



May 27th 2021

From: Andrew Sampsell, EI (D&K)

To: Shadow Lake Association

CC: Town of Glover, Andrew Hoak, PE (D&K)

Re: Shadow Lake – Glover, VT - Spring Runoff & Lake Level Analysis

1.0 - Introduction & Background:

This technical memorandum summarizes a hydrologic & hydraulic analysis (H&H) performed by DuBois & King, Inc. (D&K) in reference to lake level rise following spring runoff events at Shadow Lake in Glover, VT. Shadow Lake is primarily used for recreational purposes and a number of residential properties surround the lake. In past years, these properties have experienced shorefront erosion damage due to rising lake levels in the spring time.

The analysis presented in this technical memorandum utilizes information from a previous H&H analysis performed by D&K for the Town of Glover regarding the ability for Shadow Lake Dam to meet dam safety hydraulic design criteria. The previous analysis was titled “Shadow Lake Dam Hydrologic & Hydraulic Study” dated July 14th 2020. The conclusion of the previous analysis was that the dam was not able to meet dam safety hydraulic design criteria given its current Significant Hazard Classification.

The Shadow Lake Dam is owned and operated by the Town of Glover. Outflow from the lake is controlled by a principal spillway structure, which consists of a trash rack, gate house, stop logs, and 30” diameter concrete outlet. In addition the dam also has a concrete auxiliary spillway that sits approximately 1.5 ft above the normal pool elevation of the lake. The purpose of the auxiliary spillway is to help pass lower frequency (larger magnitude) storm events, which cannot be handled by the discharge capacity of the principal spillway alone.

The principal spillway structure controls the normal pool elevation within the lake. In past years prior to the onset of winter the Town has lowered the lake level by approximately 1 foot to help address the lake level rise which occurs during spring. The Vermont Department of Environmental Conservation (VT DEC) has requested that the Town of Glover eliminate the fall lake level drawdown procedure. VT DEC would like a year round normal pool to be established to prevent ecological damages from occurring as a consequence of the lake drawdown procedure.

2.0 – Purpose:

The purpose of the spring runoff and lake level H&H analysis is to:

1. Quantify the volume of runoff that might occur during a spring time runoff event to better understand why the shorefront property damage is occurring and how it might be prevented,
2. Identify potential measures that can be taken to reduce shorefront property damage and eliminate the fall drawdown procedures such that the normal pool elevation of the lake remains relatively constant year round.

3.0 - Hydrologic Analysis:

The hydrologic analysis was performed using US Army Corps of Engineers HEC-HMS version 4.6.1 hydrologic & hydraulic modeling software. HEC-HMS offers a number of different methods for analyzing hydrologic events. The two main methodologies applied in this analysis are the following:

- Temperature Index Method (Snow Melt),
- NRCS Curve Number Method (Runoff).

Documentation for the methods applied within the hydrologic model can be found in the National Engineering Handbook Part 630 – Hydrology. The Key chapters are listed below.

- Chapter 4 - Stormfall Rain Depth and Distribution
- Chapter 7 - Hydrologic Soil Groups
- Chapter 8 – Land Use and Treatment Classes
- Chapter 9 – Hydrologic Soil Cover Complexes
- Chapter 10 – Estimation of Direct Runoff from Storm Rainfall
- Chapter 11 – Snow Melt
- Chapter 15 – Time of Concentration
- Chapter 16 – Hydrographs

Additional documentation can be found within the HEC-HMS user’s manual, technical reference manual, and applications guide.

Some key inputs for the hydrologic model were sourced from the previous H&H analysis and are summarized in the following tables. For more detail regarding the data summarized in Table 1, refer to the previous technical memorandum. Detail pertaining to the modifications made to the previous H&H model regarding input and parameters specific to the spring runoff / snowmelt analysis are described in the following sections.

3.1 – Watershed Description & Data Carried over from Previous H&H Analysis

The drainage area corresponding to the Shadow Lake watershed is 5.3 square miles. Approximately 1.4 square miles of the 5.3 square mile watershed drains to Daniels Pond. A 70” x 42” corrugated metal arch pipe controls Daniels Pond outflow and if the storm is large enough (requires storm in excess of 1000-yr recurrence interval) roadway overtopping. Flow from Daniels Pond travels through a forested wetland area prior to reaching Shadow Lake. Approximately 76% of the watershed is forested, 8% of the watershed is residential development, 7% of the watershed is

field/open land, and 9% of the watershed is either a waterbody or soils most often completely saturated with water.

Table 1: Hydrologic Parameters

	Daniels Pond	Shadow Lake
Drainage Area	1.4 sq. mi.	3.9 sq. mi.
Time of Concentration	95.9 min	101.5 min
Curve Number ¹	88.0	89.0
Base Flow	2.91 cfs	7.84 cfs

¹ Curve number corresponds to an antecedent moisture condition III (less infiltration due to frozen/saturated ground).

3.2 – Basis for Analysis

A member of the Shadow Lake Association indicated that a significant spring runoff event occurred at the end of March 2019 in which reportedly 18” of water was flowing through the Shadow Lake Dam’s concrete auxiliary spillway. This would mean that the water level was up 4.0 feet higher than its fall drawdown normal pool elevation (assuming a 1-foot drawdown).

While the end of March 2019 event is not the only notable spring runoff event that has happened at Shadow Lake, D&K used this event as a basis for analyzing spring runoff within the hydrologic model since an observed flow condition was provided.

