FLOOD STUDY
MAD RIVER AREA

Towns of Fayston, Moretown, Waitsfield, Warren and Waterbury, Vermont

Washington County

Prepared for:

Central Vermont Regional Planning Commission

Prepared by:

DuBois & King inc.

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D&K #123677

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ATTACHMENTS

1.0 INTRODUCTION

This report summarizes the methods, assumptions, and results of the flood study of several streams located in the Mad River watershed, and the Thatcher Brook/Graves Brook watershed in Washington County. The streams included in this study are listed in Table 1. This flood study was funded through a Community Development Block Grant (CDBG) for Disaster Recovery administered by the Central Vermont Regional Planning Commission (CVRPC).

Table 1. Flood Study Streams

Flood Study Streams	Location Towns in Vermont	Length of Flood Study Stream (Miles)
Mad River	**Moretown, Waitsfield and Warren**	**23.5**
Thatcher Brook	**Waterbury**	**7.2**
Shepard Brook	**Waitsfield**	**1.1**
Mill Brook	**Waitsfield and Fayston**	**3.7**
Folsom Brook	**Waitsfield**	**0.3**
Freeman Brook	**Warren**	**1.9**

1.1 Purpose

This flood study was performed for two primary purposes. First, to develop updated hydraulic models that can be used to generate new inundation data for the study streams. The new hydraulic models can be used to support any future work requiring hydraulic analysis on the study streams. The new inundation data were exported to shape files suitable for use in GIS applications. Second, to identify key vulnerable infrastructure and identify treatment options for the vulnerable sites. CVRPC is providing input on the key sites with vulnerable infrastructure. Details of the vulnerability investigations are included in separate reports.

2.0 METHODS

2.1 Survey Methods

For this flood study, the geometry of the stream channel and overbanks was developed using the recently acquired high resolution topographic data based on LIDAR (2013 West Washington County 0.7m Hydro-Flattened DEM) augmented with field surveyed bathymetry data of the channel bottom. LIDAR cannot collect data below the water surface in the stream, therefore channel bathymetry was collected using traditional field surveying techniques.

The bathymetry was collected with survey grade GPS equipment or robotic total stations and tied to local control where practical. In addition to channel bathymetry, the geometry of bridge and dam structures located along the streams were also field surveyed using the same survey methods. Photographs of the bridges and dams on the study streams are included in Attachment II-A.

2.2 Hydrologic Methods

The peak-discharges for each stream studied were developed from the data obtained from the FEMA Flood Insurance Study (FIS) for Washington County dated March 19, 2013. The FEMA FIS provided the 10% (10-year), 2% (50-year), 1% (100-year) and the 0.2% (500-year) annual exceedance probability peak discharges for the study streams. The Gumbel probability distribution was used to develop the 4% (25-year) peak discharge from the 10%, 2%, 1% and 0.2% data. The 50% (2-year) peak discharge was obtained from the USGS Streamstats program. Watershed maps are included in Attachment I-A. The Summary of Peak Discharge Tables are included in Attachment I-B.

The FEMA FIS peak discharges for the Mad River and were compared to the USGS calculated 100-year discharges at 150 stream gages as reported in "Estimation of Flood Discharges at Selected Annual Exceedance Probabilities for Unregulated, Rural Streams in Vermont dated 2014. Based on this comparison the FEMA FIS peak discharges were considered reasonable flows for the the Study Streams. Plots of the 100-year peak discharges are included in Attachment I-C.

2.3 Hydraulic Analysis

2.3.1 Overview

The hydraulic analysis of the streams in this flood study was conducted using U.S. Army Corps of Engineers HEC-RAS computer model (Version 5.0.3). The HEC-RAS model requires the geometry of the stream channel and its floodplain, the geometry of the hydraulic structures such as bridges, culverts and dams, the estimated discharge in the stream, the channel and valley roughness coefficients, expansion-contraction coefficients and the starting water surface level at the downstream end of the model. The program computes a wide range of hydraulic variables for each discharge simulated including water surface elevation, depth, velocity, flow area, and shear stress. All models were computed in steady state sub-critical conditions, using the peak flows reported in Attachment I-B.

2.3.2 Model Extents and Cross Section Locations

The extents of all the streams included in this flood study are listed in Table 2. River Stations (RS), measured in feet, are used to describe cross section locations along the river system. Cross section locations are shown on the maps in Attachment II-B. The locations were selected based on the topography of the stream valley, the presence of features such as road crossings (bridges and culverts), and dams that have significant potential to affect the flood water levels.

Table 2. Flood Study Extents (Study Limits)

Flood Study Streams	Downstream Extent (Study Limit)	Upstream Extent (Study Limit
Mad River	Confluence with the Winooski River	1650 feet upstream of the confluence Stetson Brook
Thatcher Brook	Confluence with the Winooski River	1750 feet upstream of the Guild Hill Road and Maple Street intersection in Waterbury, VT
Shepard Brook	Confluence with the Mad River	The Waitsfield and Fayston town line
Mill Brook	Confluence with the Mad River	7070 feet upstream of the confluence with Chase Brook
Folsom Brook	Confluence with the Mad River	2000 feet upstream of the RT100 large culvert
Freeman Brook	Confluence with the Mad River	460 feet upstream of the Behn Road bridge

2.3.3 HEC-RAS Model Geometry

The geometry of the stream channel and its floodplain and the structures were obtained by two methods, extraction from the LIDAR derived DEM and field survey. The base geometry of the stream channel and floodplain cross sections were developed from a LIDAR derived DEM. Field surveyed bathymetry was merged with the DEM derived cross section data using ArcMap and HEC-RAS GIS tools. On the tributaries and upper reaches of Mad and Thatcher where LIDAR water surface data error was assumed to be small, simple manual adjustments to the channel bottom were made using bathymetric data collected at nearby bridges and engineering judgement. Table 3 is a summary of the geometric data used for the six HEC-RAS models developed in this flood study. Survey data for this project were tied to the NAD 83 horizontal datum and the NAVD 88 vertical datum.

Table 3. Geometry Summary for HEC-RAS Models

HEC-RAS Model	Bathymetry (underwater survey) at Cross Sections	Bridge Survey	Dam Survey
Mad River	• RS 362.45 to RS 106956.1 (20.2 miles) bathymetry [1] • RS106956.1 to RS 124463.5(3.3 miles) no bathymetry, used LIDAR data only	• Surveyed 14 bridges with bathymetry. • Other data 2 bridges.[2]	• Surveyed 2 dams • Other data 1 dam [2]
Thatcher Brook	• RS 334.98 to RS 38559.44 (7.2 miles) bathymetry [1] • RS 4985.09 to RS 5356.91 no bathymetry used LIDAR for ledge gorge • RS 9307.47 to RS 9955.30 no bathymetry used LIDAR for ledge gorge	• Surveyed 12 bridges with bathymetry. • Bridge Plans used to supplement LIDAR and survey for the I-89 N&S Bound and I-89 Ramp	Total - 4 dams • Used LIDAR to model areas with the dams, no survey. Dams located in gorge area. Two of the dams partially breached.

Shepard Brook	• Bathymetry obtained at 2 bridges. • Channel bottom lowered 0.5 to 1.0 ft below LIDAR data.	• Surveyed 2 bridges with bathymetry.	No dams.
Mill Brook	• Bathymetry obtained at 7 bridges. • Channel bottom lowered 0.5 to 1.0 ft below LIDAR data.	• Surveyed 7 bridges with bathymetry.	No dams.
Folsom Brook	• Bathymetry obtained at 1 bridges. • Channel bottom lowered 0.5 to 1.0 ft below LIDAR data.	• Surveyed 1 bridges with bathymetry.	No dams.
Freeman Brook	• Bathymetry obtained at 1 bridges. • Channel bottom lowered 0.5 to 1.0 ft below LIDAR data.	• Surveyed 5 bridges with bathymetry.	No dams.

[1] For channel cross sections with no bathymetry, the channel bottom was developed from nearby underwater information.
[2] Other data includes available bridge plans or other hydraulic reports.

Manning's "n" roughness values were assigned to the channel and overbanks on the basis of field observation, standard references and in some cases calibration to an observed high water level. Table 4 is a summary of the Manning "n" values used in the six HEC-RAS models for this flood study. The expansion and contraction coefficients are used in HEC-RAS models to account for flow expansions and contractions that occur naturally on a river system and the artificial ones that are created at hydraulic structures. The expansion and contraction coefficients were assigned in the models in accordance with the standard references.

The HEC-RAS model requires a starting water surface to perform the calculation. The starting water surface elevations for the six HEC-RAS models were determined by the normal depth method. This method uses the downstream slope of the stream being modeled. The slope was determined using the DEM.

The hydraulic analysis for this flood study was based on unobstructed flow. The flood levels calculated are considered valid only in the hydraulic structures remain unobstructed, operate properly and do not fail.

Table 4. Manning "n" Values (Roughness Coefficients)

HEC-RAS Model / Stream	Channel "n"	Overbank "n"
Mad River	0.035 to 0.075	0.03 to 0.08
Thatcher Brook	0.045 to 0.075	0.03 to 0.10
Shepard Brook	0.055	0.03 to 0.10
Mill Brook	0.065	0.03 to 0.10
Folsom Brook	0.055	0.03 to 0.10
Freeman Brook	0.075	0.03 to 0.10

2.3.4 HEC-RAS Model Calibration

Calibration of HEC-RAS models is a method used to improve the results of the computer models of stream and rivers. The most common calibration approach for a HEC-RAS model requires good channel and floodplain geometry (Geometry constructed from LIDAR is the best method to develop geometry), a known flood flow (measured flow) on the river and a known high water mark (HWM). With reliable geometry, a known flow and a known HWM, the calibration of a HEC-RAS model is accomplished by adjusting the model's parameters, such as roughness coefficients and expansion and contraction coefficients to match the known HWM. Some of the factors that can affect the calibration results of a HEC-RAS model are the accuracy of the flow data, channel and floodplain geometry, roughness coefficients, changes in roughness at high flows, channel and floodplain storage, debris and accuracy of the high water marks.

