Hydrologic Modeling of a Small Wetland Complex to Inform Estimates of Phosphorus Retention

Honors Thesis

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by

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Abstract.

Phosphorus (P) is an important nutrient in ecosystems and is often limiting in freshwater systems and the human application of P in agriculture has made P management a priority to maintain freshwater ecosystem health. Previous studies suggest that small wetlands play a disproportionately large role in landscape-scale nutrient processing. Modeling watershed P dynamics requires estimates of water budgets within the areas of interest. The objective of this work is to model the inflow, outflow, stage, and storage relationships of a small wetland with an active beaver dam in the Prindle Brook floodplain in Addison, VT using HydroCAD. A sensitivity analysis was performed to assess how various parameters, such as curve number, antecedent moisture condition, and the length of storms affect results. The sensitivity analysis also addressed the outlet structure which represents an active beaver dam. Limited research has been published with guidance for modeling a beaver dam in HydroCAD. Changing the parameters in the sensitivity analysis had a much larger effect on smaller storms than larger ones. Antecedent moisture conditions affected the peak inflow, outflow, and water level values while changing the length of storms altered the time to peak. Altering the outlet structure changes the water level within the wetland and how quickly it drops but does not generally change the peak outflow. This model will be coupled with a P model to understand P dynamics in restored riparian wetlands on former agricultural land during flood events. These results will be important for recommendations to the state and non-profit agencies about how to best prioritize potential restoration sites.

Introduction.

Phosphorus is an important nutrient in ecosystems and is often limiting in freshwater systems and the human application of P in agriculture has made P management a priority to maintain freshwater ecosystem health. Research conducted by Dr. Eric Roy (Assistant Professor, RSENR and CEMS) and Adrian Wiegman (Ph.D. Candidate, RSENR) for the LCBP project examines formerly drained and actively farmed wetlands that have been conserved by landowners to assess the movement and dynamics of phosphorus through these wetland complexes and demonstrate the extent to which the wetlands act as a P sink or source. These results will be important for recommendations to the state and non-profit agencies about how to best target funding for potential restoration sites.

There is a growing understanding that small water bodies have a disproportionately large part impact on the health of the overall watershed [1]. This is especially true when it comes to nutrient cycling – small wetland systems have a higher nutrient retention efficiency than larger wetland systems [1], making the modeling of these systems all the more important. It has also been shown that it is wetland hydrology that most strongly controls nutrient export, not the presence of wetland vegetation [2]. In addition, riparian wetlands also have a high potential for nutrient export, in part due to hydroclimate variability [3].

Attention is also being paid to the spatial distribution of wetlands across the landscape. It has been found that riparian wetlands (or wetlands that are close and hydrologically-connected to the stream network) have the greatest impact on the attenuation of peak flow [4]. The hydrologic and hydraulic modeling of these systems, then, is important for flood mitigation and the prioritization of restoration.

In summary, creating hydrologic models of wetlands is important for understanding many things, including flood hazards and nutrient cycling. It is also particularly important to understand smaller wetland systems, as they play a large role within their watersheds. This is complicated, however, by a traditionally time- and cost-intensive modeling process because of the lack of monitoring data and a clear modeling approach. There is a need to better understand small wetland systems, particularly those connected to a stream network in agriculturally-dominated systems, and their influence on floodwater and nutrient storage and release.

Hydrologic and hydraulic modeling of wetlands is not a new idea; researchers have been modeling these systems since the 1980s with success [5]. As the computational power of computers and programs has increased, the complexity and accuracy of hydrologic models have also increased. These models are almost always specific to a particular system and are not easily transferrable to any other system, even one that is similar. As a result of the complexity and specificity of today's models, creating one is costly and time-consuming. Some work has been done to simplify the model structure and data inputs to reduce the cost and time required, but this was only successful for very large systems [6]. This indicates that for small systems, a one-size-fits-all model is not practical.

What has happened, then, is a wide variety of highly specific models for small systems that rely on intensive monitoring and use many different modeling applications. The exact outputs of the model will depend on the needs and questions of the individual project and site. Key relationships usually include stage/volume, stage/velocity, stage/discharge and stage/detention time. One may also be interested in maximum storage capacity, maximum/minimum detention time, time to reach maximum storage capacity, maximum discharge, and/or maximum velocity. The variation of these variables spatially may also be important depending on the specific questions the model is designed to answer. These modeling applications include:

- Wetland Solute Transport Dynamics – WETSAND [7]
- Storm Water Management Model – SWMM5 [7]
- Terrain-based GIS models [2]
- Soil and Water Assessment Tool – SWAT [8]
- MIKE SHE [9]
- MODFLOW [10]
- MIKE 21 hydrodynamics (HD), advection-dispersion (AD), and ECO Lab Model [11]
- Simple Refuge Stage Model [12]
- BATHTUB Model [13]

This study aimed to construct a hydrologic model of the Prindle Brook floodplain wetland complex in Addison County, VT. This system was chosen because it is small in size in an agriculturally dominated setting with well-defined inflows and outflows. In addition, it provided an opportunity to explore methods for modeling beaver-dam outflows, which have not been well-characterized in the hydrologic literature. This model will be coupled with a phosphorus (P) model to understand P dynamics in restored riparian wetlands during flood events. The model will be used in a larger project funded by the Lake Champlain Basin Program (LCBP) entitled "Quantifying phosphorus retention in restored riparian wetlands of the Lake Champlain Basin."

Deliverables.

HydroCAD®[14] , a physically-based model was chosen by the authors to model the Prindle Brook wetland complex. This reflects the available data and the benefits of the available HydroCAD software. HydroCAD is an extremely popular physically-based stormwater modeling software that is used in both research and industry. It is relatively easy to create a simple model in HydroCAD and estimate flow data for a small catchment. HydroCAD also has modular features for

representing more complicated systems with combined outlet structures, custom ponds, and multiple catchments.

This report includes the development of the HydroCAD model and sensitivity analysis to judge the effect that changing parameters in the model has on the outputs. This analysis will be used to calibrate the model using the water level data collected by Adrian Wiegman and the calibrated model will then be used in a phosphorus dynamics model created by Adrian Wiegman.

Methods.

Study Area Description.

The wetland modeled in this work is located in Addison, VT along the Prindle Brook. The Prindle Brook flows into Lewis Creek which drains into Lake Champlain. The wetland is in an agriculturally dominant area. The two inlets are culverts that cross underneath Prindle Road and the outlet is an active beaver dam. Figure 1 shows the wetland's location relative to Prindle Brook, Lewis Creek, and the state of Vermont. It also shows the locations of the two culverts and the beaver dam.

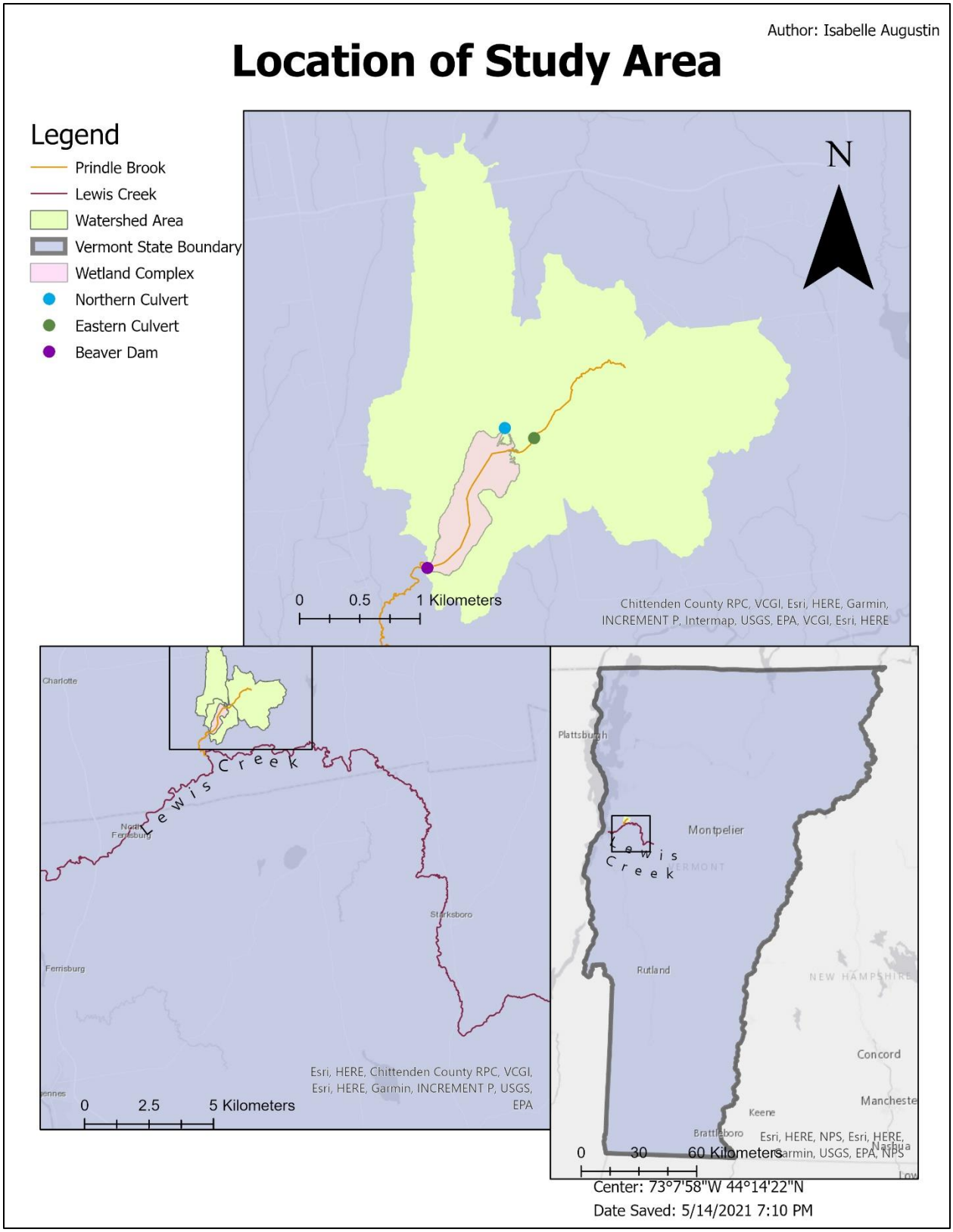

Figure 1: Overview of study area.

Geospatial data sources.

Several datasets for the study area were downloaded to support analysis, including 0.7 m resolution Digital Elevation Model (DEM) rasters for the study area from the Vermont Center for Geographic Information's (VCGI) geodata portal [15]. The NRCS Soil Survey Units for the State of Vermont were also downloaded from VCGI [15], and 2016 30 m resolution National Land Cover Database (NLCD) rasters were obtained through the Multi-Resolution Land Characteristics Consortium [16]

Geospatial analyses.

The inputs required for the HydroCAD model are: subcatchment areas of unique land uses and hydrologic soil groups, slope and hydraulic lengths of subcatchments, and a stage-storage relationship for the wetland. These were obtained using the procedure outlined below.

Watershed delineation.

The first part of the geospatial analysis was defining the watershed of the wetland complex. All individual downloaded DEMs were stitched together into a single raster. The Fill tool was used to remove any sinks in the raster and the raster was visually inspected to ensure the tool worked as anticipated. This filled DEM was used in all further steps. The Flow Direction tool was used with the D8 method to create a flow direction raster. This flow direction raster was used with the Flow Accumulation tool, also using the D8 method, to create a flow accumulation raster. The Conditional tool was used to assign all cells of the flow accumulation raster that had an accumulation of greater than 2500 a value of 1. The Stream Link tool was then used on this modified flow accumulation raster to create streams. The Stream Order tool was run using the Strahler method on the stream segments, and the output from the Stream Order was converted into a feature class using the Stream to Feature tool.

It was desired that the watershed be split into multiple subcatchments that align with monitoring locations. The watershed draining to the beaver pond wetland was modeled as four subcatchments connected to the pond. Four subcatchments were chosen because the watershed contains four unique areas—two watersheds upstream of culverts in Prindle Rd, the wetland complex area, and the area that drains to the wetland through neither culvert (Figure 1). By splitting up the watershed in this way, model results can also later be compared to data collected in the field under the larger LCBP project. Inflow data is collected at each culvert occasionally and a water level recorder collects water level every 15 minutes at the eastern culvert and in the middle of the wetland complex. This will aid in model calibration and validation in the future.

