November 2020

Project: Hydrological Impact of Beaver Habitat Restoration in the Milwaukee River Watershed

MMSD Contract P-2890

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Executive Summary

Objectives of this project are to (1) assess the potential of beaver reestablishment in the Milwaukee River watershed through GIS modeling and through habitat assessment field surveys; and (2) conduct hydrological modeling to evaluate the potential impacts of beaver constructed dams on river hydrograph processes and flood mitigation in the watershed.

The Beaver Restoration and Assessment Tool (BRAT) was adapted for this project to estimate the likelihood of beaver dam building activity and beaver dam capacities in the Milwaukee River watershed, based on GIS analysis of the stream network, vegetation cover, and stream power under baseflow and high-flow conditions. BRAT model simulation suggested that hydrologic conditions in the Milwaukee River watershed are favorable for beavers to establish colonies, as the landscape is generally flat and river slopes are mild throughout most of the watershed. Riparian vegetation type is the primary factor that determines the potential of beaver habitat restoration. The three northern subwatersheds including the East-West branch Milwaukee River, the North branch Milwaukee River and the Cedar Creek, are more suitable for beaver restoration. Model predicted maximum beaver dam capacities are greater than 6 dams/km on average in the three sub-basins. The dam capacities are about 5, 4, and 1 dams/km for Menomonee River, Milwaukee River South, and Kinnickinnic River subwatersheds, respectively. Model predicted dam capacity in this report should be interpreted as a measure of relative importance, since it has not been calibrated with field observations in riverscapes that are similar to the Milwaukee River watershed.

Hydrological processes in the Milwaukee River watershed, including soil infiltration, groundwater storage, evapotranspiration, baseflow, and stream flows, are simulated by a distributed continuous hydrologic model, HEC-HMS. The model was calibrated for the watershed with stream flow data from USGS streamgages. With the calibrated HEC-HMS model, hypothetical analysis was conducted to evaluate hydrologic impacts of beaver dams. Locations of beaver dams were identified based on BRAT model results and validated through field surveys. 52 beaver restoration sites were selected representing those with the highest potential for beavers in five subwatershed (not including Kinnickinnic River). These beaver dams were included in the model with four stages with progressively increased dam numbers and dam heights, and the total potential ponding area varied between 777 acres (18 dams in Stage 1) and 3,793 acres (52 dams in Stage 4). Simulation results with and without dams were evaluated at 8 observation locations, including outlets of the five subwatersheds, and river cross sections in three urban river flood zones (in Thiensville, Brown Deer and Glendale).

Simulation with realistic past storm events suggested that beaver dams can significantly reduce flood flows at 8 observation locations. The peak flow rates were reduced by 6% ~ 48%, and flood flow volumes were reduced by 14% ~ 48%, depending on the development stages of beaver dams, and actual storm characteristics. Two factors contribute to peak flow reduction: (1) flow interception by storage capacity of beaver dams makes the primary contribution; and (2) energy dissipation through dam overflow when the storage capacity is filled. Water evaporation from the impounded water is the primary loss that contributes to discharge volume reduction. Model simulations also indicated that most beaver dams were near their full capacity before the occurrence of major storms, due to water accumulation through prior flow events. Therefore, despite the vast disparity in potential storage among different beaver development stages, the effects the total effective storage capacity may not be significantly different before a major storm. As beaver development stage changed from Stage 1 to Stage 4, the flood mitigation effects increased only slightly (about 5% for peak flow reduction, and 3% for volume reduction on average).

Ten synthetic frequency storms were generated for simulation, they are standard 6-hour and 24-hour storms with recurrence intervals ranging from 10 years to 200 years. Total precipitation depth of these storms varied between 2.99 and 7.44 inches. Since synthetic storms were designed with a uniform spatial distribution over the entire watershed, all beaver dams were able to contribute to flow reduction at river reaches at the lower end of the watershed. Consequently, more significant flow reductions were reported at the eight observational locations. At Stage 1, average flood peak reduction ranged between 26% (24-hour 200-year storm) and 37% (6-hour 10-year storm). At the full Stage 4, the range of average peak reduction was 36% to 46%.

Modeling analysis with both realistic past storms and synthetic frequency storms approved the hypothesis that **beaver dams that are largely dispersed in the upper tributaries of the watershed can potentially mitigate flood flows in urban flood zones at the lower end of the watershed.** Considering flood zones in the northern urban area of the Milwaukee County, modeled beaver dams could have reduced the peak flow by 7~40% according to the past storm simulations, and by 25~50% according to synthetic storm simulations.

Another question this project sought to address was whether or not the Milwaukee River Watershed could reasonably support a healthy beaver population. A field team was assembled to conduct a Basin-wide habitat assessment that would indicate if there exists sufficient space and forage to support reintroduced beaver pairs and their offspring. A set of criteria for beaver reestablishment was determined based on (1) water depth; (2) access to adjoining wetlands; (3) existing forage of diverse aquatic plants and woody materials; and (4) potential flooding conflict with infrastructure. Following these criteria and BRAT model results, potential sites for restoration were identified and assessed through reviewing aerial images and follow-up field visits.

Of the 163 sites visited throughout the Basin, 85 were ranked with moderate to high potential to support beaver reintroduction. From these sites, 52 were selected as having a high potential to reduce downstream flooding and/or lower the hydrograph of the streams during rain events if beavers were to construct dams and establish ponds at these sites. The field team also identified 14 sites that exhibit high potential to immediately support reintroduced beaver pairs. In addition to conducting field visits, the team used research established calculations to estimate the beaver carrying capacity of each of the six subwatersheds within the 89,000 acres of wetland in the Milwaukee River Basin. Based on these calculations, the Basin has the potential to support as many as 4,563 beavers in 840 colonies, indicating that the Milwaukee River Basin has sufficient wetland habitat to support the reintroduction of beavers.

Finally, the field team put together a set of recommendations for successfully reintroducing beavers into the Basin, including policy changes, habitat enhancements, educational opportunities, land acquisition partners, conflict management opportunities, and wildlife biologist partners.

1 Introduction

1.1 Background

According to a Wisconsin Department of Natural Resources (WDNR) report (Burzynski 2001):

> "The Milwaukee River Basin is located in portions of seven counties, contains (entirely or portions of) 13 cities, 32 towns, 24 villages and is home to about 1.3 million people. The Southern quarter of the basin is the most densely populated area in the state, holding 90 percent of the basin's population. The basin is divided into six watersheds (see Figure 1.1). Three of the watersheds (Milwaukee River North, Milwaukee River East-West and Milwaukee River South) contain the Milwaukee River from start to finish and collectively occupy two-thirds of the basin area (584 square miles). The other three watersheds (Cedar Creek, Menomonee River, and Kinnickinnic River) are named after the major rivers they contain. Collectively the six watersheds contain about 500 miles of perennial streams, over 400 miles of intermittent streams, 35 miles of Lake Michigan shoreline, 57 named lakes and many small lakes and ponds. Wetlands encompass over 68,000 acres, or 12 percent of the basin land area.
>
> The Natural Heritage Inventory (WDNR, 2000) has documented 16 endangered, 26 threatened, 65 special concern plant and animal species, and 30 rare aquatic and terrestrial communities within the basin. The Southeastern Wisconsin Regional Planning Commission (SEWRPC) identified over 18,000 acres of high-quality natural communities and critical species habitats remaining in the basin (SEWRPC, 1997). About 18 percent of the land area of the basin is covered by urban uses, while the remainder is considered rural. Agriculture is still dominant in the northern half of the basin."

Prior to the fur trade, beavers were common and abundant in the Milwaukee River and all of the Wisconsin watersheds. Historic accounts chronicle that fur exploitation started here about 1650, and by 1730 beavers were locally extinct in the Milwaukee area (White, 2010). Since settlers arrived in this area in the 1830s, beavers' presence was largely unknown. Recently, however, a tiny remnant population has made its presence known after 350 years of absence. This genetic stock is incredibly valuable and needs protection to thrive.

Numerous scientific beaver studies over the past 30 years have cited the ecosystem benefits of beavers for biodiversity, water quality, and flood abatement (Woo and Waddington 1990, Green and Westbrook 2009). However, in Wisconsin, many ecologists and natural area managers are suffering from a case of ecological myopia regarding the significant potential and the role of this keystone species in restoring structure and stability to the geomorphology of watersheds. River systems and watersheds with established beaver populations are much more resilient to floods. This is due to the effect of the dams and the resulting ability of wetland complexes to store and slow down water during peak high-water events (Meentemeyer and Butler 1999, Nyssen, Pontzeele and Billi 2011, Puttock, et al. 2017). Beaver dams can flatten the curve on hydrographs. With climate change, storms are increasing in intensity and frequency. Beavers can be a keystone partner protecting valuable infrastructure from flood events.

Milwaukee Riverkeeper and its partners, including the Milwaukee Metropolitan Sewerage District (MMSD) and the University of Wisconsin-Milwaukee (UWM), are investigating watershed-scale restoration that 'partners' with beavers in order to achieve a range of watershed restoration goals. Of particular importance is increasing the efficiency of the MMSD Greenseams program and prioritizing future actions.

The project presented is a preliminary study conducted collaboratively by researchers from UWM and Milwaukee Riverkeeper. The UWM research team has developed geospatial and hydrological models to assess the potential of beaver restorations in the basin and the impacts of beaver dams on flood flow reductions in major streams. Milwaukee Riverkeeper served as the fiscal agent, provided project oversight and coordination, and conducted fieldwork evaluations of more than 100 identified sites.

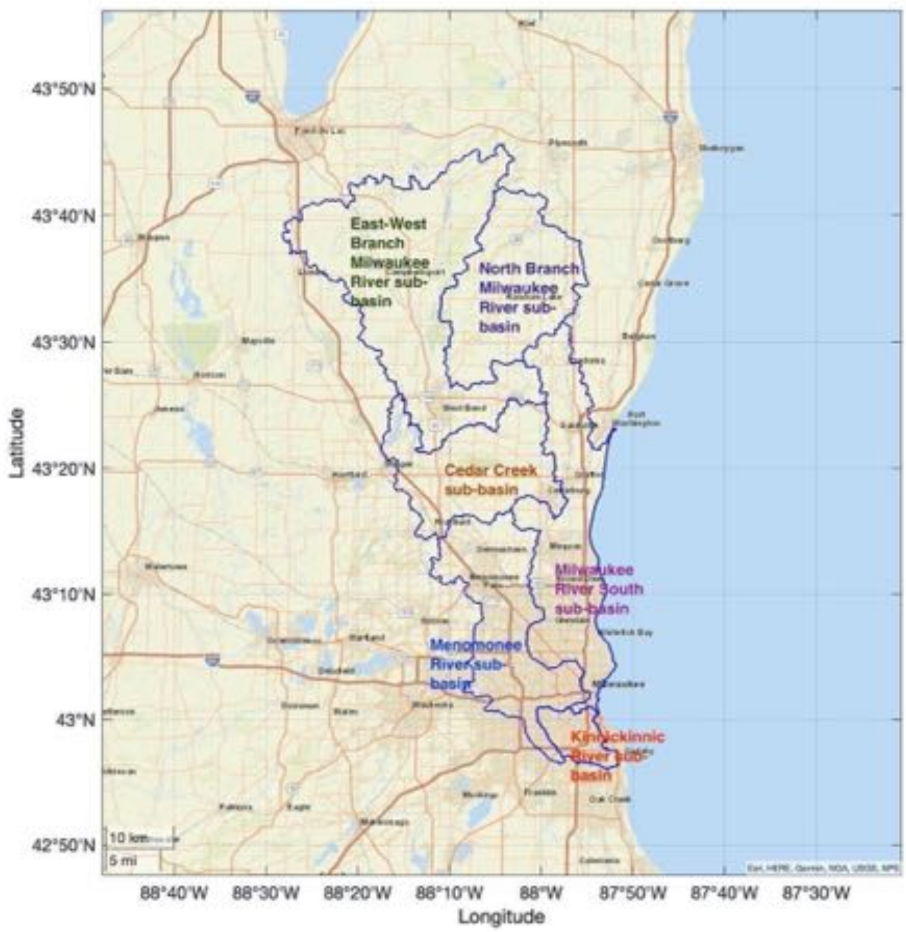

Figure 1.1 Milwaukee River watershed and its six subwatersheds

1.2 Objectives

The primary objective of this project is to develop a modeling framework to assess the potential impacts of beaver constructed dams on the hydrological processes in the Milwaukee River watershed. Research activities included

1. Developing a GIS-based model to assess the potential of beaver reestablishment in the watershed.

2. With the guidance of the beaver restoration model results, identifying sites as having the best-estimated metrics for potential flood mitigation, and conducting field studies to create a summary report with a habitat overview.
3. Developing and calibrating a hydrological model that can simulate infiltration, surface runoff, groundwater storage, and flows in the stream network of the watershed in response to precipitation events.
4. Developing hydraulic beaver dam models and evaluating their impacts on the hydrographs of river flows and flood mitigation through the calibrated hydrological model.

Many studies have demonstrated that beavers and their dam building activities have profound impacts on the hydrology of a riverine system, such as: increasing the groundwater recharge (Westbrook, Cooper and Baker 2006); attenuating flow speed and increasing water temperature (Green and Westbrook 2009, Majerova, et al. 2015); increasing water loss through evaporation (Woo and Waddington 1990); promoting sedimentation and improving water quality (Meentemeyer and Butler 1999, Puttock, et al. 2017); and reducing flood peak flows (Nyssen, Pontzeele and Billi 2011). Fewer studies are found in literature that applied numerical models to assess beavers' hydrologic impact. MODFLOW model has been applied to investigate the effects of beaver dams on regional groundwater flow through a wetland (Feiner and Lowry 2015). Hydraulic routing simulations were conducted to evaluate how beaver dams may attenuate peak flow from storms of various recurrence intervals (Beedle 1991). A recent study that applies beaver restoration and hydrologic models to assess beaver impacts on water resources in the Jemez watershed in New Mexico (Caillat, et al. 2014) is the most relevant reference to this project in terms of technical approaches.

Through modeling studies proposed for this project, The research team hoped to test an **overarching hypothesis**: *Restoration of beaver habitats in the Milwaukee River watershed can significantly mitigate river flood flows, even for urban areas at the downstream end of the watershed*.

2 Modeling the potential of beaver restoration in the Milwaukee River watershed

2.1 Beaver Restoration and Assessment Tool (BRAT)

The Beaver Restoration and Assessment Tool (BRAT) (MacFarlane, et al. 2017) is an open-source model developed by Joseph Wheaton and William MacFarlane at the Utah State University (http://brat.joewheaton.org). The BRAT model was adapted for this project to estimate the likelihood of beaver dam building activity and the number and distribution of dams in the Milwaukee River watershed, based on the analysis of the stream network, vegetation cover, and stream power under baseflow and high-flow conditions. Most parameters required to run the model are readily available from public resources, primarily from the US Geological Survey's (USGS) public database. Geodata has been collected and analyzed through GIS-based tools (e.g., ArcGIS and Geospatial Modeling add-ons) to generate modeling inputs to BRAT. Parameters for hydraulic regression models were specified based on the hydrological statistics of streams within and near the Milwaukee River basin and supplied to BRAT for simulation.

While BRAT has been applied successfully in western regions of the United States, it has not been tested in the Midwest states that are significantly different in landscape and climate characteristics. Additional studies, including model development, parameterization, and validation with field observations, may be required to more realistically predict the capacity of the watershed to support beaver dams and the potential of beaver restoration. Therefore, the presented work should be considered as the first step to build a working framework for future research.

2.2 BRAT model configuration

BRAT is a stream network model that helps resource managers to plan and prioritize where beaver may build dams naturally, to estimate the capacity of the streamscape to support their dam building activity, to predict where the potential for human-beaver conflicts may arise, and to highlight where beaver reintroduction makes sense as a conservation or restoration tool and where it does not. The BRAT model estimates potential density of beaver dams along a riverscape (dam count per length of stream) by evaluating the following factors (MacFarlane, et al. 2017):

- Existence of reliable water source (e.g., perennial vs. ephemeral rivers);
- Riparian vegetation types that are favorable to foraging and dam building;
- Vegetation within 100 m of the stream to support the expansion of dam complexes and maintain a large colony;
- The likelihood that channel-spanning dams could be built during low flows (In the original BRAT model documentation, a low flow is defined as a base flow condition derived from a regional regression model);
- The likelihood that a beaver dam is likely to withstand typical floods (In the original BRAT model documentation, a typical flood is defined as the peak discharge of a 2-year flow); and
- A suitable river that is not too large to restrict dam building or persistence.

A fuzzy inference modeling system is then applied to combine these factors to estimate beaver dam densities on each stream segment.

The BRAT model is generally provided as a toolbox for ArcGIS by the research group at Utah State University. Alternatively, matBRAT is a Matlab implementation of the BRAT model, which consists of (1) a set of manual ArcGIS geoprocessing steps and (2) a series of Matlab Scripts. ArcGIS procedures are summarized in GitHub at: https://github.com/Riverscapes/matBRAT/tree/master/docs/matBRAT, and the Matlab source script can be downloaded from https://github.com/Riverscapes/matBRAT. In this study matBRAT was selected for modeling beaver restoration potentials in the Milwaukee River watershed, due to the flexibility of model modifications.

Before executing the Matlab scripts, a set of manual procedures was taken to prepare model input data in an ArcGIS environment. The processed geodata for subsequent model runs include:

- Processed stream network in the watershed;
- Digital Elevation Model (DEM) of the watershed;
- Flow accumulation raster map; and
- Raster maps of existing (EVT) and potential vegetation (BPS), i.e., biophysical settings that represent the vegetation which may have been dominant on the landscape prior to Euro-American settlement.

Following the pre-processing of geodata in ArcGIS, a suite of Matlab programs was developed specifically for this project to calculate input parameters for the matBRAT model. The processing of these Geodata are summarized in the following sections

2.2.1 Stream network processes

Stream network data of the Milwaukee River watershed are downloaded from USGS's National Hydrography Dataset (NHD) following its National Map Downloader page: https://viewer.nationalmap.gov/basic/?basemap=b1&category=nhd&title=NHD%20View. Data for the Milwaukee River basin is identified with the Hydrologic Unit (HU) 8 - 04040002. The dataset contains the stream network in an ESRI shapefile, which was imported into ArcGIS. The following steps were taken to process the stream network for BRAT modeling:

1. The stream network was projected into the coordinate system "NAD_1983_UTM_Zone_16N".
2. Lakes were removed from the stream network using ArcGIS's "erase" function. Optionally, a threshold lake or pond size can be specified to exclude waterbodies smaller than the size, before conducting "Erase" function. Ponds smaller than this size can be considered as potential beaver ponds.
3. All stream segments were first "dissolved" into one segment unit. Then it was re-segmented with a nominally uniform length, which was set to be 300 m for this study. Therefore, the subsequent BRAT modeling process considers each stream segment individually, and the results are presented as potential beaver capacity (dams per km) for every 300 m of stream reach.

4. The processed stream network was exported into a shapefile, which serves as an input to Matlab programs.

Figure 2.1 presents the processed stream network for the entire Milwaukee River watershed.

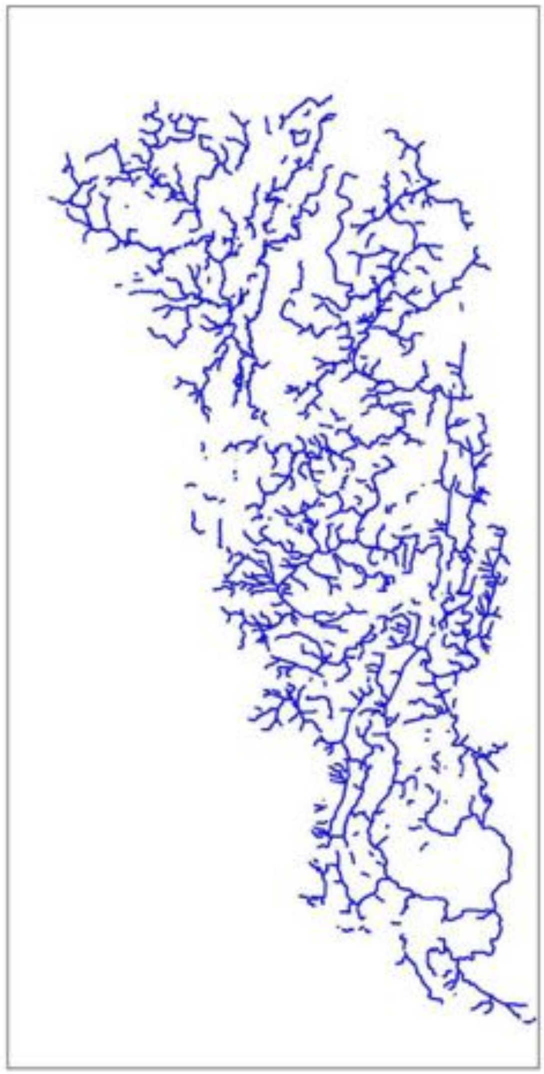

Figure 2.1 NHD stream network of Milwaukee River watershed processed with lakes removed and segmented (300 m segments)

2.2.2 Vegetation classification

The potential for beaver restoration depends largely on the availability of vegetation and wood materials, particularly in the riparian regions of a stream. The BRAT model examined vegetation types within 30-meter and 100-meter buffer zones along both sides of a drainage line. Specifically, a numerical score is calculated based on the vegetation type in the buffer zones to evaluate the suitability for beavers' foraging and dam construction. The score ranges from 0 for unsuitable to 4 for preferred materials.

Raster maps of vegetation types, including the existing (EVT) and historical (or potential, BPS) vegetation, were obtained through the LANDFIRE database. LANDFIRE is a partnership between the wildland fire management programs of the United States Department of Interior, the USDA Forest Service, and the Nature Conservancy. EVT and BPS maps were directly imported into ArcGIS with its online downloading tool. The dataset included a raster image layer of vegetation type (specified by an ID number) and an attribute table that describes the specifics of each vegetation type in the map. The raster image was projected to the "NAD_1983_UTM_Zone_16N" coordinate system, cropped by the watershed boundary, and exported as GeoTIFF files for Matlab processing. The attribute table was exported as an EXCEL spreadsheet for evaluation.

The exported EXCEL spreadsheet was modified by adding a "VEG_CODE" column that represents the score value (0 ~ 4). The score was then manually assigned according to the vegetation type description. A full spreadsheet for existing vegetation is presented in Table 2.1. In general, "hardwood" types were assigned to 4; "herbaceous" types were assigned to 2 or 3, "agriculture" and "grass" types were assigned to 2; and developed urban areas were assigned to 0. Similar evaluation criteria were applied to historical vegetation types (BPS). It is not presented in this report since the study focuses on evaluating beaver potential of the existing landscape.

Table 2.1 Vegetation scores of existing vegetation types (EVT)

ID VALUE	CLASSNAME	EVT_PHYS	VEG_CODE
3238	Laurentian-Acadian Northern Oak Forest	Hardwood	4
3239	Laurentian-Acadian Northern Pine-Oak Forest	Conifer-Hardwood	4
3240	Laurentian-Acadian Hardwood Forest	Hardwood	4
3241	Laurentian-Acadian Pine-Hemlock-Hardwood Forest	Conifer-Hardwood	4
3242	Laurentian Oak Barrens	Hardwood	4
3243	Laurentian Pine-Oak Barrens	Conifer-Hardwood	4
3244	Boreal Hardwood Forest	Hardwood	4
3245	Boreal White Spruce-Fir-Hardwood Forest	Conifer-Hardwood	4
3269	Laurentian Shrubland Barrens	Shrubland	4
3270	North-Central Interior Sand and Gravel Shrubland	Shrubland	3
3275	Central Interior and Appalachian Floodplain Shrubland	Riparian	3
3276	Laurentian-Acadian Floodplain Herbaceous	Riparian	2
3278	Boreal Acidic Peatland Herbaceous	Riparian	2
3279	Boreal Acidic Peatland Shrubland	Riparian	3
3280	Central Interior and Appalachian Swamp Shrubland	Riparian	4
3281	Laurentian-Acadian Alkaline Conifer-Hardwood Swamp Shrubland	Riparian	**4**
3283	Central Interior and Appalachian Shrub Wetlands	Riparian	4
3284	Laurentian-Acadian Herbaceous Wetlands	Riparian	4
3285	Laurentian-Acadian Shrub Wetlands	Riparian	4
3292	Open Water	Open Water	0
3294	Barren	Barren	4

3295	Quarries-Strip Mines-Gravel Pits	Quarries-Strip Mines-Gravel Pits	0
3296	Developed-Low Intensity	Developed-Low Intensity	0
3297	Developed-Medium Intensity	Developed-Medium Intensity	0
3298	Developed-High Intensity	Developed-High Intensity	0
3299	Developed-Roads	Developed-Roads	0
3301	Boreal Aspen-Birch Forest	Hardwood	4
3302	Laurentian-Acadian Northern Hardwoods Forest	Hardwood	4
3310	North-Central Interior Dry-Mesic Oak Forest and Woodland	Hardwood	4
3311	North-Central Interior Dry Oak Forest and Woodland	Hardwood	4
3313	North-Central Interior Beech-Maple Forest	Hardwood	4
3314	North-Central Interior Maple-Basswood Forest	Hardwood	4
3344	Boreal Jack Pine-Black Spruce Forest	Conifer	4
3362	Laurentian-Acadian Northern Pine Forest	Conifer	4
3365	Boreal White Spruce-Fir Forest	Conifer	4
3366	Laurentian-Acadian Pine-Hemlock Forest	Conifer	4
3394	North-Central Interior Oak Savanna	Hardwood	4
3395	North-Central Oak Barrens Woodland	Hardwood	4
3407	Laurentian Pine Barrens	Conifer	4
3412	North-Central Interior Sand and Gravel Tallgrass Prairie	Grassland	2
3421	Central Tallgrass Prairie	Grassland	2
3444	Eastern Boreal Floodplain Woodland	Conifer	4
3466	Great Lakes Wooded Dune and Swale	Riparian	4
3471	Central Interior and Appalachian Floodplain Forest	Riparian	4
3475	Laurentian-Acadian Floodplain Forest	Riparian	4
3477	Boreal Acidic Peatland Forest	Riparian	4
3479	Central Interior and Appalachian Swamp Forest	Riparian	4
3481	Laurentian-Acadian Alkaline Conifer-Hardwood Swamp Forest	Riparian	3
3492	Great Lakes Coastal Marsh Herbaceous	Riparian	2
3493	Central Interior and Appalachian Herbaceous Wetlands	Riparian	2
3517	Paleozoic Plateau Bluff and Talus Woodland	Hardwood	4
3534	Managed Tree Plantation-Northern and Central Hardwood and Conifer Plantation Group	Conifer	4
3905	Eastern Cool Temperate Urban Deciduous Forest	Developed	4
3906	Eastern Cool Temperate Urban Evergreen Forest	Developed	4
3907	Eastern Cool Temperate Urban Mixed Forest	Developed	4
3908	Eastern Cool Temperate Urban Herbaceous	Developed	2
3909	Eastern Cool Temperate Urban Shrubland	Developed	3
3930	Eastern Cool Temperate Developed Ruderal Deciduous Forest	Developed	4

3931	Eastern Cool Temperate Developed Ruderal Evergreen Forest	Developed	4
3932	Eastern Cool Temperate Developed Ruderal Mixed Forest	Developed	4
3933	Eastern Cool Temperate Developed Ruderal Shrubland	Developed	3
3934	Eastern Cool Temperate Developed Ruderal Grassland	Developed	2
3950	Eastern Cool Temperate Undeveloped Ruderal Deciduous Forest	Developed	4
3951	Eastern Cool Temperate Undeveloped Ruderal Evergreen Forest	Developed	4
3952	Eastern Cool Temperate Undeveloped Ruderal Mixed Forest	Developed	4
3953	Eastern Cool Temperate Undeveloped Ruderal Shrubland	Developed	4
3954	Eastern Cool Temperate Undeveloped Ruderal Grassland	Developed	2
3970	Eastern Cool Temperate Orchard	Agricultural	4
3971	Eastern Cool Temperate Vineyard	Agricultural	3
3973	Eastern Cool Temperate Row Crop - Close Grown Crop	Agricultural	2
3974	Eastern Cool Temperate Row Crop	Agricultural	2
3975	Eastern Cool Temperate Close Grown Crop	Agricultural	2
3976	Eastern Cool Temperate Fallow/Idle Cropland	Agricultural	2
3977	Eastern Cool Temperate Pasture and Hayland	Agricultural	2
3978	Eastern Cool Temperate Wheat	Agricultural	2
3994	Eastern Warm Temperate Row Crop	Agricultural	2
3995	Eastern Warm Temperate Close Grown Crop	Agricultural	2
3998	Eastern Warm Temperate Wheat	Agricultural	2

With pre-processed EVT and BPS raster maps as input images, the Matlab program read the vegetation score spreadsheet as a look-up table and reconstructed a new raster map of vegetation scores (see Figure 2.2). The program then read in the segmented stream network and computed the zonal average for each river segment. The zonal average procedure searched the area within 30-m and 100-m buffer zones of each segment and reported the average vegetation scores in the two zones, respectively. Results are exported into a spreadsheet, which was fed into the matBRAT program for analysis.