The Mad River has a USGS stream gage No. 04288000 near Moretown, VT that has measured flows on the Mad River since 1928. During the Tropical Storm Irene on August 28, 2011 the USGS gage on the Mad River measured 24,200 cfs (Stage 19.3 feet) at 7:15 pm. Since the flood flow and the stage were known at this location on the Mad River, the Mad River HEC-RAS model was calibrated at this location. The USGS known stage-discharge rating curve at the Mad River gage was compared to the HEC-RAS computed water surface elevations at the Mad River gage location, RS 21006.12. Attachment II-C includes a plot comparing the computed water surface elevation to the USGS rating curve. Based on this analysis, an "n" value of 0.05 matches reasonably well to the USGS rating curve from 7,500 cfs to 24,000 cfs. An "n" value of 0.045 was modeled to show the effects of lowering the roughness coefficient.

HWMs were known at a number of hydraulic structures along the Mad River from RS 1665.9 (Demas Road in Warren) to RS 91019 (Butternut Hill Road in Waitsfield). The HWMs were documented in a USGS report entitled "High –Water Marks from Flooding in Lake Champlain from April through June 2011 and Tropical Storm Irene in August 2011 in Vermont". The Irene flood flows at the HWM locations were not known (not measured by the USGS). The Irene flood flows at the other locations were estimated using a discharge-drainage area ratio equation and the known Irene flow at the USGS stream gage in Moretown. The estimated Irene flood flows along the Mad River are included in Attachment I-B. The HEC-RAS model was run with the estimated Irene flows and the HEC-RAS computed water surface elevations were compared to the USGS HWMs. The calibration approach on the Mad River was to focus on the reach in the vicinity of the USGS stream gage and based on the "n" values needed to match the known data at the gage. That information and engineering judgement was used on other reaches of the Mad River. The results are documented in Attachment II-D.

The following general statements can be drawn from comparing the computed HEC-RAS water surface elevation to the HWMs:

- The HEC-RAS model computed water surface elevation (CWSEL) agrees very well with the USGS rating curve at the USGS gage using a channel "n" of 0.05. See Attachment II-C.
- The Model's CWSEL agrees reasonably well with the HWMs on the upstream side of the bridges. The CWSELs typically are lower than the HWMs from 0.0 to -1.5 feet.
- The Model's CWSEL varies significantly with the HWMs on the downstream side of the bridges. Typically calibrating to a HWM on the downstream side of a bridge is more difficult, flow depths and patterns vary greatly during flood events.

2.3.5 Inundation Mapping

The modeled water surface elevations were used to develop inundation maps for the study streams under the 10%, 4%, 2%, 1% and 0.2% AEP storm events. The development of inundation limits was conducted using the HEC-RASMapper application within HEC-RAS. Water surface elevations at each cross section were interpolated onto a HEC-RAS generated triangulated irregular network (TIN) surface representing the water surface along the study stream. The TIN water surface was then compared with the LIDAR derived DEM in order to generate a continuous depth map along the entire study reach. Locations on the depth map that are equal to zero represent the perimeter of flooded areas and are delineated and plotted as inundation limits on the maps in Attachment II-B.

In some areas where the water surface elevation changes abruptly, such as at overtopping roads, the automated inundation mapping processes do not fully capture potentially flooded areas. Sites with complex hydraulic geometry require individual evaluation. Inundation results from this study should be used as a starting point in evaluating the degree of flood impact at those sites.

The inundation maps were generated using flow conditions only in the study streams, and did not include influence of backwater from downstream reaches. This was done to evaluate the flooding impacts due to flow solely in the study stream without making assumptions about flow conditions on influencing streams. If a particular site is susceptible to flooding from multiple streams, the effects of flooding conditions from all influential streams must be considered to accurately characterize the potential flooding condition.

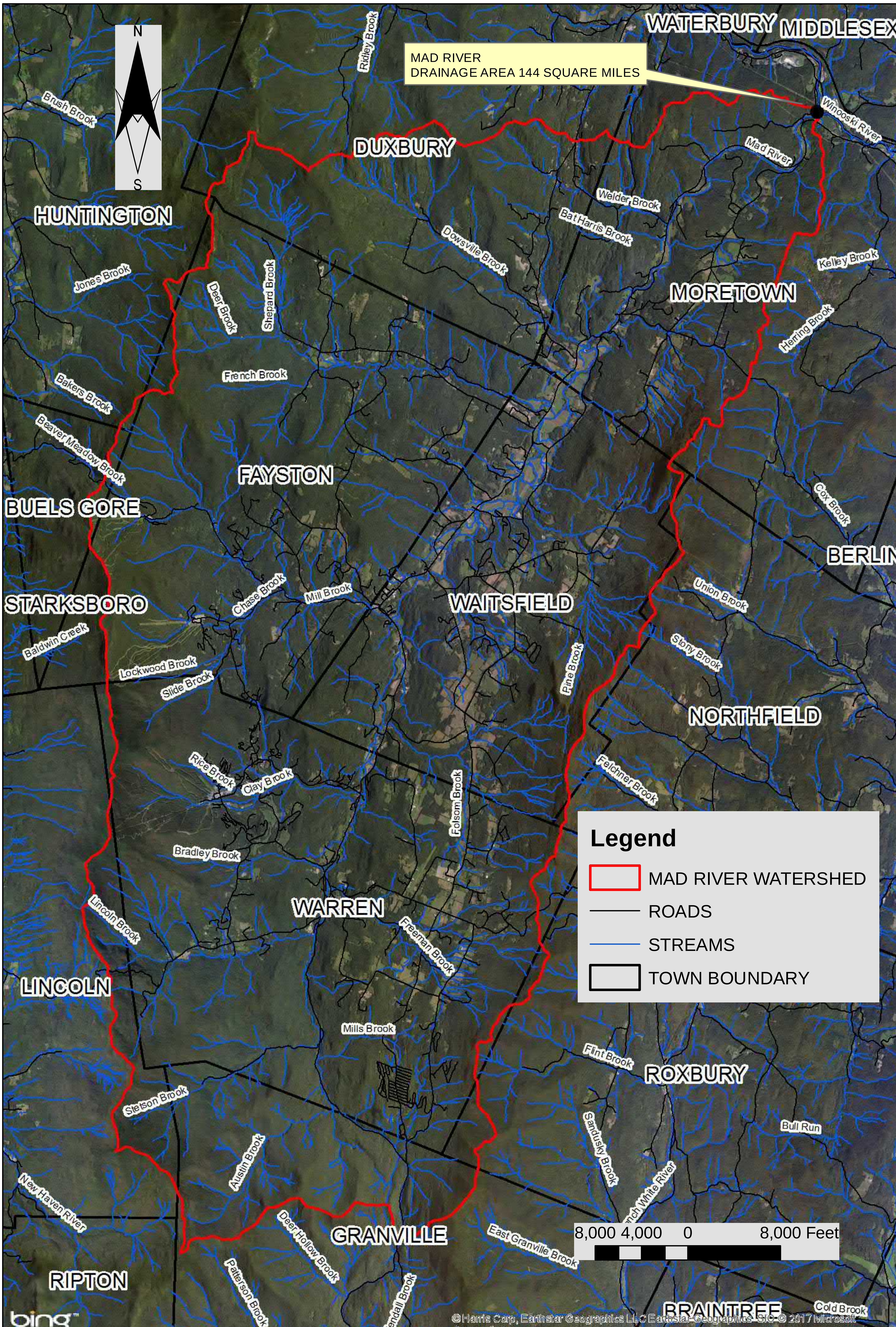
3.0 RESULTS AND DISCUSSION

The primary goal for this flood study was the development of new HEC-RAS models of the flood study streams. New inundation maps were created based on the results of the model and are available in paper and electronic form (shape files) for the study streams. The electronic data deliverables include the HEC-RAS models, stream centerlines, flowpath centerlines, the location of the river cross sections and the flood inundation shape files for the 10% to the 0.2% AEP storm events.

A summary of modeling notes is included in Attachment III which documents observations and challenges encountered in the development of the model. The updated models generally agree with the existing models with several key differences described in Attachment III. Where high water marks were available on the Mad River, the model was successfully calibrated to the extent practical. Areas where it was difficult to match high water marks were generally areas with complex hydraulic geometry that demonstrate the limitations of traditional 1-dimensional hydraulic modeling in steep mountain streams. The results of this study should be used and interpreted carefully, especially in areas of rapid water surface elevation change. At many of these complex sites the use of higher resolution modeling (including 2-dimensional models) may be necessary to better characterize and understand the flow patterns.

