AYRES

Design Flood Hydrologic Analyses

Secord, Smallwood, Edenville, and Sanford Dams

Gladwin and Midland Counties, Michigan

Prepared for:

Four Lakes Task Force
Midland, MI

July 2021

www.AyresAssociates.com

Design Flood Hydrologic Analyses

Secord, Smallwood, Edenville, and Sanford Dams
Gladwin and Midland Counties, MI

26-1145.00

Contents

Page No.

List of Exhibits

List of Tables

Summary

The Four Lakes Task Force (FLTF) has contracted with Ayres Associates (Ayres) to complete hydrologic analyses to support the selection of spillway design floods for the Secord, Smallwood, Edenville, and Sanford dams on the Tittabawassee River in Michigan. The FLTF, a delegated authority of Gladwin and Midland Counties, MI, is in the process of redesigning and reconstructing the dams following a destructive flood in 2020, and the selection of appropriate design floods is a cornerstone of that effort.

Design flood hydrographs developed in this study included the Probable Maximum Flood (PMF); the “half-PMF,” which is defined by Michigan dam safety regulators as the flood resulting from half of the Probable Maximum Precipitation (PMP); and floods generated from precipitation events having annual exceedance probabilities (AEPs) of .01, .005, .002, .001, and .0002.

The U.S. Army Corps of Engineers HEC-HMS model, Version 4.7.1, was used to generate flood hydrographs at various locations throughout the watershed. The HEC-HMS model was calibrated to four observed events using precipitation time series developed by Applied Weather Associates. This resulted in four sets of calibrated unit hydrograph and loss parameters. These were weighted for use in the PMF and half-PMF model based on flood magnitude and calibration quality. For the exceedance probability flood model, the calibrated parameters were weighted based on calibration quality and correspondence between the exceedance probability of the rainfall event and the exceedance probability of the modeled flood. The adopted model was tested against a fifth flood and accepted with no further modifications.

Table 1 summarizes the resulting peak inflows at each of the dams, assuming the spillway capacity that existed prior to the 2020 flood event. Spillway rating curves used for this study are derived from calculations provided by GEI Consultants prior to the May 2020 flooding (GEI, 2020). Note that the Smallwood, Edenville, and Sanford inflows are based on the pre-failure 2020 storage-discharge relationships at upstream dams. The spillway redesign currently underway will affect these relationships and therefore will also affect the downstream flow releases for a given inflow hydrograph.

Table 1: Summary of Estimated Design Flood Flows

	Secord	**Smallwood**	**Edenville** *Edenville and Tobacco spillways*	**Sanford**
Drainage Area (square miles; remeasured for this study)	177	289	904	945
2020 Zero Freeboard Spillway Capacity (cubic feet/ second (cfs))	7,695 (gated spillway); 12,135 (total)	10,185 (gated spillway); 29,835 (total)	20,670 (2 gated spillways)	36,175 (gated spillway and fuse plug)
PMF Peak Inflow (cfs)	29,200	48,200	113,400	117,200
Half-PMF Peak Inflow (cfs)	12,700	15,600	44,600	44,900
.01 AEP (100-year) Storm Peak Inflow (cfs)	6,730	9,020	21,300	18,200
.005 AEP (200-year) Storm Peak Inflow (cfs)	7,900	10,400	25,400	20,700
.002 AEP (500-year) Storm Peak Inflow (cfs)	9,710	12,600	32,100	28,700
.001 AEP (1,000-year) Storm Peak Inflow (cfs)	11,300	14,500	37,400	34,600
.0002 AEP (5,000-year) Storm peak Inflow (cfs)	15,900	21,200	52,800	53,400

Introduction

Secord Dam, Smallwood Dam, Edenville Dam, and Sanford Dam are located on the Tittabawassee River in Gladwin and Midland Counties, Michigan and upstream of the city of Midland. The dams were constructed as hydropower projects in the early 20th century and while under past ownership, were found to have inadequate spillway capacity as defined by the Federal Energy Regulatory Commission (FERC). In May, 2020, a large flood occurred on the watershed and an embankment at Edenville Dam collapsed, with a partial failure of the downstream Sanford Dam ensuing. The FLTF is working to reconstruct Edenville Dam and Sanford Dam, and improve Secord Dam and Smallwood Dam, for the purpose of safely restoring and maintaining the lakes retained by the dams.

There are currently no plans to restore the dams for hydropower generation. Therefore, they will fall under the dam safety jurisdiction of Michigan's Department of Environment, Great Lakes, and Energy (EGLE). With respect to selection of design floods, the FLTF has stated the intent of following both EGLE requirements and Federal Emergency Management Agency (FEMA) guidance (FEMA, 2013). FEMA's guidance suggests several possible approaches. One is a prescriptive approach based on the hazard potential classification of the dam. Typically, high hazard dams are required to pass the PMF when using a prescriptive approach. Incremental hazard assessments, in which the potential adverse consequences associated with a flood-induced failure are compared to the consequences of the same flood without a failure, can be used for dams whose failure at extremely high flows becomes inconsequential relative to the pre-existing flood. Finally, a risk informed approach utilizes hydrologic hazard information and expected consequences to determine if a given spillway design flood selection reduces the risk to a tolerable level. The design flood hydrologic analyses described in this report are intended to support both prescriptive and risk-based reasoning so that both considerations can be used as benchmarks in design flood selection.

In this report, storms and floods having an estimated annual probability of exceedance are referred to in terms of both AEP (annual exceedance probability) and return period. The AEP description (such as 0.01 for an event having a one-percent chance of exceedance in a given year) is typically used for technical communication and risk studies, but the return-period concept is also commonly used in informal and public communication (a 1-percent AEP event is also called a "100-year" event because the long-term average period between such events would be 100 years).

Project Background and Descriptions

The four Tittabawassee River hydroelectric projects were constructed between 1923 and 1925 by the Wolverine Power Company. From 2006 through 2020 they were owned and operated by Boyce Hydropower, LLC. In 2018, hydroelectric generation ceased at the Edenville project after the Federal Energy Regulatory Commission revoked its hydropower license. In 2019 the FLTF began the process of acquiring the four dams from Boyce with the intent that the dams would transition to public ownership. The impetus for the acquisition was the desire on the part of public and private stakeholders to secure and maintain the environmental, economic, recreational, and aesthetic benefits of the four dams' impoundments.

Prior to beginning required spillway upgrades at the Secord and Edenville projects, the FLTF determined that the PMF should be reviewed and updated if appropriate. A PMF study was initiated by Ayres Associates in 2019 under contract to Spicer Group and included the development, calibration, and application of a hydrologic model to identify the PMF inflow and outflow at each of the four dams. A draft study report was complete just before the storm and flood of May 19, 2020. The present report incorporates precipitation and flow data from the May 2020 event, as well as updated estimates of the PMP and probability-based precipitation data.

Pertinent project features are described below. Note that the drainage areas listed are based on the 2020 redelineation of the basin using the National Elevation Dataset (NED) (10-meter resolution) and 2016 USGS 1-meter resolution digital elevation models (DEMs) for Michigan. The re-measured drainage areas differ from areas reported in older (1993 – 2019) documents. Project-related elevations use the NGVD29 vertical datum. To convert to NAVD88, subtract 0.5 foot from the NGVD29 elevation for the Secord and Smallwood projects, and 0.6 foot for the Edenville and Sanford projects. Spillway geometry and discharge data were taken from an April 2020 Technical Memorandum prepared by GEI Consultants.

The dams' locations in the upper Tittabawassee River basin are shown on Exhibit 1. As of this writing, all four impoundments are drawn down, Edenville and Sanford because of embankment breaches and Secord and Smallwood for assessment and repairs.

Secord Dam

Secord Dam (NID MI-00547; FERC Project No. 10809) is located in Gladwin County and is the most upstream of the four dams, at a drainage area of 177 square miles. It impounds the 979-acre Secord Lake. At normal pool elevation 750.8, freeboard to the top of the embankments is seven feet.

Flood flows are passed through two tainter gates, one 20.5 feet wide and one 23.6 feet wide. According to investigations by Spicer Group and GEI Consultants in 2020, the smaller gate's maximum opening height is 7.5 feet and the larger gate opens to 10.5 feet. GEI's calculations indicate that at zero freeboard (pool elevation 757.8) the total gate capacity is 7,695 cfs. An additional 4,440 cfs flows over the left abutment and the east reservoir rim towards Tea Creek, for a total zero freeboard discharge of 12,135 cfs.

The Secord watershed is largely undeveloped except for lakeshore properties. Relief is generally low and land cover types include forest, wetland forest, and agriculture.

Smallwood Dam

Smallwood Dam (NID MI-00548; FERC Project No. 10810) is located in Gladwin County at a drainage area of 289 square miles. Impoundment area measurements vary: the project Supporting Technical Information Document (STID) lists the impoundment area as 500 acres, but the Michigan DNR lists the impoundment area as 232 acres. Ayres' measurement using 2018 aerial imagery and the National Elevation Dataset is 360 acres. Normal pool elevation is 704.8 feet and zero freeboard elevation is 715.7 feet.

Flood flows are passed through two 23.4-foot-wide tainter gates. One of the gates opens to an estimated height of 10 feet and the other to a height of 9.9 feet. At zero freeboard elevation 715.7 the gates discharge 10,185 cfs. "Zero freeboard" refers to the top of a sheetpile wall driven into the upstream faces of the embankments, but a 680-foot length of the left embankment has been left unprotected due to its low height and non-critical failure consequences. Overtopping of this length of embankment adds 19,650 cfs in capacity at zero freeboard elevation, for a total capacity of 29,835 cfs.

The watershed at Smallwood Dam is mostly undeveloped, but has more agricultural use in the Sugar River subbasin than the watershed upstream of Secord. Lancer Lake Dam on the Sugar River impounds a 500-acre lake.

Edenville Dam

Edenville Dam (NID MI-00549) is constructed across both the Tittabawassee and Tobacco Rivers just above their confluence, at a combined drainage area of 904 square miles. Its reservoir, Wixom Lake, has a normal surface area of 1,980 acres. Wixom Lake is bifurcated by the Michigan Highway 30 causeway. The causeway bridge was destroyed in the flood and is currently being redesigned with a greater span. For the purposes of the model calibration and design flood analysis, the routing component of the HEC-HMS model was simplified by assuming a single combined spillway rating curve combining the capacity of both spillways. Normal pool elevation before the 2020 failure was 675.8 feet and the zero freeboard elevation was 682.1 feet.

Gated spillways containing three tainter gates each are located on each branch of the reservoir. On the Tittabawassee River (or Edenville) side, two of the gates are 20 feet wide and the third is 23.5 feet wide. On the Tobacco River side, two spillway gates are 23.6 feet wide and the third is 20 feet wide. All of the spillway gates open to a height between 8.9 and 9.6 feet. The total calculated zero-freeboard spillway capacity is 20,670 cfs, of which 10,750 cfs passes through the Edenville gates and 9,920 cfs passes through the Tobacco River gates.

Tributaries to the Tittabawassee River between Smallwood and Edenville include the Tobacco River, draining 458 square miles of mixed forest, wetland forest, and agriculture to the west; and the Molasses River, draining 78 square miles of mostly wetland forest to the east. The Tobacco River drainage includes the cities of Gladwin and Beaverton and two significant impoundments: the 500-acre Wiggins Lake, dammed by Chappel Dam; and the 300-acre Ross Lake, dammed by the Beaverton Dam.

Smaller dams and impoundments are present on the Molasses, Black, and Cedar Rivers but were not represented in the HEC-HMS model.

Sanford Dam

Sanford Dam (NID MI-00550, FERC Project No. 2785) is situated on the Tittabawassee River at a drainage area of 945 square miles. It impounds the 1,430-acre Sanford Lake. Normal pool elevation is 630.8 feet and the zero freeboard elevation is 636.8 feet. Spillways include four 22-foot-wide tainter gates and two 25.4-foot wide tainter gates, with opening heights ranging from 10.1 to 11 feet. The dam was also equipped with a fuse plug spillway which was designed to be overtopped at elevation 634.8 feet and was washed out during the 2020 flood. According to GEI’s 2020 calculations, the total spillway capacity, including the fuse plug spillway, was 36,175 cfs. The incremental 41-square-mile drainage area between Edenville and Sanford consists of wetland forests and the developed shoreline of Sanford Lake.

Historic Streamflow Data

There are two USGS stream gages within the Tittabawassee River basin upstream of Sanford Dam, and one downstream of Sanford at Midland, Michigan. Table 2 summarizes available stream gage data.

Table 2: Tittabawassee Basin Stream Gages and Floods of Record

Gage Name	USGS Gage Number	Drainage Area (square miles, as reported by USGS)	Period of Record	Flood of Record (cfs) and date
South Branch Tobacco River near Beaverton	04152238	160	1987-present	3,280 April 14, 2014
Tobacco River at Beaverton	04152500	487	1948-1982, 2015 - present	8,460 May 19, 2020
Tittabawassee River at Midland *(downstream of all projects)*	04156000	2,400	1907, 1910-present	*Natural flooding:* 39,100 June 24, 2017; *Upstream dam failures:* 51,800 May 20, 2020

In addition, inflow and outflow hydrographs at the Tittabawassee River dams were reconstructed for the calibration events used in this study, based on maximum annual flow event reports compiled by Boyce Hydro (including hourly gate opening, turbine setting, and pool level for one to three days around each annual peak). These reconstructions provide to be somewhat unstable due to the limitations of the data and the back-routing method, especially at Secord and Smallwood. However, they could be used to trace the general inflow hydrograph shape for the calibration events.

The annual peak flow series at the three USGS gages listed above are plotted in Exhibit 2. Exhibit 2 also shows a time series of calculated annual outflows from Edenville Dam since 1929, based on the data extracted for previous studies by Boyce Hydro. These annual peak outflows were adjusted for the updated spillway rating curves prepared by GEI in 2020.

Existing Flood Frequency Data

The 2013 Midland County Flood Insurance Study (FIS) lists one-percent annual exceedance probability (AEP) flood discharges for the Tobacco River “above confluence with the Tittabawassee River” and the Tittabawassee River “upstream of Sanford Dam.” These .01 AEP discharges are 14,958 cfs and 19,817 cfs respectively.

Figure 1 is a HEC-SSP (Version 2.2) flood frequency plot for Edenville Dam annual maximum outflows. The curve was computed using Bulletin 17C procedures and calculated maximum outflows from 1929 through 2020. Annual maxima from 2015, 2016, 2018, and 2019 were not available from the plant logs and were estimated by transfer from the Midland gage. The HEC-SSP estimate of the .01 AEP outflow from Edenville Dam is 16,600 cfs with a 5% - 95% confidence interval of 14,600 cfs to 20,100 cfs. The HEC-SSP estimated exceedance probability of the estimated 2020 pre-failure outflow (19,100 cfs) is 0.002.

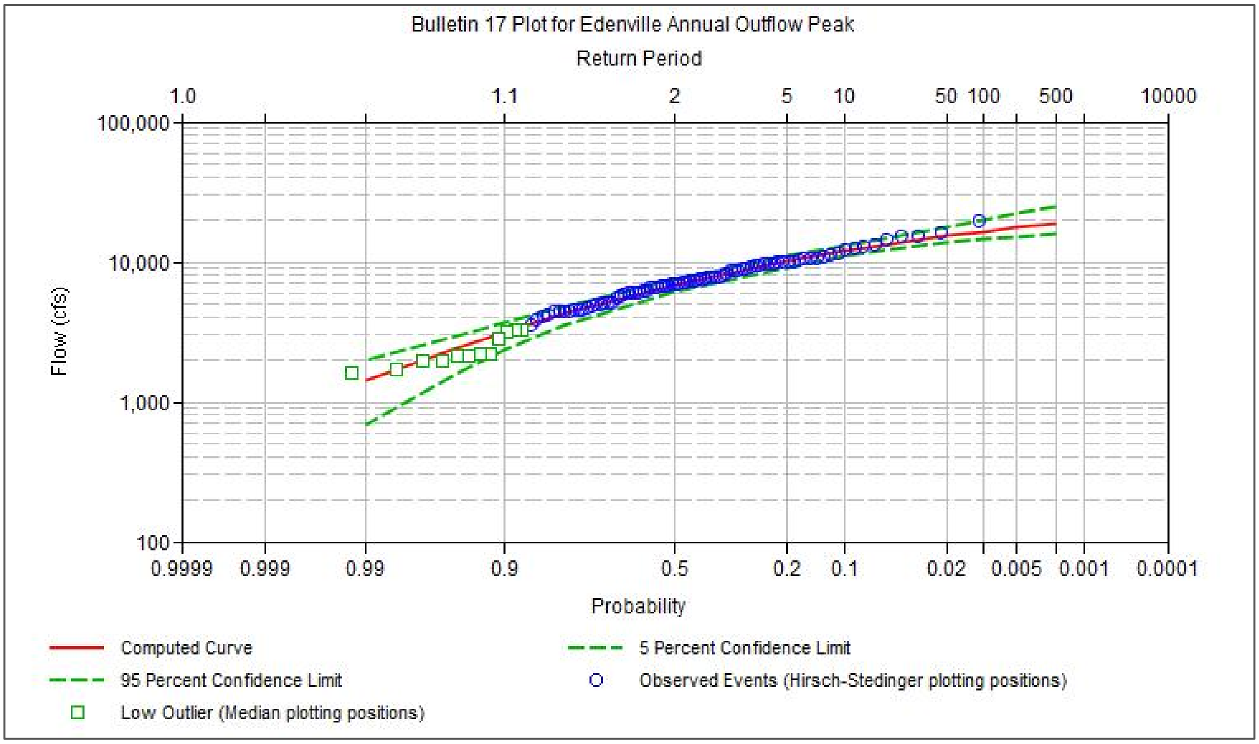


Figure 1: HEC-SSP Edenville Dam Outflow Frequency Plot

Previous Studies

Previous design flood studies have focused on the PMF because FERC, which has dam safety authority over nonfederal hydropower facilities, uses a deterministic PMF standard unless incremental hazard analyses justify a smaller design event.

PMF Studies, 1994 - 2011

With the exception of Edenville Dam, the documented PMF values at the dams date from a 1994 study conducted for Wolverine Power by Mead & Hunt. That study used the HEC-1 and UNET models and divided the watershed at Sanford Dam into eight subbasins. Warm- and cool-season PMP values were taken from the 1993 Wisconsin-Michigan Probable Maximum Precipitation Study (EPRI, 1993).

The 1994 unit hydrographs were developed from limited gage records from the South Branch of the Tobacco River and an adjacent gaged watershed, the Rifle River. Clark unit hydrograph parameters for the model subbasins were derived by transferring the channel length/time of concentration relationship from one of the gaged basins to the model subbasins, with the analogous gaged basin being chosen based on apparent hydrologic similarity to the ungaged model subbasin.

Spatially distributed losses were calculated outside of the HEC-1 program by dividing each subbasin into loss classes based on the NRCS STATSGO soils database, calculating individual soil class losses and runoff, and summing all of the runoff over a subbasin before returning it to the HEC-1 model. Loss rates were modified for the presence of wetlands. The constant loss rate was assigned based on the

STATSGO saturated hydraulic conductivity (Ksat), using the geometric mean of the published range for each soil layer and unit. The approach of separating the subbasins by soil class and computing runoff separately from each class was adopted to account for a non-linear runoff relation, in which more intense precipitation produces runoff from areas of the watershed that did not contribute runoff from lesser precipitation amounts.

Channel routing was also performed outside of the HEC-1 model in the UNET model. UNET was a U.S. Army Corps of Engineers unsteady-flow model that preceded the unsteady version of the HEC-RAS model.

The resulting PMF inflows and outflows are listed in Table 2 below. In 2011, Mill Road Engineering concluded that the 1994 model misrepresented the offset in timing between the Tittabawassee River and Tobacco River contributions to Wixom Lake. The two branches of the reservoir were re-analyzed using a HEC-RAS model, resulting in a peak spillway flow at Edenville of 62,000 cfs.

PMF Study Update, 2019-2020

In 2019 an updated PMF study for the four dams was initiated by Ayres under contract to Spicer Group, which was coordinating design studies on behalf of the FLTF. A report was completed in early May, 2020. The most significant difference between the 2019 – 2020 study and earlier studies was the availability of model calibration data, in the form of operating records from the dams, new stream gage data, and NEXRAD precipitation coverage for floods occurring in 2014 and 2017. In addition, the study used updated topographic data, including the National Elevation Dataset’s 10-meter resolution topography and 2016 USGS LiDAR-based 1- meter DEMs; SSURGO county-level soils data; and updated spillway rating curves. The PMP sequence was derived from the 1993 Michigan-Wisconsin PMP study, which was also used for the earlier studies. A cool season flood was not investigated in detail, because cool season storms had not controlled in the earlier studies and the warm-season loss rates derived in the 2020 study had moved closer to cool season rates, suggesting that a cool-season event could not overtake the new warm-season estimates.

Table 3 summarizes the PMF flows resulting from previous studies between 1994 and May 2020.

Table 3: Tittabawassee River PMF Flows – 1994, 2011, and May 2020 Studies

Dam	Study Year and Author	PMF Inflow (cfs)	PMF Outflow (cfs)
Secord	1994, Mead & Hunt	27,200	27,100
	2020, Ayres	29,400	28,100
Smallwood	1994, Mead & Hunt	41,000	40,700
	2020, Ayres	41,200	41,000
Edenville	1994, Mead & Hunt	74,400	73,900
	2011, Mill Road Engineering	62,000	62,000
	2020, Ayres	80,900	80,100
Sanford	1994, Mead & Hunt	75,500	73,200
	2020, Ayres	80,600	79,100

Watershed Model Updates (2021)

Following the May 2020 flood and dam failures, the project team (FLTF, Spicer Group, GEI, and Ayres) determined that the 2020 event should be included in the model calibration, given that it appeared to represent the flood of record at Edenville and Sanford and on the Tobacco River. Initial calibration and PMF modeling demonstrated that estimates of the PMF and frequency-based floods were very sensitive to the use of calibration data from the 2020 flood. To improve the robustness of the study, FLTF contracted with Applied Weather Associates (AWA) to provide the following information:

- Hourly precipitation series, by model subbasin, for model calibration events occurring in 1996, 2014, 2017, and 2020
- Updated Probable Maximum Precipitation estimates for the Tittabawassee River watershed; and
- Updated precipitation-frequency data including depth, area, and duration relationships.

FLTF also contracted with YSJ International to provide a peer review of the hydrology modeling. The calibration-weighting approach described in the following sections was a key outcome of consultation with YSJ International. The weighting approach is a practical solution to the problem of model calibrations that are inconsistent from one event to another. Such inconsistencies are only partly related to data quality. They can also be attributed to a runoff response that can vary significantly as a result of antecedent watershed conditions.

Model Structure

The HEC-HMS model, Version 4.7.1, was calibrated to four observed events and used to develop the design flood hydrographs. The model includes a total of 12 subbasins, shown in Exhibit 1 and summarized from upstream to downstream order in Table 4 below.

In addition to the 12 watershed subbasins, Secord Lake and Wixom Lake are represented as separate subbasins with zero permeability and a nominal one-hour time of concentration. This was done primarily to aid in calibration of the three back-routed events (1996, 2014, and 2017) in which very rapid and early rises in reservoir level could be partly explained by rain falling directly on the reservoir.

Table 4: HEC-HMS Model Subbasins

Subbasin Number	HEC-HMS Name	Area (square miles)	Description
1	Secord	129.1	Upper Tittabawassee River, drains to Secord Lake storage element
8	W Br Tittabawassee	46.3	West Branch Tittabawassee River, drains to Secord Lake storage element
-	Secord Res	1.5	Secord Reservoir; 100 percent impervious with nominal (1 hour) time of concentration; drains to Secord Lake storage element
2	Sugar Springs	34.4	Sugar River above Lake Lancer, discharges to routing reach and then Smallwood Lake
4	Smallwood	77.4	Smallwood Reservoir drainage below Lake Lancer and Secord Dam, drains to Smallwood Lake storage element
3a	Chappel	117.2	Cedar River above Wiggins Lake (Chappel Dam); dam discharges to routing reach to Ross Lake
3b	Beaverton-Cedar	136.9	Lower Cedar River drainage plus North and Middle Branches Tobacco River, drains to Ross Lake storage element
3c	Beaverton-Tobacco	153.3	South Branch of the Tobacco River, drains to Ross Lake storage element.
6	Edenville-Tobacco	50.5	Tobacco River drainage below Beaverton Dam, drains to Wixom Lake storage element
5a	Molasses	77.9	Molasses River, drains to routing reach between Smallwood and Wixom Lake
5b	Edenville-Tittabawassee	57.4	Tittabawassee River drainage below Smallwood Dam, drains to Wixom Lake storage element
5c	Black Creek	19.0	Black Creek just below Smallwood Dam, drains to routing reach between Smallwood and Wixom Lake
-	Wixom-subbasin	3.1	Wixom Lake, 100 percent impervious with nominal time of concentration; drains to Wixom Lake storage element
7	Sanford	40.8	Direct drainage to Sanford Lake, includes Sanford Lake as impervious fraction

Unit Hydrograph Parameters

The Clark unit hydrograph parameters Tc (time of concentration in hours) and R (storage coefficient, also expressed in hours) were initially estimated using relationships between Tc, R, and main channel length (L) developed in the 1994 Mead & Hunt study. The 1994 unit hydrograph relationships were based on analysis of flood hydrographs at USGS gages on the South Branch of the Tobacco River and on the Rifle River, a gaged basin bordering the Tittabawassee River to the northeast. The 1994 approach related both Tc and R to maximum channel length in the subbasin, and defined all of the model subbasins as analogous either to the Rifle River the South Branch of the Tobacco River, based on land cover and basin morphology.