3.3 - Stream Gauge Analysis

D&K reviewed discharge values at downstream USGS Streamgauge 04296280 (Barton River near Coventry, VT). The drainage area corresponding to USGS 04296280 is approximately 155 square miles, but is generally similar in terms of land cover type, soils, climate, and elevation to the Shadow Lake Watershed. Table 2 below depicts the monthly peak discharge recorded at the USGS streamgauge in month of March for water years 2011 through 2020. Out of the past 10 years the March 2019 event ranks third in terms March monthly peak discharges.

Table 2: USGS Streamgauge 04296280 March Peak Discharge Data (2011 – 2020)

Date	Rank	Peak Discharge (cfs)	Peak Discharge (cfs/sq. mi.)
3/19/2011	2	1,580	10.2
3/8/2012	7	1,040	6.7
3/13/2013	1	2,600	16.8
2014	10	Not Available	Not Available
3/28/2015	9	225	1.5
3/11/2016	8	936	6.0
3/2/2017	5	1,140	7.4
3/31/2018	6	1,090	7.0
3/31/2019	3	1,490	9.6
3/11/2020	4	1,160	7.5

Table 3 below depicts the annual peak discharge for water years 2011 through 2020. The peak recorded annual discharge fell within months that have a potential for snowmelt/frozen ground runoff conditions to occur 7 out of 10 years (November – April). Four out of those seven times it was during the months of February – April where freeze/thaw events frequently occur in the State of Vermont.

Table 3: USGS Streamgauge 04296280 Annual Peak Discharge (2011-2020)

Date	Peak Discharge (cfs)	Peak Discharge (cfs/sq. mi.)
4/27/2011	6,070	39.2
5/30/2012	1,840	11.9
5/26/2013	3,450	22.3
4/16/2014	2,880	18.6
6/10/2015	2,620	16.9
2/25/2016	4,160	26.8
2/26/2017	1,930	12.5
1/13/2018	1,990	12.8
12/22/2019	2,920	18.8
11/1/2020	3,340	21.5

3.4 - Temperature & Precipitation

Precipitation & Temperature data was collected from a nearby rainfall gauge to see what happened in the days leading up to March 31st 2019. The nearest publically available precipitation gage to source data from was located in Greensboro, VT. The gauge is located approximately 3.75 mi (straight-line distance) from Shadow Lake. The elevation of the gauge is approximately 588.8 feet higher than the crest elevation of the shadow lake auxiliary spillway.

Weather Station ID: KVTGREEN4

Station Name: Town Highway 8

Latitude / Longitude: 44.631° N, 72.281° W

Elevation: 1985 NAVD88 feet

City: Greensboro

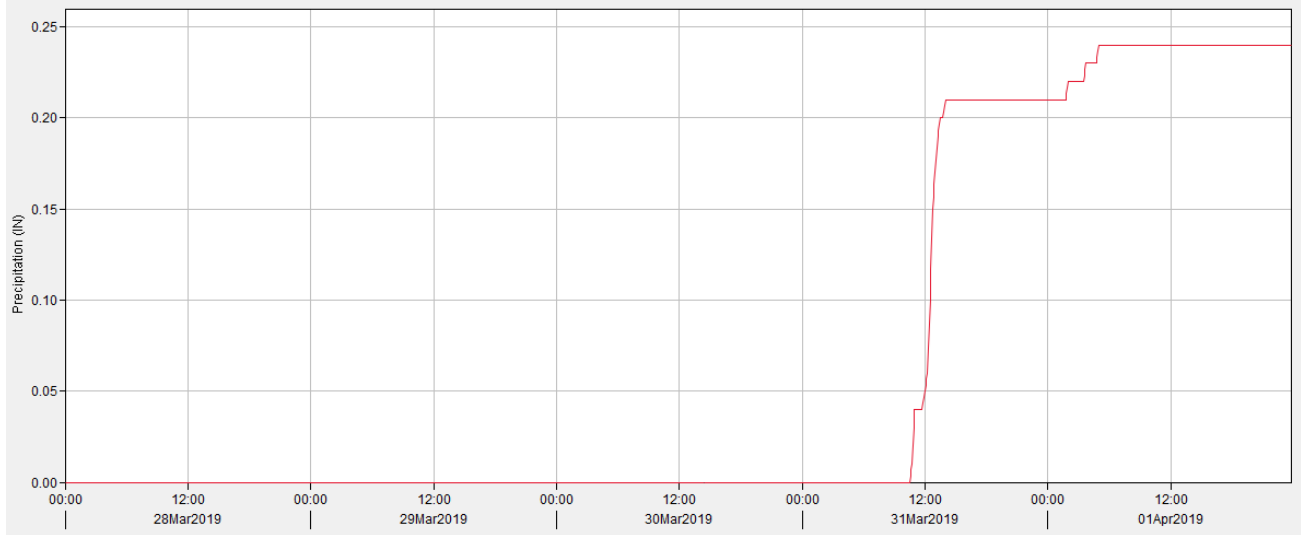
State: VT

Hardware: Davis Vantage Pro2 Plus (Wireless)