ATTACHMENT I-A

WATERSHED MAPS



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WATERSHED ORTHOPHOTO MAP
MAD RIVER

TOWN OF MORETOWN, TOWN OF WAITSFIELD,
TOWN OF WARREN, TOWN OF FAYSTON, VERMONT
CALEDONIA COUNTY

MAY 2017

DRAWN BY: CJK	DATE: 05/28/2017
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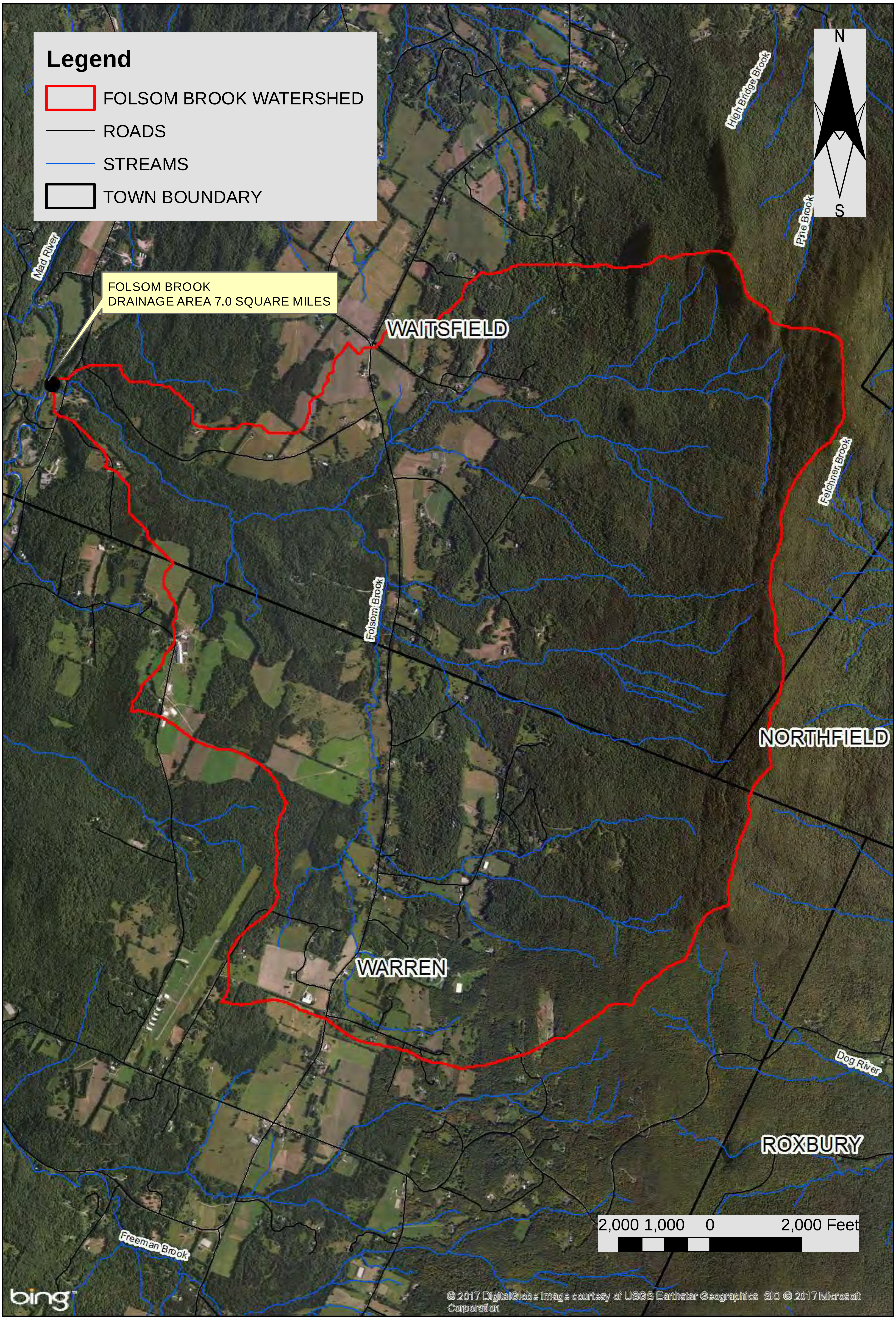

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WATERSHED ORTHOPHOTO MAP
FOLSOM BROOK

TOWN OF WAITSFIELD, TOWN OF WARREN, VERMONT
WASHINGTON COUNTY

MAY 2017

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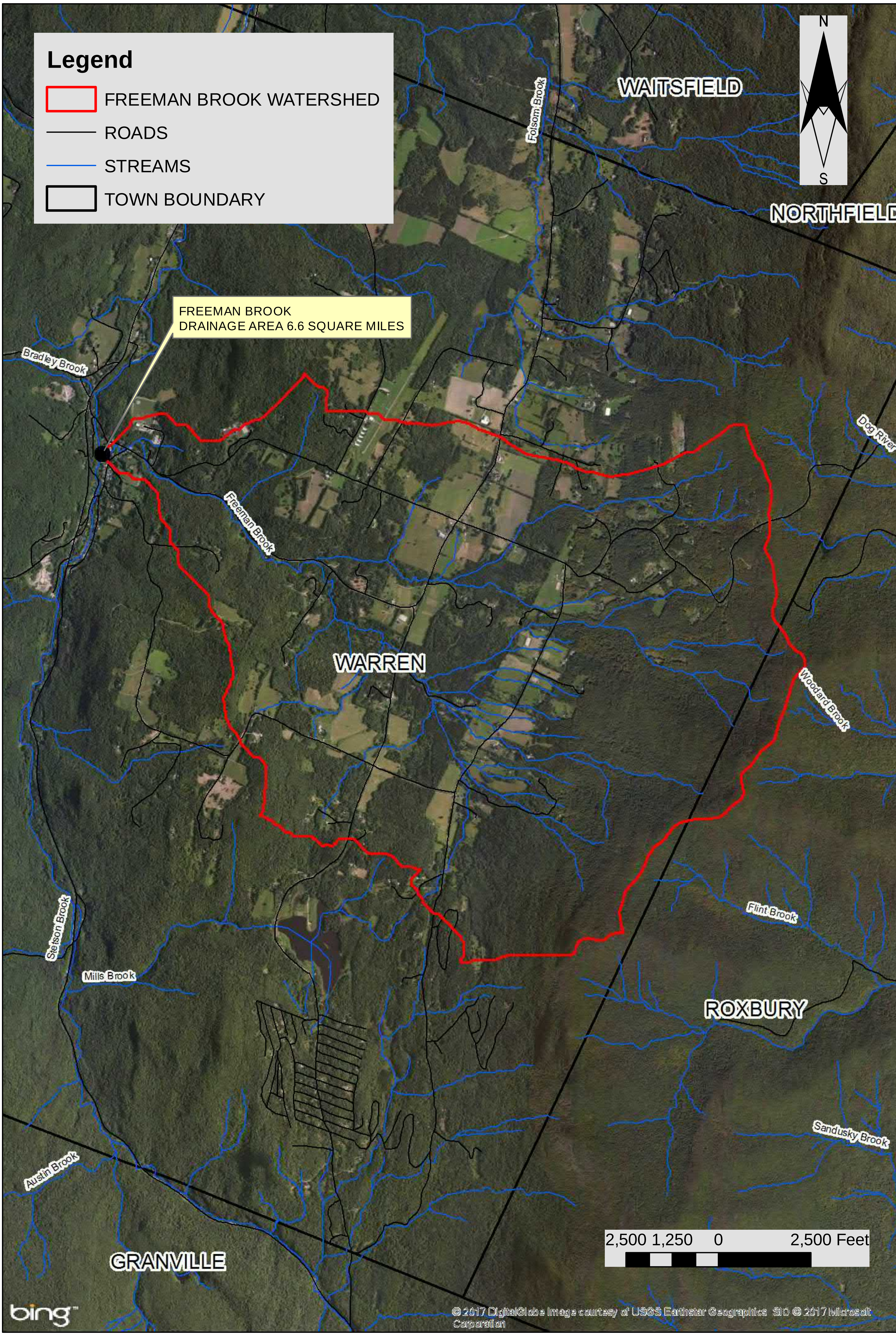

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WATERSHED ORTHOPHOTO MAP
FREEMAN BROOK

TOWN OF WARREN, VERMONT
WASHINGTON COUNTY

MAY 2017

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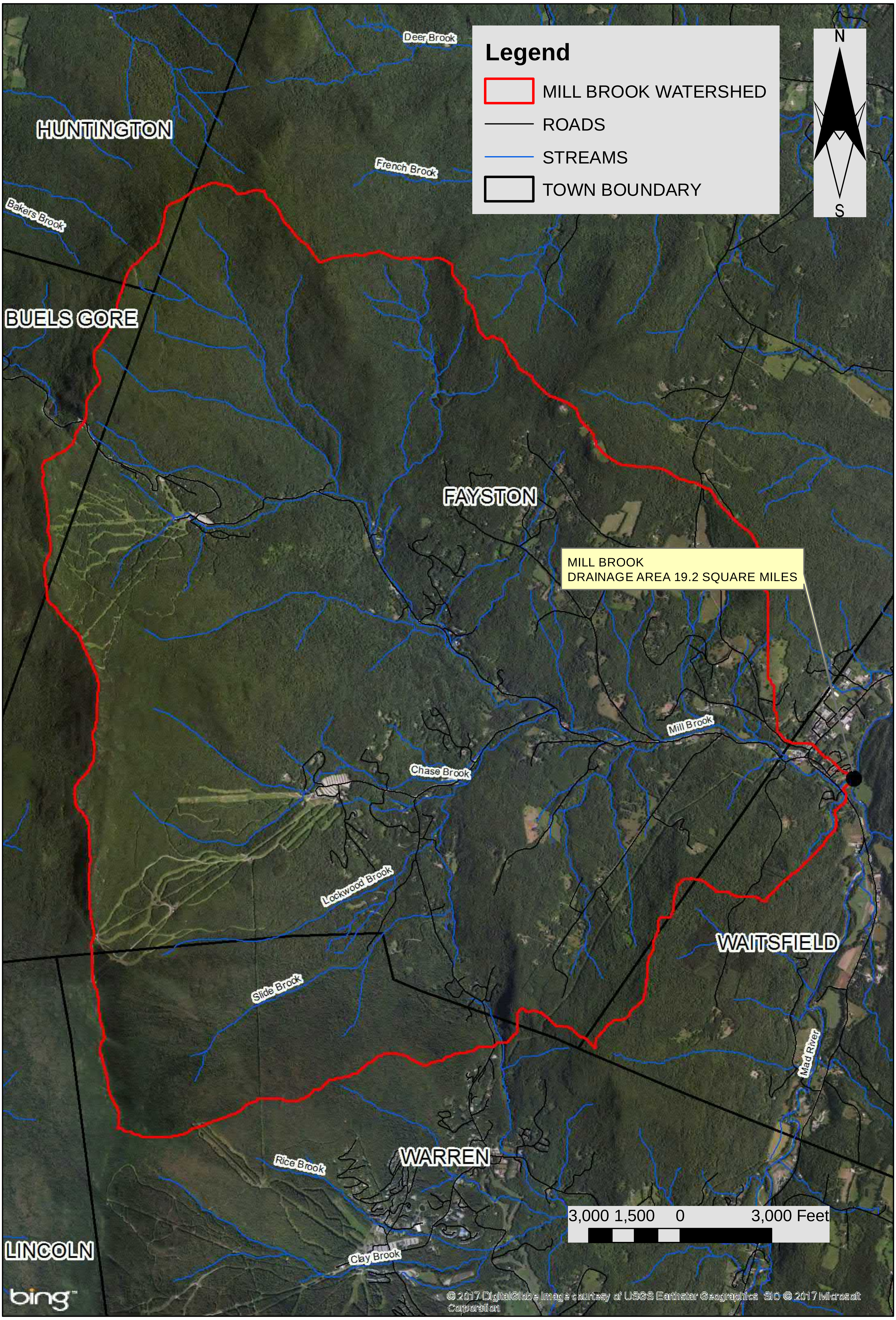

