Spring 5-2020

The Importance of River Influx and Pump Storage Operation on Water Quality in a Storage Reservoir

Ethan Batchelor

The Importance of River Influx and Pump Storage Operation on Water Quality in a Storage Reservoir

Ethan Batchelor

Senior Honors Project

Submitted in partial fulfilment of the graduation requirements

of the Westover Honors College

Westover Honors Program

May, 2020

Thomas Shahady PhD

Jennifer Styrsky PhD

Nina Salmon PhD

Abstract

Pump storage hydroelectricity is a system built by power companies where a dam separating an upper and lower reservoir is used in power generation by passing water between both reservoirs. Environmental regulations require a minimum of 5mg/L of dissolved oxygen be maintained at all times passing through each dam. In central Virginia, American Electric Power operates a hydroelectric Pump Storage Project that includes an upper reservoir, Smith Mountain Lake (SML), and a lower reservoir, Leesville Lake (LL). Unique to this system is the influx of high concentrations of nutrients and other pollutants into the upper reaches of Leesville Lake from a 1015 km^2 Pigg River watershed less than 10 km from SML dam. This study examined the pump-storage operational influence of water exchanged between reservoirs with movement of Pigg River influx creating low dissolved oxygen concentrations at dam release. The study found that pump-storage coupled with Pigg River influx influences water quality parameters in Smith Mountain Lake release, specifically pertaining to dissolved oxygen reductions. Based on these findings, pump-storage operation should be considered in water quality management as these movements of water can be implicated in both release and overall observations in operational reservoirs.

Introduction

Pump-storage hydroelectric is a system built by power companies where a dam separating an upper and lower reservoir is used in power generation by passing water between both reservoirs. Pump-storage systems create two reservoirs used for hydroelectric power generation, where one reservoir is at a higher elevation than the other. During periods of energy demand, the pump-storage dam releases water from the upper reservoir to the lower reservoir spinning turbines to generate electricity. Pump-storage dams are unique as they pump water against gravity from the lower reservoir to the upper reservoir by reversing the spinning of the turbines (Hale 2016). Water is pumped back to the upper reservoir when the cost of electricity is relatively cheaper, and demand is low, so that the water can then be released again later to generate more electricity at a profit.

Reservoir limnology

To understand how pump storage alters the water quality in storage reservoirs, behavior of typical eutrophic lakes not influenced by pump-storage is required. Lakes are classified by their water chemistry and their primary productivity (Carlson 1977). The four main classifications are oligotrophic, mesotrophic, eutrophic, and hypereutrophic (Bhateria and Jain 2016; Thomas et al. 2016). An oligotrophic lake is one with low turbidity, high oxygen levels, and low nutrients along with low primary productivity with less than 10 parts per billion (ppb) of phosphorous. Mesotrophic lakes have intermediate levels of nutrients and primary productivity with 10-20 ppb of phosphorous. Eutrophic lakes have an excess of phosphorous with 20-50 ppb and an excess of nitrogen resulting in have high levels of primary productivity in the waters. Hypereutrophic lakes have even greater levels of productivity than eutrophic lakes and very low transparency, typically less than 1 meter deep of visibility. These lakes have greater than 50 ppb of phosphorous.

During summer when sunlight directly hits the northern hemisphere, the surfaces of lakes heat much faster and to a greater extent than during other seasons. Sunlight does not penetrate as deeply into eutrophic lakes due to turbidity scattering of light (Heinonen et al. 2000). Therefore, surface waters heat up to a greater temperature than the deeper waters. Diffusive heat cannot warm the entire water column during summer because it takes about a month for diffusive heat to travel one meter in lakes (Boehrer and Schultze 2008). This unequal heating results in large differences in temperature between the surface and bottom of lakes which generates thermal stratification.

Thermal stratification creates three primary zones; the epilimnion, metalimnion, and hypolimnion (Heinonen et al. 2000). The epilimnion consists of the top layer of lakes and is the only layer which can exchange temperature and gasses with the atmosphere. It has high productivity from aquatic plants and contains more oxygenated waters than the other layers (Boehrer and Schultze 2008). The bottom of the lake is the hypolimnion. During summer, this layer is cool and contains decomposing organic matter depleting dissolved oxygen (DO) creating a DO deficit in eutrophic lakes (Heinonen et al. 2000). The metalimnion is the middle section of lakes and contains the thermocline which is a transition zone where temperature decreases greater than 1 degree per meter (Heinonen et al. 2000).

In fall, cooling temperatures and reduced sunlight do not heat the epilimnion as much as in summer, causing turnover (Boehrer and Schultz 2008). Turnover occurs when lake waters at different depths mix causing densities to become homogenous. During turnover the hypolimnion mixes into surface waters (Boehrer and Schultz 2008). Colder water contains greater dissolved oxygen when it is not impacted by eutrophication, so during fall circulation the entire water column can be oxygenated, and we typically see an oxygen maximum at the end of fall (Heinonen et al. 2000). In eutrophic waters the hypolimnion, even while cool, is depleted of oxygen and during fall turnover can cause oxygen minimums.

Pump-storage reservoirs

Pump-storage impact on reservoirs' water quality is not uniform among all sites reviewed, but rather is site specific due to different factors like shape and depth of reservoirs, or natural limnology (Bermudez et al. 2018; Kobler, Wüest, and Schmid 2018; Bonalumi et al. 2012). Reviewed studies do not share the same results on water quality but do support the idea that pump-storage dams alter expected observations on the natural state of reservoirs. There is scientific consensus that pump storage creates two separate lakes, each impacting the water quality observed in each.

Bermudez et al. (2018) asserts that pump-storage alters water circulation, deep water mixing, and thermal stratification of lakes. Pump-storage has potential negative or positive impacts on reservoirs depending on water quality observed. Effects are positive when eliminating anoxic hypolimnion through mixing, preventing decomposition and release of nutrients. However, negative effects occur when mixing creates isothermal waters resulting in less oxygen at the surface.

Kobler et al. (2018) found that hypolimnion withdrawal decreases water temperatures moving the thermocline down. They further discovered that dissolved oxygen and nutrient concentrations were altered between lakes when pump-storage movement occurred. Bermudez et al. (2018) found changes in temperature, stratification, and nutrients in areas in the immediate vicinity of the inlets/outlets of the reservoirs. Bonalumi et al. (2012) discovered temperatures in both reservoirs along the inlet/outlet were nearly uniform. This suggests that pump-storage dams indeed alter each reservoir's water properties. Nutrient carrying sediment exchanged between reservoirs, alters turbidity and nutrient concentration in each lake. (Bonalumi et al. 2012). Reviewed studies suggest that water quality properties are altered by pump-storage connections between reservoirs, even if results of mixing vary on a case by case basis.

Importance of river inputs

Understanding how pollutants like nutrients and sediment enter rivers is critical when rivers are diffuse sources in pump-storage systems. To limit water quality degradation of reservoirs, water quality of river diffuse sources needs improving. The correct land-use type in rivers' catchments is important in limiting stormwater runoff of sediment.