Software: Weatherlink.com 1.10

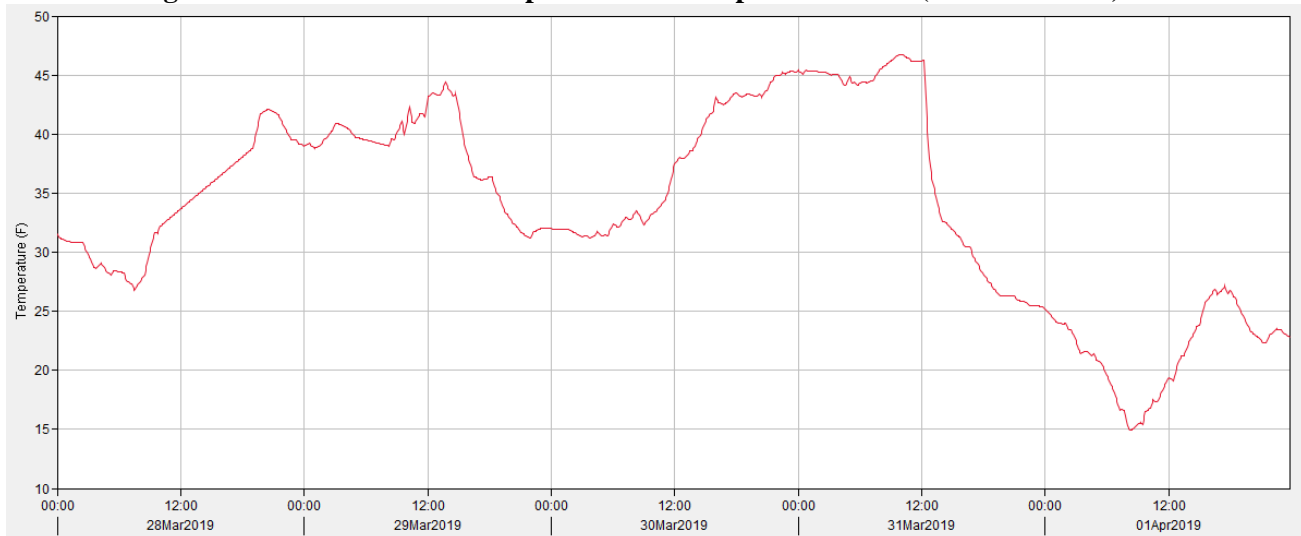
Sourced From: Weather Underground

Figure 1: March 28th 2019 to April 1st 2019 Cumulative Precipitation Data (KVTGREEN4)



The gauge indicates a small amount of precipitation over the course of the 5 days. Based upon the temperature profile displayed in Figure 2 below it is likely that the bulk of this precipitation fell as rain.

Figure 2: March 28th 2019 to April 1st 2019 Temperature Data (KVTGREEN4)



The gauge depicts temperatures above the freezing point of 32 degrees Fahrenheit. Given that this gauge is higher in elevation than Shadow Lake it is possible that temperatures within the Shadow Lake watershed were slightly warmer. The temperature and precipitation data supports the notion of a spring runoff event occurring.

3.5 - Snow Pack Data

Measured snow pack data was not available for the study area. The United States Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) maintains a network of snow telemetry gauges called SNOTEL, which monitor snow depth, snow water equivalent, and other snow parameters. Currently this network of gauges only covers the northwestern portion of the United States. Due to the lack of measured data within the Shadow Lake watershed, this study relies on snow pack prediction data.

The National Snow & Ice Data Center (NSIDC) maintains a project called Snow Data Assimilation System (SNODAS), which estimates snow pack conditions such as depth of snow and snow water equivalent (SWE), from data collected by the NOAA National Weather Service's National Operational Hydrologic Remote Sensing Center (NOHRSC). SNODAS is a modeling and data assimilation system developed by NOHRSC to provide the best possible estimates of snow pack parameters to support hydrologic modeling and analysis. The data set essentially estimates snow parameters using remote sensing techniques. Each day analysts decide whether or not to update the snow water equivalent state within the model based on the collected remote sensing data. The data set has a spatial resolution of 1 kilometer and a temporal resolution of 1 hour.

The parameters used in this study were sourced from the March 28th 2019 SNODAS data.

3.6 – Temperature Index Method & Key Snowmelt Parameters

The following sections (3.6 – 3.6.14) quote/summarize key snowmelt parameter information outlined in the HEC-HMS user's manual. These parameters need to be defined in order to utilize the Temperature Index Method within HEC-HMS. In order to better understand how the Temperature Index Method works it is recommend to read the full snowmelt section of the HEC-HMS user's manual, and refer to its supporting documentation/references.

The temperature index method is an extension of the degree-day approach to modeling a snowpack. A typical approach to the degree-day method is to have a fixed amount of snowmelt for each degree above freezing. This method includes a conceptual representation of the cold energy stored in the snow pack along with a limited “memory” of past conditions and other factors to compute the amount of melt for each degree above freezing. As the snowpack internal conditions and atmospheric conditions change, the melt coefficient also changes.

3.6.1 – Lapse Rate (Deg. F / 1000 feet) –

Lapse rate represents the change in temperature per 1000 feet. The temperature for each elevation band within the watershed is computed using the temperature recorded in the time series data.

Lapse rate was not used for this study. The temperature was assumed uniform for the entire watershed.

3.6.2 - PX Temperature (Deg. F) –

The PX temperature is used to discriminate between precipitation falling as rain or snow. When the air temperature is less than the specified temperature, any precipitation is assumed to be snow. When the air temperature is above the specified temperature, any precipitation is assumed to be rain.

This study used a Px temp of 32.1° F.

3.6.3 – Base Temperature (Deg. F) –

The difference between the base temperature and the air temperature defines the temperature index used in calculating snow melt. Meltrate is multiplied by the difference in temperature to estimate the amount of snow melt. Typically, the base temperature is set to 32.0° F.

This study used a base temp of 32.0° F.