The Prindle Brook site is monitored at three unique locations: within the ponded area and at each of the two culverts that allow water to pass underneath the road. Three empty point feature classes were created using the Create Feature Class tool. Using the Create Feature function and the stream features for guidance, points were created just downstream of each of the culverts and at the desired outlet point. In this case, the outlet point was placed in the immediate vicinity of a beaver dam which serves as the site's outlet. The Snap Pour Point tool was used to move the newly created points to a raster cell within 2 m that has the greatest flow accumulation. With these three snapped points and the flow direction raster created previously, the Watershed tool was run three times to delineate the watershed upstream of the two culverts and upstream of the outlet of the study area. These raster outputs were then converted to polygons using the Raster to Polygon tool.

The next step of the geospatial analysis was to separate the watershed into subcatchments for HydroCAD: the subcatchment above the northern culvert, the subcatchment above the eastern culvert, the wetland complex, and the subcatchment that flows into the wetland complex through neither culvert. The pond encompasses the wetland complex and has to include the five plots that are being studied in the larger phosphorus dynamics study. The pond was defined using an elevation isoline at 114 m. Using the Extract by Mask tool, the DEM was clipped to the extent of

the watershed polygon. The Contour List tool was run to generate the 114 m isoline for the entire watershed. Using the modify feature function, this isoline was edited to remove all smaller line segments and polygons and to close the contour along the downstream watershed boundary. The result is an enclosed polyline. The Feature to Polygon tool was run to convert the line feature to a polygon. Using the Clip feature tool, the pond boundary polygon was used to clip the watershed polygon. The result is that the pond and watershed polygons do not overlap. The Clip feature tool was also used to clip out the watershed above the two culverts from the entire watershed. The result is that the large watershed polygon is clipped down to exclude the wetland complex area and the area of the two watersheds above the culverts. It now represents the subcatchment that flows into the wetland complex through neither culvert.

Land use and hydrologic soil groups.

The next step in the geospatial analysis was to generate a table summarizing unique combinations of land use and hydrologic soil group for each of the four subcatchments. This table is necessary for generating the curve number (CN) of each subcatchment in HydroCAD. The following procedure was used for each subcatchment.

First, both the NRCS Soil Survey Units feature class and the NLCD Land Cover data sets were clipped to the extents of the subcatchment by using the Clip Layer and Extract by Mask tools, respectively. The Raster to Polygon tool was used to convert the clipped land cover dataset to a polygon format, keeping the Land Cover Classification field in the transformation. The land cover and soil polygons were intersected using the Intersect tool. Finally, the Summary Statistics tool was run on the intersected feature class with the statistic type set as “sum,” the field as “Shape_Area,” and the case fields as the land cover classifications and the hydrologic soils groups. The result is a table of the sum of the areas of each unique combination of land cover type and hydrologic soil group for the subcatchment.

Time of Concentration.

Another required geospatial analysis was obtaining the two parameters necessary for calculating Time of Concentration (Tc) for each of the subcatchments. The two required parameters were flow length and average slope of the Prindle Brook channel. Using the DEM for each subcatchment, the Flow Direction tool was run using the D8 method to obtain a flow direction raster for the subcatchment. The Flow Length tool was then run using the flow direction raster to calculate the upstream flow length. The Slope tool was also run for each subcatchment and the average or mean slope was summarized using Summary Statistics.

Pond geometry.

The final geospatial analysis required was for obtaining the parameters necessary for defining the pond in HydroCAD. The filled DEM was clipped to the pond boundary using the Extract by Mask tool and this DEM was used as the input for the Storage Capacity tool to calculate the cumulative storage in 0.1 m elevation increments.

HydroCAD model.

The model in HydroCAD was set up as four subcatchments connected to a pond. Each subcatchment's curve number (CN) was calculated in HydroCAD's interface using the areas of unique combinations of hydrologic soil group and land cover. The land cover condition type was selected as "fair" for all applicable land cover types and the drained condition was selected for all combination soil types. The time of concentration was calculated using the Lag/CN method. The Lag/CN method was developed by the NRCS for small, natural watersheds[17]. Most of the watersheds used in development were less than 2,000 acres in size[17]. The equation for the Lag/CN method is presented below.

Equation 1:

$$T_c = \frac{l^{0.8} * (S+1)^{0.7}}{1140 * Y^{0.5}}$$

Where:

$$l = Hydraulic\ Flow\ Length\ [ft]$$

$$S = Potential\ Retention\ [unitless] = \frac{1000}{CN} - 10$$

$$Y = Average\ Land\ Slope\ [\%]$$

$$Tc = Time\ of\ Concentration\ [hr]$$

The pond was defined using the custom stage data obtained from the geospatial analysis. The outlet of the pond (a beaver dam) was simulated as a compound outlet. The primary outlet structure was a sharp-crested weir with the same dimensions as the beaver dam. A vertical grate with 0.2 in diameter holes was nested within the weir to allow for water to flow through the weir to account for the permeability of the beaver dam. A depiction of this outlet structure is given in Figure 2.

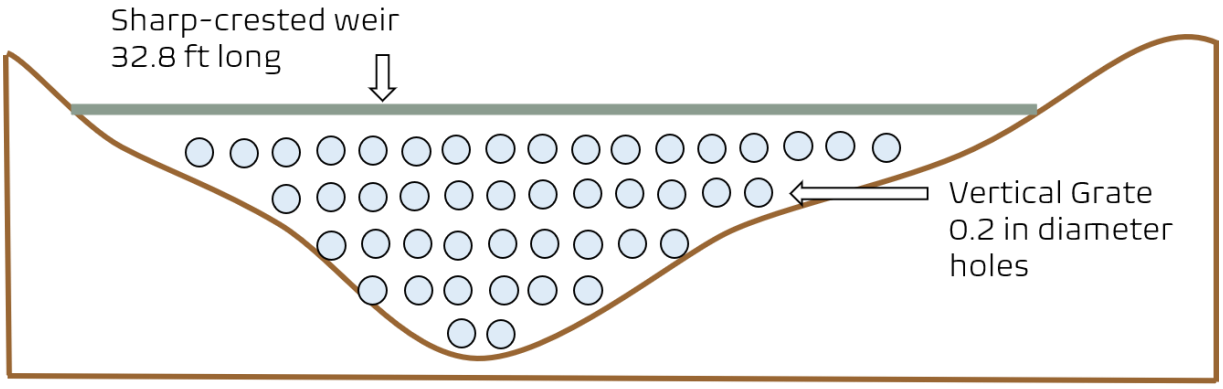

Figure 2: Rendering (not to scale) of outlet structure as defined in HydroCAD model.

Precipitation data was taken from NOAA Atlas 14[18] for the location of the site. The storms were inputted as Type II 24-hour storms with the precipitation amounts specified for the 1-year, 2-year,

5-year, 10-year, 25-year, 50-year, and 100-year recurrence intervals from Atlas 14. In addition, smaller 24-hour storms of 0.25, 0.5, and 1 inch were run. Storms were run with normal antecedent moisture conditions. Runoff was calculated using the SCS TR-20 method[17].

Sensitivity Analysis.

A sensitivity analysis was also conducted to assess how different parameters affected modeled results. The 1-inch storm, the 1-year storm, and the 25-year storm were tested. For each storm, the following conditions were changed:

- The length of the storm was changed from 24 hours to 12 hours
- The storm was run back-to-back to simulate two storms happening one immediately after the other
- The antecedent moisture condition (AMC) of the subcatchments was changed from normal (2) to dry (1)
- The AMC of the subcatchments was changed from normal (2) to wet (3)
- The condition of the land in the subcatchments was changed from fair to poor
- The condition of the land in the subcatchments was changed from fair to good
- The water level in the wetland was raised to simulate a rain event occurring when the wetland already contains standing water
- Baseflow was added so that the water level in the wetland did not fall below this raised water level simulated previously. This system shows evidence of some baseflow because the pond has never completely emptied, even during a drought.
- The number of holes in the vertical grate of the outlet structure was reduced by half
- The number of holes in the vertical grate of the outlet structure was doubled
- The height of the outlet structure was increased by a foot and the number of holes in the vertical grate was adjusted proportionally

The resulting inflow rates, outflow rates, and water levels were graphed and tabulated for each storm and the various conditions tested in the sensitivity analysis. To gauge the impacts of the changing conditions of the sensitivity analysis, each condition was described as a percent of the baseline condition for the maximum inflow rate, outflow rate, and water level. Also captured was the time required to reach this maximum value.

Results and Discussion.

Geospatial.

Figure 3 shows a general overview of the watershed subcatchments delineated in ArcGIS Pro. The largest subcatchment is the eastern culvert watershed at 828 acres. The wetland complex is 99 acres and is relatively flat. The sideslopes area has a steeper slope, as shown by the hillshade in the figure. The locations of the northern and eastern culverts are shown by a pink and orange point, respectively. The locations of the five study plots are shown in green.

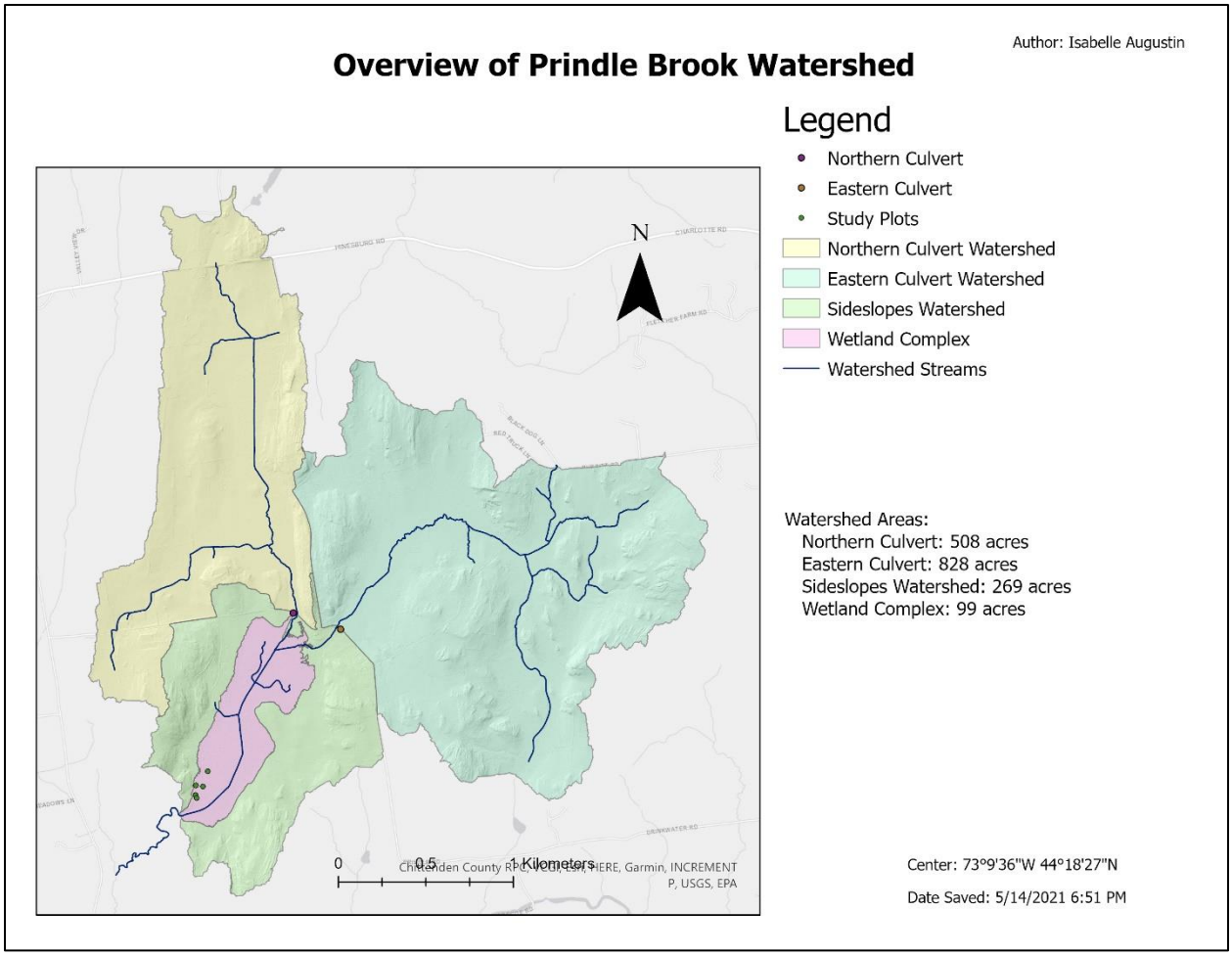

Figure 3: Overview map of Prindle Brook watershed.

