Final Report: Turbidity and Flow Monitoring in Lake Merriweather



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1.0 INTRODUCTION

1.1. Background

Under the Federal Clean Water Act (1972), states are required to assess the quality of their waterbodies and develop clean-up plans for waters that do not meet water quality standards. In 1996, the Little Calfpasture River was listed as not meeting the general water quality standard for aquatic life. The reason for the impairment was determined to be excess sediment, and in 2010, the Virginia Department of Environmental Quality (VDEQ) developed a Total Maximum Daily Load (TMDL) for sediment in the Little Calfpasture River (VDEQ, 2010). This TMDL called for an overall 56% reduction in sediment from the watershed and a 34% reduction in sediment from the management of Lake Merriweather.

Lake Merriweather is a 444-acre lake located on the Little Calfpasture River in Rockbridge County, Virginia. The lake and the dam are owned and operated by the National Capital Area Council of the Boy Scouts of America. The lake receives sediment loads from upstream, and much of that sediment settles in the lake. During the winter, however, current lake management practice is to lower the level of the lake for maintenance and removal of debris. During this time period of lake drawdown, exposed mudflats erode during storm events and move excess sediment downstream below the lake, impacting benthic aquatic life.

In 2018, VDEQ developed a Water Quality Improvement Plan (VDEQ, 2018) designed to implement the 2010 TMDL. This plan recommended actions that could be taken to meet the required reductions in sediment. These actions included agricultural control measures, such as livestock exclusion, riparian buffers, and improved management for pastures, cropland, and timber harvesting. The plan also recommended lake management control measures to reduce the load of sediment coming from Lake Merriweather. These control measures included reducing the depth or the amount of time that the lake is drawn down in the winter, revegetating exposed mudflats, excavating sediment from mudflats, and stabilizing the emergency spillway.

Modeling suggests that these lake management control measures can reduce sediment loads by 34%, however, there is great uncertainty in these estimates. In addition, sediment loads are dynamic and respond to changing weather conditions and operation of the dam. This project was designed to develop a lake management tool to assess sediment conditions in real time and inform

lake management so that dam operations can be optimized to meet stakeholder needs and reduce sediment loads.

1.2. Project Objectives

This project was designed to develop a lake management tool to optimize lake management control measures and ensure that they meet sediment reduction goals (Brent, 2021). More specifically, project objectives were to:

- Install and maintain real-time depth and turbidity monitoring equipment at Lake Merriweather for one year
- Use turbidity monitoring data to make recommendations for lake management
- Train project partners to maintain equipment long-term.

By achieving the objectives described above, this project will deliver the following outcomes:

- Improved understanding of the impact of lake management decisions on turbidity levels
- Lake management that decreases downstream sediment loads.

1.3. Project Personnel and Organization

This project was funded by the Environmental Protection Agency (EPA) through a grant from the VDEQ. JMU coordinated with Nesha McRae from VDEQ and other project partners throughout the project based on the organizational chart in Figure 1. Important project partners included the following:

- VDEQ – provided funding and project oversite
- JMU – provided procurement of equipment, one-year monitoring effort, summary and recommendations for lake management, and training for project partners
- Rockbridge County – provided project grant and subcontract to JMU, coordination among partners, and long-term equipment maintenance
- Boy Scouts of America – provided site access and technical assistance

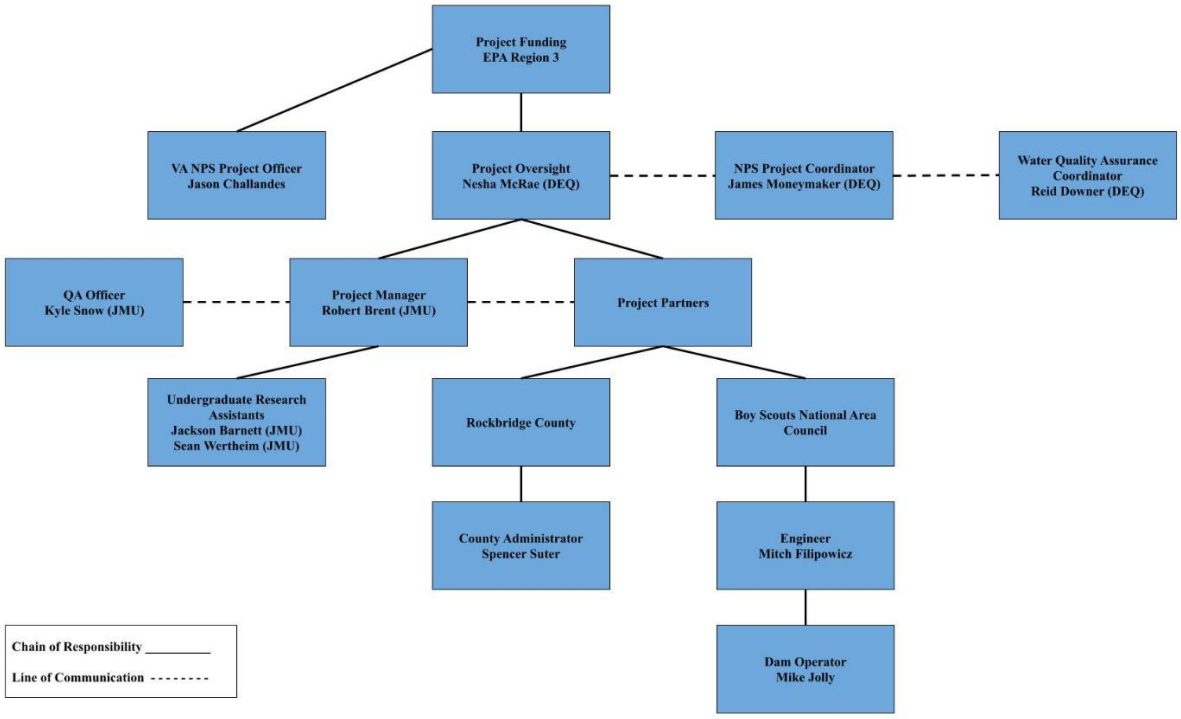


Figure 1. Project organizational chart.

JMU personnel involved in project implementation are listed in Table 1, with assigned responsibilities. Dr. Robert Brent was the Project Manager, Kyle Snow was the QA Officer, and Jackson Barnett and Sean Wertheim were Undergraduate Research Assistants.

Table 1. Project implementation personnel.

Name	Role in Project, Title, Organizational Affiliation	Responsibilities
Dr. Robert Brent	Project Manager, JMU	• Developing project plans and schedules • Overseeing implementation of the project • Ordering equipment and supplies • Training personnel • Managing Undergraduate Research Assistants • Reporting results
Kyle Snow	QA Officer, JMU	• Maintaining the official, approved QAPP • Assisting with ordering equipment and supplies • Calibrating equipment for secondary turbidity confirmation • Reviewing installation and standard operating procedures • Reporting equipment or QA issues to the Project Manager

Jackson Barnett	Undergraduate Research Assistant, JMU	• Installing and maintaining equipment • Cleaning and calibrating equipment • Performing QC checks • Downloading and storing data
Sean Wertheim	Undergraduate Research Assistant, JMU	

1.4. Project Tasks and Schedule

The project was designed to develop a lake management tool to optimize lake management control measures and ensure that they meet sediment reduction goals. To meet this objective, the following tasks were accomplished according to the schedule in Table 2.

- Purchase and Install Equipment - The project procured and installed monitoring equipment to measure lake level and downstream turbidity in real time and transmit that information to project partners.
- Train Field Staff – Once equipment was purchased and installed, field staff (JMU Undergraduate Research Assistants) were trained on operating and maintaining the equipment. This includes routine maintenance and periodic QA checks.
- Data Collection – JMU collected continuous turbidity and depth data for a one-year period. Data were downloaded monthly, processed, stored, analyzed, and used to make lake management recommendations.
- Routine Maintenance and QA Checks – During the one-year deployment, the probes were maintained and QA checks completed on a regular basis. Maintenance and QA checks were completed every 15 days during the summer and 30 days during the winter. During each visit, probes were cleaned, calibration checks were performed (low and high), and a precision check was performed (pre-service and post-service).
- Train Project Partners - After one year of testing and operation, project staff trained project partners to maintain the equipment long-term.
- Final Report – This report summarizes the work completed under the project and details the findings and recommendations resulting from the project.

Table 2. Project schedule.

Task Name	Task Description	Start Date	End Date
Prepare QAPP	Prepare draft of QAPP, circulate to project partners, and get review and comments from VDEQ	3/1/2022	3/15/2022
Purchase and Install Equipment	Install equipment on the Lake Merriweather Dam	4/1/2022	5/31/2022
Train Field Staff	Field staff will be trained on equipment operation, maintenance, and QA assessments	4/1/2022	6/1/2022
Collect Data	Collect data continually and download data periodically	6/1/2022	4/15/2023
Routine Maintenance, QA Checks (Summer)	Field visits to clean the instruments and check calibration during will be required every 30 days during the summer	6/1/2022 6/15/2022 7/1/2022 7/15/2022 8/1/2022 8/15/2022 9/1/2022	6/15/2022 6/30/2022 7/15/2022 7/31/2022 8/15/2022 8/31/2022 9/15/2022
Routine Maintenance, QA Checks (Winter)	Field visits to clean the instruments and check calibration during will be required every 60 days during the summer	10/1/2022 11/1/2022 12/1/2022 1/1/2023 2/1/2023 3/1/2023	10/31/2022 11/30/2022 12/31/2022 1/31/2023 2/28/2023 3/31/2023
Train Project Partners	Train project partners on the use and maintenance of equipment	3/1/2023	4/1/2023
Final Report	Prepare and submit final report on findings	4/1/2023	5/31/2023

2.0 MATERIALS AND METHODS

2.1. Equipment

For the project, a remote monitoring system was designed and installed on the Lake Merriweather dam to monitor, record, and transmit turbidity and depth data from the lake. The monitoring system included a turbidity sensor to measure turbidity, a pressure transducer to measure depth, a data logger to record and store data, a cellular modem to transmit data, a battery pack to provide continuous power, a solar panel to charge the battery, and a weather-resistant

case to house the electrical equipment. This equipment is listed in Table 3 with life expectancy and maintenance requirements.

Table 3. List of equipment with anticipated life expectancy and routine maintenance.

Equipment	Description	Life Expectancy	Maintenance
	ClariVUE 10 side-scatter turbidity sensor	10 yr	-Clean each field visit (0.5-1 mo.) -Factory recalibration when QC calibration checks fail or every 2 years
	CS451 pressure transducer	10 yr	-Clean each field visit (0.5-1 mo.) -Factory recalibration when QC calibration checks fail or every 2 years
	CR-350 datalogger	15 yr	-Inspect connections for corrosion and contact (6 mo.)
	Cell210-V-25-Y1 4G LTE Cat 1 cellular module for Verizon	10 yr (or when 4G no longer supported by Verizon)	-Inspect connections for corrosion and contact (6 mo.)
	BP24 12V sealed rechargeable battery	5 yr	-Inspect connections for corrosion and contact (6 mo.) -Check battery voltage at data download (1-2 mo.)
	SP20-PT-SM 20W solar panel	10 yr	-Clean and inspect surface for damage each field visit (0.5-1 mo.)
	ENC16/18 UL-SC-SB-NM 16x18” weather-resistant enclosure with UL508A compliance	15 yr	-Inspect desiccant each field visit (0.5-1 mo.) and replace when needed

2.1.1. Turbidity

Turbidity data was collected with a Campbell Scientific ClariVUE 10 side scatter turbidity sensor. The ClariVUE 10 uses a near-infrared (NIR) laser and a photodiode for detecting the intensity of light scattered from suspended particles in water. The detector is positioned at 90 degrees to the emitter to measure the side-scatter energy. The ClariVUE 10 meets ISO 7027-1:2016 (side scatter) standard for turbidity measurements. Detailed specifications of the instrument are shown in Table 4.

2.1.2. Depth

Depth data was collected with a Campbell Scientific CS451 submersible pressure transducer. The CS451 pressure transducer provides a reliable, accurate pressure/level measurement that is fully temperature compensated. Its 24-bit A/D has simultaneous 50/60 Hz rejection and automatic calibration for each measurement. Detailed specifications of the instrument are shown in Table 4.

Table 4. Specifications for field meters.