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WATERSHED ORTHOPHOTO MAP
MILL BROOK

TOWN OF FAYSTON, TOWN OF WAITSFIELD,
TOWN OF WARREN, VERMONT
WASHINGTON COUNTY

MAY 2017

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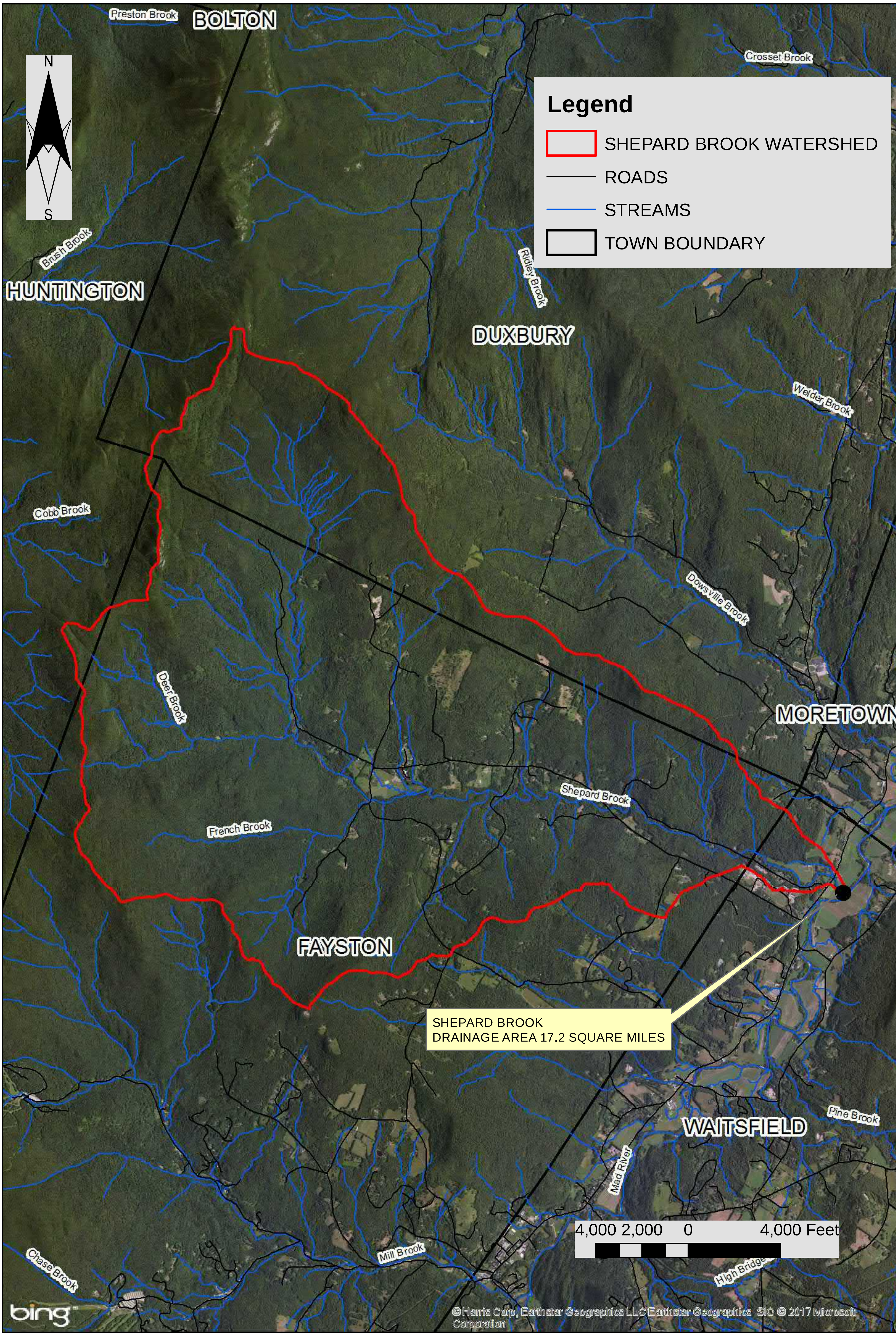

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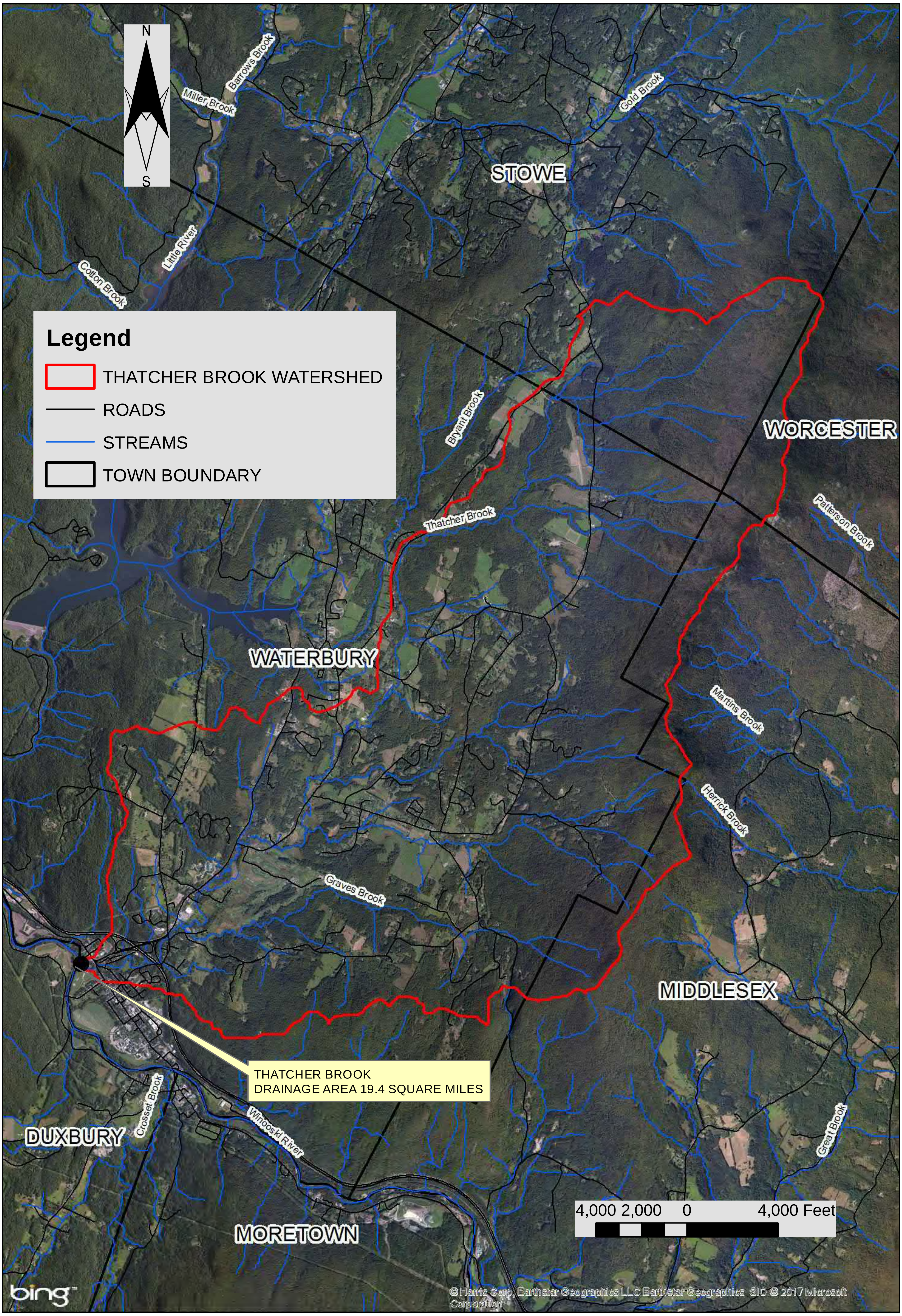
WATERSHED ORTHOPHOTO MAP *SHEPARD BROOK* TOWN OF FAYSTON, TOWN OF MORETOWN, TOWN OF DUXBURY, VERMONT WASHINGTON COUNTY MAY 2017	DRAWN BY: CJK	DATE: 05/28/2017
	CHECKED BY:	PROJECT NO: 123677
	PROJ. ENG: CJK	FIGURE NO:
	SCALE:	