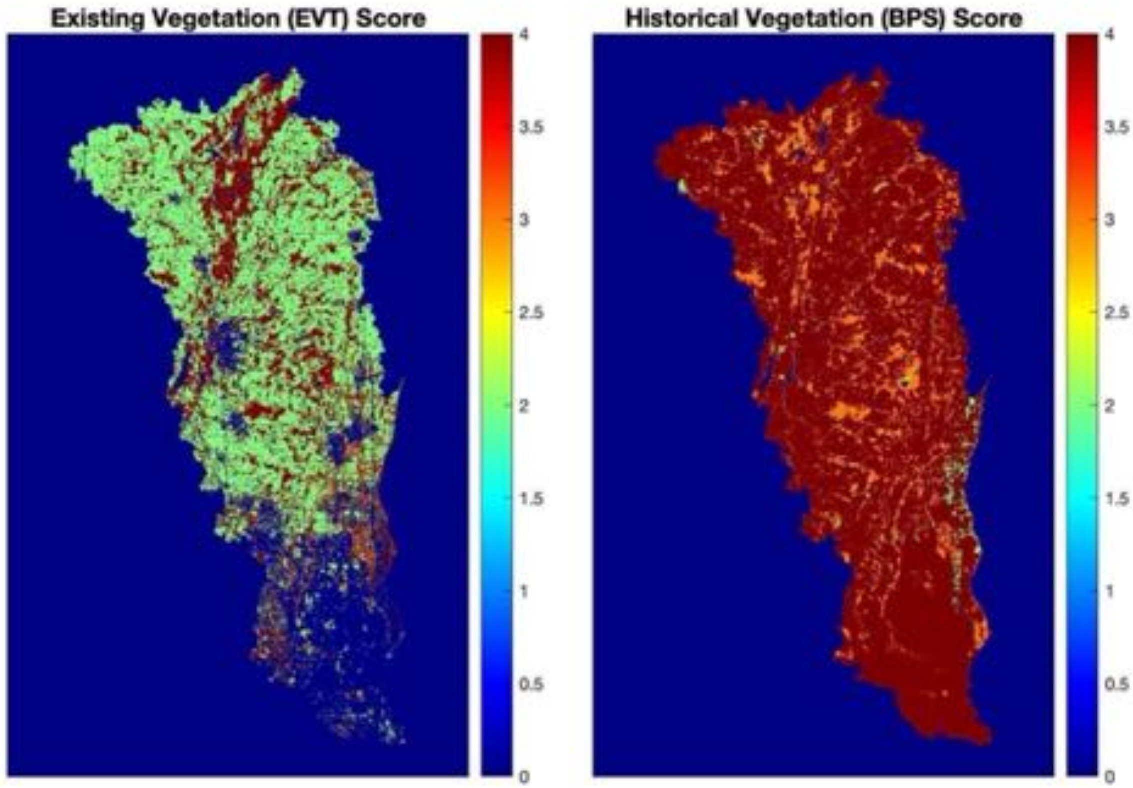

Figure 2.2 Maps of vegetation scores (0~4) for beaver restoration potential according to existing vegetation and historical vegetation types (processed from LANDFIRE database)

2.2.3 Stream power analysis

Hydrologic properties of stream segments are factors that are as important as riparian vegetation cover that determines the likelihood of a beaver colony forming. Specifically, the BRAT model evaluates hydrological factors through the magnitude of baseflows, 2-year flow (channel forming), and 25-year flood flows to determine if (1) the stream segment will have significant water supply for pond forming; (2) if beaver dams can be constructed during low flow durations; and (3) if the integrity of dam structures can be compromised during frequent floods. The stream channel slope is also considered as an additional hydrologic factor.

To estimate base flow, 2-year and 25-year flood flow magnitudes at all stream segments, a regional regression approach was adopted. Regional regressional relations for ungagged Wisconsin streams are available through a recent USGS report (Walker et al., 2017), which can estimated flood flows of various recurrence intervals based on drainage area, saturated hydraulic conductivity, main channel slope and serval land-use variables. While future model improvements should consider a more comprehensive regression model such as that reported by Walker et al. (2017), and that generally recommended by USGS, the current BRAT model allows the input of a regression model based on drainage area only. In this study, it was assumes that flow rate with specified frequency is proportional to the drainage area at a stream cross section. The assumption was tested by collecting flow statistics at available USGS stream gage stations in and around the Milwaukee River watershed, and then regression analysis is applied to correlate base flows and flood flows with the drainage area. Historical daily continuous flow data and annual peak flows were acquired from 25 stream gages. By examining the probability distribution of the daily flow, the flow rate which is less than 80% of the data was determined as the baseflow. The 2-year and 25-year flows were determined from annual peak series using the standard log-Pearson type III distribution model (Mays 2010). Base flows and flood flows (2-year and 25-year) at the 25 USGS stations are plotted against corresponding drainage areas in Figure 2.3. Linear trends can be observed in log-log scale plots of all three flows, which suggests that power law functions can be applied to scale based flow, 2-year and 25-year flows with the drainage area.

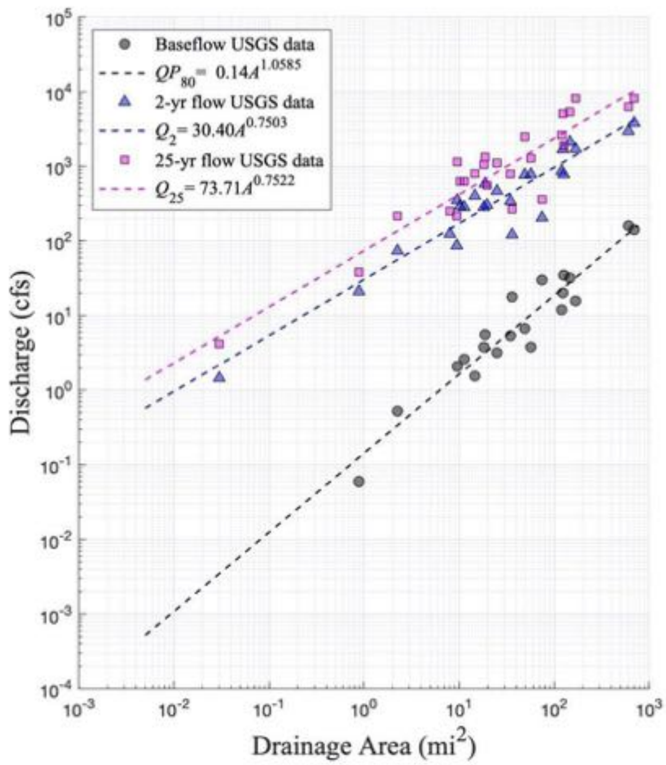

Figure 2.3 Regional regression analysis of base flow, 2-year, and 25-year flows with discharge data from 25 USGS stream gages within and around the Milwaukee River watershed. Flows are correlated with drainage areas following power-law relations.

Linear regression analysis was applied to log-log scaled data, and the following power-law relations were determined for base flow (QP_{80} in cfs), 2-year flow (Q_2 in cfs) and 25-year flow (Q_{25} in cfs) as functions of drainage area (A in mi^2), respectively

$$QP_{80} = 0.14\, A^{1.0585} \tag{2.1}$$

$$Q_2 = 30.40\, A^{0.7503} \tag{2.2}$$

$$Q_{25} = 73.71\, A^{0.7522} \tag{2.3}$$

The three equations were then applied to estimate flow and stream power at all stream segments in BRAT modeling. The stream power (SP) per unit length of stream is calculated as

$$SP = \rho g Q S \tag{2.4}$$

where ρ is the density of water, S is the slope of the stream.

To calculate discharge and stream power, the drainage area and slope of each stream segment was estimated. These two parameters were also necessary for hydrologic models, and they were obtained from processing the DEM data of the watershed. The calculation of drainage area for every point in the watershed is described in detail in section 3.2.1. Specifically, it is processed with HEC-GeoHMS by "flow direction" and "flow accumulation" tools. The flow accumulation calculates the number of DEM raster pixels that contribute to drainage of runoff at any given point in the watershed, following the calculated map of flow directions. Stream slope is readily available through DEM. It was calculated as the difference in elevation between two ends of the stream segment and divided by the segment length.

To illustrate the results of the stream flow and stream power analysis, the estimated 2-year flow and stream power distribution over all stream segments are shown in Figure 2.4.

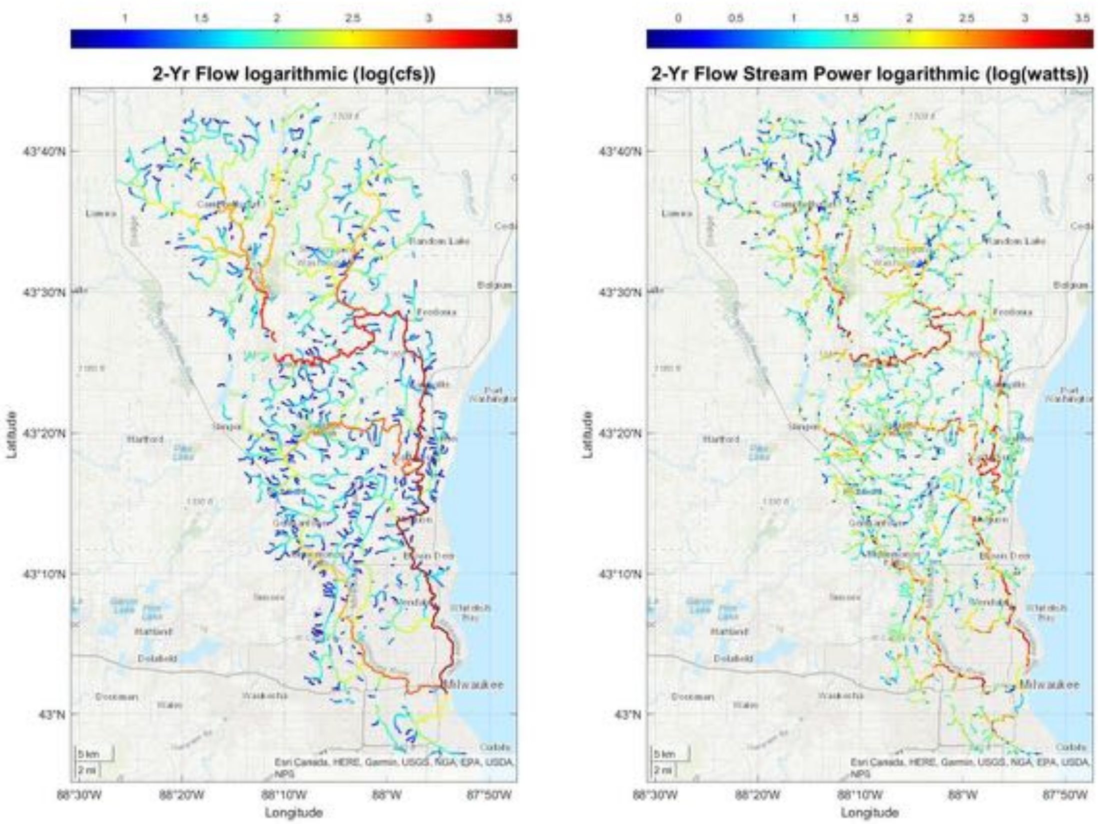

Figure 2.4 Estimated 2-year flow discharge and stream power of all stream segments of the Milwaukee River watershed with the regional regression model

Drainage areas and stream slopes were exported into a spreadsheet, along with the vegetation score for the subsequent BRAT model run.

2.3 BRAT model process

The BRAT model employs a Fuzzy Inference System (FIS) method to estimate potential beaver dam density on a stream segment. Specifically, the FIS method in BRAT uses a set of simple rules to map a set of input parameters (vegetation score, stream power, etc.) to an output (potential for beaver dam building). While both input and output can be continuous variables, they are categorized with overlapping member functions, which account for categorical ambiguity and uncertainty.

BRAT model simulation takes at least two steps. Step one is a vegetation capacity model, i.e., potential beaver capacity is predicted by the vegetation type alone. This step takes two input parameters, which are vegetation scores in the 30-m (riparian) and 100-m (adjacent) buffers, respectively. The output is a “defuzzified” beaver density from the output categories. For both inputs and output, the categories are defined as the following (MacFarlane, et al. 2017):

Table 2.2 Inputs and output of BRAT beaver capacity FIS system based only on vegetation

Input (Riparian and adjacent vegetation)		Output	
Vegetation score	***Category***	***Beaver density***	***Category***
0	Unsuitable	0 (dam)	None
1	Barely suitable	0-1 (dam/km)	Rare
2	Moderately suitable	1-4 (dam/km)	Occasional
3	Suitable	4-15 (dam/km)	Frequent
4	Preferred	15-40 (dam/km)	Pervasive

Following configuration of input and output parameters, definitions of membership functions are illustrated in Figure 2.5.

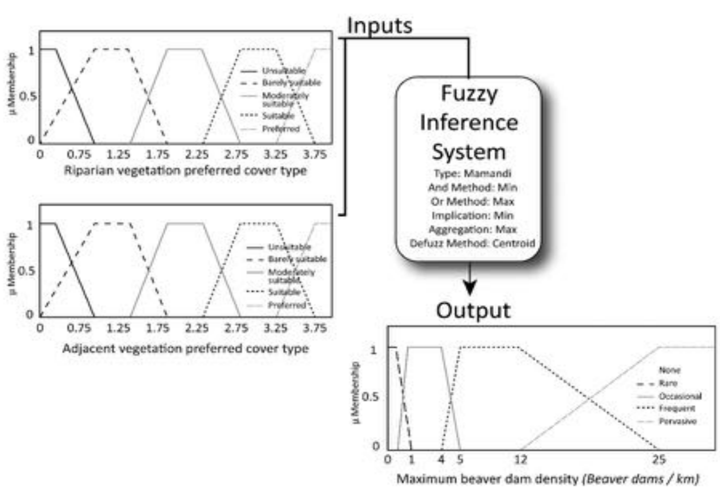

Figure 2.5 Membership function of the FIS system in BRAT model, which predicts beaver capacity based only on vegetation availability. (Figure adapted from (MacFarlane, et al. 2017))

Figure 2.6 shows the rule table applied in the vegetation only FIS system to predict beaver capacity.

	If	Inputs			Output	
		Suitability of streamside vegetation		Suitability of riparian/upland vegetation		Dam density capacity
Rules	1	Unsuitable	&	Unsuitable	, then	None
	2	Barely suitable	&	Unsuitable	, then	Rare
	3	Moderately suitable	&	Unsuitable	, then	Occasional
	4	Suitable	&	Unsuitable	, then	Occasional
	5	Preferred	&	Unsuitable	, then	Occasional
	6	Unsuitable	&	Barely suitable	, then	Rare
	7	Barely suitable	&	Barely suitable	, then	Occasional
	8	Moderately suitable	&	Barely suitable	, then	Occasional
	9	Suitable	&	Barely suitable	, then	Frequent
	10	Preferred	&	Barely suitable	, then	Frequent
	11	Unsuitable	&	Moderately suitable	, then	Occasional
	12	Barely suitable	&	Moderately suitable	, then	Rare
	13	Moderately suitable	&	Moderately suitable	, then	Frequent
	14	Suitable	&	Moderately suitable	, then	Frequent
	15	Preferred	&	Moderately suitable	, then	Pervasive
	16	Unsuitable	&	Suitable	, then	Rare
	17	Barely suitable	&	Suitable	, then	Frequent
	18	Moderately suitable	&	Suitable	, then	Frequent
	19	Suitable	&	Suitable	, then	Frequent
	20	Preferred	&	Suitable	, then	Pervasive
	21	Unsuitable	&	Preferred	, then	Occasional
	22	Barely suitable	&	Preferred	, then	Frequent
	23	Moderately suitable	&	Preferred	, then	Frequent
	24	Suitable	&	Preferred	, then	Pervasive
	25	Preferred	&	Preferred	, then	Pervasive

Figure 2.6 Rule table of FIS system that predicts beaver capacity based only on vegetation (Adapted from Table 2 in (MacFarlane, et al. 2017)).

Step two of the BRAT process takes the output from step 1 (beaver capacity with vegetation only) as one input, and three additional inputs considering hydrologic factors; the FIS output is the combined beaver capacity based on vegetation and hydrology. The three additional inputs include baseflow stream power, 2-year flow stream power, and the stream slope. Defined categories of all four input parameters are listed in Table 2.3; their corresponding membership functions are illustrated in Figure 2.7; and Figure 2.8 shows the rule table for the combined capacity model.

Table 2.3 Input and output categories of BRAT combined beaver capacity FIS system

Input				Output
Beaver capacity supported by vegetation	***Baseflow stream power***	***2-year flow stream power***	***Stream slope***	***Combined beaver capacity***
None	Can build dam	Dam persists	Really flat	None
Rare	Probably can build	Occasional breach	Can build dam	Rare
Occasional	Cannot build	Occasional blowout	Probably can build	Occasional
Frequent		Blow out	Cannot build	Frequent
Pervasive				Pervasive

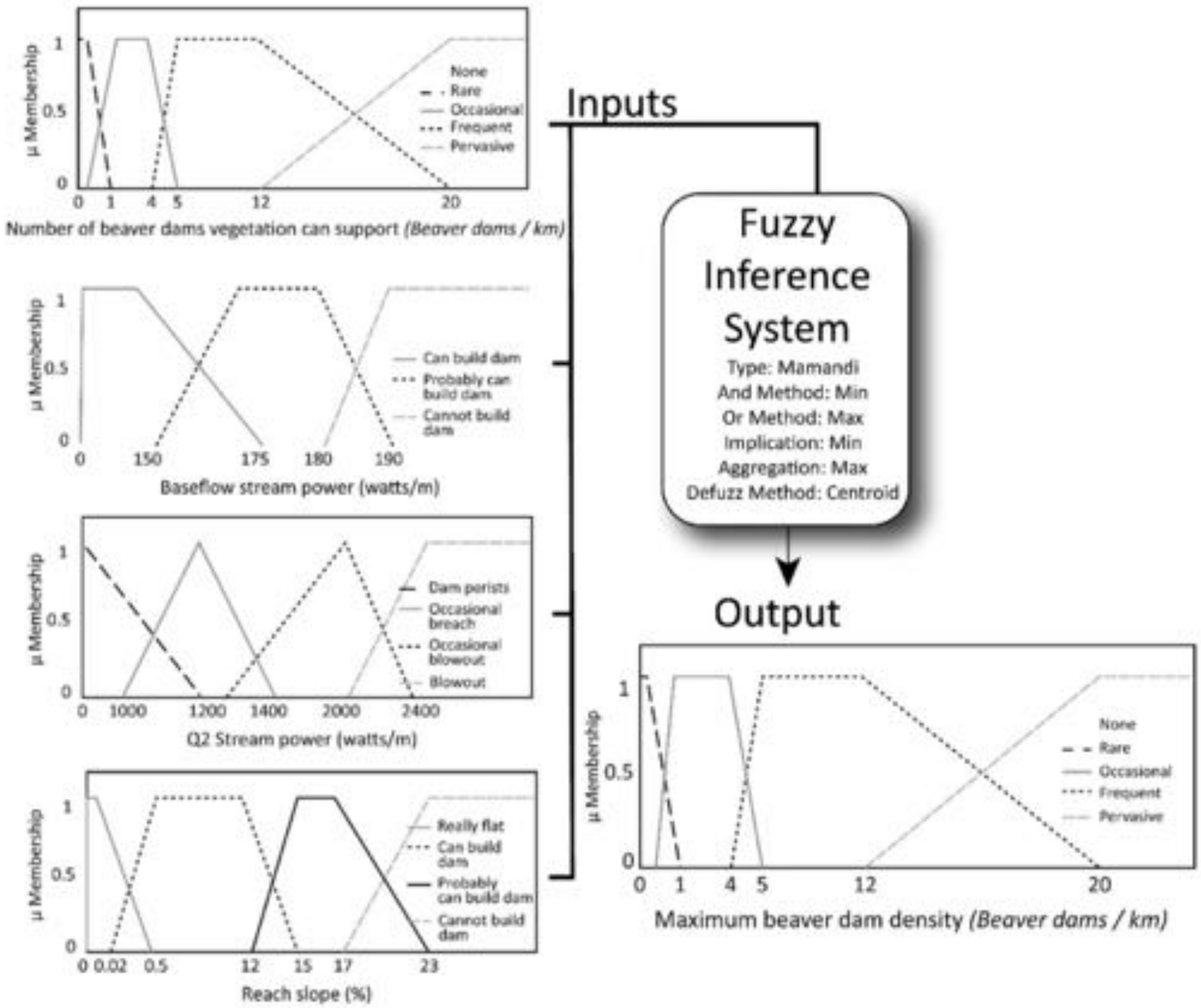

Figure 2.7 Membership functions of BRAT combined beaver capacity FIS system (figure adapted from (MacFarlane, et al. 2017))

	If	Inputs								Output
		Vegetative dam density capacity (FIS)		Baseflow stream power		2-year flood stream power		Reach slope (%)		Dam density capacity
Rules	1	Unsuitable	&	–	&	–	&	–	, then	None
	2	–	&	Cannot build dam	&	–	&	–	, then	None
	3	–	&	–	&	–	&	Cannot build dam	, then	None
	4	Rare	&	Can build dam	&	Dam persists	&	–	, then	Rare
	5	Occasional	&	Can build dam	&	Dam persists	&	–	, then	Occasional
	6	Frequent	&	Can build dam	&	Dam persists	&	Can build dam	, then	Frequent
	7	Frequent	&	Can build dam	&	Dam persists	&	Probably can build dam	, then	Occasional
	8	Pervasive	&	Can build dam	&	Dam persists	&	Really flat	, then	Pervasive
	9	Pervasive	&	Can build dam	&	Dam persists	&	Can build dam	, then	Pervasive
	10	Pervasive	&	Can build dam	&	Dam persists	&	Probably can build dam	, then	Occasional
	11	Rare	&	Can build dam	&	Occasional breach	&	–	, then	Rare
	12	Occasional	&	Can build dam	&	Occasional breach	&	–	, then	Occasional
	13	Frequent	&	Can build dam	&	Occasional breach	&	Can build dam	, then	Frequent
	14	Frequent	&	Can build dam	&	Occasional breach	&	Probably can build dam	, then	Occasional
	15	Pervasive	&	Can build dam	&	Occasional breach	&	Really flat	, then	Occasional
	16	Pervasive	&	Can build dam	&	Occasional breach	&	Can build dam	, then	Frequent
	17	Pervasive	&	Can build dam	&	Occasional breach	&	Probably can build dam	, then	Occasional
	18	Rare	&	Can build dam	&	Occasional blowout	&	–	, then	Rare
	19	Occasional	&	Can build dam	&	Occasional blowout	&	–	, then	Occasional
	20	Frequent	&	Can build dam	&	Occasional blowout	&	Can build dam	, then	Frequent
	21	Frequent	&	Can build dam	&	Occasional blowout	&	Probably can build dam	, then	Occasional
	22	Pervasive	&	Can build dam	&	Occasional blowout	&	Really flat	, then	Occasional
	23	Pervasive	&	Can build dam	&	Occasional blowout	&	Can build dam	, then	Frequent
	24	Pervasive	&	Can build dam	&	Occasional blowout	&	Probably can build dam	, then	Occasional
	25	Rare	&	Can build dam	&	Blowout	&	–	, then	None
	26	Occasional	&	Can build dam	&	Blowout	&	–	, then	Rare
	27	Frequent	&	Can build dam	&	Blowout	&	Can build dam	, then	Rare
	28	Frequent	&	Can build dam	&	Blowout	&	Probably can build dam	, then	None
	29	Pervasive	&	Can build dam	&	Blowout	&	Really flat	, then	Rare
	30	Pervasive	&	Can build dam	&	Blowout	&	Can build dam	, then	Occasional
	31	Pervasive	&	Can build dam	&	Blowout	&	Probably can build dam	, then	Rare
	32	Rare	&	Probably can build dam	&	Occasional breach	&	–	, then	Rare
	33	Occasional	&	Probably can build dam	&	Occasional breach	&	–	, then	Occasional
	34	Frequent	&	Probably can build dam	&	Occasional breach	&	Can build dam	, then	Frequent
	35	Frequent	&	Probably can build dam	&	Occasional breach	&	Probably can build dam	, then	Occasional
	36	Pervasive	&	Probably can build dam	&	Occasional breach	&	Really flat	, then	Occasional
	37	Pervasive	&	Probably can build dam	&	Occasional breach	&	Can build dam	, then	Frequent
	38	Pervasive	&	Probably can build dam	&	Occasional breach	&	Probably can build dam	, then	Occasional
	39	Rare	&	Probably can build dam	&	Occasional blowout	&	–	, then	Rare
	40	Occasional	&	Probably can build dam	&	Occasional blowout	&	–	, then	Occasional
	41	Frequent	&	Probably can build dam	&	Occasional blowout	&	Can build dam	, then	Occasional
	42	Frequent	&	Probably can build dam	&	Occasional blowout	&	Probably can build dam	, then	Rare
	43	Pervasive	&	Probably can build dam	&	Occasional blowout	&	Really flat	, then	Occasional
	44	Pervasive	&	Probably can build dam	&	Occasional blowout	&	Can build dam	, then	Frequent
	45	Pervasive	&	Probably can build dam	&	Occasional blowout	&	Probably can build dam	, then	Occasional
	46	Rare	&	Probably can build dam	&	Blowout	&	–	, then	None
	47	Occasional	&	Probably can build dam	&	Blowout	&	–	, then	Rare
	48	Frequent	&	Probably can build dam	&	Blowout	&	Can build dam	, then	Rare
	49	Frequent	&	Probably can build dam	&	Blowout	&	Probably can build dam	, then	None
	50	Pervasive	&	Probably can build dam	&	Blowout	&	Really flat	, then	Rare
	51	Pervasive	&	Probably can build dam	&	Blowout	&	Can build dam	, then	Occasional
	52	Pervasive	&	Probably can build dam	&	Blowout	&	Probably can build dam	, then	Rare

Figure 2.8 Rule table of combined beaver capacity FIS (Adapted from Table 3 in MacFarlane, et al. 2017).