Land-use in river catchments impacts water quality (Maybeck et al. 1989; Baker 2003) causing degradation depending on land-use type. Forests filter non-point pollution through biological fixation or leaching while other land-uses like agriculture and pasture generate pollution entering waterways (De Oliveira et al. 2016). Biological fixation occurs when atmospheric nitrogen in the soil is converted by plant roots to ammonia. Leaching occurs when nitrates drain from soil into water flowing over land. Forests help decrease impairment of streams by minimizing runoff of water which reduces the loss of nitrates from soil.

Riparian forests, defined as forests directly adjacent to rivers, are critical for improving water quality by providing a sink for ammonia and a source of dissolved oxygen in streams (De Oliveira et al. 2016). Hunsaker and Levine (2004) found that forested lands with little fragmentation correlates well with low nutrient levels in streams. However, the riparian forest must be alongside the waterway to effectively assist as a buffer filtering nutrient pollutants (De Oliveira et al. 2016). Quinn et al. (1993) found that even small riparian zones have an enormous positive effect on water quality by either filtering overland flow or by removing nitrates from shallow groundwater. Since riparian zones and non-fragmented forested land are so critical for healthy rivers, they are of concern when there are stretches of land along the Pigg River without this buffer.

The conversion of forest into other land uses like pastureland/agriculture and urban land generates high nutrients and *E. coli* in rivers (Meybeck et al. 1989). Pastureland correlates strongly with higher concentrations of nitrogen, phosphorous, and turbidity in rivers (Buck et al.

2004). Nitrogen concentrations can be seven to eight times higher in an agricultural watershed (27–33 kg N ha^{-1} $year^{-1}$) when compared to a forested watershed (4 kg N ha^{-1} $year^{-1}$).

The maximum nitrate concentrations in their study occurred in areas of the watershed with extreme agricultural land cover, with minimization of nitrates in areas with extreme forest cover (Buck et al. 2004). Johnson et al. (1997) found areas of flat terrain associated with heavy agricultural areas correlated to nitrogen—related chemical parameters. Furthermore, dissolved oxygen is negatively correlated with agriculture and pasture while it is positively correlated with riparian buffers and riparian forests (De Oliveira et al. 2016).

This study seeks to explore the interrelationships between Leesville and Smith Mountain lakes as parts of a pump storage hydroelectric project with the consequence of Pigg River input onto head waters of Leesville Lake and pump back to Smith Mountain Lake. The Pigg River is suspected of transporting high concentrations of nutrients and other pollutants into Leesville Lake and subsequently to Smith Mountain Lake through pump operations. Since the Pigg River has a significant portion of land use as agriculture, there is great concern for the water quality being poor (Pigg River IP Steering Committee 2009). Understanding how pollutants like *E. coli*, phosphorous, or nitrogen enter the Pigg River, then transport to each reservoir is of critical management importance in this system. It is suspected that water quality properties are not only altered by pump-storage connections between reservoirs, but primarily through the consequence of Pigg River input onto head waters of Leesville, which, as Bermudez et al. (2018) suggests, will degrade overall water quality.

Study Site Descriptions

The Pigg River Watershed, Smith Mountain and Leesville Lakes are located in south-central Virginia in Pittsylvania Country (Figure 1). The Pigg River originates above Rocky Mount, Virginia in western Franklin Country and flows east into Leesville Lake about 6.43 kilometers downstream of Smith Mountain Lake Dam. The Pigg River watershed land use consists of a 30.3% pasture/agriculture, 64.8% forest and 4.7% urban. Land cover percentages were calculated using the United States Geological Survey's StreamStats websites (Ries et al. 2008).

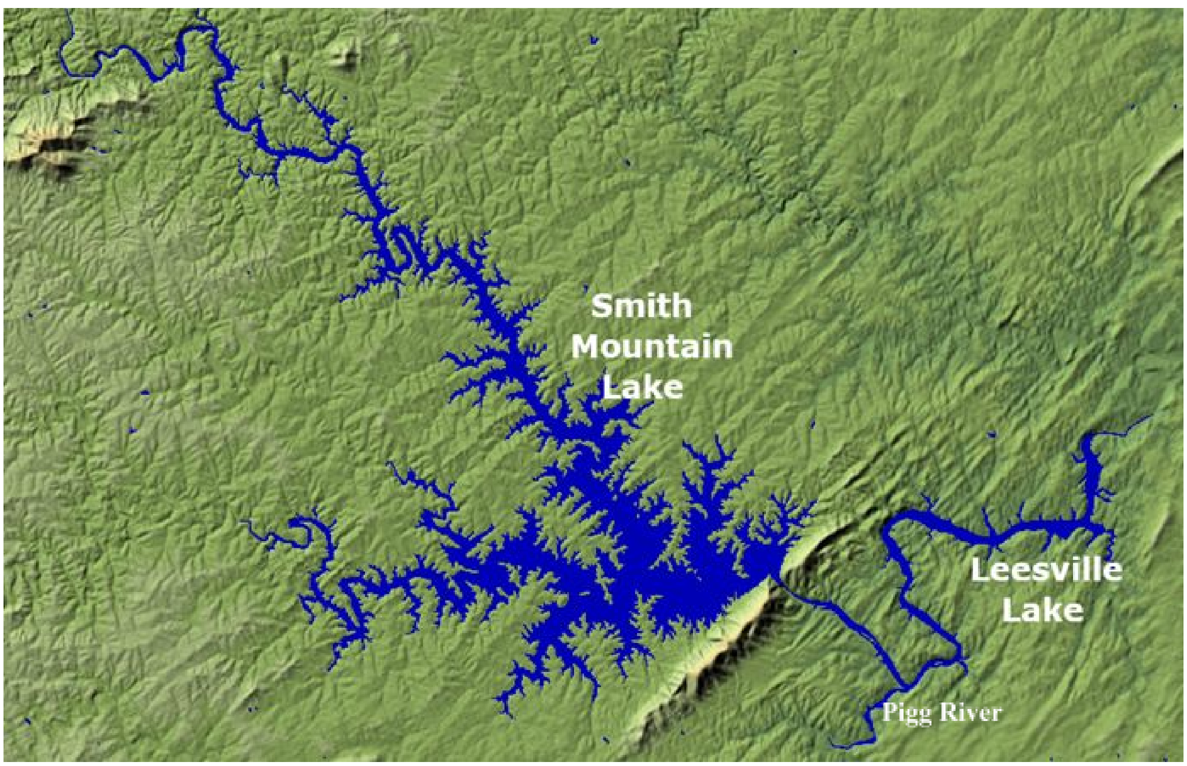

Figure 1- Aerial view illustration of Smith Mountain Lake, Leesville Lake, and Pigg River (retrieved from http://www.virginiaplaces.org/watersheds/smithmountain.html). Visual shows proximity of Smith Mountain Lake Dam located at the pass-through, Smith Mountain (hydroelectric generating source), Leesville Lake (pump storage reservoir) and entrance of Pigg River (source of water quality concerns).