TURBIDITY SENSOR		
	Turbidity	***Temperature***
Measurement Range	0 to 4000 FNU	-2° to 40° C
Accuracy	+/- 2% or 0.5 FNU, whichever is greater	+/- 0.2° C
Resolution	0.2 FNU	0.1° C
Response Time	9 to 22 seconds	
DEPTH SENSOR		
Measurement Range	0 to 334.5 ft	0° to 60° C
Accuracy	+/- 0.1% of full range	+/- 0.2° C
Resolution	0.0035% of full range	0.006° C
Response Time	<1.5 seconds	

2.2. Installation

Turbidity and depth monitoring equipment were housed in PVC electrical conduit mounted on the wingwall of the dam near the cold-water release. Figure 2 shows a detailed drawing of the installation, and Figure 3 shows the sensors as installed. Each of the two probes was housed in a separate 3” PVC electrical conduit. At the lower end of the conduit, the pipe narrows to a 2” diameter, and holes were drilled into the pipe to allow the surrounding water to easily flow into the conduit. The sensor ends of the probes extend into this perforated section of the conduit to measure turbidity and depth. The conduit was mounted to the wing wall at three points with stainless steel bolts and brackets. Holes were drilled into the wingwall and bolts were fixed in the holes with a concrete epoxy resin. The epoxy was allowed to completely fill the holes, so that water cannot get into the hole and cause freezing and cracking. The conduit was mounted such that the sensors are approximately 2 ft below the water when the lake level is lowered to the 17-ft mark.

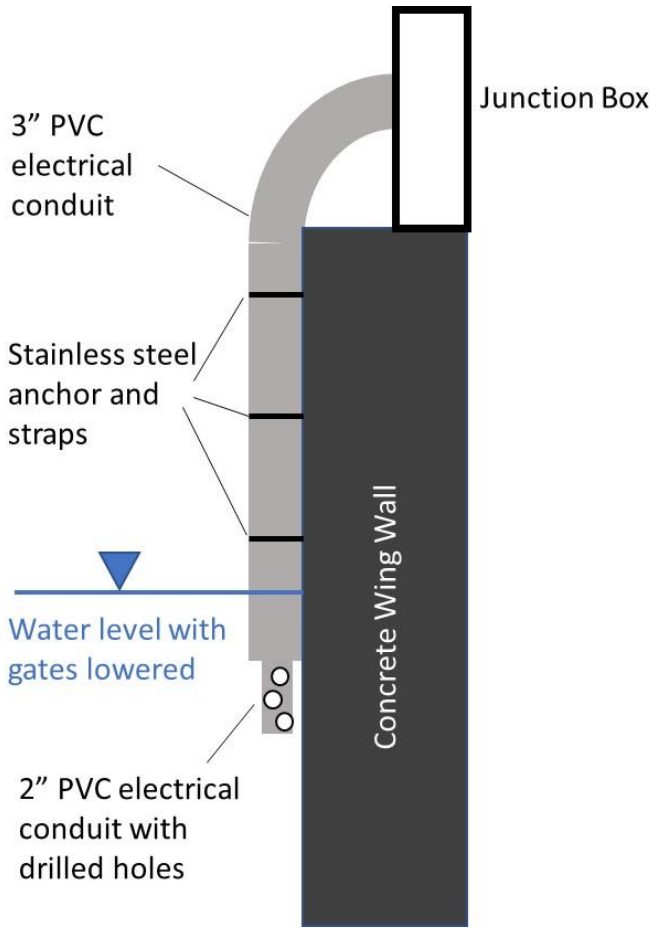


Figure 2. Detailed drawing of equipment installation on the dam wingwall.



Figure 3. Equipment as installed on the Lake Merriweather dam wingwall.

At the top of the conduit, a 90-degree elbow directs the conduit into a junction box mounted on the chain link fence. Figure 4 provides a detailed drawing of the junction box, and Figure 5 shows the junction box as installed. The two 3” conduits from the probes come into the junction box, and two 1.5” conduits leave the junction box. The purpose of this junction box is to provide access to the probes. From the junction box, the probes can be dropped down the conduit into their position

within the lake. For service and maintenance, the junction box can be accessed and the probes can be pulled up the conduit by the cable. Maintenance can be performed, and then the probes can be lowered back down the conduit into the proper position.

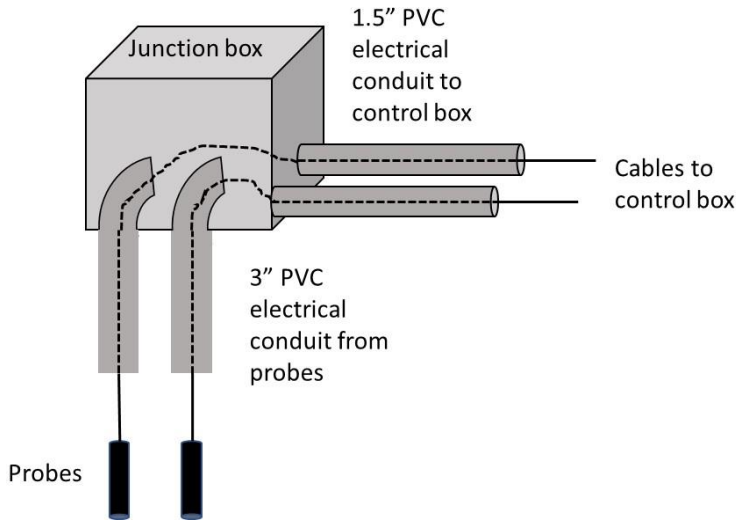


Figure 4. Detailed drawing of junction box.



Figure 5. Installed junction box closed (A) and open (B).

From the junction box, the 1.5” conduit follows the wingwall up to and around the stone building to the chain link fence surrounding the propane tank. On the chain link fence, a control box was mounted to house the electrical equipment (Figure 6). The control box is a water-tight container that houses the battery, data logger, and cell modem. A stainless-steel mounting pole was secured to the corner post of the chain link fence to mount the solar panel and the cellular antennae (Figure 7). A lighting rod was fixed to the top of the mounting pole and grounded to a 5-ft copper rod driven into the ground. The junction box and the control box were locked with a weather resistant lock to avoid tampering.

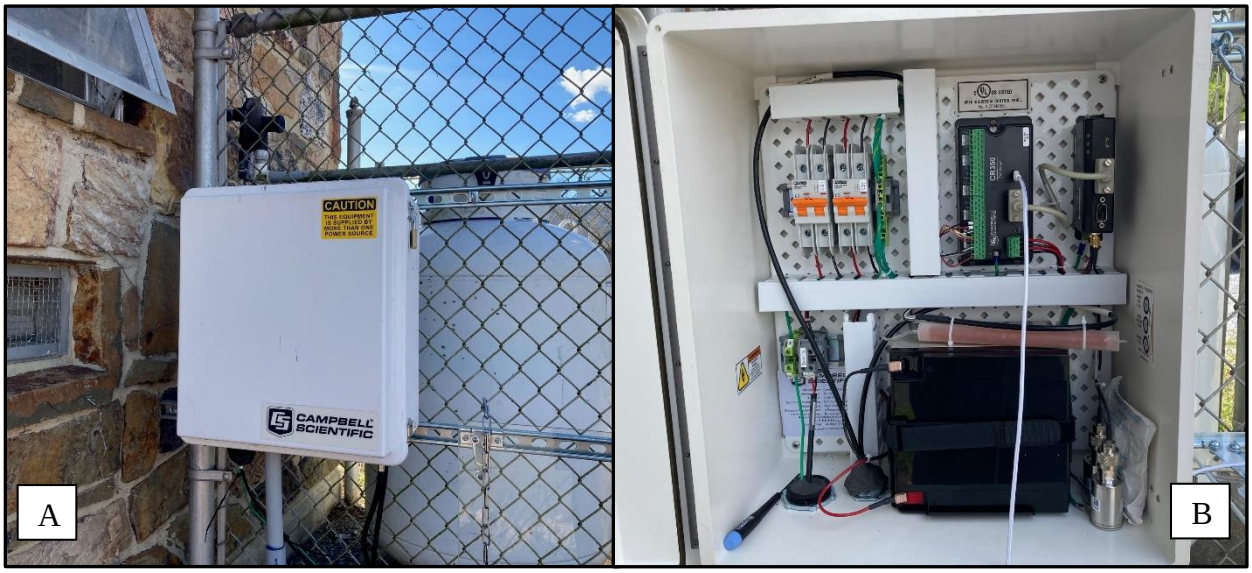


Figure 6. Control box closed (A) and open (B).



Figure 7. Solar panel, lightning rod, and cellular antennae.

2.1. Monitoring

The experimental design for the project entails the permanent installation of turbidity and depth sensors on the Lake Merriweather dam structure for continuous monitoring. This placement of the sensors represents the turbidity of water leaving the lake through the dam structure. The details of continuous monitoring are shown in Table 5. For each parameter, data were collected at 15-minute

intervals for one year. For each 15-minute interval sampling, the sensors averaged 30, 30-second averages. Each 30-second average consists of 30, 1-second pulse measurements. The averaging of discrete measurements was conducted by the datalogger internally, and only the 15-minute average data was stored. Data was temporarily stored on the Campbell Scientific datalogger (CR-350) in the control box. At least once per month, data was downloaded from the datalogger to a JMU personal computer and then uploaded to the JMU server for security and long-term storage. Data was downloaded using Campbell Scientific proprietary software (PC400) through a cellular connection with the datalogger.

Table 5. Frequency and duration of continuous monitoring.

Parameter	Subsampling	Frequency	Duration
Turbidity	30 measurements averaged over 30 seconds; 30, 30-second averages averaged over 15 minutes	15-minute	1 year
Depth	30 measurements averaged over 30 seconds; 30, 30-second averages averaged over 15 minutes	15-minute	1 year

2.1. Calibration

The turbidity and depth sensors were calibrated by the manufacturer prior to initial deployment and should be recalibrated after two years of use or if calibration checks vary by more than 5% from the standard in two consecutive visits. Sensors did not vary by more than 5% during the one-year deployment and were not recalibrated during the project.

2.2. Maintenance

Field visits were conducted every 15 days during summer and 30 days during winter to inspect, clean, and maintain the equipment. Cleaning and routine maintenance were performed according to equipment manuals (Campbell Scientific, 2021a; Campbell Scientific, 2021b) and project SOPs. At every field visit, the sensors were inspected, cleaned, and various quality control checks were performed (Section 2.3).

For maintenance, probes were pulled out of the water through the junction box access. Probes were inspected and cleaned with a squirt bottle of deionized water and Kimwipes (Kimberly-Clark), rubbing the exposed surface of the probes to remove any dirt or biological growth. In addition, the copper and glass end of the turbidity probe was cleaned with a Scotch-Brite scouring pad (3M) to remove any oxidation or pitting on the end surface. After cleaning and quality control checks, probes were redeployed through the junction box, making sure that they were seated properly at the bottom of the conduit. Other routine maintenance performed during field visits included cleaning the solar panel when needed and replacing the desiccant in the control box when humidity levels in the box reached 40%.

2.3. Quality Control

Quality control elements for monitoring in this project include repeated measures, calibration checks (low and high), and pre-service and post-service precision checks. The frequency, criteria, and corrective action for these QC elements are shown in Table 6 and Table 7.

Table 6. Quality control (QC) elements for turbidity monitoring.

DQI Type	QC Element	Frequency	Criteria	Corrective Action
Precision	Repeated measures	30 measurements averaged over the course of 30 seconds; 30, 30-second averages averaged over 15 minutes	RSD < 25%	This could be normal if turbidity values are changing quickly. Flag only if RSD >25% and average turbidity value >25% outside of range from previous to successive15-minute measurements
Bias, Accuracy, and Sensitivity	Calibration Check - Low (0 NTU)	At every field visit (Summer: max 15 days; Winter: max 30 days)	<2 NTU	Re-clean, refill standard, retest. Return sensor to manufacturer for recalibration if 2 consecutive months fail
Bias and Accuracy	Calibration Check - High (400 NTU)	At every field visit (Summer: max 15 days; Winter: max 30 days)	95-105% Recovery	Re-clean, refill standard, retest. Return sensor to manufacturer for

				recalibration if 2 consecutive months fail
Precision and Comparability	Precision Check – Pre-service	At the beginning of every field visit (Summer: max 15 days; Winter: max 30 days)	If >10 NTU: RPD < 20% If <10 NTU: +/- 2 NTU	Flag data
Precision and Comparability	Precision Check – Post-service	At the end of every field visit (Summer: max 15 days; Winter: max 30 days)	If >10 NTU: RPD < 20% If <10 NTU: +/- 2 NTU	Reclean, readjust probe, retest. Flag data if still outside criteria
Completeness	Total data points and duration	While at full pool	>8640 data points >3-month duration	Extend monitoring
Completeness	Total data points and duration	While gates and lake level are lowered	>8640 data points >3-month duration	Extend monitoring

Table 7. Quality control (QC) elements for depth monitoring.