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WATERSHED ORTHOPHOTO MAP
THATCHER BROOK

TOWN OF WATERBURY, VERMONT
WASHINGTON COUNTY

MAY 2017

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ATTACHMENT I-B

SUMMARY OF PEAK DISCHARGES

Flooding Source and Location	**Drainage Area [1] (sq. miles)**	**Peak Discharge [2] (cfs) for given Annual Exceedance Probability**						
Mad River		50% [3] (2-year)	10% (10-year)	4% [4] (25-year)	2% (50-year)	1% (100-year)	0.2% (500-year)	Irene Est. Flow [5]
Mouth of River	144.0	5,480	10,900	14,500	17,600	21,300	32,200	24,910
Upstream of Welder Brook	134.0	5,310	10,300	13,500	16,600	20,100	30,500	23,480
Upstream of Dowsville Brook	116.0	4,750	9,210	12,500	14,900	18,000	27,300	20,860
Upstream of Shepard Brook	96.0	3,970	8,000	10,750	12,800	15,600	23,600	17,850
Upstream of Pine Brook	87.6	3,710	7,400	10,000	12,000	14,500	22,000	16,620
Upstream of High Bridge Brook	77.8	3,380	6,800	9,250	10,900	13,200	20,100	15,050
Upstream of Mill Brook	57.4	2,480	5,300	7,250	8,600	10,400	15,800	11,630
Upstream of Folsum Brook	47.3	2,090	4,600	6,000	7,400	9,000	13,700	9,930
Upstream of Clay Brook	39.7	1,750	3,82	4,570	5,915	6,857	9,289	8,640
Upstream of Bradley Brook	34.5	1,540	3,664	4,040	5,443	6,319	8,548	7,700
Upstream of Freeman Brook	27.7	1,260	3,089	3,900	4,589	5,327	7,206	6,430
Upstream of Lincoln Brook [6]	19.2	870	2,314	2,950	3,409	3,941	5,279	4,760
Upstream of Stetson Brook [6]	12.3	550	1,644	2,050	2,364	2,700	3,500	3,300

[1] Drainage area measured using the USGS Streamstats program.

[2] Peak discharges are from the FEMA Flood Insurance Study dated 2013 or the HEC-2 data obtained from FEMA or the State of Vermont.

[3] 50% Annual Exceedance Probability obtained from USGS Streamstats program.

[4] 4% Annual Exceedance Probability based on a probability plot of the 10%, 2%, 1% and 0.2% Annual Exceedance Probabilities.

[5] Estimated peak discharges along the Mad River based on the USGS estimated Irene flow at the USGS 0428800 stream gage on the Mad River in Moretown with a drainage area of 139.0 square miles. The USGS estimated the Irene flow at the Mad River gage to be 24, 200 cfs at 7:15 PM on August 28, 2011. The Irene peak discharges at other locations on the Mad River were estimated using the following equation, $Q_{Irene} = Q_{Gage} (A_{Irene}/A_{Gage})^{0.822}$.

[6] Peak discharges based on a regression equation developed from the FEMA Mad River data from its Mouth to upstream of Freeman Brook.

Summary of Discharges for Thatcher Brook and Tributaries of the Mad River

Flooding Source and Location	Drainage Area [1] (sq. miles)	Peak Discharge [2] (cfs) for given Annual Exceedance Probability					
Thatcher Brook		50% [3] (2-year)	10% 10-year)	4% [4] (25-year)	2% (50-year)	1% (100-year)	0.2% (500-year)
Mouth of River	19.4	800	1650	2250	2850	3350	4350
Upstream of Graves Brook	15.4	600	1450	1950	2500	2950	3850
Upstream of Unnamed Brook just north of second Guptil Road bridge	10.5	510	1150	1600	2000	2300	2900
Shepard Brook							
Mouth of Shepard Brook	17.2	940	1530	2100	2550	3100	4660
Mill Brook							
Mouth of Mill River	19.2	1080	1600	2250	2800	3400	5200
Downstream of the third RT17 bridge from Mill Brook's mouth	15.3	924	1420	1800	2133	2538	3815
Upstream of Chase Brook near German Flats Road	8.0	514	630	800	950	1130	1715
Folsom Brook							
Mouth of Folsom Brook	7.0	390	750	1000	1290	1610	2510
Freeman Brook							
Mouth of Freeman Brook	6.6	350	1031	1300	1532	1778	2405
	4.0	240	710	900	1050	1220	1660

[1] Drainage area measured using the USGS Streamstats program.

[2] Peak discharges are from the FEMA Flood Insurance Study dated 2013 or the HEC-2 data obtained from FEMA or the State of Vermont.

[3] 50% Annual Exceedance Probability obtained from USGS Streamstats program.

[4] 4% Annual Exceedance Probability based on a probability plot of the 10%, 2%, 1% and 0.2 % Annual Exceedance Probabilities.

