence affects downstream temperature. I also modeled sediment input to the pond, testing the feasibility of using the USLE equation to accurately predict annual sediment input to the chiller pond and aid in planning for other urban ponds. Additionally, I calculated a water budget in order to have a better understanding of the pond's hydrology and change in storage over time.

Methods

Study Area: Duke Pond

Constructed in 2015, the Duke Pond (or chiller pond, Fig.1) captures stormwater runoff from 265 acres (106 ha) of Duke University's campus, which is used to supplement the evaporative cooling plant's water needs. There are two inflow streams: the main inflow that runs below Circuit Drive (referred to as "CP1"), and the secondary inflow stream that drains the Circuit Drive parking lot (referred to as "CP2"). Just downstream of the inflow structure is a forebay that allows the incoming water to slow down and sediment to settle out. The water then travels to the deep-water, longer-term storage area of the pond. Then, the water exits the pond via a dam ("CP3") that controls how much water is let out. Also in this deep-water area is a pump located at the bottom of the pond near CP3 that the chiller plant uses to withdrawal water. The pond's deepest area is 10-11 feet (3 – 3.35 meters). It has an area of approximately 5 acres (2 ha) with a normal pool water holding capacity of 1,600,000 cubic feet (44,800 cubic meters). It is expected that the pond will experience a 4-foot (1.22 meter) flux in water level.

Figure 1: Aerial photo (left) and ground photo of the chiller pond (right).

Water Budget Calculation

Duke Facilities Management is also interested in determining how the chiller plant's water withdrawals affect the water budget of the pond. Using water level, withdrawal and precipitation data provided by FMD, pan evaporation data downloaded from the State Climate Office of North Carolina (2015), and the flow data described above, I calculated a water budget to evaluate the change in storage over time. The basin for the pond was dug down to bedrock during the construction process, therefore I assumed that groundwater flux is zero. I used the following equation to determine the change in storage over time for a four-month period from October 2015 – January 2016:

$$\Delta S = \text{Inflow} + \text{Precipitation} - \text{Outflow} - \text{Evapotranspiration} - \text{Withdrawals}$$

A stage/area relationship was calculated in order to determine evapotranspiration and precipitation over the pond surface (see Figures 2 and 3) (table of calculations in Appendix 1). Data from the months of August-September were not included in the water budget due to construction at the main inflow stream during this time and the flow meters were removed. The stream channel was being altered; therefore a stage-discharge relationship would have been inaccurate.

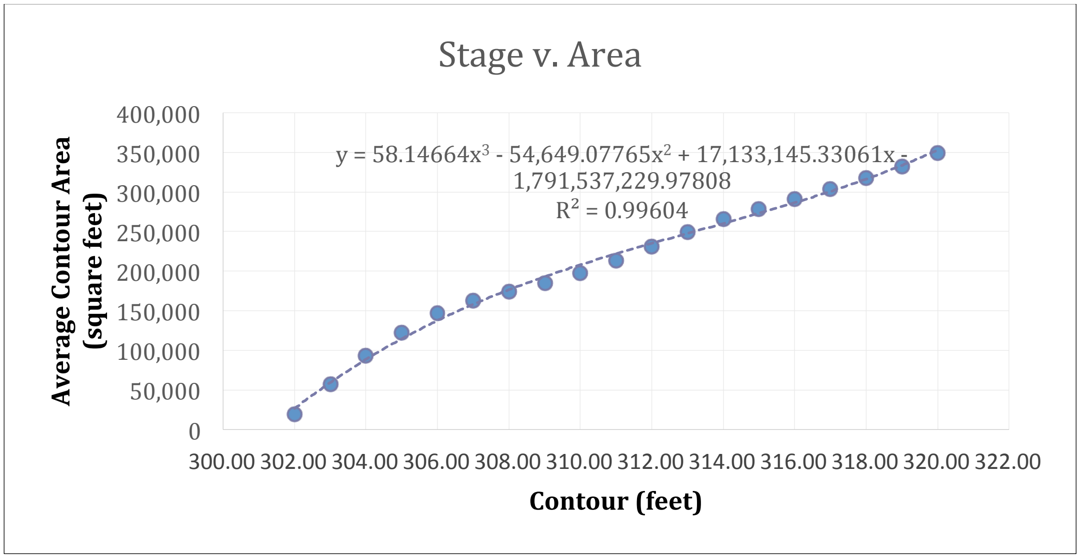

Figure 2: Stage versus area relationship calculation.

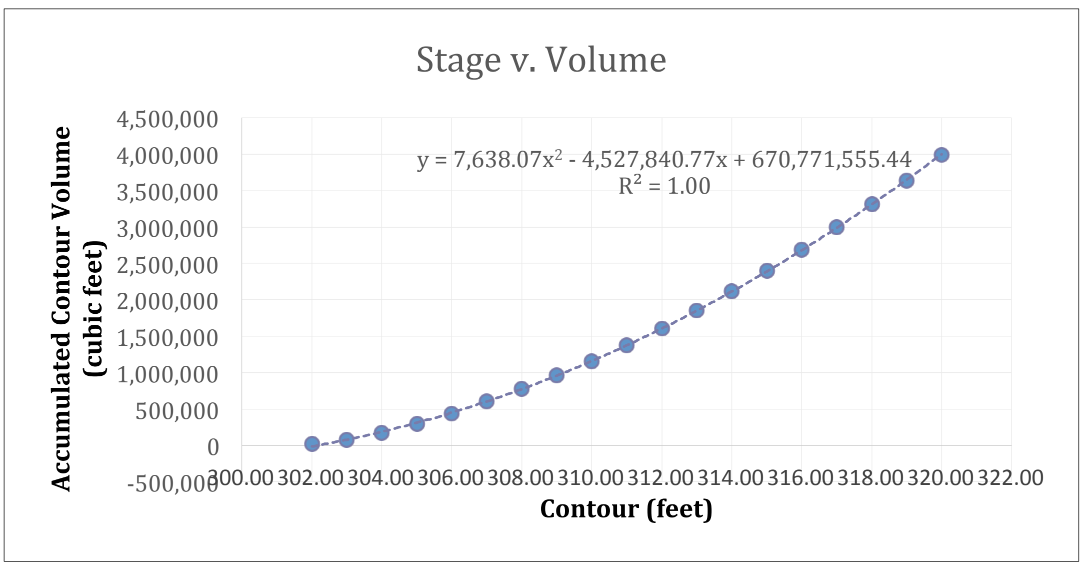

Figure 3: Stage versus discharge relationship calculation.

Data Collection – Monitoring Physical and Biological Conditions within the Pond

Long-term, permanent monitoring sites were established to monitor water quality parameters in the open-water areas of the pond. At one site, a multi-parameter sonde (Hach/Ott

DS5), suspended approximately 60 centimeters (23.6 inches) beneath the water surface, is in place to continuously measure dissolved oxygen, pH, temperature, and specific conductance at one-hour intervals. These data are transmitted wirelessly to a Telog server for examination and are collected to determine both the pond's compliance with state water quality standards, and to be used in the determination of whether the water level in the pond/withdrawals affect water quality.

Two additional long-term monitoring sites are in place for the purpose of monitoring chlorophyll-a concentrations and identifying algal bloom potential, determining what sort of vertical profile exists within the pond (that would be the result of pond stratification), and to collect turbidity data. One site is located in a deep-water zone (approximately 2.74 – 3.35 meters) close to the pond inflow point ("CPD"), the other in a deep-water zone close to the pond outflow ("CPPG"). On a monthly basis depth-integrated samples were collected in triplicates at each site using a Van Dorn water column sampler. Secchi depth was used to measure turbidity at each site. Then, the samples were taken at intervals within the photic zone of the pond (one at the surface, one at the secchi depth, and one at twice the secchi depth) and composited. These samples were analyzed for total nitrogen (TN), ammonium ($NH4^{+}$-N), nitrate ($NO3^{-}$-N), total phosphorus (TP), phosphate (PO_4-P), and Chlorophyll a. Additionally, pH, dissolved oxygen, specific conductance, and temperature were recorded at a depth profile from just below the surface (0.1 meters), at mid-depth (1 - 1.7 meters), and at the sediment-water interface at the bottom of the pond using a YSI 556 MPS Handheld Multi-parameter Instrument.