DQI Type	**QC Element**	**Frequency**	**Criteria**	**Corrective Action**
Precision	Repeated measures	30 measurements averaged over the course of 30 seconds; 30, 30-second averages averaged over 15 minutes	RSD < 25%	This could be normal if depth values are changing quickly. Flag only if RSD >25% and average depth >25% outside of range from previous to successive 15-minute measurements
Precision and Comparability	Precision Check – Pre-service	At the beginning of every field visit (Summer: max 15 days; Winter: max 30 days)	+/- 0.5 ft	Flag data
Precision and Comparability	Precision Check – Post-service	At the end of every field visit (Summer: max 15 days; Winter: max 30 days)	+/- 0.5 ft	Reclean, readjust probe, retest. Return sensor to manufacturer for recalibration if 2

				consecutive months fail or at 2 years
Completeness	Total data points and duration	While at full pool	>8640 data points >3-month duration	Extend monitoring
Completeness	Total data points and duration	While gates and lake level are lowered	>8640 data points >3-month duration	Extend monitoring

2.3.1. Precision Checks

At each field visit, precision checks of turbidity and depth sensors were performed before (pre-service) and after (post-service) cleaning and calibration checks. Precision checks were intended to test the sensors against independent measurements of turbidity and depth. This ensured that all collected data was bracketed by valid precision checks and unaffected by instrument drift or cleaning procedures.

Turbidity precision checks were performed by comparing the ClariVUE readings with a separate independent turbidity reading taken with an Analite NEP260 (McVan Instruments) handheld turbidity sensor. The Analite was calibrated on site during each field visit using a two-point calibration of 0 NTU and 400 NTU. Before and after cleaning (pre-service and post-service), the Analite and the ClariVUE were placed in the lake side-by-side at approximately one-foot depth. The readings from the two instruments were compared and the Relative Percent Difference (RPD) was calculated using the formula:

$$RPD = \frac{(C_1 - C_2)}{(C_1 + C_2)/2} \times 100$$

RPD = relative percent difference between two values (C_1 and C_2)
C_1 = larger of two observed values
C_2 = smaller of two observed values

If values were less than 10 NTU, the precision criterion was +/- 2 NTU difference between the readings. If values were greater than 10 NTU, the precision criterion was RPD <20%.

Depth precision checks were performed by comparing the pressure transducer depth reading with the visual depth reading from the markings on the dam wingwall. Differences of less than 0.5 ft were acceptable.

2.3.2. Calibration Checks

At each field visit, a calibration check of the ClariVUE turbidity sensor was performed after cleaning. The calibration check involved comparison of the ClariVUE turbidity sensor against two known standards. A low standard of 0 NTU and a high standard of 400 NTU were used. The low standard was be a turbidity-free deionized water prepared from a 3-column Millipore ion exchange resin with a 0.5-um polishing filter. The low standard was measured in a matte black 2-gal bucket with minimum of 9-inch diameter. The bucket was fitted with a black top to limit outside light, and the sensor was suspended from the top in the center of the bucket. The high standard was a 400 NTU Hach StablCal solution. The high standard was measured in a matte black 500-mL container with a minimum of 4-inch diameter. The container was fitted with a black top to limit outside light, and the sensor was suspended from the top in the center of the container. For the low calibration check, values less than 2 NTU was acceptable, and for the high calibration check, % recovery of 95%-105% (380 – 420 NTU) was acceptable.

During the 1-year monitoring period, deionized water was used for the low turbidity standard, however, Rockbridge County did not have easy access to deionized water for continued long-term maintenance. JMU tested different store-bought brands of distilled water, and all were acceptable for meeting the low turbidity standard of <2 NTU. Long-term maintenance and low calibration checks will be performed using 1-gallon store-bought distilled water.

2.4. Data Retrieval and Storage

Sixteen variables were measured by the sensors and recorded by the datalogger every 15 minutes. A description of these variables is provided in Table 8. At the end of each month, internally stored data were downloaded from the Campbell Scientific CR-350 datalogger to a JMU computer and stored on JMU's network server. All data on the server is secure and is backed-up every 24 hours. Data were downloaded using the Campbell Scientific PC 400 software. Electronic data were stored as original datafiles (.dat) and converted to Microsoft Excel

workbooks for analysis. Electronic data were also uploaded to EPA's Water Quality Exchange (WQX/WQX web) database.

Table 8. Variables measured and recorded by the datalogger.

Variable	Units	Description
TIMESTAMP	MM/DD/YY 00:00	Date and time
RECORD	NA	Sequential number of the record stored
BattV	V	Voltage of the internal battery
Board_Temp	C	Temperature of the internal electronic motherboard
Turbidity_Mean	NTU	Mean turbidity measured over the 15-minute period
Turbidity_Median	NTU	Median turbidity measured over the 15-minute period
Turbidity_Min	NTU	Min turbidity measured over the 15-minute period
Turbidity_Max	NTU	Max turbidity measured over the 15-minute period
Turbidity_STD	NTU	Standard deviation of interim measurements
Turbidity_RSD	%	Relative standard difference of interim measurements
Turbidity_Temp	C	Lake temperature measured by the turbidity sensor
Turbidity_Err_Code	NA	Error code reported by the turbidity sensor
Uncorrected_Level	ft	Depth measurement from the sensor to the water surface
Offset	ft	Depth offset to correct for mounted position of the sensor
Lake_Level	ft	Corrected depth measurement
Level_Temp	C	Lake temperature measured by the depth sensor

2.5. Data Review and Validation

Following download, data were reviewed and anomalous datapoints were identified and flagged or removed from the dataset. Table 9 describes the data review steps and the reasons for flagging or removing data. In general, recorded data during routine maintenance was flagged and removed, statistical outliers were flagged and removed, anomalous data from step changes following maintenance were removed, and data prior to failed QC checks were flagged but retain within the dataset.

Table 9. Data review steps for identifying and flagging or removing anomalous data.

Data Review Step	Description	Action
Maintenance period review	Recorded data at the time of routine maintenance was reviewed and removed if necessary. During routine maintenance, recorded data reflects results from calibration checks and precision checks and does not represent lake conditions.	Datapoints recorded during maintenance period were removed
Outlier analysis	Individual data points could represent outliers if large debris happens to block or pass in front of the turbidity sensor at the time of measurement. Outliers were identified as measurements that failed to meet both of the following criteria: 1) The 15-minute median turbidity varied by more than 25% from previous or subsequent 15-minute median turbidity values 2) The Relative Standard Deviation of 30-second turbidity measurements used to calculate the 15-minute median was greater than 25%.	Identified outliers were removed
Step change	Lake turbidity and depth values before and after routine maintenance were investigated for step changes that could indicate improper repositioning of the probes.	If obvious step changes were observed, data since the last maintenance period were removed
QA flags	Precision checks and calibration checks were evaluated against QA criteria.	If any QA checks failed to meet QA criteria, data since the last maintenance period was flagged as provisional.

2.6. Calculations

In addition to parameters that were directly measured by the sensors, discharge and sediment load were calculated.

2.6.1. Discharge

Based on the lake depth measured by the pressure sensor, discharge (or flow) from Lake Merriweather was calculated based on the following equation for flow over a weir.

$$Q = 2.84 + L * C * H^{1.5}$$

Where,

Q = Flow over the weir (cfs),

L = Length of the weir,

C = Constant (3.33), and

H = Head over the weir (ft).

The length of the weir (L) was determined by the number of gates in the lowered position. Each of 10 gates is 13 ft in length, so if all gates are at the same position, the weir length is 130 ft. Often, though, two or three gates are in a lower position than the remaining gates, so the weir length is just the width of the lowered gates. The head over the weir is calculated based on the measured lake depth and the position of the gates. The 2.84 cfs in the above equation accounts for the flow through the cold-water release valve, which remains relatively constant.

2.6.2. Sediment Load

The first step in calculating sediment load is translating turbidity levels into total suspended solids (TSS) concentrations. This was done by preparing 50 samples of known TSS levels, measuring the turbidity of these samples, and developing a turbidity to TSS regression. Several hundred grams of sediment were collected with a stainless-steel trowel from the streambed of the Little Calfpasture River downstream from Lake Merriweather. This sediment represents the size, distribution, and composition of sediment particles passing through the lake and the dam. The sediment was dried in a fume hood for 48 hours and sieved through a #230 sieve to capture the silt and clay fraction of 0.05 mm and smaller.

Dried and sieved sediment was then weighed on an analytical balance to the nearest 0.1 mg and gravimetrically added to deionized water in 500-ml HDPE bottles to prepare 50 samples of known TSS concentrations ranging from 2 to 200 mg/L. Each of the samples was thoroughly mixed and turbidity was measured using the ClariVUE turbidity sensor. TSS of each sample was then measured by Standard Method 2540D, Total Suspended Solids Dried at 103-105°C (APHA, 1998). Samples were suction filtered through a pre-weighed glass fiber filter. Filters were then dried for 24 hours at 103-105°C, cooled in a desiccator, and weighed to a constant weight. TSS was then calculated as the mass of the dried, filtered solids divided by the volume filtered.

Measurements of turbidity and TSS for the 50 prepared samples were plotted, and a regression line was calculated (Figure 8). The regression relationship was very strong, with an r^2 of 0.978. This regression was used to translate turbidity measurements in Lake Merriweather to TSS values for the purpose of calculating sediment loads moving through the dam over time.

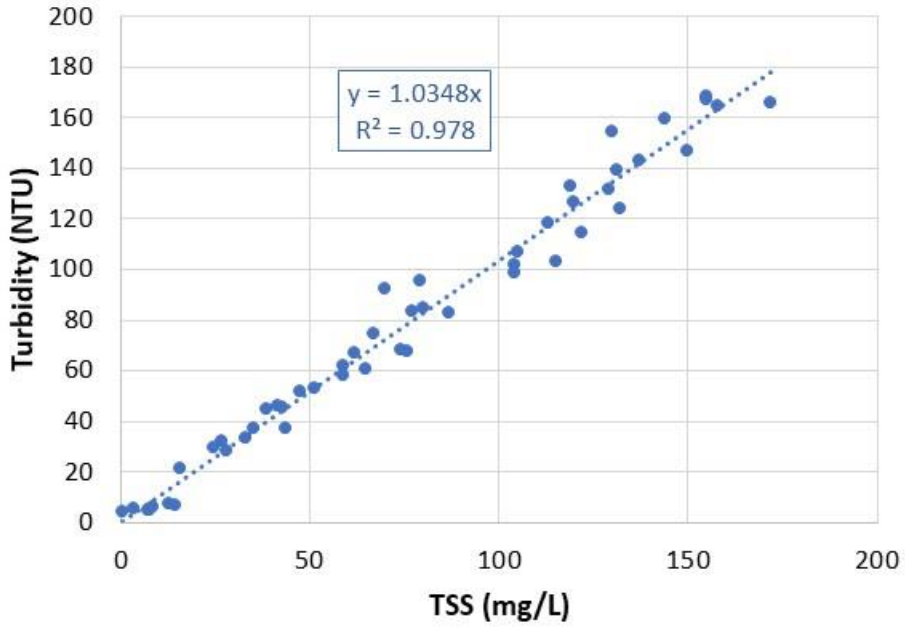


Figure 8. Relationship between turbidity and total suspended solids (TSS) for Little Calfpasture River sediment.

Sediment loads were calculated based on measured turbidity in the lake translated to TSS, discharge over the dam calculated from lake depth and gate position, and appropriate unit conversions. For each 15-minute time period, the sediment load was calculated using the following equation:

$$SL = Q * Turb/1.0348 * dt * 28.3168 * 1x10^{-9}$$

Where,

SL = sediment load (tonnes),

Q = discharge (cfs)

Turb = measured turbidity (NTU),

dt = change in time between turbidity measurements, which is typically 15 minutes or 900 seconds (s).

The individual sediment loads for each 15-minute time period were then summed for each month to produce monthly sediment loads in tonnes.

2.7. Flow Validation

To validate the accuracy of the calculated flow from Lake Merriweather, the calculated flows were added to the gauged flow in the Calfpasture River and compared to the gauged flows in the Maury River downstream. Theoretically, the gauged Maury River flows monitored by the USGS at Rockbridge Baths should be equal to the sum of calculated Little Calfpasture River flow, gauged Calfpasture River flow at Goshen, and all other ungauged flows to the Maury River upstream of Rockbridge Baths. The following equation was used to calculate Maury River flows.

Calculated MR Flow = Calculated LC Flow + Gauged CR Flow +
0.3178*Gauged MR Flow

Where:

MR = Maury River,

LC = Little Calfpasture River,

CR = Calfpasture River.