The primary objective of this project is to establish a model framework for beaver restoration evaluation in the Milwaukee River watershed. Therefore, the BRAT model was adopted without changing the rule tables or membership functions. It is noted that the original parameterizations were calibrated based on the characteristics of riverscape and discoveries from field surveys of beaver dams of the mountainous states. Such a set of parameterizations may not be suitable to Midwestern states. For example, streampower in the Milwaukee River watershed that determines the suitability of dam building, and that determines dam breach could differ from that in the western mountainous states from where the BRAT model parameters were calibrated. Due to the limited scope of the work, the model was applied to the Milwaukee River watershed with only two modifications:

- The regional regression models in the source code were modified following equations (2.1) ~ (2.3).
- The original publication based on BRAT model analysis (MacFarlane, et al. 2017), the maximum dam capacity was calibrated to 40 dams/km, as suggested by a field study (Gurnell 1998). The field study also noted that such a high density (1 dam every 25 meters) was only found where multiple colonies maintain a large complex of 3 to 15 dams. However, several studies of beaver populations in habitats similar to Wisconsin suggested a potential density of 1 beaver colony per mile (or 0.66 km) potentially. A good estimate of maximum dam number per km in the Milwaukee River watershed has yet to be determined as it may require thorough field survey research. In this project, the maximum potential was set to 15 dams/km. The BRAT model was modified to scale down the range of the five categories of beaver capacity following a 40:15 ratio.

Pre-processed geodata by Matlab programs were exported into a spreadsheet with a format matching the matBRAT input file. Specifically, it is a CSV file with required parameters for all stream segments in columns. Model results were also exported to a CSV spreadsheet which includes four major parameters for each stream segment: potential beaver capacity (dams/km), dam counts of each segment, and existing and historical vegetation covers.

2.4 Model results and discussion

BRAT simulations were conducted with vegetation-only and vegetation-hydrology combined models. Both existing (EVT) and historic (BPS) vegetation covers were applied for model runs. Results are presented in Figure 2.9 ~ Figure 2.12.

Model results suggested that vegetation type is the dominant factor that determines beaver potential capacity in the Milwaukee River watershed, as the difference between the outputs of vegetation-only and combined models is barely noticeable, when comparing Figure 2.9 to Figure 2.10, or comparing Figure 2.11 to Figure 2.12. Specifically, mean beaver capacities averaged over all river segments are: 5.82 dams/km with the EVT-only model; 5.58 dams/km with the EVT-combined model; 9.00 dams/km with the BPS-only model; and 8.48 dams/km with the BPS-combined model. The landscape of the Milwaukee River watershed is generally flat, and slopes of most river reaches are very mild except the main river in the South Milwaukee River sub-basin. The hydrological condition is favorable for beavers at most river segments, which explains the minor difference between the vegetation-only and combined models.

Considering the six sub-basins in the watershed separately, the East-West branch, North branch, and Cedar Creek sub-basins are largely rural areas featured with extensive cover of grassland, farmland, forests, and wetlands; and the Menomonee River, Kinnickinnic River, and Milwaukee River South sub-basins have higher percentage of developed urban areas. Consequently, the EVT-combined model predicted that average beaver capacities are 6.29, 6.81, and 6.04 dams/km for East-West branch, North branch, and Cedar Creek sub-basins, respectively; and 4.61, 4.38, and 1.32 dams/km for Menomonee River, Kinnickinnic River, and Milwaukee River South sub-basins, respectively.

It should be noted that model predictions presented in this report are uncalibrated results. However, reported dam capacities can serve as a reference for beaver restoration site evaluations. In this project, BRAT model results were used as a planning tool for field survey studies.

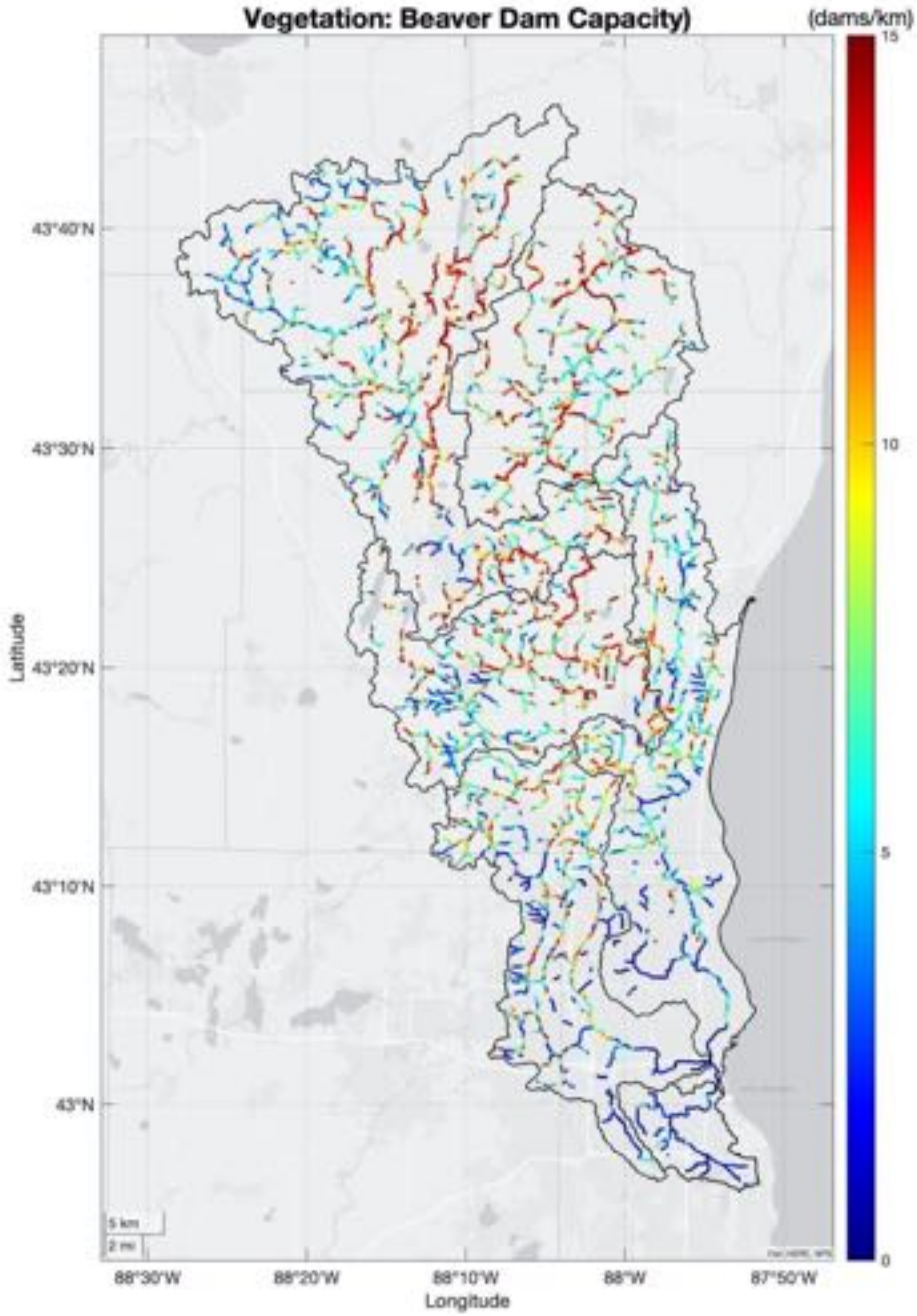

Figure 2.9 Potential beaver capacity distribution as result of BRAT FIS model based on current vegetation cover

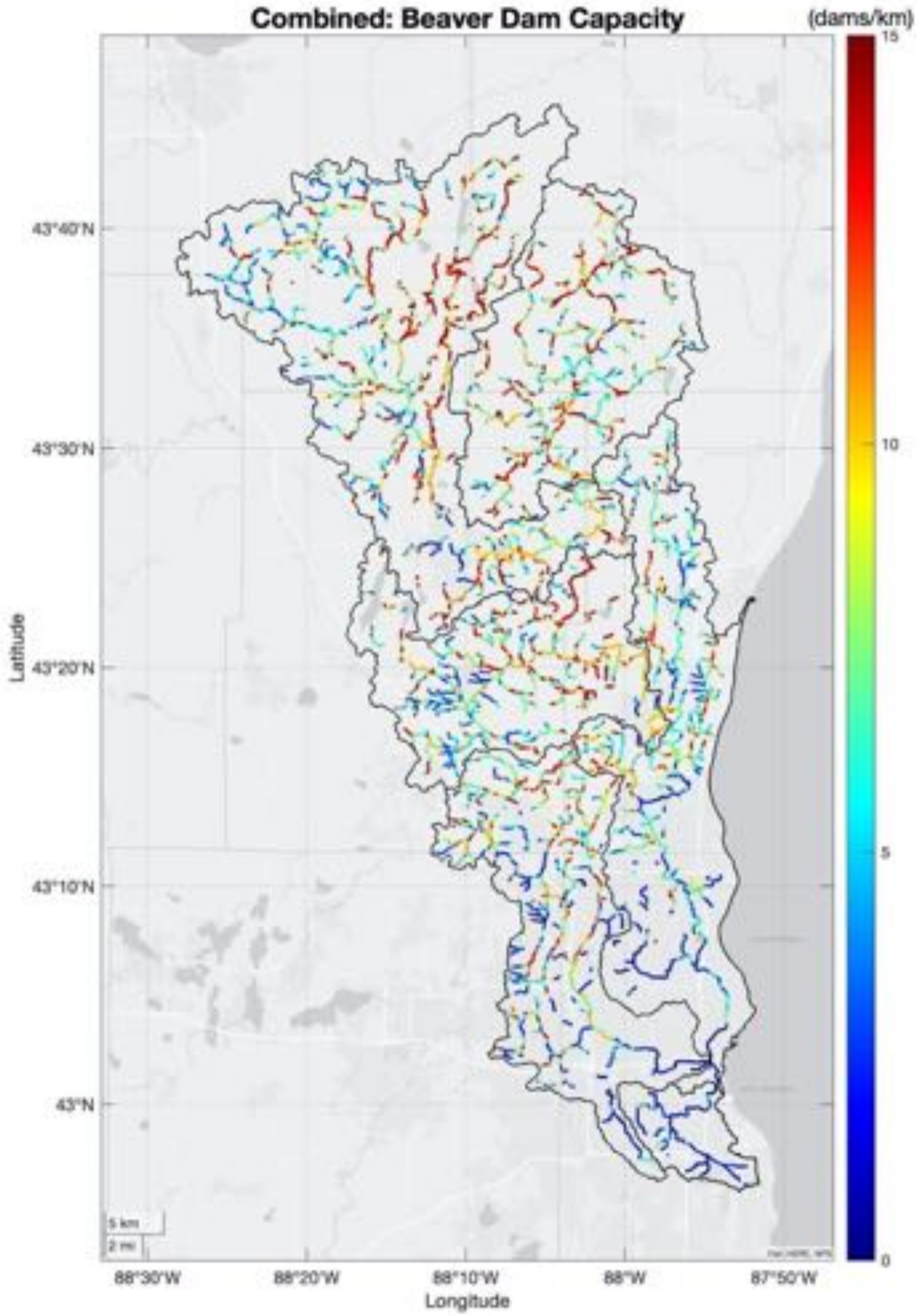

Figure 2.10 Potential beaver capacity distribution as result of BRAT FIS with vegetation (existing) and hydrologic factors combined model

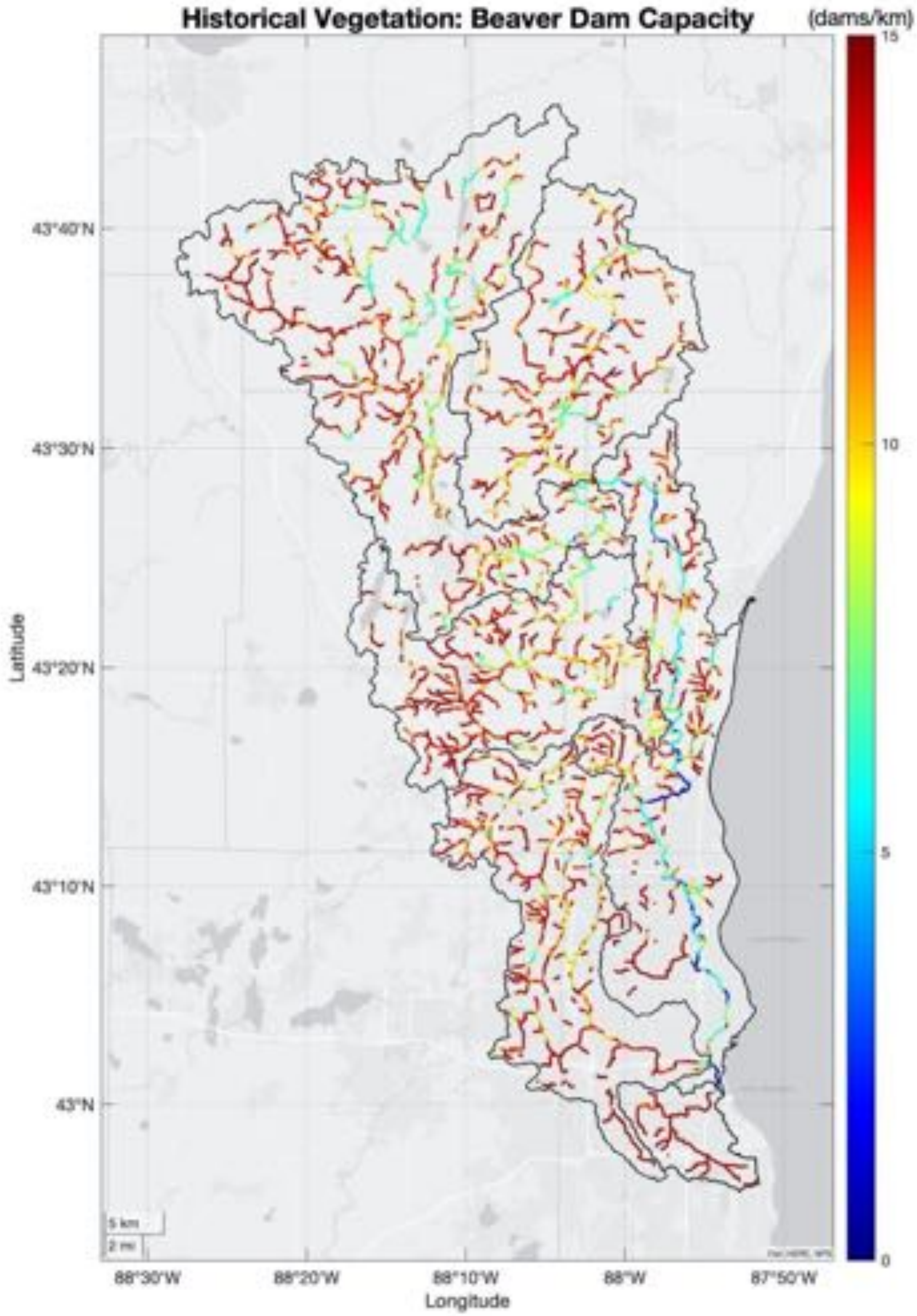

Figure 2.11 Potential beaver capacity distribution as result of BRAT FIS model based on historic vegetation cover

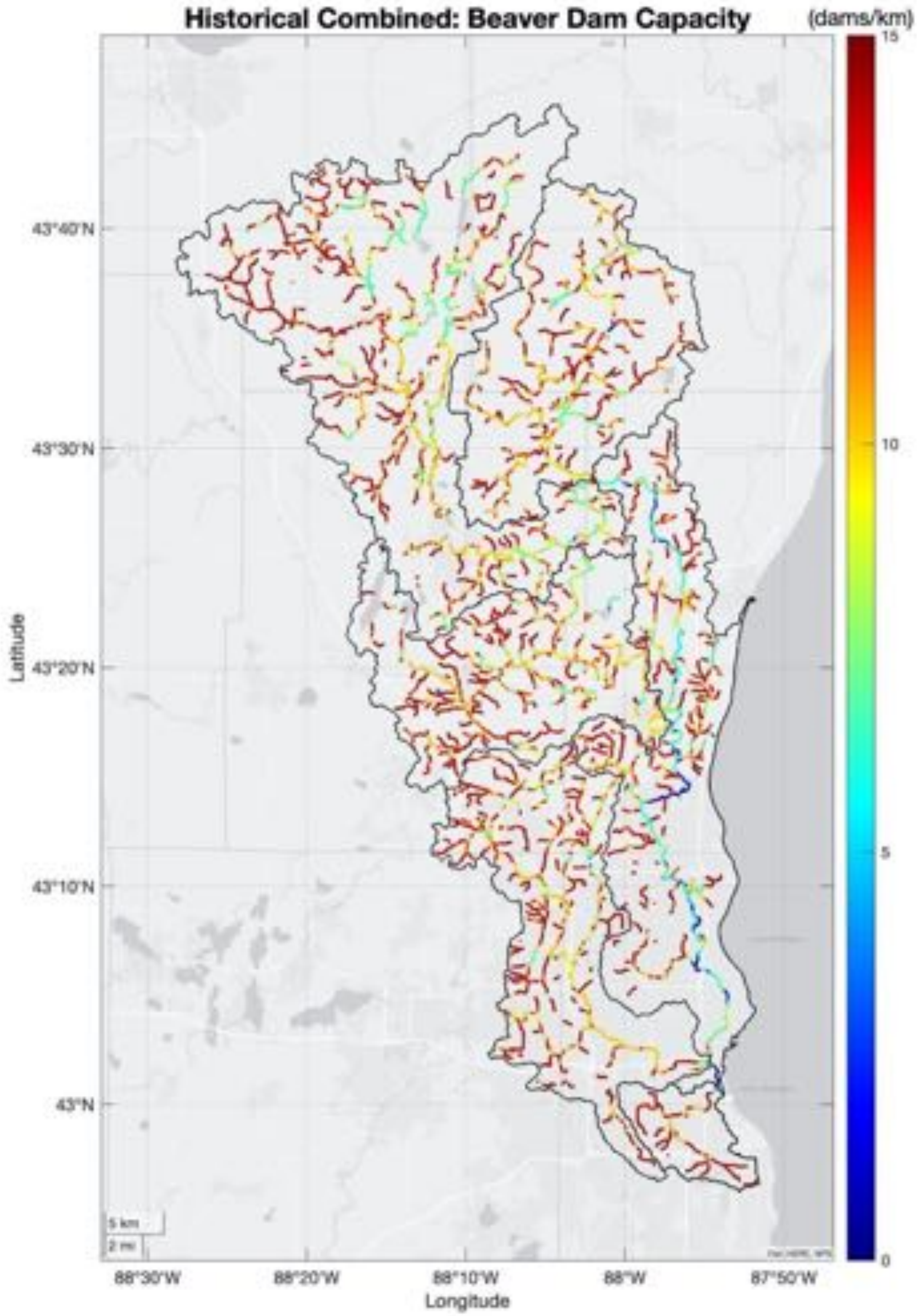

Figure 2.12 Potential beaver capacity distribution as result of BRAT FIS with vegetation (historic) and hydrologic factors combined model

3 Modeling hydrologic impacts of beaver restoration in Milwaukee River watershed

3.1 Hydrologic modeling framework: HEC-GeoHMS and HEC-HMS

Hydrograph processes across the Milwaukee River Basin, which includes watersheds of the Milwaukee River, Menomonee River and Kinnickinnic River, were simulated with a Hydrologic Modeling System developed by the US Army Corps of Engineers Hydrologic Engineering Center (HEC-HMS). HEC-HMS is capable of simulating precipitation-runoff processes of dendritic watershed systems. Beaver dams were modeled as reservoir components in HEC-HMS.

To prepare inputs to HEC-HMS modeling, geodata were pre-processed with HEC-GeoHMS, which is an interface software between HEC-HMS and ArcGIS. These processes included delineating the watershed and its sub-basins, and reconditioning river channels. Hydrological parameters that are related to vegetation interception, soil infiltration and storage, groundwater storage, and the time of concentration of each sub-catchment were also analyzed and specified through the HEC-GeoHMS interface.

Modeling procedures using HEC-GeoHMS and HEC-HMS are presented in detail in the following sections.

3.2 Model preparation with GIS analysis tools

3.2.1 Basin pre-processing

The Milwaukee River Watershed was delineated using ArcHydro tools in the HEC-GeoHMS module on a 1/3 arc-second (10-meter) resolution Digital Elevation Model (DEM). This DEM was downloaded from the United States Geological Survey (https://viewer.nationalmap.gov/basic/). Source DEM data that covers the entire river basin included four mosaic patches, which were merged and then projected in the North American Datum (NAD) 1983 Universal Transverse Mercator (UTM) Zone 16N projection (see Figure 3.1(a)). The watershed boundary and stream network were obtained through USGS National Hydrograph Dataset (NHD) (https://www.usgs.gov/core-science-systems/ngp/national-hydrography). The DEM was then cropped with the known watershed divide line to reduce the computation efforts in the subsequent terrain process (see Figure 3.1(b)). After that, the DEM was reconditioned through a "burning in" method for stream identification, i.e., the DEM cells that intersect with known drainage lines are artificially lowered such that streams, particularly those with low gradient and meanders, can be correctly identified. The NHD flow network of the Milwaukee River watershed was applied for the "burning in" process.

With the reconditioned DEM, the following procedures were carried out to reconstruct the flow network in the watershed:

- Flow direction raster map was calculated for every pixel of the DEM.
- Flow accumulation raster map was calculated to evaluate the drainage area of each "pixel" of the DEM.

- Streams were defined based on a specified minimum drainage area, which was set to 8 km^2 in this study, i.e., a pixel on the DEM is defined as part of a stream if its flow accumulation area is greater than 10 km^2. The specified minimum drainage area will eventually define the number of sub-basins to be created in the model.
- Stream segmentation process was carried out to link all defined “stream pixels” to linked stream network.

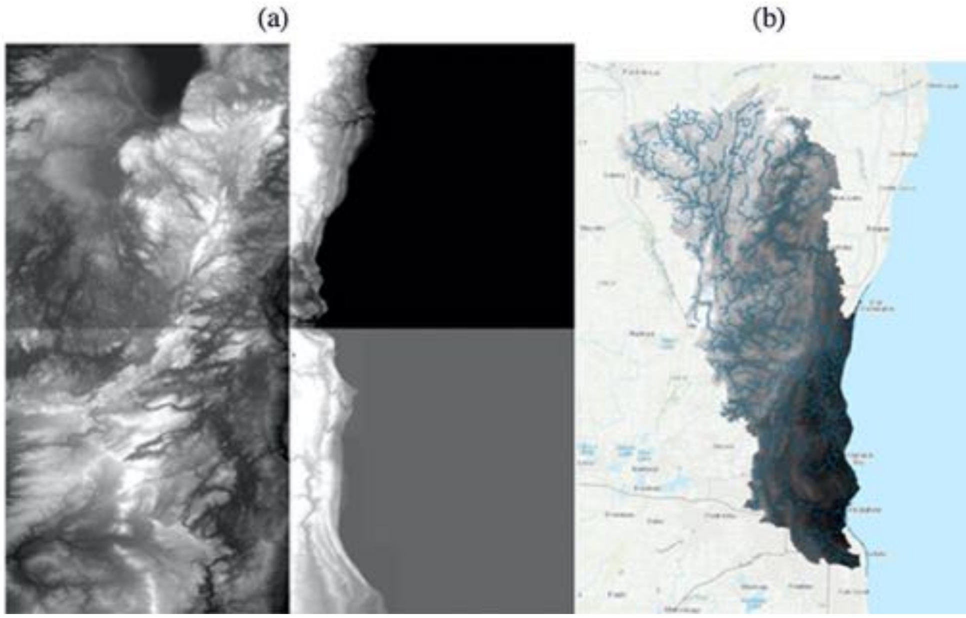

Figure 3.1 (a) 10-m resolution DEM data from USGS (b) NHD flow network data of the Milwaukee River watershed.