3.6.4 - Wet Meltrate (In/Deg. F-Day) –

The wet meltrate is used during time intervals when precipitation is falling as rain, and the rainfall rate is greater than the rain rate limit. It represents the rate at which the snowpack melts when it is raining on the snowpack.

A constant wet meltrate was used for this study.

3.6.5 – Dry Meltrate (In/Deg. F-Day) –

The dry meltrate is used during time intervals when snowmelt is occurring without rainfall precipitation.

A constant dry meltrate was used for this study.

3.6.6 – Cold Limit (In/Day) –

The cold limit accounts for the rapid changes in temperature that the snowpack undergoes during high precipitation rates. When the precipitation rate exceeds the specified cold limit, the antecedent cold content index is set to the temperature of the precipitation. If the temperature is above the base temperature, the cold content index is set to the base temperature. If the temperature is below the base temperature, the cold content index is set to the actual temperature. If the precipitation rate is less than the cold limit, the cold content index is computed as an antecedent index. The default value of 0 in/day is used if no value is entered, meaning that even a trace of snowfall will reset the cold content.

For this study a cold rate greater than the total amount of precipitation was entered to prevent the cold content value from being reset. This resulted in a conservative amount of snowmelt.

3.6.7 – Cold Rate Coefficient –

The cold content antecedent temperature index coefficient is used to update the antecedent cold content index from one time interval to the next. This is a separate index from the one used to update the meltrate index. A default value of 0.5 is used if no value is entered.

A cold rate coefficient of 0.35 was used for this study.

3.6.8 – Water Capacity (%) –

The maximum liquid water capacity specifies the amount of melted water that must accumulate in the snowpack before liquid water becomes available at the soil surface for infiltration or runoff. Typically, the maximum liquid water held in the snowpack is on the order of 3% to 5% of the snow water equivalent, although it can be higher. Liquid water can persist in the snow only if the snowpack temperature is at 32° F or higher, at which point the cold content is zero.

For this study it was assumed that the liquid water capacity of the snow was 0% to produce a conservative runoff result (in an attempt to recreate the observed 18 inches of flow depth).

3.6.9 – Groundmelt (In/Day) –

Heat from the ground can cause snowmelt, especially if the snowpack accumulates on ground that is only partially frozen or completely unfrozen. In these cases the warm ground is insulated by the snowpack. Heat from the warm ground will cause the bottom of the snowpack to melt.

For this study no snow melt resulting from ground heat was represented within the model (data not available).

3.6.10 – Initial Snow Water Equivalent (SWE) (In) –

Measurement that describes the amount of liquid water contained within the snowpack (the amount of water that is released when the snow melts). If there is no snowpack at the start of simulation than this value is set to 0.

Initial SWE values for both the Shadow Lake and Daniels Pond subcatchments were referenced from the SNODAS data and are listed in Table 4 below.

3.6.11 – Initial Cold Content (In) –

The initial cold content that exists at the beginning of the simulation must be entered. It represents the heat required to raise the temperature of the snow pack to 32° F and is expressed as a number equivalent to inches of frozen water. If there is no snow at the beginning of the simulation, it can be set to zero. If there is a snowpack, it can be estimated as the depth of snow multiplied by the snow density multiplied by the heat capacity of snow multiplied by the number of degrees below the freezing point.

The initial cold content used for this study was set to 0 in an attempt to recreate the observed 18 inches of flow depth.

3.6.12 – Initial Liquid Water (In) –

The liquid water held within the snowpack at the beginning of the simulation must be entered. Liquid water can persist in the snow only if the snowpack temperature is at 32° F or higher. There are few conditions when this value can be exactly known. One case is when there is no snowpack and it can be set to zero. A second case is when the air temperature has been continually below freezing for several days and it can be set to zero.

For this study the initial liquid water content was set to zero. Leading up to March 28th 2019 the temperature was below freezing.

3.6.13 – Initial Cold Content ATI (Deg. F) –

The initial cold content antecedent temperature index is an index to the snow temperature near the surface of the snowpack. It should be set to the approximate snowpack temperature at the beginning of the simulation. If the initial temperature is not known, it can be set to 32° F.

For this study the initial cold content ATI was set to 32° F.

3.6.14 – Initial Melt ATI (Deg. F – Day) –

The seasonal variation of melt rate is indexed by an antecedent temperature function. The initial melt rate ATI should be thought of as similar to "the accumulated thawing degree days." This antecedent temperature function allows the melt rate to change as the snowpack matures and ages. If there is no snow on the ground at the start of the simulation this term can be set to zero. It can also be set to zero if the simulation is starting during or at the end of a cold period when air temperatures were continually below the base temperature. Otherwise, it must be calculated as the accumulation of degree-days since the last period of sustained air temperature below freezing.

March 28th was the end of a cold period. Therefore this study the initial melt rate ATI was set to zero.

A limited sensitivity testing effort was performed on each of the parameters to gauge the effect they had on the results of the analysis. In general, the selected values were based on recommended ranges by the HEC-HMS user's manual, other snowmelt hydrologic studies (see references), and values included in the SNODAS data set. The final selected values were chosen with a bias towards trying to recreate the result of 18" flow depth above the Shadow Lake Dam auxiliary spillway crest. Some parameters were chosen outside of recommended ranges in an attempt to create a conservative analysis. Table 4 below depicts the final parameters used in the HEC-HMS model.