The 1994 study was conducted using limited calibration data. Although the 1994 relationships were used as the basis for the initial HEC-HMS model setup, the unit hydrograph parameters required extensive adjustment to reproduce the calibration events analyzed in 2021. Ultimately, each subbasin's unit hydrograph parameters Tc and R were adjusted to fit the observed hydrograph shapes in the HEC-HMS model. Unlike the 1994 study, the 2021 calibration did not establish a fixed relationship between Tc and R across multiple subbasins.

Final subbasin unit hydrograph parameters are detailed in Table 10 in a later section of this report.

Hydrologic Loss Functions

Quasi-Distributed Loss Accounting: Rationale and Overview

Soil permeability types in the watershed range from sands with very high saturated hydraulic conductivity (Ksat) to silty clays and hydric soils with very low Ksat values. While Ksat is not the only determinant of loss potential (land cover, slope, and depth to the water table are some other factors) it is a useful baseline value for the constant loss rate when initial moisture deficits are satisfied.

When very high and very low Ksat values are present in the same subbasin, the effective average constant loss rate is mathematically related to the peak rainfall rate. As a very simple example, if 30 percent of a basin has a Ksat of zero and the remaining 70 percent has a Ksat of 6 inches per hour, for all precipitation events up to 6 inches per hour, no single-valued loss rate would apply. Instead, the calculated basin-averaged loss rate would be 70 percent of the rainfall rate. The calibrated loss rate for a 2-inch-per-hour storm (around a 10 year event in Michigan) will be 1.4 inches per hour, but the appropriate average loss rate for a 6-inch-per-hour storm (typical of a Probable Maximum Storm) would be 4.2 inches per hour. In a lumped hydrologic model, a solution to this is to further divide subbasins into a manageable number of loss (or runoff potential) classes.

For this study, soil hydrologic characteristics were classified in a spatial analysis by Spicer Group, consisting of overlaying the USDA SSURGO database for Gladwin, Midland, Roscommon, Clare, Bay, Ogemaw, Arenac, and Isabella Counties on the subbasin boundaries. Hydrologic losses were modeled in a quasi-distributed manner by modeling each subbasin as three parallel sub-subbasins, one representing high permeability soils, one representing moderately permeable soils, and one representing low permeability soils. All three sub-subbasins within a given subbasin have identical unit hydrograph parameters and discharge to the same point in the model. Zero-permeability areas were also treated separately by assigning a fixed impervious percentage to the low- permeability sub-subbasin. In this report we use "permeability" loosely to mean the overall hydrologic loss potential, in inches per hour, of a given spatial soil unit, which becomes the HEC-HMS "constant loss rate." Ksat refers to the saturated hydraulic conductivity listed in SSURGO, which varies by depth for a given spatial soil unit and is also expressed as a range at each depth, based on soil texture. These ranges are generally logarithmic. When expressed in inches per hour they have values such as 0.06–0.2 inch per hour; 2–6 inches per hour, and 6-20 inches per hour. "Soil unit" refers to the map units in the SSURGO database, which may be a single soil type (e.g. Roscommon fine sand) or an association (e.g. Roscommon-Brevort-Timakwa).

Initial Assignment of Loss Rates

Based on the spatial analysis performed by Spicer Group, soil units in each subbasin were tabulated according to area covered and the minimum of the listed Ksat range for the least permeable layer in the top 60 inches of the soil column. This typically gave 10-15 Ksat classes based on the minimum published Ksat in each soil unit (see Exhibit 3). These were grouped into four more general categories as described below. (Note that gaps between Ksat classes represent real gaps in the ranges used in the SSURGO database.)

Zero Losses: Soils with a minimum-of-range Ksat of 0.0 inch per hour to 0.016 inch per hour in the top 60 inches of the soil column. These were initially assigned a HEC-HMS constant loss rate of zero and grouped with the low-permeability loss classes by adding them to the low-permeability sub-subbasins as an impervious percentage. The assigned impervious percentage did not change as the result of calibration.

Low Permeability: Soils with minimum-of-range Ksat values from 0.06 inch per hour to 0.2 inch per hour. These were initially assigned a constant loss rate equal to the minimum loss rate in the top 60 inches of the soil column, area-averaged over all soil units identified as being in the “low permeability” range in the sub-subbasin. This initial value ranged from 0.12 inch/hour to 0.19 inch/hour. In calibration, these values ranged from 0.03 to 0.55 inches per hour, depending on the event and the subbasin.

Moderate Permeability: Soils with minimum-of-range Ksat values ranging from 0.6 inch per hour to 2.0 inches per hour. The initially assigned, area-averaged moderate-permeability Ksat ranged from 1.32 inch per hour to 1.93 inch per hour, depending on the subbasin. These loss rates exceed the maximum hourly precipitation rates used in model calibration and therefore could not possibly be calibrated upward. The calibration (described in a later section) did not justify a downward change, so these loss rates remained at the initial values in the final design flood model runs. As computed by the HEC-HMS model, these soil classes do not generate runoff during the calibration events. However, some do generate runoff during the intense local-storm events modeled, consistent with the concept that watersheds have a “variable contributing area” which expands as precipitation becomes more intense.

High Permeability: Soils with minimum-of-range Ksat values of 6 inches per hour (or 5.95 inches per hour as reported for some SSURGO groups). These were assigned a loss rate of 5.95 - 6 inches per hour, and showed no computed runoff during either the calibration events or the PMF.

Table 5 lists the area in each subbasin assigned to the four loss classes listed above. The small subbasins representing Secord Lake and Wixom Lake were considered 100 percent impervious.

Table 5: Constant Loss Rate Distribution by Subbasin

Subbasin No.	Total Area (square miles)	Area of Subbasin Assigned to Loss Class (square miles)			
		Zero Permeability	Low Permeability	Moderate Permeability	High Permeability
1	129.1	6.4	63.2	33.8	25.6
2	34.4	1.9	21.3	9.3	1.8
3a	117.2	10.5	56.9	36.2	13.5
3b	136.9	23.2	70.7	37.8	5.3
3c	153.3	35.4	69.8	44.6	3.5
4	77.4	6.4	49.2	12.0	9.8
5a	77.9	1.8	23.1	2.6	50.4
5b	57.4	6.8	23.5	5.0	22.1
5c	19.0	0.7	8.7	0.5	9.1
6	50.5	20.7	8.4	13.8	7.7
7	40.8	9.0	17.4	6.5	7.9
8	46.3	1.5	18.5	19.5	6.8
Secord and Wixom Lakes	4.6	4.6	-	-	-
Entire Basin at Sanford Dam	945	129	431	222	162

The methodology described above does not include assigning a zero loss rate to all areas classified as wetlands, as was done in the 1994 study. Preliminary calibration runs found this approach to be excessively conservative, failing to account for the substantial storage and slow infiltration of precipitation in wetland forests.

No initial losses were modeled in either the calibration runs or the PMF modeling.

Channel/Floodplain Routing

The Muskingum-Cunge routing option in the HEC-HMS model was used to translate calculated flood hydrographs through rivers and floodplains, from one computation point downstream to another. The channel and floodplain were represented by a trapezoidal cross section and a length, slope and Manning's "n" value representative of the routing reach. Length and slope were measured in ArcGIS and Manning's "n" values initially assigned based on watershed imagery. Routing parameters were adjusted within physically realistic constraints during model calibration, but were not varied between calibration events as discussed below.

HEC-HMS Model Calibration

The HEC-HMS model was calibrated to four historic flood events, summarized in Table 6 below. The calibration events were chosen primarily on the basis of the estimated peak outflow from Edenville Dam, because that location offered the longest and most consistent streamflow record of any in the watershed. As shown in Exhibit 2, the calibration events represented the four largest outflow events in the record at Edenville Dam since 1960. Hourly, spatially distributed precipitation data for the calibration events were developed from rain gauge and NEXRAD data by AWA as detailed in a separate report (AWA, 2021).

The 1996, 2014, and 2017 calibration compared HEC-HMS modeled reservoir inflows to the back-routed inflow series at the dams, because the partial gate openings during those floods were too complex to represent as a single-valued rating curve in HEC-HMS. In 2020, however, the operators' logs and interview indicated that the spillway gates were fully open starting the day before the peak, so the single-valued, full-open gate rating curve used in the HEC-HMS model was applicable to the calibration flows. Therefore, the 2020 calibration was judged by comparing the model's calculated outflows to the outflows indicated by the log records.

Table 6: HEC-HMS Model Calibration Events

Dates of Event	Estimated Peak Outflow at Edenville Dam (cfs)	Estimated Basin Total Rainfall (inches)	Available Streamflow Data Locations
June 17-19, 1996	12,500	3.1	Secord, Edenville, So. Branch USGS Gage
April 12-14, 2014	14,900	4.4	Secord, Smallwood, Edenville, So. Branch USGS gage
June 22-23, 2017	10,900	3.5	Secord, Smallwood, Edenville, So. Branch USGS gage, Tobacco R. USGS Gage
May 18-19, 2020	19,100 *(prior to dam failure)*	4.3	Secord, Smallwood, Edenville, Sanford, So. Branch USGS gage, Tobacco R. USGS Gage

Model Calibration Procedure

For each storm and flood event listed in Table 6, AWA provided hourly rainfall sequences for each of the model's 12 subbasins. Model parameters including the Clark unit hydrograph time of concentration (Tc), Clark storage coefficient (R), and constant loss rate (LU) for the low- permeability soil classes were calibrated individually for each subbasin and each storm. Calibration of the intermediate- and high-permeability soil class loss rates was not possible, because no hourly rainfall increment exceeded the initially assigned loss rate; and all of the observed flood volumes could be reproduced by adjustment of only the low-permeability loss rates. Referring to Table 4, this meant that the loss rate for 431 square miles, or approximately 46 percent of the watershed at Sanford, was calibrated and the remainder of the watershed area assumed not to contribute direct runoff during calibration events.

One set of Muskingum-Cunge routing parameters was also calibrated across all four events. Segment lengths, slopes, and equivalent cross sections were adjusted slightly but remained consistent with map values. Calibrated Manning's "n" values were generally 0.04 and 0.05, with one value of 0.03 assigned to a reach that is partially impounded by Smallwood Dam.

This process resulted in four different sets of calibrated of Tc, R, and low-permeability LU parameters, which in some cases differed significantly between storms. This is a realistic outcome for watersheds whose hydrologic response is highly sensitive to antecedent condition. The process for combining the calibrated parameters for the final design-flood models is described in a later section of this report.

Calibration proceeded from upstream to downstream. For example (referring to Exhibit 1), Subbasin 3c's model parameters were calibrated to produce the observed hydrograph at the South Branch of the Tobacco gaging station, then left unchanged while Subbasins 3a and 3b were calibrated to reproduce, in combination with 3c, the observed hydrograph at the Tobacco River gaging station. Likewise, the inflow hydrograph to Secord Dam – the most upstream of the four – was estimated by back-routing from the

Boyce operating records; and then Subbasins 1 and 8 were calibrated to reproduce that hydrograph as closely as reasonably achievable. Because of the uncertainty involved in back-routing an hourly hydrograph in a large impoundment and the fact that HEC-HMS's single-valued spillway rating curve cannot replicate time-dependent spillway gate openings, an acceptably calibrated inflow hydrograph to Secord Lake did not always produce an equally well calibrated outflow hydrograph. Therefore, once the above-Secord calibration was considered satisfactory, the outflow from Secord was reset to the observed outflow sequence so that the upper subbasins were computationally isolated and errors introduced by imprecise calibration did not impact the calibration of the more downstream subbasins. The same approach was used at Smallwood when records were available and the single-valued spillway rating curve did not accurately route the modeled inflow hydrograph.

Calibrated Model Parameters

Table 7 lists the Tc, R, and low-permeability LU parameters calibrated for each storm and subbasin (Tc, R in hours; LU in inches per hour).

Table 7: Calibrated HEC-HMS Model Parameters for Four Storms

	1996			2014			2017			2020		
Sub-basin	Tc	R	LU (low)	Tc	R	LU (low)	Tc	R	LU (low)	Tc	R	LU (low)
1	12	15	0.09	33	21	0.05	7	16	0.15	13	16	0.05
2	7	10	0.09	8	10	0.11	6	12	0.13	5	9	0.03
3a	10	14	0.1	18	23	0.07	17	23	0.16	9	16	0.06
3b	16	20	0.1	22	28	0.07	22	33	0.16	14	24	0.06
3c	22	50	0.11	30	20	0.2	18	48	0.55	20	34	0.12
4	11	15	0.09	10	12	0.11	6	16	0.14	7	14	0.025
5a	22	18	0.08	32	21	0.05	16	32	0.2	17	12	0.05
5b	10	7	0.08	16	12	0.05	6	12	0.2	8	5	0.05
5c	5	3	0.09	6	4	0.05	4	5	0.2	5	3	0.05
6	6	8	0.09	8	11	0.05	4	7	0.2	4	6	0.05
7	17	13	0.14	17	13	0.14	17	13	0.14	17	13	0.14
8	7	12	0.09	17	17	0.06	4	8	0.15	6	10	0.05

For many of the model subbasins, the most critical calibrated parameters (the lowest values of Tc, R, and LU) were concentrated in the May 2020 event. This is consistent with the observation that the size of the May 2020 flood was somewhat anomalous. The flood itself appeared to be the largest by far recorded at Edenville since 1929, whereas the driving rainfall was not a record-setting event.

Exhibit 4 shows calibration plots for the 1996, 2014, 2017, and 2020 events.

Model Parameter Weighting Strategy

Previous analyses in 2020 had sought to identify a single set of calibrated model parameters that produced a reasonable collective fit to all events. This proved very difficult and resulted in calibrations that did not reproduce any individual event closely. YSJ International and Ayres concurred that a more logical approach would be to achieve as close as possible a fit to each observed event, recognizing that significant differences between calibrations would emerge. Then, representative design flood parameters would be assigned by choosing a weighting scheme that incorporated all four events but favored certain characteristics of each calibration event.

The weighting approach for the four calibrated parameter sets was to assign a score from 1 to 4 for each of two characteristics, sum the two scores, and weight the calibrated parameters based on the event scores. For the PMF and half-PMF model, these two characteristics were (a) confidence in the calibration, including data quantity, quality, and closeness of fit to the observed hydrographs; and (b) magnitude of the event. Flood magnitude was made a factor in choosing PMF model parameters to reflect the understanding that the PMF results from an exceptionally severe combination of meteorological and hydrologic conditions. Using this weighting scheme, the total number of points allotted to all four events is 20, and any event's set of calibrated parameters could receive a minimum weight of 10 percent ((1+1)/20) and a maximum weight of 40 percent ((4+4)/20).

For the confidence score, AWA staff were queried for their ranking of the reliability of the calibration precipitation data; Ayres ranked the hydrologic data and calibration fit; and an average of the AWA and Ayres scores was taken. Table 8 summarizes the process of developing weighting scores for the PMF model. The highest score (4) refers to the top-ranked event in either the magnitude or confidence columns.

Table 8: Calibration Event Weighting Process for PMF/Half PMF Model

Year of Event	Peak Edenville Flow (cfs)	Magni-tude Score	Confidence Score (rain, flow data, model fit combined)	Comments on Confidence Score	Sum of Scores	Weight = sum of scores / 20 total points
1996	12,500	2	1	1 USGS gage, dam data only at Edenville and Secord, poor timing fit at Secord. Precip: "one main precipitation pulse, decent radar coverage, fewer stations".	3	0.15
2014	14,900	3	2.5	1 USGS gage, Boyce data at 3 dams and good fit at Edenville, less conclusive at other 2	5.5	0.275
2017	10,900	1	2.5	2 USGS gages, Boyce data available at 3 dams but timing not well calibrated. Precip: "two precipitation pulses, good radar coverage, good station distribution and timing"	3.5	0.175
2020	19,100	4	4	Two USGS gages, data from all 4 dams, good fit to all. Precip: "one main precipitation pulse, good radar coverage, good station distribution and timing, and had most stations"	8	0.4

The confidence scores listed in Table 8 were also used to weight calibration events for input to the model for converting frequency-based rainstorms to frequency-based floods. The frequency-based flood model parameters, however, were not weighted for the calibration event magnitude, as this would favor the effects of severe antecedent watershed conditions over more typical conditions. Instead, the calibration events were given "representativeness" scores based on how closely the observed flood peak at Edenville matched the estimated flow with a return period the same as the precipitation event. For example, the event with the best "representativeness" was the 1996 flood, in which a 15-year precipitation event produced a flood that was just 3.7% smaller than the statistically estimated 15-year flood. The 2017 flood was the least "representative," with a 23 percent difference between the observed peak flow and the flow matching the storm's 26-year return period. Table 9 summarizes this weighting process.

Table 9: Calibration Event Weighting Process for Frequency-Based Flood Model

Year	Precip return period (years)	Edenville outflow with same return period based on HEC-SSP	Actual Edenville outflow (cfs)	Percent Difference	"Represent-ativeness" Match Score	Confidence Score from Table 7	Sum of Scores	Weight
1996	15	13,002	12,521	-3.7	4	1	5	0.25
2014	65	15,936	14,897	-6.5	3	2.5	5.5	0.275
2017	26	14,196	10,941	-22.9	1	2.5	3.5	0.175
2020	70	16,074	19,100	18.8	2	4	6	0.3

In the end, the two sets of weights did not differ greatly, with the main difference being that the 2020 event and the 1996 event were more evenly weighted for the frequency-based flood model than for the PMF model.

Summary of Calibrated Model Parameters

Table 10 lists the assigned subbasin parameters Tc, R, and low-permeability LU for the two design flood models, after the calibration and weighting process was complete. Other loss-related parameters (LU for moderate and high-permeability soils, percent impervious) were not adjusted from the values initially assigned. The two models provided to be very similar, with a slightly slower response time (Tc) and higher low-permeability loss rates (LU) on some of the subbasins for the flood frequency model.

Table 10: HEC-HMS Model Parameters for Design Flood Models after Calibration and Weighting

	PMF/Half PMF Model			AEP (Return Period) Based Model		
Subbasin	Tc	R	LU (low)	Tc	R	LU (low)
1	17	17	0.07	17	17	0.08
2	6	10	0.08	7	10	0.08
3a	13	19	0.09	13	19	0.09
3b	18	26	0.09	18	26	0.09
3c	23	35	0.22	23	37	0.22
4	8	14	0.08	9	14	0.08
5a	22	19	0.08	22	19	0.08
5b	10	8	0.08	10	9	0.08
5c	5	4	0.08	5	4	0.09
6	5	8	0.08	6	8	0.09
7	17	13	0.14	17	13	0.14
8	9	12	0.08	9	12	0.08

HEC-HMS Model Verification

To confirm the reasonable performance of the design flood models, each was tested against a flood occurring in July, 1957. Prior to the 2020 flood, this was the flood of record at the USGS Tobacco River stream gage, peaking at 7,860 cfs. At the Edenville spillway, the 1957 flood peaked at an estimated flow of 11,100 cfs. Flow data were available for the Edenville and Secord dams, consisting of hourly gate opening and pool height records for July 8-10, 1957. Daily flow data at the USGS Tobacco River gage (drainage area 487 square miles) were available, as well as a peak flow of 7,860 cfs recorded on July 9.

Hourly precipitation data were available from one NOAA rain gage inside the basin at Beaverton; and two outside the northern divide at Roscommon and Rose City. Daily precipitation data were also available at Gladwin and Harrison inside the watershed, and at Houghton Lake, Mt. Pleasant, West Branch, and Standish outside of the watershed. A subbasin map showing hourly and daily precipitation gages and Thiessen polygons used to estimate subbasin rainfall totals is provided in Exhibit 5.

Exhibit 5 also shows the 1957 observed and calculated hydrographs using the PMF and AEP models. The two HEC-HMS model parameter sets produced nearly identical estimates of the runoff hydrographs, with the PMF model generating slightly higher peaks and volumes. At two locations (the Tobacco River gage and inflow to Wixom Lake) the models overestimated the observed hydrograph. At the backrouted Secord inflow, the models underestimated the observed inflows. The Secord inflow calculation exhibits considerable hour-to-hour instability, but the model performance can still be gaged by a comparison to overall volume and general shape. In general, the model timing was appropriate. These results did not indicate a systematic deficiency in the calibrated HMS models, and the models were accepted for use in estimating design floods.

Design Storm Development

The design storms evaluated for each FLTF dam included the Probable Maximum Storm (the storm resulting from the PMP for a certain duration, location, and basin area), the half PMP storm, and return period-based storms ranging from the 100-year event to the 5,000-year event. The development of the storm depth-area-duration relationships and temporal patterns is discussed in a separate report by Applied Weather Associates (AWA, 2021). AWA also provided subbasin-by-subbasin precipitation sequences for the PMP, half-PMP, and frequency-based storms.

All of the storms modeled in the development of the design floods were assumed to be warm season (snow-free) events. All of the calibration and validation events, in addition to an April 1959 flood – which comprise the largest 6 events recorded at Edenville since 1950 - occurred in snow-free conditions, based on NOAA records at Gladwin. Furthermore, the reasoning used in 2020 comparing potential runoff from the cool season PMP to the calculated warm-season runoff is still appropriate: that the 1994 study showed the warm season storms controlling; PMP precipitation estimates are similar to those used in 1994; and the 2021 model has far more conservative warm-season loss rates than the 1994 model.

The AWA study provides a 72-hour “synthetic storm” temporal distribution, a single-peaked distribution in which approximately 85 percent of the total storm depth falls during the middle third of the event. The 72-hour synthetic storm temporal distribution is based on historic storm analyses and was adopted for all of the 72-hour design storms used in this analysis. For local storms, AWA provided a 24-hour synthetic distribution that is “front-loaded” with almost all of the rainfall occurring in the first 6 hours.

<u>Note:</u> a “local storm” is an intense, thunderstorm-type event and is defined as having has a maximum duration of 24 hours and an area of 500 square miles or less. Because of the drainage area limitation, local storms are candidate design storms only for Secord Dam and Smallwood Dam. “General storms” are longer in duration and less intense and can occur over any drainage area. General storms were investigated for all four dams but controlled only at Edenville and Sanford.

Probable Maximum Storm

Table 11 summarizes the depth-duration characteristics of the Probable Maximum Storm (PMS) for each dam. Unlike the 1994 and 2020 analyses, the PMS was not analyzed as a hypothetical elliptical storm shape with the most intense rain at the centroid. Instead, AWA’s analysis indicated a PMP depth at each analytical grid point in the basin based on spatial analysis of historic storms. In general, AWA’ s study shows PMP increasing from southwest to northeast across the basin. The point PMP and maximum basin-average precipitation also vary with storm area size; the average PMP depth over a 200-square mile area will be larger than the average PMP over a 1,000-square mile area centered at the same location.

Cumulative basin-averaged precipitation curves for the PMP and half-PMP are plotted in Exhibit 6. The precipitation series were not identical across all model subbasins due to the spatial variation in PMP depths over the upper Tittabawassee watershed. Individual subbasin temporal patterns are contained in the HEC-HMS precipitation time series.

Table 11: Basin Average Precipitation Depths and Durations for the Probable Maximum Storm

Duration	**Secord (177 sq. mi.)**	**Smallwood (289 sq. mi.)**	**Edenville (904 sq. mi.)**	**Sanford (945 sq. mi.)**
24-hr Local Storms	*Inches of Precipitation*			
1 hour	4.0	3.8		
6 hour	10.5	10.0		
24 hour	15.2	14.4		
72-hr General Storms	*Inches of Precipitation*			
1 hour	1.3	1.3	1.3	1.3
6 hour	6.5	6.5	6.6	6.6
24 hour	14.2	14.4	14.4	14.4
72 hour	16.9	17.2	17.2	17.2

Annual Exceedance Probability-Based Storms

Annual exceedance probability (AEP)- or return-period based storms, including the 100-year, 200-year, 500-year, 1,000-year and 5,000-year storms, were also considered as both local (24-hour) or general (72-hour) events. The depth of rain reported by AWA for a given return period and storm area varied by less than one percent between the model subbasins, so the total storm depths were calculated as a single value averaged over each dam’s drainage basin. The synthetic 24-hour or 72-hour temporal distribution was then applied to each design event depth. As in the case of the PMF, the local storms created larger inflows and outflows at Secord and Smallwood than general storms. Only general storms were analyzed for Edenville and Sanford because of the drainage area size at those projects.

Table 12 summarizes the local and general storm depths associated with each dam and return period. Cumulative exceedance-probability-based precipitation plots for the critical design storms are included in Exhibit 6.