Compliance with North Carolina water quality standards were compared with standards established by the NC Department of Natural Resources outlined in Table 1. For freshwater aquatic life survival in non-trout waters, the applicable standards the chiller pond must follow are for Chlorophyll-a concentrations, dissolved oxygen concentrations, and pH.

Table 1: North Carolina state water quality standards.

NC Water Quality Standards

Pollutant	Freshwater Aquatic Life standard
Chlorophyll-a	40 μg/L
Dissolved oxygen	5 mg/L
pH	Between 6.0 - 9.0

Data Collection – Measuring the Volume and Quality of Water Entering and Exiting the Pond

To evaluate the hydraulic flux into and out of the pond, we have employed Doppler radar velocity-sensing flow meters at the two main influent locations (three pipes) and at the effluent (two pipes) using Hach FL900 flow meters that provide continuous measurements of flow (Fig. 4). Along with flow data, sampling during both storm and baseflow conditions was performed in order to determine nutrient and sediment concentrations entering and leaving the pond. Monthly baseflow grab samples were collected at both inflow sites and at the outflow site. Storm samples were collected approximately once every three months from June 2015 to November 2015 using ISCO storm samplers that collect samples on an hourly basis for a 24-our period. These samples were analyzed for TN, NO_3-N, NH_4-N, TP, PO_4,-P, filtered ortho-phosphate (FOP), and total suspended solids (TSS) to be used in the future to determine a nutrient budget.

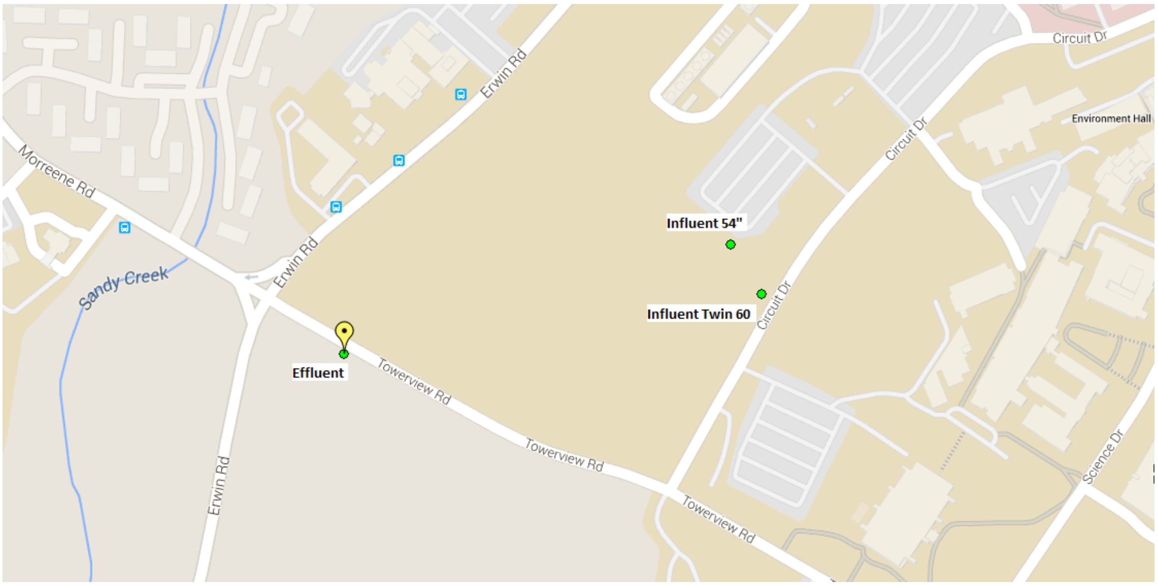

Figure 4: Map showing the locations of two influent structures and the effluent structure (green points).

Statistical Analysis: Stream Temperature

In order to determine whether the pond's presence significantly changed the temperature of the water leaving versus entering, I used the statistical software package, R (R Core Team, 2015). I decided to use a non-parametric test because the samples are spatially not independent of each other (one sampling location is upstream from the other), therefore do not follow the assumption of independence required for an ANOVA test. Using the Wilcoxon Rank Sum test, I tested the null hypothesis that there is no difference in the mean temperatures of the inflow stream and the outflow stream (code in Appendix 2).

Statistical Analysis: Water Level and Water Chemistry

To determine what relationship exists between water level and dissolved oxygen, pH, temperature, or specific conductance I performed a simple linear regression using the daily median value for each variable. Since the number of samples is sufficiently large, I will assume that the data are normally distributed. The other assumptions of independent samples, little to no multicolinearity, and homoscedasticity are met (code and diagnostic plots in Appendix 2). I was unable to use the Shapiro-Wilk test because the sample size is too large (must be between 3 and 5000). Instead, I divided the dependent variable's standard deviation by each independent variable's standard deviation to determine if the criterion is met that the largest standard deviation is less than 2 times larger than the smallest.

GIS Analysis: USLE Suitability to Model Sediment Input

Typically, the Universal Soil Loss Equation (USLE) has been used to estimate annual soil loss in agricultural areas. Due to the model's ease of use, limited data requirements, and GIS-compatibility, USLE is progressively being used in more urban settings, mainly construction sites (Mattheus and Norton, 2013). Using the Model Builder in ArcMap version 10.3 (2015) I have developed a tool that allows a user to click on a map and it will delineate the upstream contributing area and calculate the annual soil loss for that area. Due to the lack of budget/man-power, there is currently no data collection occurring that allows the calculation of continuous sediment input. The purpose of this tool is to provide an estimate of annual soil input to the pond.

Data were downloaded from the USGS National Map Viewer (2013), which include a land cover land use raster and a digital elevation model (DEM) raster for Durham County, NC. A soil map was downloaded from the NRCS Web Soil Survey website (2013) to determine each soil type's corresponding K factor. To delineate the watershed, the tool uses the DEM as an input to the Flow Direction tool that indicates the direction a drop of water would flow out of each pixel, based on the slope at that location (left, right, up, or down). Then, the Flow Accumulation tool uses this output to produce a raster where each pixel is assigned a numerical value that represents the number of pixels that flow into it. The Snap Pour Point tool then uses the user-specified point to ensure the pour point is on or near a stream. Finally, the Watershed tool uses the flow accumulation raster and the pour point to determine the boundary of the watershed.

The USLE equation is A = R * K * LS * C * P, where:

A = Annual soil loss (lb/acre/year)
R = Rainfall-erosivity factor
K = Soil erodibility factor
LS = Slope/length factor
C = Crop type
P = Erosion control practice factor
(USDA, 2009).

I created a raster layer to represent the R factor. Since the scope of the tool is Durham County, and the rainfall-erosivity factor is regionally determined, all of the pixels were classified to equal 250 (foot-ton-inches/ac/hr), from the EPA Stormwater Phase II Final Rule (2012). The LS factor was determined first by using the Slope tool to create a slope raster. Then, I used the Raster Calculator with the following equation to obtain a raster representing the LS factor:

*Power (flow accumulation * cell resolution / 22.1, 0.4) * Power (Sin(slope * 0.01745) / 0.09, 1.4) * 1.4*

Pelton et al. (2014), where “flow accumulation” and “slope” are raster layers, and the cell resolution is 9.453 x 9.453.

I reclassified the soil map to display the K factor for the corresponding soil type, using data provided by the NRCS Web Soil Survey. Altering the C and P factors are what make this equation unique to urban, rather than agricultural areas (Table 2). A study conducted by Fernandez et al. (2003) uses GIS and a Revised Universal Soil Loss Equation to model sediment yield at a watershed scale based on land use (National Land Cover Database, 2011).