Smith Mountain Lake (SML) has a surface area of 83 km^2 and is in Franklin and Pittsylvania County, with the dam located in Pittsylvania County 48.3 km downstream of SML headwaters. Leesville Lake has a surface area of 13.2 km^2 located in Pittsylvania, Bedford, and Campbell Counties. Smith Mountain Lake water quality changes moving towards the dam (Thomas et al. 2018). Total nitrogen, total phosphorus, and chlorophyll a concentrations increase as distance from SML Dam increases with significant trends of R^2= 0.5568, 0.5517, and 0.4827 respectively. Nutrients and sediment settle out of water as distances from diffuse sources increase.

Using the Carlson Trophic State Index (TSI, Carlson 1977) to characterize the lake, Thomas et al. (2018) found a very strong relationship where TSI improved as distance from the headwaters increased. The exception to the improving water quality trend was phosphorous concentrations closest to SML dam were higher than the total phosphorous trend predicted. The study attributes this to the pump-back of the Pigg River which discharges high concentrations of nutrients into Leesville Lake.

Figure 2 – View from Leesville Lake of Smith Mountain facing the dam at the Tailwater station. In the foreground of Smith Mountain is the operational bridge for the dam.

Leesville Lake is considered eutrophic (Shahady 2019) and is the focus of this study. Each sampling station is located in Leesville Lake with the following stations:

1. Pigg River Mouth at Leesville Lake— Characterized by high levels of Total Phosphorous (TP), *E. coli,* and Turbidity (Turb) (Shahady 2019). This station is referred to as the "Pigg River" in the study. The study assumes that water quality measurements at the Pigg River Mouth represent Pigg River contributions to the Leesville Lake-Smith Mountain Lake system. Water was sampled upriver, isolated from SML inputs.

2. Smith Mountain Lake (SML) Tailwater— Characterized by very good quality water from hypolimnion of Smith Mountain Lake during discharge or poor water quality during pump-back. This station is referred to as "Tailwater." This study characterizes Tailwater station as water quality below the hydroelectric dam as representative of the water quality passing through American Electric Power's turbines.

3. Toler Bridge— This station is 0.92 km downstream of the Pigg River representing water mix from Smith Mountain Lake and Pigg River. This station is referred to as "Toler Bridge." It is considered to represent Leesville Lake headwater water quality containing two sources of water which make up Leesville Lake (Shahady 2019).

4. Mile Marker 6— This station is downstream of Toler Bridge and 17.7 kilometers downstream of Smith Mountain Lake Dam. The station is referred to as "MM6." It is included in the study as a mid-point of water quality further down Leesville Lake.

5. Leesville Lake Dam— It is 27.3 km downstream of Smith Mountain Dam. This station is referred to as "LVL Dam." LVL Dam is included in the study to analyze how water quality at the end of Leesville Lake correlates to pump storage at the headwaters.

American Electric Power (AEP) operates the Smith Mountain Dam Project in Virginia which includes Smith Mountain Lake and Leesville Lake reservoirs. As part of their operational permit, dissolved oxygen (DO) passing through the pump-storage dam must be maintained above 5.0 mg/L at all times (Hreben 2019). AEP faces difficulty in meeting this requirement as Smith Mountain Lake hypolimnion may have DO below the requirement particularly during the late summer and fall seasons (Hreben 2019).

The Smith Mountain Dam was constructed in the early 1960s on the Roanoke River in Pittsylvania County Virginia by the Appalachian Power division of American Electric Power. It is located between Smith Mountain Lake and Leesville Lake, and is 248.7 meters in length and 74.6 meters in height (Hale 2016). Smith Mountain dam has five turbine/generator units generating 605 megawatts of electricity (Hale 2016). This two-reservoir system reuses water providing a renewable source of energy with close to zero emissions from greenhouse gases (Hale 2016). Leesville Lake is the storage reservoir for Smith Mountain Dam. Leesville Lake is 27.3 kilometers long and has a smaller 50-megawatt standard hydroelectric dam (Hale 2016). Smith Mountain Project is not a standard hydroelectric dam, but a pump-storage system used for hydroelectric power generation.

Methods

Two areas in each reservoir are identified by AEP for measurement of water exchange. SML tailwater measures water elevation in feet above sea level at SML dam. LVL forebay is water level at LVL dam before release into the Staunton River. This data is continuously published by AEP and I collected it from the American Electric Power website throughout the 2019 study period twice each day (AEP 2019). Data is reported here from the start of April to the end of October to correspond with our sampling season. Water quality sampling dates of collection were April 24, May 29, June 25, August 28, September 25, and October 28.

To determine the intensity and direction of water flow from pump-storage activity, I used the formula:

(1) LVL forebay elevation – SML tailwater elevation = Flow Direction

A positive calculated difference demonstrates pump-back from LVL to SML because forebay elevation is greater than tailwater elevation. This pump-storage circumstance occurs when tailwater elevation decreases below forebay elevation. For tailwater to decrease below forebay elevation, water needs to be drawn from the tailwaters and pumped-back into SML. Thus, when the formula calculates a positive difference, it shows pumping back into SML. If tailwater elevation is greater than forebay, water is added from SML into the headwater of LVL. Thus, a greater tailwater elevation results in a negative calculation in the formula. Below are two scenarios of pump-back and release of water, respectively:

LVL forebay is at an elevation of 611 ft and SML tailwater is at an elevation of 610 ft. For this scenario the formula is [611–610= 1]. The elevation difference of the two points is 1 ft, thus pump-back to SML. Or LVL forebay is at an elevation of 610 ft and SML tailwater is at an elevation of 611 ft. For this scenario the formula is [610–611= -1]. The elevation difference of the two points is -1 ft, thus release of water from SML to LVL.

I define morning as 12:00 am until 11:59 am each Julian day, and evening as 12 pm until 11:59 pm. I calculated pump-back and release information to correlate with 2019 Leesville Lake water quality data published by Shahady (2019). Thus, each morning and evening period when data was collected in this study, a flow direction was calculated. To create an index of water flow, I compiled these calculated intensities into longer term data descriptions. From the point in time prior to each water quality sampling date, the net sum of the pump-back/release difference at 24, 48, 72, 168, and 368 hours was calculated. These numbers became part of the collected data during the 2019 water quality study and form the basis of comparison in this study.

Table 1. – Calculated intensity and flow direction (negative number = release from SML to LVL and positive number = pump back from LVL to SML) of water movement between SML and LVL for various periods of time prior to each sampling date in 2019.