3.2.2 Watershed and subwatershed delineation

Following the results from the stream process, the entire watershed and sub-basins were delineated by taking a number of steps in HEC-GeoHMS: (1) Catchment grid delineation; (2) Watershed polygon processing; (3) Drainage line processing; and (4) Adjoin catchments.

A final step was taken to define the Milwaukee River watershed based on a selected outflow point (Figure 3.2). The outlet was selected to be at the confluence point of the Milwaukee River and the Kinnickinnic River. HEC-GeoHMS automatically tracks back to include all sub-basins that contribute to the flow at the outlet.

As a result, 135 sub-basins and 135 river reaches were defined in this model. The final number of sub-basins will be increased as some sub-basins will be sub-divided at locations where river gages and beaver dams are inserted in the flow network.

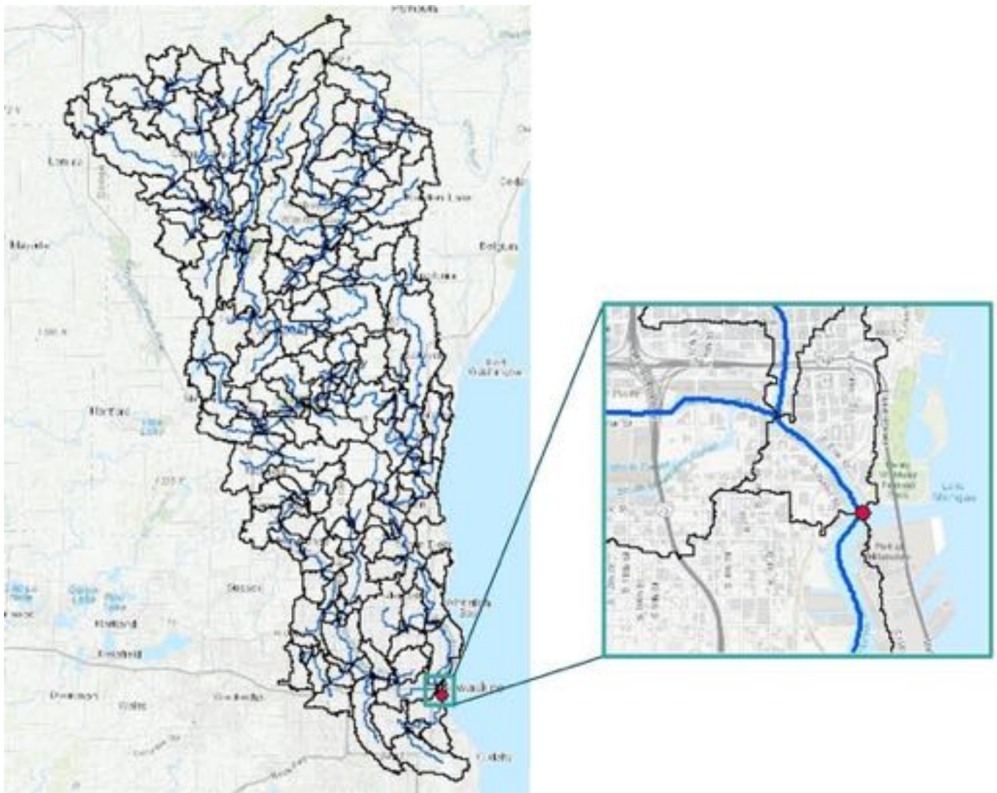

Figure 3.2 Sub-basins and river reach segments identified from HEC-GeoHMS process, the entire Milwaukee River watershed was delineated based on the selection of outlet point where the Milwaukee River discharges into the Milwaukee harbor (inserted figure)

3.2.3 Placement of beaver dams and stream gages

The locations where beaver dams were placed for modeling were determined following BRAT modeling and field surveying studies, which are detailed in section 3.3.5. For the HEC-HMS model to recognize a beaver dam as a portion of the stream regime, it is vital to make both an upstream and downstream connection to the dam and relative storage. Each dam is associated with an upstream river reach and a sub-basin so that the flow and the storage can be measured when the water travels through the dam. Therefore, a subbasin was created manually using the "subdivide basin" in HEC-GeoHMS by inserting a dividing point at a beaver dam location (Figure 3.3a). The inserted point was then considered as a "junction" component in HEC-HMS. This junction point can be converted into a "reservoir" component subsequently to model the hydrologic impact of a beaver dam. In this study, "beaver dams" were inserted in HEC-GeoHMS for simulation cases with and without beavers. In the latter case, they were considered simply as a placeholder in terms of "junctions".

Similarly, USGS stream gauges were added to the map as junctions, which serves as placeholders for extracting simulated flow series to be compared with USGS flow data. As illustrated in section 3.4.2, 11 streams were selected for model calibration, which were placed in the watershed. Figure 3.3(b) shows locations of beaver dams and stream gauges placed using the “subdivide basin” tool in HEC-GeoHMS. With these added “junctions”, the total number of sub-basins in HEC-HMS was increased from 135 to 213.

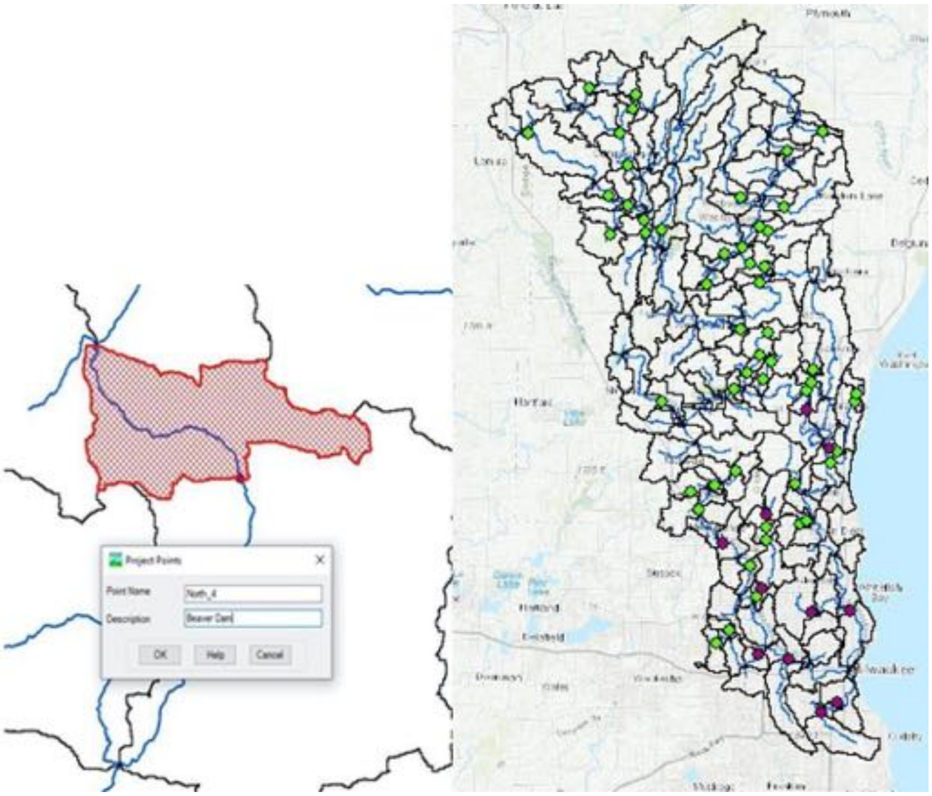

Figure 3.3 (a) Placement of beaver dam using sub basin division tool (b) Location of Beaver dams (green diamond) and stream gauges (purple circles)

3.2.4 Post-processing sub-basins and river reaches

Post-processes in Geo-HMS included calculations of river slope, basin slope, and longest flow path to collect geometric and topographic information of sub-basins for surface runoff transformation analysis. The longest flow path computes the length from the farthest point to the outlet for each sub-basin, which is used to estimate the time of concentration during processing of hydrologic parameters. In addition, basin centroids are identified for each sub-basin based on the longest flow path method. Geographic coordinates, elevations and centroidal longest flow path of sub-basin centroids were calculated as well. In this study, precipitation on each sub-basin was determined based on land-based rain gauge data using an “inverse distance” approach (see section 3.4.1 for details). Geographic coordinates of rain gauges used in this study were imported as a point layer in Geo-HMS for preparing the meteorological model components.

With physical characteristics of streams and sub-basins determined, TR55 flow path segments, TR55 flow path segment parameters are estimated in HEC-GeoHMS. For the TR-55 methodology, surface runoff process consists of sheet flow, concentrated flow and channel flows, with the corresponding lengths and slopes of flows computed in GeoHMS. These parameters were exported for a subsequent process as detailed in section 3.3.2.

In the final step of the HEC-GeoHMS process, data was converted into a HEC-HMS input file, i.e., a “basin file,” which is an ASCII file that describes all HEC-HMS components. For this purpose, HEC-GeoHMS map layers were first converted into HMS units (SI Units); watershed schematics such as HMS link and HMS node were then added to the map before exporting to HEC-HMS input files (Figure 3.4). The layers for sub-basins and rivers were exported to GIS shape files and the attribute tables of longest flow path, basin centroids, HMSLink, HMSNode and project point are exported as excel files for the subsequent Matlab analysis. In this study, Matlab programs have been developed to post-process HEC-GeoHMS results and to generate ASCII files for HMS modeling inputs which include: (1) a “basin” file; (2) a precipitation “gage” file; and (3) a meteorological “met” file.

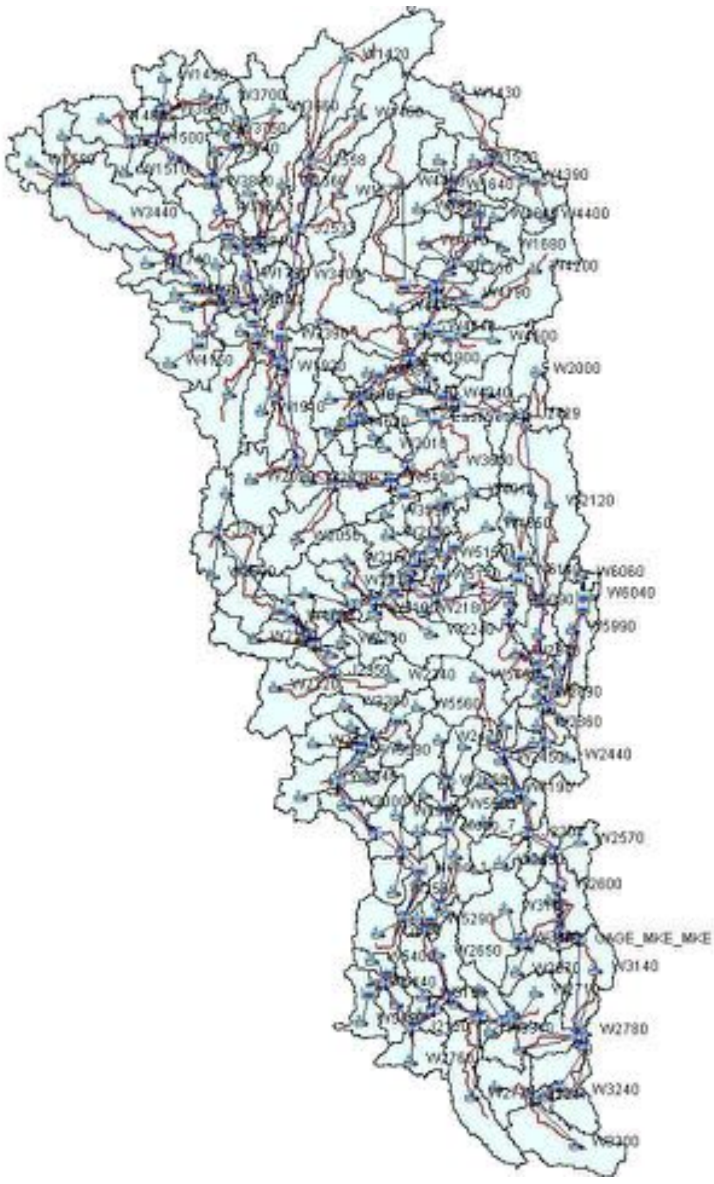

Figure 3.4 HEC-HMS basin file of the Milwaukee River watershed as a result of HEC-GeoHMS processes. The processed watershed included 213 sub-basins, 138 river reaches, 88 river junctions and 52 reservoirs (beaver dams).

3.2.5 Additional geodata: soil, land surface and vegetation

Matlab programs developed for post-processing combines geographic and geometric outputs of HEC-GeoHMS with additional geodata to calculate and assign hydrological parameters to each HEC-HMS component, i.e., sub-basins, links (rivers), and reservoirs (beaver dams). Additional geodata included primarily information about the soil, land cover and vegetation.

Soil data were used to parameterize hydrological losses through infiltration and evapotranspiration. Soil data were acquired from the SSURGO database collected by the National Cooperative Soil Survey (https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/geo/?cid=nrcs142p2_053627) SSURGO datasets consist of map data, tabular data, and information about how the maps and tables were created. The extent of a SSURGO dataset is a soil survey area, which may consist of a single county, multiple counties, or parts of multiple counties. SSURGO map data were downloaded from the Web Soil Survey in ESRI® Shapefile format for all the seven counties (Milwaukee, Waukesha, Washington, Ozaukee, Fond du Lac, Sheboygan, and Dodge) that contain the entire Milwaukee River watershed. However, SSUGO coverage does not include City of Milwaukee. Soil information for that particular area was derived from the STATGO database, which has a less spatial resolution than SSURGO.

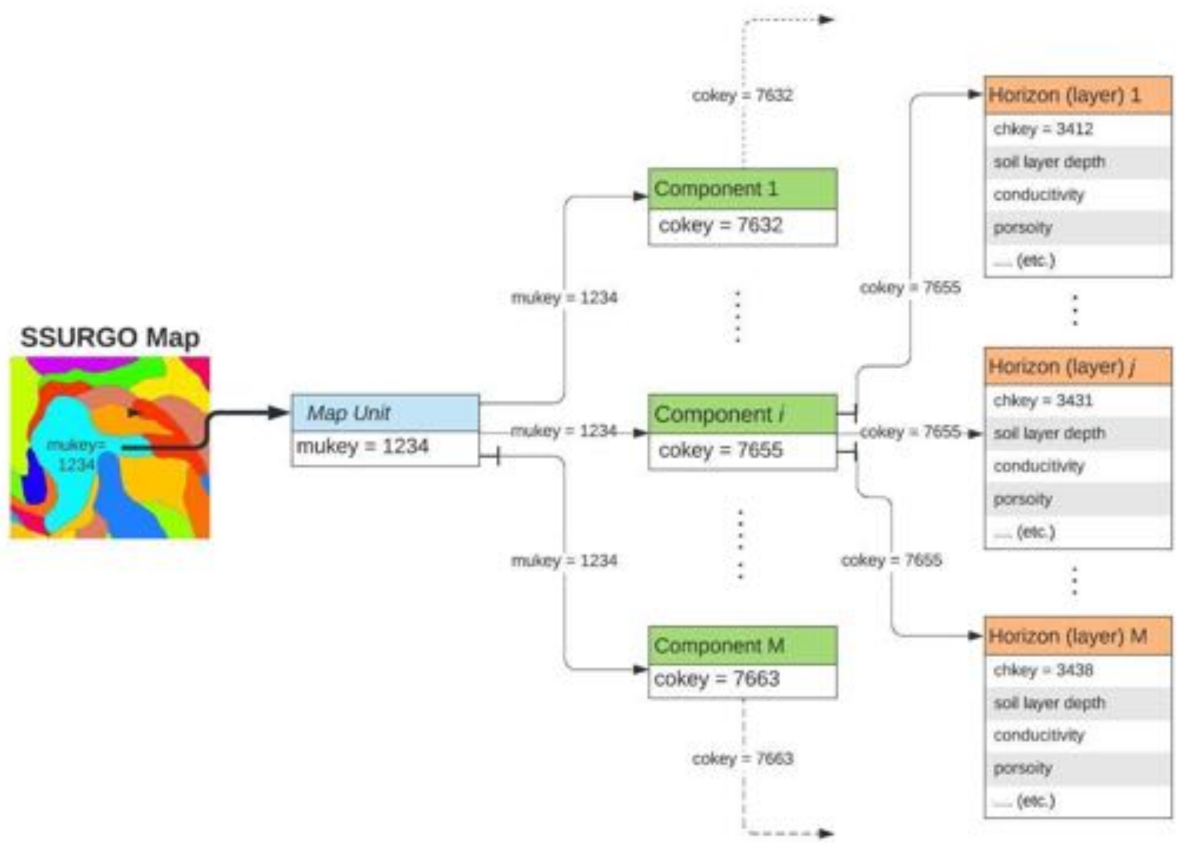

Figure 3.5 Structure of SSURGO soil data

SSURGO dataset included a map of geographic regions (a polygon shape) with each region assigned with a map-unit (identified by mukey). Every map unit contains multiple soil components (identified by co-key). Each component is a single type of soil which has multiple soil layers (identified by chkey). The relations among map units, components and layers are presented in tables for lookup. Soil properties, such as soil layer depth, saturated conductivity, soil capacity and porosity, are listed in the soil layer table. The hierarchy SSURGO data structure is illustrated through Figure 3.5.

In this study, a Matlab program was developed to read the SSURGO map (shape files) and data tables, process the data following their relations, and to compute relevant soil properties for HEC-HMS modeling. The calculation methods for soil parameters were similar to those reported by Holberg (2015). Specifically, the following soil properties were calculated with weighted averaging for each map unit according to the percentage of various components in the unit and the depth of each layers in a component:

- **Maximum Infiltration Rate ($Infil$)** is the fastest rate at which precipitation seeps from the ground surface into the soil profile. It is calculated as the saturated hydraulic conductivity of the top soil layer (K_{top}) multiplied by the component percentage (Pc)

$$Infil = \sum_{i=1}^{M} K_{top_i} Pc_i \tag{3.1}$$

- **Maximum Percolation Rate ($Perc$)** is the velocity with which water is transferred through the soil profile and groundwater layer(s). In this study, the maximum percolation rate is taken as the weighted average of the layer-averaged (layer thickness is denoted as b) saturated hydraulic conductivity (K) for all components in a map unit, following that described in Bennett (1998) and Fleming (2002).

$$Perc = \sum_{i=1}^{M} \left(Pc_i \frac{\sum_{j=1}^{N_i} K_{ij} b_{ij}}{\sum_{j=1}^{N_i} b_{ij}} \right) \tag{3.2}$$

- **Maximum Soil Profile Storage (S_P)** is the storage depth available in voids and soil pores when the soil is dry. Soil voids can be drained by gravity or evaporation (HEC 2000). The soil profile storage is calculated by multiplying the component percent, average porosity (α), and the soil layer thickness (b) together for each component and then summing these values to reach a total for each map unit.

$$S_P = \sum_{i=1}^{M} \left(Pc_i \frac{\sum_{j=1}^{N_i} \alpha_{ij} b_{ij}}{\sum_{j=1}^{N_i} b_{ij}} \right) \tag{3.3}$$

- **Maximum Tension Zone Storage (S_T)** is the storage depth available in the form of water attached to soil particles. This water can only be removed through evaporation, suction, or contact with a dry, porous material (Jury and Horton 2004). Field capacity is the amount of water left in the soil profile after water has stopped draining from the soil; it is analogous to the tension zone (Veihmeyer and Hendrickson 1931). The tension zone storage is calculated by multiplying the component percent, average field capacity (*Cap*), and the soil layer thickness together for each component and then summing these values to reach a total for each map unit.

$$S_T = \sum_{i=1}^{M} \left(Pc_i \frac{\sum_{j=1}^{N_i} Cap_{ij} b_{ij}}{\sum_{j=1}^{N_i} b_{ij}} \right) \tag{3.4}$$

In all equations presented above, subscript i represents the i-th component of the current map unit, and subscript j represents the j-th soil layer (horizon) of a component. M is the total number of components in the map unit, and N_i is the number of layers in the i-th component.

Calculated soil parameters for all map units in the watershed were converted to raster maps (see Figure 3.6), and the Matlab program computed the regional average of the raster images for each sub-basin of the HEC-HMS model.

The hydrological modeling requires information about the percentage of impervious land area in each sub-basin. This information is provided by USGS's National Land Cover Database (NLCD), which can be directly downloaded from ArcGIS's online database (https://www.arcgis.com/home/item.html?id=1fdbb561c58b45c58f8f966c00c78ae6). The downloaded data were projected, cropped and exported as a raster map. The Matlab program then calculated the regional average of imperviousness for each sub-basin.

Since the simple canopy method was applied in the hydrological modeling to account for interception of precipitation by vegetation, the LANDFIRE data (Existing Vegetation Type) that were used in BRAT modeling were also used to estimate the canopy storage. A lookup table was created to relate the type of vegetation to a storage depth, which ranged between 0 ~ 3 mm in this study.

Figure 3.7 shows the process raster images of the percentage of impervious land and the canopy storage distribution.

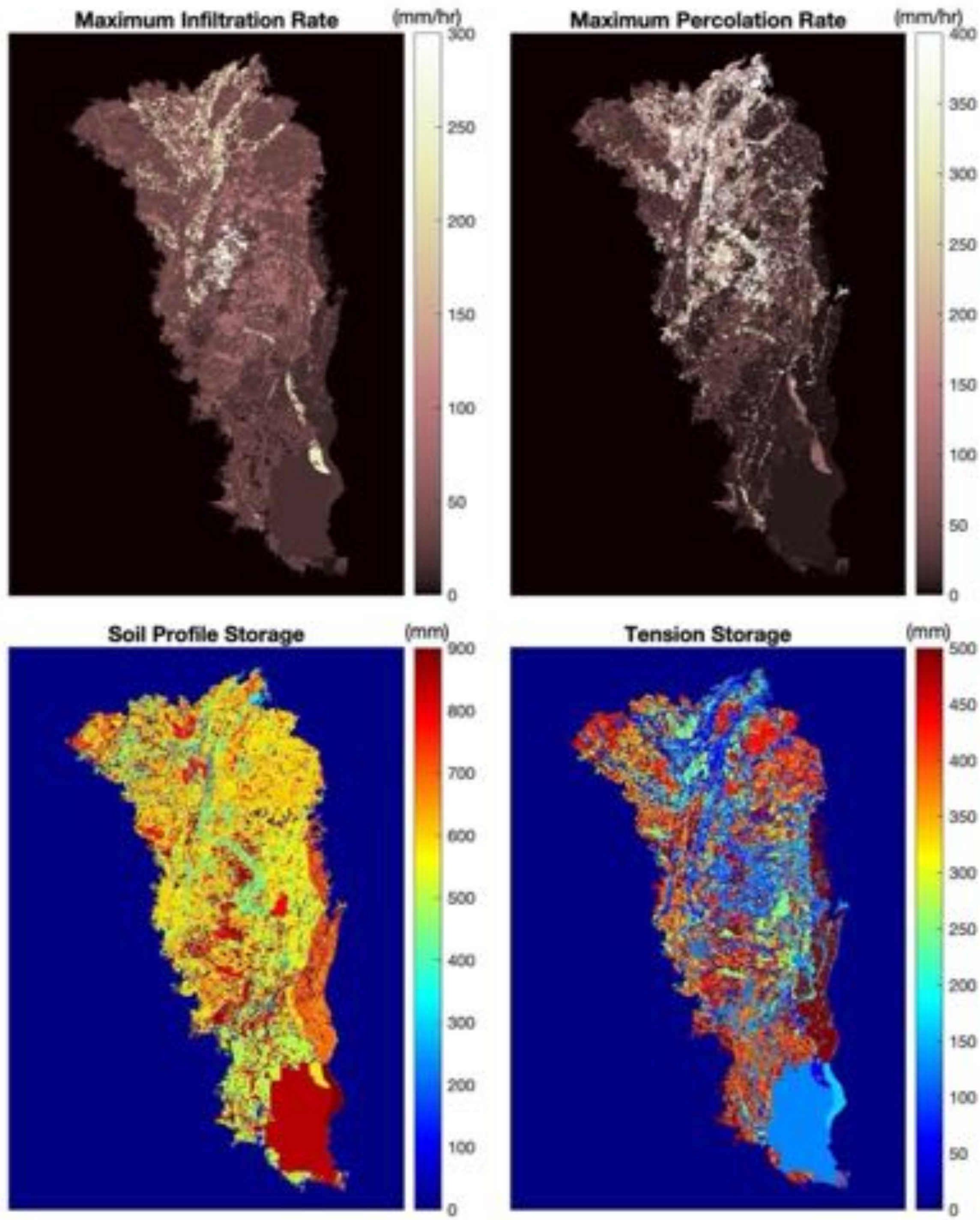

Figure 3.6 Raster images of processed SSURGO soil data: maximum infiltration rate, maximum percolation rate, soil maximum profile storage, and soil maximum tension storage.