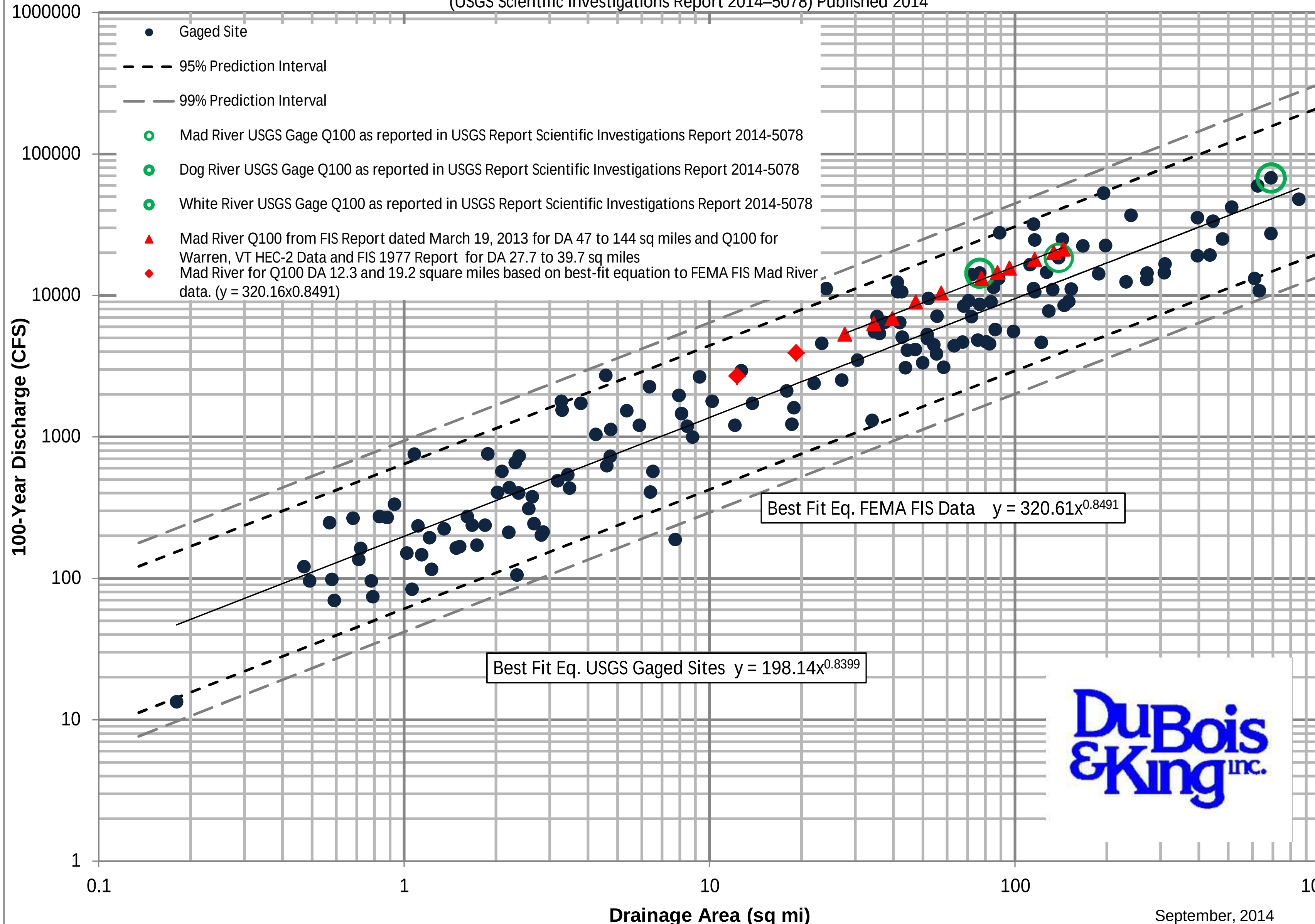
ATTACHMENT I-C

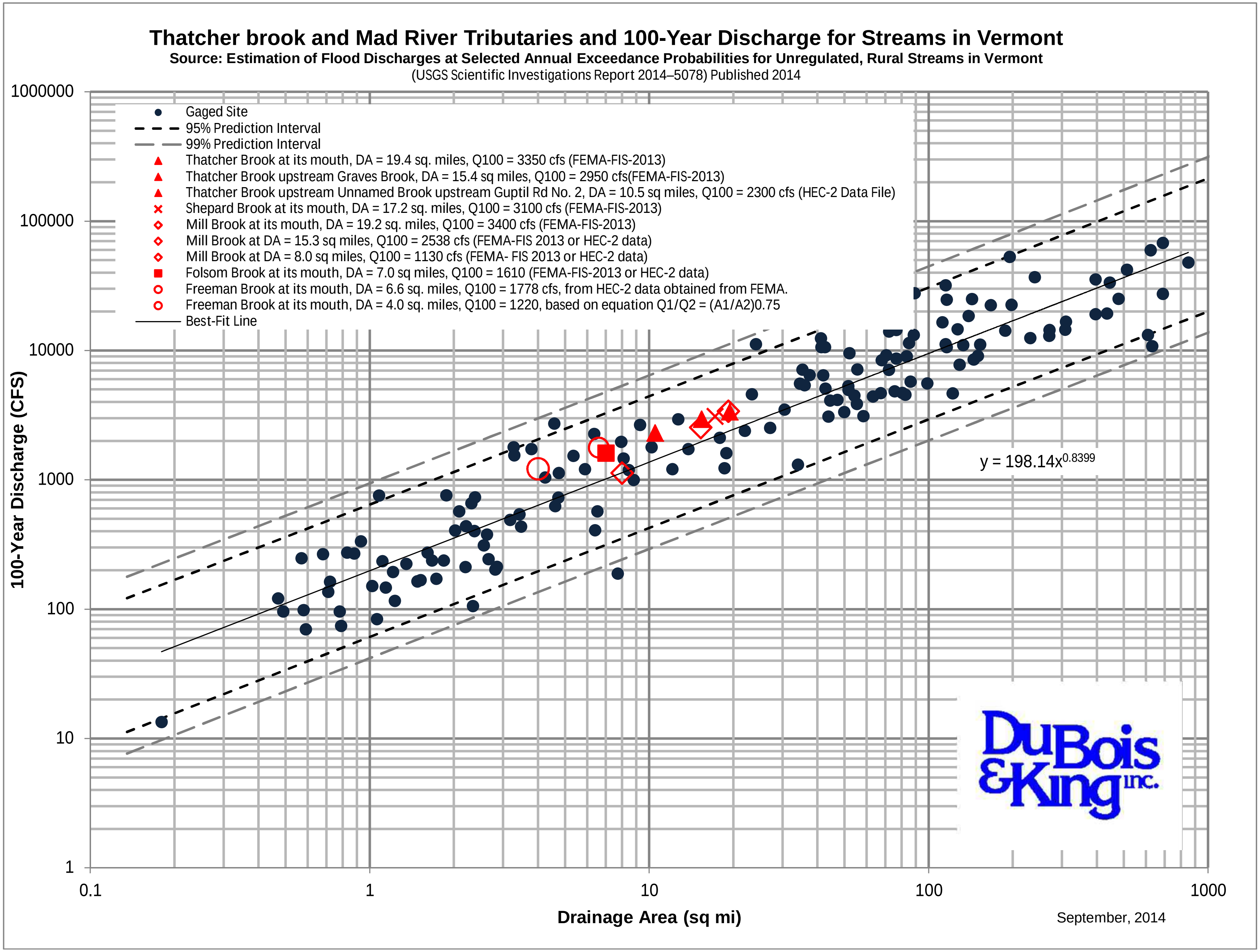
PLOTS OF ESTIMATED 100-YEAR DISCHARGES VS. GAUGED DATA

100-Year Discharge for Streams in Vermont

Source: Estimation of Flood Discharges at Selected Annual Exceedance Probabilities for Unregulated, Rural Streams in Vermont

(USGS Scientific Investigations Report 2014–5078) Published 2014





Thatcher brook and Mad River Tributaries and 100-Year Discharge for Streams in Vermont
Source: Estimation of Flood Discharges at Selected Annual Exceedance Probabilities for Unregulated, Rural Streams in Vermont
(USGS Scientific Investigations Report 2014–5078) Published 2014
Gaged Site
95% Prediction Interval
99% Prediction Interval
Thatcher Brook at its mouth, DA = 19.4 sq. miles, Q100 = 3350 cfs (FEMA-FIS-2013)
Thatcher Brook upstream Graves Brook, DA = 15.4 sq miles, Q100 = 2950 cfs(FEMA-FIS-2013)
Thatcher Brook upstream Unnamed Brook upstream Guptil Rd No. 2, DA = 10.5 sq miles, Q100 = 2300 cfs (HEC-2 Data File)
Shepard Brook at its mouth, DA = 17.2 sq. miles, Q100 = 3100 cfs (FEMA-FIS-2013)
Mill Brook at its mouth, DA = 19.2 sq. miles, Q100 = 3400 cfs (FEMA-FIS-2013)
Mill Brook at DA = 15.3 sq miles, Q100 = 2538 cfs (FEMA-FIS 2013 or HEC-2 data)
Mill Brook at DA = 8.0 sq miles, Q100 = 1130 cfs (FEMA- FIS 2013 or HEC-2 data)
Folsom Brook at its mouth, DA = 7.0 sq miles, Q100 = 1610 (FEMA-FIS-2013 or HEC-2 data)
Freeman Brook at its mouth, DA = 6.6 sq. miles, Q100 = 1778 cfs, from HEC-2 data obtained from FEMA.
Freeman Brook at its mouth, DA = 4.0 sq. miles, Q100 = 1220, based on equation Q1/Q2 = (A1/A2)0.75
Best-Fit Line
1000000
100000
10000
1000
100
10
1
100-Year Discharge (CFS)
y = 198.14x^0.8399
0.1
1
10
100
1000
Drainage Area (sq mi)
September, 2014
DuBois &King inc.

ATTACHMENT II-A

BRIDGE AND DAM PHOTOGRAPHS

MAD RIVER

BRIDGE AND DAM PHOTOGRAPHS

Demas Road – Entrance to bridge (RS 1665.91)

RT110B_B7 – Entrance to bridge (RS 6161.17)

RT110B_B7 (RS 6161.17)

RT110B_B7 (RS 6161.17)

RT110B_B7 (RS 6161.17)

Dam Ampersand (RS 8262.22)

Dam Ampersand (RS 8262.22)

Low dam at USGS Gage downstream of Bridge Road (RS 20933.88)

Bridge Road upstream USGS gage (RS 21081.72)

Bridge Road upstream USGS gage, looking upstream. (RS 21081.72)

Bridge Road upstream USGS gage , looking upstream (RS 21081.72)

RT110B_B4 – Entrance to bridge, left overbank (RS 31326.51)

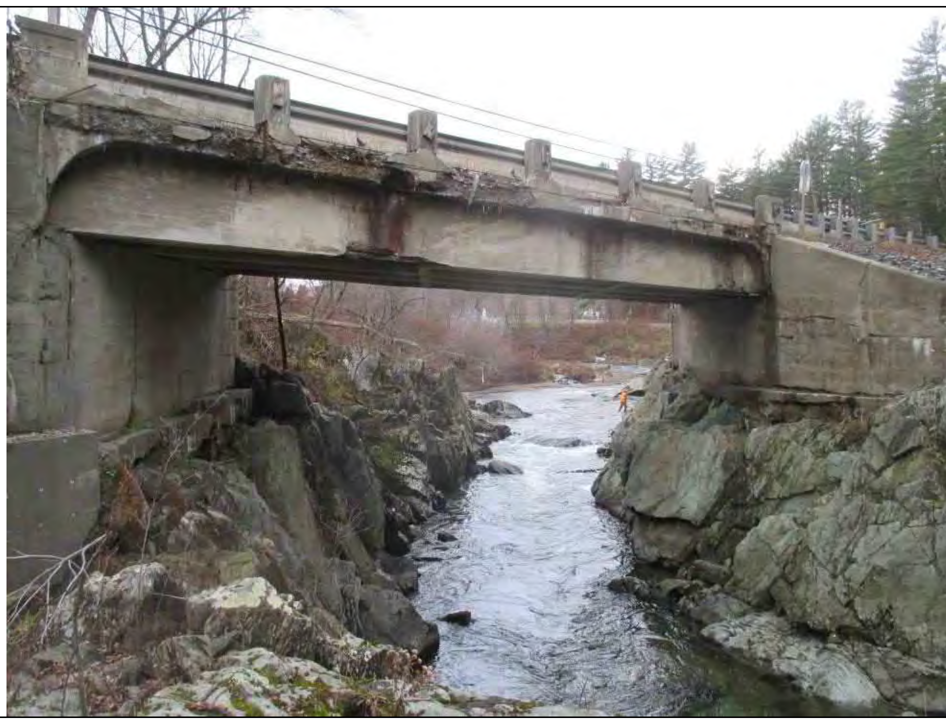
RT110B_B4 – Entrance to bridge, right overbank (RS 31326.51)

Fletcher Road_B42 outlet of bridge, looking upstream (RS 33765.39)

Fletcher Road_B42 outlet of bridge, looking upstream (RS 33765.39)

RT110B_B2- Entrance to Bridge, looking downstream (RS 36781.04)

RT110B_B2- Entrance to Bridge, looking downstream (RS 36781.04)



RT110B_B2- Outlet, looking upstream (RS 36781.04)

Meadow Road_B24- Entrance to bridge (RS 51950.98)

Meadow Road_B24- outlet of bridge (RS 51950.98)

Tremblay Road_B25 – Entrance to bridge (RS 64099.75)

Tremblay Road_B25 – Entrance to bridge (RS 64099.75)

Bridge Street Covered Bridge_CB4- Entrance to Covered Bridge (RS 73267.20)

Bridge Street Covered Bridge_CB4- Outlet from Covered Bridge (RS 73267.20)

RT100_B177 – Entrance to bridge (RS 81704.02)

RT100_B177 – Outlet from bridge (RS 81704.02)

Butternut Hill Road_B22- Entrance to bridge (RS 91019.45)

Butternut Hill Road_B22- Looking upstream, left abutment (RS 91019.45)

Butternut Hill Road_B22- Looking upstream, right abutment (RS 91019.45)

RT100_B173-Entrance to the bridge(Looking downstream) (RS 96377.68)

RT100_B173-Outlet to the bridge(Looking upstream) (RS 96377.68)

Main Street_B30- Entrance to bridge (RS 107786.8)