	24 Hours n = 2	48 hours n = 4	72 hours n = 6	168 hours n = 14	336 hours n = 28
24-Apr	1.17	0.51	1.15	-0.35	-15.65
29-May	0.67	0.08	-0.14	2.08	4.02
25-Jun	0.99	-6.64	-6.48	-5.37	-6.72
25-Jul	2.0	4.05	4.03	5.59	8.98

28-Aug	-1.48	-0.96	-0.2	-0.31	2.15
25-Sep	0.8	1.83	1.95	3.52	-1.83
28-Oct	-1.26	-0.06	0.99	3.68	-0.54

Dissolved Oxygen (DO), percent saturation of dissolved oxygen saturation (DO%), conductivity (Cond), pH, oxidation reduction potential (ORP), turbidity (Turb), Temperature (TEMP), Chlorophyll *a* (CHL), and pheophytin (PHY) were collected in the field using a Hydrolab HL7 probe (Hydrolab 2019). The instrument was calibrated before and after each use following pre and post calibration QA/QC procedures in accordance with EPA protocols (EPA 2017). Nutrient samples were collected in acid washed Nalgene bottles, carefully collecting each sample in the water avoiding contamination with debris. I used an EasyChem autoanlyzer following all procedures and QA/QC for Total Phosphorous analysis. The EasyChem analysis is compatible with Ascorbic Acid Total Phosphorus Analysis detailed in Standard Methods for Analysis of Water and Wastewater (Baird and Bridgewater 2017). I used a modified NO^{3-} analysis compatible with Standard Methods and EasyChem analysis (Chinchilla 2008).

To measure bacterial contamination, I used the Colilert-18 test to quantify *Escherichia coli* concentration levels. The Colilert-18 is an approved test meeting all EPA standards for testing (Warden et al. 2011). This methodology uses MPN to quantify E. *coli* and I report my findings as MPN/100 ml of sample in accordance with federal and state standards.

Data Analysis

I used Principle Components Analysis (PCA) and Regression using XLSTAT (Addinsoft 2019) to examine all relevant correlations of measured parameters for water quality. PCA standardized all variables equally, then correlated each parameter to a common factor. From PCA analysis, I inferred the relationships between data, reporting positive and negative covariance variation along each factor axis as strength of the relationship. PCA searches for the highest variance and captures the best angle to analyze the data, continuing this until there is no more variance (Jaadi 2020). Regression analysis further explored relationships in the data.

Results

To establish patterns in release and pump-back of water between reservoirs, I plotted collected data across Julian Days (Fig 3). There is no discernable pattern when American Electric Power pumps or releases water between SML and LVL. However, volume of water release did show a pattern. Release intensity (from SML to LVL) is greater and is for fewer consecutive days in duration than pump-back (from LVL to SML). This conclusion is inferred from the distance of values deviating from the baseline and consecutive days in which this deviation occurred. This pattern suggests quantities of water delivered to the storage reservoir may have a greater instantaneous water quality impact than water pumped-back to SML based on volume.

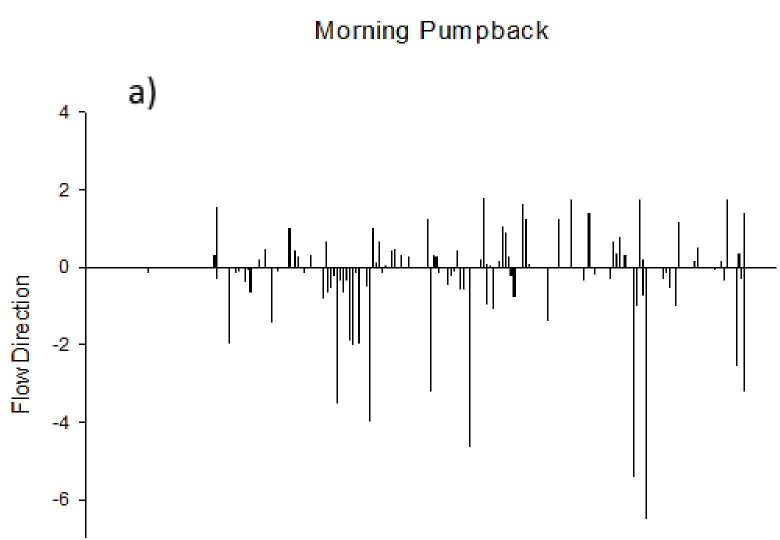

Figure 3 - The difference in measured elevation between the LVL forebay and SML tailwater in feet plotted during a) morning (12:00 am – 11:59 am) and b) evening (12:00 pm to 11:59 pm). Positive values on the y-axis represent flow direction to SML and negative values represent flow direction into LVL. The greater deviation from 0 feet baseline, the greater the intensity.

Water quality parameters throughout Leesville Lake suggest an interesting pattern based upon tailwater release from SML and input from Pigg River (Table 2). Data suggests Pigg River input is clearly degraded with measures ranging from eutrophic to hypereutrophic. Conversely, tailwater readings vary from mesotrophic to eutrophic. Water quality at Tailwater station is dependent upon pumping direction before a sampling event. Toler Bridge is often a combination of both Pigg River and Tailwater input additionally impacted by directional flow. The remaining stations down Leesville Lake operate as a eutrophic reservoir with some improvement in conditions as water flows toward the dam.

Table 2.— Means and Standard Error readings for each of the studied stations in 2019 as described in the text. Temp = Temperature (C), DO = Dissolved Oxygen (mg/L), E. coli = cfu/100 ml, Cond. = Conductivity ms/cm, pH, Turb. = Turbidity (NTU), Chl *a* = Chlorophyll *a* (ug/L), NO_3 = Nitrate mg/L, TP = Total Phosphorus (mg/L).

	Temp	DO	E. coli	Cond	pH	Turb.	Chl *a*	NO_3	TP
Pigg River	21.3 ± 1.1	8.1 ± 0.2	3670 ± 3421	0.07 ± 0.00	7.4 ± 0.0	90.4 ± 67.5	7.8 ± 1.6	2.61 ± 0.5	0.26 ± 0.15
Tailwater	19.2 ± 1.6	7.5 ± 0.5	171 ± 136	0.15 ± 0.01	7.4 ± 0.0	9.8 ± 3.3	7.0 ± 1.7	2.02 ± 0.3	0.08 ± 0.02
Toler Bridge	20.7± 1.2	7.5 ± 0.5	1296 ± 1228	0.14 ± 0.01	7.5 ± 0.0	32.4 ± 22.3	10.7 ± 2.5	2.21 ± 0.3	0.13 ± 0.06
MM6		9.3 ± 0.3	24.8 ± 18			6.4 ± 1.0	16.2 ± 2.8		0.07 ± 0.01
LVL Dam		9.3 ± 0.3	19.0 ± 13.5			4.0± 0.8	16.8 ± 4.3		0.07 ± 0.01

Because pumping direction and duration of water flow between Leesville and Smith Mountain lakes is assumed influential on observed water quality, I analyzed key water quality parameters at Tailwater station in relationship to water flow between the reservoirs (Fig 4.). Water quality along F1 axis demonstrates an expected response to eutrophic conditions in reservoirs. With increasing Temp, Chl *a*, *E. coli* and Turb. we see corresponding decreases in pH, Cond, NO_3, and Oxygen. One exception is TP as it did not correspond along either axis.