Figure 4 shows the landcover types for the watershed. Notably, much of the watershed is designated as Hay/Pasture. There are also significant forested areas, especially on the eastern side of the watershed and on either side of the study area. The wetland areas may be under-represented by this data. This NLCD dataset is from 2016. We know that beavers are active in this watershed, particularly at the outlet. Beaver activity since 2016 likely has changed some of the hay/pasture areas to herbaceous wetland due to longer periods of flood inundation.

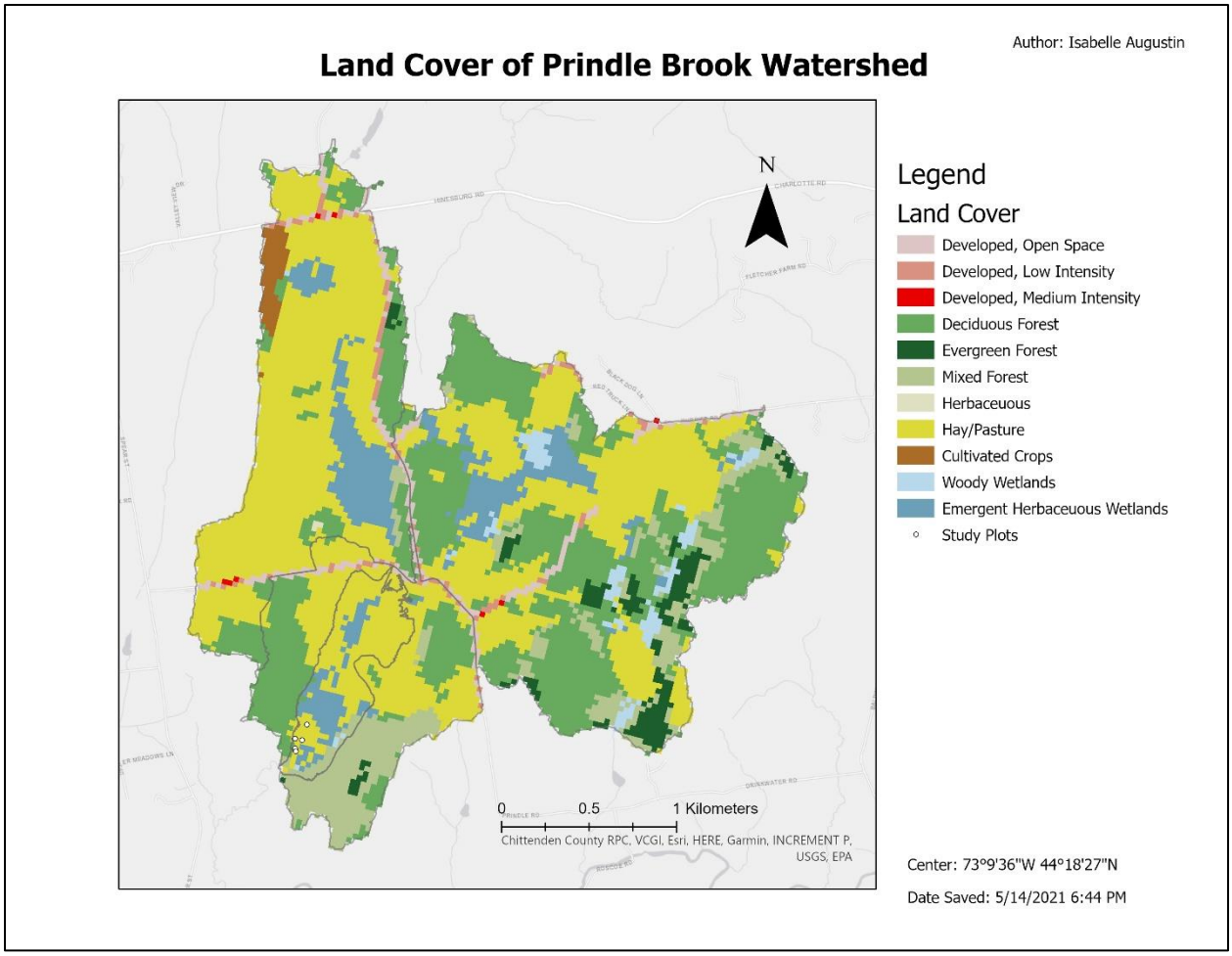

Figure 4: Land cover map of Prindle Brook watershed.

Figure 5 shows the hydrologic soil group distribution across the watershed. Notably, much of the watershed is classified as hydrologic soil group D, which produces the most runoff and has the smallest infiltration capacity[19]. The wetland complex near the study plots has both type D soils and combination C/D soils. Combination soils describe the soils in both the drained and undrained conditions. In this case, these soils are type C when drained and type D when undrained. Because of the beaver dam at the outlet, these soils are undrained. This means that there is very little infiltration in these soils. For this reason, infiltration was not modeled in the pond structure in HydroCAD.

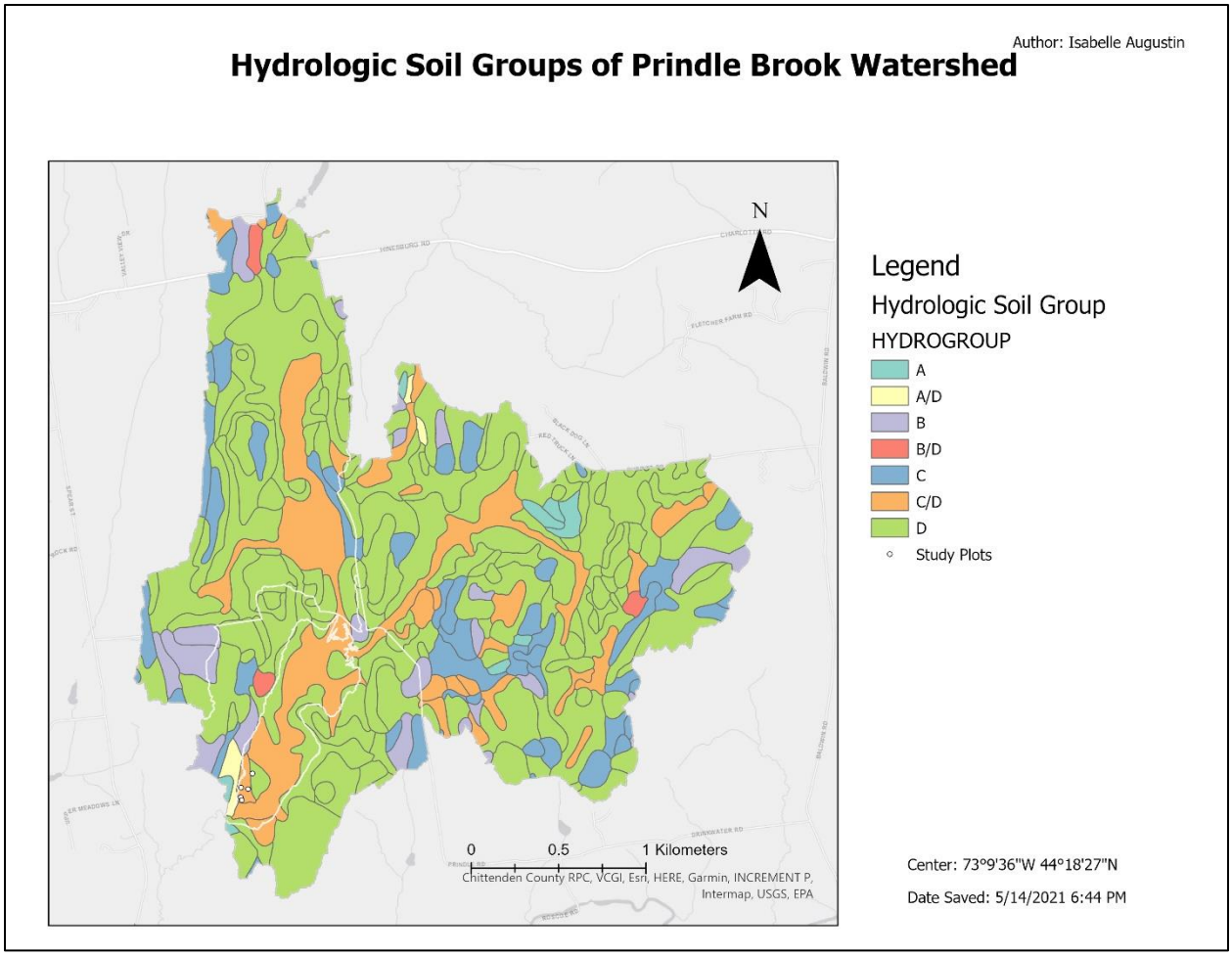

Figure 5: Hydrologic soil groups map of Prindle Brook watershed.

HydroCAD Model.

Figure 6 shows the general setup of the HydroCAD model. Each of the four individual subcatchments flows into the wetland complex, which is represented as a pond. The parameters used to model each subcatchment are displayed in Table 1. The curve numbers (CN) are relatively large under all conditions. An impervious surface where all precipitation becomes runoff would be represented by a CN of 100. Poor conditions result in an increase of about 6 from normal for all subcatchments and good conditions result in a decrease of about 4 from normal for all subcatchments. The time of concentration (Tc) for the sideslopes watershed is substantially smaller than for the other watersheds (26.6 minutes). This is due to its steep slope and shorter

hydraulic length. While the calculated Tc for the northern and eastern culvert watersheds are similar, the eastern culvert watershed likely has a shorter Tc than modeled. This is because the flow becomes channelized above the culvert and this channelization is not captured in the CN/Lag method for estimating Tc.

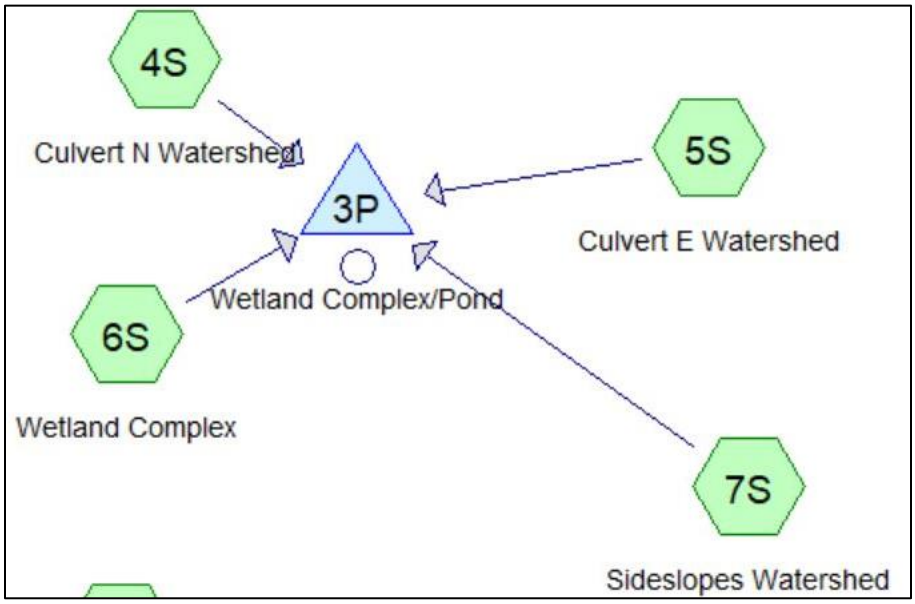

Figure 6: HydroCAD model setup with four subcatchments flowing into a pond.

Table 1: Important parameters for modeling each subcatchment.