Main Street_B30- outlet from bridge (RS 107786.8)

Warren Dam (RS 109709.7)

Warren Dam (RS 109709.7)

Warren Dam – Downstream of Warren Dam (RS 109709.7)

Warren Covered Bridge – Entrance (RS 110006.4)

Warren Covered Bridge – Outlet (RS 110006.4)

Rt100_B169- Outlet of bridge (RS 112101.0)

Rt100_B167- Entrance to bridge (RS 122795.8)

MAD RIVER TRIBUTARIES

BRIDGE PHOTOGRAPHS

Shepard Brook – RT 100 - Entrance to bridge (RS 939.49)

Shepard Brook – Entrance to Private Bridge (RS 1941.68)

Mill Brook – RT100 – Entrance to bridge (RS 822.25)

Mill Brook – RT17 – Entrance to bridge (RS 2954.57)

Mill Brook – Private bridge – Entrance to bridge (RS 4504.76)

Mill Brook – Mill Brook Road (RT17) bridge No. 01- Entrance to bridge (RS 7688.50)

Mill Brook – Mill Brook Road (RT17) bridge No. 02- Entrance to bridge (RS 8966.95)

Mill Brook – Mill Brook Road (RT17) bridge No. 03- outlet of bridge (RS 11109.40)

Mill Brook – German Flats Road bridge – entrance to culvert (RS 12181.35)

Mill Brook – German Flats Road bridge – outlet of culvert (RS 12181.35)

Mill Brook – Mill Brook road (RT17) bridge – entrance to bridge (RS 19247.60)

Folsom Brook – Entrance to RT100 culvert (RS 462.75)

Folsom Brook – Outlet of the RT100 culvert (RS 462.75)

Folsom Brook – Outlet of the RT100 culvert (RS 462.75)

Freeman Brook – Entrance to Main Street bridge in Warren Village (RS 300.40)

Freeman Brook – Outlet of the Main Street bridge in Warren Village (RS 300.40)

Freeman Brook – Wall upstream of Entrance to Main Street bridge in Warren Village (RS 300.40)

Freeman Brook – Entrance to Brook Road bridge No. 01 in Warren Village (RS 1058.64)

Freeman Brook – Outlet of the Brook Road bridge No. 01 in Warren Village (RS 1058.64)

Freeman Brook – Entrance to Brook Road bridge No. 02 in Warren Village (RS 2068.04)

Freeman Brook – Outlet of a private drive to a residential home in Warren (RS 5729.84)

Freeman Brook – Entrance to a bridge on Behn Road in Warren (RS 9431.22)

THATCHER/GRAVES BROOK

BRIDGE AND DAM PHOTOGRAPHS

Thatcher Brook – RT 2 - N. Main- Union and Railroad bridge – Entrance to bridge (Union Street) RS 1051.27

Thatcher Brook – Rt2- Outlet at N. Main Street (RS 1051.27)

Thatcher Brook – RT2 - Railroad Bridge at N. Main Street and Union Street (RS 1051.27)

Thatcher Brook – Armory Drive (RS 1393.64)

Thatcher Brook – I-89 view looking downstream (northbound in the foreground)
I-89N and I-89S (RS 4556.90)

Thatcher Brook – I-89 view looking downstream (Stowe/Waterbury Ramp in the foreground)
Ramp has two piers. (RS 4556.90) Ramp (RS 4731.99)

Thatcher Brook – Entrance to Stowe Rd bridge (sewer or water main in front of bridge) (RS 5970.35)

Thatcher Brook – Entrance to Stowe Rd bridge (RS 5970.35)

Thatcher Brook – Entrance to Mill Rd bridge (RS 9557.16)

Thatcher Brook – Entrance to Laurel Lane bridge (RS 10001.77)

Thatcher Brook – Entrance to Guptil_01 (RS 13848.04)

Thatcher Brook – Entrance to Guptil_02 (RS 16399.55)

Thatcher Brook – Entrance to Guptil_03 (RS 21154.95)

Thatcher Brook – Entrance to Guptil_04 (RS 25962.18)

Thatcher Brook – Entrance to Loomis Hill Road bridge (RS 30963.89)

ATTACHMENT II-B

1% AEP (100-YEAR) INUNDATION MAPS

MAPS DISTRIBUTED AS SEPARATE PDF FILE

ATTACHMENT II-C

USGS STAGE-DISCHARGE RATING CURVE


USGS Stage-Discharge Rating Curve at Mad River gage in Moretown, VT vs.
HEC-RAS calculated Water Surface Elevation at the USGS gage location RS 21006.12
Stage (Water Surface Elevation) NAVD 88 (feet)
567
566
565
564
563
562
561
560
559
558
557
556
555
554
553
552
551
550
549
548
547
546
545
0
5000
10000
15000
20000
25000
30000
35000
Discharge (cfs)
USGS Rating Curve at the Mad River USGS Gage in Moretown, VT, 2017- 03-07
HEC-RAS Results, RS 21006.12, Channel n = 0.045
HEC-RAS Results, RS 21006.12, Channel n = 0.05

ATTACHMENT II-D

MAD RIVER CALIBRATION TABLE

Comparison Mad River Irene High Water Marks [1] and the HEC-RAS model computed water surface elevation (CWSEL)

HEC-RAS River Station	Description	CWSEL NAVD88(feet)	Irene High Water Mark (HWM) NAVD88 (feet)	Difference (feet)
Column A	Column B	Column C	Column D	Column C-D
RS 1594.23	DS [2] Demas Road	454.37	457.30	-2.93
RS 1739.04	US [3] Demas Road	468.19	468.54	-0.35 [5]
RS 6114.54	DS RT100B-B7	492.65	493.67	-1.02
RS 6300.07	US RT100B-B7	492.69	490.82	+1.87
RS 8213.26	DS Ampersand Dam	511.69	512.49	-0.80
RS 8287.20	US Ampersand Dam	536.27	537.16	-0.89
RS 21006.12	USGS Gage	563.02	562.99	+0.03
RS 31277.63	DS RT100B-B4	582.50	591.78	-9.28
RS 31370.10	US RT100B-B4	584.52	586.06	-1.54
RS 33676.56	DS Fletcher Road	591.42	594.26	-2.84
RS 33833.01	US Fletcher Road	599.69	607.40 [4]	-7.71
RS 36744.11	DS RT100B-B2	614.98	626.86	-11.88
RS 36905.16	US RT100B-B2	628.43	628.37	+0.06
RS 64010.71	DS Tremblay Road	667.79	671.02	-3.23
RS 64197.73	US Tremblay Road	672.81	673.32	-0.51
RS 73129.46	DS Waitsfield Covered Bridge	694.26	697.39	-3.13
RS 73345.59	US Waitsfield Covered Bridge	697.99	699.5	-1.51
RS 81526.28	DS RT100-B177	720.17	722.52	-2.35
RS 81817.63	US RT100-B177	724.62	724.5	+0.12
RS 90989.39	DS Butternut Hill Road	760.96	766.43	-5.47
RS 91055.20	US Butternut Hill Road	768.28	769.41	-1.13

[1] HWMs from USGS report, "High Water Marks From Flooding in Lake Champlain from April through June 2011 and Tropical Storm Irene in August 2011 in Vermont" dated 2013.
[2] DS = Downstream
[3] US = Upstream
[4] Not an official USGS HWM, obtained information from the USGS and locals on this HWM during the progress of this project.
[5] Grey hi-lited the difference between the HEC-RAS CWSEL and the HWM located upstream of the bridges.

ATTACHMENT III

NOTES FROM MODEL DEVELOPMENT

Mad River Area Flood Study
Notes from Model Development

Mad River

- The HEC-RAS model of the Mad River was calibrated to the USGS Stream gage No. 04288000 near Moretown, VT and to the Irene high water marks recorded in the USGS "High –Water Marks from Flooding in Lake Champlain from April through June 2011 and Tropical Storm Irene in August 2011 in Vermont." The HEC-RAS Computed Water Surface Elevation (CWSEL) agrees very well at the gage and reasonably well along most of the Mad River.
- Calibration of the HEC-RAS model at the USGS gage required a channel "n" value of 0.05. The HEC-2 model used to develop the FEMA FIS maps and profiles of this reach used a channel "n" of 0.035. (This is a 43% increase in the channel "n".) Larger "n" values (increased roughness) creates greater flow depths. Since the channel "n" was increased to match the known stage-discharge relationship at the USGS gage, the increase in "n" means the 1% Annual Exceedance Probability (100-year) storm depths will increase. In this reach the 100-year water surface elevation will increase 1 to 4 feet above the FEMA FIS elevation. Other factors that can affect the computed water surface elevations include:
    - Improvement in the geometry of the stream and its floodplain. The use of LIDAR data greatly improves the ability to describe a stream and its floodplain. LIDAR allows for additional cross sections use in the model and improved placement of the cross sections to improve the model.
    - The software (HEC-RAS vs HEC-2) used to calculate the water surface elevations and map the inundation areas have greatly improved since the 1980s. The methods to calculate bridge losses at bridges have improved.
    - Since the 1980s, more studies have been performed evaluating "n" values. Studies suggest that "n" values may need to be increased in mountain stream areas. Many of the Vermont streams fall into the mountain stream category.
- The HEC-RAS CWSEL upstream of the Waitsfield Covered bridge was 1.5 feet lower than the USGS HWM. Photographs taken during Irene (see attached) show the water level at the Covered bridge in the channel and the overbank can be at two different elevations. The differential water surface across a river cross section is due to the velocity in the channel being much higher than the overbank at a constriction such as a narrow bridge opening. At this location the HWM was most likely measured in the overbank area. This HWM would more closely represent the energy grade line (EGL) upstream of the bridge. At this location the EGL is 0.7 feet lower that the USGS HWM. The EGL agrees reasonably well with the HWM.
- Calibration of the HEC-RAS model upstream of the Warren Covered bridge between river station (RS) 110333.1 and 110909 agrees reasonably well with elevations visible in a photograph taken during the flood event. (There was no surveyed HWM at this location.) A map of the Irene inundation limits for this reach of the Mad River and the photograph have been included. The HEC-RAS model used a channel "n" value of 0.045. The FEMA FIS HEC-2 model of this reach used a channel "n" of 0.035. Larger "n" values (increase roughness) should create greater flow depths. However, at this location the 1% Annual Exceedance Probability (100-year) water surface elevation was approximately 1 foot lower

than the FEMA FIS 100-year upstream of the Covered Bridge. This change is due to a geometry change in the stream channel. The original FEMA HEC-2 model shows the old timber crib dam downstream of the Covered bridge to have a crest elevation of 896.0 feet. DuBois & King performed some previous work in 2004 and 2013 on this reach of the Mad River and had surveyed this area in detail, the timber crib dam crest elevation was 892.4 feet. The LIDAR data shows the ground in the vicinity of the crest to be 892.5 feet. This change in geometry affected the CWSEL.