Flow from the ungauged portion of the Maury River watershed was calculated as 0.3178 * Gauged MR Flow, since the ungauged portion represented 31.78% of the total watershed.

Based on the above equation, gauged Maury River flow and calculated Maury River flow were compared to check the accuracy of the Little Calfpasture River flow calculations (Figure 9). Flows were surprisingly consistent given the assumptions involved in this comparison. This is validation that the equation to calculate flow from Lake Merriweather is reasonably accurate. One of the largest sources of error in this comparison is the assumption that flow from the ungauged portion of the Maury River is proportional to the watershed area. While this assumption holds in general, it does not account for differing rainfall patterns and intensity in different portions of the watershed, which could be significant for a watershed as large as the Maury River. As a result, the peak flows, which are most influenced by rainfall patterns throughout the watershed, often fail to meet the peaks recorded in the Maury. Another time period when calculated and measured Maury River flows were less consistent was during late September and early October. This was the time period when the gates at Lake Merriweather were being lowered. The Boy Scouts of America Capital Area Council did not record the timing

and magnitude of individual gate movements, and JMU tried to re-create the daily gate positions from the observed depths throughout this period. This method was not as accurate as it could have been with precise data on the timing and magnitude of gate movements. If the time period of gate movements is removed, the overall flow records are relatively accurate. The r^2 value of measured to calculated flows was 0.982 for the 8-month period. In addition, 75% of calculated values were within 10% of measured values, and 91% of calculated values were within 20% of measured values. This validation shows that flows calculated from Lake Merriweather are accurate and reliable for calculating sediment discharge.

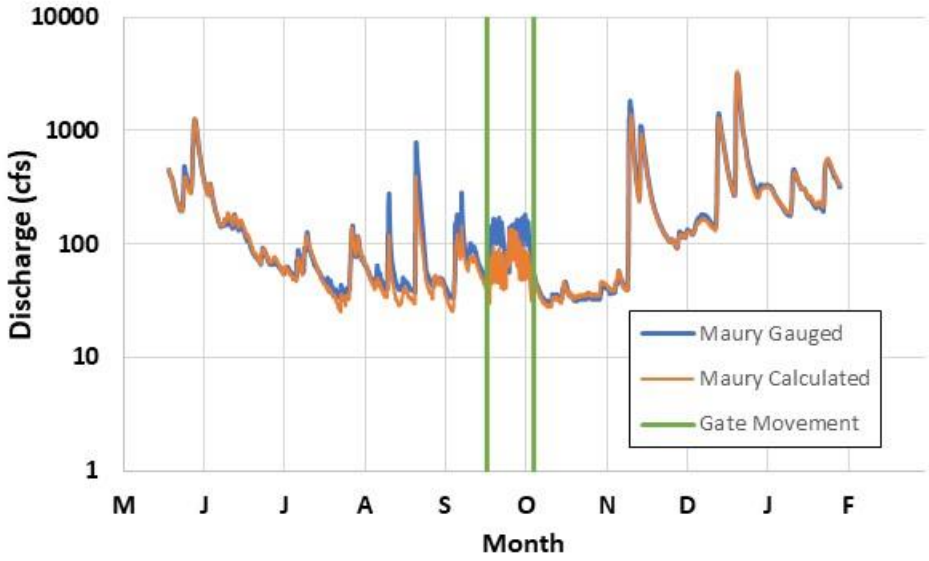


Figure 9. Gauged versus calculated flow in the Maury River.

3.0 RESULTS

3.1. Quality Control

The turbidity and depth monitoring system performed extremely well for the one-year monitoring period. The quality control systems in place ensured that high quality data were generated throughout the project.

3.1.1. Completeness

The data quality objectives for completeness in this project were to achieve a minimum of 3 months of monitoring and 8640 datapoints during the summer when the lake was at full pool and a minimum of 3 months of monitoring and 8640 datapoints during the winter when gates were in the lowered position. The project achieved 12,442 datapoints at full pool and 20,298 datapoints at the lowered position. This represents 144% and 235% of the summer and winter completeness goals, respectively.

Table 10 shows the monthly data completeness statistics for the project. In all months except for May, 100% of possible data was collected. Less than 100% was collected in May, because the monitoring system was being installed in early May and was not operational until May 18.

Only small amounts of data were removed as outliers or invalid data. For most months, less than 1% of data were removed. On one occasion in June, the turbidity probe was not reset correctly into the base of the conduit after maintenance. This caused the probe to read incorrectly and invalidated data for a ten-day period until the probe was reset at the next field visit. This resulted in 14% of data invalidated for the month of June. In July, 4% of data were removed as outliers. The outlier rate in July was higher than for most months, because turbidity values were generally very low and outlier calculations based on percent differences were more likely to flag outliers.

Some data (48% in June and 23% in August) were flagged for QC violations, but were not invalidated. These data were flagged for pre-service precision checks not meeting QC criteria. This means that turbidity data may have drifted and could be higher than actual prior to maintenance. Overall, the valid data completion rate was very high for the project. Several minor data quality issues were resolved within the first several months of deployment, and since that time, the data completion rate has been >99% for the past nine months.

Table 10. Monthly data completeness statistics.

Month	Total Data Points Possible	% Collected	% Removed	% Completion	% Flagged
May	2976	43.35%	0.54%	43.11%	0.00%
June	2880	100.00%	14.24%	85.76%	48.02%
July	2976	100.00%	4.17%	95.83%	0.00%
August	2976	100.00%	0.20%	99.80%	22.51%
September	2880	100.00%	0.45%	99.55%	0.00%
October	2976	100.00%	0.20%	99.80%	0.00%

November	2880	100.00%	0.69%	99.31%	0.00%
December	2980	100.00%	0.37%	99.63%	0.00%
January	2976	100.00%	0.07%	99.93%	0.00%
February	2688	100.00%	0.07%	99.93%	0.00%
March	2972	100.00%	0.24%	99.76%	0.00%
April	2880	100.00%	0.21%	99.79%	0.00%
Total	35040	95.19%	1.82%	93.44%	6.16%

3.1.2. Calibration Checks

During each of 17 field visits, a calibration check-low and a calibration check-high sample were analyzed to ensure that the ClariVUE turbidity sensor was producing accurate results. The calibration check-low standard of 0 NTU was within the acceptable range (< 2 NTU) at every visit (100%). Turbidity measurements on the 0 NTU standard ranged from 0.23 to 1.19 NTU and averaged 0.70 NTU across all field visits.

The calibration check-high standard of 400 NTU was also within the acceptable range (380-420 NTU) at every visit (100%). Turbidity measurements on the 400 NTU standard ranged from 384 to 417 NTU and averaged 401 NTU across all field visits. When measured values began to drift from the standard value, it was typically due to expiration of the standard solution rather than drift of the instrument. The 400 NTU standard solution needed to be replaced approximately every three months. Replacing the standard solution typically restored instrument readings to very near the standard value.

3.1.3. Precision Checks

During 16 of the 17 field visits, pre-service and post-service precision checks were conducted for the turbidity and depth sensors. Precision checks were not conducted during the last visit in April 2023 because the maintenance protocol was transitioned from JMU to Rockbridge County and a second independent turbidity meter was not available. For the sixteen turbidity pre-service precision checks, all but two (on 6/15/22 and 8/10/22) meet QC criteria. This means that on two occasions the two independent turbidity measurements did not agree within 20%. This doesn't necessarily mean that values are invalid, since error could come from either of the two independent measurements. For this reason, data since the previous field visit was flagged, but was not

invalidated or removed. The RPD for turbidity pre-service precision checks ranged from 1.4 to 22.7% and averaged 11.3%.

For turbidity post-service precision checks, measurements were more consistent, with all checks meeting QC criteria. This is expected since cleaning of the probe should improve performance and reliability of measurements. The RPD for turbidity post-service precision checks ranged from 3.1 to 12.6% and averaged 8.3%.

For depth, pre- and post-service precision checks were very consistent, with all checks meeting QC criteria. The pressure transducer is not an optical sensor like the turbidity probe, so it is less affected by biological growth over time. Depth pre-service precision checks ranged from <0.1 to 1.3% and averaged 0.6%. Post-service precision checks ranged from <0.1 to 1.3% and averaged 0.7%.

3.2. Lake Level and Turbidity Time Series

Turbidity and lake level monitoring was conducted from May 2022 to May 2023. Over that time period, a total of 32,740 individual turbidity and depth measurements were made at 15-minute intervals. Figure 10 shows turbidity and lake level over the entire year.

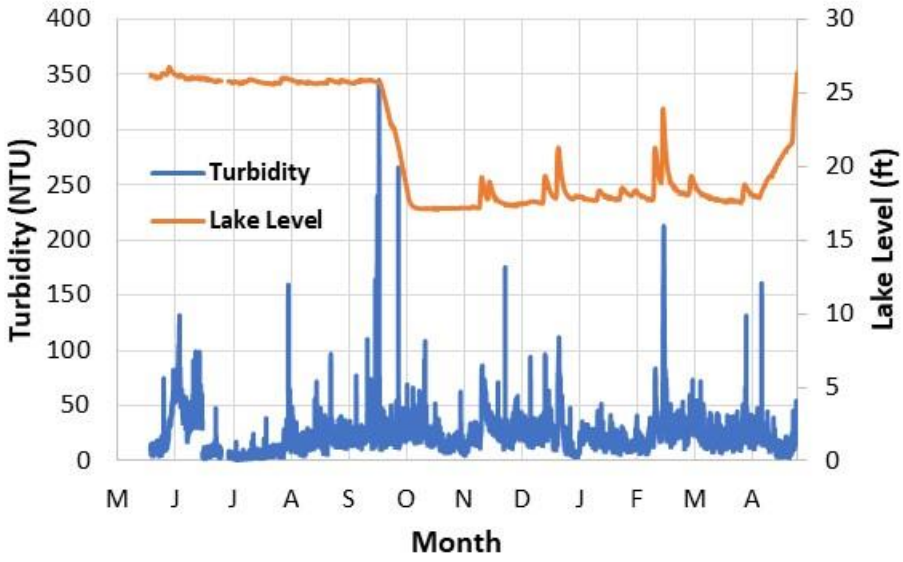


Figure 10. Time series of turbidity and lake level in Lake Merriweather from May 2022 to May 2023.

3.2.1. Lake Level

The most prominent feature of the yearly time series is the lowering of the gates and lake level in late September and early October. Prior to September, the lake level was relatively consistent at 26 ft. Beginning on 9/19/2022, the lake level was lowered through 10/5/2022. Lake level was then maintained at approximately 17 ft from October through April. In April, the lake level was slowly raised from 17 ft back to the full pool level of 26 ft by April 30, 2023.

When the lake was at full pool, storm events had very small impacts on lake level, but when the lake level was lowered, storm events had a much more significant impact on lake level. This was in part due to the size of storm events experience throughout the year, with the largest storm events occurring in December and February. However, the positioning of the gates also contributed to more significant lake level increases when gates were lowered. When gates were lowered, only two gates were lowered and the remaining gates were at the full pool mark. This means that the width of the spillway is only 26 ft at lake levels of 17 ft to 26 ft, rather than the 130 ft spillway width when the lake is at full pool. This causes winter storm events to have a much greater rise and fall in lake level than similarly-sized summer storm events. This can be easily seen in Figure 11, which compares the discharge and lake level. The two storm events in May and November were similarly sized, with peak discharges of 332 cfs on 5/28/23 and 327 cfs on 11/12/23. However, the May storm at full pool only increased lake level by 0.24 ft, but the November storm with the lake lowered increased lake level by 2.08 ft. Larger storms in December and February had even larger influences on lake level, raising the lake level by 3.4 and 5.0 ft, respectively.

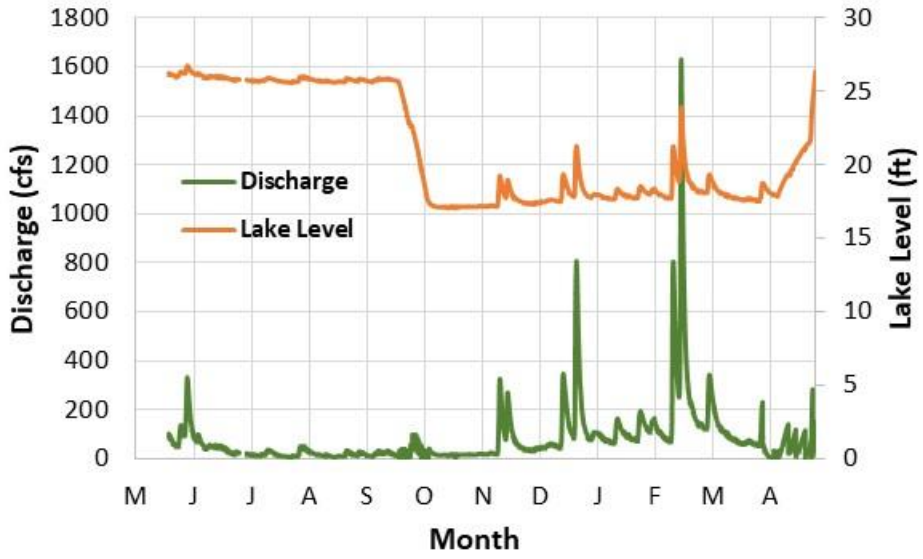


Figure 11. Time series of discharge and lake level in Lake Merriweather from May 2022 to May 2023.