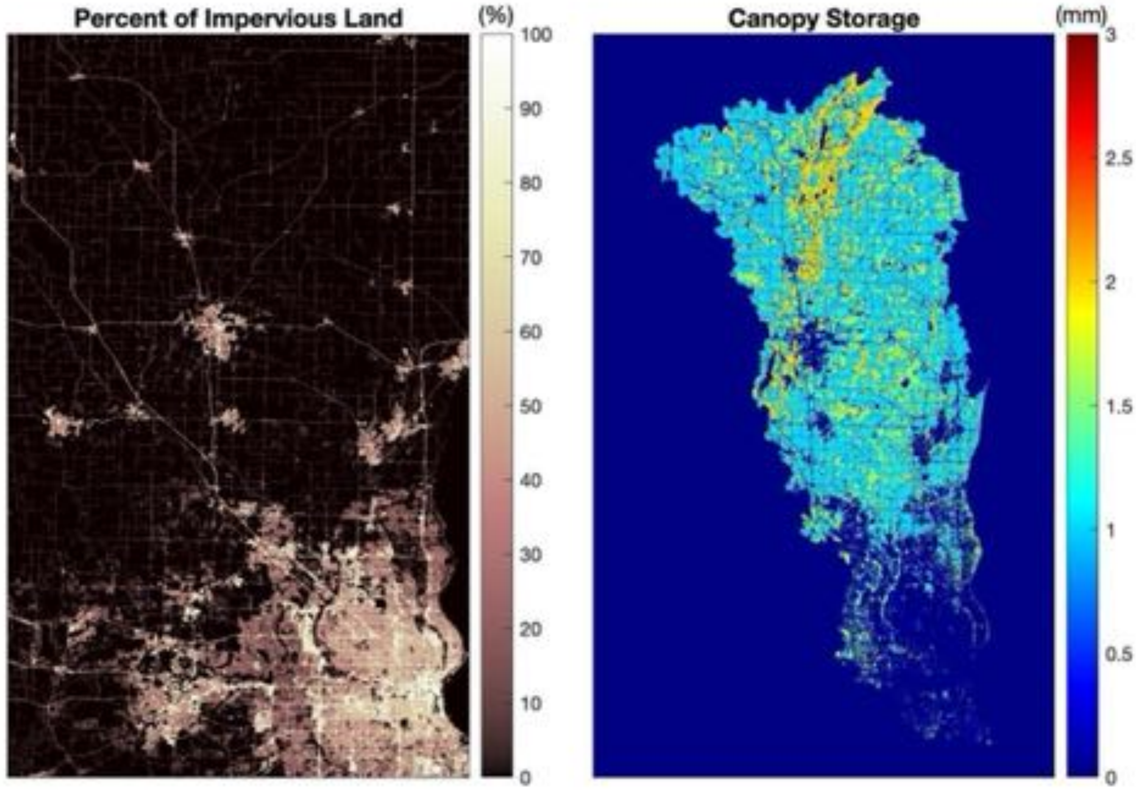

Figure 3.7 Raster image of percent of impervious land (processed from NLCD data) and canopy storage (from LANDFIRE data)

3.3 HEC-HMS model configuration

HEC-HMS is a distributed model for the simulation of complete hydrologic processes of dendritic watershed systems. A watershed is typically divided into "sub-basins" components from which water drains to "junction" points, and junctions are connected by streams or "reach" components. In a sub-basin, the model simulates losses due to surface storage, interception, infiltration and evapotranspiration; the transform process which produces surface runoff; and the groundwater storage and baseflow. The model also simulates the routing (stream flow) process in reach components.

For this project, hydrologic processes in the Milwaukee River watershed are simulated with the following configurations:

- Hydrologic losses through infiltration, evapotranspiration, interception and detention were modeled using the simple surface, simple canopy and soil moisture accounting methods;
- Rainfall – runoff conversion was modeled by the Clark Unit Hydrograph method;
- Interflow and base flows due to groundwater seepage were modeled through a linear reservoir method;
- Streamflow in river channels was modeled by the Muskingum-Cunge routing method.

The overall model framework and processes simulated are shown in Figure 3.8. Details of model configuration and parameterizations are presented in the following sub-sections.

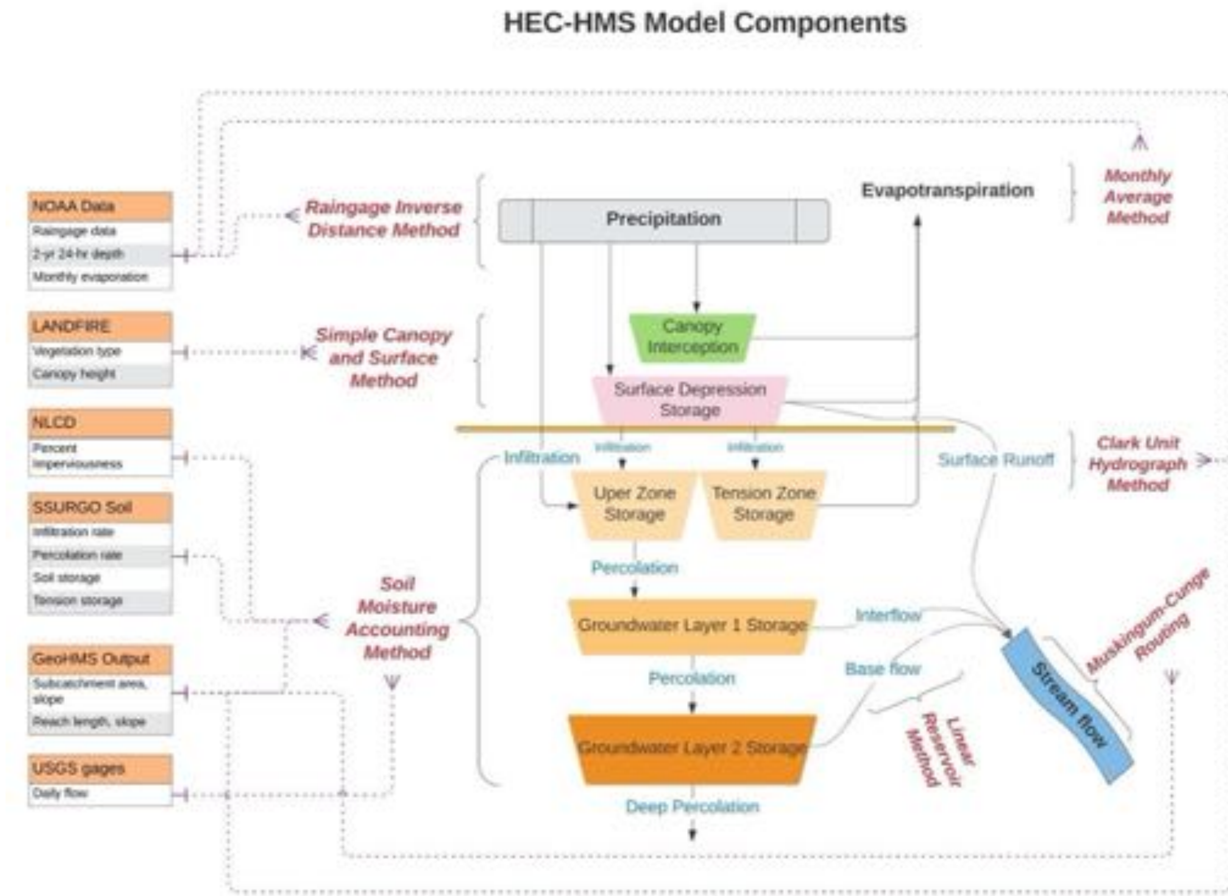

Figure 3.8 Model framework and hydrologic processes simulated in the current study. Solid lines with arrows indicate flow directions of water cycles. Dashed lines with arrows represent data dependency for parameters of sub-model components.

3.3.1 Soil Moisture Accounting method for hydrologic losses

The Soil Moisture Accounting (SMA) was selected as the loss method. SMA is a continuous model that captures extensive loss through multiple storage components in the soil. This method determines how much and how fast precipitation will be lost to five different storage components including canopy-interception storage, surface-interception storage, soil profile storage and two groundwater storage components (see Figure 3.8). Each storage compartment is assigned a maximum storage depth, and the soil compartments include rates of influx and outflow. When precipitation starts, it first fills canopy storage. Once the canopy storage is filled, the additional precipitation, not captured by canopy interception and in excess of the infiltration rate, is held by shallow surface depressions. When the volume of these surface depressions is filled, the excess water flows over the land creating surface-runoff. After filling the canopy-interception storage and surface-interception storage, precipitation starts to infiltrate through soil profile storage. Soil profile storage is divided into two regions, the upper zone and tension zone. Precipitation fills the tension zone first and then it moves to the upper zone. From the soil profile, storage precipitation percolates into the first layer of groundwater storage. Excess percolation to the first layer of groundwater storage percolates to the second layer of groundwater storage. Stored water can percolate from the second layer of groundwater storage to a deep aquifer and is considered lost from the system.

Most parameters that are required to model processes involved in the SMA method are available from the processed SSURGO soil data (see section 3.2.5). In this project, the following SMA parameters were determined as the following:

- **Surface maximum infiltration** is the maximum rate at which precipitation in excess of maximum surface storage enters the soil. It was set to equal the maximum infiltration rate ($Infil$) from SSURGO data following equation (3.1).
- **Soil maximum storage** is the maximum amount of precipitation that can be stored in the uppermost soil layer. It is equivalent to the maximum soil profile storage (S_P) of the SSURGO data as calculated by equation (3.3).
- **Soil tension storage** is the amount of precipitation in the soil storage that is held against gravity. All precipitation stored in the soil that exceeds the tension storage is available for percolation to the groundwater storage. It is equivalent to the soil tension storage (S_T) of the SSURGO data, as calculated by equation (3.4).
- **Soil maximum percolation** is the maximum rate at which precipitation stored in soil storage, in excess of tension storage, enters the first groundwater storage compartment used in the SMA loss method. It was set to equal the maximum percolation rate ($Perc$) from SSURGO data following equation (3.2).
- **Groundwater 1 (GW_1) and groundwater 2 (GW_2) maximum storage** are the maximum amount of precipitation that can be stored in the upper and lower groundwater storage compartments, respectively. The two parameters are not available from soil data. They were considered to be proportional to the soil storage depth in this project, and the proportionality was treated as tuning parameters during the calibration process (see section 3.4.4). It was found that the following relations produced good calibration results:

$$GW_1 = 0.9S_P \tag{3.5}$$

$$GW_1 = 1.2S_P \tag{3.6}$$

- **Groundwater 1 and groundwater 2 maximum percolation ($Perc_{GW1}$ and $Perc_{GW2}$)** are the maximum rate at which groundwater leaves the upper storage and enter the lower storage, and leaves the lower groundwater storage to deep aquifer, respectively. They were also treated as "tuning" parameters in this project, which were set as the following after calibration:

$$Perc_{GW1} = 0.1Perc \tag{3.7}$$

$$Perc_{GW2} = 0.5\,Perc_{GW2} \tag{3.8}$$

- **Groundwater 1 and groundwater 2 storage coefficients (ST_{GW1} and ST_{GW2})** are parameters that control the time scale of interflows and baseflows. In the SMA method, stream interflows originate from groundwater 1 storage and baseflows originate from groundwater 2 storage, as groundwater becomes saturated in the two storage compartments. For a typical stream hydrograph after an isolated storm event, the tail end of the receding "limb" represents effects of interflows and baseflows. Following the method described in Holberg (2015), exponential functions can be applied to fit the receding "limbs" of a stream hydrograph and subtracted from the original hydrograph to isolate interflow and baseflow successively. The time scale of the exponential fit is considered as an estimate of groundwater storage coefficient. Since hydrograph data were not available for most river reaches in the model, a regional regression method was applied to scale the storage coefficient with the drainage area, similar to the approach applied in estimating baseflows and flood flows in BRAT modeling (see section 2.2.3). Specifically, hydrograph data from 25 regional USGS stream gages were applied to estimate the storage coefficients by selecting isolated storm-runoff events at each station. The best-fitted storage coefficients were plotted against the drainage area. A linear trend was evident in the log-log scale graph, which suggested power-law relations for both ST_{GW1} and ST_{GW2} (see Figure 3.9) as

$$ST_{GW1} = 2.02A^{0.621} \tag{3.9}$$
$$ST_{GW2} = 5.54A^{0.664} \tag{3.10}$$

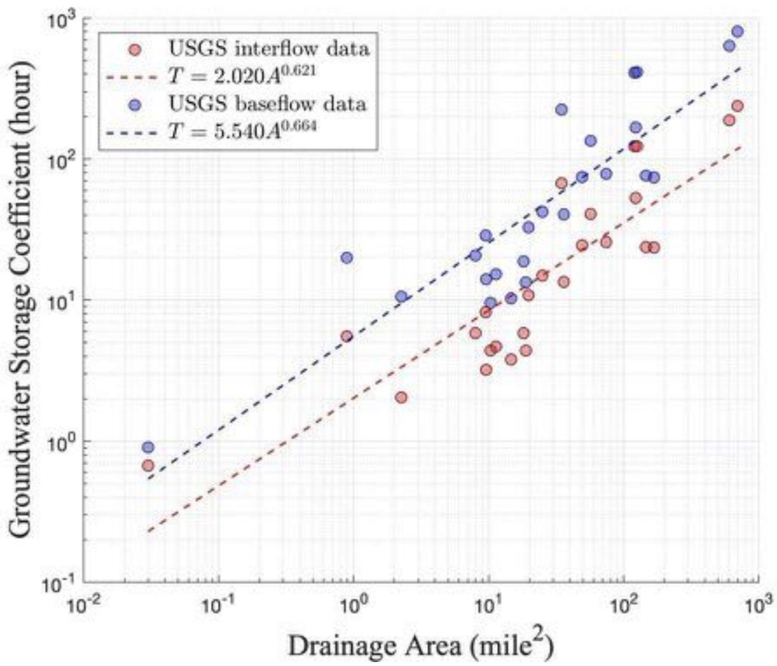

Figure 3.9 Regional regression analysis of USGS stream gage interflow and baseflow data for the estimation of groundwater storage coefficients.

where storage coefficients are in (hours) and the drainage area A is in (mi^2). Equation (3.9) and (3.10) were subsequently applied to all sub-basins in the HEC-HMS model to calculate ST_{GW1} and ST_{GW2} according to sub-basin areas.

3.3.2 Clark unit hydrograph approach for transformation

The Clark unit hydrograph is a synthetic unit hydrograph method. A time versus area curve (time-area curve) built into HEC-HMS is used to develop the translation hydrograph resulting from a burst of precipitation. The resulting translation hydrograph is routed through a linear reservoir to account for storage attenuation effects across the subbasin. The Clark unit hydrograph requires two parameters for each sub-basin: (1) the time of concentration (T_c) defines the maximum travel time in the subbasin; and (2) the storage coefficient (S_c) is used in the linear reservoir that accounts for storage effects.

Data needed to estimate T_c and S_c were readily available through the GeoHMS analysis (see section 3.2.4), which prepares geographic parameters necessary for the Soil Conservation Service (SCS) TR-55 model (Cronshey 1996). The TR-55 method considers water moves through a catchment as (1) sheet flow; (2) shallow concentrated flow; and (3) open channel flow. Therefore, time of concentration of a sub-basin is the summation of travel time values for the three consecutive flow segments, i.e.,

$$T_c = T_{sheet\ flow} + T_{concentrated\ sheet\ flow} + T_{channel\ flow} \tag{3.11}$$

and

$$T_{sheet\ flow} = 0.007\frac{(nL_S)^{0.8}}{P_{24}^{0.5}S_S^{0.4}} \tag{3.12}$$

$$T_{concentrated\ sheet\ flow} = \frac{L_{CS}}{16.13\sqrt{S_{CS}}}\ or\ \frac{L_{CS}}{20.33\sqrt{S_{CS}}} \tag{3.13}$$

$$T_{channel\ flow} = \frac{nL_C}{1.49R^{\frac{2}{3}}\sqrt{S_C}} \tag{3.14}$$

where $L_S, L_{CS}\ and\ L_C$ are flow lengths of sheet flow, concentrated sheet flow and channel flow, respectively; $S_S, S_{CS}\ and\ S_C$ are slopes of the three segments, respectively. Flow lengths and slopes were all calculated by GeoHMS for each sub-basin. The Manning's roughness was set to be $n\ =\ 0.03$ for both sheet flows and channel flows. The hydraulic radius R of channel flows was manually set for each sub-basin channel with values varying between 0.1 ~ 0.5 m, depending on the drainage area. In equation (3.13) coefficients 16.13 and 20.33 are for unpaved and paved land surfaces, respectively. They were specified for each sub-basin based on the percentage of imperviousness.

Field studies suggest that the storage coefficient is correlated with the time of concentration, specifically,

$$\frac{S_c}{S_c + T_c} = 0.5 \sim 0.6 \tag{3.15}$$

over a region. This correlation was applied to calculation S_c for all sub-basins.

3.3.3 River routing

River routing process for reach (river) components in HEC-HMS accounts for attenuation of flood waves. The Muskingum-Cunge method was selected for routing in this project. The method is a combination of the conservation of mass and a diffusion representation of the conservation of momentum. Parameters need to be specified for Muskingum-Cunge includes channel length, slope, cross-section geometry, and the Manning's roughness. Channel length and slope of all reaches were readily available from GeoHMS output. All channels were assumed to have a trapezoidal cross-section. Since it is beyond the scope of this study to acquire cross-section geometry for every channel reach, it was assumed that side slopes of all channels equal to 2 (horizontal vs vertical), and channel width varies between 5 and 70 meters, which scales with the drainage area of each reach. The Manning's roughness was assumed as $n = 0.035$ uniformly for all channels.

3.3.4 Modeling surface, canopy interception and evapotranspiration losses

In HEC-HMS the surface is a sub-basin component which represents the ground surface where water may accumulate in surface depression storage. In this project, a "Simple Surface" method was selected to model the surface depression storage. A storage capacity was assigned for each sub-basin. Water storage on the surface will infiltrate into soil even when the capacity is not full. Surface runoff will start when the precipitation rate exceeds the infiltration rate. As suggested by (Bennett 1998), ground surface storage is related to the ground slope. For paved impervious areas, the surface storage is between 3.18 and 6.35 mm. Otherwise, it is 50.8 mm for slope between 0 ~ 5%; 5-30 mm for slope between 5 ~ 30%; and 1.02 mm for slope greater than 30%. Following this reference, maximum surface storage was assigned based on average slope of each sub-basin, which was available from the results of GeoHMS procedures.

Canopy is also a sub-basin component in HMS, which represents the presence of plants and vegetation in the landscape that can intercept precipitation and reduce runoff. The intercepted water can evaporate between storm events. Moreover, plants extract water from soil through transpiration. The combination of evaporation and transpiration is known as the evapotranspiration, which represents an important hydrologic loss term. A "Simple Canopy" method was selected to model this process in the present study. Specifically, a maximum canopy storage in terms of equivalent water depth was assigned for each sub-basin. The storage value was estimated from the LANDFIRE vegetation data, as described in section 3.2.5 and presented in Figure 3.7. All precipitation is intercepted until the storage capacity is full. Excess precipitation will fall to the surface and go through the surface storage and infiltration processes subsequently. Between storm events, the canopy storage will be depleted at a rate set by the potential evapotranspiration rate (see section 3.4.3). After the canopy storage is emptied, water will be extracted from soil for additional evapotranspiration. The "Tension Reduction" method was applied in this study to model this process, where water was first extracted from the gravity zone at the full rate defined by the evapotranspiration rate, then water will be extracted from the tension zone at a reduced rate. This method was selected as it can work along with the soil moisture account method.

3.3.5 Beaver dam identification and model reconstruction

According to BRAT modeling results and site evaluations, sites with evaluation scores of 4 and above were evaluated for potential of beaver restoration. An in-house Matlab program was developed to identify the most likely locations for beavers to build dams. The program allows users to zoom into a candidate site to display the surrounding topography (DEM image) and aerial image in separate figure windows. Then users can manually pick a location on the DEM image, typically a point along a streamline where local topography presents a narrow "throat" feature. The program will also request an input of a "designed" dam height to calculate the boundary lines of ponded water and present the ponded area on both DEM and aerial images. This interactive process can be conducted repeatedly by adjusting the dam location and height, until the result satisfies the following two criteria:

- The beaver dam does not create significant ponding on buildings, roads, lawns, and farmlands shown on the satellite image.
- The width of the beaver dam resulting from the designed dam height does not exceed 100 meters.

Once the dam location is determined, the program will record the designed dam height and resulting dam length. Then a rating process will be conducted to calculate the change of ponding area and volume by setting water levels varying between 0 and the designed dam height. This process produces Stage-Area and Stage-Volume rating curves for HEC-HMS modeling.

With the interactive process, 52 dam locations were identified for the subsequent hydrologic modeling. These dams are distributed in 5 sub-watersheds, with

- 14 dams in the East-West Branch Milwaukee River watershed (EastWest),
- 11 dams in the North Branch Milwaukee River watershed (North),
- 8 dams in the Cedar Creek watershed (Cedar),
- 10 dams in the Menomonee River watershed, and (Meno)
- 9 dams in the Milwaukee River South watershed (South).

(words in parentheses represent acronyms of each sub-watershed). No dams are identified as suitable for the Kinnickinnic River watershed.

Locations of the 52 identified dams are shown in Figure 3.10. For each of the five sub-watersheds, identification and reconstruction processes for two selected sample sites are shown in Figure A-1 ~ Figure A-10 in Appendix A, where the location of the sample site in the watershed, the surrounding 3D topography and satellite images with ponding area boundary lines superimposed (maximum water level ponded with the dam), as well as the rating curves are presented.

Table 3.1 lists all identified dams, including their designed dam heights, dam lengths, ponding water surface areas and storage volumes with dam-full condition. Beaver ponds within or in the vicinity of MMSD's Greenseams project areas are also indicated in the table.

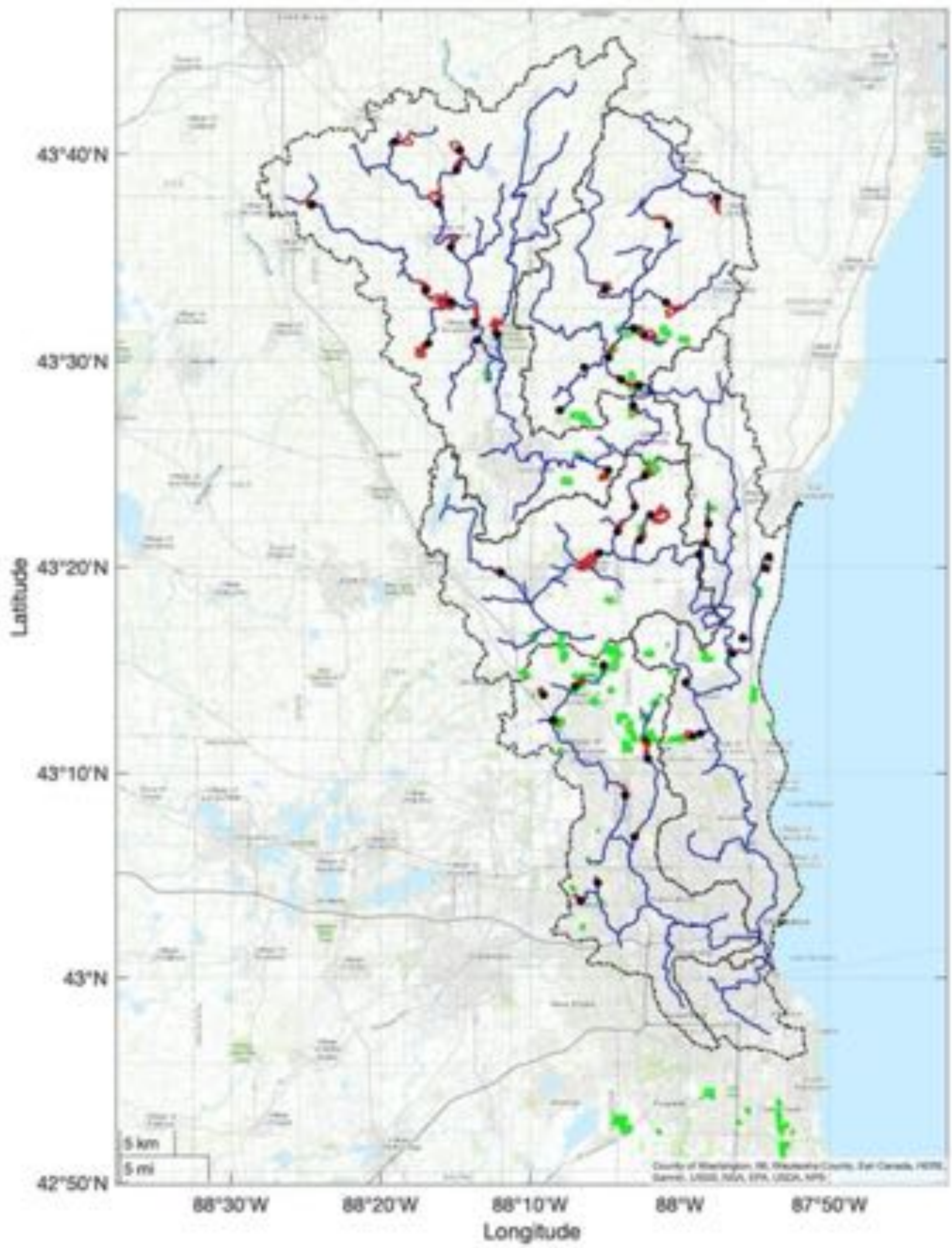

Figure 3.10 Distribution of beaver dams identified for hydrologic modeling. Solid circles indicate dam locations; red lines are boundary lines of water ponded by dams; green lines represent MMSD's Greenseams project areas; blue lines represent the stream network in the HEC-HMS model; and black dashed lines are dividing lines of the six sub-basins of the Milwaukee River watershed.

Table 3.1 Summary table of all 52 identified and reconstructed beaver dams in five sub-basins of the Milwaukee River watershed, including designed dam heights, lengths, ponding water area and volume with dam-full conditions, and the indication if the dam is within or in the vicinity of a MMSD Greenseams project area.