Interestingly, the movement of water dominated predictions along the positive portion of the F2 axis. When coupled with predictions along the F1 axis, the longer duration of time of pumping (compare 24 hr. to 336 hr. diff.) correlates with the water quality pattern observed. Thus, short-term pumping associated with declining parameters, such as pH and Cond, and long-term pumping associated with increasing Temp, Chl *a* and Turb. Thus, both water quality and pumping patterns are useful descriptors of water quality patterns observed at the Tailwater site.

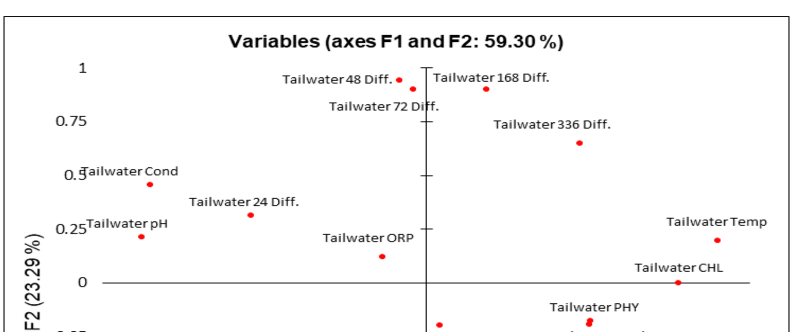

Figure 4— Principal Component Analysis of Tailwater water quality parameters plotted using F1 and F2 on each axis. These two factors accounted for 59.3% of all variability in this data set. F1 on the x-axis represents Factor 1, or Principal Component 1, and F2 on y-axis represents Factor 2. The greater the distance each datum point deviates from an axis, the greater influence that individual water quality parameter on each predictive factor.

Squared cosines values for each variable support my conclusions (Table 3). Key water quality parameters: Temp (0.811), CHL (0.610), pH (0.774), Cond (0.728), and NO_3 (0.637) have strongest correlations on the F1 axis. Key water pumping parameters strongly associate along the F2 axis. Short-term release (24 Diff.) associates with Cond, pH, $NO_{3,}$ DO%, and DO decline on F1 axis, while long-term release (336 Diff.) associates with increasing Temp, CHL, PHY, *E. coli*, and Turb. Pump durations of 48, 72 and 168 hours, while an important part of the F2 axis, do not correlate strongly on the F1 axis. This suggests water quality at Tailwater station is immediately (within 24 hours) or much longer (336 hours) influenced by pumping activities.

Table 3.— Squared cosines of all water quality parameters suggesting the importance of each measured parameter at Tailwater station along the F1 and F2 axes. Values in bold correspond to each variable for which the squared cosine is the largest. The greater the squared cosine, the greater the link with the corresponding axis

Squared cosines of the variables:

	F1	F2
Tailwater 24 Diff.	0.294	0.100
Tailwater 48 Diff.	0.007	**0.893**
Tailwater 72 Diff.	0.002	**0.811**
Tailwater 168 Diff.	0.035	**0.814**

Since pump-storage operations interconnect Pigg River, Tailwater, and Toler Bridge to the same system, I analyzed key water quality parameters in relationship to their sampling location within Leesville Lake (Fig. 5). The F1 axis suggest that declining CHL at all stations and turbidities are associated with increasing Dissolved Oxygen, pH at Tailwater and Toler Bridge, and rising Cond at Tailwater.

These relationships suggest that much of the water quality changes observed at Tailwater station are driven by Pigg River input rather than release from SML. Trends along F2 axis suggest declining Temp and Cond at Pigg and Toler associate with increasing Turbidity, *E. coli* and Nitrates from these same stations. While these results suggest Toler Bridge water quality is driven by Tailwater, position of additional data along each axis emphasize the complex nature of water exchange between these three stations.

In some instances, I see the direct influence of Pigg River on overall water quality in the headwaters of LVL. Yet, some conclusions from Figure 5 suggest Tailwater and Toler stations have greater correlation. This suggests tailwater release is often a mixture between the Pigg

River and SML hypolimnion and elements of Pigg River water quality are often seen at Toler Bridge.

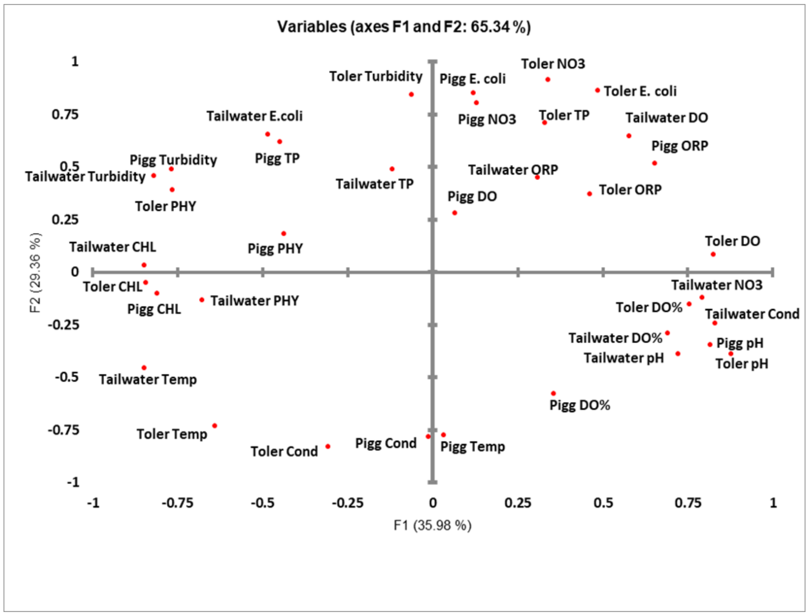

Figure 5— Principal Component Analysis of Tailwater, Toler, and Pigg water quality parameters. F1 on the y-axis represents factor 1, or principal component 1. The greater the distance the data deviates from the y-axis, the greater influence that individual water quality parameter has affecting all other water quality parameters. The greater the data deviates from the x-axis for Factor 2, the greater the influence that individual water quality parameter has on affecting all other water quality parameters

Further, the cluster of all CHL for all stations correlated with each other supports the idea that these stations are all part of the same system in some way. Since Pigg River was sampled at a location isolated from Tailwater release, the correlation suggests Pigg River turbidity is essentially Tailwater turbidity. Therefore, when tailwater turbidity is very low (Table 2) and near zero then release is only from SML. Therefore, I infer that the Pigg River generates observed Tailwater turbidity. Toler Bridge turbidity is not clustered near the other two stations, suggesting Pigg River is not the direct influencer on Toler Bridge, but that Toler Bridge is more of a mix between Tailwater and Pigg River.

Analyzed data supports the following pattern in the headwaters of LVL. Water flow from Pigg River dominates water quality at the Tailwater station. Pigg River's effect on Tailwater is generated by the pump back operation of AEP. Through continued water movement, Tailwater influences Toler station more so than Pigg River input. Thus, the overall predominate water flow impacting water quality of LVL is Pigg River.