- At the upstream side the Fletcher Road bridge the Model's CWSEL were significantly lower (8-feet) than the HWM. This bridge spans a narrow gorge with many protruding rock features, which are very difficult to capture in the model geometry. The calculated water surface profiles through the gorge are very steep, the velocities are high, even with adjustments made to the channel "n". The flow patterns during the storm event at this location were likely much more complex than the model assumptions allow for and this can make it problematic to calibrate to a HWM in such a location.
- There are sixteen bridges on the Mad River within the study area. Based on the FEMA FIS report dated March 19, 2013, the hydrologic and hydraulic work for the Mad River was completed in 1977 and revised in 1983. Five of the sixteen bridges have been replaced with new bridges. The five new bridges were installed from 1994 to 2015. The existing 1983 FEMA HEC-2 model does not include the new bridges. New bridge installations almost always improve the hydraulic flow conditions. The new HEC-RAS model includes the five new bridges.

<u>Thatcher Brook</u>

- There is no USGS stream gage or HWMs that can be used to calibrate the new HEC-RAS model of Thatcher Brook.
- D&K compared the FEMA FIS 1% Annual Exceedance Probability (100-year) WSEL to the new HEC-RAS CWSEL at similar locations on Thatcher Brook. The new HEC-RAS model in general calculated lower water surface elevations.
- There were many differences between the HEC-2 model and the new HEC-RAS model that makes a direct comparison of the calculated 100-year water surface very difficult. The some of the differences are listed below:
  - In HEC-2 Main Street and Union Street were modeled as two bridges, with the area for flows under the bridge deck at both bridges equal to 380 square feet. In HEC-RAS Main Street and Union Street were modeled as one longer bridge with the area for flows under the bridge deck equal to 438 square feet based on the survey data.
  - At Armory Drive the area under the bridge deck was 345 square feet for the HEC-2 Model. The HEC-RAS model has an area under the bridge deck equal to 438 square feet based on the new survey.
  - The HEC-2 model modeled the I-89 bridges as cross sections, the new HEC-RAS modeled the I-89 bridges North and South Bound and the I-89 Ramp as bridges with piers.
  - At Stowe Road the area under the bridge deck was 530 square feet for the HEC-2 Model. The HEC-RAS model has an area under the bridge deck equal to 586 square feet based on the new survey.

- The HEC-2 model has only two cross sections between Stowe Road and RS 9307.47, the HEC-RAS model has four cross sections. Improved the channel and floodplain geometry with LIDAR DEM.
- The HEC-2 model at Mill Road has a 2.4 foot pier. There is no pier at Mill Road bridge. This bridge must have been replaced. The HEC-RAS model used the new survey to model this bridge.
- D&K was not able to survey the dam at RS 9773.32 due to dangerous ice/ winter conditions. D&K was able to develop dimension and elevation from the LIDAR DEM. This data agreed reasonably well with the HEC-2 data.
- At Laurel Road bridge the HEC-RAS CWSEL is higher than the HEC-2 model CWSEL. The HEC-RAS model's area under the bridge deck is 797 square feet based on the new survey. The HEC-2 model's area under the bridge deck was 868 square feet. Based on the LIDAR just upstream of the Laurel Road bridge there is a constriction at RS 10379. This constriction was not included in the HEC-2 model.
- The HEC-2 model of Guptil Bridge No. 1 (RS 13848) is not correct. The HEC-2 data shows the lowest elevation of the road to be El. 586.2. Based on D&K recent survey there is a low elevation of 583.1 and the LIDAR shows a low point of 582.5.

<u>Shepard Brook, Mill Brook, Folsom Brook and Freeman Brook</u>

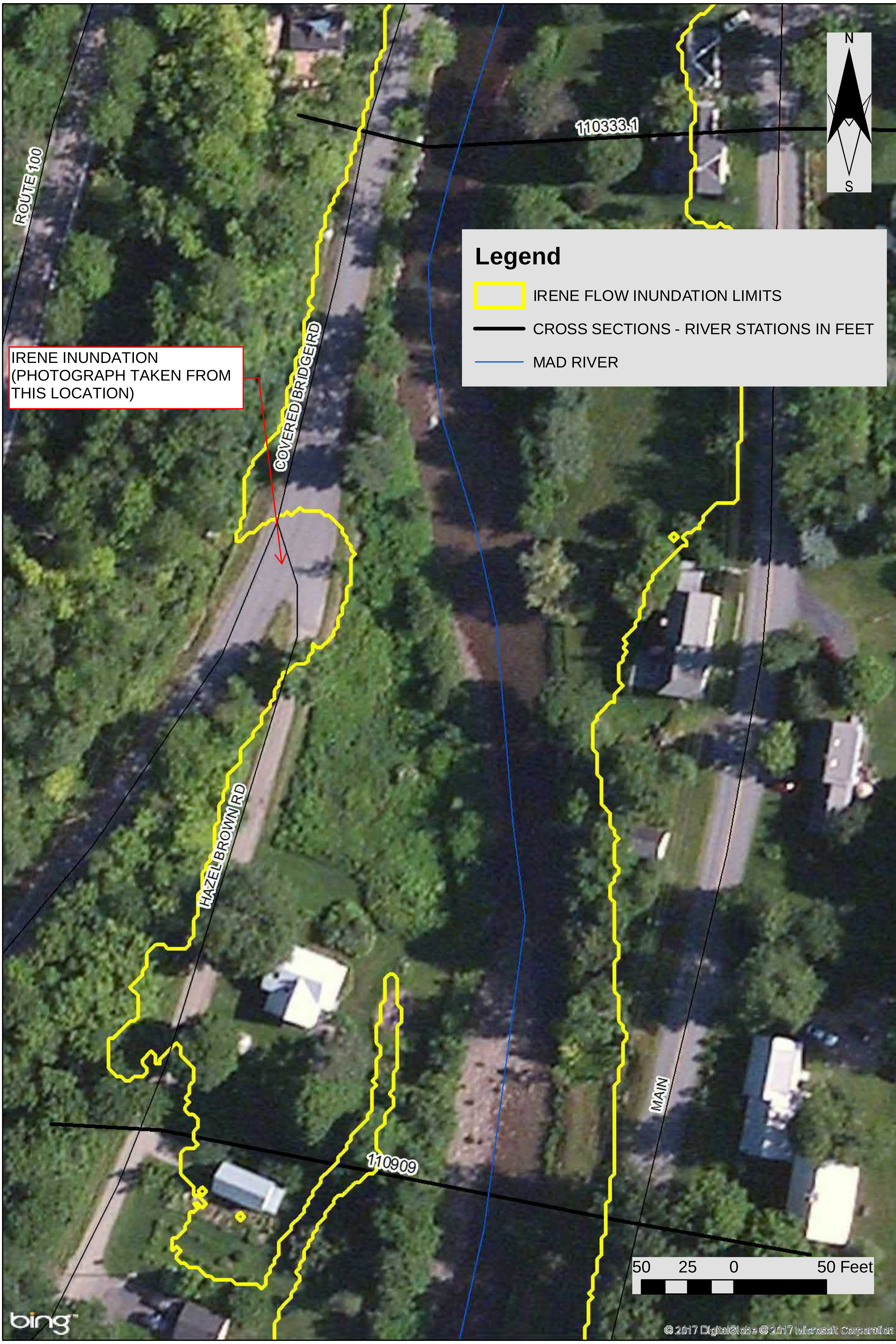
- There are no USGS stream gages or HWMs that can be used to calibrate the new HEC-RAS model of the Brooks listed above.

- Since there were a large number of differences between the original hydraulic models (HEC-2 models completed in 1977 revised 1983) and the new HEC-RAS models of the Mad River and Thatcher Brook as previously discussed, no comparisons were made for the Mad River tributaries.

Irene flood waters in Waitsfield, VT at the Covered Bridge at an estimate time of 3:30 pm on August 28, 2011. Credit Jeff Knight

Irene flood waters in Waitsfield, VT at the Covered Bridge at an estimate time of 5:30 pm on August 28, 2011. Credit Jeff Knight

Irene flood waters in Warren, VT at the intersection of Covered Bridge Road and Hazel Brown Road, at an estimate time of 5:00 pm on August 28, 2011. Credit Dorothy Tod



DuBois & King inc.
ENGINEERING • PLANNING
MANAGEMENT • DEVELOPMENT

MAD RIVER INUNDATION
IRENE FLOW

WASHINGTON COUNTY
VERMONT

JUNE 2017

DRAWN BY:	CJK	DATE:	06/01/2017
CHECKED BY:		PROJECT NO:	123677
PROJ. ENG:	CJK	FIGURE NO:	
SCALE:			