Parameter	Northern Culvert Subcatchment	Eastern Culvert Subcatchment	Sideslopes Subcatchment	Wetland Complex Subcatchment
Watershed Area (acres)	500	819	260	96
Weighted CN (fair/normal conditions)	80	77	77	78
Weighted CN (poor conditions)	86	82	82	84
Weighted CN (good conditions)	76	74	74	73
Tc (min)	72.0	76.7	26.6	70.8
Hydraulic Length (ft)	10,689	13,292	3,830	5,724
Average Slope (%)	8.62	12.92	14.73	3.71

The important parameters for defining the outlet structure of the pond are presented in Table 2. The outlet structure, an active beaver dam, is modeled as a sharp-crested weir with a vertical grate nested within it. The weir's dimensions were taken from the DEM. The vertical grate was designed

to have small holes to mimic the small spaces in a beaver dam in between sticks, leaves, and mud. Different configurations of the outlet were tested in the sensitivity analysis. The number of holes was doubled by increasing the number of columns to 48 to model a more pervious dam. The number of holes was decreased by changing the number of columns to 12 to model a less pervious dam. The height of the dam was also increased by one foot to model continued beaver activity. This change in height was accompanied by a proportional increase in the number of rows of holes to 11. While the permeability of the beaver dam is uniform with depth in the model, this might not be the case. Permeability might decrease with depth due to greater rates of organic decomposition in the upper portions of the beaver dam that are more often exposed to air. This source of uncertainty could be adjusted during calibration.

Table 2: Important parameters for modeling the outlet structure of the pond.

Weir	Length (ft)	32.8
	Top elevation (ft)	370
	Height (ft)	1.09
Grate	Bottom elevation (ft)	369
	Hole Diameter (in)	0.2
	Columns	24
	Rows	6
	Distance between holes (in)	2

Baseline Conditions.

Eleven storms of various sizes were modeled in HydroCAD. In addition to storms of various recurrence intervals and small storms that occur below the 1-year recurrence interval (0.25 in, 0.5 in, and 1.00 in), a 3.71 in storm was modeled. This is intended to mimic the largest storm in the monitoring period for the LCBP project which occurred on 10/31/2019.

Table 3 shows the maximum **inflow** for these storms and the time to maximum inflow. There is no inflow for the 0.25 and 0.5 in storms because all precipitation is infiltrated or intercepted and

does not become runoff. As anticipated, inflow increases as precipitation increases. This is visualized in Figure 7. The time to maximum inflow does not vary widely with precipitation amounts but does decrease slightly as precipitation increases. In general, peak inflow is achieved 12.8 hours after the storm begins. Figure 7 shows that for all storm sizes, inflow occurs from approximately the tenth hour to the twenty-fifth hour. All the hydrographs share the same general shape.

*Table 3: Maximum **inflow** and time to maximum inflow for various storm sizes.*

Precipitation Amount (in)	Recurrence Interval	Maximum Inflow (cfs)	Time to Maximum Inflow (hours)
0.25 in		0	0
0.5 in		0	0
1.00 in		17.11	13.2
1.99 in	1 year	284.19	12.85
2.34 in	2 year	431.83	12.85
2.91 in	5 year	704.16	12.8
3.38 in	10 year	950.39	12.8
3.71 in		1131.22	12.8
4.04 in	25 year	1317.19	12.8
4.53 in	50 year	1602.07	12.75
5.04 in	100 year	1906.73	12.75

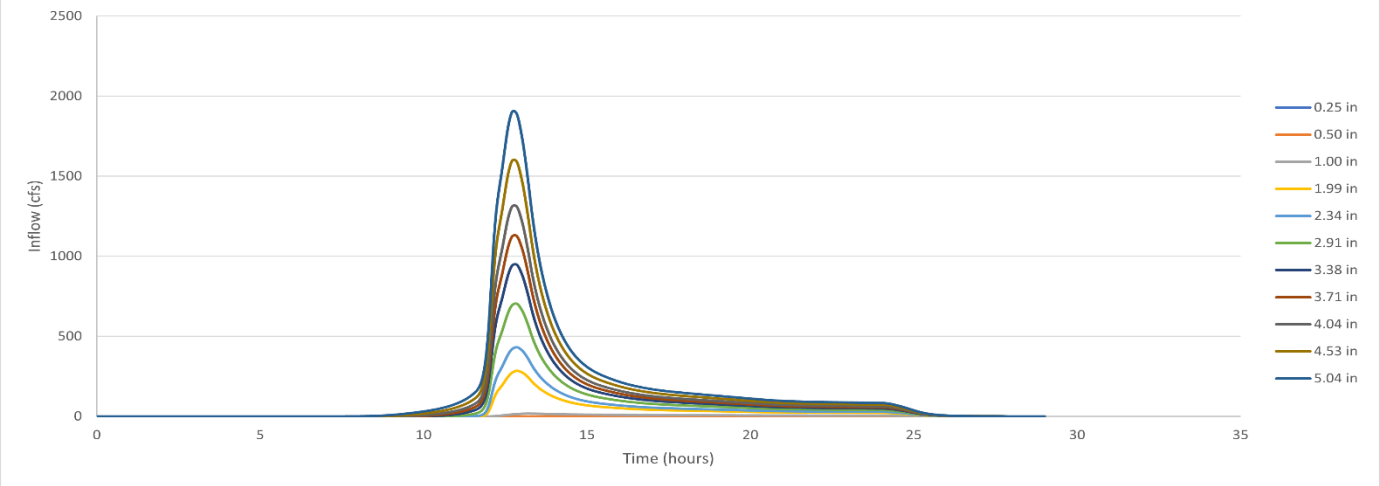

Figure 7: Hydrograph for tested storms under baseline conditions.

Table 4 shows maximum **outflows** and time to maximum outflow for the different storms. Outflow increases as the precipitation amount increases. The time to the maximum outflow decreases before hitting the lowest possible value of fourteen hours. This maximum outflow is achieved while water is flowing over the top of the beaver dam.

*Table 4: Maximum **outflow** and time to maximum outflow for various storm sizes.*

Precipitation Amount (in)	Recurrence Interval	Maximum Outflow (cfs)	Time to Maximum Outflow (hours)
0.25 in		0	0
0.5 in		0	0
1.00 in		7.22	17.65
1.99 in	1 year	106.9	14.15
2.34 in	2 year	156.86	14.1
2.91 in	5 year	248.66	14
3.38 in	10 year	327.68	14
3.71 in		383.04	14
4.04 in	25 year	439.09	14
4.53 in	50 year	521.95	14
5.04 in	100 year	611.91	14

Table 5 shows the maximum **water level** and time to maximum water level for the tested storms. The elevation of the wetland with no standing water is 368.91 ft. This means water rises to a maximum of 4.32 feet during the 100-year storm. On average it takes about fourteen hours to achieve maximum water level. This roughly coincides with the time taken to reach maximum outflow and is about one hour after maximum inflow is achieved. Water level over time is visualized in Figure 8. Water is above the beaver dam (elevation 370 ft) for about 24 hours during all storms larger than 1.00 inch, with higher water levels for larger storms. After the water level falls below the beaver dam, the water level drops at the same rate for all storms as the water exits slowly through the holes in the outlet structure. The water level is graphed for 336 hours, or 14 days. During this 14-day period, the water level does not return to its original elevation but drops about half of a foot.

*Table 5: Maximum **water level** and time to maximum water level for various storm sizes.*

Precipitation Amount (in)	Recurrence Interval	Maximum Water Level (ft)	Time to Maximum Water Level (hours)
0.25 in		368.91	0
0.5 in		368.91	0
1.00 in		370.16	16.65
1.99 in	1 year	371	13.95
2.34 in	2 year	371.29	13.85
2.91 in	5 year	371.76	13.85
3.38 in	10 year	372.12	13.85
3.71 in		372.36	13.9
4.04 in	25 year	372.59	14
4.53 in	50 year	372.91	14
5.04 in	100 year	373.23	13.85

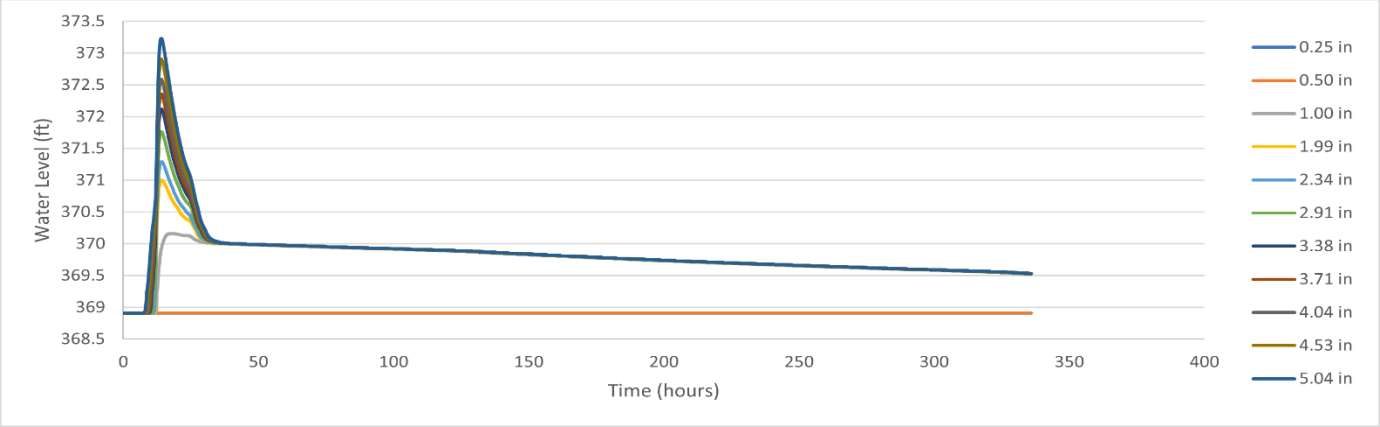

Figure 8: Water level in wetland over time for tested storms under baseline conditions.

Sensitivity Analysis.

The 1.00 in, 1.99 in, and 4.04 in storms were used in the sensitivity analysis. The same results as the baseline conditions were generated for each tested condition. Tested conditions were grouped into four categories.

- Storm conditions: 12-hour storm and 2 storms back-to-back.
- Subcatchment conditions: AMC 1, AMC 3, poor conditions, and fair conditions.
- Water level conditions: Raised water level and baseflow.
- Outlet conditions: Increased dam height, more holes, and fewer holes.

Tables showing the peak inflow, peak outflow, maximum water level, and the time to these peaks and maximums for each tested condition are in Appendix A. In addition, tables showing these values as a percent of the baseline condition were also generated and can be found in Appendix A. Inflows and water levels for each tested condition were also graphed over time for the three different storm event sizes. Inflow does not change for different water level conditions and outlet conditions, so these graphs are omitted.

Inflow.

The hydrographs for each of the three storm sizes generally follow similar patterns and have similar shapes that increase in magnitude as the storm size increases (Figures 9-14). The peak inflow values and time to the peak value are annotated on the figures for each condition. The peak inflow for the back-to-back storms is delayed for all storm sizes. While it produces the largest maximum inflow for all three storm sizes, the difference between it and other conditions becomes less pronounced as storm size increases. This can be seen in Figures 9-11 because the baseline conditions and the 12-hour storms' peak inflow get larger and closer in magnitude to the inflow produced by the back-to-back condition. This is verified in Table 6 as the percent value decreases as storm size increases. The time to reach peak inflow does not change dramatically across

subcatchment conditions and storm sizes (Figures 9-14). The 12-hour storm has a shorter time to peak and the back-to-back storms have a longer time to peak, as expected (Figures 9-14). Antecedent moisture conditions and the condition of the land in the subcatchments have a noticeable and predictable impact on the magnitude of the hydrographs (Figures 12-14). Poor conditions and a wet antecedent moisture condition increase inflow, while good conditions and dry antecedent moisture conditions decrease inflow. Good land conditions indicate more and healthier vegetation and uncompacted soil, which would infiltrate more precipitation and decrease runoff. Dry antecedent moisture conditions also decrease runoff because the soil has a greater infiltration capacity, while wet antecedent moisture conditions would limit the amount of precipitation the soil could infiltrate. The relative impact of these conditions, however, changes for different storm sizes. This can be seen in Table 6. The tested conditions affect the smaller storms more than the larger storms. This is reflected in a larger percent value (farther away from 100% in the positive direction) for AMC 3 and Poor conditions and a smaller percent value (farther away from 100% in the negative direction) for AMC 1 and Good conditions for the 1.00 in storm and the 1.99 in storm.