3.2.2. Turbidity

Throughout the year, turbidity varied significantly based on storm events and lake conditions (Figure 10). Turbidity ranged from <1 NTU to 343 NTU with a median of 20.6 and average of 23.0 NTU for the year. Figure 12 shows the cumulative distribution of turbidity values in Lake Merriweather. The 10th and 90th percentiles were 7.66 and 38.4 NTU, respectively, meaning that lake turbidity was below 7.66 NTU 10% of the time and above 38.4 NTU 10% of the time. The first and third quartiles (25th and 75th percentiles) were 13.9 and 28.0 NTU, respectively, meaning that lake turbidity was below 13.9 NTU 25% of the time and above 28.0 NTU 25% of the time.

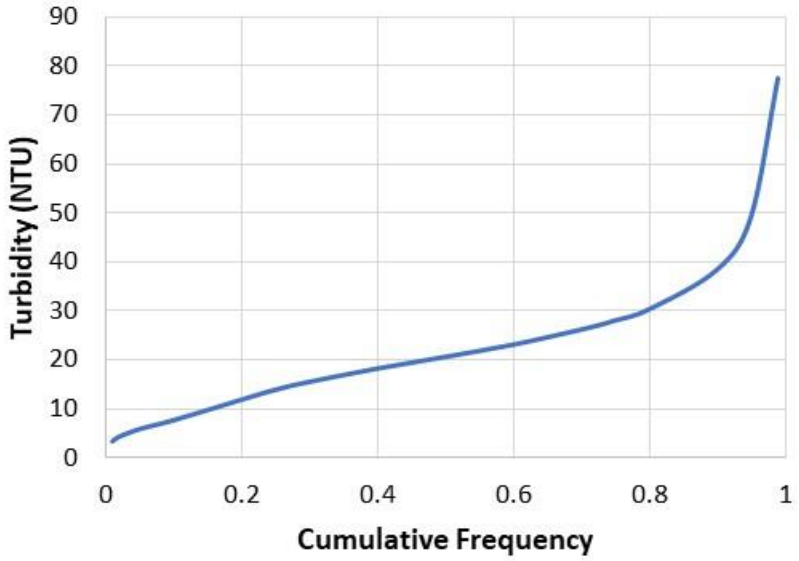


Figure 12. Cumulative distribution of turbidity in Lake Merriweather.

Monthly turbidity statistics are shown in Table 11. September had the highest minimum and highest maximum turbidity levels. Turbidity levels in September ranged from 10.7 to 343 NTU. There were no significant storm events in September, so higher turbidity levels could be due to lake lowering which began approximately 9/19/2022 and continued through the end of the month. The month with the highest average turbidity was June, however, this finding could be an artifact of the data. Nearly half (48%) of June data were flagged for failing to meet the pre-service precision check. This means that data during this time period may have been biased high due to biological growth. Following June, the next months of highest turbidity were February, November, December, and September.

Turbidity data were also divided between times when the lake was at full pool and times when the lake was lowered. Because the gates were lowered over several weeks spanning from mid-September to early October, the lake was considered at full pool from May 2022 to September 15, 2022, and the lake was considered lowered from October 15, 2022 to March 31, 2023. The minimum, maximum, and average turbidity was lower when the lake was at full pool than when the lake level was lowered (Table 11). At full pool, turbidity averaged 20.3 NTU, and when the lake was lowered, turbidity averaged 24.5 NTU. While this difference is relatively small, it is statistically highly significant. In a t-test with unequal variance and alpha of 0.05, the p-value was $<1 \times 10^{-92}$. While this does not necessarily implicate the lake level as the causal factor, it does

indicate that statistically the turbidity during those two times periods (when the lake is at full pool versus when the lake is lowered) is significantly different.

Table 11. Monthly turbidity statistics.

Month	Turbidity (NTU)			
	Min	Max	Average	Standard Deviation
May	5.06	82.4	22.4	18.6
June	2.40	132	32.6	25.6
July	0.89	157	7.95	7.60
August	5.15	95.3	20.1	7.45
September	10.65	343	25.9	16.3
October	7.05	108	22.6	8.43
November	6.01	175	27.3	13.5
December	5.08	111	26.1	15.1
January	4.62	51.5	18.2	6.77
February	6.75	213	29.5	24.4
March	7.15	73	25.5	8.4
April	3.39	161	19.6	10.1
Full Pool	0.89	157	20.3	17.1
Gates Lowered	4.62	213	24.5	14.7

3.3. Sediment Loads

Sediment loads flowing out of Lake Merriweather were calculated as described in Section 2.6.2. Figure 13 shows the instantaneous (actually every 15-minutes) sediment loads from Lake Merriweather. Instantaneous loads vary widely due to both turbidity and flow conditions, so they are shown here on a log scale. Periods of highest sediment load are obviously associated with large storm events. This can easily be seen in Figure 14 as cumulative sediment loads increase sharply during storm events and rise more steadily during inter-storm periods.

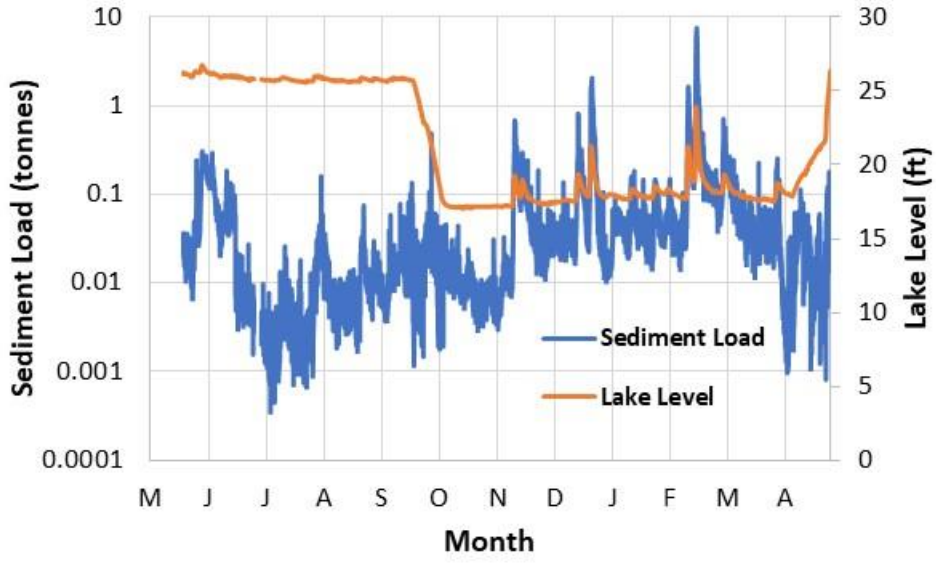


Figure 13. Instantaneous (15-minute) sediment loads from Lake Merriweather.

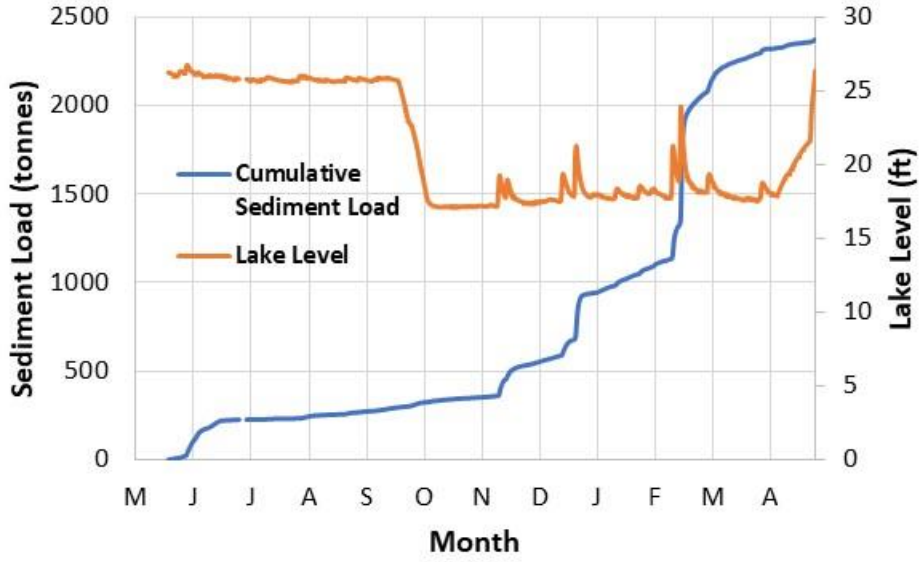


Figure 14. Cumulative sediment load from Lake Merriweather.

Sediment loads were also summed by month and shown in Table 12 and Figure 15. Monthly sediment loads ranged from 15.2 tonnes in July to 973 tonnes in February. The total annual sediment load passing through Lake Merriweather from May 2022 – April 2023 was 2373 tonnes. This is remarkably consistent with TMDL modeling, which estimated an average annual sediment load of 2595 tonnes under existing conditions during a 7-year modeling period from 2000-2006

(VDEQ, 2010). The TMDL also set an annual sediment load of 1138 tonnes as the target for restored aquatic life conditions. During the 2022/23 monitoring year, the sediment load downstream from Lake Merriweather was over twice the annual TMDL target and exceeded the target by 1235 tonnes of sediment. With monitoring beginning in May, discharged sediment loads were on track for meeting the TMDL target during the first six months, with a 6-month sediment discharge of 351.7 tonnes and only 31% of the annual target. Sediment loads then increased beginning in November, and the annual TMDL target was exceeded by early February (Figure 16).

Table 12. Monthly sediment loads from Lake Merriweather.

Month	Sediment Load
May	106
June	121
July	15.2
August	29.9
September	49.2
October	30.4
November	192
December	396
January	143
February	973
March	239
April	78
Total	**2373**
TMDL	1138
Full Pool[1]	291
Gates Lowered[1]	1955

[1] Excludes sediment loads during gate lowering (9/16/22 - 10/15/22) and raising (4/1/23 - 4/30/23)

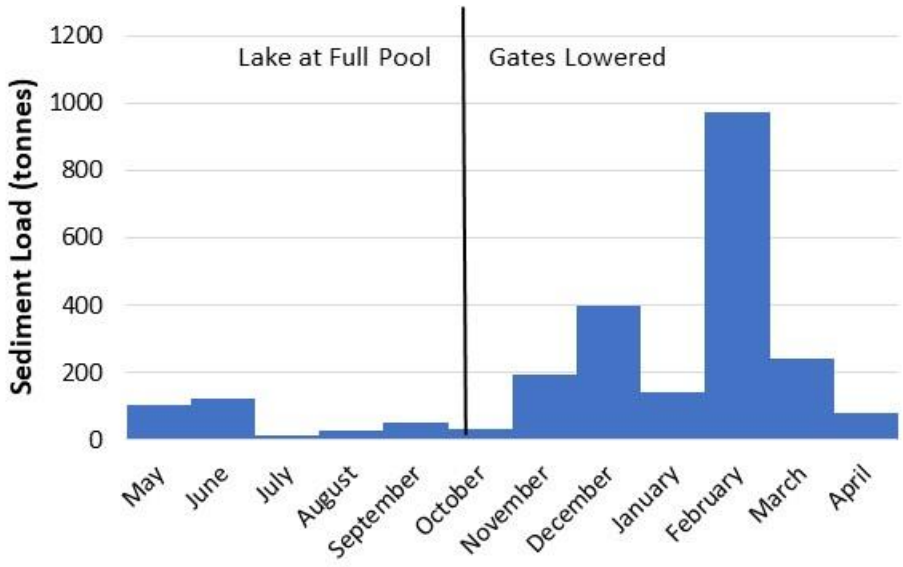


Figure 15. Monthly sediment loads from Lake Merriweather.