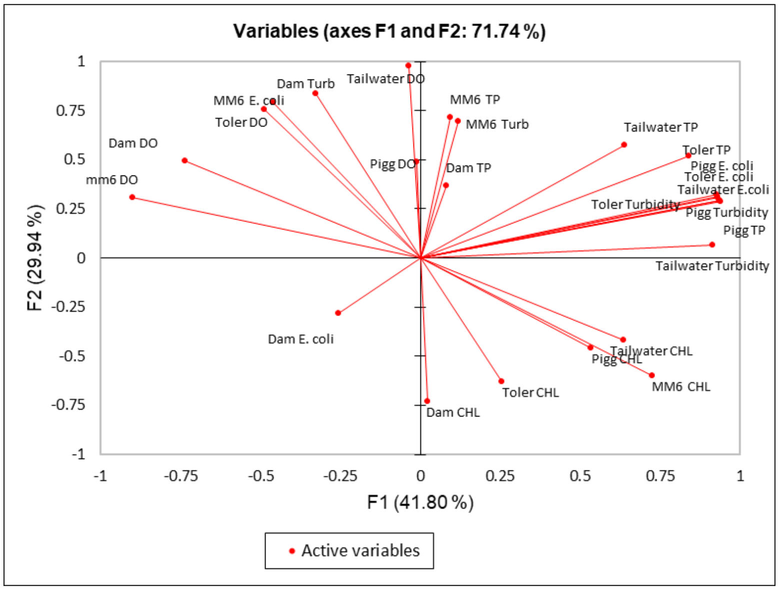

Figure 6— Principal Component Analysis of Pigg River, Tailwater, Toler Bridge, MM6, and Dam LVL Dam water quality parameters. F1 on the y-axis represents factor 1, or principal component 1. The greater the distance the data deviates from the y-axis, the greater influence that individual water quality parameter has affecting all other water quality parameters. The greater the data deviates from the x-axis for Factor 2, the greater the influence that individual water quality parameter has on affecting all other water quality parameters.

To determine how water quality parameters trended throughout the rest of LVL, I analyzed key water quality parameters in relationship to five different stations located throughout the lake (Fig. 6). The purpose is to analyze how lower portions of the lake (MM6 and Dam) are influenced now through the understanding of the operation of the upper portion lake.

Decreasing DO at MM6 and Dam correlate to increasing Turb, TP, CHL, and *E. coli* for all the headwater stations. Water quality parameters at the headwater stations correlate together independent of the remainder of the lake. This suggests that headwater water quality is isolated from the remainder of LVL. The contrast between the lower and upper reservoir is more apparent when correlated along the F2 axis. Decreasing CHL in the lower portion of the reservoir correlates with increasing DO at Tailwater, Dam turbidity, and multiple parameters at MM6.

The final concern I addressed in this study was the relationship between water movement and dissolved oxygen concentrations at the Tailwater station. For 2019, after regression of all variables, I found a significant relationship ($p = 0.038$) between long term pump-storage release (two weeks) and percent of oxygen concentration in the tailwater. This relationship suggests that during long term pump-back periods, water from Pigg River decreases oxygen concentrations at Tailwater station while long term periods of release from SML increase oxygen. Correlations with all other pumping durations were not significant.

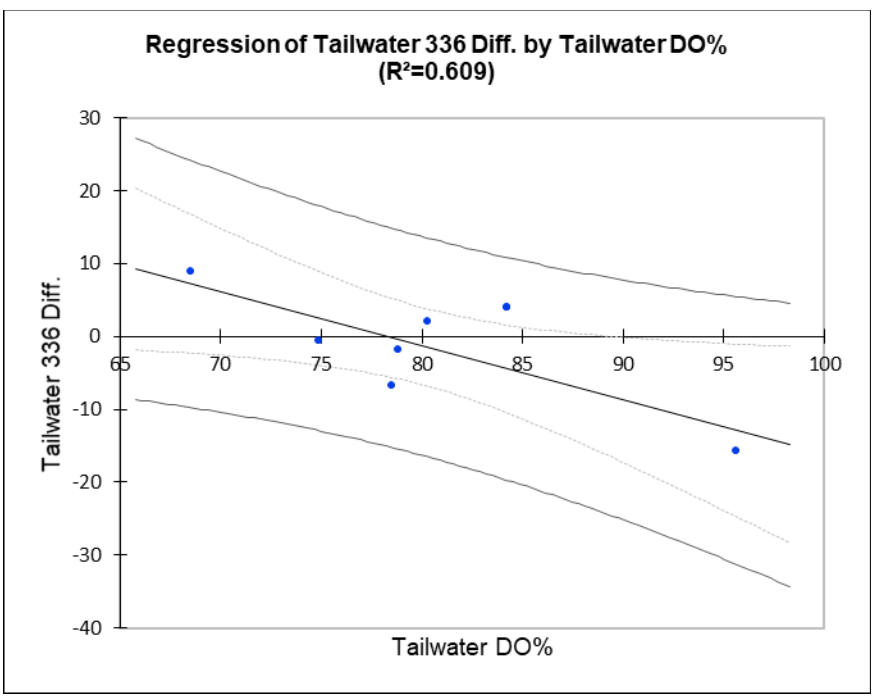

Figure 7— Relationship between Tailwater DO% and calculated pumping direction and intensity for 368 hours (two weeks) prior to sampling time and date. A negative difference represents release from SML to LVL and positive difference represents pump-back from LVL to SML.

Discussion

Water exchange between SML and LVL is clearly driven by external demands for electricity and not necessarily the interrelationship between reservoirs. Harby et al. (2013) and Vojvodic et al. (2016) describe these systems as very nimble with an ability to respond to energy demand quickly both on a local level and to the grid. I can infer the response to energy demand is what drives the dam operation and water exchange patterns between these reservoirs, as any discernable pattern of pump-back or generation did not emerge. Thus, any water quality conclusions must be based upon empirical observation about water exchange rather than seasonality or other inferred patterns.

In this study, I focused on the interrelationship between operation of SML dam, headwaters of LVL, and understanding water flow impacts on water quality. It is clear from collected data that general water quality is degraded in the headwaters of LVL due to the Pigg River input. The exchange of water between pump-storage reservoirs is known to impact water quality (Anderson 2010; Gailiusis 2003; Kobler et al. 2018; Bermudez et al. 2018) through alteration in stratification patterns. Temperature differences between Pigg River and SML hypolimnion may exacerbate pollution as cool SML hypolimnion buoys warm Pigg River input. This temperature difference allows greater volumes of Pigg River input to flow over cooler hypolimnion water into SML during pump-back. Since most of the water driven into SML forebay during pump-back is Pigg River water the impacts of this may be profound.