Table 2: C and P values assigned to each land use group for the Durham urban watershed.

Land Use	C Factor	P Factor
Urban	0.030	1.00

Forest	0.001	1.00
Grasses	0.003	1.00
Cropland	0.128	0.92

Fernandez et al. (2003) and Albertson (2001)

I used their estimates for C and P values to reclassify land use raster layers to reflect these values. The P value 1.0 is used to simulate no erosion control practices and the low C factor values represent the absence of crop cover (Table 2). While the National Land Cover Database has 14 land use classes, Fernandez only classifies four. Similar land classes were grouped together (see Appendix 3 for groupings). Additional land cover C factors not included in Fernandez's paper were obtained from a paper by Albertson (2001). These additional classes include water, barren land, and wetlands. In Raster Calculator each layer serves as an input to the USLE equation (Appendix 4) and the result is the annual soil loss in lb/acre/year (Model diagram in Fig. 5).

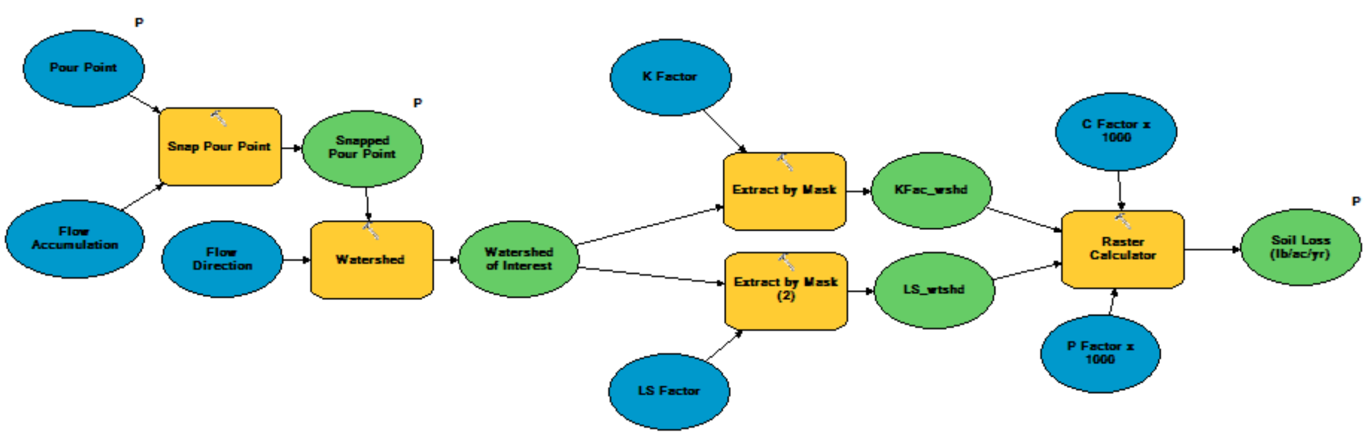

Figure 5: USLE model flow diagram developed to calculate annual soil loss in urban watersheds.

Results

Table 3 quantifies the monthly water budget for the chiller pond. Values are given for the inputs, outputs, and change in storage (in cubic feet) experienced by the chiller pond due to withdrawals, outflow, precipitation and evapotranspiration (ET). In October, there was a net loss in storage. During November through January, there was a net gain of water in the pond.

Water Budget

Table 3: Water budget - inputs, outputs, and storage (in cubic feet).

	Withdrawals	Outflow	ET Loss	Precipitation	Inflow	Storage
Oct 2015	1,136,200	1,362,258	58,138	89,833	2,015,658	-451,105
Nov 2015	560,400	1,113,479	39,000	100,140	4,318,751	2,706,012
Dec 2015	1,080,400	3,559,548	31,766	171,249	8,162,056	3,661,591
Jan 2016	1,035,500	640,225	30,211	32,654	3,258,123	1,584,842

Compliance with Water Quality Standards

For most of the sampling period, the dissolved oxygen levels remain above the state standard of 5 mg/L (Fig. 6). Measurements from 10/7 – 10/28 were omitted due to the sonde being exposed to air because the pond level was drawn down too far. The sonde units were then placed on a float system to allow them to track changing water levels. Also, measurements from 11/13 – 12/8 are omitted due to sonde maintenance. During early startup where the pond was adjusting to water inputs there were numerous days in late September where there were levels below the state standards for dissolved oxygen. This could be attributed to construction upstream coupled with large storms that caused a heavy sediment and subsequent phosphorus flux into the pond. During this time there were severe algal blooms recorded on September 30.

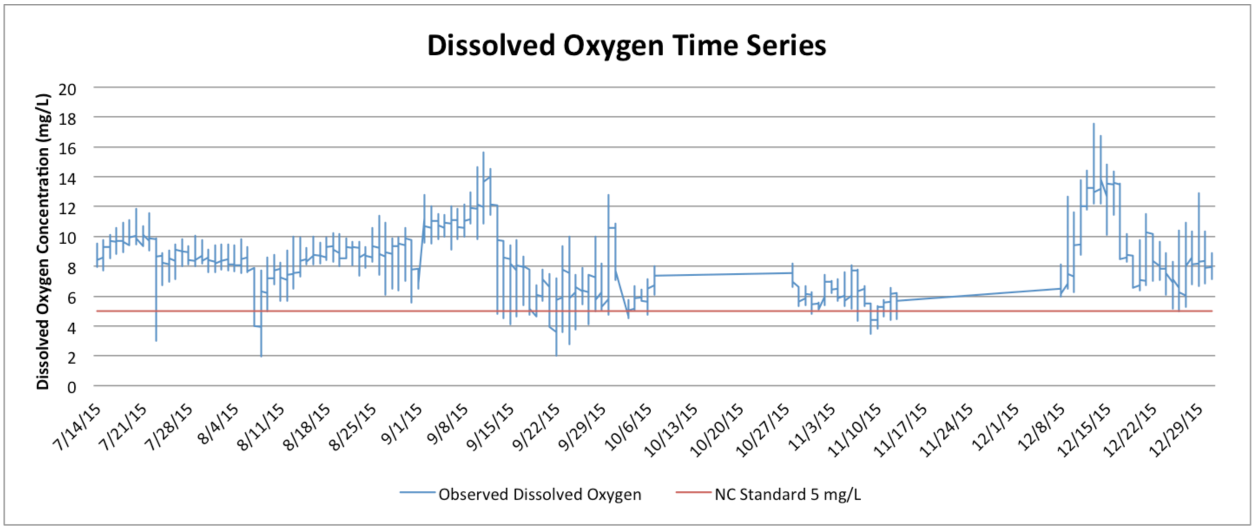

Figure 6: Dissolved oxygen time series. The red line represents the state standard of 5 mg/L. Straight lines (10/7/2015 to 10/28/2015 and 11/13/2015 to 12/8/2015) indicates missing data.

The pond pH typically remained within the range for pH compliance, except for a few occurrences in September (Fig. 7). Note that the same sonde data gaps apply to pH measurements as described above for dissolved oxygen.