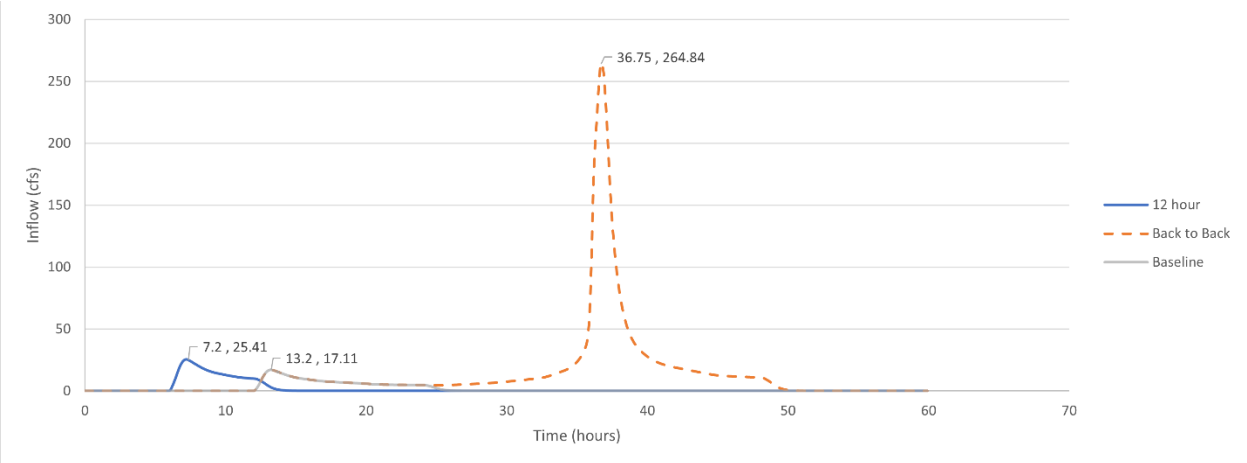

Figure 9: Inflow over time for a 1.00 in storm under changing storm conditions.

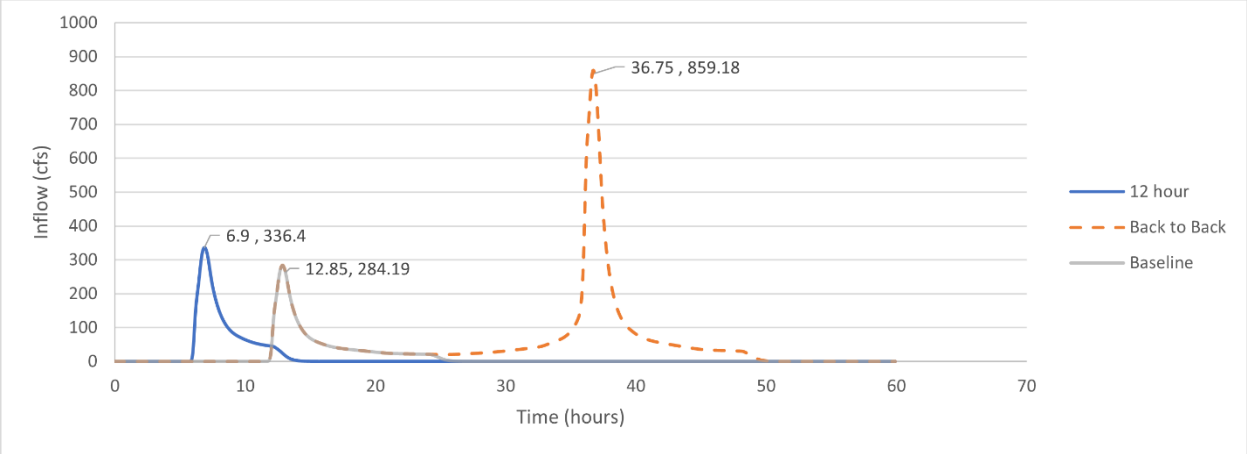

Figure 10: Inflow over time for a 1.99 in storm under changing storm conditions.

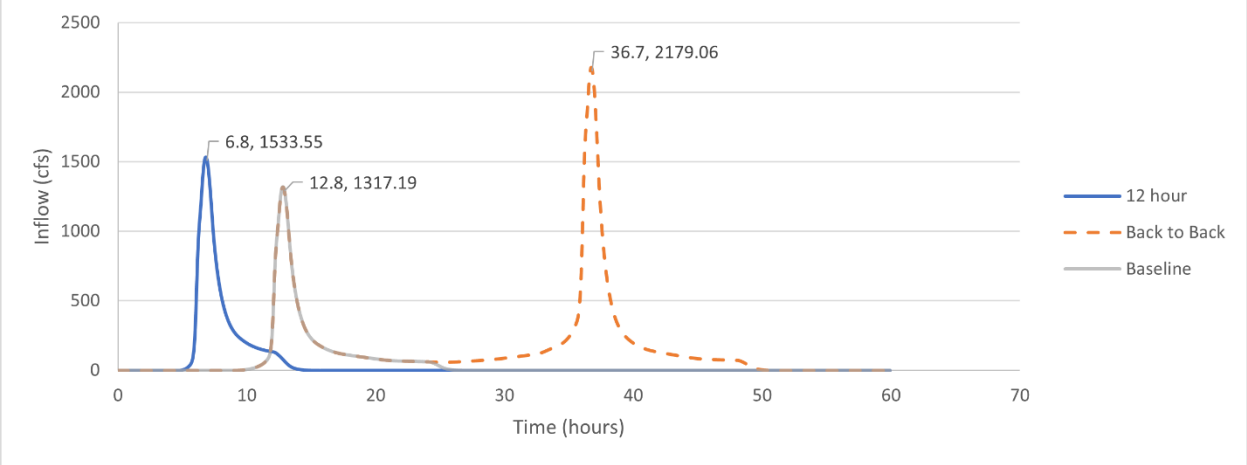

Figure 11: Inflow over time for a 4.04 in storm under changing storm conditions.

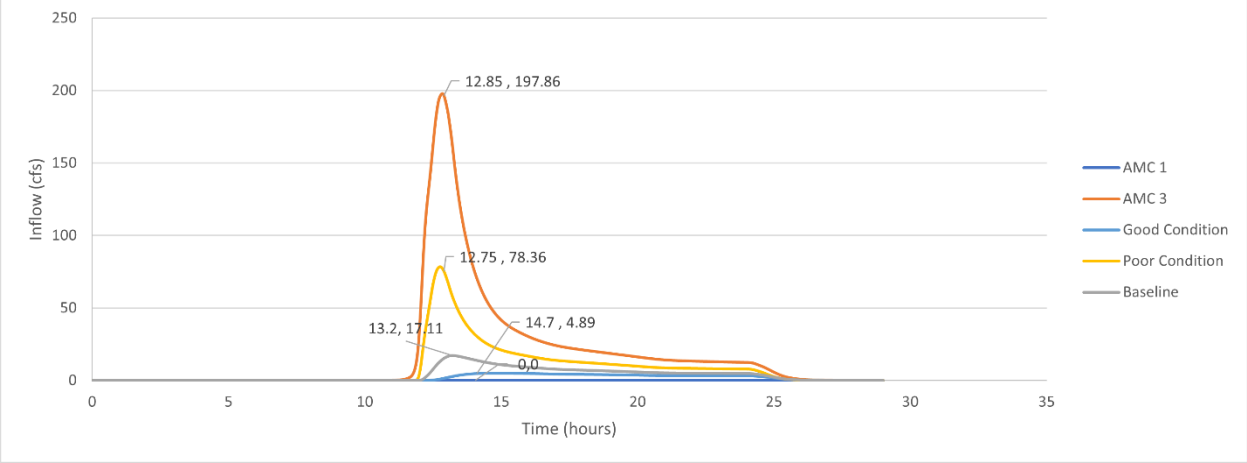

Figure 12: Inflow over time for a 1.00 in 24-hour storm under changing subcatchment conditions.

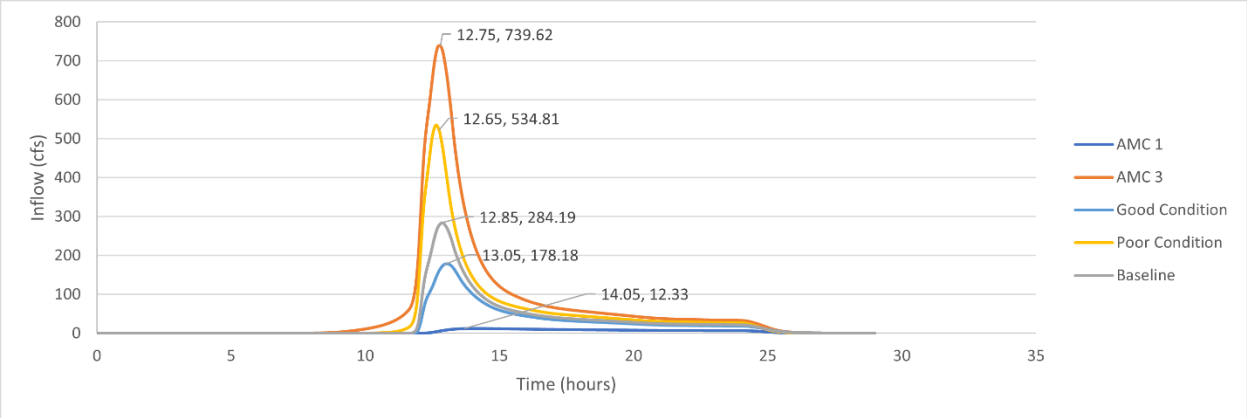

Figure 13: Inflow over time for a 1.99 in storm under changing subcatchment conditions.

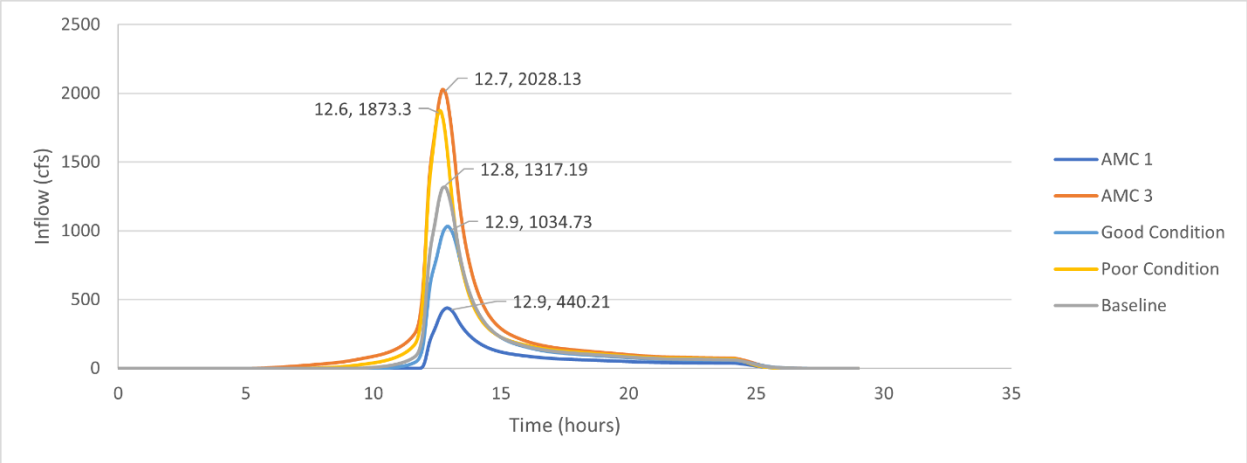

Figure 14: Inflow over time for a 4.04 in storm under changing subcatchment conditions.

Table 6: Maximum inflow as a percent of the baseline condition.

Tested Condition	1.00 in	1.99 in	4.04 in
12 hour	149	118	116
AMC 1	0	4	33
AMC 3	1156	260	154
Back to Back	1548	302	165
Baseflow	101	100	100
Fewer Holes	100	100	100
Good Condition	29	63	79
Increase Dam Height	100	100	100
More Holes	100	100	100
Baseline	100	100	100
Poor Condition	458	188	142
WL Raised	100	100	100

Outflow.

Peak outflow values for each tested condition as a percent of the baseline condition are shown in Table 7. As is the case for the inflows, changing conditions affects smaller storms more than larger storms. Like inflow, the back-to-back condition increases outflow the most regardless of storm size. Other conditions that increase outflow are storms of shorter duration (12-hour storms), more saturated antecendant moisture conditions (AMC 3), and poor land conditions. Drier pre-storm conditions (AMC 1) and good land conditions decrease outflow. Baseflow and a raised water level increase outflow slightly. An increased beaver dam height decreases outflow since less water is flowing over the top of the dam and there is more transient storage within the pond. Increasing or decreasing the number of holes in the beaver dam does not substantially change the maximum outflow. It likely does effect outflow duration, but in all cases the outflow does not cease within the 14-day modeling period so this effect was not captured.