Table 12: Basin Average Precipitation Depths for AEP- Based Storms

Annual Exceedance Probability (Return Period)	**Secord (177 sq. mi.)**	**Smallwood (289 sq. mi.)**	**Edenville (904 sq. mi.)**	**Sanford (945 sq. mi.)**
24-hr Local Storms	*Inches of Precipitation*			
.01 (100-year)	4.7	4.5		
.005 (200-year)	5.3	5.1		
.002 (500-year)	6.3	6.0		
.001 (1,000-year)	7.0	6.8		
.0002 (5,000-year)	9.2	8.8		
72-hr General Storms	*Inches of Precipitation*			
.01 (100-year)	5.7	5.5	5.0	5.0
.005 (200-year)	6.4	6.3	5.7	5.7
.002 (500-year)	7.6	7.4	6.7	6.7
.001 (1,000-year)	8.5	8.3	7.6	7.5
.0002 (5,000-year)	10.9	10.7	9.8	9.8

Design Flood Inflows and Outflows

Probable Maximum Flood and “Half PMF”

The precipitation values presented in Table 11 and Exhibit 6 were applied to the final PMF-weighted HEC-HMS model to develop PMF and half-PMF inflow hydrographs for Secord, Smallwood, Edenville, and Sanford Dams. Computed PMF and half-PMF hydrographs are plotted in Exhibit 7. Table 13 summarizes calculated peak inflows and outflows for the PMF and “half PMF” (the flood resulting from half of the PMP). Note that all of the peak outflows, and all of the inflows with the exception of Secord’s, are premised on the spillway discharge rating curves that existed prior to the May 2020 flooding. Modifications to the spillways and the storage-discharge relationships at the dams will result in slightly different flood flows downstream of those dams. Furthermore, some of the modeled floods overtop the dams by a significant amount. The overtopping discharge calculations used were approximate and did not account for erosion of the embankments or abutments, emergency protection measures such as sandbags, or other processes that might take place during an actual overtopping flood. Therefore, Table 13 notes when overtopping occurs but does not specify a peak elevation.

Table 13: Calculated PMF and "Half PMF" Inflows and Outflows at Tittabawassee River Dams

Dam	Flood Event	Peak Inflow (cfs)	Peak outflow (cfs)	Freeboard (ft)
Secord (local storms)	PMF	29,200	28,600	overtops
	"Half PMF"	12,700	8,600	1.0 (flow occurs over east rim)
Smallwood (local storms)	PMF	48,200	47,700	overtops
	"Half PMF"	15,600	15,500	3.1
Edenville (general storms)	PMF	113,400	111,400	overtops
	"Half PMF"	44,600	43,400	overtops
Sanford (general storms)	PMF	117,200	114,400	overtops
	"Half PMF"	44,900	43,300	overtops

AEP/Return Period-Based Floods

Table 14 lists the peak inflows and outflows at the four dams for floods computed to result from the 100-year through 5,000-year storms, as presented in Table 12 and Exhibit 6. The flood hydrographs were developed using the HEC-HMS model weighted for "representative" AEP events. Nevertheless, users of these estimates should recognize that it is a simplification to assume that a precipitation event having a given AEP produces a flood having the same AEP.

AEP flood inflow and outflow hydrographs for the 100-year, 1,000-year, and 5,000 year events are plotted in Exhibit 7. The estimated PMF, half-PMF, and inflow and outflow frequency are plotted together for each dam in Exhibit 8.

Table 14: Calculated AEP/Return Period Inflows and Outflows at Tittabawassee River Dams

Dam	AEP (Return Period)	Peak Inflow (cfs)	Peak outflow (cfs)	Freeboard (ft)
Secord (local storms)	.01 (100-year)	6,730	5,020	4.9
	.005 (200-year)	7,900	5,670	4.1
	.002 (500-year)	9,710	6,750	2.9
	.001 (1,000-year)	11,300	7,740	1.9
	.0002 (5,000-year)	15,900	12,600	overtops
Smallwood (local storms)	.01 (100-year)	9,020	8,560	7.0
	.005 (200-year)	10,400	10,000	5.2
	.002 (500-year)	12,600	12,400	4.3
	.001 (1,000-year)	14,500	14,300	3.5
	.0002 (5,000-year)	21,200	21,000	1.9
Edenville (general storms)	.01 (100-year)	21,300	18,000	1.8
	.005 (200-year)	25,400	20,400	0.1
	.002 (500-year)	32,100	28,500	overtops
	.001 (1,000-year)	37,400	34,300	overtops
	.0002 (5,000-year)	52,800	51,900	overtops
Sanford (general storms)	.01 (100-year)	18,200	17,900	4.2
	.005 (200-year)	20,700	20,300	3.4
	.002 (500-year)	28,700	27,300	1.4
	.001 (1,000-year)	34,600	33,600	0.4
	.0002 (5,000-year)	53,400	51,700	Overtops

Comparison to Previous Flood Estimates

Previous watershed model studies conducted in 1994 and 2020 focused on determining the PMF only. Table 15 reprises the information from Table 3, with the addition of the present (2021) estimates.

Table 15: Tittabawassee River PMF Estimates – 1994, 2011, 2020, and 2021

Dam	Study Year and Author	PMF Inflow (cfs)	PMF Outflow (cfs)
Secord	1994, Mead & Hunt	27,200	27,100
	2020, Ayres	29,400	28,100
	2021, Ayres/AWA	29,200	28,600
Smallwood	1994, Mead & Hunt	41,000	40,700
	2020, Ayres	41,200	41,000
	2021, Ayres/AWA	48,200	47,700
Edenville	1994, Mead & Hunt	74,400	73,900
	2011, Mill Road Engineering	62,000	62,000
	2020, Ayres	80,900	80,100
	2021, Ayres/AWA	113,400	111,400
Sanford	1994, Mead & Hunt	75,500	73,200
	2020, Ayres	80,600	79,100
	2021, Ayres/AWA	117,200	114,400

With the exception of the Secord PMF estimate, which has changed very little over all iterations of the study, the 2021 values are significantly higher than past estimates. At Edenville and Sanford, the PMF peak flow estimates have increased approximately 40 percent since the 2020 estimates and 50 percent since the 1994 estimates. The increase cannot be attributed to the updated PMP estimates; at the Edenville and Sanford basin sizes, the 2021 AWA PMP analysis yielded generally slightly lower rainfall depths than the EPRI study used in past analyses.

The primary difference between the 1994, 2020, and 2021 modeling efforts was in the amount and quality of calibration data. The 1994 study had no storm or flood data for direct model calibration. The 2020 analysis used two events, occurring in 2014 and 2017, and pre-dated the May 2020 storm and flood, which highlighted the role of critical antecedent basin conditions in generating high flood flows. The 2021 study added information from the 2020 event (and weighted it relatively heavily) and also utilized the 1996 calibration event for the first time. The result was a significantly more critical hydrologic loss rate distribution after the 2021 calibration. In the 2021 models, 50 percent of the overall basin area was assigned a loss rate of 0.1 inch per hour or less. In both the 1994 and 2020 models, the 50-percentile point in the loss rate distribution was 0.35 inch per hour.

The AEP-based flood estimates at Edenville can also be compared to the statistical estimates derived from the historic dam outflow record and presented in Figure 1 of this report. Figure 2 shows a segment of the HEC-SSP frequency curves, the largest nine Edenville outflow peaks, and the flood frequency curve estimated with the HEC-HMS model. The HEC-HMS model tracks the HEC-SSP calculated curve fairly closely up to the 200-year event, and is within the 95 percent confidence interval up to the 300 year event. Above the 300 year event, the HEC-HMS curve departs upward from the statistical estimate. However, the 2021 event (the highest event in the observed series) also plots close to the upper 95 percent confidence bound from HEC-SSP, and the five highest outflows in the annual peak series all plot above the SSP estimated curve. Furthermore, the upward inflection in the HEC-HMS curve occurs approximately at the point of overtopping at Edenville Dam (20,700 cfs) – the point above which storage in Wixom Lake would cease to affect outflows.

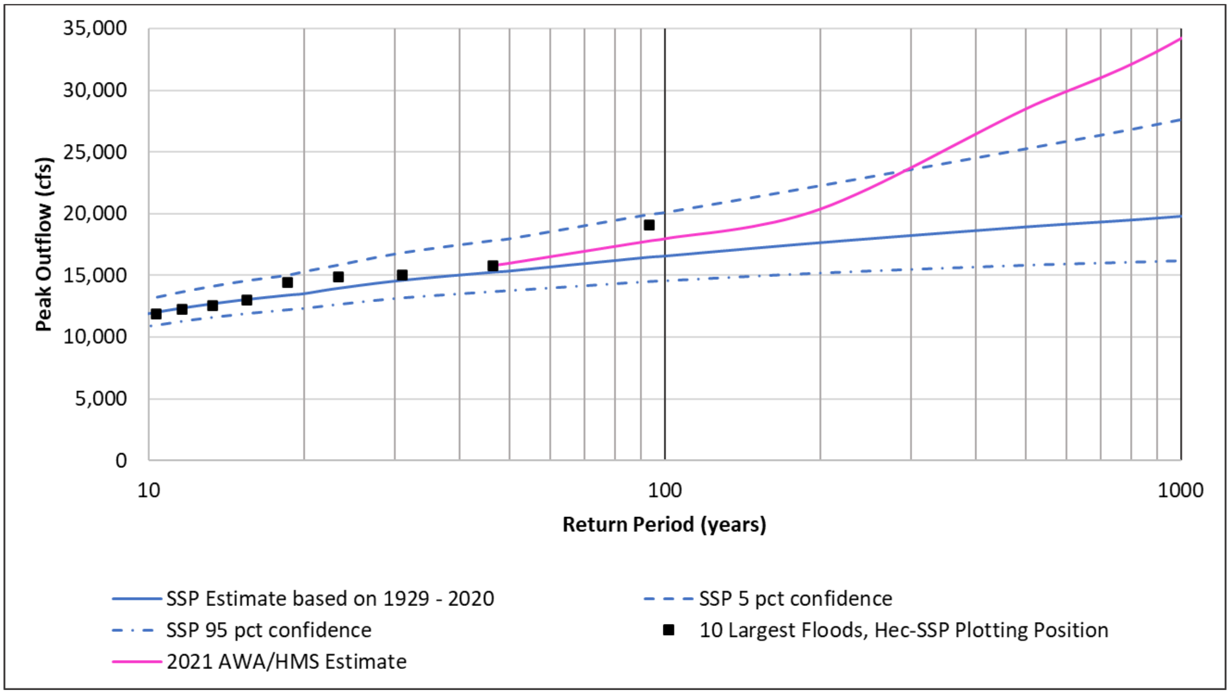


Figure 2: Estimated Return Periods for Edenville Dam Outflows: HEC-HMS, HEC-SSP, and Largest Observed Spillway Flows

Design Flood Sensitivity Analysis

A HEC-HMS sensitivity analysis was conducted for the Clark unit hydrograph and low-permeability loss rate model parameters. For each model subbasin, the standard deviation among the four calibrated parameters of each type was used as a guide for reasonable variation of the parameters in the sensitivity analysis. Across all model subbasins, the median standard deviations for the calibrated Clark Tc, Clark R, and low-permeability soil loss rates were 0.33, 0.25, and 0.58 respectively. Based on these values, sensitivity analyses were conducted in which Clark Tc and R were varied together by +/- 25 percent, and the low-permeability loss rate by +/- 50 percent. In each sensitivity run, the relevant parameters for all subbasins were changed in the same direction and by the same percentage. Collectively this creates an extreme test, as it is unlikely that a given parameter would be inappropriately – but consistently - assigned across all subbasins.

The sensitivity analysis was run for the PMF and the “half-PMF” inflows at Secord Dam and Edenville Dam. Table 16 shows how the computed inflows responded to variation in the unit hydrograph and loss parameters. Note that in each case, the entries headed “low estimate” and “high estimate” actually result from higher and lower values, respectively, of the parameters in question. In other words, a higher loss rate, Tc, and/or R value results in a lower flow estimate, and vice versa.

Table 16: Sensitivity Analysis for Tc and R, Lu (low permeability)

Parameter Varied	Flood Event	Peak Inflow to Secord Lake (cfs)			Peak Inflow to Wixom Lake (Edenville Dam) (cfs)		
		Low estimate	Base case	High estimate	Low estimate	Base case	High estimate
Tc, R (+/- 25%)	PMF	23,200 (-21%)	29,200	36,500 (+25%)	92,300 (-19%)	113,400	136,300 (+20%)
	Half PMF	7,500 (-41%)	12,700	16,000 (+26%)	37,200 (-17%)	44,600	51,900 (+16)
LU (low permeability soils) (+/- 50%)	PMF	27,700 (-5%)	29,200	30,000 (+3%)	111,100 (-2%)	113,400	131,000 (+15%)
	Half PMF	8,000 (-37%)	12,700	13,510 (+6%)	40,900 (-8%)	44,600	53,300 (+20%)

The sensitivity analysis gave somewhat mixed results, as shown in Table 15. In general, the model is more sensitive to the unit hydrograph timing parameters than to the low-permeability loss rate. The largest percent change in a computed peak flow cam from increasing the unit hydrograph parameters at Secord by 25 percent, leading to a 41 percent reduction in the peak half-PMF inflow. We interpret this to be because increasing Tc and R reduces the flood peaks roughly proportionally, and at the same time reduces the degree to which the hydrographs arriving from two separate subbasins superimpose upon each other. A similar decrease in the half-PMF came from increasing the low-permeability loss rate by 50 percent. In general, the model sensitivity to loss rate, as a percentage, is related to the magnitude of the hourly rainfall increments. The tested variation in loss rates, as a percentage of the peak hourly rainfall, is very small for the local storm PMF at Secord – a few hundredths of an inch per hour in loss compared to peak hourly rainfalls of 3 to 4 inches. General storms, especially at larger areas, have lower peak precipitation rates but more hours over which to experience the constant loss (see Table 11).

With the exception of the two large reductions mentioned above, varying the tested parameters generally produced a peak-flow change less than or equal to the percent change in the input parameter. As noted above, the model runs tested an extreme situation in which all the model subbasins' loss or timing parameters were shifted simultaneously.

There is no single "correct" model parameter set for the upper Tittabawassee River basin. The parameter-weighting method used to develop the final models acknowledges that the variability in the calibrated parameters represents real variability in hydrologic response. This variability is most likely related to antecedent conditions and the individual storm's temporal and intensity pattern. Considering this and the results of the sensitivity analysis, it is Ayres' opinion that the adopted models provide appropriate estimates of extreme floods.

References

Applied Weather Associates, 2021, *Site-Specific Probable Maximum Precipitation Study For Tittabawassee River Basin, Michigan: Final Report*

GEI Consultants, April 2020, *Technical Memorandum Re: Discharge Rating Curves (Secord, Smallwood, Edenville, and Sanford Projects)*

Electric Power Research Institute/North American Weather Consultants, 1993, *Probable Maximum Precipitation Study for Michigan and Wisconsin,* EPRI TR-101554

Federal Emergency Management Agency, 2013, *Selecting and Accommodating Inflow Design Floods for Dams,* FEMA P-94

Mead & Hunt, 1994, *Probable Maximum Flood Study for Secord, Smallwood, Edenville, and Sanford Hydroelectric Projects, FERC Projects 10809, 10810, 10808, 2785*

Mill Road Engineering, 2011, *Edenville Dam PMF Reanalysis*, cited in Boyce Hydro, 2015, *Edenville Hydro Project Supporting Technical Information.*

Exhibit 1

Upper Tittabawassee River Watershed Map

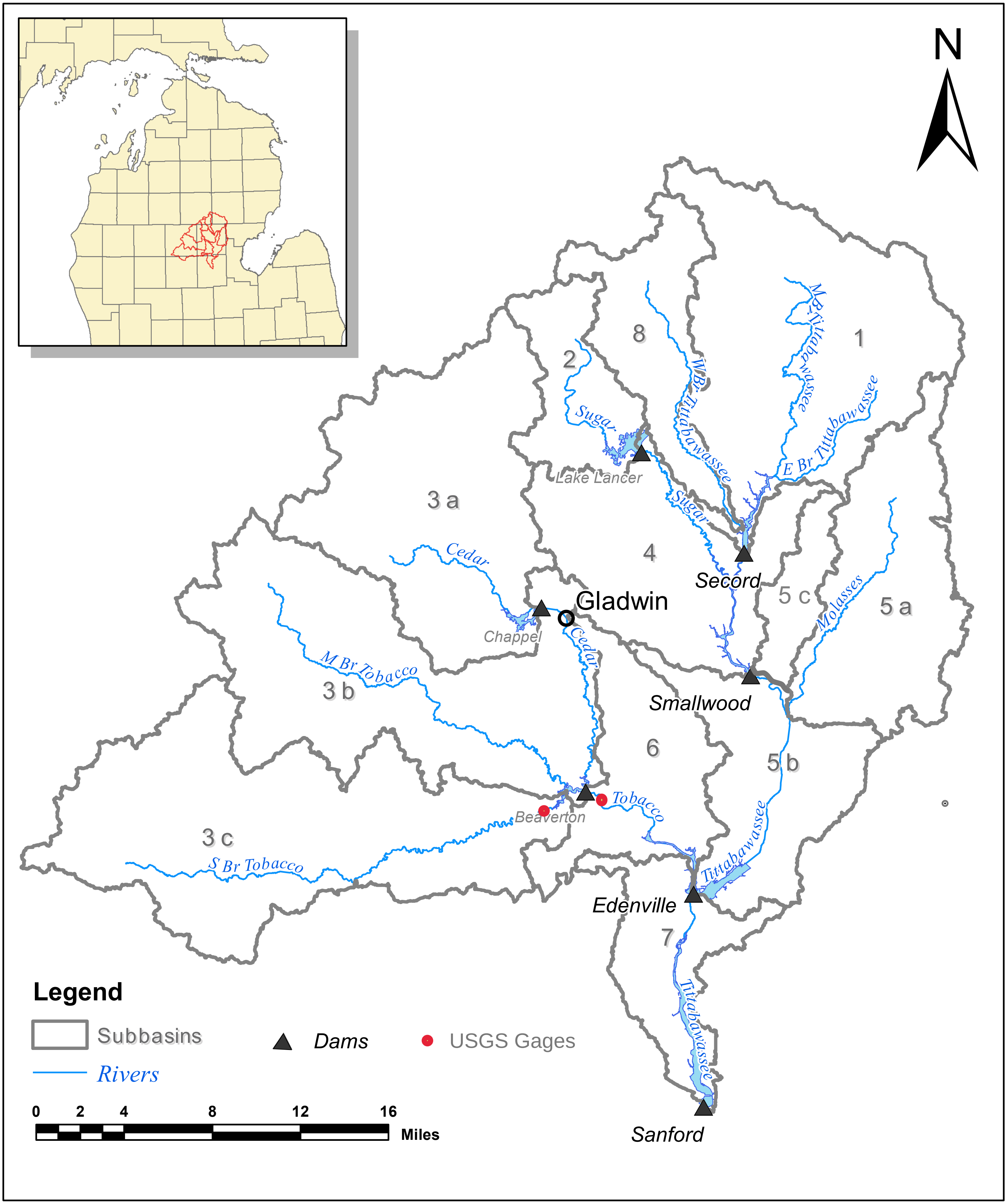
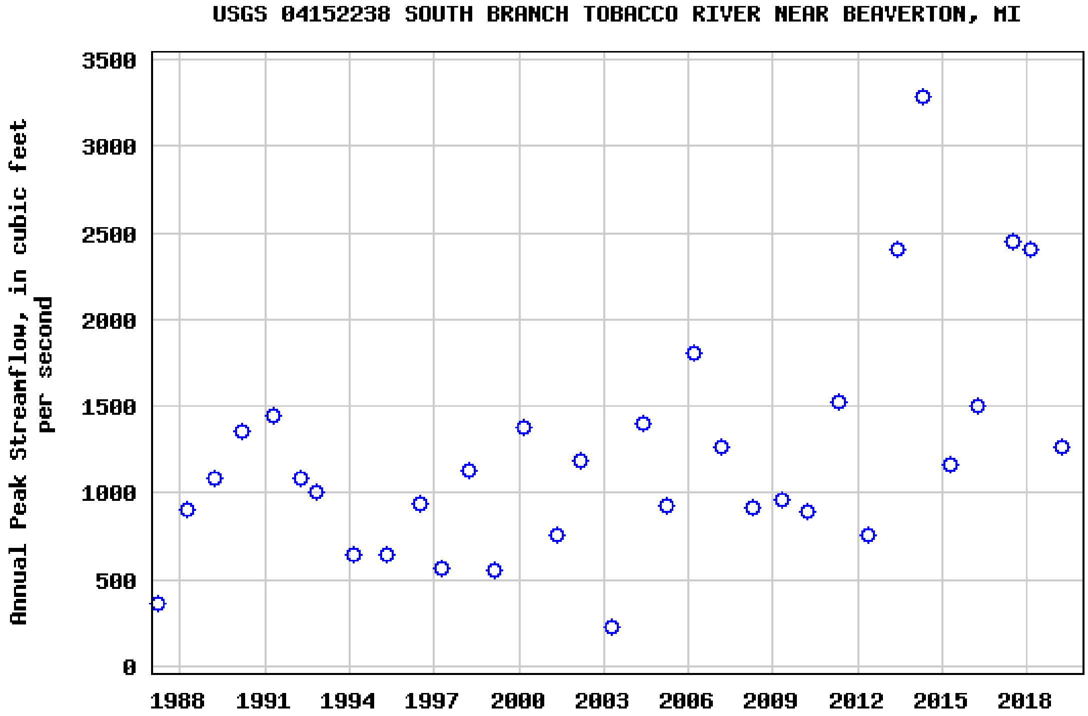


Exhibit 1: Tittabawassee River Watershed
Tittabawassee River Dams
Gladwin and Midland Counties, Michigan
June, 2021

AYRES
RIVER ENGINEERING+
WATER RESOURCES

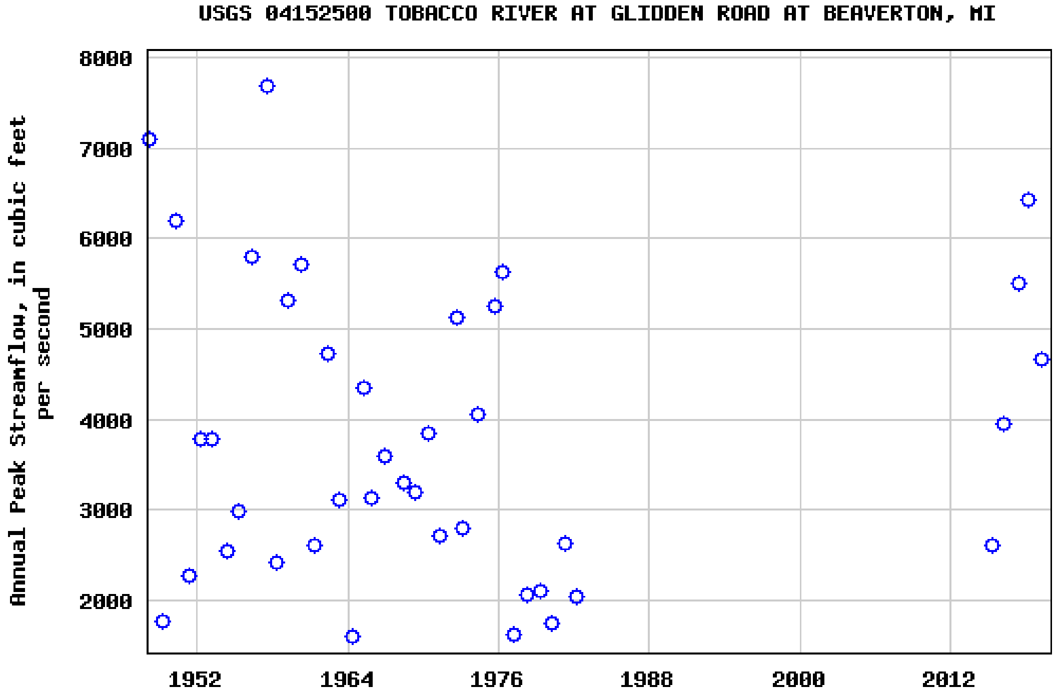
Exhibit 2

Annual Peak Flow Series in the Upper Tittabawassee Watershed



Annual Peak Flows at South Branch Tobacco River Gage: 160 square miles

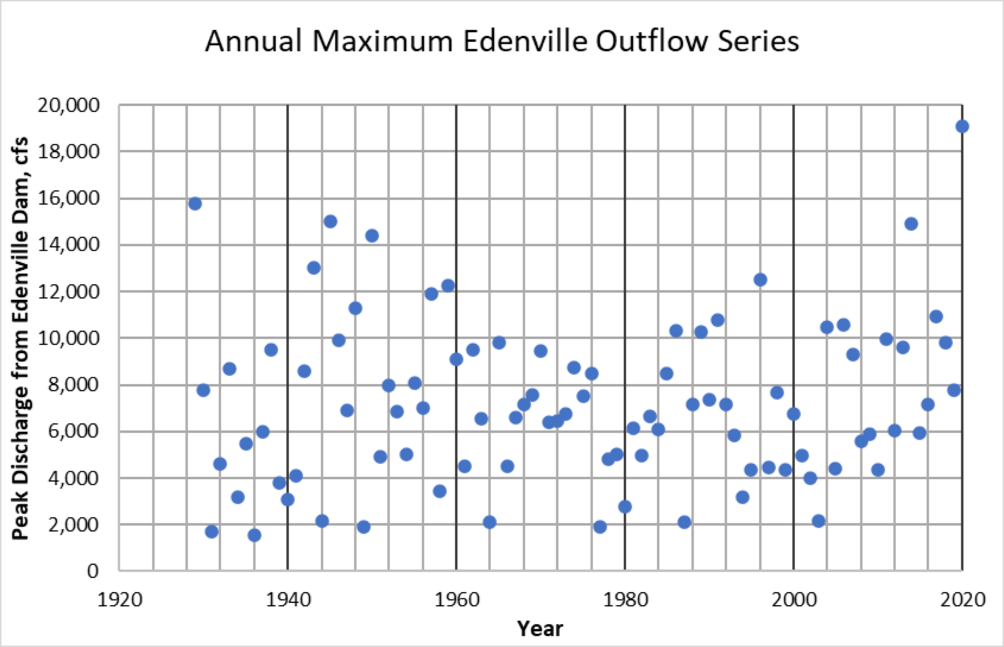
From https://nwis.waterdata.usgs.gov/mi/nwis/peak/?site_no=04152238&agency_cd=USGS