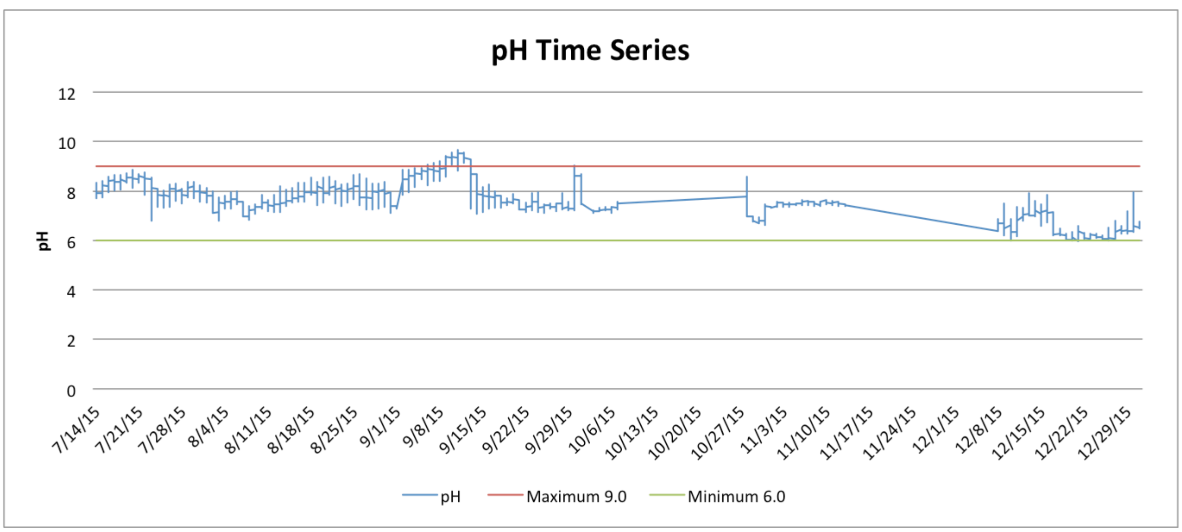

Figure 7: pH time series. The green and red lines represent the state standard range of 6.0 and 9.0, respectively.

Figure 8 shows a 24-hour time series of dissolved oxygen and pH during a day in July compared to a day in December. Dissolved oxygen does not fluctuate noticeably during July, but there is a noticeable fluctuation in December There is not a large daily fluctuation in pH during either time of the year.

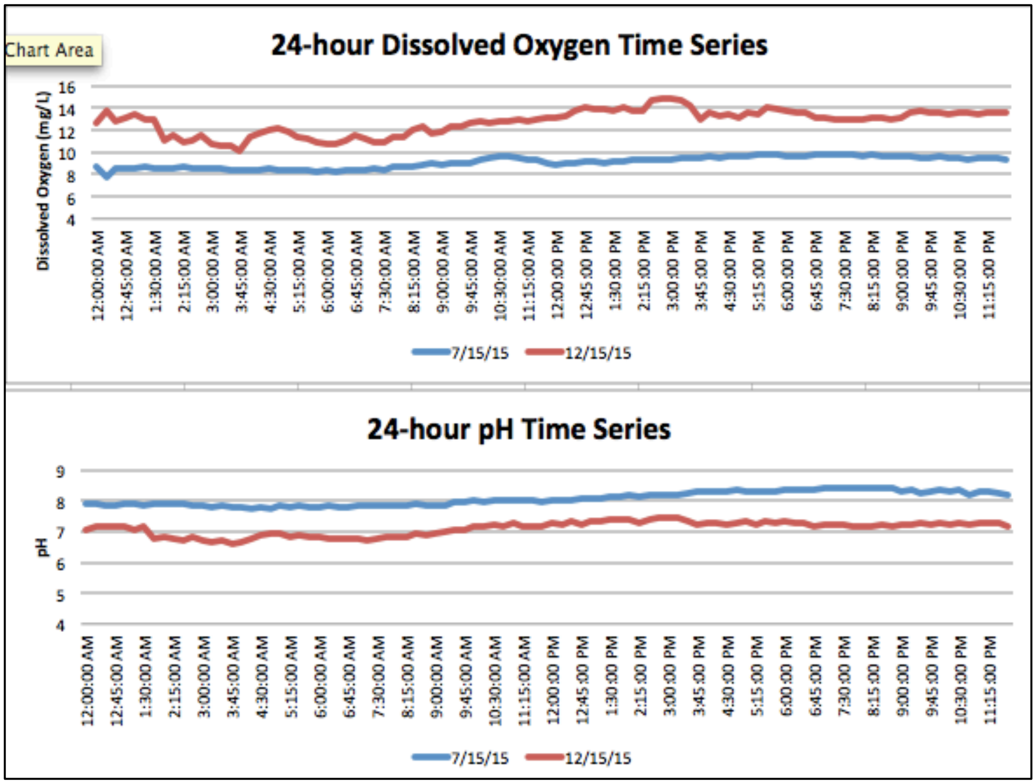

Figure 8: 24-hour dissolved oxygen and pH time series in the pond.

Results: Chlorophyll-a Concentrations

Table 4: Chlorophyll-a concentrations. Red indicates a violation.

Sampling Date	Chlorophyll-a Concentration (ug/L)
6/12/2015 CPPG	**10.64**
6/12/2015 CPD	**3.25**
6/23/2015 CPPG	2.24
6/23/2015 CPD	2.13
7/7/2015 CPPG	**21.59**
7/7/2015 CPD	**15.91**
9/9/2015 CPPG	55.63
9/9/2015 CPD	42.28

Table 4 displays the results of the two depth-integrated composite samples taken from the photic zone of the pond at the deep-water monitoring location ("Chiller Pond at Pagoda", or "CPPG") and at the deep-water location closer to the inflow ("Chiller Pond by Dock", or "CPD") for three sampling dates.

The chlorophyll-a concentrations are averages of each composite sample collected at each permanent monitoring site. On September 9 the concentrations were above the state water quality standard of 40 µg/L. I suspect this is due to the aforementioned flux of sediment and nutrients from nearby construction during the month of September. This is likely the cause of this intensified algal growth during this period. In June, July, and September it is clear that temperature and dissolved oxygen decrease with increasing depth (Table 5). All data in Table 5 are from the site 'CPPG'.

Depth Profile

Table 5: Vertical profile of water quality parameters in pond[1].

Date	Site	Sample Depth (ft)	Sample Depth (m)	Temp C	DO mg/L	pH
6/11/15	Surface	0.5	0.15	31.05	8.95	7.74
6/11/15	Mid-depth	5.5	1.67	25.48	9.02	7.45
6/11/15	Bottom	11.0	3.35	22.66	3.57	7.15
7/7/15	Surface	0.5	0.15	28.22	8.09	8.32
7/7/15	Mid-depth	4.96	1.51	25.84	3.61	7.11
7/7/15	Bottom	9.92	3.02	22.58	2.24	6.82
9/9/15	Surface	0.5	0.15	29.18	11.68	9.38
9/9/15	Mid-depth	4.75	1.45	26.49	11.45	9.3
9/9/15	Bottom	9.5	2.90	22.51	1.01	7.21

Nutrient Concentrations: Influent versus Effluent

Figures 9, 10, and 11 show the average total nitrogen, total phosphorus, and total suspended solids concentrations in the pond influent, respectively, observed from four baseflow grab samples. Tables 6, 7, and 8 provide a comparison of the inflow and outflow total nitrogen, total phosphorus, and total suspended solids, respectively, for each sampling date. On average,

[1] November 2015 measurements omitted from this report due to inaccurate YSI readings.

total nitrogen is 202.3 ug/L lower at the outflow, total phosphorus is 73.4 ug/L lower at the outflow, and total suspended solids is 1.4 mg/L higher at the outflow compared to the inflow concentrations. This results in a 35 % reduction for N and 55% reduction for P and TSS are virtually unchanged.