Table 4: Selected Snowmelt Parameters

	Daniels Pond Subcatchment	Shadow Lake Subcatchment
Lapse Rate (Deg. F / 1000 feet)	0	0
PX Temperature (Deg. F)	32.1	32.1
Base Temperature (Deg. F)	32.0	32
Wet Meltrate (In/Deg. F-Day)	0.15748	0.15748
Dry Meltrate (In/Deg. F-Day)	0.07874	0.07874
Cold Limit (In/Day)	1	1
Cold Rate Coefficient	0.35	0.35
Water Capacity (%)	0	0
Groundmelt (In/Day)	0	0
Snow Pack Depth (ft)	3.0	3.1
Initial SWE (In)	12.50	12.94
Initial Cold Content (In)	0	0
Initial Liquid Water (In)	0	0
Initial Cold Content ATI (Deg. F)	32	32
Initial Melt ATI (Deg. F – Day)	0	0

4.0 - Hydraulic Analysis:

The hydrologic analysis was performed using US Army Corps of Engineers HEC-HMS version 4.6.1 hydrologic & hydraulic modeling software. HEC-HMS allows the user to perform level pool routings through reservoirs with varying outlet structures. The storage capacity and outlet structures of both Daniels Pond and Shadow Lake were included within the model. The lag time for flow to travel from Daniels Pond to Shadow Lake was estimated to be 10.25 minutes using the NRCS velocity method outlined in NEH 630 Hydrology Chapter 15.

Elevations used within the hydraulic model are based on a combination of 2014 Hydroflattened (0.7m) LIDAR DEM data and field measurements collected as part of the previous H&H analysis. A detailed field survey was not performed.

4.1 - Daniels Pond

Daniels Pond Road controls the flow of water out of Daniels Pond via a 70" x 42" CMP arch and if the storm is large enough, roadway overtopping (requires storm in excess of 1000-yr recurrence interval). The Daniels Pond outlet structure was modeled using a rating curve based on the discharge performance of the culvert in the previous H&H analysis.

Roadway overtopping was modeled as broad crested weir flow (discharge coefficient $C = 2.63$) using a surface profile derived from the LIDAR elevation data. No roadway overtopping occurred as part of the snowmelt analysis.

Storage values for Daniels Pond were calculated for elevations above the invert elevation of the 70" x 42" CMP arch culvert, which controls the ponds "normal pool" elevation. Table 5 below depicts the storage values used in the analysis.

The HEC-HMS model assumes free discharge conditions (no backwater).

Table 5: Daniels Pond Stage Storage Curve

Elevation (NAVD88 FT)	Storage (Acre-ft)	Description
1630.0	0.0	Normal Pool / Outlet Invert Elevation
1630.4	1.1	
1630.5	2.2	
1630.6	3.3	
1630.7	4.6	
1630.8	6.3	
1630.9	9.2	
1631.2	14.5	
1631.6	23.3	
1632.1	36.1	
1632.6	52.8	
1633.2	72.5	
1633.9	94.0	

1634.6	111.5	
1635.2	118.2	
1635.9	130.4	
1636.6	143.6	Roadway Low Point
1637.2	155.2	
1637.7	164.8	
1638.2	172.8	
1638.6	179.2	
1639.0	184.4	
1639.3	188.6	
1639.5	192.0	
1639.7	194.4	
1639.8	192.8	
1639.9	191.4	
1640.0	190.1	
1640.1	189.0	
1640.2	187.7	

Table 6: Daniels Pond Culvert Discharge Rating Curve

Elevation (NAVD88 FT)	Discharge (cfs)
1630.0	0.0
1630.4	1.1
1630.5	2.2
1630.6	3.3
1630.7	4.6
1630.8	6.3
1630.9	9.2
1631.2	14.5
1631.6	23.3
1632.1	36.1
1632.6	52.8
1633.2	72.5
1633.9	94.0
1634.6	111.5
1635.2	118.2
1635.9	130.4
1636.6	143.6
1637.2	155.2
1637.7	164.8

1638.2	172.8
1638.6	179.2
1639.0	184.4
1639.3	188.6
1639.5	192.0
1639.7	194.4
1639.8	192.8
1639.9	191.4
1640.0	190.1
1640.1	189.0
1640.2	187.7

4.2 - Shadow Lake

Shadow Lake Dam controls the flow of water out of Shadow Lake via principal spillway gate house structure, and the concrete chute auxiliary spillway. In order to model the principal spillway structure within HEC-HMS, the principal spillway structure discharge was approximated by a rating curve which considers both weir and orifice flow. The discharge capacity of the principal spillway is limited by the 36” diameter concrete orifice at higher heads.

Both the auxiliary spillway and dam crest overtopping flow were represented with discharge coefficients corresponding to broad crested weir flow. The auxiliary spillway was represented with a discharge coefficient of 2.70, the dam crest was represented with a weir coefficient of 2.63. Discharge coefficient selection was based on observations made during a site visit and general guidance provided in the US Bureau of Reclamation’s “Design of Small Dams – third edition” technical publication (1987).

The HEC-HMS model assumes free discharge conditions downstream of the dam (no backwater).