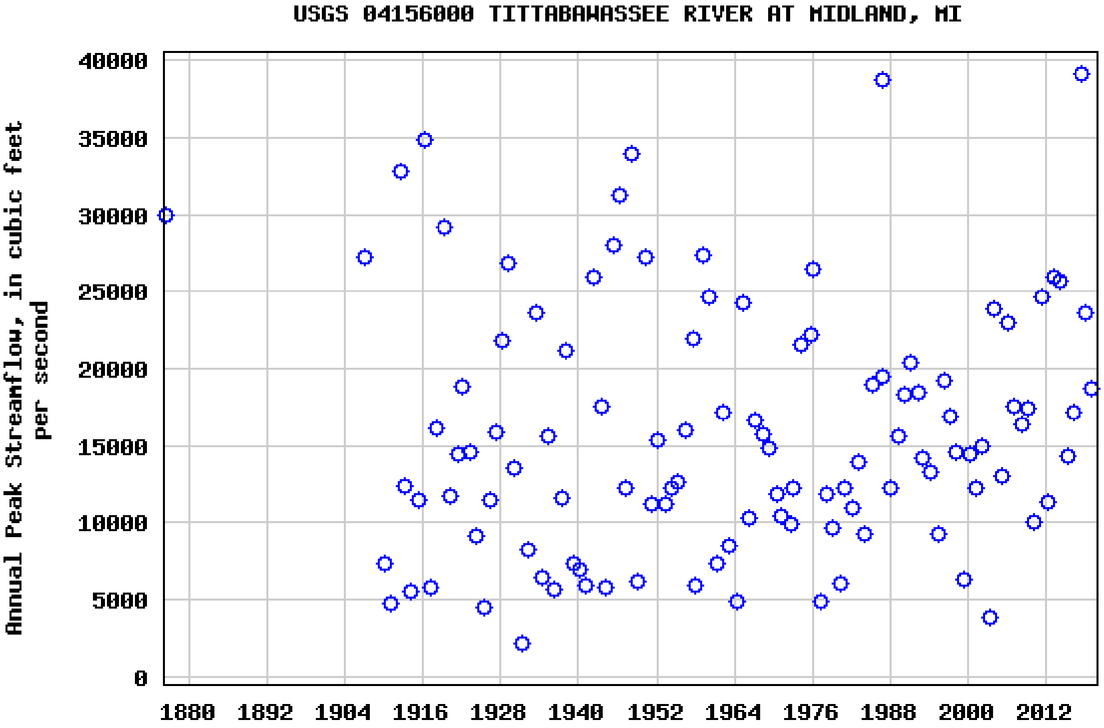
Annual Peak Flows at Tobacco River Gage: 487 square miles

From https://nwis.waterdata.usgs.gov/mi/nwis/peak/?site_no=04152500&agency_cd=USGS

Exhibit 2, Sheet 2



Peak Annual Outflows from Edenville Dam: 904 square miles
(data derived from Boyce Hydro logs)



Annual Peak Flows, Tittabawassee River at Midland Gage: 2,400 square miles, of which 945 square miles are above Sanford Dam
From https://nwis.waterdata.usgs.gov/mi/nwis/peak/?site_no=04156000&agency_cd=USGS

Exhibit 3

Development of Constant Loss Rate Parameters by Soil Class and Subbasin

EXHIBIT 3 Sheet 1

SUBBASIN 1 - SSURGO SOIL DATA SUMMARY

Minimum Permeability (60") (inches/hour)	Percentage		129.1	BASIN AREA	WTD LU (min)
0.000	3.6%	impervious			
0.001	1.3%	5.0%	6.40	sq mi	**use 0**
0.060	19.7%				
0.142	5.6%				
0.198	23.3%	low permeability			
0.200	0.3%	49.0%	63.25	sq mi	**0.14**
0.567	0.8%				
1.417	10.1%				
1.559	2.5%				
1.984	12.7%	mid permeability			
2.000	0.1%	26.2%	33.84	sq mi	**1.68**
5.953	17.6%	high permeability			
6.001	2.2%	19.8%	25.61	sq mi	**5.96**

AREA	**LU**	**PCT IMP**	
69.65	**0.14**	**9.200**	**Low + Zero**
33.84	**1.68**	**0.000**	**Med**
25.61	**5.96**	**0.000**	**High**

129.10 *check total area*

Subbasin area based on 2019 boundaries delineated using LiDAR ground elevation data.
Permeability calculated using 2018 SSURGO soil data.

SUBBASIN 2 - SSURGO SOIL DATA SUMMARY

Minimum Permeability (60") (inches/hour)	Percentage		34.4	BASIN AREA	WTED LU
0.000	5.1%	impervious			
0.001	0.6%	5.7%	1.94	sq mi	**use 0**
0.060	33.2%				
0.142	9.8%				
0.198	9.7%	low permeability			
0.200	9.2%	61.9%	21.31	sq mi	**0.12**
0.567	5.2%				
1.417	10.7%				
1.559	2.3%				
1.984	7.5%	mid permeability			
2.000	1.5%	27.1%	9.32	sq mi	**1.46**
5.953	3.9%	high permeability			
6.001	1.4%	5.3%	1.82	sq mi	**5.97**

AREA	**LU**	**PCT IMP**	
23.26	**0.12**	**9.100**	**Low + Zero**
9.32	**1.46**	**0.000**	**Med**
1.82	**5.97**	**0.000**	**High**

34.40 *check total area*

Subbasin area based on 2019 boundaries delineated using LiDAR ground elevation data.
Permeability calculated using 2018 SSURGO soil data.

EXHIBIT 3 sheet 2

SUBBASIN 3a - SSURGO SOIL DATA SUMMARY

Minimum Permeability (60") (inches/hour)	Percentage			117.2	BASIN AREA	WTD LU (min)
0.000	2.1%	impervious	9.0%	10.51	sq mi	**use 0**
0.001	6.9%					
0.014	0.0%					
0.060	16.9%	low permeability	48.6%	56.91	sq mi	**0.14**
0.142	11.5%					
0.198	19.7%					
0.200	0.4%					
0.567	1.4%	mid permeability	30.9%	36.24	sq mi	**1.52**
1.417	21.3%					
1.559	0.8%					
1.984	6.8%					
2.000	0.6%					
5.953	11.0%	high permeability	11.6%	13.54	sq mi	**5.95**
6.001	0.5%					

AREA	**LU**	**PCT IMP**	
67.42	**0.14**	**15.600**	**Low + Zero**
36.24	**1.52**	**0.000**	**Med**
13.54	**5.95**	**0.000**	**High**

117.20 *check total area*

Subbasin area based on 2019 boundaries delineated using LiDAR ground elevation data.
Permeability calculated using 2018 SSURGO soil data.

SUBBASIN 3b - SSURGO SOIL DATA SUMMARY

Minimum Permeability (60") (inches/hour)	Percentage			136.9	BASIN AREA	WTD LU (min)
0.000	3.2%	impervious	17.0%	23.21	sq mi	**use 0**
0.001	10.1%					
0.014	3.7%					
0.060	18.7%	low permeability	51.6%	70.65	sq mi	**0.13**
0.142	19.3%					
0.198	13.7%					
0.567	1.4%	mid permeability	27.6%	37.75	sq mi	**1.59**
1.417	14.7%					
1.559	1.6%					
1.984	10.0%					
5.953	2.5%	high permeability	3.9%	5.29	sq mi	**5.97**
6.001	1.4%					

AREA	**LU**	**PCT IMP**	
93.86	**0.13**	**24.700**	**Low + Zero**
37.75	**1.59**	**0.000**	**Med**
5.29	**5.97**	**0.000**	**High**

136.90 *check total area*

Subbasin area based on 2019 boundaries delineated using LiDAR ground elevation data.
Permeability calculated using 2018 SSURGO soil data.

EXHIBIT 3, sheet 3

SUBBASIN 3c - SSURGO SOIL DATA SUMMARY

Minimum Permeability (60") (inches/hour)	Percentage			153.3	BASIN AREA	WTD LU (min)
0.000	3.2%					
0.001	17.7%					
0.014	2.1%	impervious				
0.016	0.2%		23.1%	35.39	sq mi	**Use 0**
0.060	14.6%					
0.142	16.3%					
0.198	14.4%	low permeability				
0.200	0.2%		45.5%	69.80	sq mi	**0.13**
0.567	0.4%					
1.417	14.6%					
1.559	0.4%	mid permeability				
1.984	13.6%		29.1%	44.59	sq mi	**1.67**
5.953	2.0%	high permeability				
6.001	0.3%		2.3%	3.52	sq mi	**5.96**

Subbasin area based on 2019 boundaries delineated using LiDAR ground elevation data.
Permeability calculated using 2018 SSURGO soil data.

AREA	**LU**	**PCT IMP**	
105.19	**0.13**	**33.600**	**Low + Zero**
44.59	**1.67**	**0.000**	**Med**
3.52	**5.96**	**0.000**	**High**

153.30 *check total area*

SUBBASIN 4 - SSURGO SOIL DATA SUMMARY

Minimum Permeability (60") (inches/hour)	Percentage			77.4	BASIN AREA	WTD LU (min)
0.000	1.4%					
0.001	6.4%	impervious				
0.014	0.4%		8.3%	6.40	sq mi	**use 0**
0.060	37.1%					
0.142	1.2%	low permeability				
0.198	25.3%		63.5%	49.17	sq mi	**0.12**
0.567	1.1%					
1.417	4.3%					
1.559	0.1%	mid permeability				
1.984	10.1%		15.5%	12.00	sq mi	**1.73**
5.953	11.9%	high permeability				
6.001	0.9%		12.7%	9.83	sq mi	**5.96**

Subbasin area based on 2019 boundaries delineated using LiDAR ground elevation data.
Permeability calculated using 2018 SSURGO soil data.

AREA	**LU**	**PCT IMP**	
55.57	**0.12**	**11.500**	**Low + Zero**
12.00	**1.72**	**0.000**	**Med**
9.83	**5.96**	**0.000**	**High**

77.40 *check total area*

EXHIBIT 3, sheet 4

SUBBASIN 5a - SSURGO SOIL DATA SUMMARY

Minimum Permeability (60") (inches/hour)	Percentage			77.9	BASIN AREA	WTD LU (min)
0.000	0.7%					
0.001	0.0%	impervious				
0.014	1.6%		2.3%	1.82	sq mi	**use 0**
0.060	2.4%					
0.198	26.1%	low permeability				
0.200	1.2%		29.7%	23.13	sq mi	**0.19**
0.567	0.0%					
1.417	0.3%					
1.559	0.0%					
1.984	2.0%	mid permeability				
2.000	1.0%		3.3%	2.58	sq mi	**1.93**
5.953	64.3%	high permeability				
6.001	0.4%		64.6%	50.36	sq mi	**5.95**

Subbasin area based on 2019 boundaries delineated using LiDAR ground elevation data.
Permeability calculated using 2018 SSURGO soil data.

AREA	**LU**	**PCT IMP**	
24.96	**0.19**	**7.300**	**Low + Zero**
2.58	**1.93**	**0.000**	**Med**
50.36	**5.95**	**0.000**	**High**

77.90 *check total area*

SUBBASIN 5b - SSURGO SOIL DATA SUMMARY

Minimum Permeability (60") (inches/hour)	Percentage			57.4	BASIN AREA	WTD LU (min)
0.000	5.0%	impervious				
0.001	2.6%					
0.014	4.3%		11.90%	6.83	sq mi	**USE 0**
0.060	11.0%	Low permeability				
0.142	0.2%					
0.198	25.0%					
0.200	4.8%		41%	23.54	sq mi	**0.16**
0.567	0.7%	mid permeability				
1.417	5.4%					
1.984	2.6%		8.69%	4.99	sq mi	**1.52**
5.953	32.9%	high permeability				
6.001	5.6%		38.45%	22.07	sq mi	**5.96**

Subbasin area based on 2019 boundaries delineated using LiDAR ground elevation data.
Permeability calculated using 2018 SSURGO soil data.

AREA	**LU**	**PCT IMP**	
30.37	**0.16**	**22.500**	**Low + Zero**
4.99	**1.52**	**0.000**	**Med**
22.07	**5.96**	**0.000**	**High**

57.43 *check total area*

EXHIBIT 3, Sheet 5

SUBBASIN 5c - SSURGO SOIL DATA SUMMARY

Minimum Permeability (60") (inches/hour)	Percentage			19	BASIN AREA	WTD LU (min)
0.000	0.5%	impervious				
0.001	1.6%					
0.014	1.7%		3.77%	0.72	sq mi	**Use 0**
0.060	13.4%	Low permeability				
0.198	32.3%		45.7%	8.68	sq mi	**0.16**
0.567	0.2%	mid permeability				
1.417	0.6%					
1.984	2.0%		2.78%	0.53	sq mi	**1.75**
5.953	47.4%	high permeability				
6.001	0.4%		47.75%	9.07	sq mi	**5.95**

Subbasin area based on 2019 boundaries delineated using LiDAR ground elevation data.
Permeability calculated using 2018 SSURGO soil data.

AREA	**LU**	**PCT IMP**	
9.40	**0.16**	**22.000**	**Low + Zero**
0.53	**1.75**	**0.000**	**Med**
9.07	**5.95**	**0.000**	**High**

19.00 *check total area*

SUBBASIN 6 - SSURGO SOIL DATA SUMMARY

Minimum Permeability (60") (inches/hour)	Percentage			50.5	BASIN AREA	WTD LU (min)
0.000	10.7%					
0.001	18.2%	impervious				
0.014	12.0%		40.9%	20.65	sq mi	**use 0**
0.060	4.6%					
0.142	0.4%					
0.198	11.4%	low permeability				
0.200	0.2%		16.6%	8.39	sq mi	**0.16**
0.567	0.7%					
1.417	9.1%	mid permeability				
1.984	17.4%		27.3%	13.78	sq mi	**1.76**
5.953	8.5%					
6.001	6.7%		15.2%	7.68	sq mi	**5.97**

Subbasin area based on 2019 boundaries delineated using LiDAR ground elevation data.
Permeability calculated using 2018 SSURGO soil data.

AREA	**LU**	**PCT IMP**	
29.04	**0.16**	**71.100**	**Low + Zero**
13.78	**1.76**	**0.000**	**Med**
7.68	**5.97**	**0.000**	**High**

50.50 *check total area*

EXHIBIT 3, Sheet 6

SUBBASIN 7 - SSURGO SOIL DATA SUMMARY

Minimum Permeability (60") (inches/hour)	Percentage			40.8	BASIN AREA	WTD LU (min)
0.000	7.8%					
0.001	8.8%	impervious				
0.014	5.5%		22.1%	9.00	sq mi	**use 0**
0.060	4.8%					
0.142	0.5%					
0.198	1.5%	low permeability				
0.200	35.8%		42.6%	17.38	sq mi	**0.18**
0.567	0.4%					
0.600	0.5%					
1.417	14.8%	mid permeability				
1.984	0.3%		15.9%	6.50	sq mi	**1.39**
5.953	1.5%	high permeability				
6.001	17.9%		19.4%	7.92	sq mi	**6.00**

Subbasin area based on 2019 boundaries delineated using LiDAR ground elevation data.
Permeability calculated using 2018 SSURGO soil data.

AREA	**LU**	**PCT IMP**	
26.38	**0.18**	**34.100**	**Low + Zero**
6.50	**1.39**	**0.000**	**Med**
7.92	**6**	**0.000**	**High**

40.80 *check total area*

SUBBASIN 8 - SSURGO SOIL DATA SUMMARY

Minimum Permeability (60") (inches/hour)	Percentage			46.3	BASIN AREA	WTD LU (min)
0.000	2.24%	impervious				
0.001	1.09%		3.33%	1.54	sq mi	**use 0**
0.060	14.80%					
0.142	5.23%					
0.198	14.26%	low permeability				
0.200	5.59%		39.88%	18.46	sq mi	**0.14**
0.567	8.86%					
1.417	25.71%					
1.559	1.89%					
1.984	5.26%	mid permeability				
2.000	0.44%		42.15%	19.52	sq mi	**1.32**
5.953	4.39%	high permeability				
6.001	10.25%		14.64%	6.78	sq mi	**5.99**

Subbasin area based on 2019 boundaries delineated using LiDAR ground elevation data.
Permeability calculated using 2018 SSURGO soil data.

AREA	**LU**	**PCT IMP**	
20.00	**0.14**	**7.700**	**Low + Zero**
19.52	**1.32**	**0.000**	**Med**
6.78	**5.99**	**0.000**	**High**