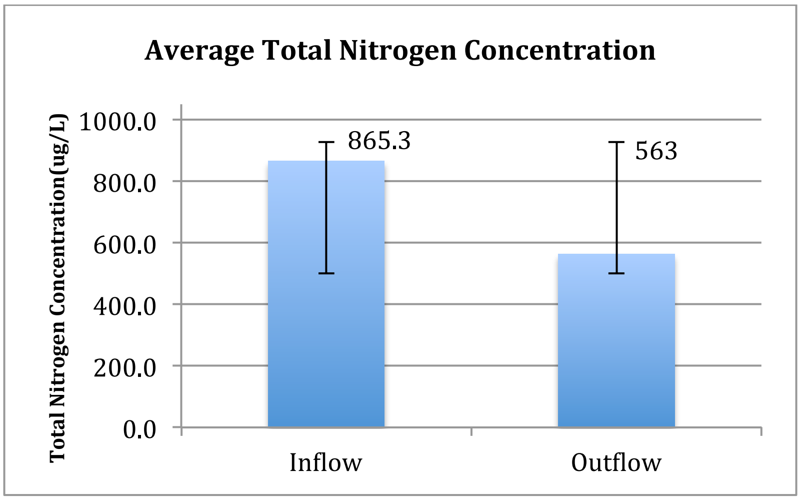

Figure 9: Comparison of baseflow average total nitrogen concentration at the pond inflow vs. outflow.

Table 6: Inflow and outflow total nitrogen concentrations (ug/L)

DATE	Inflow UTN	Outflow UTN
10/14/15	813.8	437
11/17/15	739.6	573
12/7/15	907.5	528
1/12/16	1000.3	714

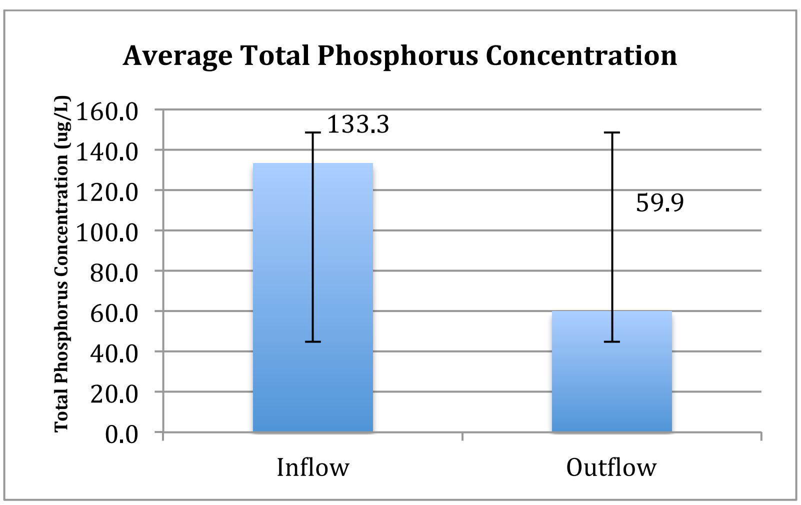

Figure 10: Comparison of baseflow average total phosphorus concentration at the pond inflow vs. outflow.

Table 7: Inflow and outflow total phosphorus concentrations (ug/L).

DATE	Inflow UTP	Outflow UTP
10/14/15	24.7	59.5
11/17/15	130.9	33.9
12/7/15	163.6	67.1
2/2/16	213.9	79.2

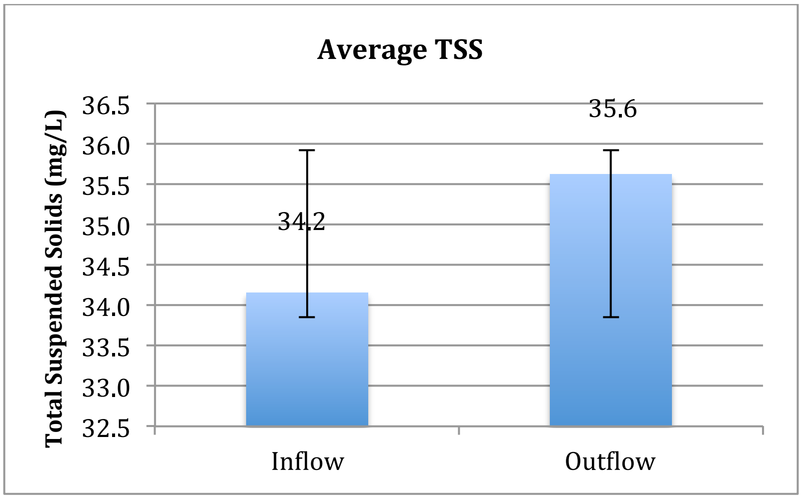

Table 8: Inflow and outflow total suspended solids concentrations (mg/L).

DATE	Inflow TSS	Outflow TSS
10/14/15	19.5	30.8
11/17/15	43.6	43.1
12/7/15	32.8	43.6
1/12/16	30.8	30.9
2/2/16	44.0	29.7

Figure 11: Comparison of baseflow average total suspended solid concentration at the pond inflow vs. outflow.

Stream Temperature: Influent versus Effluent

The results of the Wilcoxon test indicate that there is no significant difference between the temperature at the inflow structure and at the outflow structure (p-value = 0.3545, W = 1982000). Figure 12 shows the distribution of the inflow temperature data versus the outflow temperature data.

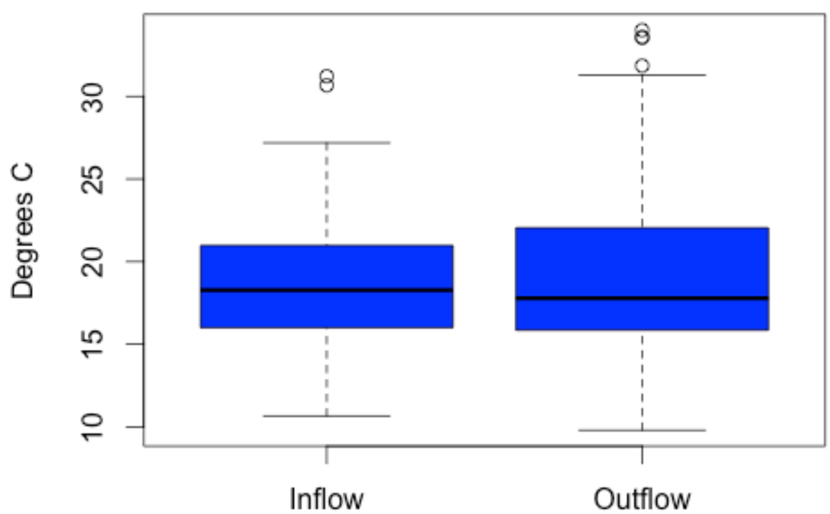

Figure 12: Boxplot showing the distribution of temperature data at the inflow and outflow streams.

Effect of Water Level on Water Chemistry in the Pond

The water level in the pond significantly affects (alpha level of 0.05) dissolved oxygen concentration (p-value = 1.45e-7), pH (p-value = 8.59e-11), temperature (p-value = 2.30e-8), and specific conductance (p-value = 1.44e-10). With every foot increase in water level dissolved oxygen decreases by 0.9 mg/L, pH decreases by 0.5, temperature decreases by 4 degrees Celsius, and specific conductance decreases by 22.3 mS (Fig. 13).