Table 7: Shadow Lake Stage Storage Curve

Elevation (NAVD88 FT)	Surface Area (acres)	Storage (Acre-ft)	Description
1393.6	213.2	0	Winter Drawdown Normal Pool
1394.6	217.3	214.8	Approx. Normal Pool (Principal Spillway Invert)
1395.0	220.0	302.0	
1396.0	221.3	522.7	
1396.2	221.5	567.0	Auxiliary Spillway Invert
1397.0	222.4	744.5	
1398.0	223.6	967.5	
1399.0	225.0	1191.7	
1399.8	225.9	1372.1	Top of Dam (Height = 13.6 feet)
1400.0	226.3	1417.3	
1401.0	227.7	1644.2	
1402.0	229.4	1872.6	

1403.0	231.6	2103.0	
1404.0	235.2	2335.9	
1405.0	240.5	2573.0	
1406.0	246.0	2815.7	
1407.0	251.2	3063.8	
1408.0	255.9	3317.0	
1409.0	260.2	3574.6	
1410.0	264.0	3836.5	

**Table 8: Shadow Lake Principal Spillway Discharge Rating Curve
(Summer Normal Operating Condition)**

Elevation (NAVD88 FT)	Discharge (cfs)
1394.6	0.0
1394.7	0.4
1394.8	1.2
1394.9	2.1
1395	3.3
1395.1	4.6
1395.2	6.0
1395.3	7.6
1395.4	9.3
1396.2	10.8
1396.4	18.6
1396.6	24.1
1396.8	28.5
1397	32.3
1397.2	35.7
1397.4	38.8
1397.6	41.7
1397.8	44.4
1398.1	48.1
1398.6	53.8
1399.1	58.9
1399.6	63.6
1399.8	65.4

**Table 9: Shadow Lake Principal Spillway Discharge Rating Curve
(Winter Drawdown Condition)**

Elevation (NAVD88 FT)	Discharge (cfs)
1393.6	0.0
1393.7	0.4
1393.8	1.2
1393.9	2.1
1394	3.3
1394.1	4.6
1394.2	6.0
1394.3	7.6
1394.4	9.3
1395.2	10.8
1395.4	18.6
1395.6	24.1
1395.8	28.5
1396	32.3
1396.2	35.7
1396.4	38.8
1396.6	41.7
1396.8	44.4
1397	46.9
1397.5	52.7
1398	57.9
1398.5	62.7
1399	67.2
1399.5	71.4
1399.8	73.8

5.0 - Results:

A summary of results for each of the different scenarios tested within the hydrologic & hydraulic model are presented below. In addition to framing/quantifying the potential for snowmelt runoff to occur at Shadow Lake, the considered scenarios also try to identify additional factors that may be amplifying the snowmelt runoff issue. The goal of each scenario considered is to provide insight that should assist with future decision-making processes regarding improving the dam's ability to control the lake level in a more satisfactory manor for the community.

5.1 – March 28th 2019 to April 1st 2019 Snowmelt Event (Existing Spillway Configuration)

The March 28th 2019 to April 1st 2019 event (snowmelt + precipitation runoff) resulted in a total inflow volume to shadow lake of 318.5 acre-ft over the course of the five days. The peak inflow rate of the runoff hydrograph was 314.3 cfs. Four different scenarios were tested with this inflow.

- **Scenario 1:** Winter drawdown board not removed, lake level starts at normal pool elevation (1394.6)
- **Scenario 2:** Winter drawdown board not removed, lake level starts at auxiliary spillway crest (1396.2)
- **Scenario 3:** Winter drawdown board removed, lake level starts at normal pool elevation (1393.6)
- **Scenario 4:** Winter drawdown board removed, lake level starts at auxiliary crest (1396.2)

Table 10: March 28th to April 1st 2019 Snowmelt Event Results

	Peak Inflow (cfs)	Peak Inflow (cfs/sq. mi.)	Inflow Volume (acre-ft)	Peak Lake Level (NAVD 88 FT)	Depth of Flow Above Aux Crest (ft)	Total Peak Discharge (cfs)	Discharge Volume (acre-ft)
Scenario 1	314.3	59.4	318.5	1395.9	-0.3	9.3	41.2
Scenario 2				1396.9	0.7	52.9	230.0
Scenario 3				1394.9	-1.3	10.2	43.9
Scenario 4				1396.4	0.2	41.5	328.8

5.2 – Steady State Discharge Required to Achieve 18” of Flow Depth

- **Scenario 1:** Winter drawdown board not removed lake level starts at auxiliary spillway crest (1396.2)
- **Scenario 2:** Winter drawdown board removed lake level starts at auxiliary spillway crest (1396.2)

Table 11: Steady State Discharge Required to Maintain 1.5 ft of Flow Depth in Aux. Spillway

	Inflow (cfs)
Scenario 1	115
Scenario 2	130

5.3 – Shadow Lake Reservoir Drawdown Test

After modeling the March 28th 2019 to April 1st 2019 event and concluding that it was unlikely that the 18” inches of flow depth over the auxiliary spillway crest was due to just the snowmelt and precipitation recorded (by the precipitation gauge) across those five days. D&K looked into to other potential contributing factors.

There are a number of possible reasons for why the snowmelt model was not able to recreate the reported 18” inches of flow depth over the auxiliary spillway crest. The reason that seemed most probable was the cyclical nature of Vermont freeze thaw events and the possibility that the existing principal spillway structure does not have the discharge capacity to drawdown the lake level before the next thaw event occurs. It is possible that if a longer period of time was analyzed (i.e. January – April) within the hydrologic model that the 18 inches of flow depth would have been recreated.

In order to get a feel for the ability for the principal spillway structure to drawdown the lake level, and its sensitivity to the drawdown board elevation, the two following scenarios were considered.