East-West Branch Milwaukee River Sub-Watershed					
Dam ID	Dam Height (ft)	Dam Length (ft)	Ponding Area (Acre)	Ponding Volume (Acre-ft)	Greenseams Area
EastWest_1	1.0	11	149	170	No
EastWest_2	1.0	41	61	61	No
EastWest_3	1.5	27	76	346	No
EastWest_4	1.5	36	40	75	Yes
EastWest_5	0.5	50	134	182	No
EastWest_6	1.0	74	107	196	No
EastWest_7	0.2	99	213	129	No
EastWest_8	1.0	36	43	72	No
EastWest_9	0.5	84	119	224	No
EastWest_10	1.5	34	54	138	No
EastWest_11	1.5	11	10	14	No
EastWest_12	0.8	100	258	463	No
EastWest_13	1.5	24	74	130	No
EastWest_14	1.0	25	136	142	No
Total Ponding Area (acre)		**1,474**	**Total Ponding Volume (Acre-ft)**		**2,342**

North Branch Milwaukee River Sub-Watershed					
Dam ID	Dam Height	Dam Length	Ponding Area (Acre)	Ponding Volume (Acre-ft)	GreenSeams Area
North_1	1.0	28	178	157	No
North_2	1.0	45	62	69	Yes
North_3	1.0	24	19	14	No
North_4	1.6	58	53	195	No
North_5	1.5	18	125	336	No
North_6	1.5	19	61	97	No
North_7	0.6	96	183	238	Yes
North_8	0.6	53	89	75	Yes
North_9	1.0	35	13	15	No
North_10	1.0	35	13	16	No
North_11	1.0	85	47	47	Yes
Total Ponding Area (acre)		**843**	**Total Ponding Volume (Acre-ft)**		**1,259**

Cedar Creek Sub-Watershed					
Dam ID	Dam Height	Dam Length	Ponding Area (Acre)	Ponding Volume (Acre-ft)	GreenSeams Area
Cedar_1	1.5	43	39	131	No
Cedar_2	0.2	48	263	233	No
Cedar_3	0.6	34	50	34	Yes
Cedar_4	1.0	39	31	42	No

Cedar_5	1.0	42	54	48	No
Cedar_6	0.6	36	304	201	No
Cedar_7	1.0	24	10	12	No
Cedar_8	1.0	34	45	25	Yes
Total Ponding Area (acre)		**796**	**Total Ponding Volume (Acre-ft)**		**726**

Menomonee River Sub-Watershed					
Dam ID	Dam Height	Dam Length	Ponding Area (Acre)	Ponding Volume (Acre-ft)	GreenSeams Area
Meno_1	1.5	23	35	44	No
Meno_2	0.7	35	20	28	Yes
Meno_3	1.0	81	27	39	No
Meno_4	1.0	32	21	26	No
Meno_5	0.6	13	47	112	No
Meno_6	0.5	31	37	34	No
Meno_7	1.0	28	83	146	Yes
Meno_8	0.6	28	12	14	Yes
Meno_9	0.6	41	58	22	Yes
Meno_10	0.5	49	43	27	Yes
Total Ponding Area (acre)		**383**	**Total Ponding Volume (Acre-ft)**		**492**

Milwaukee River South Sub-Watershed					
Dam ID	Dam Height	Dam Length	Ponding Area (Acre)	Ponding Volume (Acre-ft)	GreenSeams Area
South_1	1.0	47	95	204	Yes
South_2	1.0	39	15	20	No
South_3	0.8	27	12	11	No
South_4	0.6	20	14	9	No
South_5	0.8	50	31	63	No
South_6	0.6	69	30	43	No
South_7	0.6	46	50	32	No
South_8	1.0	45	27	31	No
South_9	1.0	49	23	34	No
Total Ponding Area (acre)		**297**	**Total Ponding Volume (Acre-ft)**		**447**

Beaver dams were modeled as “Reservoir” elements in HEC-HMS, and the “Outflow Structures” reservoir method was selected to simulate the effects of dams. Specifically, dams were modeled as a “Broad-Crested Spillway” with its crest length and elevation set to be equal to the dam width and height, respectively. The spillway method allows water to flow over the dam top in a controlled manner. The spillway coefficient, which accounts for energy loss as flow approaching the dam, was set to the maximum value of 1.66, considering the fact that beaver dams are generally constructed with a rough surface of logs and mud materials.

In HEC-HMS, reservoir storage relation can be specified through either elevation-storage or elevation-area methods, where the elevation refers to the ponded water surface elevation. The two rating curves developed for each dam can be applied for the two methods, respectively. Although the volume of ponded water is more important for mass balance of the rainfall-runoff simulation, the elevation-storage method does not account for water evaporation from the beaver pond. In this project, the elevation-area option was selected, which enables evaporation calculation. HEC-HMS automatically transforms the specified elevation-area curve into an elevation-volume curve using a conic formula. Beaver ponds added on a stream can affect the local evopotranspiration process due to added surface water area and possible impact on transpiration of the riparian forest. The potential impact of evopotranspriation process on soil water balance in the riparian area may not be accounted for in the HEC-HMS model. Considering the fact that the area of a sub-basin is generally much larger that that of a beaver pond in this study, such an impact was assumed to be negligible.

Studies showed that active beaver dams are nearly impervious, thus dam overflow and evaporation are the major loss terms to a beaver pond (Woo and Waddington 1990). However, dams may become porous over time due to decaying materials. Water seeps out from beaver dams were included in the model using the dam seepage function in HEC-HMS. An elevation-discharge curve was specified for the seepage method, which is a linear function with a maximum seepage flow rate of 5.3 ft^3/s (or 0.15 m^3/s) that occurs at the highest water level (top dam), as suggested in previous studies (Devito and Dillon 1993) (Caillat, et al. 2014).

The “Outflow Structure” method requires an initial condition for the pond water level. In this study, it was set to be 50% of the dam height for annual continuous simulation cases (see Section 3.5.1). For simulations of isolated, sythentic storm and runoff events (Section 3.5.2), it was set to 80% full, since most beaver ponds are nearly full before a major storm event according to results of long-term continuous simulations.

3.3.6 Modeling beaver dams at different stages of development

With all 52 identified and reconstructed beaver dams in the watershed, it can potentially create 3,793 acres of ponding water surface and 5,266 acre-ft of total storage when all beaver ponds are full (see Table 3.1). It should be noted that some reconstructed beaver dams create an excessive large ponding surface (greater than 100 acres), particularly those in the East-West branch, North branch and Cedar Creek sub-basins where the topography is flat and featured with extensive wetland patches. This highlights the potentials for significant water storage capacity in the northern part of the watershed if beaver colonies were able to establish in those areas. It should also be noted that it may take years for beaver colonies to develop dam structures to the “designed” capacity reconstructed in the presented model. A beaver dam complex will usually start with one or a series of smaller dams and gradually build on existing structures before the full-scale complex can be established.

To represent hydrologic impacts of beaver dams at various stages of development, it was proposed in the scope of work that model simulation would be conducted with reduced capacities, nominally with 50%, 20% and 10% of the full capacity. While it may not be practical to set the capacity at the specified percentage of reduction, four development stages were configured in this modeling study. Specifically, the four stages are:

- **Stage 4 (full capacity)** includes all 52 reconstructed dams in five sub-basins with designed dam heights and lengths as listed in Table 3.1
- **Stage 3** includes all 52 dams with dam heights reduced by 50%.

- **Stage 2**, where dams in each sub-basin were sorted by ponding area and every second dam was removed from the sorted list. In addition, dam heights were set at 50% of the designed value.
- **Stage 1**, where dams in each sub-basin were sorted by ponding area and two of every three dams were removed from the sorted list. In addition, dam heights were set at 50% of the designed value.

The total number of dams, surface areas and storage capacities of the four stages are presented in Table 3.2.

Table 3.2 Dam number, pond surface area and storage volume at four specified stages of development in five sub-watersheds

		East-West	*North*	*Cedar*	*Meno*	*South*	**Total**
Stage 4 (Full Capacity)	Dam number	14	11	8	10	9	**52**
	Surface area (acre)	1,474	843	796	383	297	**3,793**
	Storage volume (acre-ft)	2,342	1,259	726	492	447	**5,266**
Stage 3	Dam number	14	11	8	10	9	**52**
	Surface area (acre)	838	318	290	169	148	**1,763**
	Storage volume (acre-ft)	829	324	254	139	137	**1,683**
Stage 2	Dam number	7	6	4	5	5	**27**
	Surface area (acre)	468	252	112	97	105	**1,034**
	Storage volume (acre-ft)	419	278	98	52	114	**961**
Stage 1	Dam number	5	4	3	3	3	**18**
	Surface area (acre)	371	188	86	77	55	**777**
	Storage volume (acre-ft)	346	180	48	169	46	**789**

3.4 Model calibration

To calibrate the HEC-HMS model for the Milwaukee River watershed, hydrographs were simulated at locations where USGS streamgage data are available. Model runs were conducted to simulate precipitation-runoff processes between 2010 and 2019. In this study, the meteorological components in the model included precipitation and evapotranspiration processes only.

3.4.1 Precipitation data

For model calibration, precipitation input between 2010 and 2019 over the entire watershed was an interpolated map based on available land-based rain gauge data. The "inversed distance" method was selected as the interpolation scheme, where the precipitation depth at a particular location is essentially a weighted average of data from nearby gages. The weighting factor is proportional to the inverse of the squared distance to those gauges. A searching distance of 200 km was selected in this study for the inverse distance method.

Precipitation data are acquired from NOAA's National Centers for Environmental Information (NCEI) website (https://www.ncdc.noaa.gov/). Data used in this research are NCEI's land-based recording station data. Specifically, time sequence of precipitation depth (in inches) at every 15 minutes or hourly from multiple rain gauges around the Milwaukee River watershed were acquired. The entrance webpage for data request is https://www.ncdc.noaa.gov/cdo-web/datatools/lcd, which provides an interactive form allowing users to specify stations and date range for data download. Once the request is submitted, a follow-up email to users will provide a link for data download.

Local climate data (LCD) from the six stations between Jan 1st, 2010 and December 31st, 2019 were downloaded from NCEI in a "CSV" format. Names and geographic locations of the six rain gauges are listed in Table 3.3: NOAA meteorologic stations selected for precipitation data input in HEC-HMS modeling. An in-house Matlab program was developed to read and parse all "CSV" files to extract time sequences of precipitation depth. The program also processed the raw data to time sequences with a fixed, 2-hour interval for model simulation runs. Data processed by Matlab were exported to an EXCEL file, which will be subsequently processed for HEC-HMS import.

The HEC-HMS software exchange input and output data through the Army Corps of Engineers' Hydrologic Center Data Storage System (HEC-DSS), which is a database system designed to efficiently store and retrieve scientific data that is typically sequential. Precipitation time sequences for the simulation were then converted into a DSS file. A Python tool, pydsstools (https://github.com/gyanz/pydsstools), was developed by HEC to facilitate automated data conversion and process. A set of in-house Python scripts was developed for this study to convert input data (precipitation) and simulation results between DSS files and other data formats (such as EXCEL spreadsheet and Matlab data storage files) for subsequent data analysis and presentation. Figure 3.11 shows the map of the six selected rain gauges, and the precipitation time sequences in DSS data format which are visualized through the HEC-DSSVue tool.

Table 3.3 NOAA meteorologic stations selected for precipitation data input in HEC-HMS modeling

Name	WBAN	Latitude	Longitude	Location
FOND DU LAC	04840	43.76944	-88.49083	FOND DU LAC COUNTY AIRPORT
SHEBOYGAN	04841	43.76944	-87.85056	SHEBOYGAN CO MEMO AIRPORT
WEST BEND	04875	43.41667	-88.13333	WEST BEND MUNICIPAL AIRPORT
JUNEAU	04898	43.42639	-88.70306	DODGE COUNTY AIRPORT
MILWAUKEE	14839	42.955	-87.9044	GENERAL MITCHELL INTERNATIONAL AIRPORT
RACINE	94818	42.76111	-87.81361	JOHN H BATTEN AIRPORT

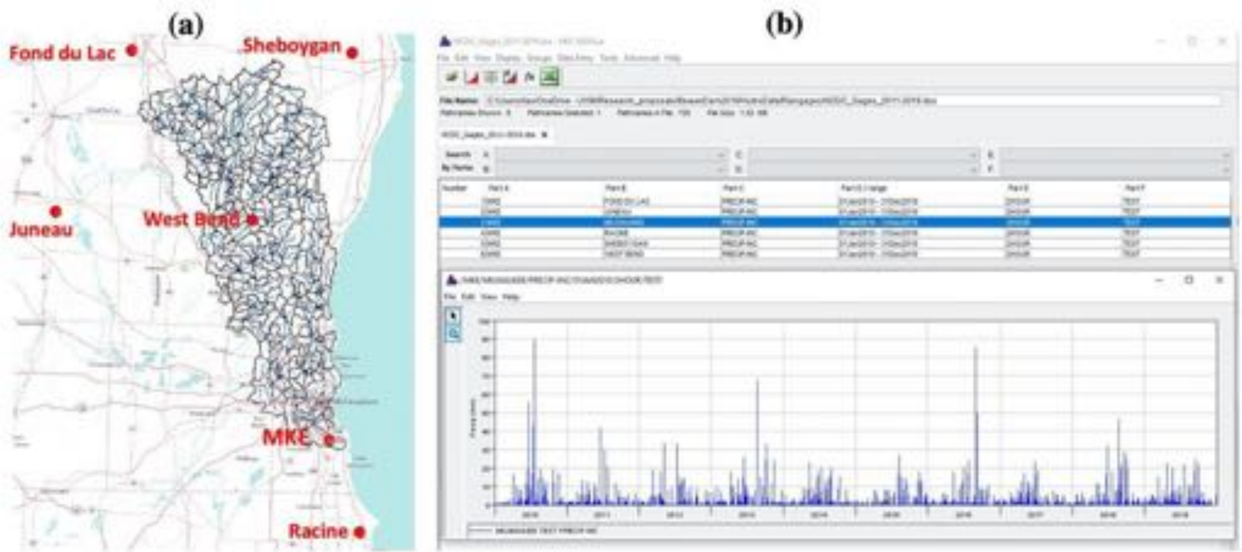

Figure 3.11 (a) Locations of six NOAA rain gauges where precipitation data were extracted for HEC-HMS simulation. (b) Processed precipitation data converted in HEC-DSS format and visualized by HEC-DSSVue.

3.4.2 USGS stream gage flow data

Stream flows simulated by HEC-HMS were calibrated by comparing the hydrograph with that recorded by USGS stream gages between the simulation period, i.e., from May 1st to Nov 30th between 2010 and 2019. Eleven stream gages within the Milwaukee River watershed were identified for the calibration. Among the 11 stations, 1 of them is in the Cedar Creek subwatershed; 3 in the Milwaukee River south subwatershed; 5 in the Menomonee River subwatershed; and 2 in the Kinnickinnic River subwatershed. There are no USGS stream gages available in the East-West Branch and North Branch Milwaukee River subwatersheds. The station number, name, location and the drainage areas of these gages are listed in Table 3.4. Locations of gages are also shown in Figure 3.12.

Table 3.4 USGS stream gage stations identified for HEC-HMS model calibration

USGS station number	Station name	Latitude	Longitude	Drainage area (mi^2)	Subwatershed
04086500	CEDAR CREEK NEAR CEDARBURG, WI	43.3230556	-87.97861111	120	Cedar Creek
04086600	MILWAUKEE RIVER NEAR CEDARBURG, WI	43.2802778	-87.94250000	607	Milwaukee River South
040869416	LINCOLN CREEK @ SHERMAN BOULEVARD AT MILWAUKEE, WI	43.0975000	-87.96694444	9.56	Milwaukee River South
04087000	MILWAUKEE RIVER AT MILWAUKEE, WI	43.1000000	-87.90888889	696	Milwaukee River South
04087030	MENOMONEE RIVER AT MENOMONEE FALLS, WI	43.1727778	-88.10388889	34.7	Menomonee

04087050	LITTLE MENOMONEE RIVER NEAR FREISTADT, WI	43.2066667	-88.03833333	8	Menomonee
04087070	LITTLE MENOMONEE RIVER AT MILWAUKEE, WI	43.1236111	-88.04361111	19.7	Menomonee
04087088	UNDERWOOD CREEK AT WAUWATOSA, WI	43.0500000	-88.04611111	18.2	Menomonee
04087120	MENOMONEE RIVER AT WAUWATOSA, WI	43.0455556	-87.99972222	123	Menomonee
040871488	WILSON PARK CR @ ST. LUKES HOSPTL @ MILWAUKEE, WI	42.9877778	-87.95194444	11.34	Kinnickinnic
04087159	KINNICKINNIC RIVER @ S. 11TH STREET @ MILWAUKEE, WI	42.9975000	-87.92638889	18.8	Kinnickinnic

The USGS stream stations recorded continuous stage and discharge data at every 15 minutes, which can be downloaded in various formats following the web link: https://waterdata.usgs.gov/wi/nwis/current/?type=flow . An in-house Matlab program was developed from this project to read in and parse the download page, and to convert flow series data into suitable formats (Matlab data file or EXCEL spreadsheet) for subsequent analysis.

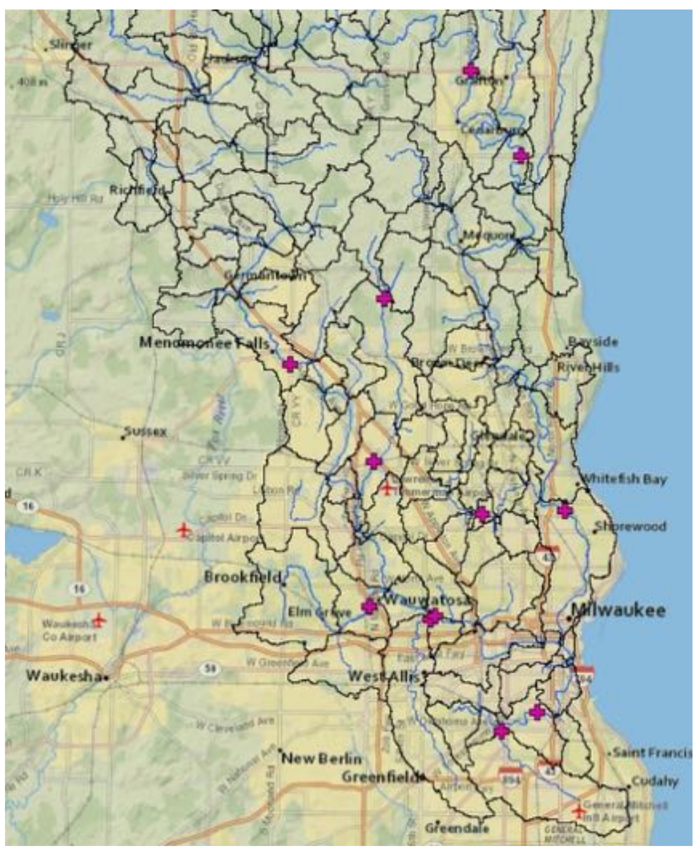

Figure 3.12 Locations of USGS stream gage stations where stream flow rate data were extract for HEC-HMS model calibration

3.4.3 Evapotranspiration data

For a continuous year-round simulation of the precipitation, infiltration, surface runoff, stream flow, groundwater storage and discharge, water loss through evaporation of surface water and the transpiration through vegetation is an important component of the water budget. Combined evapotranspiration is often responsible for returning about 50~60% of the precipitation back to the atmosphere. Transpiration, a process of vegetation extracting water from the soil through the plant root system, usually causes much more water loss than evaporation. In HEC-HMS, evapotranspiration can be modeled with a number of options, including the energy balanced Penman Monteith method, physically based Priestely Taylor method as well as simple annual or monthly evapotranspiration method. All options account for the potential evapotranspiration, which is the upper limit based on atmospheric conditions, while the actual evapotranspiration rate in each subbasin is calculated based on the soil water limitation.

In this study, a simple Monthly Average method was selected to model the evapotranspiration rate in mm of water depth per month. The North American Regional Reanalysis (NARR) is a product of NOAA's National Centers for Environmental Prediction (NCEP). NARR data provides various meteorological parameters, including evapotranspiration, from model simulations with assimilations from observational data. Monthly evaporation rates were extracted from the NARR database, interpolated and averaged over the Milwaukee River watershed area. Figure 3.13 shows the monthly average evaporation depth between 2010 and 2019. These data were inputted in the HEC-HMS model.

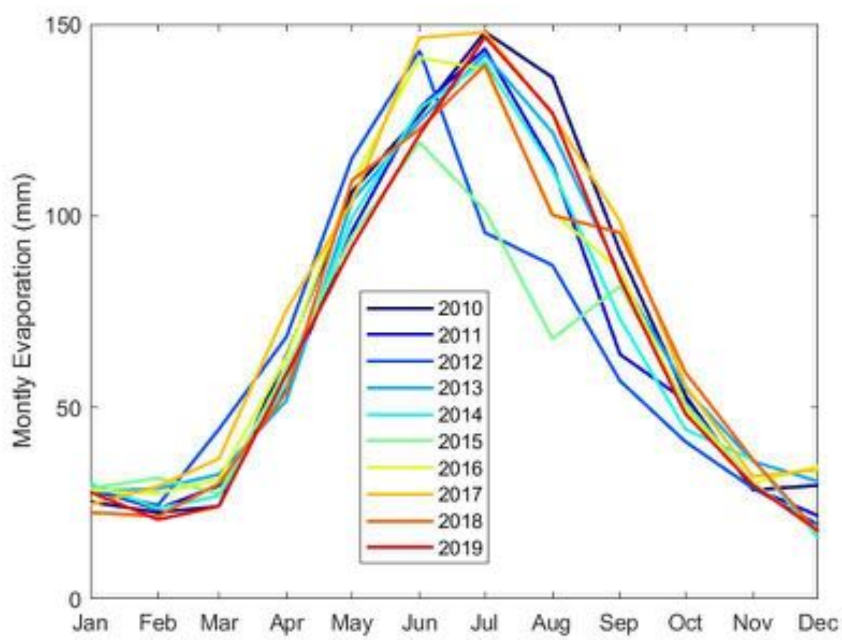

Figure 3.13 Monthly average evaporation rate obtained from NCEP's NARR database for modeling the potential evapotranspiration in HEC-HMS

3.4.4 Calibration results

For the calibration process, the reservoir function of beaver dams was switched off and changed to "junction" point. Most model parameters, particularly those in the Soil Moisture Accounting loss method and unit hydrograph transformations were obtained directly from realistic geodata and standard engineering approaches. These parameters were left as is. The groundwater storage, percolation rates and routing coefficients were considered as "tuning" parameters, since they were obtained through empirical regression relations. The "tuning" parameters were adjusted systematically, i.e., uniformly scaled by a common factor, such that the simulated hydrography matched best with that observed at the 11 USGS stream stations.

As a preliminary study, runoff due to snow falls and subsequent snow melting were not included. Therefore, calibration time window was limited to between May 1st and November 30th. For each of the calibration years (2010 ~ 2019), simulation started on March 15th with initial soil and groundwater storage set as 20% of their corresponding maximum capacity, which allowed the model to "warm up" for 1.5 months. Model results are presented starting at May 1st.

The time step of model simulation was set to 2 hours. Since the time resolution of USGS stream flow data was 15 minutes, they were smoothed by a 2-hour "moving average" window for comparison with simulation results. In addition, daily average flow data from USGS were also presented for comparison with the model.

Since the focus of the present study is to evaluate the potential of beavers on river flood abatement, calibration results for 2010, 2014, 2018 and 2019 are selected for presentation. Only in the four selected years, annual peak flow exceeded 100 m^3/s at the Milwaukee River station (USGS 04087000), which is equivalent to a 2-year flow according to historic data recorded by this station. Modeled hydrograph curves are shown in Figure B-1 ~ B-4 in Appendix B, along with the USGS 2-hour average and daily flow series.

Total 7-month discharge volume between May 1st and Nov 30th was integrated from both observed and simulated hydrograph at 11 stream stations and for the 10 years. Their correlation is shown in Figure 3.14. A linear regression with a forced 1:1 relation suggested a very good correlation with the coefficient of determination $R^2 = 89.7\%$. Linear regression with a forced zero-intercept indicated that

$$V_{Model} = 0.97 V_{USGS}\,, \tag{3.16}$$

where V represents the 7-month discharge volume at every calibration station. This suggested that model results slightly underestimate the runoff volume overall.

Relation between modeled and observed annual peak flow rate at the 11 stations over the 10 years is shown in Figure 3.15. A linear regression with a forced 1:1 relation also demonstrated a good correlation with $R^2 = 84.6\%$. A linear regression with a forced zero-interception shows that

$$Q_{P_{Model}} = 0.99 Q_{P_{USGS}}\,, \tag{3.17}$$

where Q_P represents the peak discharge. This suggested a nearly zero bias error. It should also be noted that better correlation is found at higher peak flow rate, i.e., when $Q_P > 100$ (m^3/s). Greater scattering is presented at lower flow rates, particularly for the case of the Little

Menomonee River station near Freistadt, WI (USGS 04087050), where annual peak flow had never exceeded 10 m^3/s over the 10 years.

Overall, calibration tests demonstrated that HEC-HMS with the parameterization reconstructed in this study was able to reproduce a stream flow hydrograph with good accuracy as measured by the peak flow rates and the total runoff volume.