Table 7: Maximum outflow as a percent of the baseline condition.

Tested Condition	1.00 in	1.99 in	4.04 in
12 hour	165	118	112
AMC 1	0	8	37
AMC 3	1043	249	151
Baseflow	156	104	101
Back to Back	1507	300	168
Good Condition	37	71	85
Poor Condition	370	161	125
Fewer Holes	100	100	100
Increase Dam Height	3	32	65
More Holes	100	100	100
Baseline	100	100	100
WL Raised	152	104	100

Water Level.

Perhaps some of the most interesting results from the sensitivity analysis relate to how water level changes over time in the wetland. Figures 15-17 show water level under changing storm conditions, Figures 18-20 for changing subcatchment conditions, and Figures 21-23 for changing

water level conditions, and Figures 24-26 for changing outlet conditions. As was the case for inflows and outflows, the general pattern of the graphs is maintained as storm size increases. A back-to-back storm produces a large spike in water level that lasts for only a few hours (Figure 15-17). The water level rises rapidly and decreases slowly, particularly after the water level drops below the elevation of the top of the beaver dam. This elevation is easily identified as the y-value where the slope of the line changes dramatically—at 370 ft for all tested conditions except a raised beaver dam height, which is raised to 371 ft (Figures 24-26). The decrease in water level below the top of the dam is governed by the dam's permeability, which is represented as holes in a weir. The slope of the decreasing water level line is identical for all conditions except when there is baseflow present and when the holes are altered. Baseflow ensures that there is sufficient constant flow to keep the wetland at a minimum water elevation of 370 feet (Figures 21-23). Increasing the number of holes increases the speed at which the water level drops while decreasing the number of holes decreases the speed at which the water level drops. Water still drains slowly from the wetland, even with an increased number of holes. The wetland does not empty (the water level does not reach 368.91) two weeks after a storm (Figures 24-26).

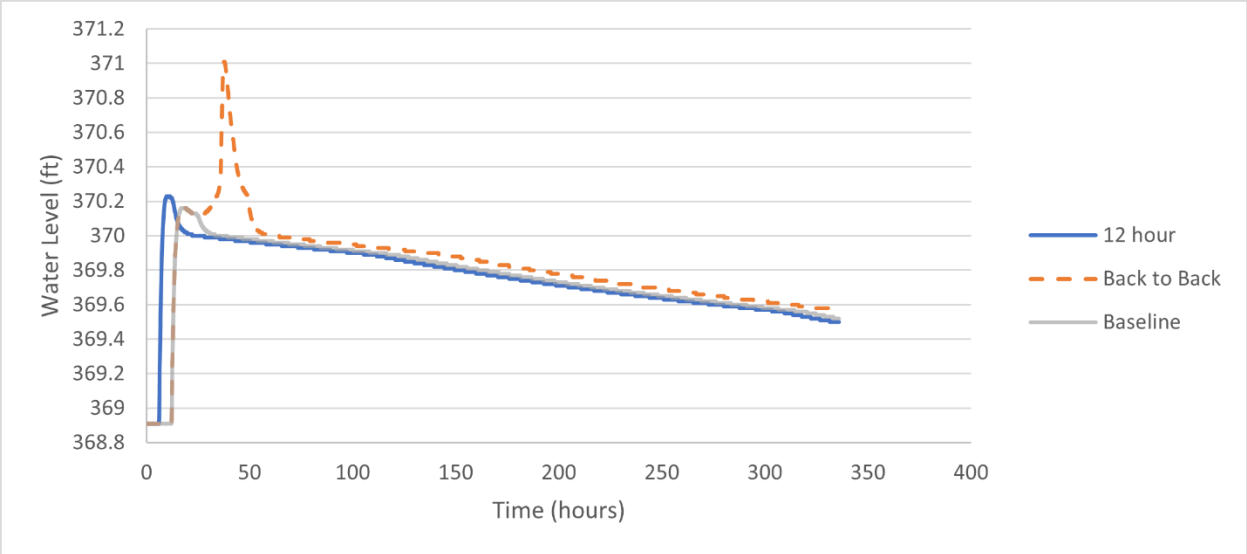

Figure 15: Water level over time for a 1.00 in storm under changing storm conditions.

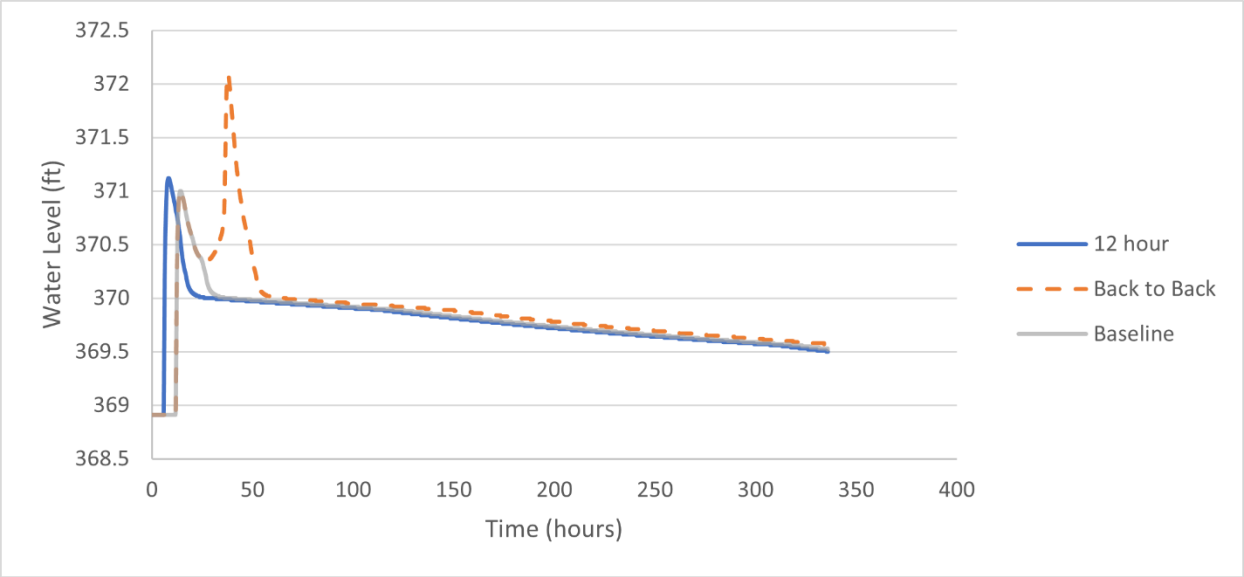

Figure 16: Water level over time for a 1.99 in storm under changing storm conditions.

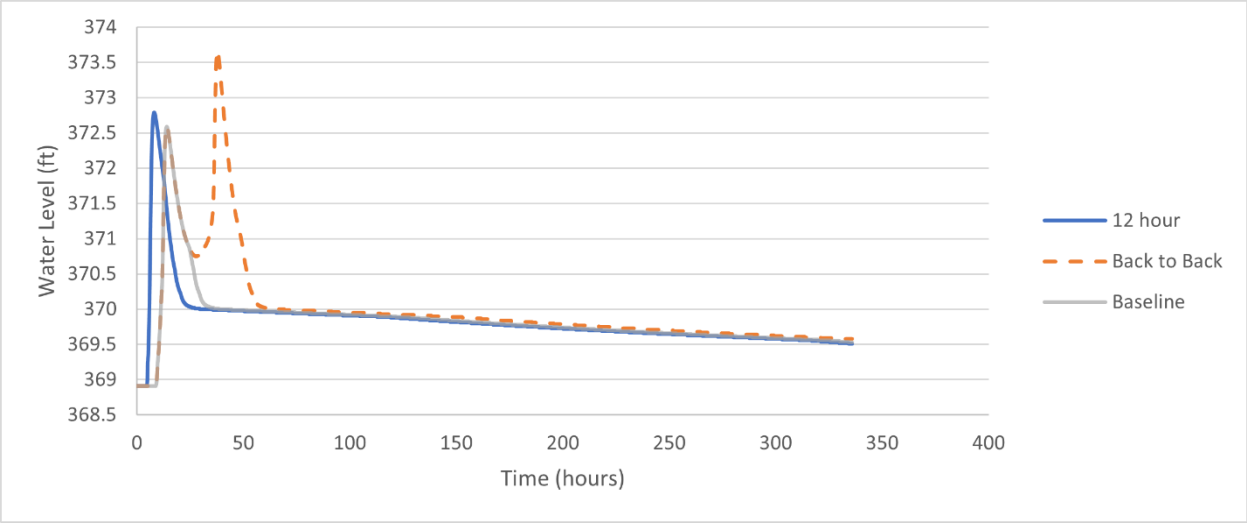

Figure 17: Water level over time for a 4.04 in storm under changing storm conditions.

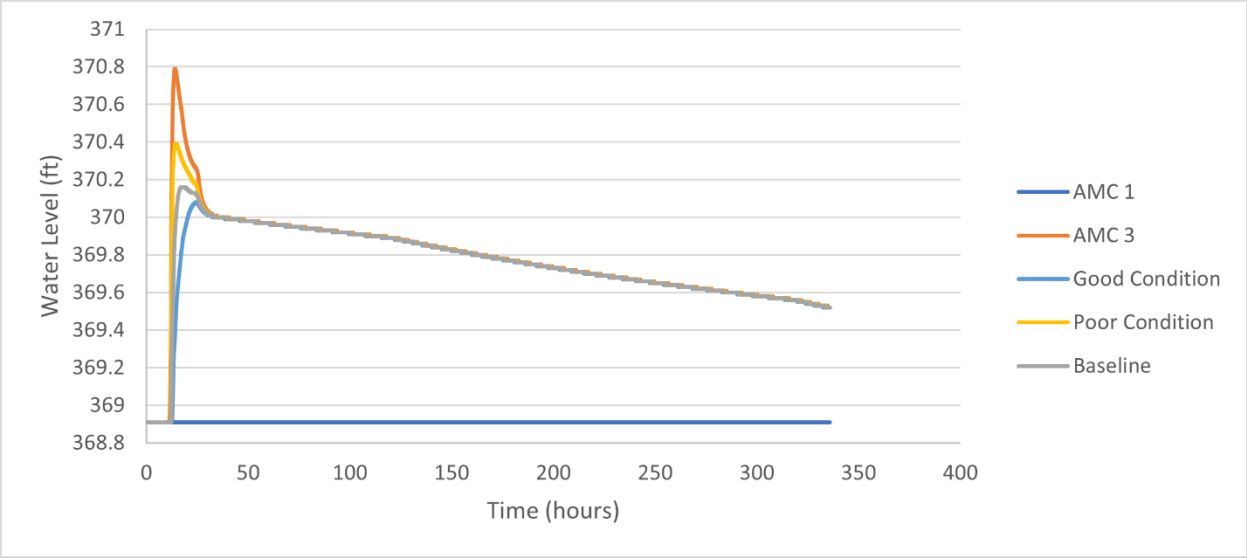

Figure 18: Water level over time for a 1.00 in storm under changing subcatchment conditions.