- **Scenario 1:** Winter drawdown board not removed, lake level starts at auxiliary spillway crest (1396.2), 0 cfs inflow
- **Scenario 2:** Winter drawdown board removed, lake level starts at auxiliary spillway crest (1396.2), 0 cfs inflow

Table 12: Drawdown Simulation Results

Elevation (NAVD88 ft)	Scenario 1		Scenario 2	
	Time	Outflow (cfs)	Time	Outflow (cfs)
1396.2	0 day 0 hr 0 min	10.8	0 day 0 hr 0 min	35.7
1396.0	1 day 15 hr 12 min	10.5	11 hrs 43 min	33.1
1395.8	4 day 0 hr 45 min	10.1	1 day 4hr 48 min	29.4
1395.6	7 ay 10 hr 18 min	9.8	2 days 0 hr 28 min	25.2
1395.4	9 days 19 hr 49 min	9.4	3 days 0 hr 2 min	20.0
1395.2	12 days 12 hr 33 min	6.8	4 days 8 hr 51 min	12.7
1395.0	16 days 20 hr 11 min	3.9	6 days 9hr 37 min	10.5
1394.8	23 days 12 hr 06 min	1.6	9 days 12 hr 51 min	10.1
1394.6	34 days 4 hr 02 min	0.0	11 days 17hrs 58 min	9.8
1394.4	-	-	14 days 0 hr 42 min	9.4
1394.0	-	-	20 days 20hr 45 min	3.9
1393.6	-	-	65 days 23 hr 43 hr	0.0

5.5 – Lowering Auxiliary Spillway Crest by 1 foot (Elevation = 1395.2)

A member of the Shadow Lake Association mentioned that a potential option for increasing the discharge capacity of the Shadow Lake dam could be to lower the auxiliary spillway crest by around 1 foot through concrete removal.

D&K tested what kind of an effect this would have on the March 28th to April 1st 2019 snowmelt event.

- **Scenario 1:** Winter drawdown board not removed, lake level starts at auxiliary spillway crest (1395.2)
- **Scenario2:** Winter drawdown board removed, lake level starts at auxiliary crest (1395.2)

Table 13: March 28th to April 1st 2019 Snowmelt Event Results with Lower Aux Crest

	Peak Inflow (cfs)	Peak Inflow (cfs/sq. mi.)	Inflow Volume (acre-ft)	Peak Lake Level (NAVD 88 FT)	Depth of Flow above Aux Crest (ft)	Total Peak Discharge (cfs)	Discharge Volume (acre-ft)
Scenario 1	314.3	59.4	318.5	1396.0	0.8	41.7	178.0
Scenario 2				1395.9	0.7	53.1	230.4

The drawdown test was also re-run to see how much the 1 foot lower auxiliary spillway crest would accelerate the drawdown time.

- **Scenario 1:** Winter drawdown board not removed, auxiliary spillway crest elevation at 1395.2, starting lake level at 1396.2, 0 cfs inflow.
- **Scenario2:** Winter drawdown board removed, auxiliary spillway crest elevation at 1395.2, starting lake level at 1396.2, 0 cfs inflow.

Table 15: Drawdown Simulation Results with Lower Aux Crest

Elevation (NAVD88 ft)	Scenario 1		Scenario 2	
	Time	Outflow (cfs)	Time	Outflow (cfs)
1396.2	0 day 0 hr 0 min	51.3	0 day 0 hr 0 min	76.2
1396.0	0 day 8 hr 39 min	42.2	0 day 5hr 44 min	64.9
1395.8	0 day 23 hr 20min	31.4	0 day 15 hr 3 min	50.7
1395.6	1 day 19 hr 45 min	22.0	1 day 3 hr 17 min	37.4
1395.4	3 days 1hr 45 min	14.5	1 day 20 hr 41 min	25.0
1395.2	6 days 5 hr 12 min	7.2	3 day 1 hr 44 min	13.2
1395.0	10 days 10 hr 13 min	3.9	5 days 2 hr 38 min	10.5
1394.8	19 days 1 hr 12 min	1.6	8 days 6 hr 0 min	10.1
1394.6	23 days 17 hr 6 min	0	9 days 11 hr 7 min	9.8
1394.4	-	-	11 days 17hr 52 min	9.4

1394.0	-	-	19 days 13 hr 56 min	4.0
1393.6	-	-	35 days 16 hrs 53 min	0

6.0 – Summary, Conclusions, and Recommendations:

The analysis indicates that springtime run off or freeze/thaw phenomena do have the potential for causing lake level rises that could impact the shore lines of the lake front properties.

Data sourced from a downstream stream gauge with similar watershed characteristics indicated that months with the potential for snowmelt runoff frequently cause the highest recorded annual peak discharges. The stream gauge analysis was able to show that the end of March 2019 produced above average discharges which supports the reported 18 inches of flow depth within the existing Shadow Lake Dam auxiliary spillway at the end of March.

However, the snowmelt runoff analysis was unable to recreate observed 18 inches of flow depth within the auxiliary spillway. This could be due to a number of different factors, potential reasons are provided below.

- Inaccuracy in reported temperature and precipitation values from weather instrumentation.
- Spatial variation in temperature and precipitation data over the watershed vs what was measured at the sensor.
- Snow water equivalent & snow depth parameters are from estimates derived from remote sensing data (not actual measurements).
- Trash rack may be limiting the flow through the principal spillway such that the principal spillway rating curve over estimates discharge.
- Ice/debris could have been limiting flow through the principal spillway resulting in reduced discharge capacity when the 18 inches of flow depth was observed.