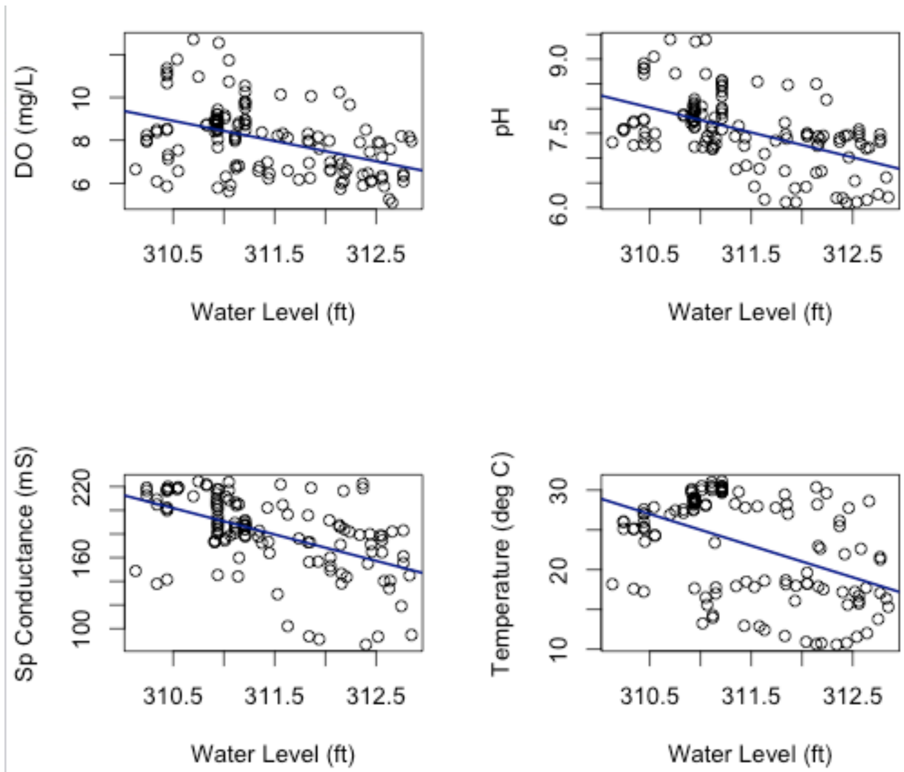

Figure 13: Plots of water quality parameters against water level (daily averages).

Additionally, I determined that a weak positive relationship exists between temperature in the pond and dissolved oxygen concentration (p-value = 0.0448) (Fig. 14). With each degree Celsius increase in temperature, dissolved oxygen increases 0.06 μg/L. More data will have to be collected in order to establish a more firm relationship.

GIS Analysis: Annual Soil Loss Modeling

Figures 14 and 15 show FMD's watershed (blue polygon indicated in Figure 14 legend) and the result of the USLE tool's watershed, respectively. Annual soil loss in the chiller pond's watershed was calculated to equal 168.2 lb/ac/year (or 188.6 kg/ha/yr).

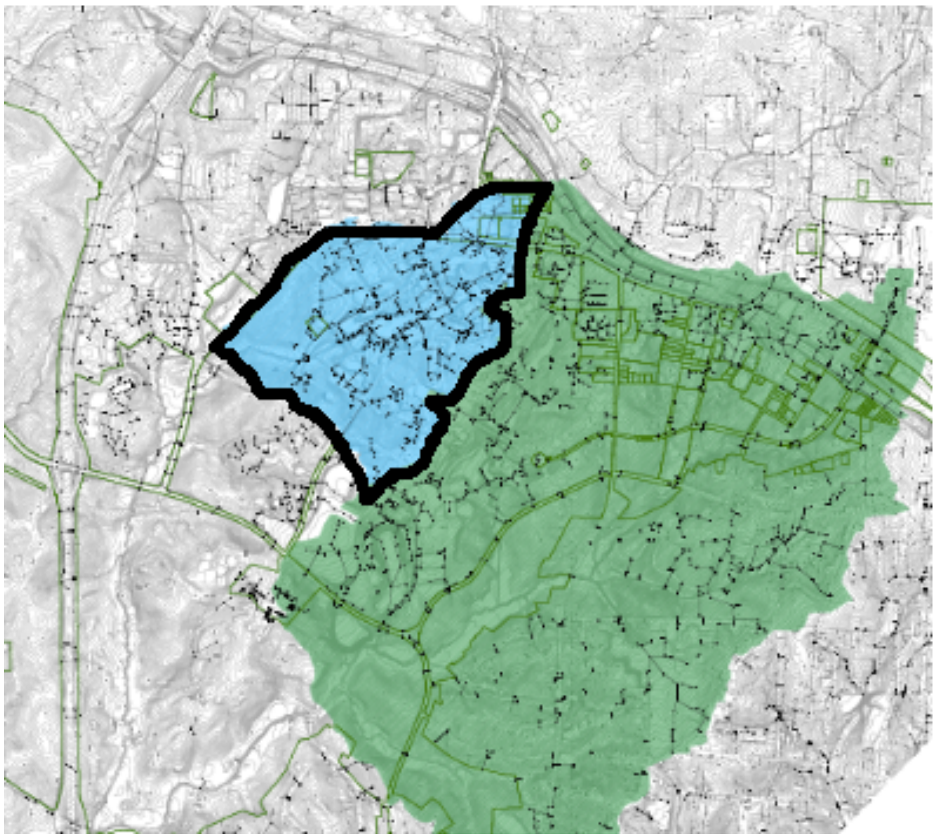

Figure 14: FMD determination of chiller pond watershed (blue polygon with thick black outline).

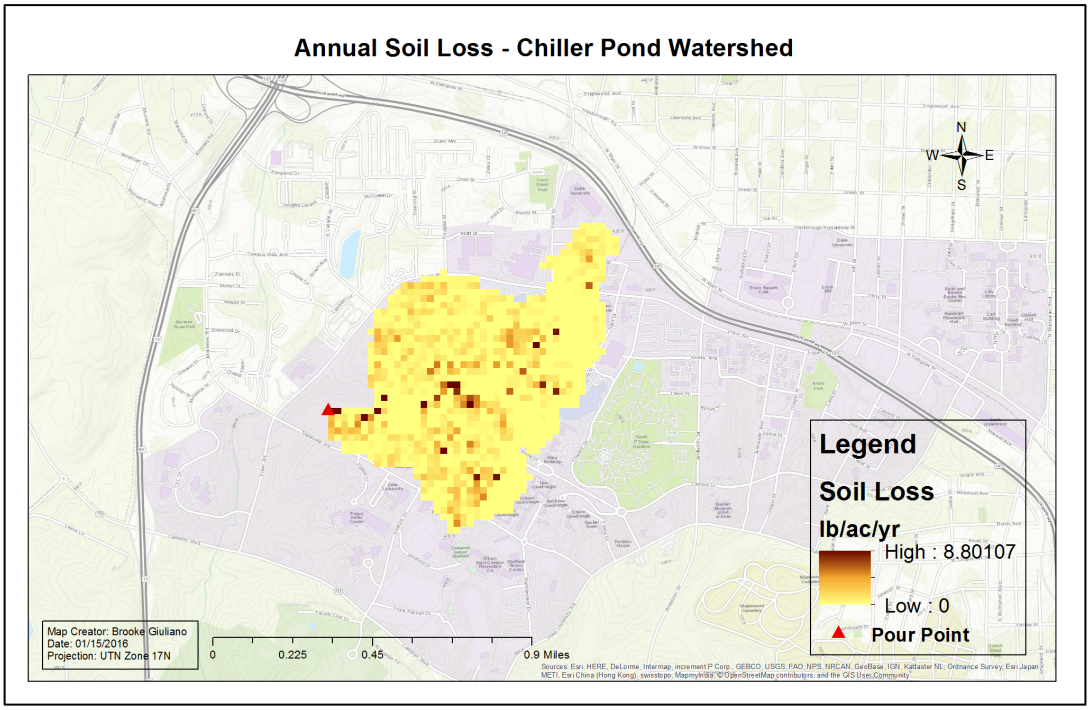

Figure 15: USLE model determination of pond watershed and annual soil loss.

Discussion

Overall the chiller pond remains in compliance with state water quality standards for oxygen, pH and water temperature. A few periods out of compliance are related to startup periods or increased construction activities in the watershed. Continuous monitoring will be conducted for four more years, as required by the state. It is in FMD's best interest to maintain a non-impaired status for the chiller pond in order to avoid mandated management strategies by the state and/or the federal government (NCDEQ, 2015). Long-term noncompliance would facilitate the need for prolonged monitoring efforts and add costs to this project, which is an undesirable outcome.