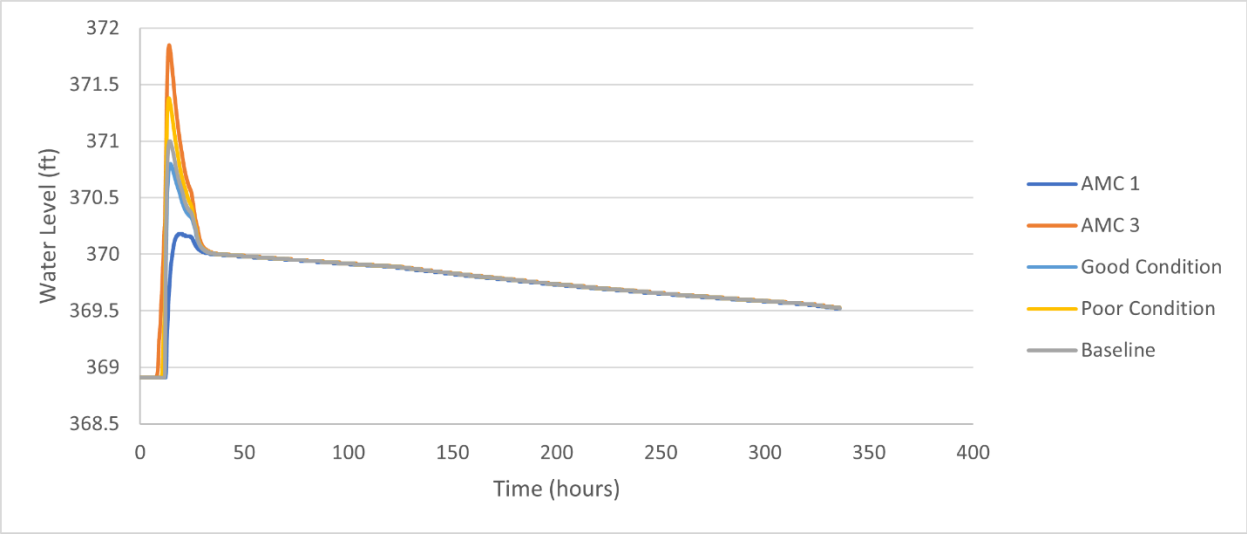

Figure 19: Water level over time for a 1.99 in storm under changing subcatchment conditions.

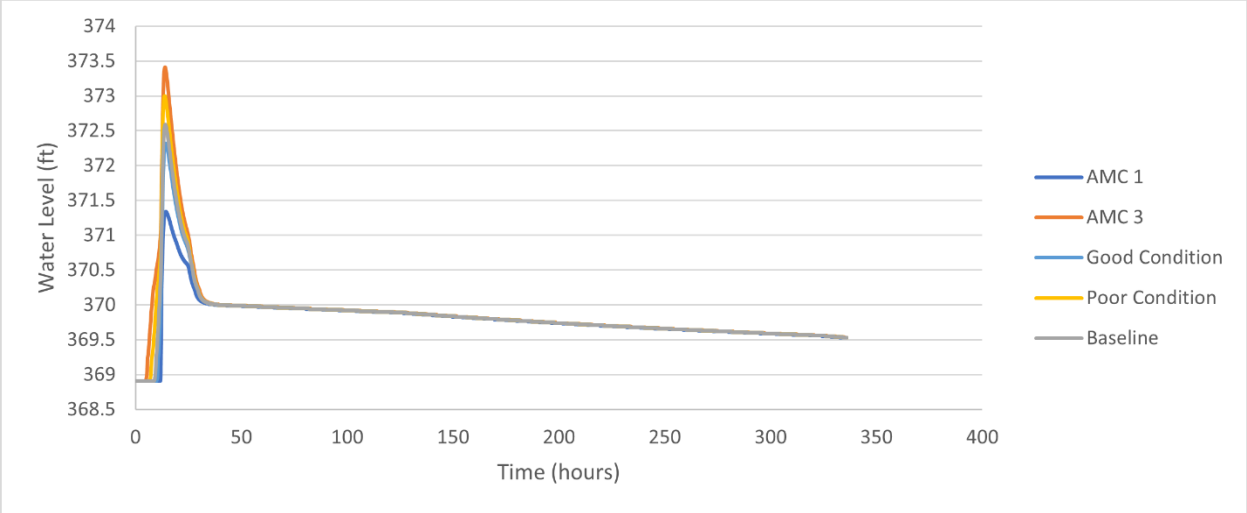

Figure 20: Water level over time for a 4.04 in storm under changing subcatchment conditions.

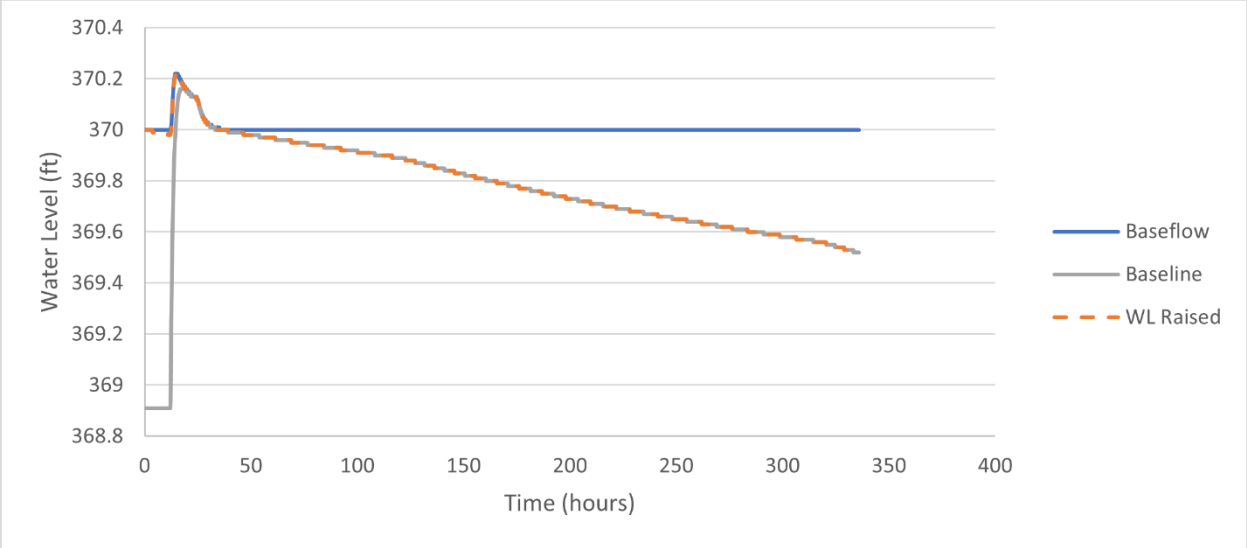

Figure 21: Water level over time for a 1.00 in storm under changing water level conditions.

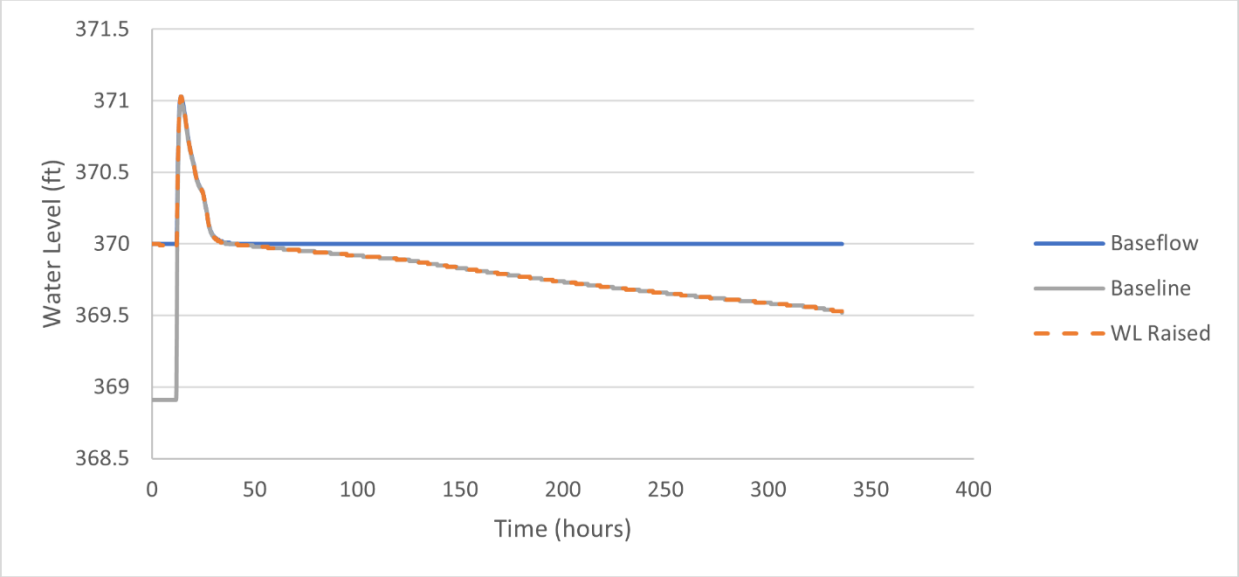

Figure 22: Water level over time for a 1.99 in storm under changing water level conditions.

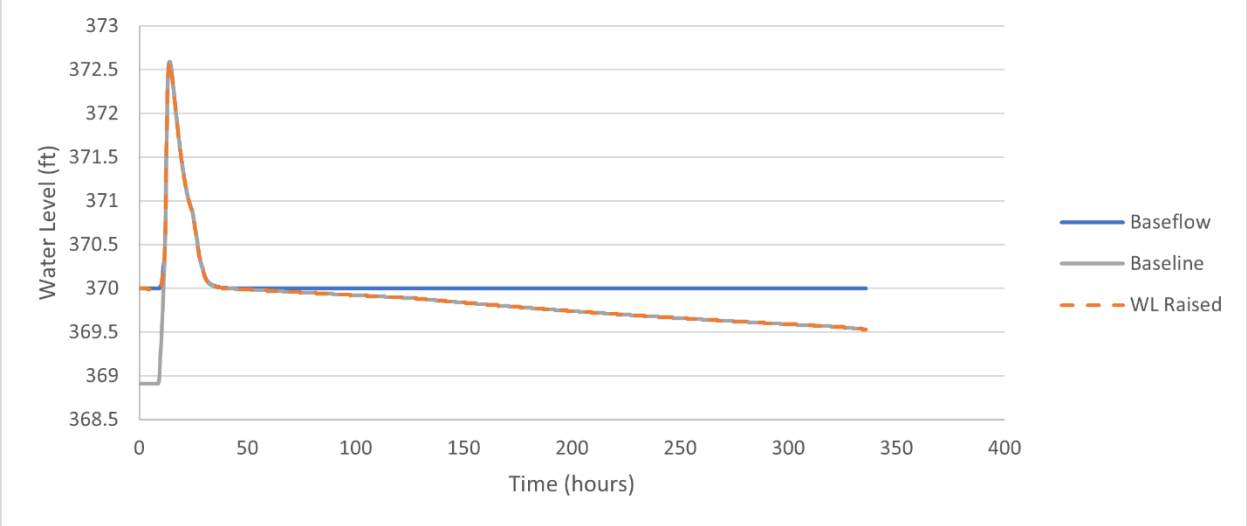

Figure 23: Water level over time for a 4.04 in storm under changing water level conditions.

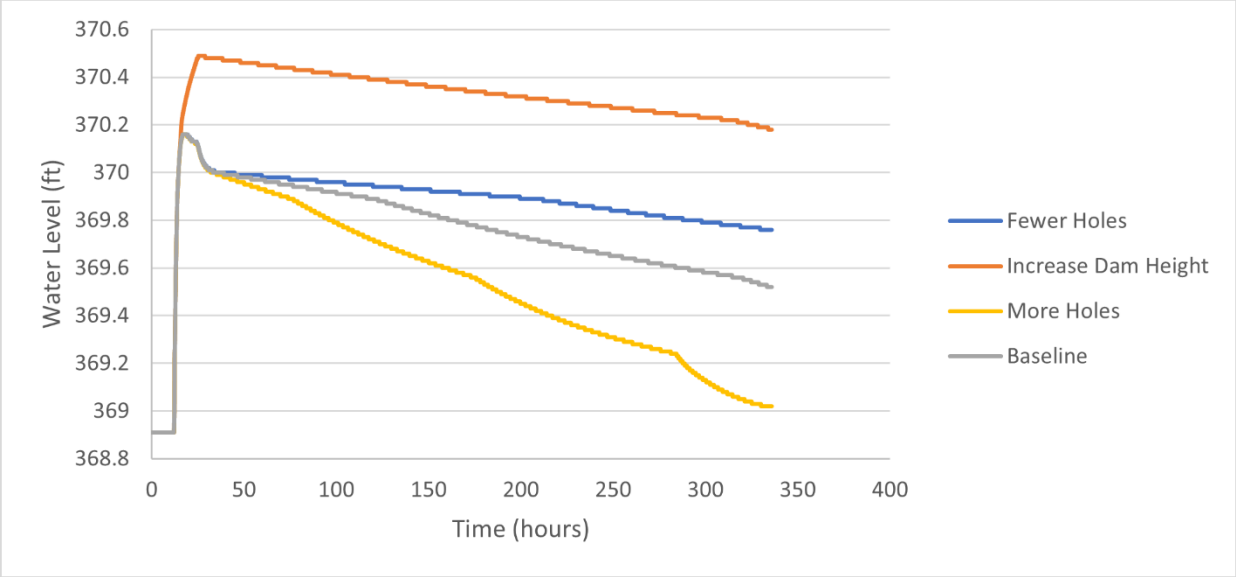

Figure 24: Water level over time for a 1.00 storm under changing outlet conditions.