Rather than focus on trying to adjust parameters within the hydrologic model (requiring values outside of typical ranges) to recreate the reported flow depth observation. D&K spent time looking at the performance of the existing spillway in reference to its ability to draw down the lake level and handle back to back spring runoff or freeze/thaw events. The existing spillway configuration at the shadow lake dam takes 12 days 12 hrs and 33 min to lower the lake level 1 foot from 1396.2 to 1395.2 when the drawdown board is not removed. With the drawdown board removed, the spillway takes 4 days 8 hr 51 min for the same drawdown (almost one third of the time).

Potential Improvements:

1. Improve the discharge capacity of the principal spillway structure such that the time it takes for the lake level to drawdown to the normal pool elevation is decreased. The State of Vermont Dam Safety Program does not currently have guidance on how quickly the outlet structures at a dam need to be able to drawdown reservoir levels. USDA NRCS guidance included in TR-210-60 Earths Dams and Reservoirs indicates that their spillways must drawdown the reservoir level from the auxiliary spillway crest to within 15% of the starting volume of the normal pool within 10 days. While NRCS dams are typically designed for flood control and the purpose of the Shadow Lake dam is primarily for recreation, this design criteria may still be a good starting point as the reason the NRCS incorporates this design criteria is to reduce susceptibility to back to back flood events.

D&K did not model specific improvements to the principal spillway structure. Improvements could include; a better trash-rack, lengthen the stop log weir crest, and/or increasing the diameter or removal of the 36” diameter orifice. Modification or removal of the existing gatehouse structure would be required.

Pros:

- Increased spillway capacity, steady state discharge required to achieve 18” of flow depth in the auxiliary spillway goes up.
- Peak water surface elevation of various runoff events goes down.
- Decreases lake level drawdown time for all runoff events.

Cons:

- Discharge downstream of the dam goes up.
- Requires modification of the existing gatehouse structure, larger scale improvements likely require removal of the gatehouse.

2. Lower the crest of the auxiliary spillway to increase discharge capacity, decrease the peak water surface elevation during various runoff events, and decrease the time it takes for the lake level to drawdown when the reservoir reaches elevations higher than the auxiliary spillway crest.

D&K looked at lowering the auxiliary spillway crest by 1 foot. This potential solution was investigated because it was thought possible to remove 1 foot of concrete from the auxiliary spillway crest as a cost effective solution. The peak water surface elevation for the drawdown board in place condition decreased by 0.9 feet. The peak water surface elevation for the draw down board removed condition decreased by 0.5 feet. The drawdown time for a 1 foot lake level reduction from 1396.2 to 1395.2 took 6 days 5 hr 12 min with the stop log in place, and 3 days 1 hr 44 min with the stop log removed. A 50.4% and 29.8% reduction in comparison to the existing spillway crest drawdown time respectively.

Pros:

- Increased spillway discharge capacity, steady state discharge required to achieve 18 inches of flow depth in the auxiliary spillway goes up.
- Peak water surface elevation of various runoff events goes down.
- Decreases drawdown time for events that results in peak water surface elevations above the auxiliary spillway crest.

Cons:

- Discharge downstream of the dam goes up (increased flooding frequency, and discharge magnitude for events that results in a peak water surface above the spillway crest elevation).
- Does not increase discharge capacity for water surfaces lower than the auxiliary spillway crest elevation.

3. Establish a permanent lake level lower than the existing summertime normal pool elevation to increase volume storage below lake levels that cause shoreline property damage, and increase the discharge required to achieve lake levels that cause damage to shoreline properties.

D&K looked at the performance of the dam spillway and peak lake levels with the pool elevation set 1 foot below the summertime normal pool. The 1 foot of drawdown resulted in a noticeable decrease in peak water surface elevation (1 foot), and increased discharge from the principal spillway structure. The drawdown time for the lake level to decreased 1 foot from 1396.2 to 1395.2 decreased from 12 days 12 hr 33 min to 4 days 8 hr 51 min (65.1% reduction).

Pros:

- Increased storage between normal pool elevation and auxiliary spillway crest (increased inflow volume require to raise lake level to previously observed highs).
- Time required to draw lake level down 1 foot from 1396.2 to 1395.2 is decreased due to additional hydraulic head on principal spillway structure.

Cons:

- Lower lake level may affect recreation & aesthetics.
- Lower lake level may be impact lake ecology.

A lower lake level elevation could be a fairly easy and cost effective solution. However, the current 1 foot of drawdown was reportedly not enough to prevent property damage from occurring during March of 2019. It is unknown to D&K how far the lake level can be drawdown before the principal spillway structure no longer is able to function, and there is most likely a limit to how much lower the lake level can be without affecting the recreational, ecological, and aesthetic features of the lake too much. The optimal solution is probably a combination of the above improvements that balances pro vs cons for all interested parties.

Assuming that a year round normal pool elevation 1 foot lower than the existing summer time normal pool elevation is acceptable. A reasonable combination that will help reduce the likelihood/frequency of property damage being could be establishing the 1393.6 pool elevation as “permanent” and lowering the existing auxiliary spillway crest by 1 foot. Since the dam currently does not meet dam safety hydraulic design criteria it may be unwise to make significant changes to the principal spillway structure, as it will likely result in a more involved project and may need to be further modified down the road as part of a more significant dam rehabilitation project. One highly recommended and seemingly minor change would be to install a new trash rack with more opening area to reduce head losses through the principal spillway structure and ensure that it is not limiting discharge. If a dam rehabilitation project takes place, additional options and the potential for a different year round lake level may become possible.

It is important to note that dam modification such as lowering the crest of the auxiliary spillway by 1 foot will require approval from the VT Dam Safety Program.

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