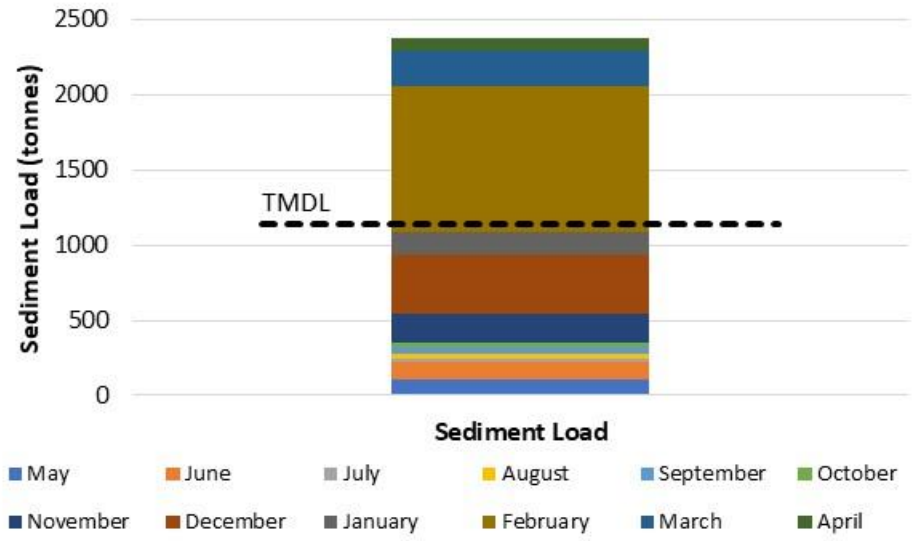


Figure 16. Cumulative monthly sediment loads from Lake Merriweather.

Sediment loads downstream from Lake Merriweather were much higher in the winter when gates were lowered than in the summer when the lake was at full pool. The five winter months when the lake was lowered (November – March) were the five highest months of sediment loading. The sediment load during the winter when gates were lowered was 1955 tonnes, compared to only 291 tonnes in the summer when the lake was at full pool. This equates to winter sediment loads that

are 6.7 times higher than summer loads. When the lake is lowered, extensive mud flats are vulnerable to erosion and increase sediment loads to the lake and downstream. This was demonstrated in the 2010 TMDL modeling (VDEQ, 2010) and confirmed in the 2022/23 monitoring.

3.4. Upstream and Downstream Monitoring

In addition to turbidity and level monitoring in Lake Merriweather, monitoring was conducted upstream and downstream of the lake (Figure 17). The upstream monitoring station was located approximately 1.7 km upstream from Lake Merriweather, and the downstream station was located approximately 1.3 km downstream from the lake and just upstream from the confluence with the Calfpasture River.

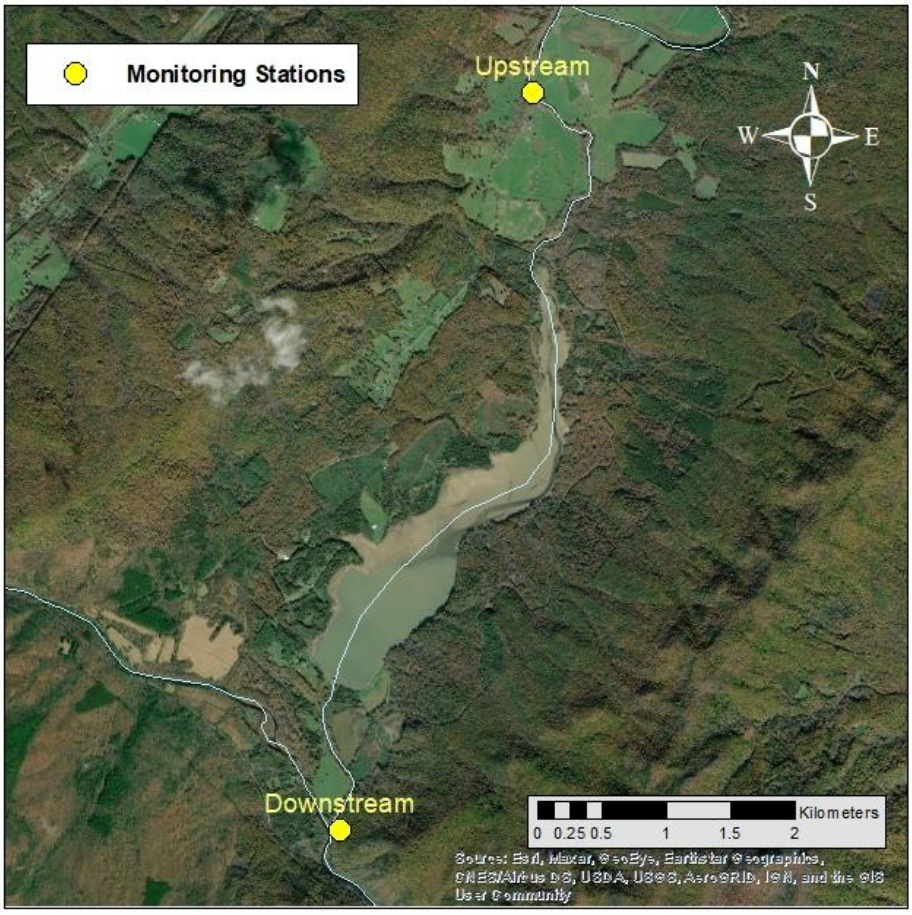


Figure 17. Location of monitoring stations on the Little Calfpasture River upstream and downstream from Lake Merriweather.

At each Little Calfpasture River monitoring station, a YSI 6920 multiparameter water quality sonde was deployed during the summer and winter seasons. Summer monitoring was conducted in June through August to assess conditions while the lake was at full pool. Winter monitoring was conducted in February through March to assess conditions while the lake was lowered. The sondes were programmed to record temperature, conductivity, turbidity, and dissolved oxygen data at 15-min intervals.

During the summer, 4686 data points were collected from 6/15/22 to 8/3/22. Sondes were cleaned and calibrated every two weeks throughout this period. During the winter, 2500 data points were collected from the upstream station, and 1375 data points were collected from the downstream station from 2/21/23 to 3/23/23. Winter monitoring data was truncated because water levels dropped during the deployment and the sondes were stranded out of the water for a portion of the deployment. During quality assurance validation of the data, all data were discarded when conductivity began to drop to zero. This was an accurate indicator of when the probes were exposed as water levels dropped.

3.4.1. Dissolved Oxygen (DO)

During the 1990s, fish kills were experienced in the Little Calfpasture River downstream from Lake Merriweather due to low oxygen conditions. These conditions were remedied by closing the lowest cold-water release gate in the dam and by raising the level of the intermediate cold-water release gate to above the thermocline. Dissolved oxygen monitoring conducted as a part of this study indicates that these remedies have resulted in healthy dissolved oxygen conditions downstream.

Figure 18 shows the dissolved oxygen conditions upstream and downstream from the lake during the summer. There were no violations of the dissolved oxygen water quality standard during the nearly two months of diurnal monitoring during worst-case, hot, dry, summertime conditions. Upstream from the lake, DO saturation ranged from 61 to 142% and averaged 95%. Downstream from the lake, DO saturation ranged from 75 to 112% and averaged 89%. Diurnal swings in DO were larger upstream from the lake, possibly indicating nutrient enrichment. When excess nutrients are present, photosynthesizing algae can increase dissolved oxygen saturation above 100% during the daytime and then consume oxygen at night. Aside from possible nutrient enrichment upstream

from Lake Merriweather, dissolved oxygen conditions upstream and downstream from the lake indicate healthy conditions.

Winter DO conditions are shown in Figure 19. As expected, winter DO conditions were more stable. Upstream from the lake, DO saturation ranged from 93 to 112% and averaged 99%. Downstream from the lake, DO saturation ranged from 95 to 105% and averaged 98%. During the winter, less biological activity consumes oxygen in the water, so DO saturation remains high. Both upstream and downstream locations showed healthy DO conditions.

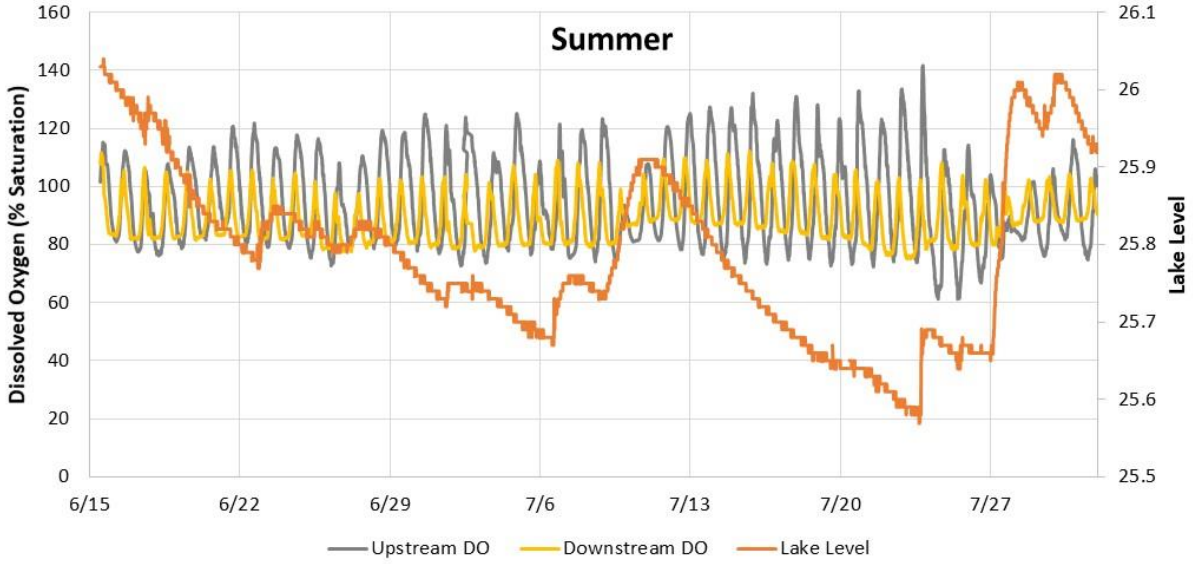


Figure 18. Dissolved oxygen upstream and downstream of Lake Merriweather during the summer.

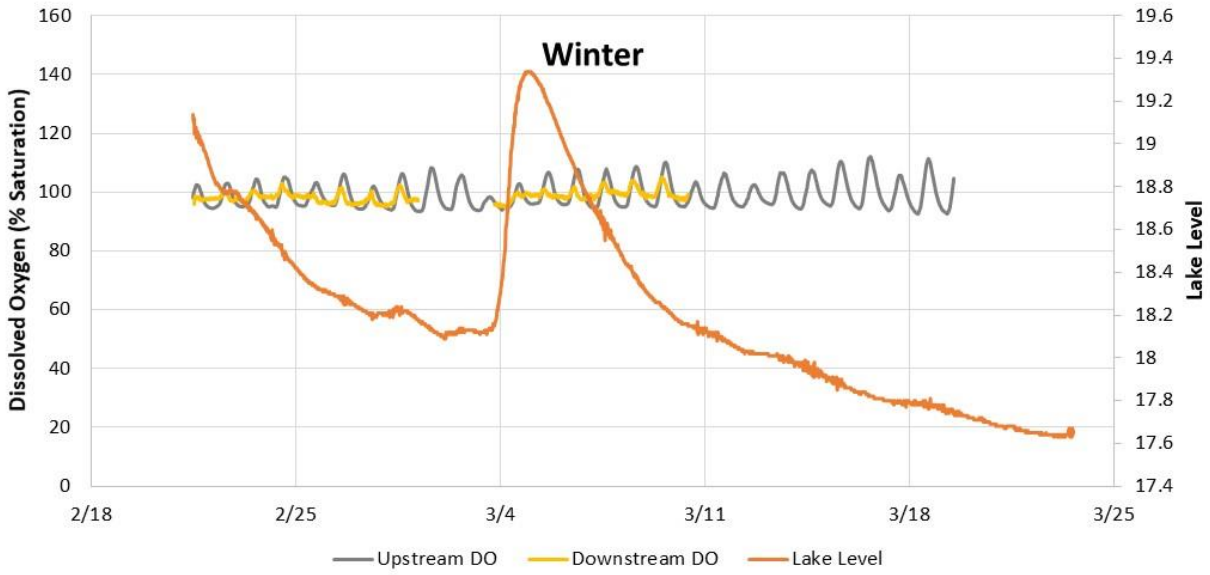


Figure 19. Dissolved oxygen upstream and downstream of Lake Merriweather during the winter.

3.4.2. Turbidity

Figure 20 shows the summertime turbidity upstream and downstream from Lake Merriweather. While average turbidity values were very similar, averaging 4.1 NTU upstream and 3.8 NTU downstream, there was a distinct difference in the pattern of turbidity at each location. At the upstream station, turbidity peaked much higher during storm events (with a maximum of 222 NTU), but quickly returned to near zero following the events. At the downstream station, turbidity peaks were much lower (with a maximum of 32 NTU), but turbidity remained elevated for longer following storm events.