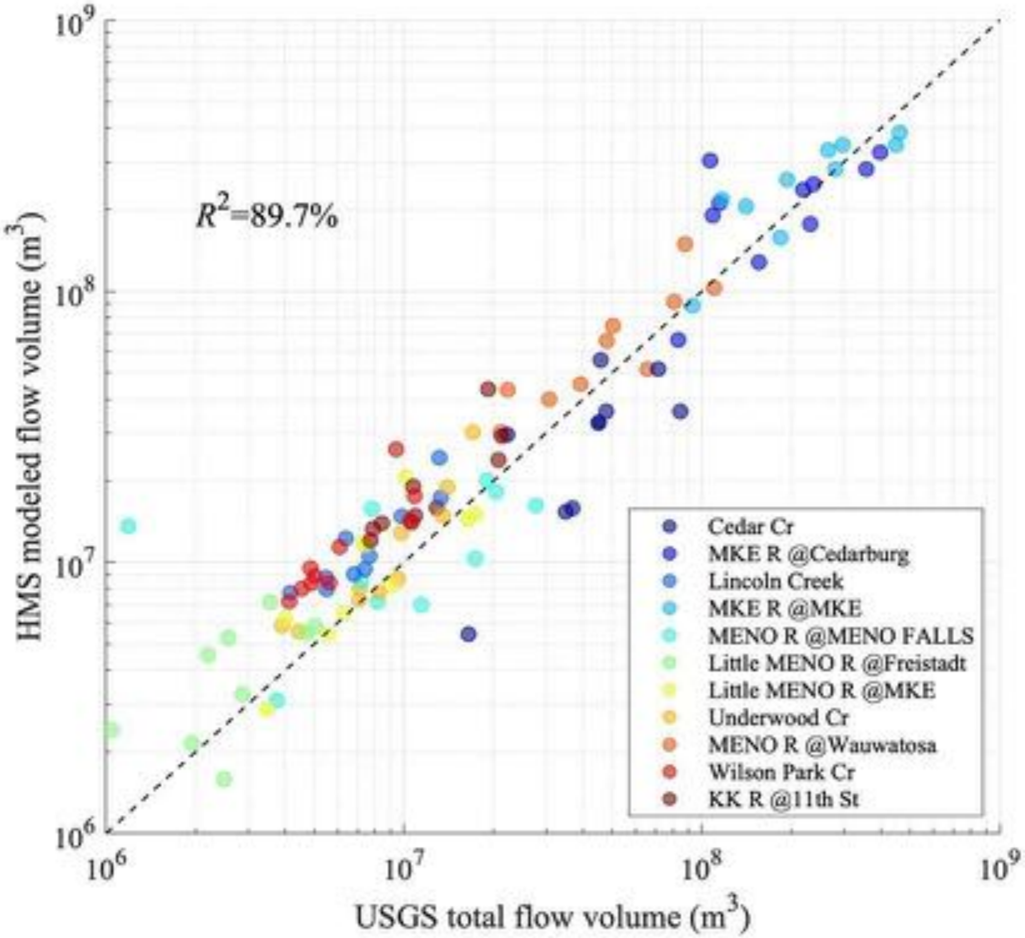

Figure 3.14 Modeled vs. observed total discharge volume between May 1st and Nov 30th, 2010~2019 at 11 USGS stream stations

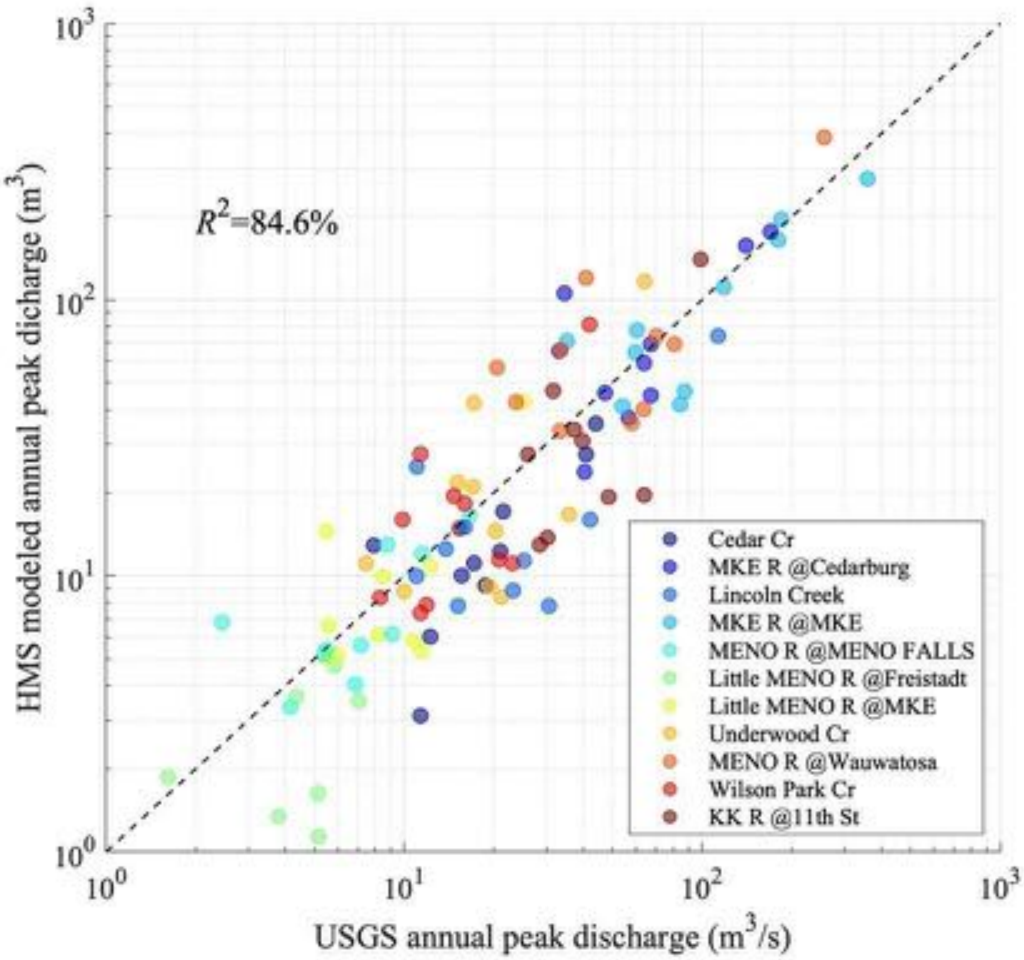

Figure 3.15 Modeled vs. observed annual peak discharge at 11 USGS stream stations

3.5 Model results

With calibrated parameters in the HEC-MHS model, beaver dams were configured as reservoirs in the model as described in section 3.3.5. Two sets of model simulations were conducted to evaluate the impact of beaver dams on the watershed-scale hydrograph: (1) simulation of hydrograph with past storm events in 2010, 2014, 2018 and 2019, with the same precipitation inputs used in the calibration runs; (2) simulation of hydrograph with synthetic storm events of varied durations and recurrence intervals (return periods). Module runs included scenarios of four stages of beaver establishment (see section 3.3.6).

Hydrograph of river discharge in the river reach that drains each of the five sub-watersheds with modeled beaver establishments was extracted from model results. They represented the flows at the outlets of the five sub-watersheds, with their locations illustrated in Figure 3.17. Hydrographs at these locations were compared among cases without beaver dams and with beaver dams at four development stages. Comparison of hydrograph at the outlets of the East-West branch (East-

West), North branch (North), Cedar Creek (Cedar) and Menomonee River (Meno) allows evaluation of beaver impact of each subwatershed separately, while the hydrograph at the outlet of South Milwaukee (South) represents the integrated impacts of beaver dams in four sub-basins that contribute to the flow (East-West, North, Cedar and South).

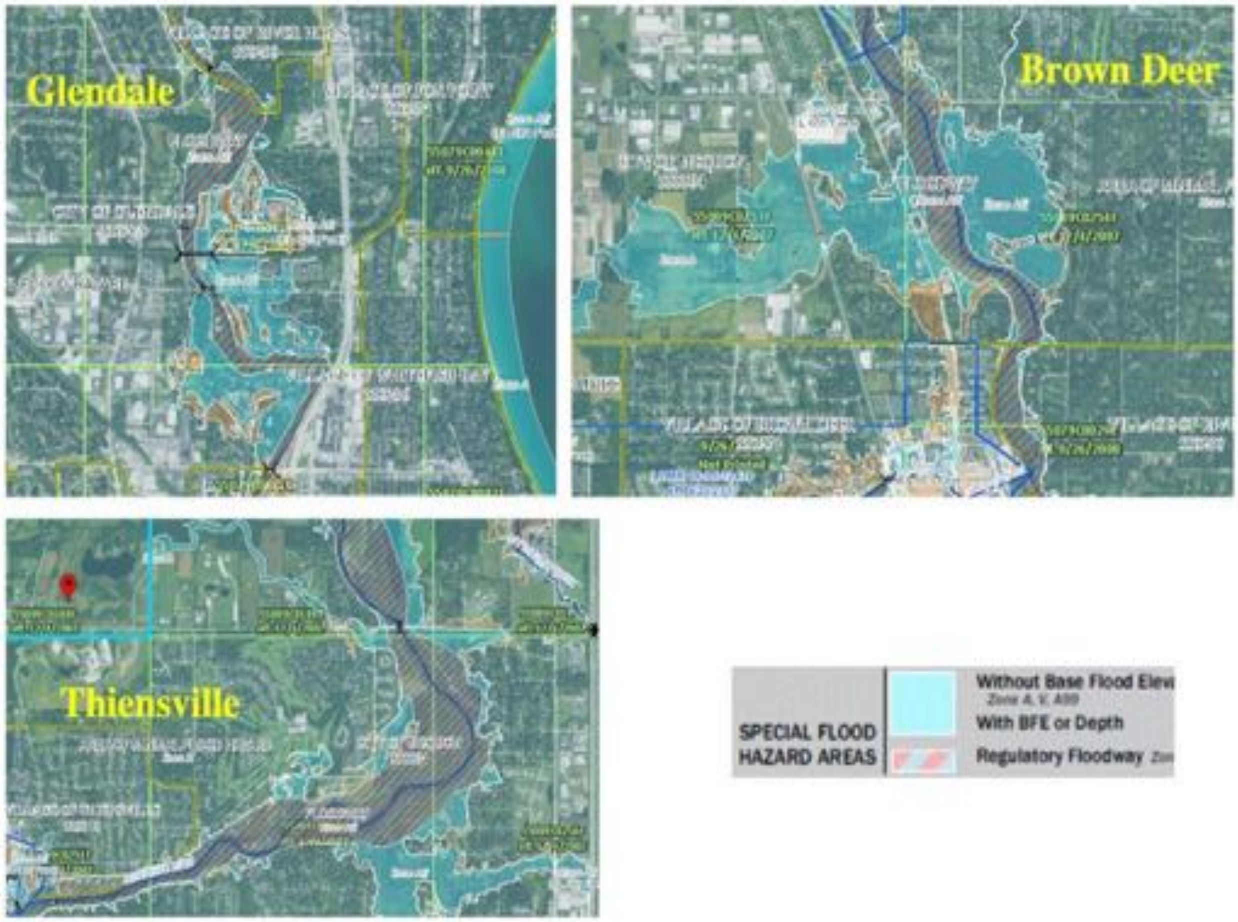

Figure 3.16 Three urban flood zones in the South Milwaukee subwatershed identified according to FEMA's flood map service (https://msc.fema.gov/portal/home)

As suggested by this study, the northern part of the Milwaukee River watershed is more suitable for beaver restoration, e.g., the East-West, North and Cedar sub-basins. An overarching question of this project is if and how beaver dams in the far northern watershed may significantly mitigate river floods in southern urban areas, particularly in MMSD's service area. To answer this question, three Milwaukee River flood zones in the South sub-basin were identified according to FEMA's flood map (Figure 3.16). Hydrographs of corresponding river reaches were extracted from model simulations for analysis. The three river reaches are near the Villages of Thiensville, Brown Deer and the City of Glendale, respectively, and their locations are also shown in Figure 3.17.

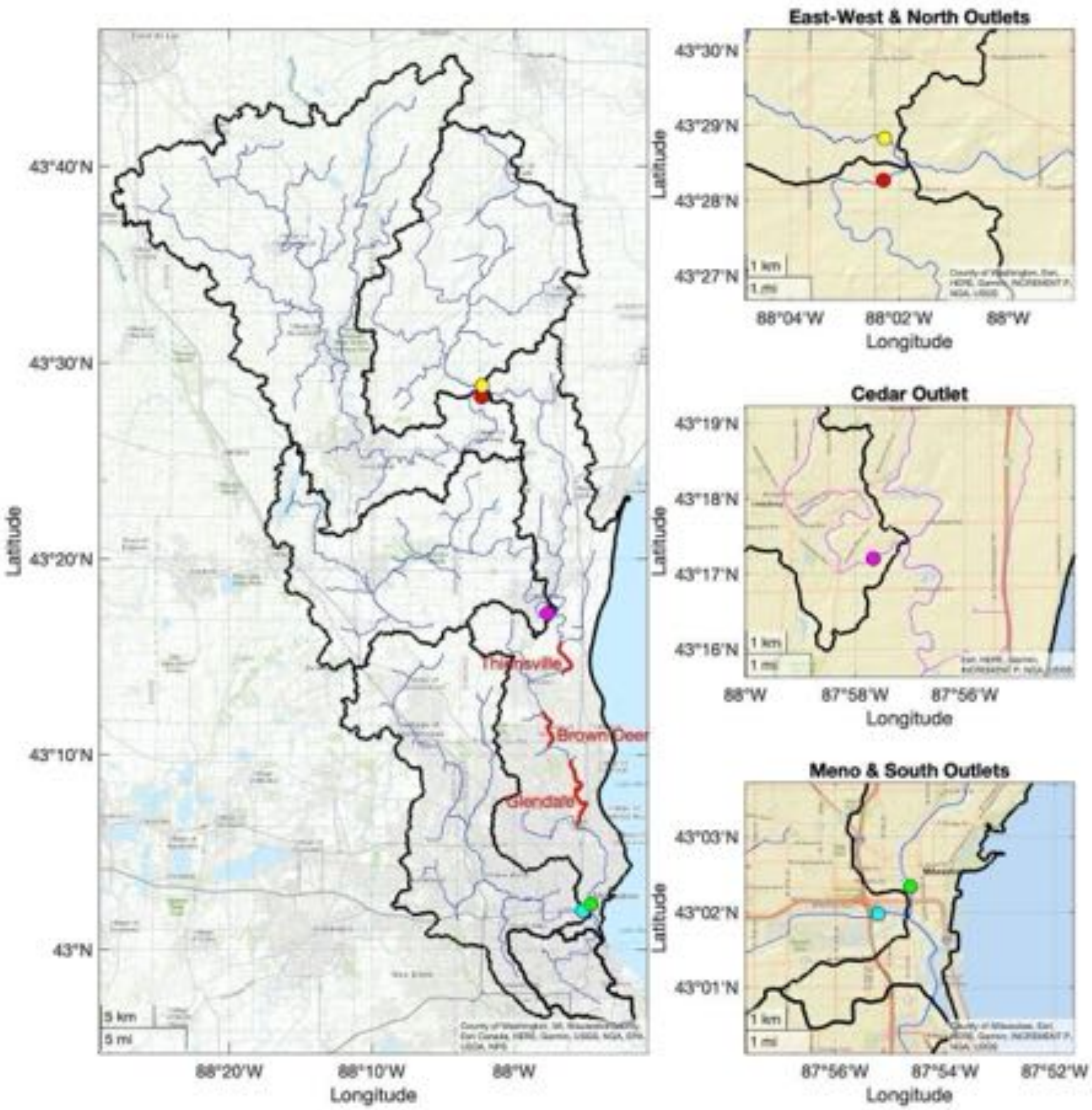

Figure 3.17 Positions of outlets (colored circles) of five sub-watersheds (East-West, North, Cedar, Meno and South) and river reaches (bold red lines) of three urban flood zones (Thiensville, Brown Deer and Glendale) where hydrograph data were extracted from HEC-HMS model runs to evaluate flow reduction due to beaver dams.

3.5.1 Assess impact of beaver dams with past storm events

Model simulations of stream flows were conducted for the year of 2010, 2014, 2018 and 2019, using the same set of parameterizations as the calibration tests described in section 3.4, except with beaver dams at four stages (see section 3.3.6) of development. In addition, the initial condition was set such that ponded water level behind all beaver dams was 50% of the dam height. Simulation runs started on March 1st and ended on November 30th of each year. Results of the first two months are not included for analysis and presentation, i.e., two months of "ramp up" time to allow meteorological driving forces control the water budget of stream flow, groundwater, and beaver pond, or, to "forget" initial conditions which were set rather arbitrarily.

Simulated hydrographs at the outlets of the five sub-basins and the three flood zone reaches between May 1st and Nov 30th of each year are shown in Figure C-1 ~ C-8 in Appendix C. Details of high flow series during major storm events of each year are highlighted in these figures. Specifically, durations of major storm events of the four simulation years were identified as

- 2010: July 12th to August 9th
- 2014: June 14th to July 12th
- 2018: August 17th to October 28th
- 2019: September 29th to October 26th

The maximum flow rate and total discharged volume during the defined storm event durations were calculated from simulation results at these locations. They are presented as bar graphs shown in Figure C-9 ~ Figure C-12 in Appendix C. Percentage reductions of peak flow and discharge volume due to beaver dams at various stages are also presented as bar graphs in these figures.

In addition, five beaver dam sites were selected, one in each sub-basin, to better illustrate hydrologic processes that occurred in beaver ponds during storm events. Time series of water level behind beaver dams, and discharge with and without dams are presented in Figure C-13 ~ Figure C-16 in Appendix C. Only stage 4, the full dam capacity, is presented for pond water budget analysis. Results of the other three stages were similar.

Several important results are observed from simulations of past storm events with beaver dam placed at potential locations in the watershed:

1. As shown in Figure C-13 ~ Figure C-16 in Appendix C, a beaver pond can be filled up to its maximum capacity quickly after a major precipitation event. Excess water overflows above the dam, which may still effectively reduce flow rate due to overflow energy loss. During an interval of two major storm events, ponded water level gradually drops through evaporation and dam seepage flow, which helps to empty storage space for the next storm event. Simulation results suggest that water loss through seepage flow is negligible compared with that due to evaporation.
2. Results suggest that beaver dams at all stages can significantly reduce both peak flows and discharge volume at most of the eight observation locations (5 outlet points and 3 river reaches), except for the peak flow event in 2019. The peak flow occurred on October 2nd, 2019 at all eight observation locations. However, several prior storm events during the month of August and September filled up most beaver ponds, leaving little storage capacity for the Oct 2nd event.
3. As capacities increase with dam numbers and dam heights, the effects on peak flow and volume reduction are not as significant. From stage 1 to 4, total beaver pond area increased nearly 5 times and total pond volume increased more than 6 times (see Table 3.2), however, the peak flow reduction increased by only 2~4% on average. This is likely due to the fact that most dams are usually near full capacity before major storm events.

Therefore, the overall remaining effective capacity before a major event is a more determining factor that affects flood flow reduction.

4. A flood event observed in the south branch of the Milwaukee River on July 22nd, 2010 was a result of a heavy storm precipitation, which poured 7.5 inches in two hours in the City of Milwaukee. The flood was nearly a 250-year flow, according to data recorded at the USGS stream station (ID 04087000) in the south branch of the Milwaukee River. Peak flows could be reduced only slightly by beaver dams at outlets of the South Milwaukee River (about 7%) and Menomonee River (about 2~3%) sub-basins. High flows at the two locations were results of precipitation concentrated in the southern part of the watershed, while most beaver dams are in the northern watershed. River flows in the three northern urban flood zones were also relatively high during the July storms in 2010, and beaver dams could effectively reduce the flood levels: (about 25% peak reduction at Thiensville, 21% peak reduction at Brown Deer, and 14% at Glendale).
5. Based on simulated hydrographs at sub-basin outlets, beaver dams in the Cedar Creek sub-basin have the greatest potential for flow reduction. At the maximum potential capacity (stage 4), the peak reduction rate ranged from 18~66% with an average of 49% and the discharge volume reduction rate ranged from 15~73% with an average of 48%. The high rate of flood reduction is likely due to the high capacity per area of the sub-watershed.
6. Beaver dams in both the East-West branch and North branch Milwaukee River sub-basins are also very effective at reducing flood flow peak and volume at their corresponding outlets. At the outlet of the East-West branch, peak reduction rate ranged from 4~36% with an average of 19% and volume reduction rate ranged from 3~28% with an average of 18%. At the outlet of the North branch, peak reduction rate ranged from 2~36% with an average of 32% and volume reduction rate ranged from 2~36% with an average of 28%.
7. Beaver dams in the Menomonee River sub-basin are relatively less in numbers and capacities. In addition, the sub-basin has a large portion of impervious land surface. Therefore, the effect on peak flow reduction was not as significant. At its outlet, the peak reduction rate ranged from 5~20% with an average of 11% and the volume reduction rate ranged from 5~38% with an average of 15%.
8. River flood flows in the South Milwaukee River sub-basin are affected by beaver dams of four sub-basins, not including the Menomonee River sub-basin. Flood flows at the outlet of the sub-basin had a peak reduction rate of between 8~36% with an average of 21%. The volume reduction rate varied between 6~39% with an average of 23%. The three flood zones in the northern suburban area of Milwaukee (Thiensville, Brown Deer and Glendale) had a peak reduction rate of between 7~50% with an average of 28%, and the volume reduction rate ranged between 6~40% with an average of 26%.

3.5.2 Assess impact of beaver dams with designed frequency storms

To evaluate impacts of beaver dams on future extreme storm events, synthetic storms were generated in HEC-HMS to simulate the hydrograph processes. The "Frequency Storm" method was selected as the meteorologic input. Statistical precipitation data were acquired from the US National Weather Service and supplied as input to the frequency storm method. Specifically, the precipitation duration-depth relation for the Milwaukee River watershed was obtained from

NOAA’s Precipitation Frequency Data Server (https://hdsc.nws.noaa.gov/hdsc/pfds/). In this study, synthetic storms included in simulations are 6-hour and 24-hour precipitation events with recurrence intervals (return period) of 10, 25, 50, 100, and 200 years, respectively. There were in total 10 synthetic storm events. Precipitation depths of these events (ranged from 2.99 to 7.44 inches, or 76 to 189 mm) are summarized in Table 3.5. Precipitation hyetograph was assumed to be uniformly distributed over all sub-basins.

Table 3.5 Precipitation depth (inches) of 6-hour and 24-hour storms with recurrence intervals of 10, 25, 50, 100 and 200 years of the Milwaukee River watershed. (Data source: NOAA Precipitation Frequency Data Server)

Duration	Recurrence Interval (Year)				
	10	*25*	*50*	*100*	*200*
6 Hour	2.99	3.70	4.37	4.92	5.83
24 Hour	3.82	4.72	5.55	6.46	7.44

All synthetic frequency storms were assumed to start on August 1st, 2020, and simulation runs for one full month with a time step of 30 minutes. The average August evaporation rate between 2010 and 2019 was applied for simulations to account for water loss in beaver ponds. According to results from simulations of past storms, most dams in the watershed were near their full storage before a major storm event. To simulate this effect, the initial pond water level was set at 80% of the dam height for all beaver dams.

Simulated hydrographs at the outlets of the five sub-basins and the three flood zone reaches from the 10 synthetic storms are shown in Figure D-1 ~ Figure D-10 in Appendix D. In these figures, results of the first six days are shown to focus on hydrographs of peak flows. The peak flood flow and total discharged volume were calculated from simulation results at these locations. They are presented as bar graphs shown in Figure D-11 ~ Figure D-20 in Appendix C. Percentage reductions of peak flow and discharge volume due to beaver dams at various stages are also presented as bar graphs in these figures.

For most storm scenarios and observational sites, a short period of “plateau” can be observed on the rising “limbs” of simulated hydrographs for cases with beaver dams (Figure D-1 ~ Figure D-10 in Appendix D). This demonstrates the effect of flow interception by available storage space (20% of full capacity) behind beaver dams. After beaver ponds were filled to their full capacity, the hydrograph rose again with a slope milder than that of the case without beaver dams. This observation demonstrates that energy loss due to dam overflow as a secondary mechanism of downstream peak flow reduction.

With modeled synthetic storms which uniformly cover the entire watershed, all beaver dams in the model can contribute to flood mitigation. Simulation results suggested a very significant effect of flow reduction at all eight observational sites. The range and average of peak and volume reductions are summarized in Table 3.6, where the minimum percentage is always from the result of the least precipitation depth (10-year 6-hour storm) and the maximum is always from the result of the greatest precipitation (200-year 24-hour storm). With the full beaver capacity (Stage 4), peak reduction was at least 31% for four sub-basins (excluding the Menomonee River sub-basin) and was as high as 51%. Due to limited dam capacity and high percentage of impervious land area in the Menomonee River sub-basin, the peak reduction rate at its outlet is notably lower than others, i.e., 20% on average at Stage 4.

For the same reason that synthetic storms were applied uniformly, the stage of beaver development contributed a more notable variation to flow reductions. For earlier stages, smaller number of dams reduced the effective storage capacity for flow interception and the decreased dam heights reduced the energy loss of overflow. For example, peak flow reduction rates of Stage 1 are generally about 10% less than those of Stage 4 (see Table 3.6).

Flood peak flow analysis was conducted according to simulation result records at the river reach through the flood zone in the City of Glendale. Historical data collected from the USGS streamgage station (04087000) in the Milwaukee River were used for frequency analysis for the Glendale reach, which is about 5 miles north of the station. Annual peak flow sequence since 1904 at the station was found to follow a log-normal distribution, which was applied to estimate the return period of flood flow at the Glendale reach. Estimated recurrence intervals of peak flows in response to the modeled synthetic storms are presented in Table 3.7, where recurrence intervals were rounded to the nearest 100th if greater than 1,000 years; to the nearest 50th if greater than 100 years; or to the nearest 10th if greater than 50 years. This analysis is intended to provide an intuitive summary of the model study, i.e., dams built by beavers populated on the tributaries of upper watershed may potentially mitigate river flood flows in the urban areas at the lower watershed. For example, a 100-year flood could potentially be downgraded to a 10-year flow or even 5-year flow (e.g., the 10-year 6-hour storm case); or a 1,200-year flood could potentially be downgraded to an 80-year flow or even 10-year flow (e.g., the 25-year 24-hour storm case), etc.