Further, overall water quality is known to be impacted between pump-storage reservoirs through pumping activity (Potter et al. 1982) and from water level fluctuations (Zohary and Ostrovsky 2011). In characterizing the water quality of the upper reservoir Smith Mountain Lake, Thomas et al. (2018) found water quality to improve over distance toward Smith Mountain Dam changing from eutrophic to mesotrophic. When examining the DO profiles from the SML headwaters to the Dam, Thomas et al. noted DO follows a gradient indicating eutrophic to mesotrophic to near oligotrophic conditions near the dam. Hreben (2019) found SML tailwaters' average monthly DO to be degraded (defined as below 5mg/L) between September (4.51 mg/L) and October (4.32 mg/L). The study period (June 1- November 30) included 4096 readings of DO, and a minimum of 5 mg/L daily average was achieved only 47% of the time. While not severe, oxygen loss into the hypolimnion of SML occurs and must be considered a source of degradation as water flows over turbines at SML.

Jones et al. (2011) found the greatest contributor to observed oxygen loss in the hypolimnion of Missouri Reservoirs was productivity measured by Chlorophyll *a* production. As Smith Mountain Lake becomes near oligotrophic at the Dam, reduced oxygen loss is not an expectation as CHL is low. Leesville Lake headwaters conversely range from eutrophic to hypereutrophic producing high amounts of decaying organic matter entering from Pigg River. American Electric Power (AEP) uses generating units 2, 3, and 4 primarily because these units draw water from above the thermocline in SML where oxygen concentrations are greater than measured below the thermocline (Hreben 2019). The degraded tailwater measures in LVL suggest the units are drawing from a degraded forebay. If the forebay is isolated from SML (Figure 1), it may operate independently from SML water quality observations. My conclusions suggest this. The tailwater chlorophyll *a* reflects higher readings similar to Pigg River (Table 2) rather than 3.2 ug/L measured in SML near the dam (Hreben 2019). Mixing due to the circulation effect of pump-storage operation (Lindim et al. 2011) is known to degrade water quality in the forebay of these systems.

Unanswered questions remain whether the observed degraded water quality at the Tailwater station is only from the remnants of Pigg River water remaining in the area from a pump-back event or degraded SML forebay release. The relationship between long pump-back periods (Fig 7) and loss of oxygen in tailwater release suggest that Pigg River pump-back is degrading SML forebay and is the source of the problem. High algal productivity is inferred to create low dissolved oxygen problems when the algae die and decompose (Jones et al. 2011). While oxygen loss in the hypolimnion occurs in SML beginning in September and October (Hreben 2019), tailwater observations suggest it is more severe than expected simply from SML release alone. While I observed that the 24-hour release period has an impact in driving the DO down in the tailwaters (Fig. 4), it was the long-term pump-back (336 hours) that correlated with changes in oxygen and thus the degradation of SML forebay.

This observation has implications on SML dam operations. The 24-hour release period represents effects of short-term release and influences the driving down of DO in the tailwaters (Fig. 4). This decrease in DO makes sense as low oxygen release from a degraded SML forebay to LVL headwaters would quickly lower oxygen levels. Longer term pumping patterns are more difficult to interpret. The 48, 72, and 168-hour pump-activities are so close the zero point on the F1 axis, they do not greatly influence the changes in DO. Pumping duration of 336 hours appears to have a clearer impact on water quality. Pumping from LVL to SML over this period of time did appear to decrease oxygen levels in the tailwaters. At this duration of pumping, I found a relationship with different points of the sampling year for DO (Fig. 7), which suggests extreme long durations of pumping and extreme short durations of release may both reduce oxygen levels in the tailwaters.

The reason DO depletion is less affected when water is released for a longer period has two parts. The first is when electricity is being generated, and water is being released, the pump-storage dam is not in a pump-back period. So, the nutrient rich water of the Pigg River is not being drawn up to the forebay during release. The second reason is the tailwater of Smith Mountain Dam is continually being diluted by the more mesotrophic Smith Mountain Lake water. Therefore, the longer water is released from Smith Mountain Dam the more we will see LVL tailwater reflect the better water quality of SML.

At 336 hours of net pumping-back, we see DO driven down and CHL, Turbidity, and *E. coli* driven up. This trend appears to show Tailwater is moving towards a reflection of Pigg station. Higher concentrations of CHL, Turbidity, and *E. coli* are often synonymous with river diffuse sources entering lakes (Lindim et al. 2011). These parameters drive DO down by increasing nutrient enrichment leading to increased Chl *a.* Enrichment has been found to speed up the onset of anoxia (Jones et al. 2011). It is reasonable then during long-term pump-back we see DO driven down in Tailwater when enriched Pigg River waters are moved to LVL headwaters.

When analyzing how the pump-storage operations affect the entirety of LVL, it appears the headwaters operate independently from the lower section of the reservoir (Fig. 6). Pump-storage effects are isolated to the Pigg, Tailwater, and Toler stations. Correlation trends of parameters suggest substantial quantities of Pigg River water flows and impacts Tailwater. Then during generation periods, we see Tailwater as the primary influencer on Toler Bridge area in LVL (Fig. 5). This movement of water is consistent with a model of water constriction (Lindim et al. 2011), and the pump-storage dynamics of these reservoirs (Gailiusis 2003; Heinonen et al. 2000).

DO decreases in water when it settles or becomes stagnant (Michaud 1991). The active movement of water between Pigg, Tailwater, and Toler due to pump-storage operations assures DO does not diffuse into the atmosphere as quickly as if it were stagnant. It makes sense that we see DO in the lower reservoir decrease from typical concentrations when nutrients in the upper reservoir increase (Fig. 6). Oxygen depleted headwaters due to nutrient enrichment flow and settle in the lower reservoir (outside the pump-storage system). The settling of degraded water allows for further depletion of DO.

Even though the upper reservoir can have a slight impact on the lower reservoir, this impact is small as water quality greatly improves at MM6 and Dam (Table 2). This vast improvement in DO, *E. coli,* and Turbidity suggests the lower section of the LVL is largely isolated from the degrading effects of Pigg River influx coupled with pump-storage operation. Rather, we see the trend of improvement Thomas et al. (2019) documented in SML. Therefore, it appears the pump-storage operation, paired with the influx of nutrients from the Pigg River, acts similar to that of headwaters in a natural reservoir. We see a section of degraded water quality where over increased distance water quality can improve and move towards a more mesotrophic classification (Lindim et al. 2011).

Conclusion

This study aimed to identify how the behavior of the pump-storage dam paired with the influx of impacted water from the Pigg River impacted the tailwaters at Smith Mountain Dam and Leesville Lake. A primary weakness of this study is a lack of targeted data since we could only sample once a month at predetermined times. Ideally, we would be able to sample on many days throughout the study period at times that would yield the exact relationships from pumping data collected, but the lack of human power and the amount of time it takes to collect data limits this from happening. I did discover the behavior of the pump-storage dam does have an influence on the water quality in the tailwaters. Specifically, longer-term pumping appears to impact Tailwater DO%. This information may have implications on permitting of the dam. Further analysis of the data may lead to more understanding in how the pumping behavior of the pump-storage dam affects the Tailwater variables.

Acknowledgements:

I acknowledge Dr. Thomas Shahady's primary role in data collection and mentorship for this study.