At both upstream and downstream stations, a curious daily cycle of turbidity was observed. Each day, turbidity would typically begin to increase near sundown, peak during the nighttime, and decrease near sunrise. This daily cycle is likely due to bioturbation, the disturbance of bottom sediments by living organisms. Carp have been observed in the Little Calfpasture River, particularly just downstream from the dam. Because carp are more active feeding at night, they disturb the bottom sediments looking for food and increase nighttime turbidity levels. The impact of this effect is small (1-5 NTU) but can be observed by the continuous monitoring of this study.

Figure 21 includes the summertime Lake Merriweather turbidity along with turbidity from upstream and downstream of the lake. Lake turbidity during the summer was consistently higher

than either upstream or downstream stations. During the same period, lake turbidity averaged 8.0 NTU, while upstream and downstream turbidity averaged 4.1 and 3.8 NTU, respectively. This increased turbidity within the lake could be due to the growth of suspended phytoplankton in the lake during the summer.

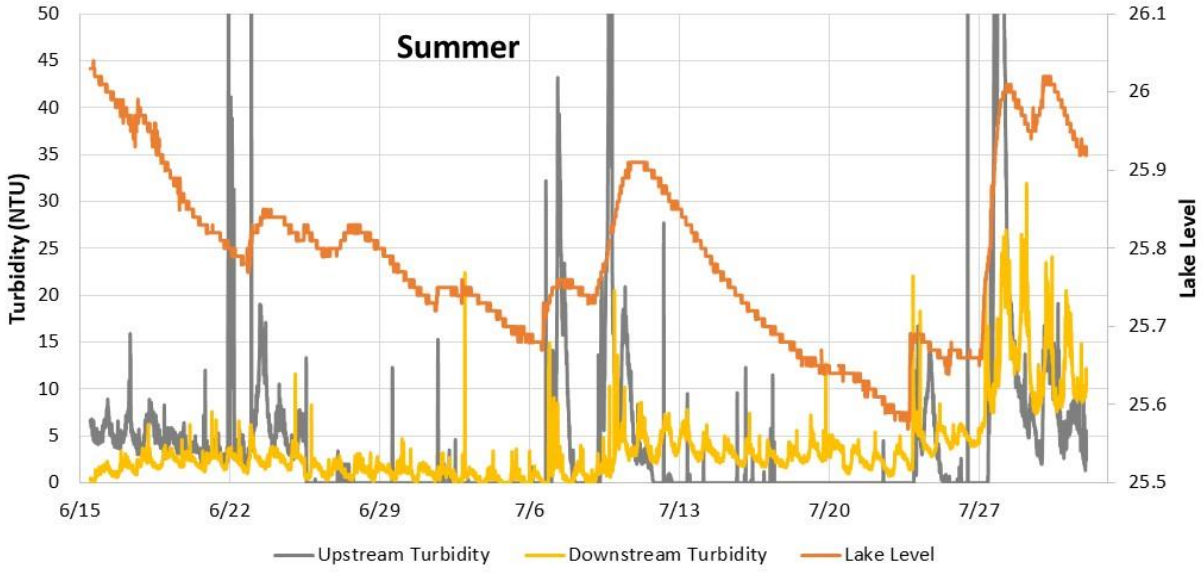


Figure 20. Turbidity upstream and downstream of Lake Merriweather during the summer.

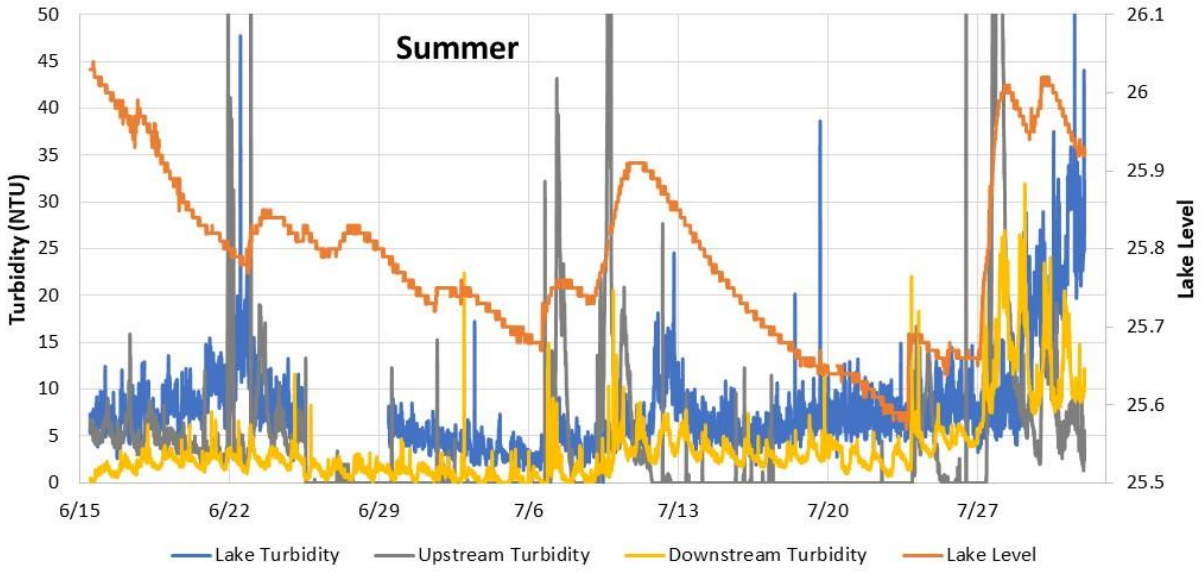


Figure 21. Summertime turbidity in Lake Merriweather compared to upstream and downstream.

Figure 22 shows the wintertime turbidity upstream and downstream from Lake Merriweather. Upstream from the lake, wintertime turbidity was very low, averaging 1.2 NTU. Turbidity peaked to 56 NTU on 3/4/23 during a storm event but quickly returned to near zero. Downstream from the lake, however, turbidity was elevated for the entire wintertime monitoring period. Downstream turbidity averaged 31 NTU during the winter, compared to 1.2 NTU upstream and 3.8 NTU during the summer. This represents a twenty-five-fold increase in average turbidity from upstream to downstream during the winter monitoring period and an eight-fold increase in downstream average turbidity from summer to winter. This stark difference in downstream wintertime turbidity is exemplified in Figure 23. Figure 23 shows the cumulative frequency of turbidity measurements at both monitoring stations (upstream and downstream) during both seasons (summer and winter). Turbidity was below 10 NTU more than 90% of the time at the upstream station and at the downstream station during the summer. During the winter, however, turbidity at the downstream station was above 25 NTU for more than 90% of the time.

Figure 24 compares the lake turbidity during the winter to the upstream and downstream turbidity. During this wintertime monitoring period, lake turbidity matched the downstream turbidity very closely. Downstream turbidity averaged 31 NTU and lake turbidity during this same period averaged 31 NTU. This indicates that high downstream sediment conditions mirrored the lake conditions during the winter.

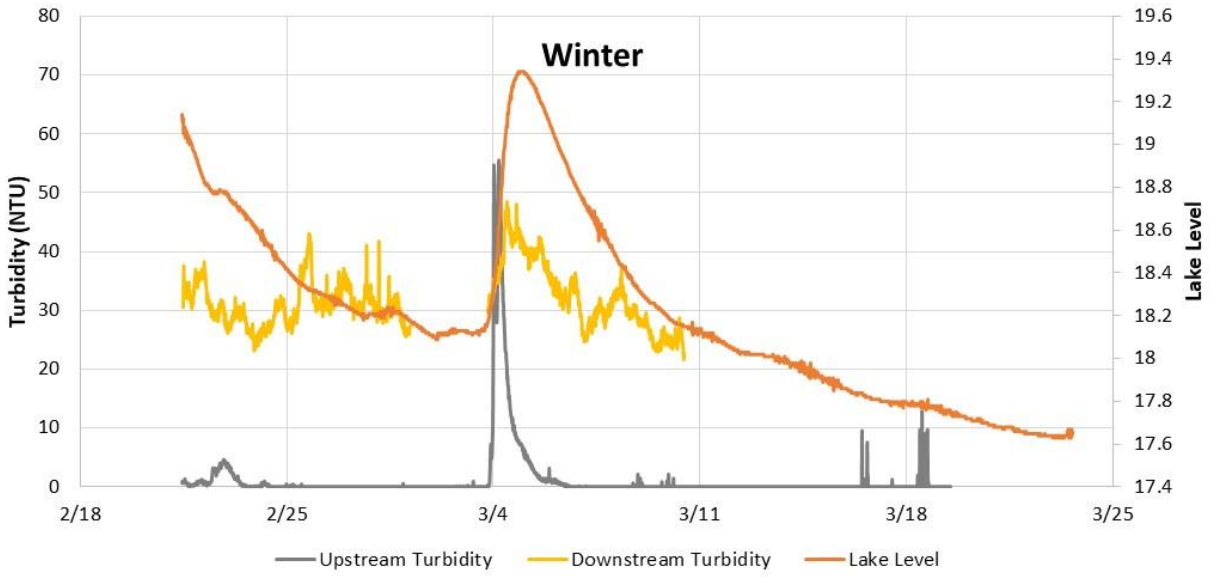


Figure 22. Turbidity upstream and downstream of Lake Merriweather during the winter.

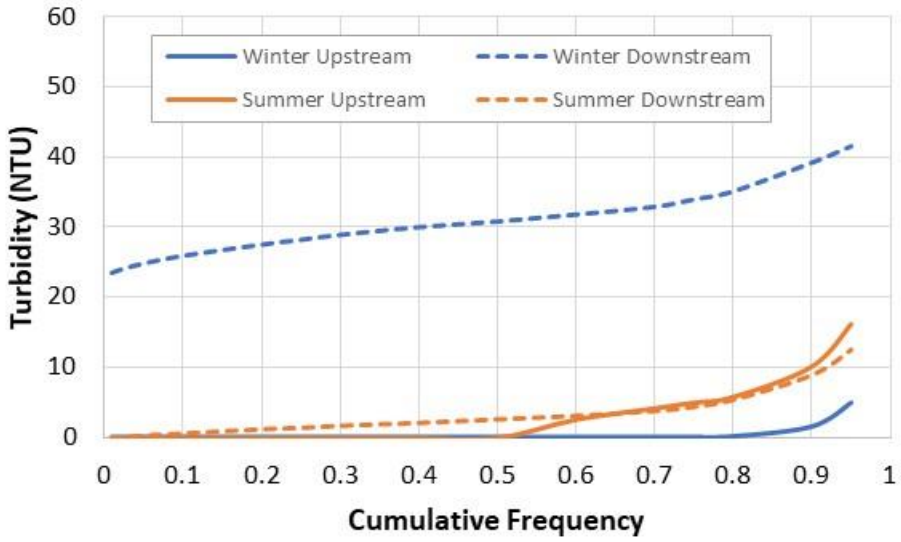


Figure 23. Cumulative frequency of turbidity by season upstream and downstream of Lake Merriweather.

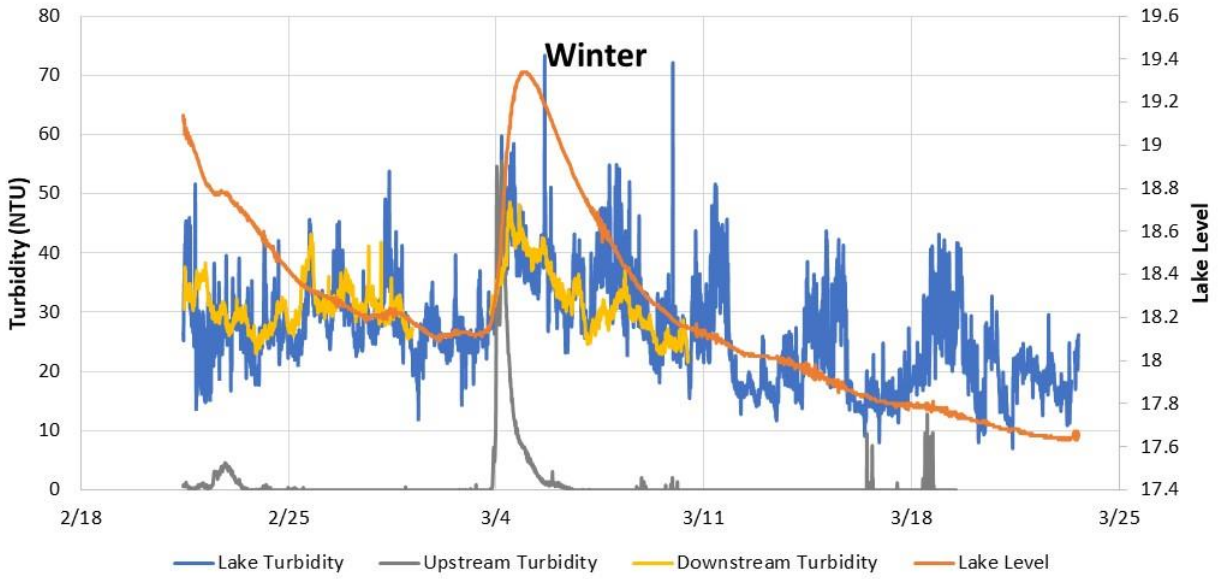


Figure 24. Wintertime turbidity in Lake Merriweather compared to upstream and downstream.