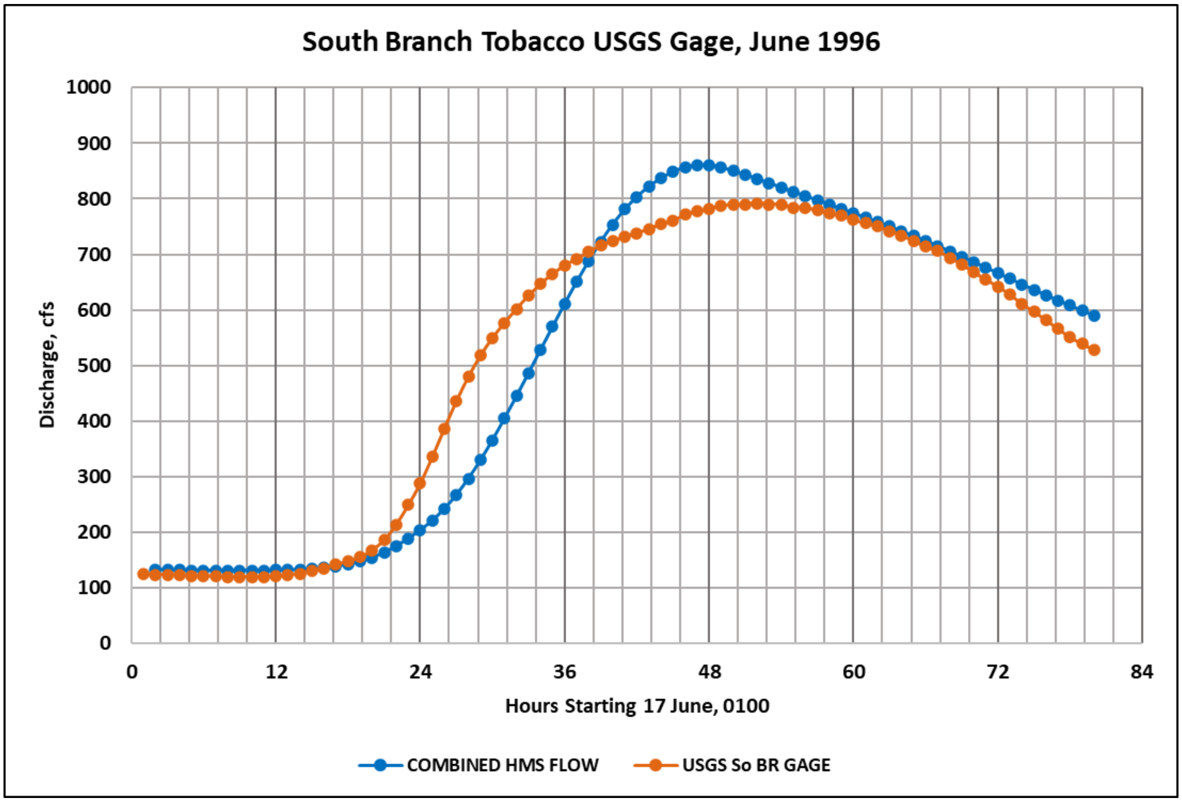
46.30 *check total area*

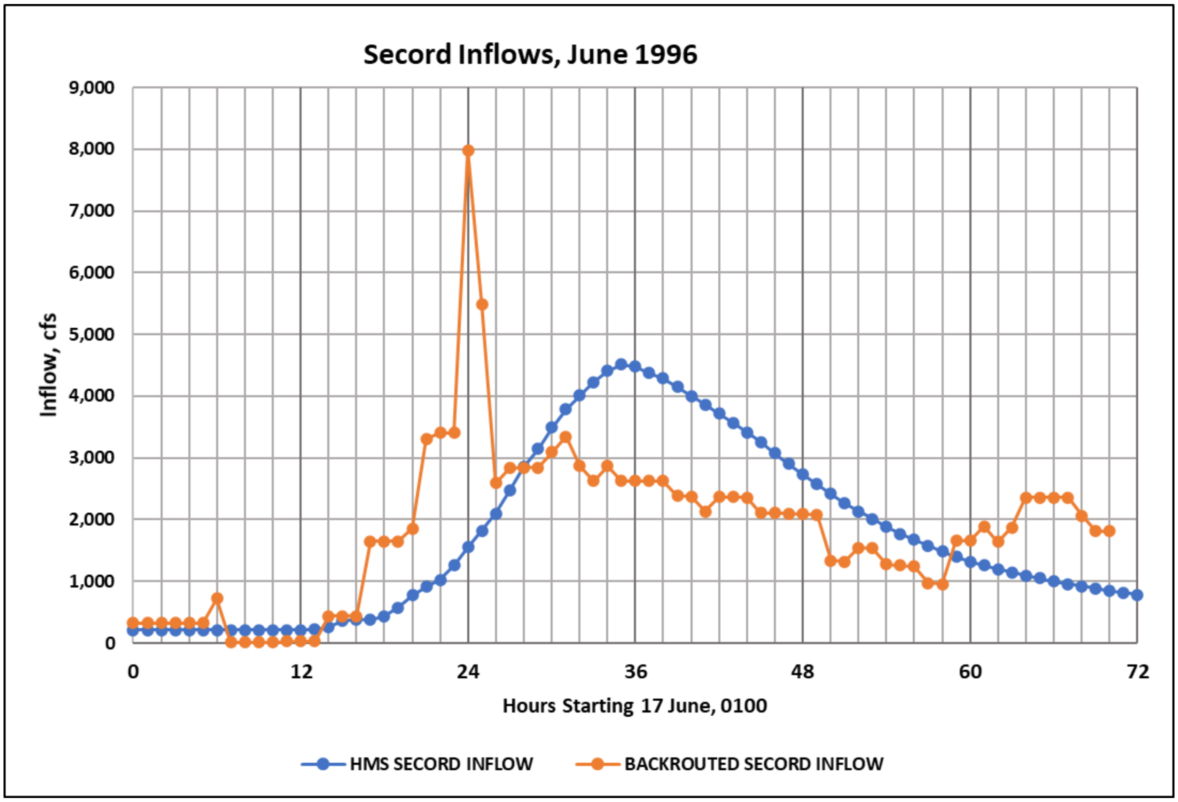
Exhibit 4

HEC-HMS Model Calibration Plots

1996, 2014, 2017, 2020

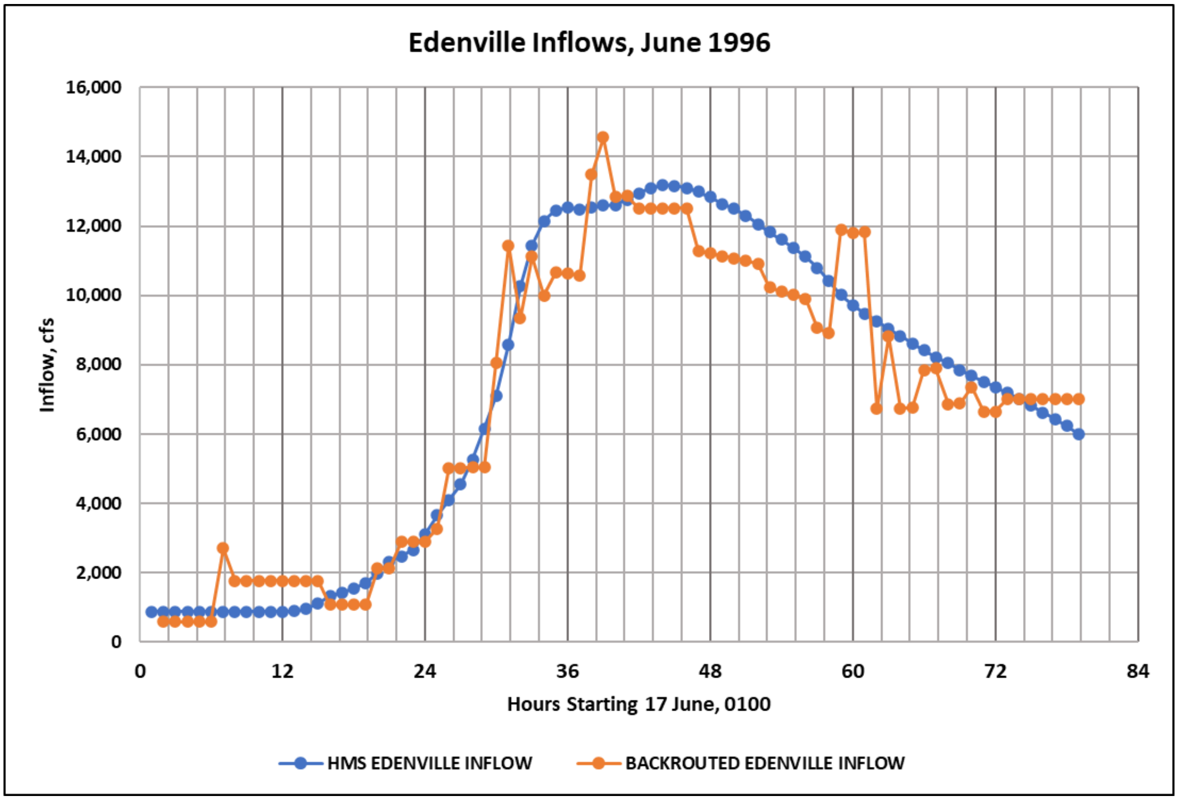
__1996 Storm Calibration__



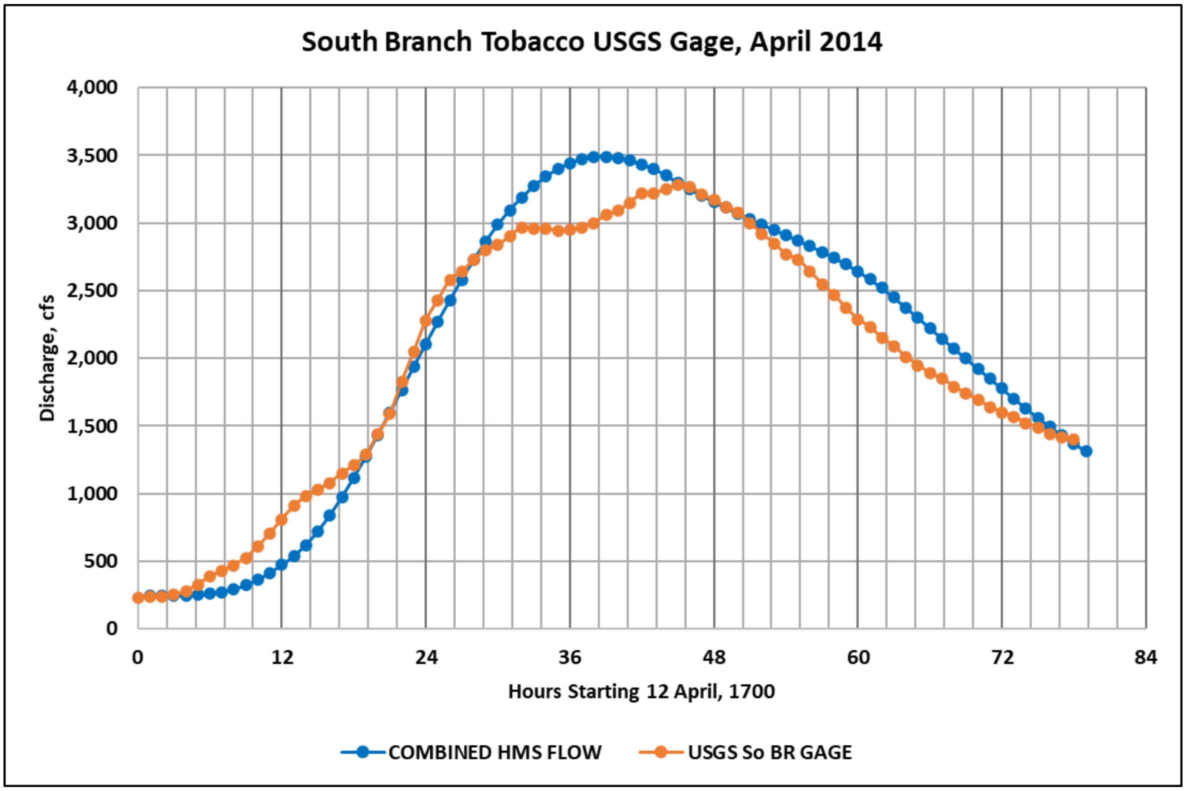


1996 Storm Calibration

Exhibit 4, sheet 2



2014 Storm Calibration Exhibit 4, sheet 3



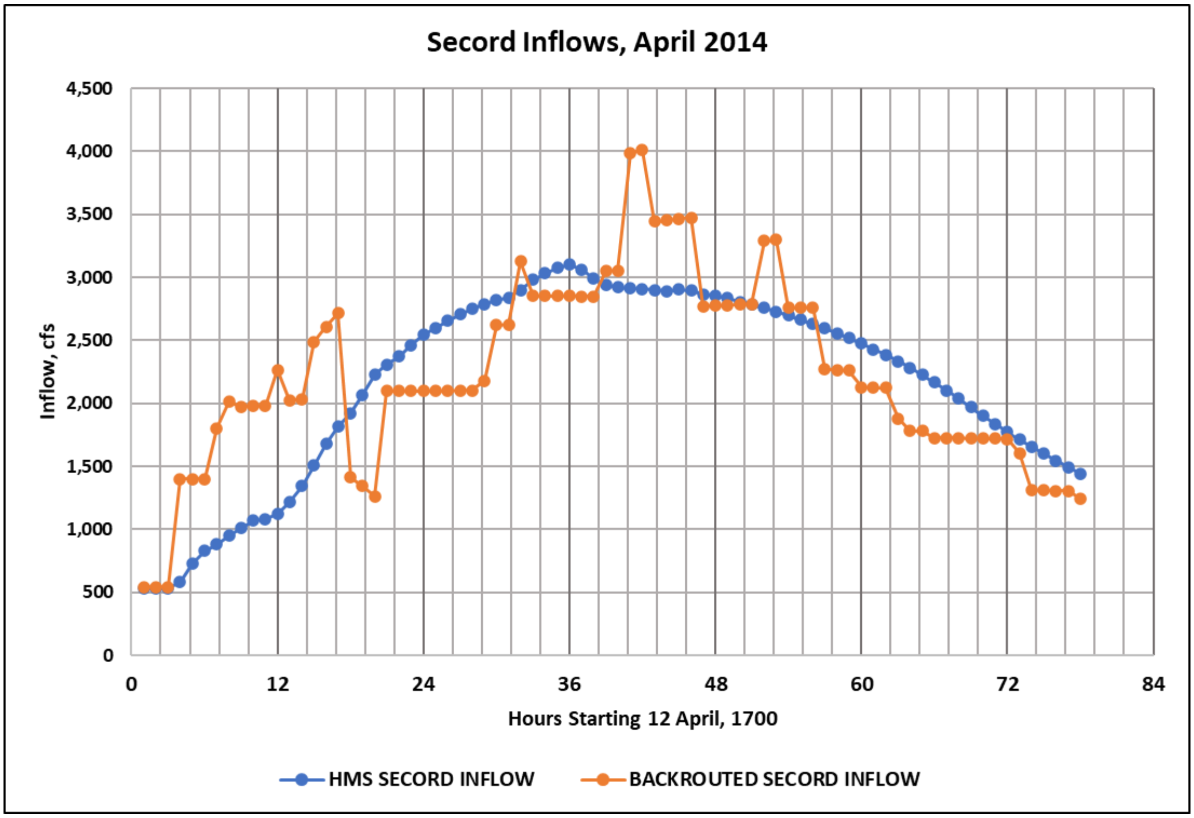
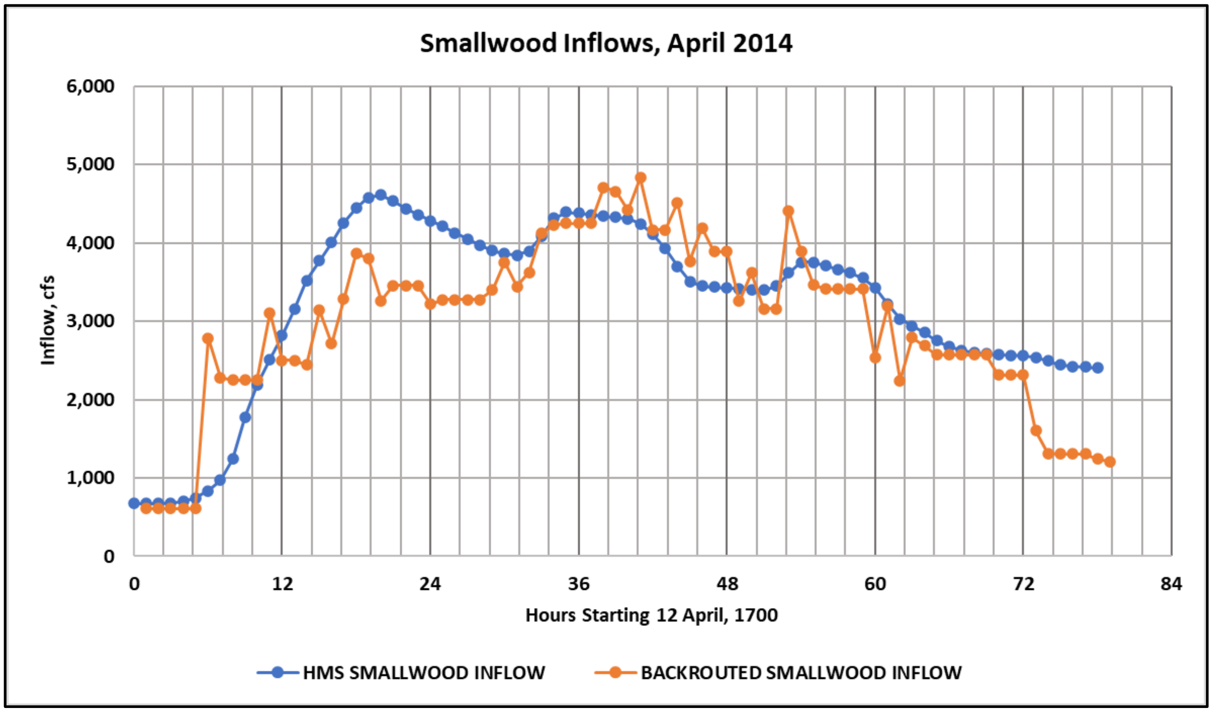
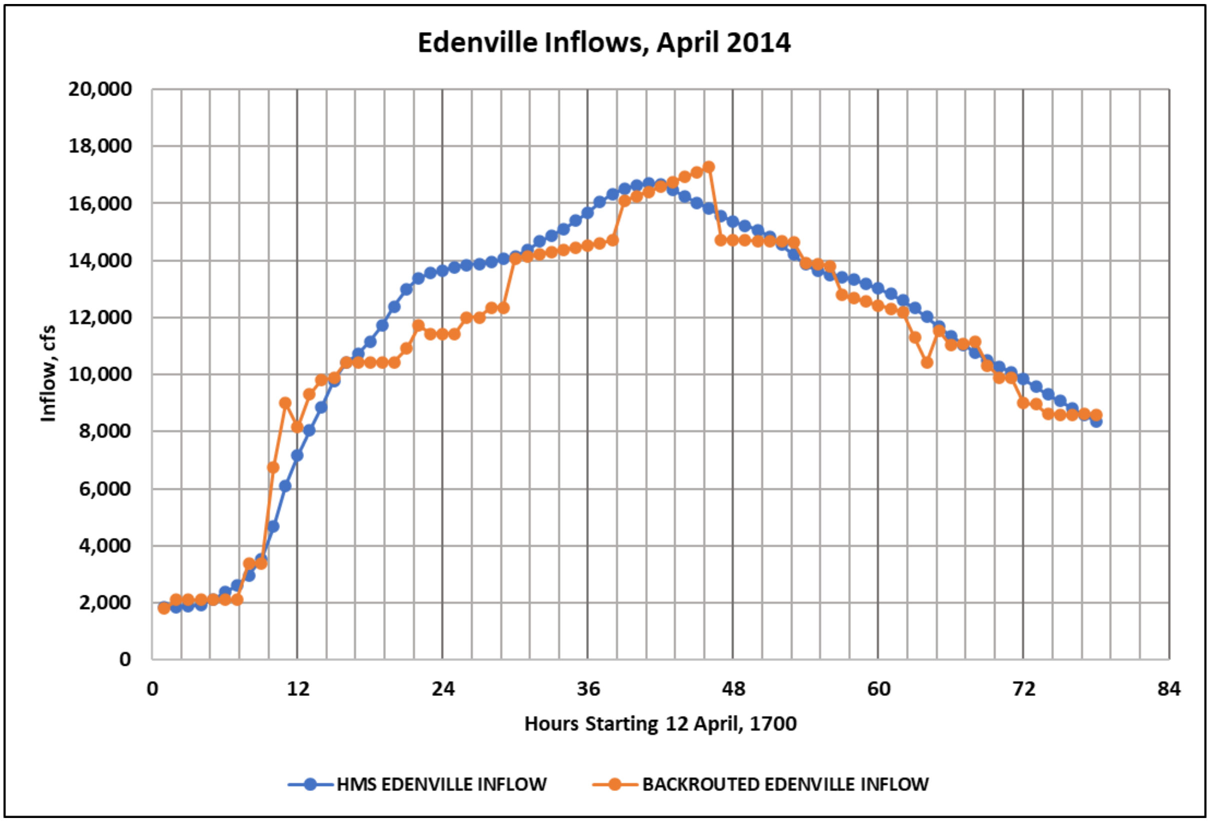
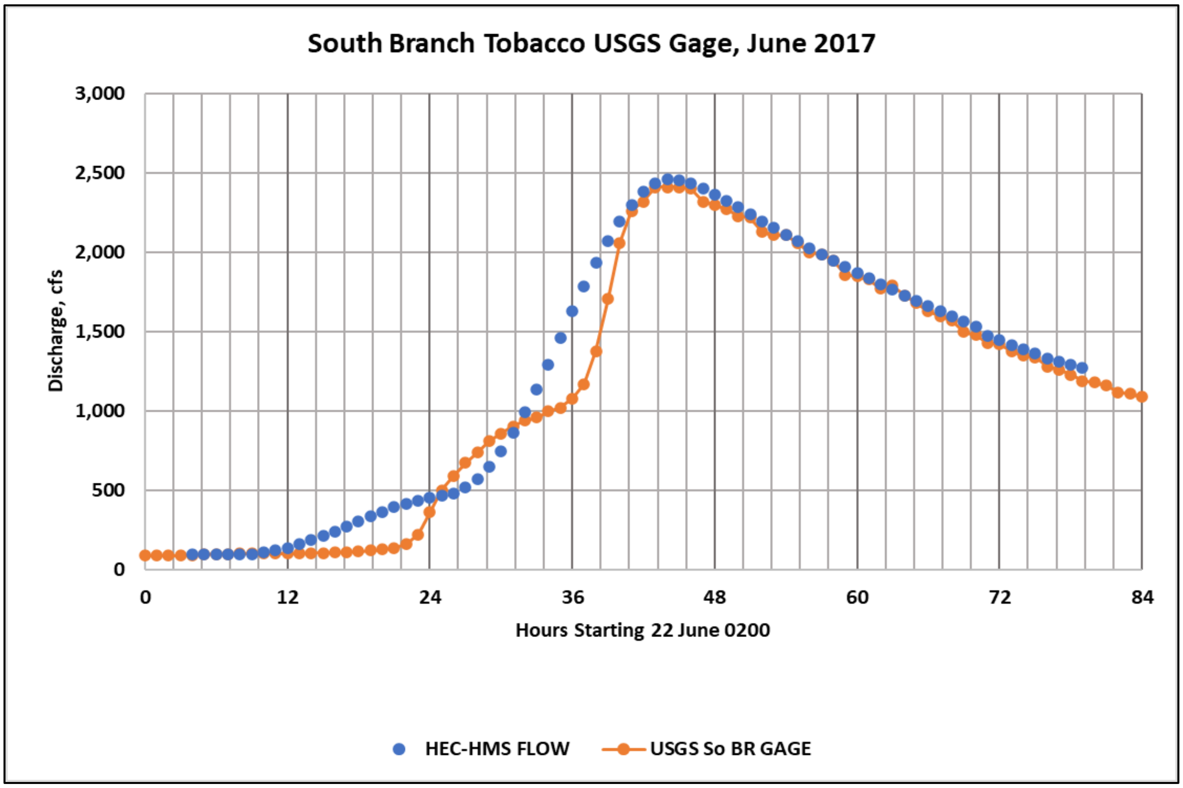
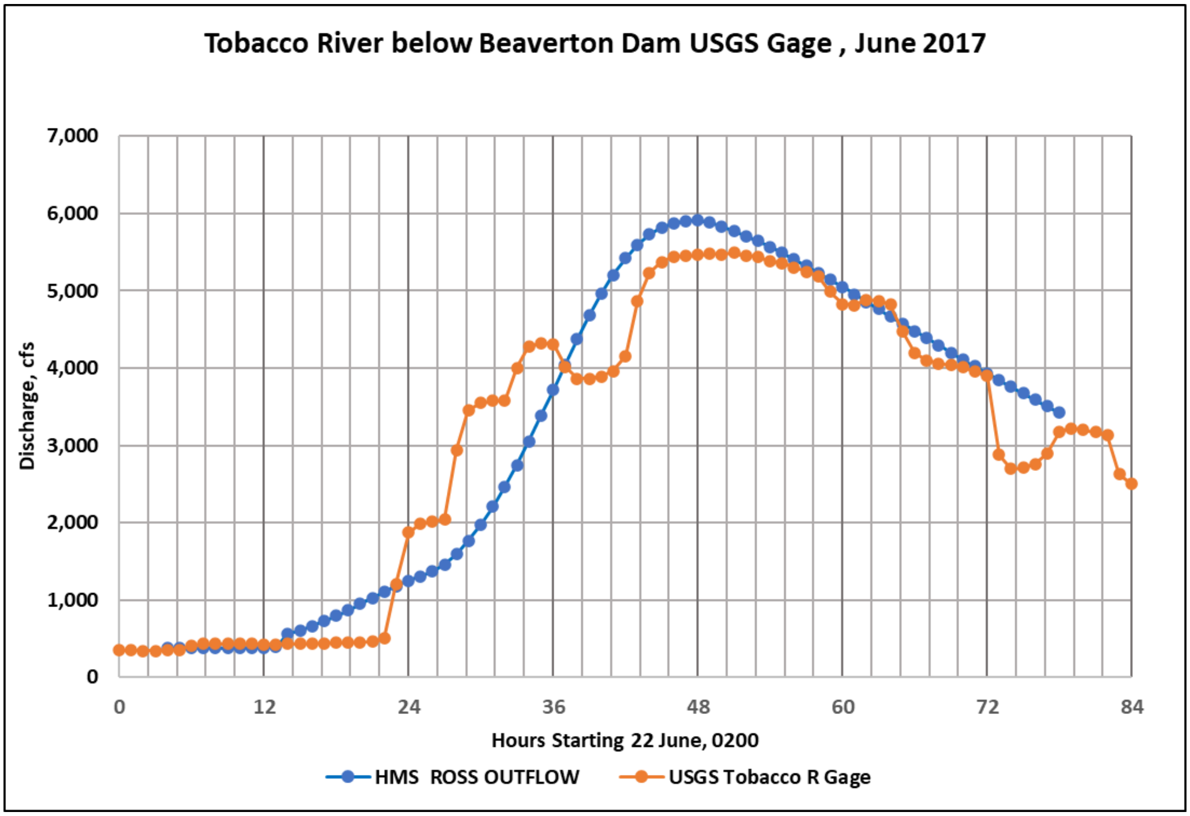