From the baseflow nutrient and sediment data, we can conclude that nitrogen and phosphorus are being removed from the influent. Total suspended solids are slightly higher on average at the outflow. Future studies on the pond will include a complete nutrient budget, which will make our data more robust and hopefully reduce the large standard deviation in our current data. This will provide information about the fate of the phosphorus entering the pond, particularly during storm flow. It will inform us whether the phosphorus is settled out at the bottom of the pond with the sediment, thus unavailable to organisms, or if it is passing through the pond and is discharged at the outflow. Knowing the proportion of the nutrients entering the pond that will be a potential source for algal blooms is important in prioritizing the sediment management techniques.

The pattern of large storms, followed by significant sediment influx, followed by increased chlorophyll-a concentrations was expected. Phosphorus is adsorbed to sediment, therefore will travel with the sediment. I would suggest solving this problem at the source of the sediment pollution: construction sites on campus. Increased construction erosion control practices within the pond's watershed should be considered to prevent future chlorophyll-a violations. These could include increased silt fence usage and energy dissipaters.

The water level in the pond must be managed in a way that allows for water quality standards to be met. Another potential concern future in the future is that FMD may be interested in stocking the pond with fish to increase the recreational value. If so they will have to manage the water level so that the dissolved oxygen is high enough to support aquatic life. Current withdrawal patterns indicate that enough oxygen was maintained in the pond but more data is needed to confirm this. I would suggest setting a threshold water level for oxygen and managing the chiller plant withdrawals to cease once the pond drops to this critical level, especially during a massive withdrawal of stored water. An alternative would be to install aerators in the pond to maintain oxygen during the summer if major problems occur. FMD has the capacity to control the volume of water leaving the pond, using the dam at the outflow structure. During dry periods, the chiller plant does not let water out of the pond. Utilization of this dam could be a useful tool in maintaining a satisfactory water level, and therefore satisfactory water quality, in the pond.

Validation of the USLE model was performed by comparing the sediment yield calculated by the model for the pond to that of similar sized watersheds with similar land uses from literature. Measured annual sediment yield from one such watershed in Kentucky is 1018 lb/ac/yr[2] (Wolman, 1967), which is an order of magnitude off from the tool's estimation of 168 lb/ac/yr. A second source provides sediment yield coefficients that are based on land use. The majority of land use within the chiller pond's watershed is medium- to high-density residential. A publication by Nelson and Booth (2002) estimates medium- and high-density residential land uses to produce 287 and 312 lb/ac/yr, respectively. This estimate brings us closer to the tool's calculation, but the high variance of estimates in the literature does not allow me to conclude that the tool is accurate. At this point, I would not suggest this tool be used in any official planning capacity until further site validation occurs. The most accurate method to validating this model is to set up continuous sediment input monitoring at the chiller pond's inflow structures.

[2] Watershed size was 0.67 square miles and sediment yield was 3670.4 lb/ac/yr. The equivalent sediment yield of 0.414 square miles (or 265 acres), the size of the chiller pond's watershed, was calculated to be 1018.2 lb/ac/yr.

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Appendix 1: Calculation of Stage-Storage Relationship

Stage-Storage Relationship in the Duke chiller Pond.

Contour (feet)	Stage (feet)	Contour Area (square feet)	Average Contour Area (square feet)	Incremental Contour Volume (cubic feet)	Accumulated Contour Volume (cubic feet)	Accumulated Contour Volume (gallons)
301.00	0.00	1,820.59				
302.00	1.00	36,054.64	18,938	18,938	18,938	141,653
303.00	2.00	78,335.00	57,195	57,195	76,132	569,471
304.00	3.00	108,468.99	93,402	93,402	169,534	1,268,118
305.00	4.00	136,897.45	122,683	122,683	292,218	2,185,788
306.00	5.00	157,264.82	147,081	147,081	439,299	3,285,955
307.00	6.00	169,342.00	163,303	163,303	602,602	4,507,464
308.00	7.00	179,240.80	174,291	174,291	776,894	5,811,164
309.00	8.00	191,173.79	185,207	185,207	962,101	7,196,515
310.00	9.00	204,960.11	198,067	198,067	1,160,168	8,678,055
311.00	10.00	221,742.02	213,351	213,351	1,373,519	10,273,921
312.00	11.00	240,363.55	231,053	231,053	1,604,572	12,002,196
313.00	12.00	258,418.61	249,391	249,391	1,853,963	13,867,642
314.00	13.00	272,334.47	265,377	265,377	2,119,339	15,852,658
315.00	14.00	284,700.57	278,518	278,518	2,397,857	17,935,969
316.00	15.00	297,118.23	290,909	290,909	2,688,766	20,111,971
317.00	16.00	310,059.49	303,589	303,589	2,992,355	22,382,816
318.00	17.00	324,316.50	317,188	317,188	3,309,543	24,755,382
319.00	18.00	339,604.22	331,960	331,960	3,641,503	27,238,446
320.00	19.00	358,211.51	348,908	348,908	3,990,411	29,848,277

Appendix 2: R Code & Model Diagnostic Plots

Stream Temperature inflow vs. outflow

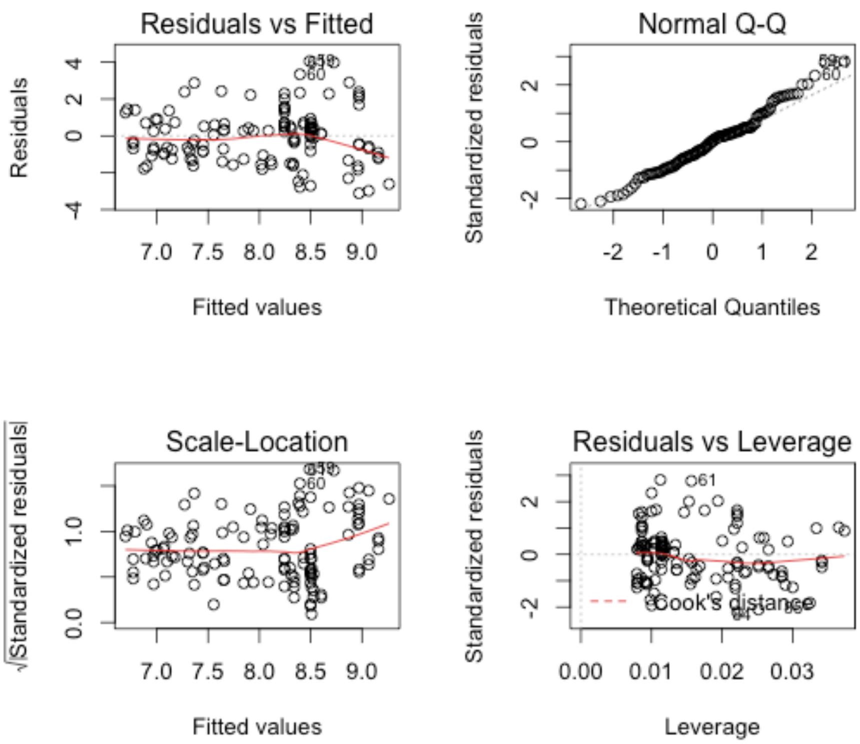
```
dattemp <- read.csv("StreamTemp.csv", header = T)
attach(dattemp)

#Must use non-parametric test - not independent samples
#Use Wilcoxon Signed rank test
#Ho: There is no difference between in/out temperatures
#Ha: There is a difference between in/out temperatures
wilcox.test(Inflow,Outflow, data=dattemp)

boxplot(Inflow, Outflow, col="blue", ylab= "Degrees C",
    names=c("Inflow", "Outflow"))
```