3.5. Partner Training

During March and April, JMU successfully completed training of Rockbridge County staff to maintain the project equipment long term. Training videos and written standard operating procedures were prepared and transmitted to county staff. On 3/23/23, an in-person training was conducted at Lake Merriweather, where JMU personnel explained and demonstrated routine equipment maintenance. On 4/18/23, a second in-person training was conducted at the lake, where county staff performed routine maintenance with JMU oversight. After successfully completing the training, JMU handed over the equipment and supplies to county staff for long-term maintenance beginning May 2023.

4.0 CONCLUSIONS

This section presents the major conclusions resulting from the study. Other, more detailed findings are presented within the results section.

4.1. Successful Monitoring System

The turbidity and depth monitoring system that was installed at Lake Merriweather proved to be highly reliable and accurate. Of a possible 35,040 data points from 15-minute interval monitoring over the course of a year, over 95% of data were successfully collected. Several minor data quality issues were resolved within the first several months of deployment, such that the data completion rate over the last nine months has increased to >99%. Data also proved to be extremely accurate, with 100% of high and low calibration checks meeting data quality objectives over twelve months and across seventeen maintenance visits.

4.2. TMDL Study Confirmation

This study confirmed many of the assumptions and findings of the Little Calfpasture River TMDL Study in 2010 (VDEQ, 2010). The 2010 study was based on computer modeling of sediment transport, and this study was based on physical monitoring of turbidity. Despite the different approaches, the following general findings were confirmed.

- Measured sediment loads from Lake Merriweather were comparable to modeled loads during TMDL development. The annual sediment load measured in 2022/23 was within 8.9% of the average modeled load for existing conditions.
- Sediment movement into and out of the lake was confirmed by upstream and downstream monitoring. The modeled pattern of high but short-lived sediment peaks into the lake and lower, longer-lasting sediment discharges downstream was confirmed through monitoring.
- Monitoring confirmed increased sediment loads during periods when gates were lowered. Wintertime sediment loads were 6.7 times higher than summertime loads when the lake was at full pool.

4.3. Healthy Dissolved Oxygen Conditions

Dissolved oxygen conditions in the Little Calfpasture River were healthy both upstream and downstream of Lake Merriweather. Downstream dissolved oxygen saturation averaged 89% during the summer of 2022. This was monitored during the worst-case scenario of hot and dry summertime conditions. Modifications to the lake discharge structure were made in 2009 in response to fish kills and low downstream dissolved oxygen. Monitoring confirms that this

modification is continuing to function properly and provide downstream aquatic life with healthy dissolved oxygen conditions.

4.4. Lake Lowering Increases Downstream Turbidity and Sediment Loads

The lake management strategy of lowering lake levels during the winter leads to significantly increased downstream turbidity and sediment loads. This was confirmed through monthly sediment load measurements and upstream and downstream turbidity monitoring. During the winter when gates were lowered, total downstream sediment loads were 6.7 times higher (1955 tonnes compared to 291 tonnes) than during the summer when the lake was at full pool. Downstream average turbidity levels during the winter were also 25 times higher than upstream average turbidity levels and 8 times higher than average summer turbidity levels. This condition is exemplified in Figure 25. This picture was taken on 4/15/2022 when lake levels were still lowered. This picture shows the confluence of the low-turbidity Calfpasture River on the left and the high-turbidity Little Calfpasture River on the right. April 15, 2022, was seven days after a small storm event in the watershed. The Calfpasture River had returned to clear conditions, but the Little Calfpasture River downstream from Lake Merriweather remained very turbid. This condition was common and persistent throughout much of the winter and early spring.



Figure 25. Picture of the Little Calfpasture River (right) and Calfpasture River (left) confluence looking upstream on 4/15/2022.

4.5. Annual Downstream Sediment Loads Continue to Exceed Ecologically Healthy Limits

Measured sediment loads from Lake Merriweather in 2022/23 exceeded the load established in the TMDL for healthy downstream aquatic life. The TMDL established a target of 1138 tonnes/yr, and the 12-month period from May 2022 to May 2023 discharged more than twice this amount (2373 tonnes). This finding is consistent with the continued aquatic life impairment on the Little Calfpasture River downstream from the lake. The average Virginia stream condition index (VSCI) for this segment of the Little Calfpasture River was 41.2 during the 2022 water quality assessment (VDEQ, 2022). VSCI scores below 60 are considered impaired, so this section of the Little Calfpasture River remains impaired.

5.0 RECOMMENDATIONS

Based on the findings of this study, the following recommendations are provided to improve lake management and reduce sediment discharge.

5.1. Reduce or Avoid Lake Lowering

This study clearly demonstrates that downstream sediment loads are increased by lowering lake levels during the winter. From an environmental standpoint, both the length and magnitude of lake lowering events should be reduced to the greatest extent possible. Shorter periods of lake lowering would mean less opportunity for storms to erode exposed mudflats, and a reduced magnitude of lowering would expose a smaller area of mudflats to erosion. Both steps would decrease the total annual discharge of sediment downstream.

In addition to environmental considerations, there are other factors that must be considered in evaluating the tradeoffs of lake lowering. These include flood risk, maintenance, and icing. For this reason, a comprehensive lake management planning process should be initiated to appropriately weigh these tradeoffs and include the views and perspectives of multiple stakeholders in the decision-making.

5.2. Develop a Lake Management Plan

A comprehensive lake management plan for Lake Merriweather should be developed. This will ensure that all functions of the lake (recreation, environmental, flood mitigation, etc.) can be properly evaluated and balanced. The following subsections provide recommended elements of the plan based on observations from this study. These recommended elements are not an exhaustive list and only reflect a limited number of observations from this study. An experienced, licensed engineer with expertise in lake management should be consulted for a full description of the needed lake management plan elements.

5.2.1. Stakeholder Input

The lake management planning process should include input from all relevant stakeholders. This includes the Boy Scouts of America National Capital Area Council, Rockbridge County, Virginia Department of Environmental Quality, Department of Conservation and Recreation, Department

of Forestry, Department of Wildlife Resources, Soil and Water Conservation District, Emergency Management personnel, upstream and downstream property owners, and possibly others. Because of the potentially competing viewpoints and recommendations of various stakeholders, stakeholder meetings and input may need to be professionally facilitated. A properly facilitated stakeholder input process will increase the likelihood that the resulting lake management plan will meet the needs of various stakeholders and be mutually agreed upon.

5.2.2. Consensus Agreement

The stakeholder input element of the lake management planning process should be facilitated with the goal of obtaining consensus agreement among the stakeholders. If stakeholders can agree on the resulting plan, it provides all parties (including the Boy Scouts) with certainty and consistent expectations regarding the lake management and operation of the dam. Currently, operation of the dam is based on several consent orders, individual requirements from various stakeholders that are often competing, historical practice, and personal judgment. This current practice likely exposes the Boy Scouts to undue legal liability and leaves other stakeholders with no certainty on lake management practices moving forward.

5.2.3. Revised Flood Risk Modeling

Flood risk modeling of the lake, the dam, and the entire Maury River network should be conducted to determine the potential risks posed by dam failure and quantify the risk reduction (if any) gained by lake lowering. Since the original models were developed, the dam has received several improvements, including upgrades to the emergency spillway and hardening and extension of the dam crest. These undoubtedly influence the flood risks posed by the dam, and decisions regarding dam operation should consider the most up-to-date estimates of estimated risks.

It is possible that the reduction in flood risk from lake lowering is actually less than anticipated, particularly under current operational practices. Currently, only two gates are lowered to establish wintertime lake levels. This reduces the full 130-ft spillway to only 26 ft at lower lake levels. As a result, large storms can quickly fill excess freeboard capacity and may provide no additional protection from peak storm flows. For instance, the largest storm this year was a peak flow of 7760 cfs measured in the Maury River at Rockbridge Baths in February. This was a relatively small storm compared to the 1985 storm of record that reached 87,700 cfs at that location. Even though

the February storm only represented 9% of the peak flow in the storm of record, lake levels quickly rose from the wintertime depth of 17 ft to 23.92 ft. So, all but two feet of reserve freeboard capacity in the lake was utilized in this relatively small storm. As a result, lake lowering may actually provide negligible risk reduction in a 500-yr design flood.

In addition, flood risk modeling should include a flood wave propagation model that extends through Goshen Pass and Rockbridge Baths under varying design flood conditions (including 500-yr flood). It is possible that the natural geologic pinch point of Goshen Pass controls downstream flowrates and creates backwater effects during a large design flood. This could reduce or negate the impacts of a catastrophic dam failure under these conditions.

5.2.4. Documentation

A lake management plan will provide needed documentation for agreed-upon standard operating procedures and decision criteria for dam operation and lake management. This will be helpful in the event of staff turnover or retirements. It will also provide consistency and assurances to all stakeholders.

The lake management plan should also require specific documentation of dam operations. Currently, lowering and raising of the dam is not sufficiently documented. For this project, JMU had to re-create information on dam gate positions after the fact based on lake level monitoring; because the actual dates, times, magnitude, and position of gate movements were not documented in real time. As mentioned in Section 2.7, this estimated re-creation of gate positions led to errors in calculated flows and sediment discharge during the time of lake lowering. In addition, the lack of documentation may expose the Boy Scouts to undue legal liability in the event of any downstream accident during or unrelated to dam lowering events.

5.2.5. Lake Lowering Decision Criteria

The first recommendation from this study is to avoid or reduce lake lowering events in order to reduce sediment discharge and improve downstream habitat and ecological health. During development of the lake management plan, the feasibility of avoiding or reducing lake lowering events should be evaluated within the context of other maintenance and emergency needs. Based

on this evaluation and stakeholder feedback, the lake management plan should establish defined decision criteria and procedures for lake lowering. The plan should address:

- needs and rationale for lake lowering events
- evaluation of alternatives to lake lowering
- recommended timing, duration, and magnitude of lake lowering to accomplish specific tasks or meet specific needs
- sediment mitigation measures during lake lowering
- decision criteria and notification procedures for emergency lowering
- procedures and documentation for lake lowering and raising

5.2.6. Alternative Sediment Reduction Measures

If after thorough evaluation and stakeholder input, lake lowering events are to continue, the lake management plan should evaluate alternative sediment reduction measures. These could include vegetation of mudflats during extended lake lowering events, dredging, or permanent establishment of the lake at a reduced elevation. Other approaches may also be investigated with the goal of reducing sediment discharge when lake levels are lowered.

5.2.7. Cold-Water Release Operation

The lake management plan should include specific instructions for if, when, and how to operate the cold-water release gates. Currently, the Boy Scouts are receiving conflicting information and instructions from different authorities on the operation of these gates. The development of a lake management plan would provide the opportunity to solicit stakeholder input and to evaluate all of the relevant guidance, requirements, and best practices to determine a consensus path forward.

From an environmental standpoint, if the lower cold-water release gates are operated, it should not be conducted while the lake is thermally stratified. During the late spring to fall, the lake typically stratifies with warm, well-oxygenated water at the top and cold, oxygen-depleted water at the bottom. Opening the lower cold-water release gates during stratification would create low dissolved oxygen conditions downstream and potentially produce fish kills. In addition, the lake management plan should consider sediment reduction strategies during the opening of lower cold-water release gates. This could include measuring sediment depths prior to operation, localized

dredging around the gate to reduce downstream sediment transport, and downstream monitoring during operation.

5.2.8. Long-term Planning

The lake management plan should also consider long-term planning for the lake. This could include a plan for addressing progressive lake infill with sediment through a long-term dredging program. The plan could also address aging equipment and infrastructure with an equipment and dam infrastructure upgrade and replacement program. Lastly, a long-term plan could even address end-of-life scenarios for the lake and the dam.

6.0 REFERENCES

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