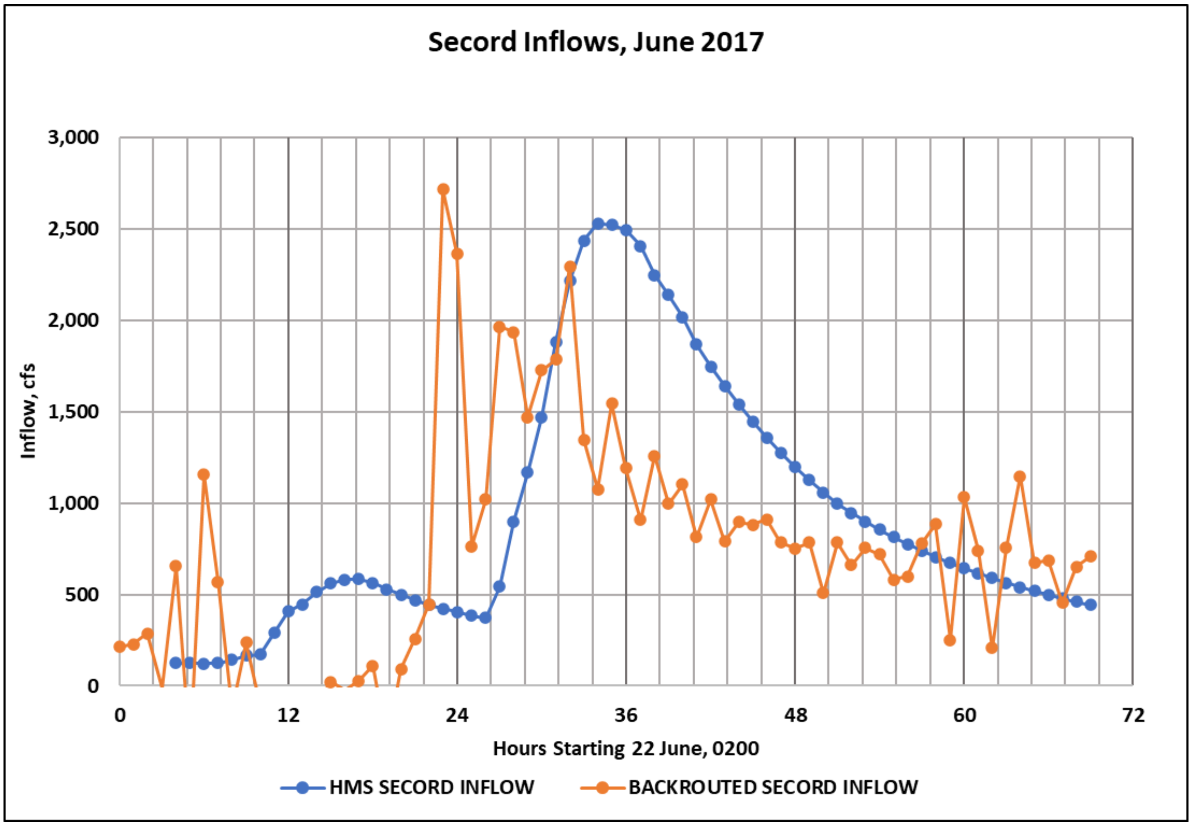
Exhibit 4, sheet 4

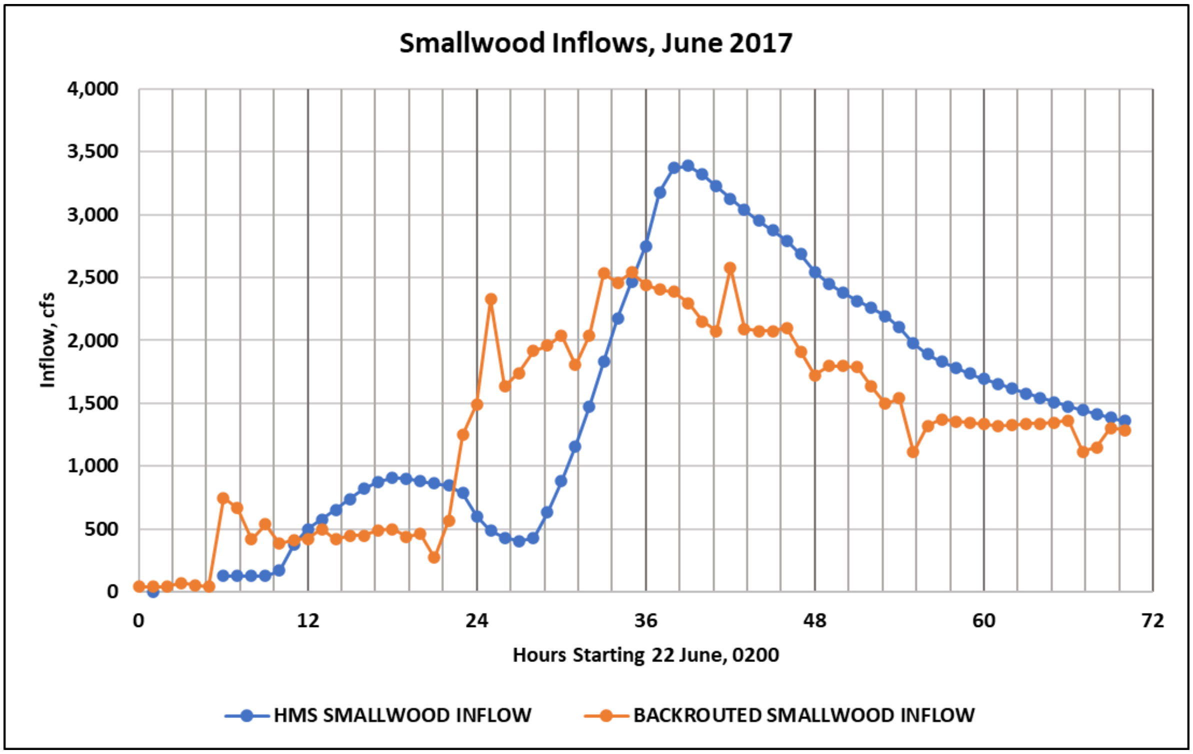


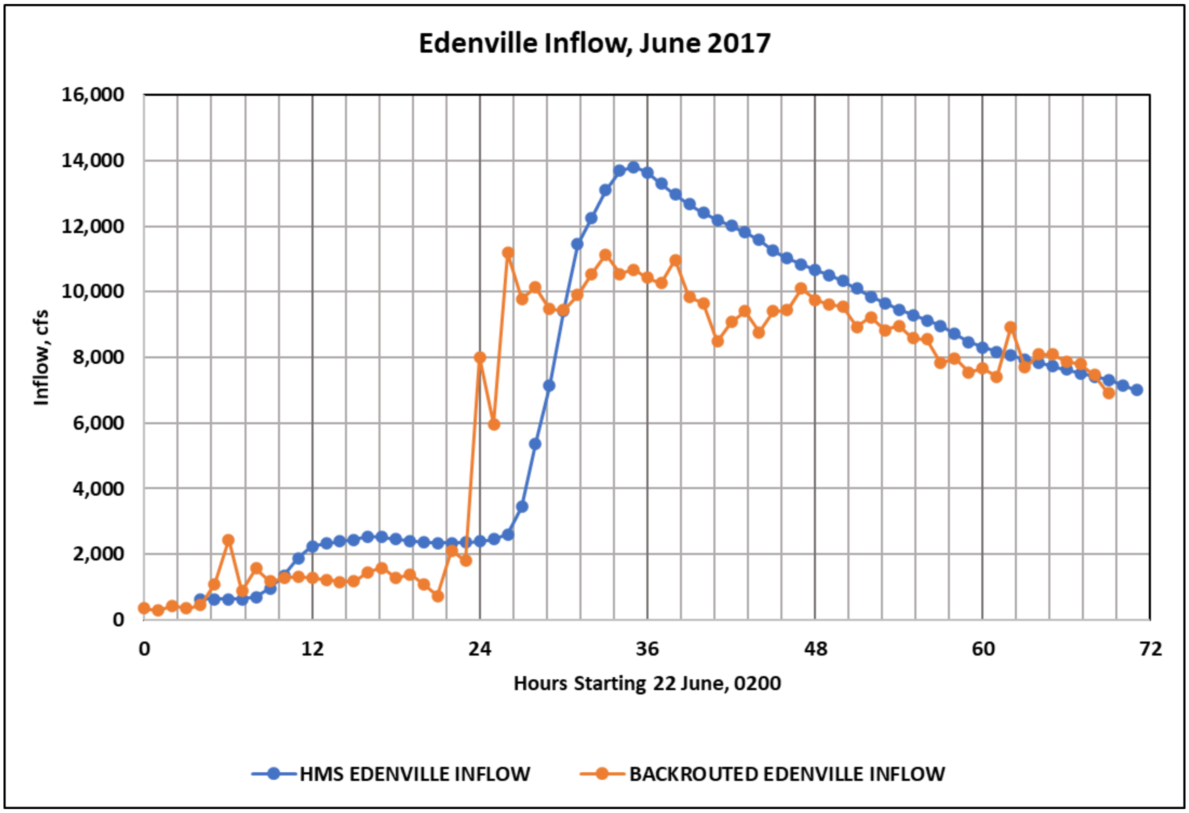


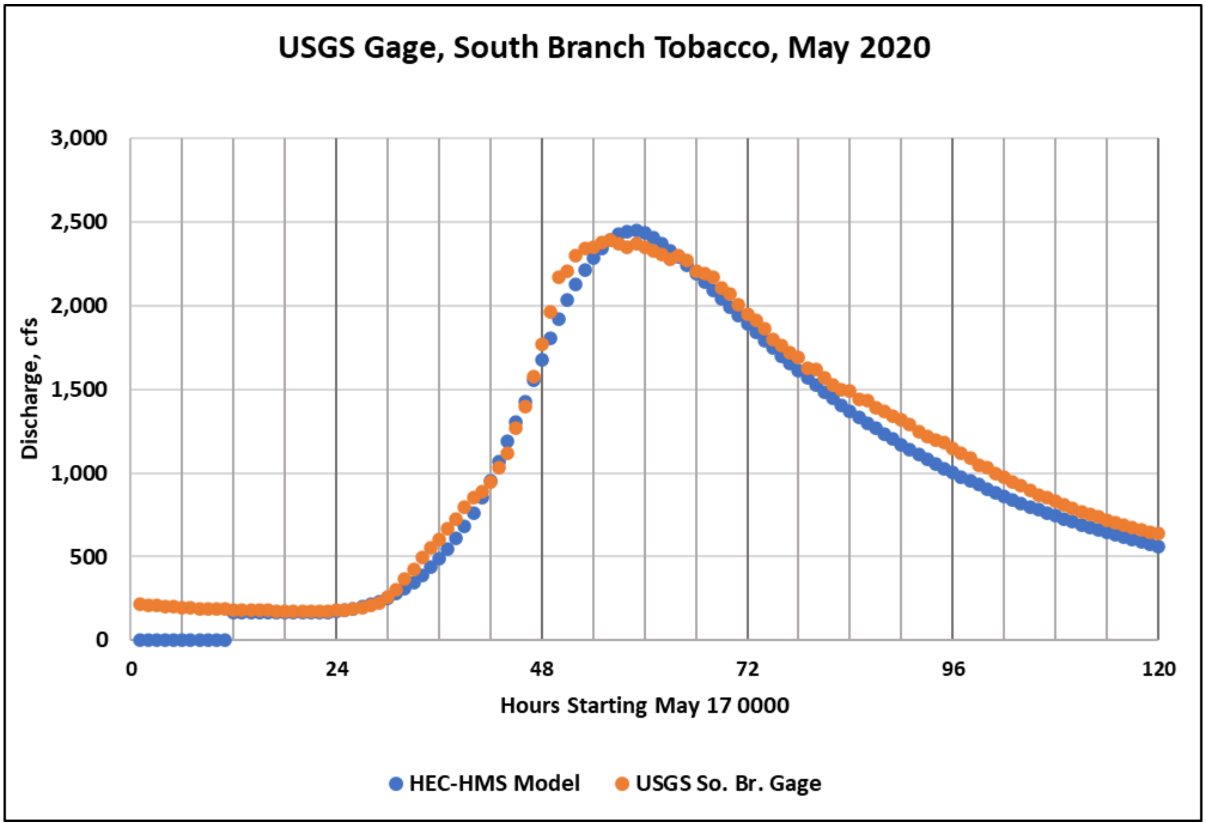

South Branch Tobacco USGS Gage, June 2017
Discharge, cfs
3,000
2,500
2,000
1,500
1,000
500
0
0
12
24
36
48
60
72
84
Hours Starting 22 June 0200
HEC-HMS FLOW
USGS So BR GAGE


Tobacco River below Beaverton Dam USGS Gage , June 2017
Discharge, cfs
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
0
12
24
36
48
60
72
84
Hours Starting 22 June, 0200
HMS ROSS OUTFLOW
USGS Tobacco R Gage


Secord Inflows, June 2017
3,000
2,500
2,000
1,500
1,000
500
0
Inflow, cfs
0
12
24
36
48
60
72
Hours Starting 22 June, 0200
HMS SECORD INFLOW
BACKROUTED SECORD INFLOW


Smallwood Inflows, June 2017
4,000
3,500
3,000
2,500
2,000
1,500
1,000
500
0
Inflow, cfs
0
12
24
36
48
60
72
Hours Starting 22 June, 0200
HMS SMALLWOOD INFLOW
BACKROUTED SMALLWOOD INFLOW


Edenville Inflow, June 2017
Inflow, cfs
16,000
14,000
12,000
10,000
8,000
6,000
4,000
2,000
0
0
12
24
36
48
60
72
Hours Starting 22 June, 0200
HMS EDENVILLE INFLOW
BACKROUTED EDENVILLE INFLOW


USGS Gage, South Branch Tobacco, May 2020
Discharge, cfs
3,000
2,500
2,000
1,500
1,000
500
0
0
24
48
72
96
120
Hours Starting May 17 0000
HEC-HMS Model
USGS So. Br. Gage

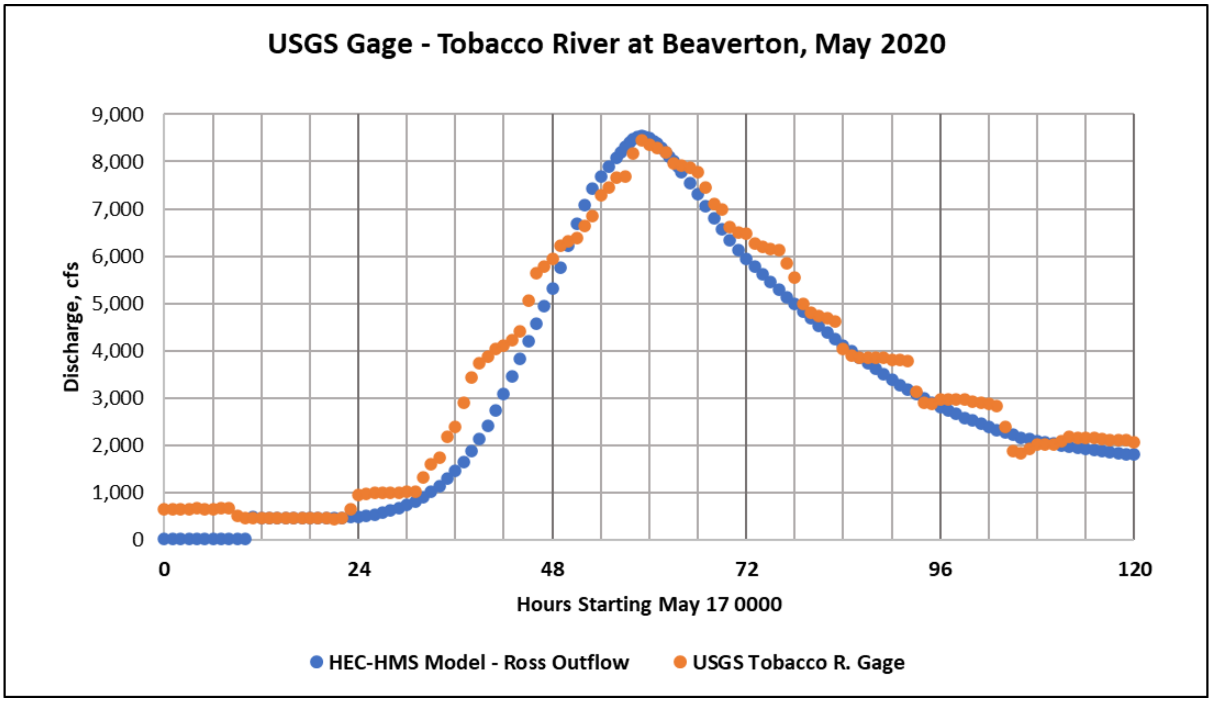
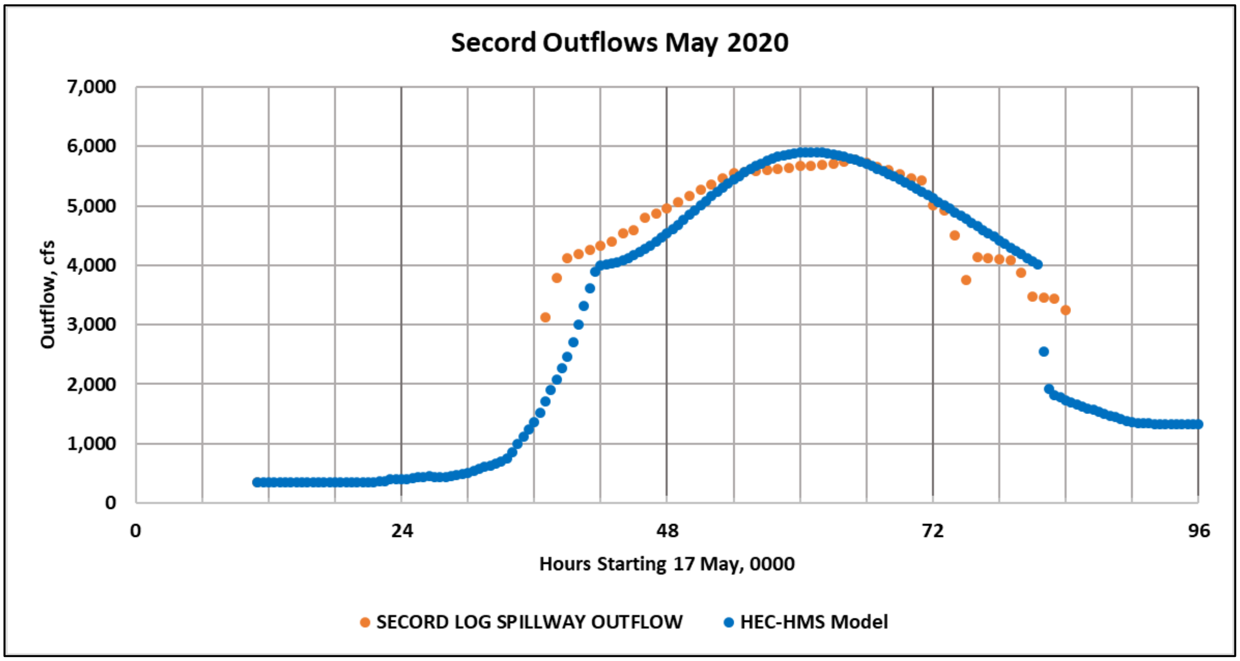
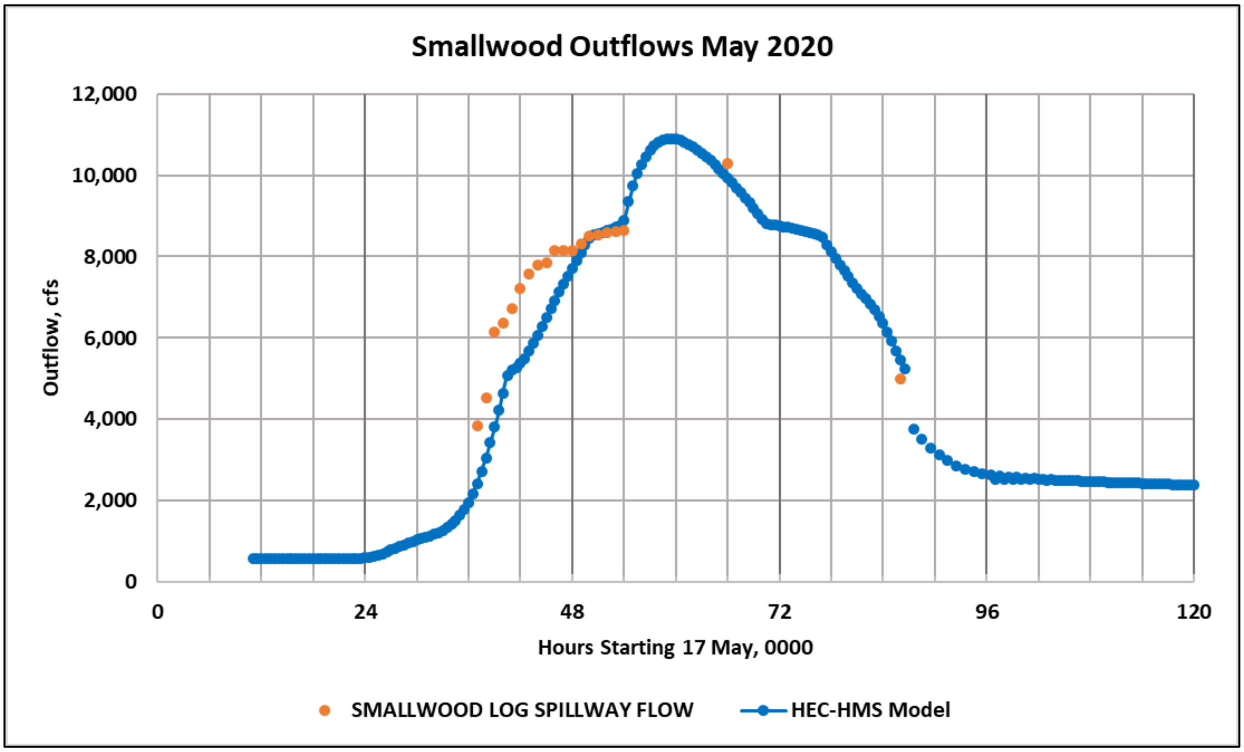
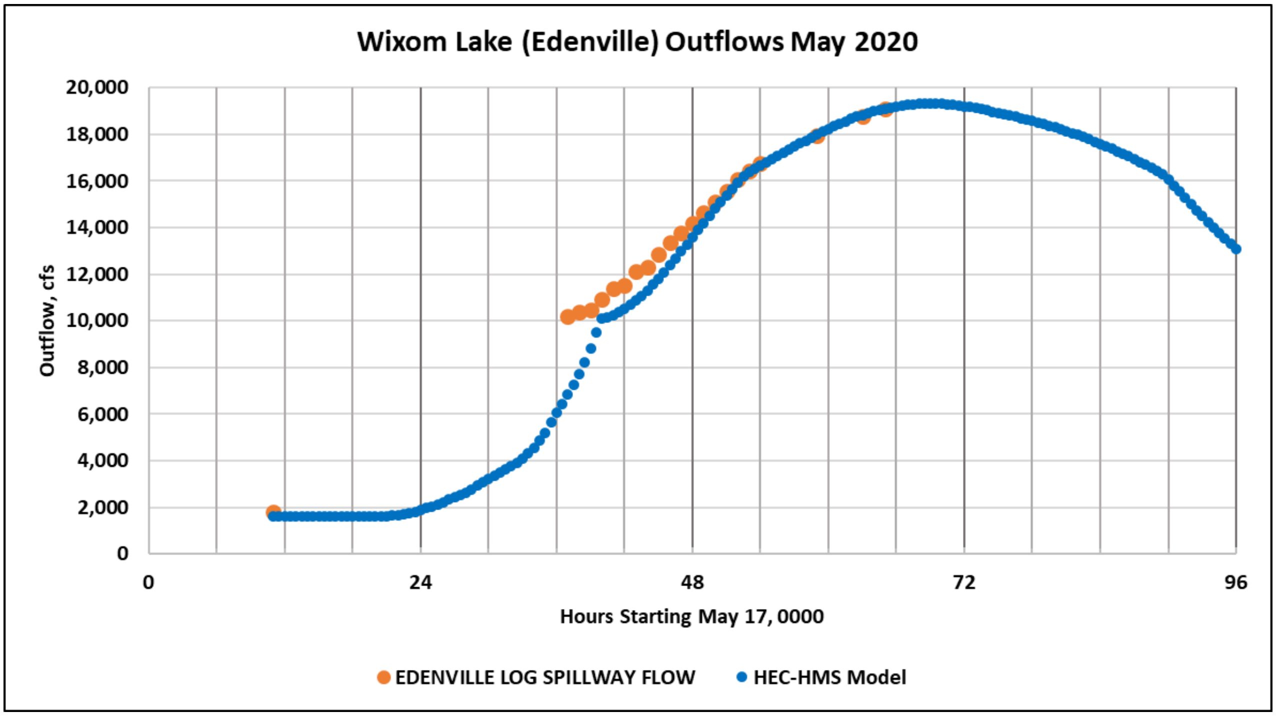

USGS Gage - Tobacco River at Beaverton, May 2020
Discharge, cfs
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
0
24
48
72
96
120
Hours Starting May 17 0000
HEC-HMS Model - Ross Outflow
USGS Tobacco R. Gage

Exhibit 4, sheet 9


Secord Outflows May 2020


Smallwood Outflows May 2020

2020 Storm Calibration Exhibit 4, sheet 10



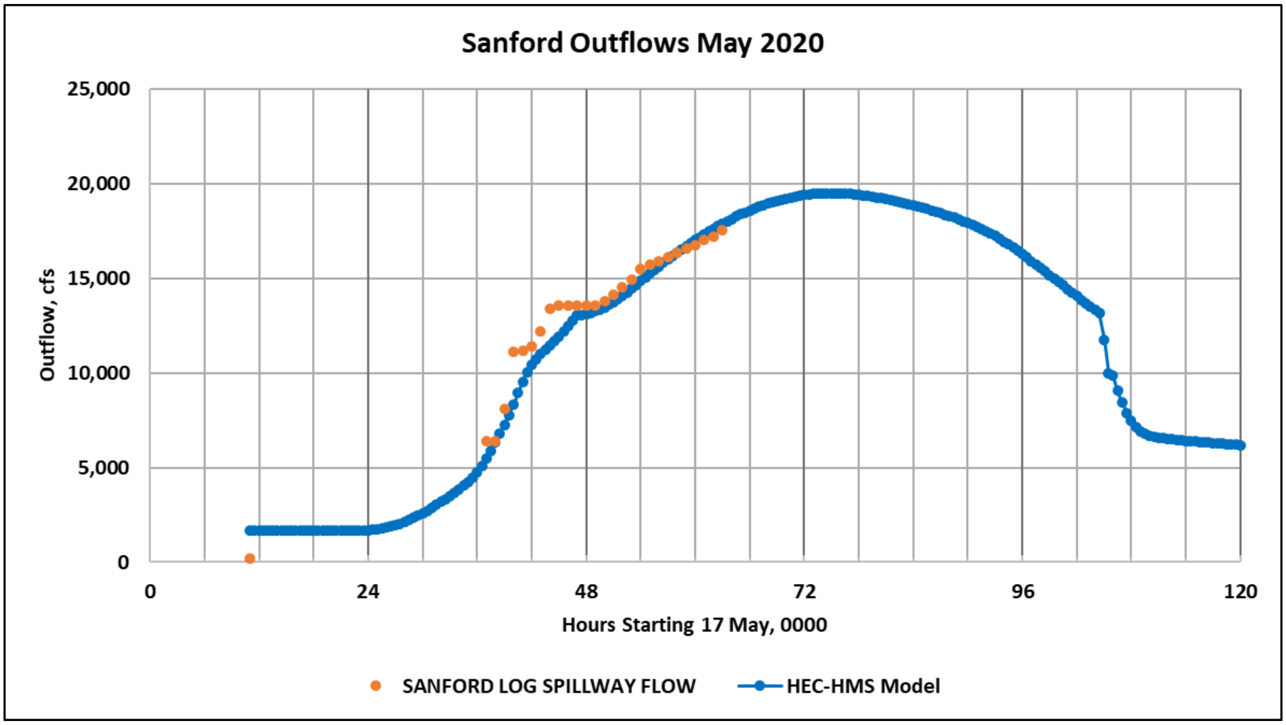
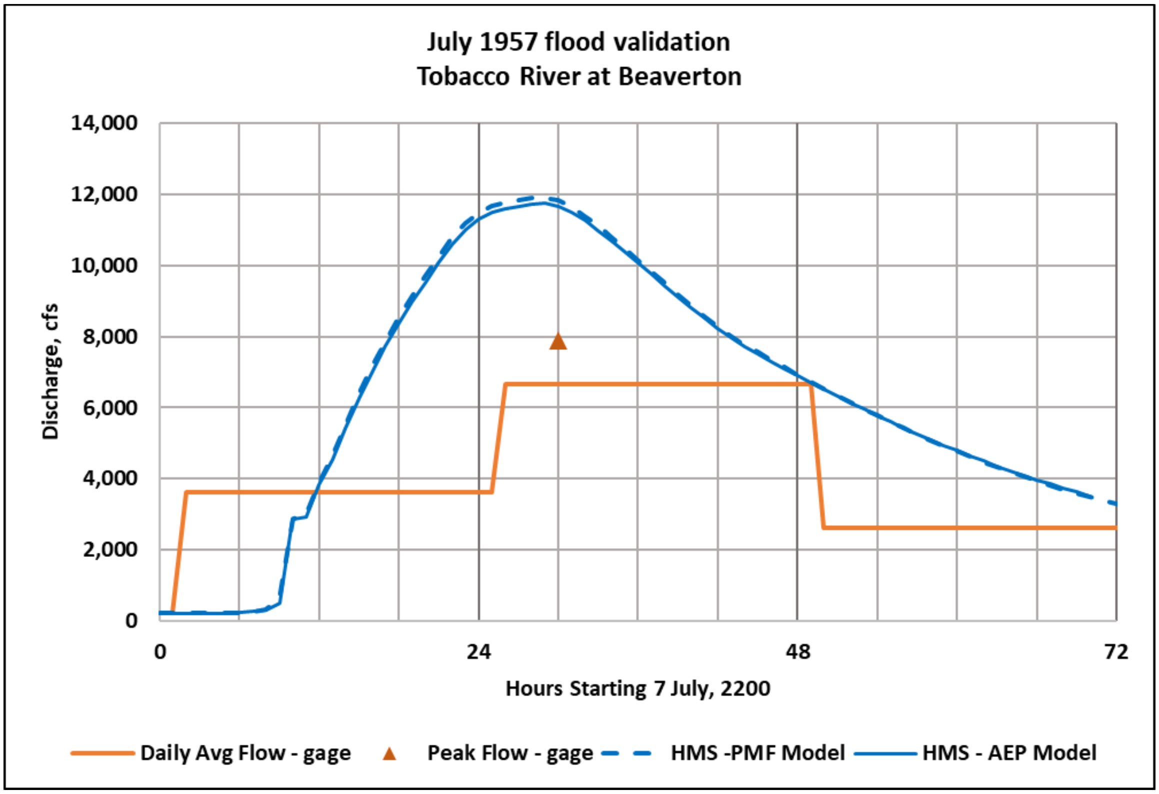