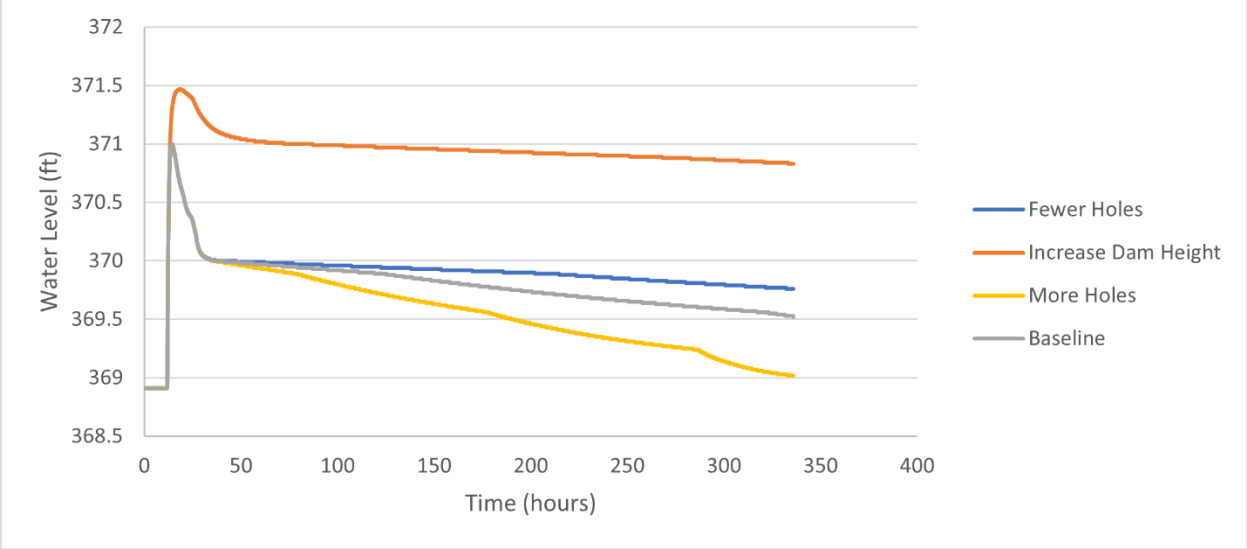

Figure 25: Water level over time for a 1.99 in storm under changing outlet conditions.

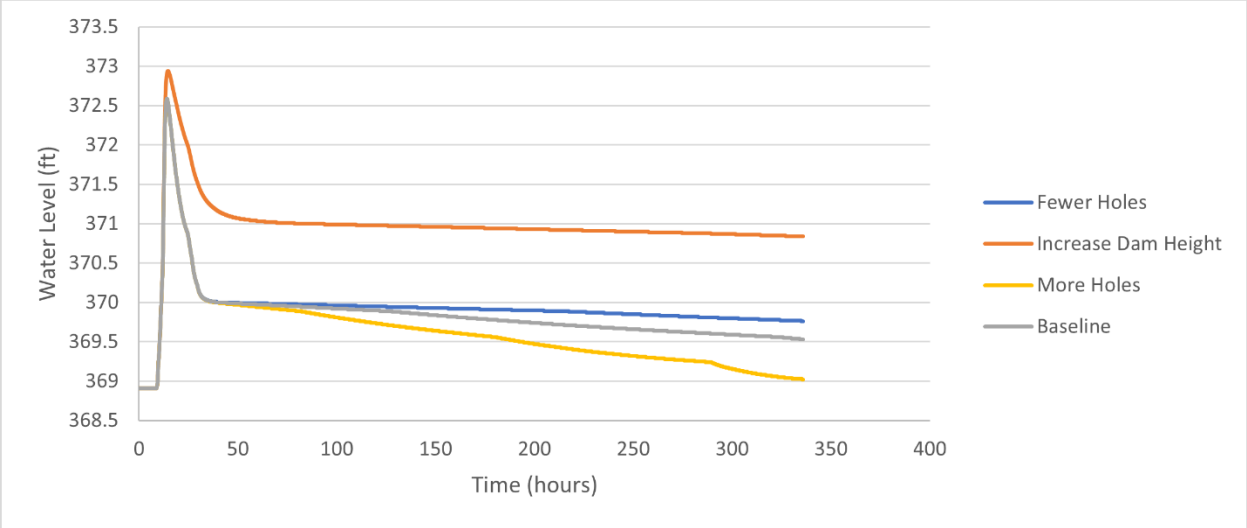

Figure 26: Water level over time for a 4.04 in storm under changing outlet conditions.

Conclusions.

A full, working hydrologic model for the Prindle Brook basin was created. A sensitivity analysis on this model was performed to understand how altering model parameters affects hydrology.

The sensitivity analysis revealed that parameters do not affect all storms equally. Smaller storms are more affected by changing parameters, and this trend is consistent for maximum inflow, outflow, and water level values. Antecedent moisture conditions heavily influence the hydrology, especially inflow over time. The only parameters that change the rate of seepage through the beaver dam are changing the number of holes. These parameters do not affect inflow and do not affect outflow substantially but do uniquely change the water level over time. Baseflow also alters the water level substantially by keeping the wetland at a certain constant water level before and after a storm. Changing the length of the storm or having storms occur back-to-back is the only way to substantially change the time to peak inflow, outflow, or water level.

This model will be used to model phosphorus retention in the Prindle Book wetland. The model will be calibrated using recorded water level data that have been collecting data for the past two

years. These recorders have captured several sized storm events, including a 3.71 in storm on 10/31/2019. The process of calibrating the model will be guided by the results of this thesis. This work is also, as far as the authors are aware, the first simulation of a beaver dam outlet in HydroCAD in hydrologic literature.

Acknowledgments.

Special thanks to Eric Roy and Adrian Weigman for their invaluable help and major contributions to this project. Thanks also to Kristen Underwood and Breck Bowden, committee members, for their support. This research was made possible by the Lake Champlain Basin Program and was supported by the Rubenstein School of Environment and Natural Resources, the College of Engineering and Mathematics, and the Honors College at the University of Vermont.

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Appendix A: Figures

Sensitivity Analysis: Inflow Tables.

Table 8: Maximum inflow in cubic feet per second.

Tested Condition	1.00 in	1.99 in	4.04 in
12 hour	25.41	336.40	1533.55
AMC 1	0.00	12.33	440.21
AMC 3	197.86	739.62	2028.13
Back to Back	264.84	859.18	2179.06
Baseflow	17.22	284.30	1317.30
Fewer Holes	17.11	284.19	1317.19
Good Condition	4.89	178.18	1034.73
Increase Dam Height	17.11	284.19	1317.19
More Holes	17.11	284.19	1317.19
Baseline	17.11	284.19	1317.19
Poor Condition	78.36	534.81	1873.30
WL Raised	17.11	284.19	1317.19

Table 9: Time to maximum inflow in hours.

Tested Condition	1.00 in	1.99 in	4.04 in
12 hour	7.20	6.90	6.80
AMC 1	0.00	14.05	12.90
AMC 3	12.85	12.75	12.70
Baseflow	13.20	12.85	12.80
Back to Back	36.75	36.75	36.70
Good Condition	14.70	13.05	12.90
Poor Condition	12.75	12.65	12.60
Fewer Holes	13.20	12.85	12.80
Increase Dam Height	13.20	12.85	12.80
More Holes	13.20	12.85	12.80
Baseline	13.20	12.85	12.80
WL Raised	13.20	12.85	12.80

Table 10: Time to maximum inflow as a percent of the baseline condition.

Tested Condition	1.00 in	1.99 in	4.04 in
12 hour	55	54	53
AMC 1	0	109	101
AMC 3	97	99	99
Baseflow	100	100	100
Back to Back	278	286	287
Good Condition	111	102	101
Poor Condition	97	98	98
Fewer Holes	100	100	100
Increase Dam Height	100	100	100
More Holes	100	100	100
Baseline	100	100	100
WL Raised	100	100	100

Sensitivity Analysis: Outflow Tables.

Table 11: Maximum outflow in cubic feet per second.

Tested Condition	1.00 in	1.99 in	4.04 in
12 hour	11.89	126.63	492.03
AMC 1	0.00	8.31	164.45
AMC 3	75.28	266.32	662.09
Baseflow	11.25	111.71	441.32
Back to Back	108.80	320.72	736.23
Good Condition	2.65	76.03	374.05
Poor Condition	26.72	172.30	547.82
Fewer Holes	7.22	106.85	439.01
Increase Dam Height	0.20	34.43	286.84
More Holes	7.21	107.00	439.24
Baseline	7.22	106.90	439.09
WL Raised	11.01	111.47	441.21

Table 12: Time to maximum outflow in hours.

Tested Condition	1.00 in	1.99 in	4.04 in
12 hour	10.40	8.25	8.10
AMC 1	0.00	19.15	14.35
AMC 3	14.00	13.90	13.90
Baseflow	14.75	14.10	14.00
Back to Back	37.70	37.75	37.85
Good Condition	24.45	14.45	14.20
Poor Condition	14.35	13.80	13.75
Fewer Holes	17.60	14.15	14.00
Increase Dam Height	25.10	18.30	14.55
More Holes	17.55	14.15	14.00
Baseline	17.65	14.15	14.00
WL Raised	14.85	14.10	14.00

Table 13: Time to maximum outflow as a percent of the baseline condition.

Tested Condition	1.00 in	1.99 in	4.04 in
12 hour	59	58	58
AMC 1	0	135	103
AMC 3	79	98	99
Baseflow	84	100	100
Back to Back	214	267	270
Good Condition	139	102	101
Poor Condition	81	98	98
Fewer Holes	100	100	100
Increase Dam Height	142	129	104
More Holes	99	100	100
Baseline	100	100	100
WL Raised	84	100	100

Sensitivity Analysis: Water Level Tables.

Table 14: Maximum water level in feet.

Tested Condition	1.00 in	1.99 in	4.04 in
12 hour	370.23	371.12	372.79
AMC 1	368.91	370.18	371.34
AMC 3	370.79	371.85	373.41
Baseflow	370.22	371.03	372.59
Back to Back	371.01	372.09	373.67
Good Condition	370.08	370.8	372.32
Poor Condition	370.39	371.38	373
Fewer Holes	370.16	371	372.59
Increase Dam Height	370.49	371.47	372.94
More Holes	370.16	371	372.58
Baseline	370.16	371	372.59
WL Raised	370.22	371.03	372.59

Table 15: Maximum water level as a percent of the baseline condition.

Tested Condition	1.00 in	1.99 in	4.04 in
12 hour	100	100	100
AMC 1	100	100	100
AMC 3	100	100	100
Baseflow	100	100	100
Back to Back	100	100	100
Good Condition	100	100	100
Poor Condition	100	100	100
Fewer Holes	100	100	100
Increase Dam Height	100	100	100
More Holes	100	100	100
Baseline	100	100	100
WL Raised	100	100	100

Table 16: Time to the maximum water level in hours.

Tested Condition	1.00 in	1.99 in	4.04 in
12 hour	9.70	8.05	7.95
AMC 1	0.00	18.30	14.25
AMC 3	13.80	13.85	13.80
Baseflow	14.30	13.90	13.85
Back to Back	37.50	37.60	37.80
Good Condition	23.70	14.35	14.05
Poor Condition	13.90	13.65	13.60
Fewer Holes	16.60	13.95	14.00
Increase Dam Height	25.25	17.85	14.40
More Holes	16.80	13.95	13.85
Baseline	16.65	13.95	14.00
WL Raised	14.55	13.95	13.85

Table 17: Time to maximum water level as a percent of the baseline condition.

Tested Condition	1.00 in	1.99 in	4.04 in
12 hour	58	58	57
AMC 1	0	131	102
AMC 3	83	99	99
Baseflow	86	100	99
Back to Back	225	270	270
Good Condition	142	103	100
Poor Condition	83	98	97
Fewer Holes	100	100	100
Increase Dam Height	152	128	103
More Holes	101	100	99
Baseline	100	100	100
WL Raised	87	100	99