R Code: Water Level vs. Water Chemistry

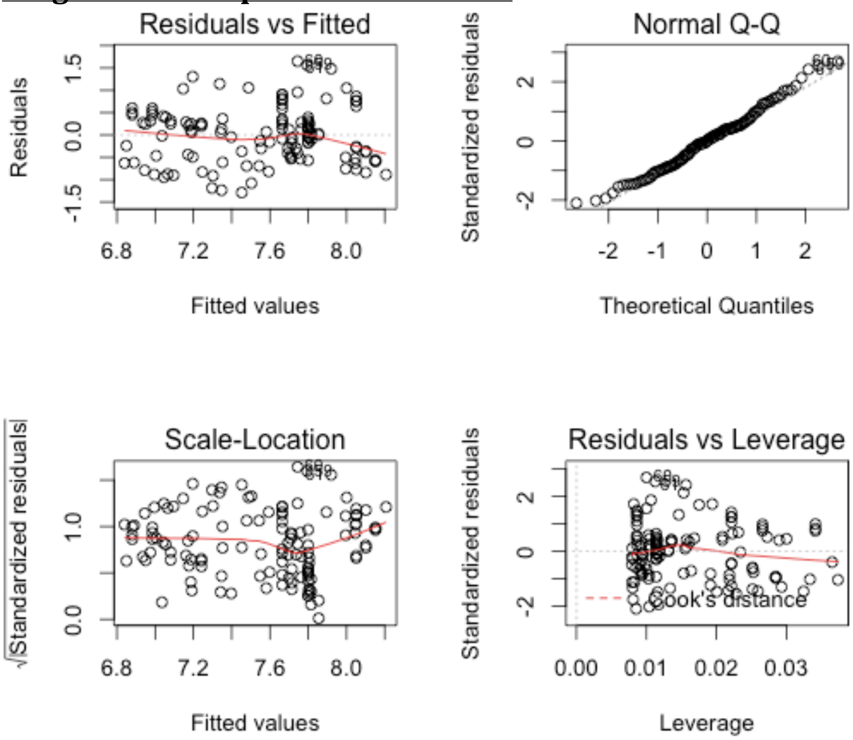
```
datmed <- read.csv("WaterLevChemMedians.csv", header=TRUE)
attach(datmed)

#Linear Regression
regLDO <- lm(DO ~ WaterLev)
summary(regLDO)
regpH <- lm(pH ~ WaterLev)
summary(regpH)
regTemp <- lm(Temp ~ WaterLev)
summary(regTemp)
regSpCon <- lm(SpCond ~ WaterLev)
summary(regSpCon)

plot(WaterLev, DO, xlab = "Water Level (ft)", ylab = "DO (mg/L)")
abline(lm(DO ~ WaterLev), col='darkblue', lwd=2)
plot(WaterLev, pH, xlab = "Water Level (ft)", ylab = "pH")
abline(lm(pH ~ WaterLev), col='darkblue', lwd=2)
plot(WaterLev, SpCond, xlab = "Water Level (ft)", ylab="Sp Conductance (mS)")
abline(lm(SpCond ~ WaterLev), col='darkblue', lwd=2)
plot(WaterLev, Temp, xlab = "Water Level (ft)", ylab = "Temperature (deg C)")
abline(lm(Temp ~ WaterLev), col='darkblue', lwd=2)

#Diagnostic Plots
par(mfrow=c(2,2))
plot(regLDO)
plot(regpH)
```

```
plot(regTemp)
plot(regSpCon)

#Check for homogeneity of variances
sd(WaterLev)/sd(Temp)
sd(WaterLev)/sd(SpCond)
sd(WaterLev)/sd(pH)
sd(WaterLev)/sd(DO)
```

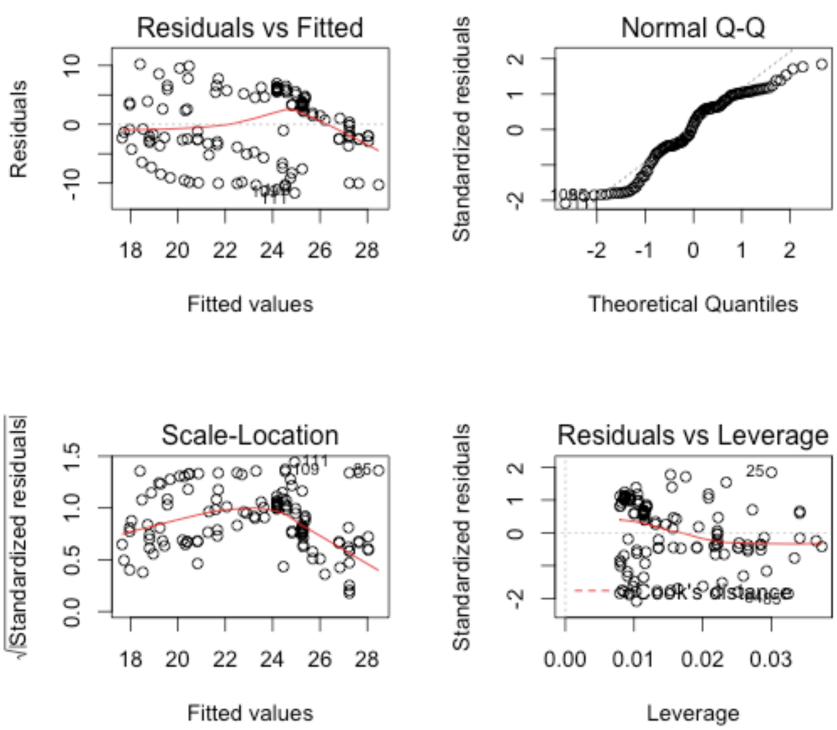
Diagnostic Plot: Dissolved Oxygen vs. Water Level



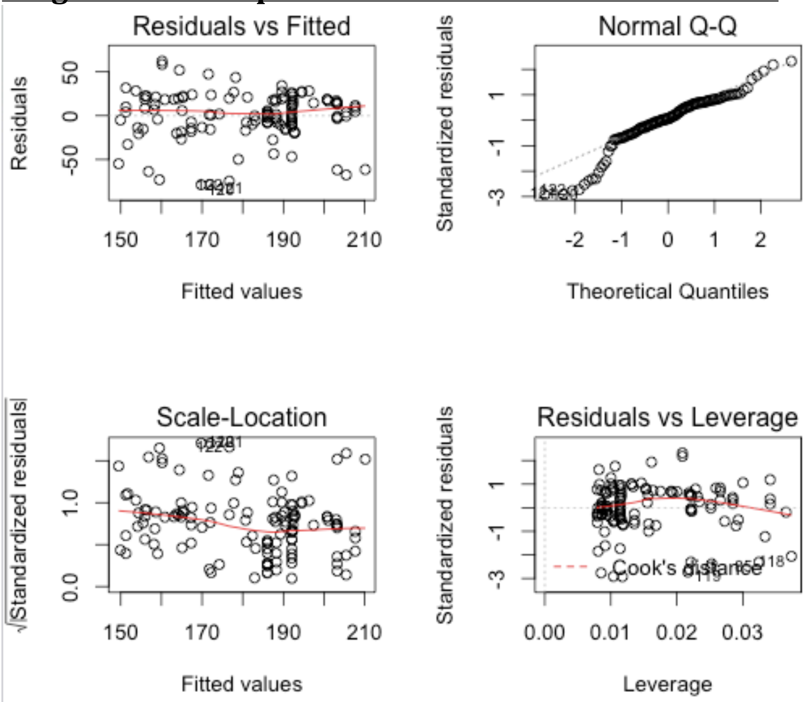
Diagnostic Plot: pH vs. Water Level



Diagnostic Plot: Temperature vs. Water Level



Diagnostic Plot: Specific Conductance vs. Water Level



Appendix 3: Land Use Groupings

Land Use Group in Tool	**NLCD Land Use**
Urban	Developed, Open Space Developed, Low Intensity Developed, Medium Intensity Developed, High Intensity
Forest	Deciduous Forest Evergreen Forest Mixed Forest
Crop	Hay/Pasture Cultivated Crops
Grass	Scrub/Shrub Herbaceous
Other – not in group defined by Fernandez (2003)	Water Barren Land Woody Wetlands Emergent Herbaceous Wetlands

Appendix 4: USLE Equation Used in Raster Calculator