Exhibit 5

HEC-HMS Model Validation: June, 1957 Storm

Exhibit 5, Sheet 1 of 2



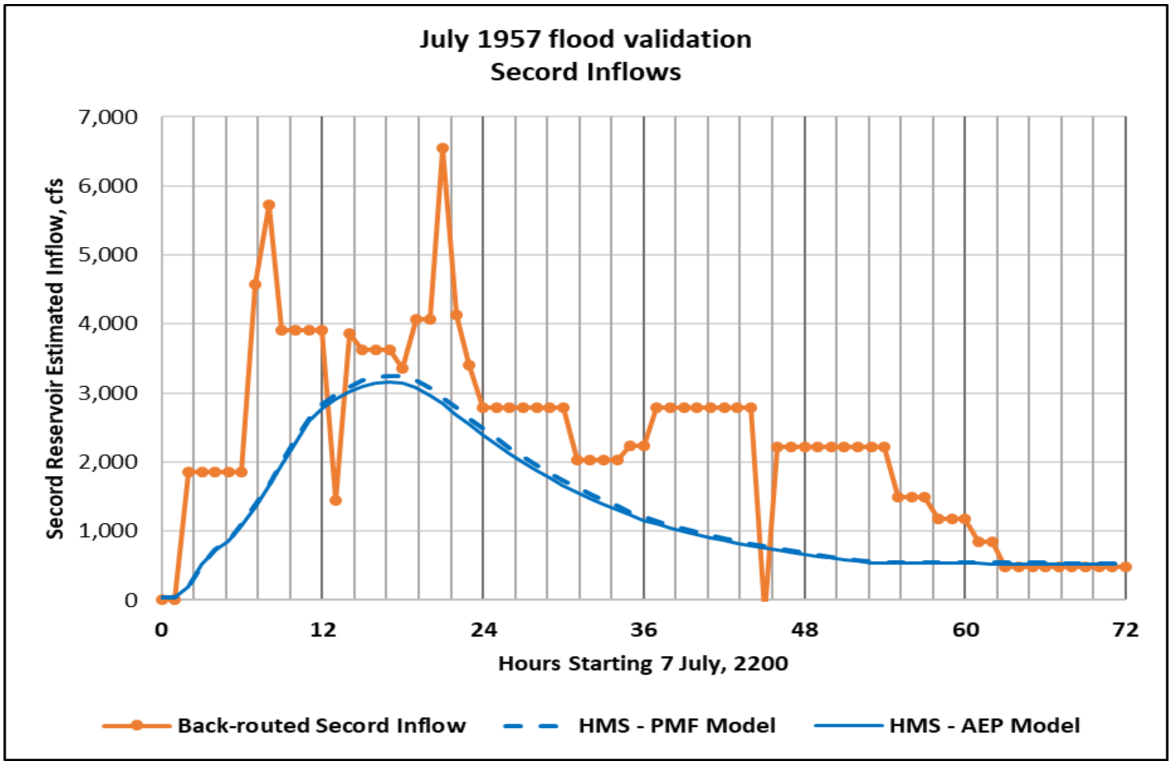


Exhibit 5, Sheet 2

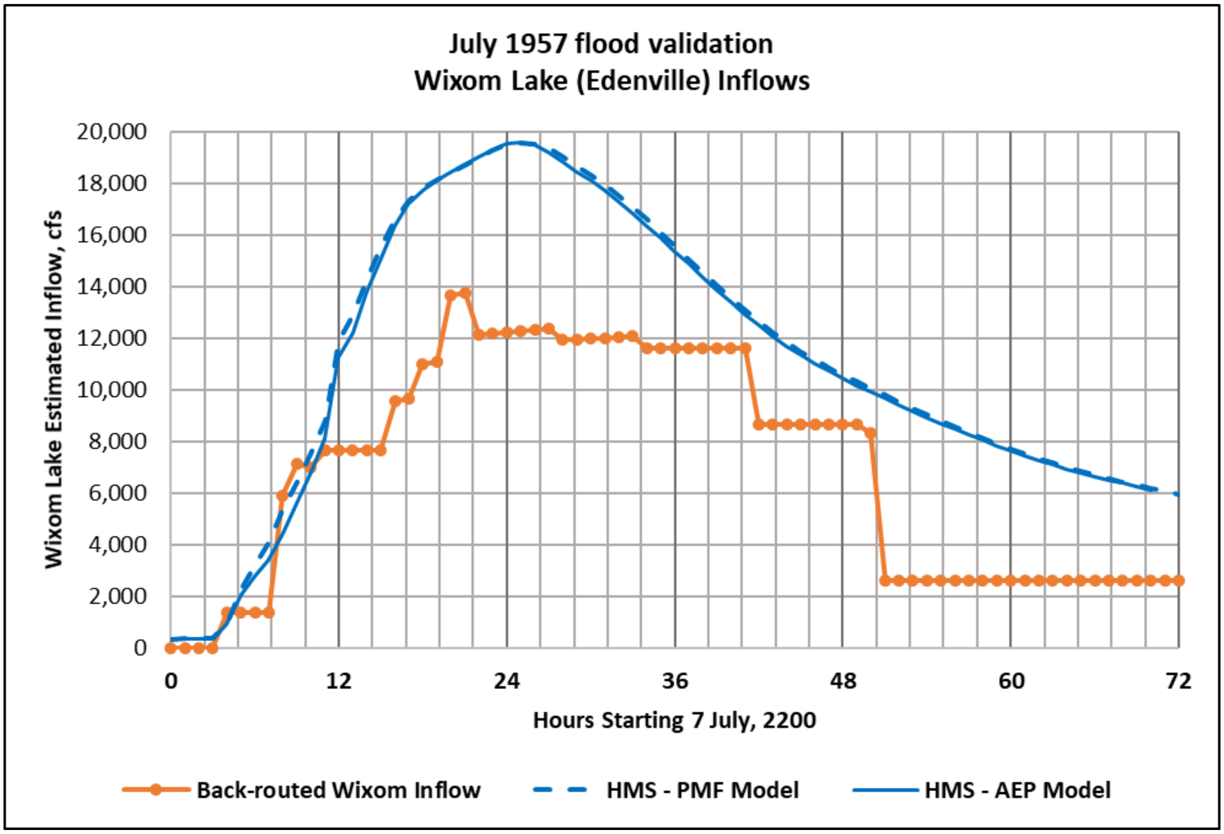
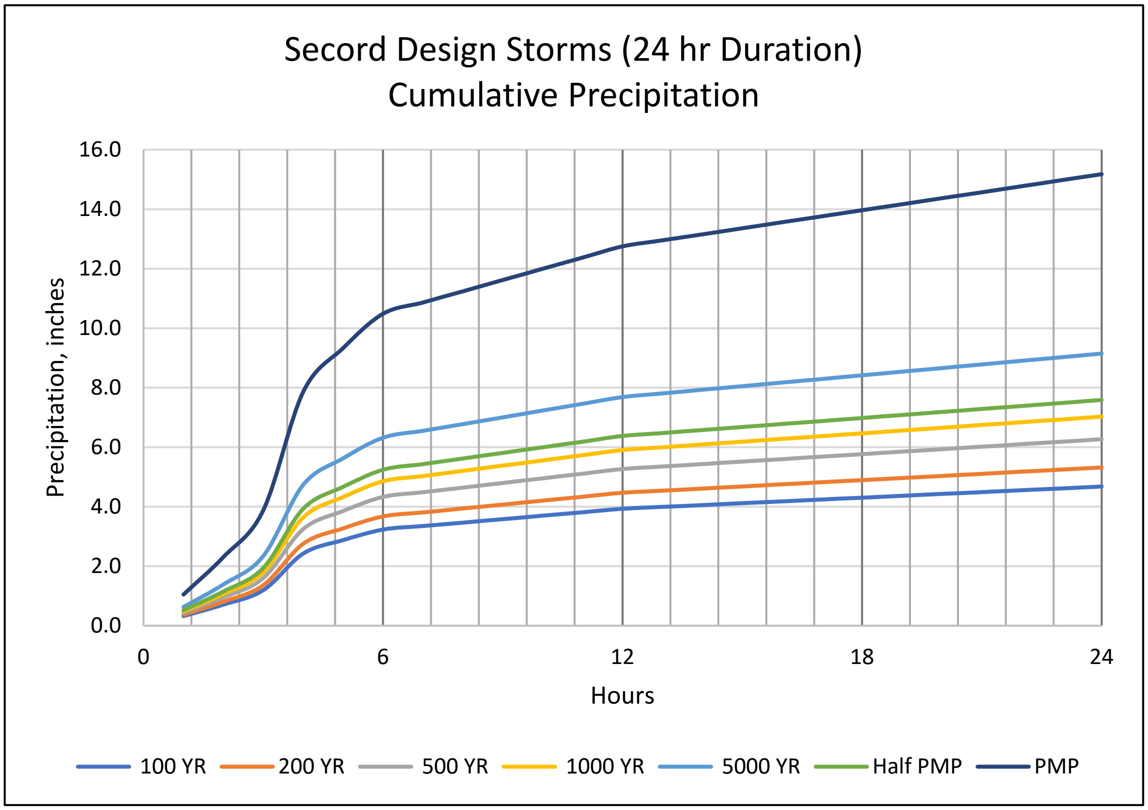


Exhibit 6

Design Flood Precipitation

Cumulative Precipitation Time Series

Exhibit 6, Sheet 1


Secord Design Storms (24 hr Duration)
Cumulative Precipitation

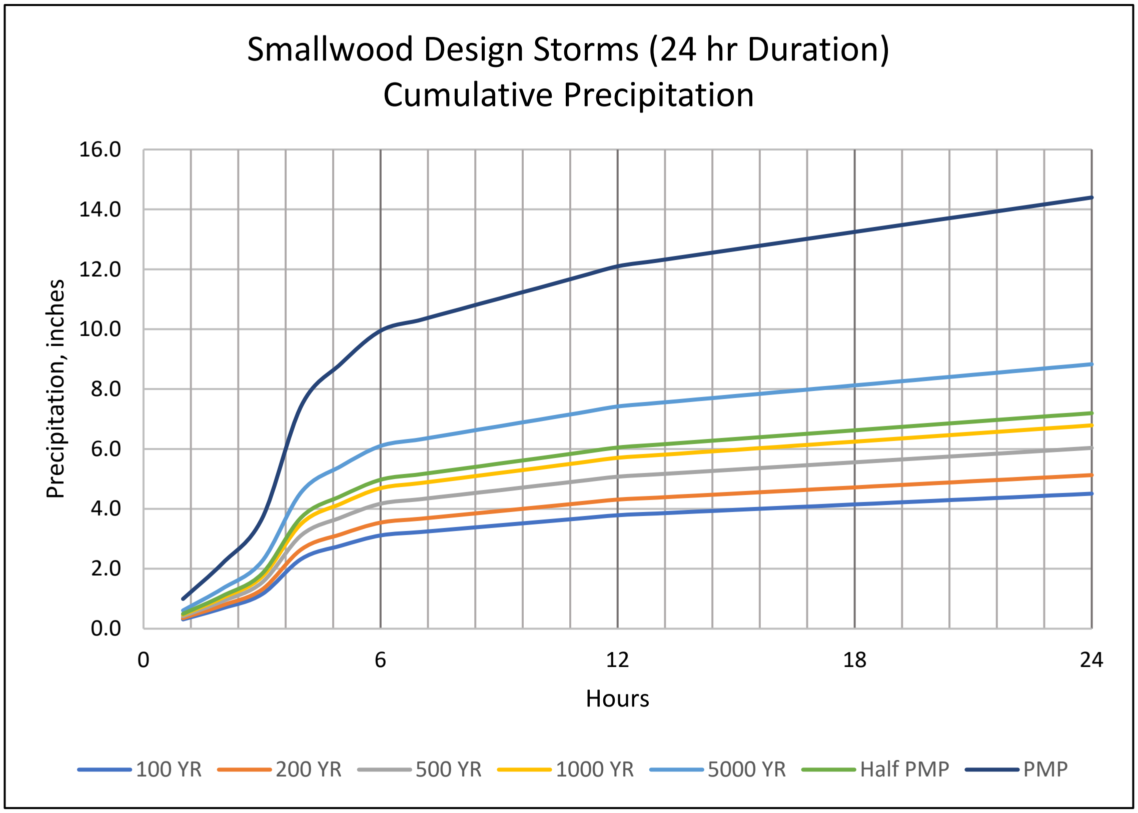
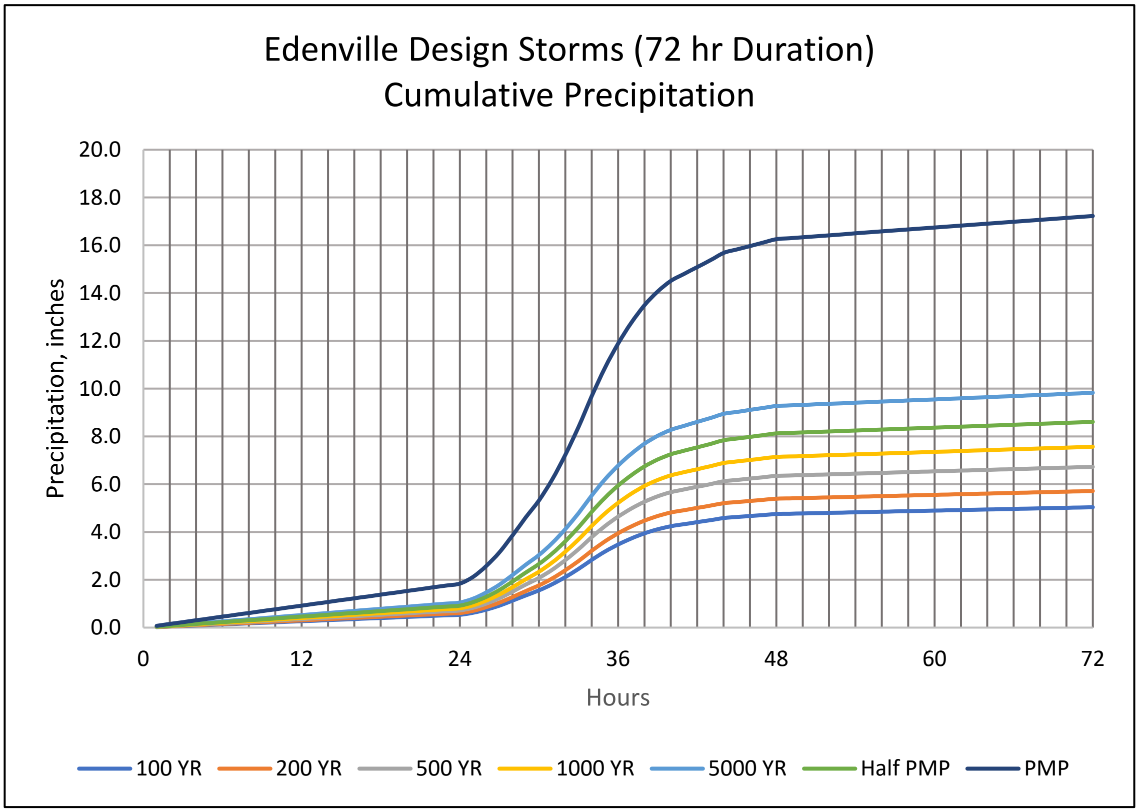

Smallwood Design Storms (24 hr Duration)
Cumulative Precipitation

Exhibit 6, Sheet 2


Edenville Design Storms (72 hr Duration)
Cumulative Precipitation

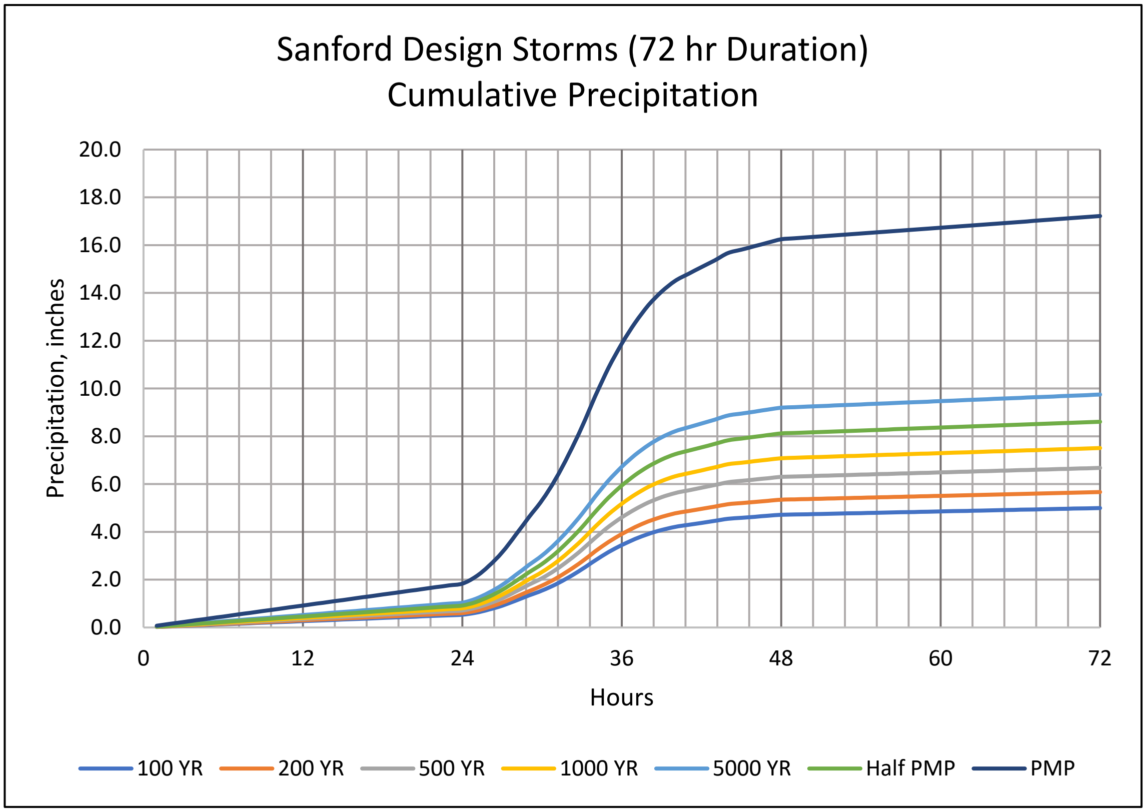
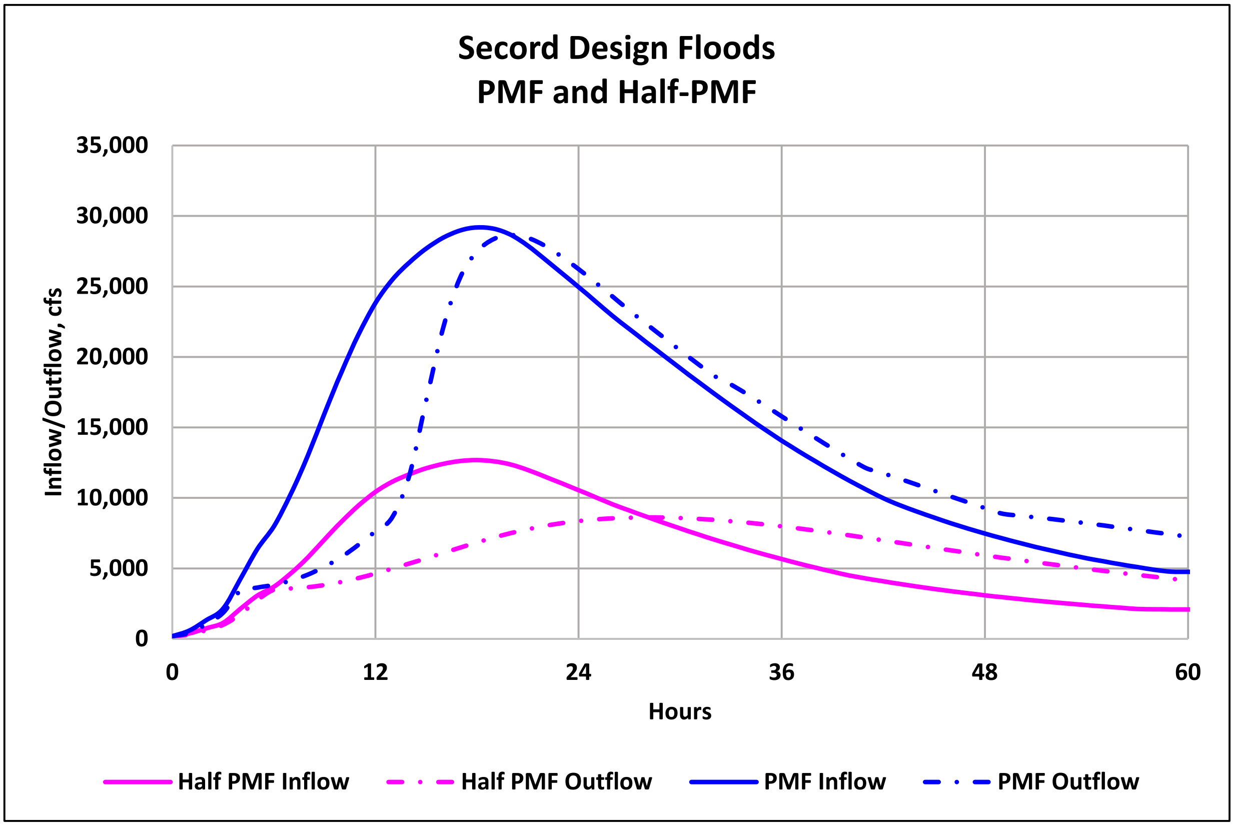