References

Abdi H and Williams L. 2010. Principal Component Analysis. Wiley Interdisciplinary Reviews: Computational Statistics. 2:433-459.

Addinsoft. 2019. XLSTAT statistical and data analysis solution. Long Island, NY, USA. https://www.xlstat.com.

Anderson MA. 2010. Influence of pumped-storage hydroelectric plant operation on a shallow polymictic lake: predictions from 3-D hydrodynamic modeling. Lake Reserv. Manage. 26:1–13.

Baird RL, Bridgewater L. 2017. Standard methods for the examination of water and wastewater. 23rd edition. Washington, D.C.: American Public Health Association.

Baker A. 2003. Land use and water quality. Hydrol. Process. 17: 2499–2501

Bermudez M, Cea L, Puertas J, Rodriguez N, Baztan J. 2018. Numerical Modeling of the Impact of a Pumped-Storage Hydroelectric Power Plant on the Reservoirs Thermal Stratification Structure: A Case Study in NW Spain. Environ. Model. Assess. 23:71-85.

Bhateria R and Jain D. 2016. Water quality assessment of lake water: review. Sustainable Water Resources Management. 2:161-173.

Bonalumi M, Anselmetti FS, Wüest A, Schmid M. 2012. Modeling of temperature and turbidity in a natural lake and a reservoir connected by pumped-storage operations. Water Resources Research. 48:1-19.

Carlson R.E. 1977. A trophic state index for lakes. Limnology and Oceanography. 22:361-369.

Chinchilla C. 2008. Automated Colorimetric Method for Nitrate Analysis. Lab Manager 3:24-27.

de Oliveira LM, Maillard P, de Andrade Pinto EJ. 2016. Modeling the effect of land use/land cover on nitrogen, phosphorous, and dissolved oxygen loads in the Velhas River using the concept of exclusive contribution area. Environ. Monit. Assess. 188:1-19.

Michaud, J. 1991. A citizens' guide to understanding and monitoring lakes and streams. Washington State Department of Ecology Publications. Pullman, Wa.

EPA. 2017. Standard operating procedure calibration of field instruments. Quality Assurance Unit U.S. Environmental Protection Agency - Region 1, North Chelmsford, MA.

Gailiusis B. 2003. Modelling the effect of the hydroelectric pumped storage plant on hydrodynamic regime of the Kaunas Reservoir in Lithuania. Nordic Hydrol. 34:507–518.

Hale J. 2016. Smith Mountain Dam is a marvel or machinery. Smith Mountain Laker Magazine. [cited 2019 October 22]. Available from: https://www.smithmountainlake.com/news/local/smith-mountain-dam-is-a-marvel-of-machinery/article_b346088b-ddd5-5cec-9bf8-8a68132f410d.html

Harby A, Sauterleute J, Korpas M, Killingtveit A, Solvang A, Nielsen T. 2013. Pumped Storage Hydropower. Transition to Renewable Energy Systems. Wiley. pp. 597-618

Heinonen P, Ziglio G, Van Der Beken A, editors. 2000. Hydrological and limnological aspects of lake monitoring. West Sussex (UK): John Wiley and Sons.

Hreben MJ. 2019. 2018 Annual Report Water Quality Monitoring Program and Dissolved Oxygen Enhancement Evaluation. Strasburg (PA): Kleinschmidt.

Hunsaker CT, Levine DA. 1995. Hierarchical approaches to the study of water quality in rivers. BioScience. 45:193–203.

Jaadi Zakaria. 2020. A Step by Step Explanation of Principal Component Analysis. [cited March 17] Available from https://builtin.com/data-science/step-step-explanation-principal-component-analysis

Johnson L, Richards C, Host G, Arthur J. 1997. Landscape influences on water chemistry in Midwestern stream ecosystems. Freshwater Biology. 37:193-208.

Jones J, Knowlton M, Obrecht D, Graham J. 2011. Temperature and oxygen in Missouri reservoirs. Lake Reserv. Manage. 27:173–182.

Kobler UK, Wüest A, Schmid M. 2018. Effects of Lake–Reservoir Pumped-Storage Operations on Temperature and Water Quality. Sustainability. 10:1968-1983.

Lindim C, Pinho J, Vieira J. 2011. Analysis of spatial and temporal patterns in a large reservoir using water quality and hydrodynamic modeling. Ecological Modeling. 222:2485-2494.

Meybeck M, Chapman DV, Helmer R. 1989. Global Freshwater Quality, a First Assessment. WHO and UNEP/Blackwell Ltd.

[OTT Hydromet] Hydrolab. 2019. [cited 20 November 2019] Available from https://www.hydrolab.com/

Pigg River IP Steering Committee. 2009. Pigg River and Old Womans Creek Watershed TMDL Implementation Plan. (VA): Virginia Department of Environmental Quality

Potter DU, Stevens MP, Meyer JL 1982. Changes in physical and chemical variables in a new reservoir due to pumped storage operations. Water Resour. Assoc. 18: 627–633.

Quinn JM, Cooper AB, Williamson RB, editors. 1993. Riparian zones as buffer strips: A New Zealand perspective. Ecology and Management of Riparian Zones in Australia. Canberra: 93:53-88.

Ries KG, Guthrie JD, Rea AH, Steeves PA, Stewart DW. 2008. StreamStats: A water resources web application: U.S. Geological Survey Fact Sheet 2008-3067.

Salvia-Castellv´ı M, Iffly JF, Borght PV, Hoffmann L. 2005. Dissolved and particulate nutrient export from rural catchments: a case study from Luxembourg. Science of the Total Environment. 344:51-65.

Shahady T. 2019. Leesville Lake 2018 Water Quality Monitoring. American Electric Power and Leesville Lake Association. Lynchburg (VA): University of Lynchburg.

StreamStats. 2019. [cited 20 Nov 2019]. Available from https://streamstats.usgs.gov/ss/

Thomas CL, Puccio MA, Heck DR, Johnson DM, Pohlad BR, Love CC. 2018. Smith Mountain Lake Water Quality Monitoring Program. Ferrum (VA): School of Natural Sciences and Mathematics Ferrum College.

Vojvodic G, Jarrah A, Morton D. 2016. Forward thresholds for operation of pumped-storage stations in the real-time energy market. European Journal of Operational Research. 254:253-268.

Warden PS, DeSarno MS, Volk SE, Eldred J. 2011. Evaluation of Colilert-18 for Detection and Enumeration of Fecal Coliform Bacteria in Wastewater Using the U.S. Environmental Protection Agency Alternative Test Procedure Protocol. Journal of AOAC International. 94:1573-1580.

World Population Review. Rocky Mount, VA Population 2019. 2019. [cited 23 Oct 2019] Available from http://worldpopulationreview.com/us-cities/rocky-mount-va-population/

Zohary T and Ostrovsky I. 2011. Ecological impacts of excessive water level fluctuations in stratified freshwater lakes. Inland Waters. 1:47–59.