Sanford Design Storms (72 hr Duration)
Cumulative Precipitation

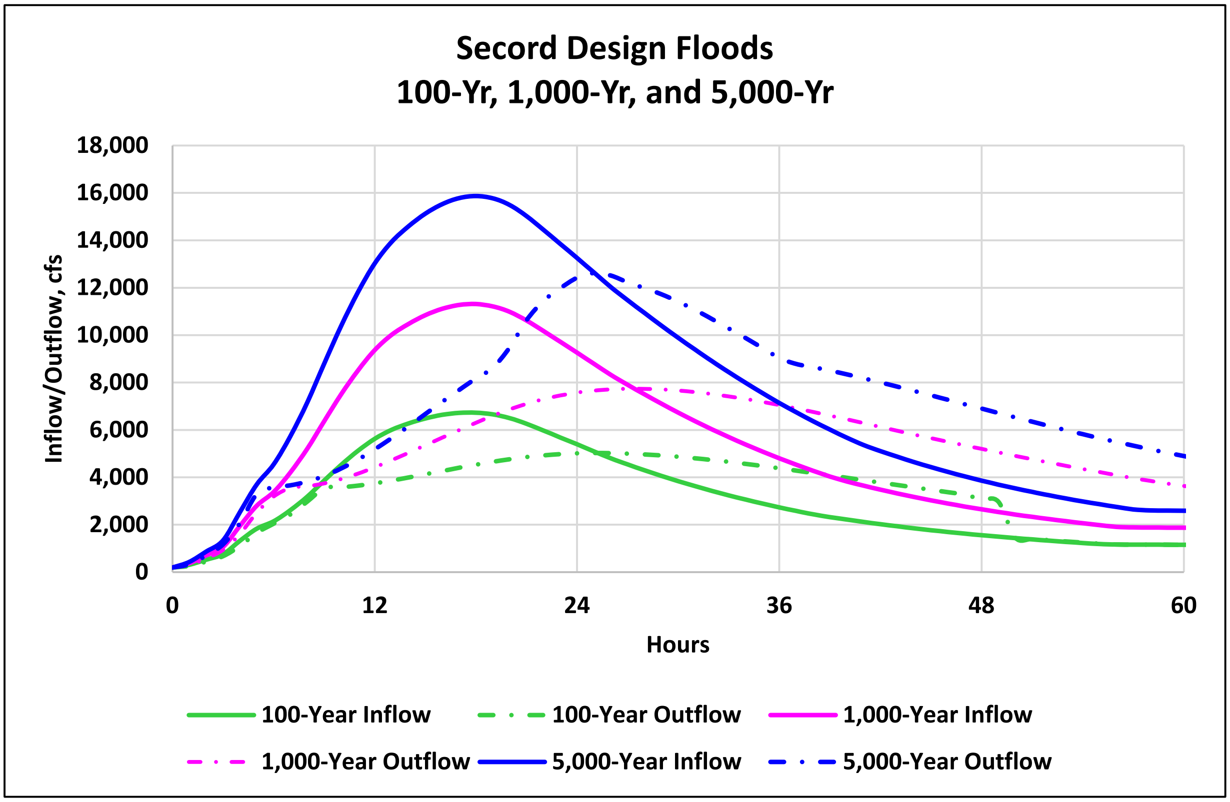
Exhibit 7

Design Flood Hydrographs

Exhibit 7, Sheet 1

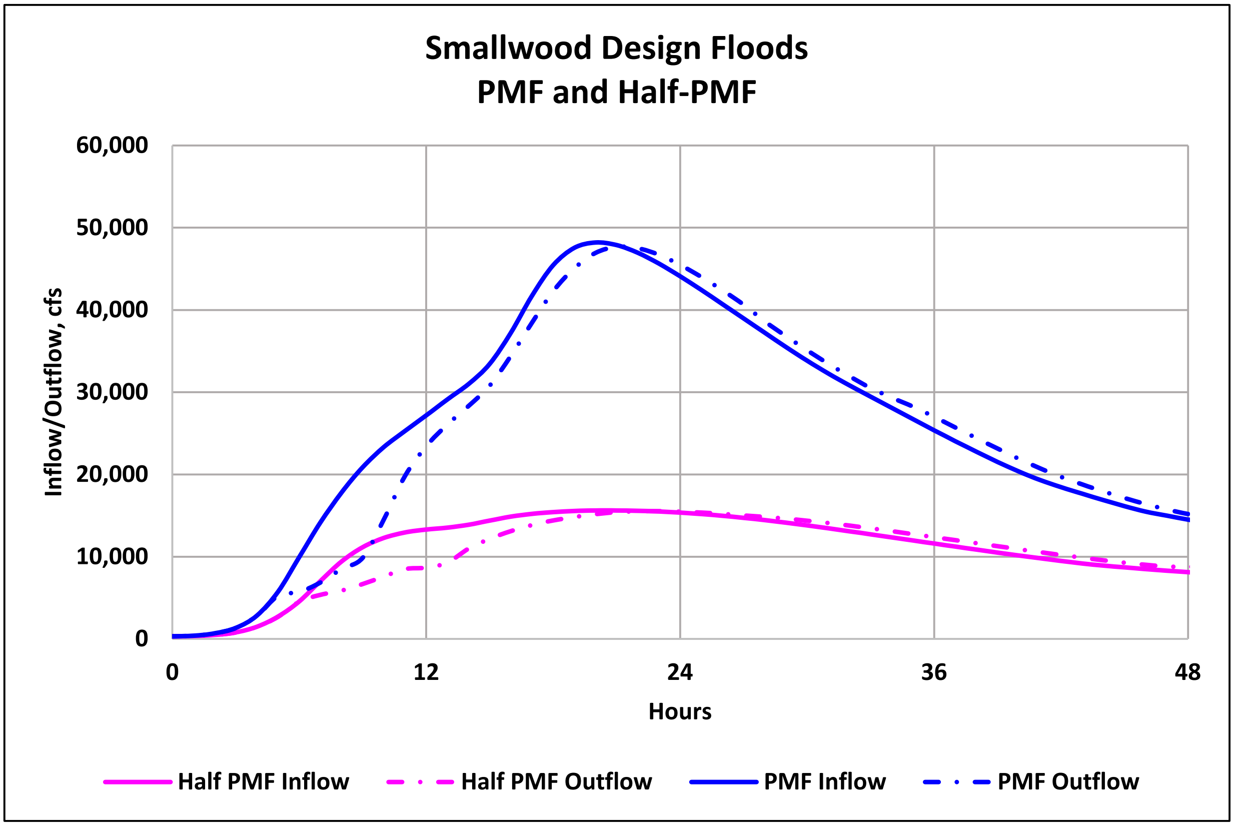


Secord Design Floods
PMF and Half-PMF



Secord Design Floods
100-Yr, 1,000-Yr, and 5,000-Yr

Exhibit 7, Sheet 2



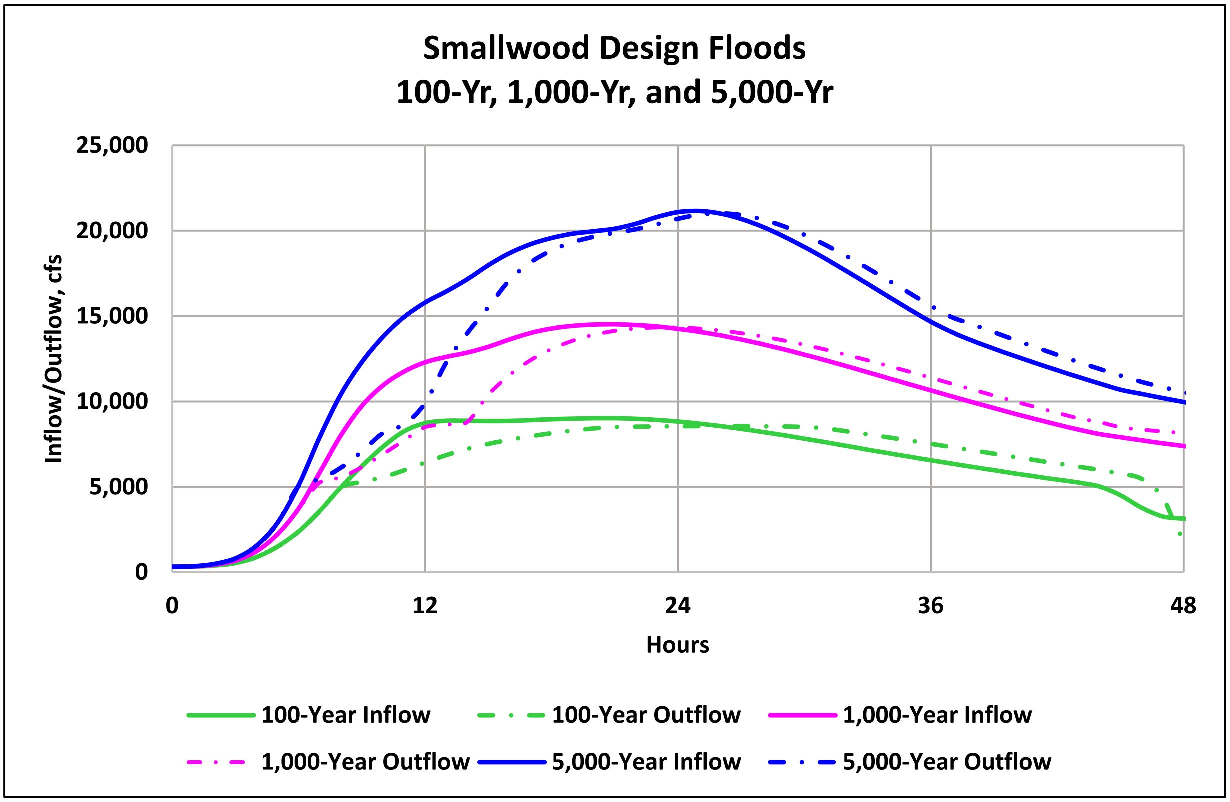
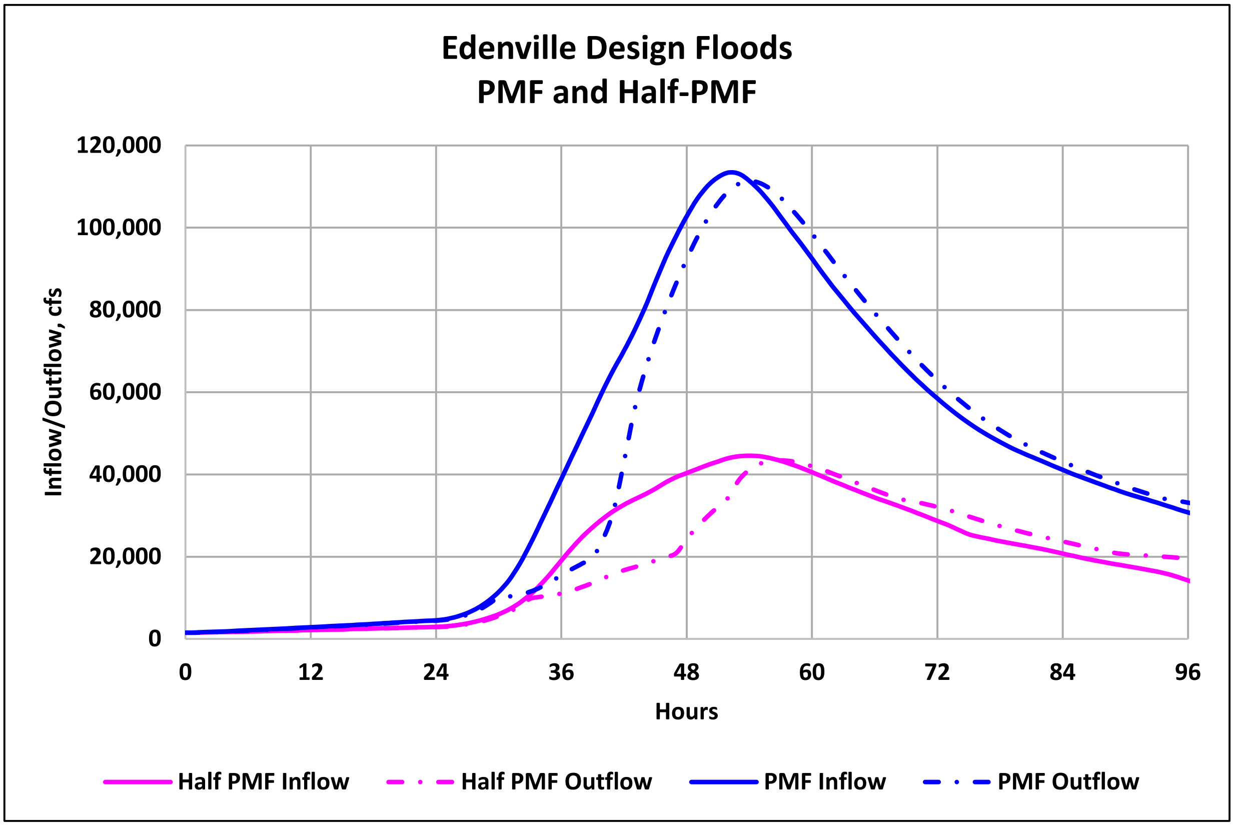


Exhibit 7, Sheet 3



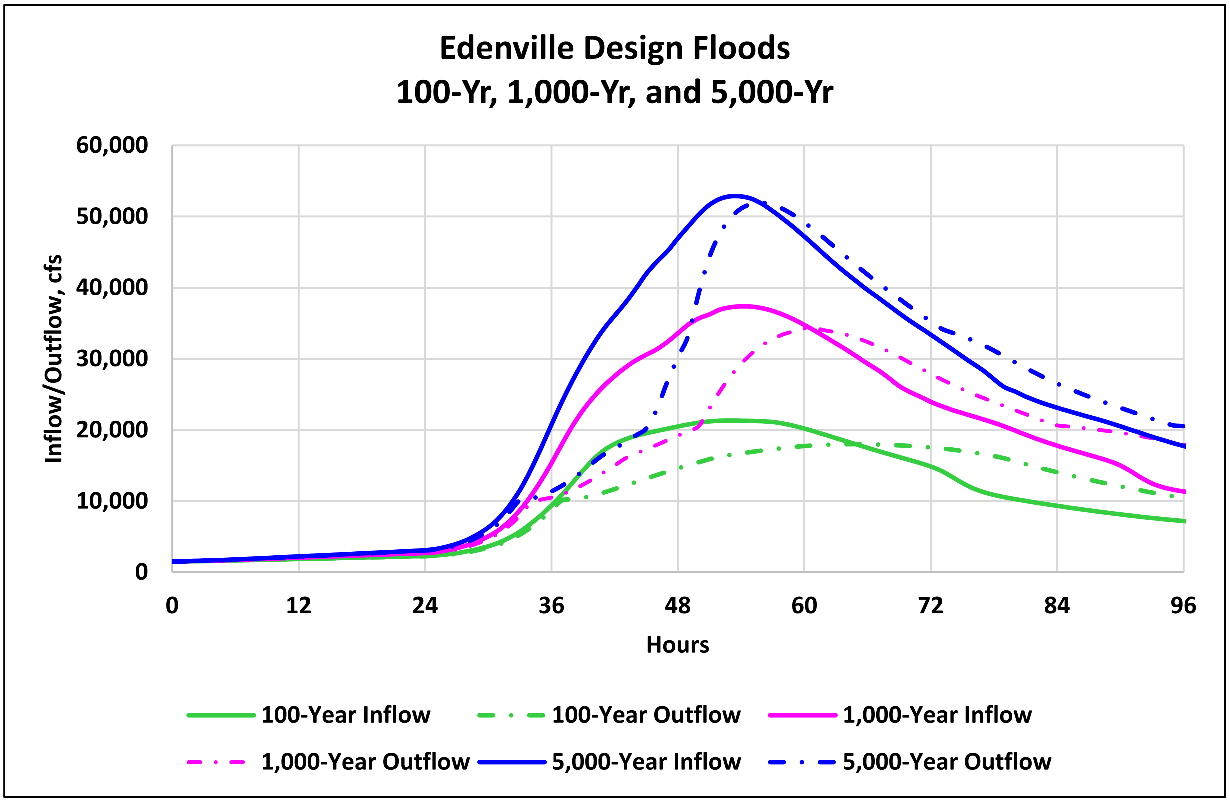
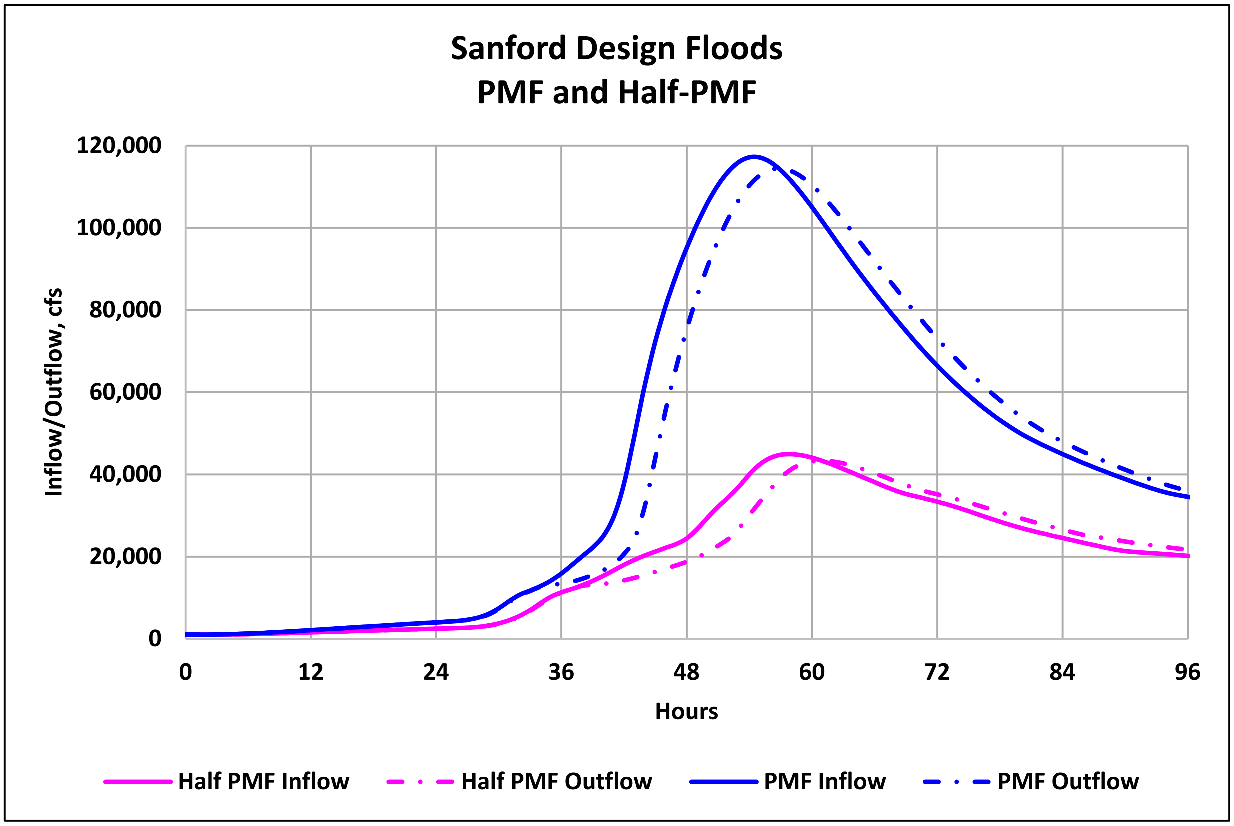


Exhibit 7, Sheet 4



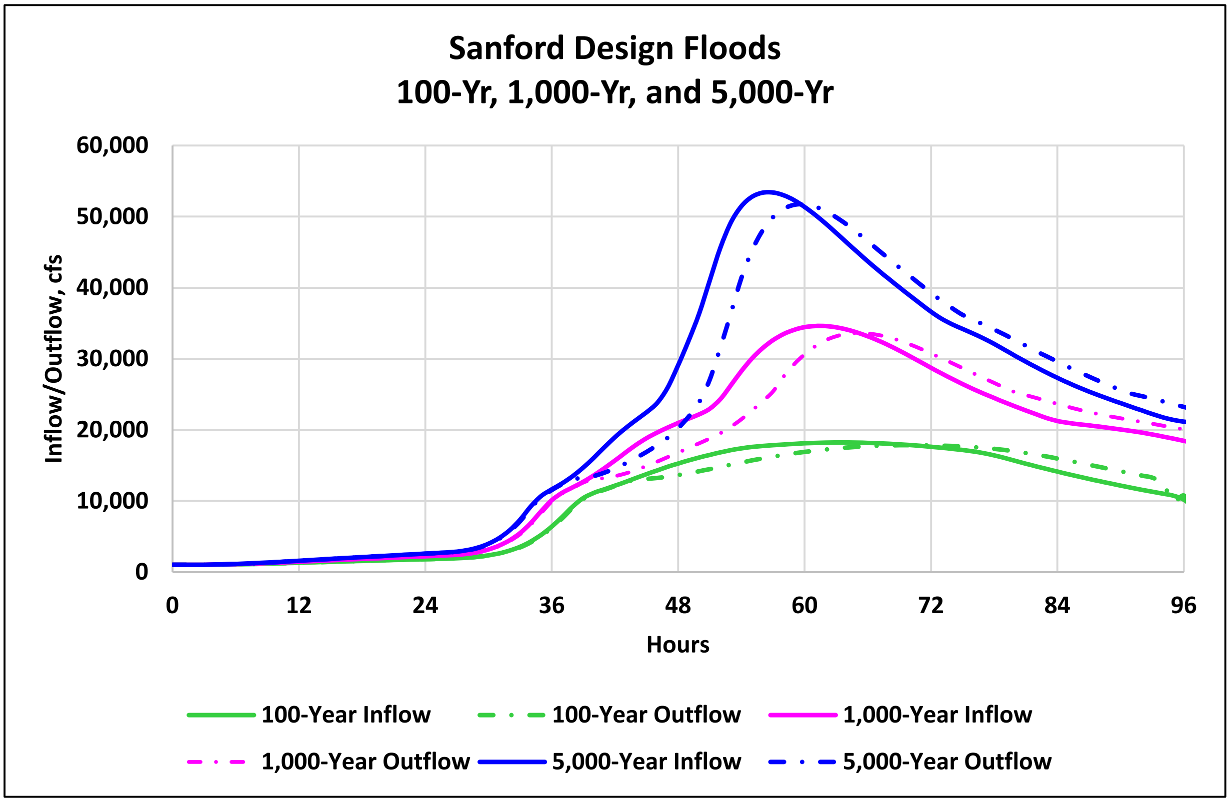
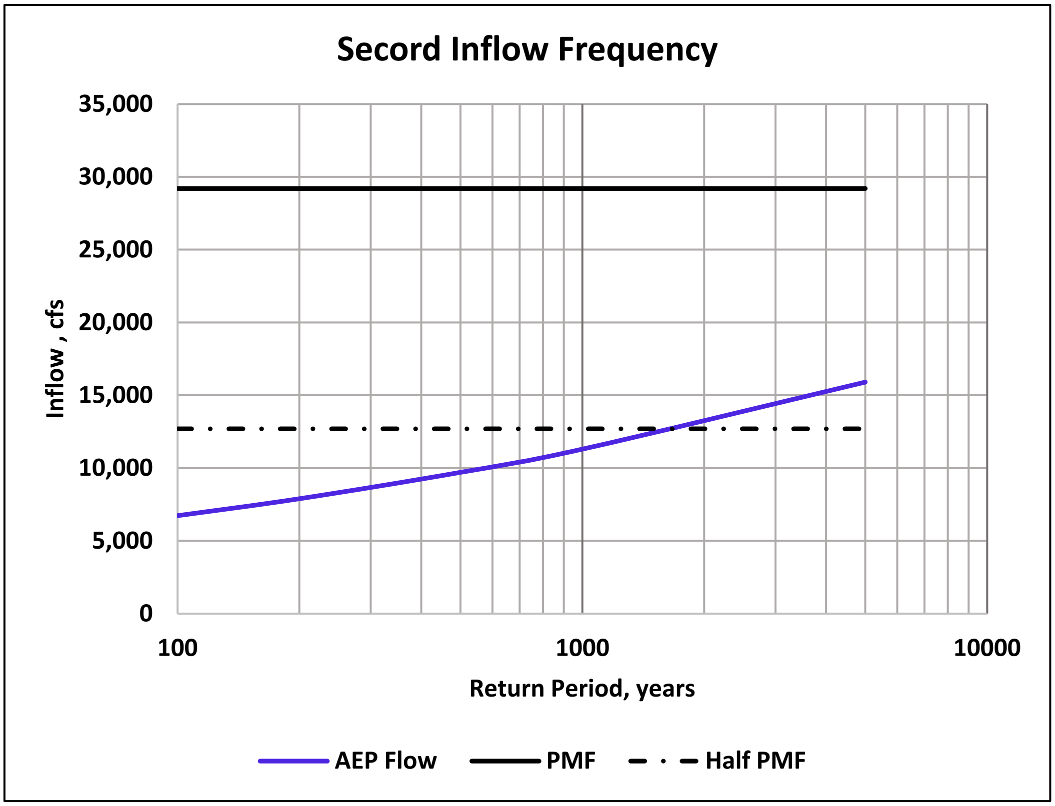


Exhibit 8

Estimated Flood Return Period Plots

Exhibit 8, Sheet 1



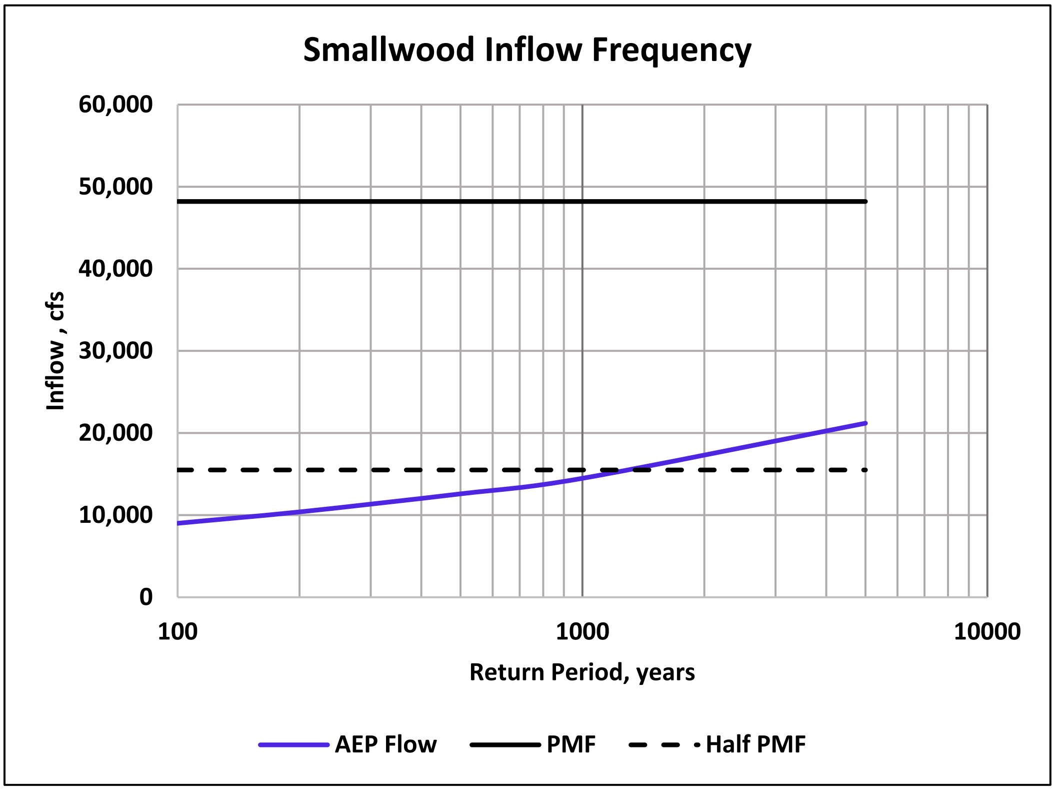


Exhibit 8, Sheet 2