Table 3.6 Summary of beaver-mitigated flood flow peak reduction and discharge volume reduction at outlets of five sub-basins and three urban flood zones in the South Milwaukee River sub-basin

Peak flow reduction						
Locations	**Stage 1**			**Stage 4**		
	Minimum	*Maximum*	*Average*	*Minimum*	*Maximum*	*Average*
East-West	26%	41%	33%	40%	51%	46%
North	21%	37%	26%	31%	47%	36%
Cedar Creek	40%	42%	41%	46%	50%	48%
Menomonee	9%	11%	10%	18%	23%	20%
South	28%	42%	33%	38%	50%	44%
Thiensville	27%	41%	33%	39%	50%	44%
Brown Deer	27%	41%	33%	39%	50%	44%
Glendale	27%	41%	33%	38%	50%	44%
Discharge volume reduction						
Locations	**Stage 1**			**Stage 4**		
	Minimum	*Maximum*	*Average*	*Minimum*	*Maximum*	*Average*
East-West	45%	49%	47%	46%	50%	48%
North	43%	49%	46%	45%	50%	47%

Cedar Creek	44%	48%	46%	45%	50%	47%
Menomonee	35%	43%	39%	36%	44%	40%
South	43%	48%	45%	44%	49%	46%
Thiensville	44%	48%	46%	45%	50%	47%
Brown Deer	43%	48%	43%	44%	49%	47%
Glendale	43%	48%	45%	44%	49%	46%

Table 3.7 Estimated recurrence intervals of flood flows in the river reach through the city of Glendale in response to isolated frequency storms

	W/O Beaver Dams	Beaver Dams Stage 1	Beaver Dams Stage 2	Beaver Dams Stage 3	Beaver Dams Stage 4
10-yr, 6-hr storm	100	10	10	8	5
25-yr, 6-hr storm	300	30	30	25	15
50-yr, 6-hr storm	1,500	150	150	100	50
100-yr, 6-hr storm	4,000	450	350	300	150
200-yr, 6-hr storm	19,000	2,200	16,00	1300	700
10-yr, 24-hr storm	300	20	20	15	10
25-yr, 24-hr storm	1,200	80	70	15	10
50-yr, 24-hr storm	6,000	400	350	300	150
100-yr, 24-hr storm	17,000	1,200	1,000	800	400
200-yr, 24-hr storm	80,000	6,000	5,000	4,000	2,000

4 Milwaukee River watershed beaver habitat recovery assessment

Prior to the fur trade, beavers were common and abundant in the Milwaukee River and all of Wisconsin's watersheds. Historic accounts chronicle that the fur exploitation started here about 1650, and by 1730 beavers were extinct in the Milwaukee area (White 2010). Since settlers arrived in this area in the 1830s, beavers' former presence was largely unknown. Recently, however, a tiny remnant population has recovered after 350 years of absence. This genetic stock is incredibly valuable and needs protection to thrive.

Numerous scientific beaver studies over the past 30 years have cited the ecosystem benefits of beavers for biodiversity, water quality, and flood abatement. Several other states have successfully reevaluated beaver management plans to include the significant potential beavers offer in restoring structure and stability to the geomorphology of watersheds. River systems and watersheds with established beaver populations are much more resilient.

This chapter describes how the Milwaukee River Basin was evaluated for potential beaver habitat. The beaver population carrying capacity of the watershed was calibrated using proven scientific methods from peer reviewed studies with similar habitats. The population potential is based on assuming that beavers would have a protected status from trapping and exploitation. It also assumes that the management goal of that recovery is for biodiversity and flood mitigation. This includes using reasonable co-existence non-lethal methods of conflict resolution, such as flow devices to manage nuisance flooding.

4.1 Field observation methods

To assess the beaver recovery habitat, fieldwork was conducted throughout the watershed from January through August 2020. A team of four people was assembled and included, Robert Boucher, Milwaukee Riverkeeper, Emeritus; Leah Holloway, Milwaukee Riverkeeper Program Manager; and two University of Wisconsin-Milwaukee (UWM) Students, Max Rock, and Madeline Flanner. Robert Boucher, an advisor to the Beaver Institute, conducted a 10 hour training with the UWM students to train them in identifying beaver forage and habitat characteristics.

A 1 to 5 scale was developed to evaluate and rank the habitat sites. The number scale characteristics would be described as follows; 1, Poor; 2, Marginal; 3, Fair; 4, Good; 5, Very good to excellent. The rating habitat system was based on evaluating the quality and scale based on the following criteria:

1. Areas with sufficient water depth to support over-wintering, with
2. Sufficient connectivity to adjoining wetland areas that will support breeding and increase the potential for population expansion to establish new territories,
3. Existing forage of diverse aquatic plants and woody material (aspen, willow, etc.) to provide food and building materials for colony establishment, and
4. A low likelihood for flooding conflict with infrastructure (buildings and roads).

Taking into consideration the variety of land characteristics, the team peer reviewed the identified sites with weekly meetings to have a consistent evaluation. Field observation sites overall characteristics were discussed to determine the grade, with a scale of 1 to 5, with 5 being the best ranking (Table 4.1). The parameters listed above and the overall suitability were considered. This evaluation was assisted by reviewing aerial maps with the wetland overlays to determine if infrastructure was within the wetland topography. The existence of quality sites such as these will be critical for the successful reestablishment of beavers in the watershed.

Table 4.1 Beaver habitat sites ranking criteria

Rank	Characteristics
1	Little to no forage for food and building; limited watershed connectivity; wetland habitat scale small; moderate or insufficient depth for over-wintering. Poor suitability.
2	Marginal forage for food and building; limited watershed connectivity; moderate depth for over-wintering. Marginal suitability.
3	Moderate to adequate forage for food and building; some watershed connectivity; suitable depth for over-wintering. Fair suitability.
4	Good varied forage for food and building; sufficient watershed connectivity; adequate depth for over-wintering. Good suitability.
5	Plentiful and varied forage for food and building; sufficient watershed connectivity; adequate depth for over-wintering. Excellent suitability.

The Milwaukee River Basin is divided into six watersheds and 31 subwatersheds (HUC 8). The team made site visits and conducted habitat assessments within each of the sub-basins and focused on the 89,000 acres of existing Basin wetlands (Figure 4.1). Photos and field observations were captured of habitat potential based on vegetation, wetland size, and the physical features of the sub-basin composition of lakes, rivers, streams, and creeks. In total, 163 field site locations were visited, and notations made, totaling approximately 125 hours of fieldwork. More than 85 field site locations ranked 4 or 5, which identified them as ideally suited for beaver reestablishment. Further assessment refined the list to the top 14 sites that would provide good habitat to immediately support reintroduced beaver pairs, and these sites are documented in Appendix E.

Figure 4.1 Map of field observation locations

The team used the ArcGIS Collector app and a map developed by UWM Student Max Rock to collate the field observations (Figure 4.2). This process allowed for efficient and effective gathering of data. The application is cloud-based and was shared between members of the team which allowed real time viewing of data, including photos, videos, or notes that were logged at each site. Six different feature layers were used in the ArcGIS Collector map: Rank, Vegetation ID, Observation Location, Watershed and Subwatershed Boundaries, Wetlands, and Stream Flow Lines.

During the field work, existing beaver lodges, cuttings, and a small number of dams ("works") were observed along the Milwaukee River from North Avenue to River Hills. In Ozaukee County, activity was observed at several sites, including Trinity Creek and other sites in the City of Mequon, along the Milwaukee River, and along Cedar Creek in Jackson Marsh.

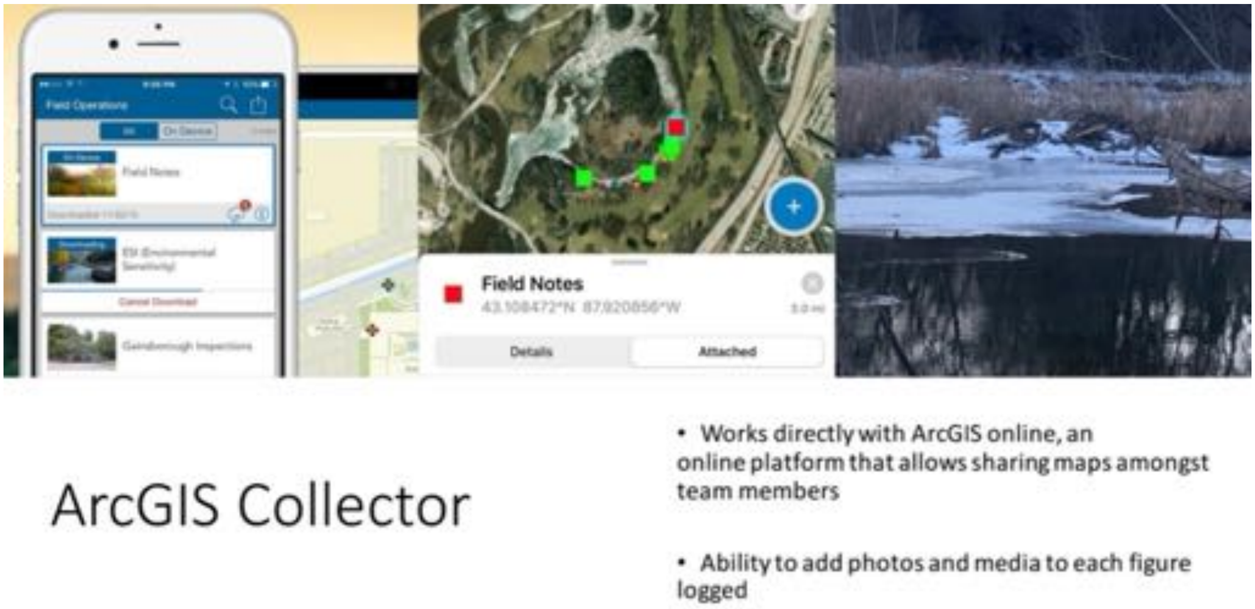

Figure 4.2 ArcGIS Collector app showing the beaver lodge at Lincoln Park

4.2 Field assessment results

4.2.1 Habitat summary of beaver forage

The food selection for beaver forage is flexible. Beavers fell trees to forage the leaves and bark, but also to secure building materials for dams and lodges. They will feed on what is available and can utilize a wide spectrum of plants, however, they do demonstrate preferences and have been referred to as "choosey generalists." Studies have documented feeding preferences for some trees such as the bark of aspen, willow, cottonwood, and alder. Still, beavers need a mixed diet and spend almost all ice-free months focused on non-woody plants: grasses, forbs, and all forms of aquatic plants. Beavers prefer herbaceous vegetation, such as water lily rhizomes, to woody vegetation in all seasons. Wetland edge vegetation and underwater plants like water lily tubers are eaten when available year-round. Over winter forage is a "cache" of forage collected in late fall (Müller-Schwarze 2011).

Beavers are "central place foragers" meaning they will go up and down waterways to forage but focus their feeding to the lodge area. They will venture onto land but generally not more than 300-500 feet because it leaves them vulnerable to predation. They feel safe in the water. Beaver forage habit resources are listed in Appendix F.

The existing 89,000 wetland acres in the Basin are composed of five wetland categories (Table 4.2).

1. Coniferous swamp is the least abundant type of wetland with 2,565 acres.

2. Hardwood Swamp / floodplain forest is the most abundant wetland type with 36,379 acres.
3. Marshes cover approximately 4,600 acres.
4. Shrub swamp is woody vegetation and occurs over approximately 13,000 acres.
5. Wet meadows often have dense vegetation; there are about 11,000 acres in the Basin.

Table 4.2 Milwaukee River basin wetland vegetation summary (WDNR, 2001)

Wetland Type	Wetland Acreage by Watershed/% of Land Area					
	East-West	North	Cedar Creek	South	Menomonee	Kinnickinnic
Coniferous Swamp	743/0.4	280/0.3	1489/1.8	27/0.03	26/0.03	0/0
Hardwood Swamp/ Floodplain Forest	16094/9.5	7765/8.1	6030/7.3	3032/2.8	3422/3.9	36/0.2
Marsh	2545/1.5	677/0.7	748/0.9	478/0.5	187/0.2	0/0
Shrub Swamp	6430/3.8	2245/2.3	2423/2.9	1146/1.1	960/1.1	16/0.08
Wet Meadow	3100/1.8	3210/3.4	2281/2.8	1335/1.2	1487/1.7	6/0.03
Totals	**28912/17**	**14177/14.8**	**12971/15.7**	**6018/5.6**	**6082/7.0**	**58/0.3**

The fieldwork confirmed that the wetland vegetation composition of the subwatersheds would provide good forage for beavers throughout the basin.

4.2.2 Potential beaver population

The beaver population estimates for this assessment and their recolonization potential is based on scientific methods that are recognized from peer-reviewed, published scientific journals. The methods we used for this report for population estimates and density are based on a review of 28 studies and used measuring methods that have been used for similar North American habitats cited in the book "The Beaver: Natural History of a Wetlands Engineer" by Deitland Müller-Schwarze (Müller-Schwarze 2003). Citations and original charts for this section are listed in Appendix G and Appendix H.

Beaver densities (the number of colonies per unit of stream length) were derived from comparing several studies that measured unexploited populations in areas with habitat similar to that of Wisconsin (Table 4.3).

Table 4.3 Beaver densities (Müller-Schwarze 2003)

Area	No./mile	No./Km
Fulton County, NY	0.87	0.54
Massachusetts	0.89	0.55
Western NY	0.93	0.58
Quabbin Reservation Mass.	1.61	1.00

This gives an average density of one colony for every 1.07 miles or 0.66 Km of length of stream. Table 4.4 depicts the number of beavers per family in areas that also have similar habitat to Wisconsin, with an average of 5.4 beavers per family.

Table 4.4 Average number of beavers per family (Müller-Schwarze 2003)

Area	Average No. / Family
Adirondacks NY	4.3
Michigan	5.1
Allegany State Park	5.4
Ohio	5.9
Isle Royale NP, Mich.	6.4

Calculation note: an "Urban Landscape" correction was made to take into account limitations to habitat quality because of degraded habits and water quality. This reduced population estimates by the percentage of the landscape in each watershed that's designated "Urban." Ironically, most of the beavers that are currently in the watershed are living in the urban areas. This small population exists because beavers are protected from trapping in Milwaukee County.

In the preliminary report to MMSD in August, a WDNR watershed data set from 2001 was used to calculate the estimated beaver population numbers that could be supported based on wetlands size, however, this report uses an updated 2020 USGS land use data set. As compared to WDNR data (2001), USGS data increased the wetland area from 68,000 acres of wetland to 89,218 acres. This is very significant because it increases the potential of available habitat by more than 30,000 acres. The East-West Branch alone has 36,354 acres of wetland, or 56.8 square miles.

Most of the wetland land use (based on aerial map review) is not utilized for agriculture or building infrastructure. This leaves ample land available for beavers to potentially flood without creating nuisance flooding to buildings, infrastructure, or farms. Total stream miles in the USGS data sets were also higher than WDNR estimates. The USGS subwatershed maps showing the numbered smaller scale subwatersheds and the data sets for that section were added to illustrate subwatershed characteristics.

The Milwaukee River watershed was divided into 31 subwatersheds. The upper subwatersheds are composed of mostly low gradient streams with 10 sub-subwatersheds having wetlands land use of between 19% to 28%. The wetland percentages of the subwatersheds are high: Cedar Creek 21%. The East-West Branch, 20%, North branch 17%, South branch 11%, Menomonee 9%. Given the overall low gradient, fewer dams, in theory, would be needed to store water. The geomorphology of the stream will determine the scale and location of dams that would be needed to create ponds.

The following pages describe each of the six watersheds within the Milwaukee River Basin and the calculations used to determine the carrying capacity of beaver colonies in each watershed, and, where possible, show an image of one of the potential beaver colony sites as identified by the field observations. All calculations are based on the estimated beaver capacity of 1.07

colonies per river mile, and 5.4 beavers per family, i.e., beaver population in each subwatershed is

$$Population = River\ miles \times 1.07\ \left(\frac{colonies}{mile}\right) \times 5.4\ \left(\frac{beavers}{family}\right) \times (1 - \%\ urban) \quad (3.1)$$

and the beaver colony in each subwatershed is

$$Beaver\ colonies = \frac{Population}{5.4\ \left(\frac{beavers}{family}\right)} \quad (3.2)$$

Milwaukee River East-West Branch

The Milwaukee River East-West branch subwatershed is 274 square miles in area, has 310 stream miles and 36,354 acres of wetlands (56.8 square miles) in the basin. These wetlands encompass 20% of the land area, which is the highest percentage of all the subwatersheds. Most of the North Kettle Moraine State Forest (30,000 acres) is in this subwatershed. Only 3% is urban. Although no beaver dam structures were observed in this upper watershed, this basin has excellent potential for restoring beaver structures on the landscape. To successfully reintroduce beaver and accelerate results in establishing colonies, a strategy could be to release sexed pairs into each of the nine subwatersheds.

Beaver Population – East/West Branch

310 river miles × 1.07 × 5.4 equals= 1791 beavers
Corrected for urban, less 3% = 1737 beavers

322 Beaver colony carrying capacity

Figure 4.3 A sample photo of one field assessment location in the East-West branch Milwaukee River subwatershed, and a photo illustrates an example of a beaver dam that is expected to see with a successful reintroduction

Milwaukee River East-West Branch

Figure 4.4 Nine sub-basins of the East-West branch Milwaukee River subwatershed

Table 4.5 Wetland areas and river miles of the nine sub-basins of the East-West branch Milwaukee River subwatershed

Sub-Basin	Sub-Basin Area (Acre)	Wetland Area (Acre)	Wetland Percentage	River Miles
1	17,367	2,600	15.0%	24.5
2	31,308	7,885	25.2%	60.8
3	19,384	3,927	20.3%	33.3
4	16,876	4,267	25.3%	33.7
5	21,520	4,180	19.4%	23.9
6	16,617	4,660	28.0%	32.7
7	13,238	2,228	16.8%	30.2
8	20,801	3,368	16.2%	29.6
9	18,660	3,238	17.4%	42.9

Milwaukee River North Branch

The Milwaukee River North Branch is 146 square miles with 156 miles of streams, 12 of which are listed as impaired. Wetlands cover 16,548 acres (25.8 sq. miles) which is 17% of the sub-basin. Less than 0.5% of the sub-basin is urban. No beaver dam structures were observed in this upper watershed.

Beaver population - North branch

144 miles × 1.07 × 5.4 equals= 832 beavers

Corrected for urban, less 0.5% = 827 beavers

154 Beaver colony carrying capacity

Figure 4.5 A sample photo of one field assessment location in the North branch Milwaukee River subwatershed, and a photo illustrates an example of beaver dam that is expected to see with a successful reintroduction

Milwaukee River North Branch

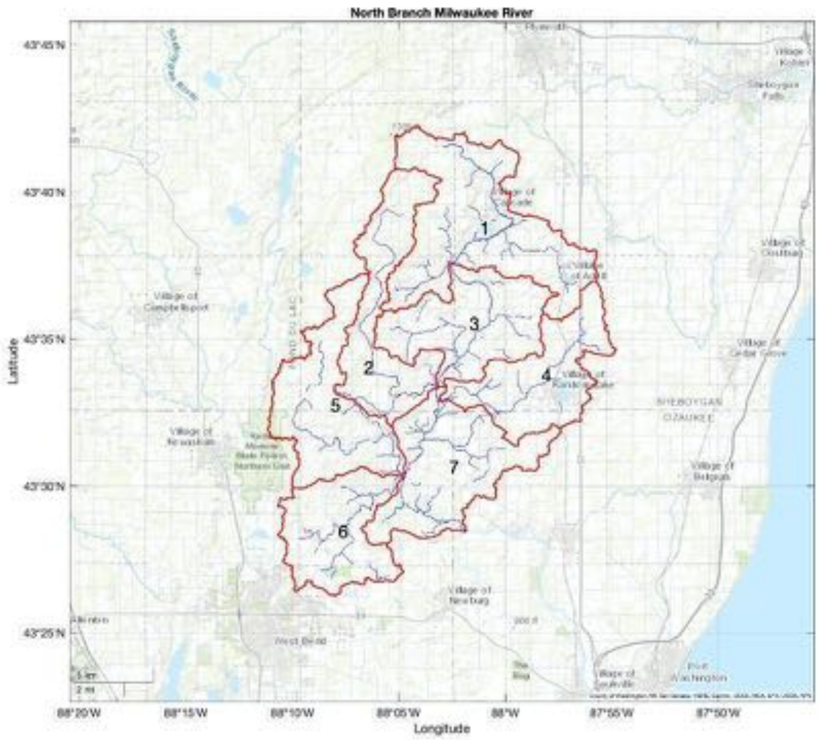

Figure 4.6 Seven sub-basins of the North branch Milwaukee River subwatershed

Table 4.6 Wetland areas and river miles of the seven sub-basins of the North branch Milwaukee River subwatershed

Sub-Basin	Sub-Basin Area (Acre)	Wetland Area (Acre)	Wetland Percentage	River Miles
1	19,938	3,263	16.4%	32.1
2	11,954	1,466	12.3%	19.7
3	12,616	1,766	14.0%	23.5
4	11,347	2,350	20.7%	16.1
5	13,307	2,018	15.2%	17.8
6	10,536	2,037	19.3%	17.5
7	14,124	3,649	25.8%	29.8

Cedar Creek

The Cedar Creek subwatershed is 127 square miles with 165 miles of stream. It has 17,245 acres of wetlands (27 square miles), which is 21% of the basin. Only 3.5% is urban. Two major wetland complexes are in the subwatershed, the Jackson Marsh and Cedarburg Bog. 12 miles of the watershed are impaired. Of those, 5 miles are in Cedarburg and are contaminated with PCB's from the Mercury Marine Superfund site. Those impaired river miles are subtracted. No beaver dam structures were observed in this watershed. At a few locations, some old cuttings were found.

<u>Beaver population - Cedar Creek</u>

165-12 = 153 river miles

153 river miles × 1.07 × 5.4 equals= 884 beavers

Corrected for urban, less 3.5% = 853 beavers

158 Beaver colony carrying capacity

Figure 4.7 A sample photo of one field assessment location in the Cedar Creek subwatershed, and a photo illustrates an example of beaver dam that is expected to see with a successful reintroduction

Cedar Creek

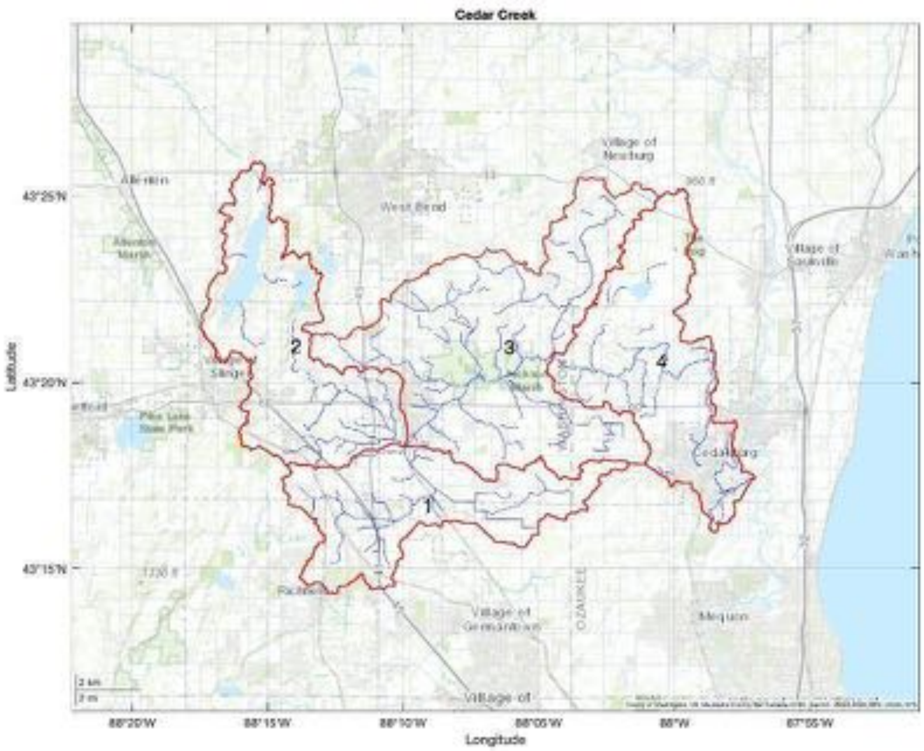

Figure 4.8 Four sub-basins of the Cedar Creek subwatershed

Table 4.7 Wetland areas and river miles of the four sub-basins of the Cedar Creek subwatershed

Sub-Basin	Sub-Basin Area (Acre)	Wetland Area (Acre)	Wetland Percentage	River Miles
1	15,233	2,356	15.5%	33.4
2	17,952	2,828	15.8%	27.6
3	29,813	7,307	24.5%	70.0
4	18,144	4,754	26.2%	34.6

Menomonee River

The Menomonee River watershed is 139 square miles, with 172 stream miles. Wetlands total 8,404 acres and represent 9% of the watershed. 42% is urban and 8.3 stream miles are impaired. No beaver dam structures were observed in this watershed. Beaver cuttings have been observed from Wauwatosa up into the upstream areas north of Menomonee Falls.

Beaver Population – Menomonee River

172-8.3 = 163.7 river miles

163.7 river miles × 1.07 × 5.4 equals= 945 beavers

corrected for urban, less 42% = 548 beavers

101 Beaver colony carrying capacity

Figure 4.9 A sample photo of one field assessment location in the Menomonee River subwatershed, and a photo illustrates an example of beaver dam that is expected to see with a successful reintroduction

Menomonee River

Figure 4.10 Five sub-basins of the Menomonee River subwatershed

Table 4.8 Wetland areas and river miles of the five sub-basins of the Menomonee River subwatershed

Sub-Basin	Sub-Basin Area (Acre)	Wetland Area (Acre)	Wetland Percentage	River Miles
1	25,542	4,370	17.1%	60.3
2	13,654	1,461	10.7%	28.5
3	12,996	1,200	9.2%	35.5
4	12,525	1,003	8.0%	21.5
5	24,522	371	1.5%	26.2

Milwaukee River South Branch

Milwaukee River South Branch subwatershed has an area of 152 square miles with 188 miles of streams. It has 10,667 acres of wetlands which is 11% of the land area. The South branch is about 33% urban with 41.5 stream miles listed as impaired by the WDNR. Impaired waters were subtracted for the calculation. A couple of small beaver dam structures were observed in the lower reaches of this watershed, such as in Lincoln Park in Milwaukee County and Trinity Creek in Mequon.

<u>Beaver Population - South Branch.</u>

188-41.5= 146.5 river miles

146.5 river miles × 1.07 X×5.4 equals= 846 beavers

Corrected for urban, less 33% = 567 Beavers

105 Beaver colony carrying capacity

Figure 4.11 A sample photo of one field assessment location in the South branch Milwaukee River subwatershed

Milwaukee River South Branch

Figure 4.12 Five sub-basins of the Milwaukee River South subwatershed

Table 4.9 Wetland areas and river miles of the five sub-basins of the Milwaukee River South subwatershed

Sub-Basin	Sub-Basin Area (Acre)	Wetland Area (Acre)	Wetland Percentage	River Miles
1	14,116	3,578	25.3%	26.2
2	18,674	2,741	14.7%	41.7
3	23,749	3,217	13.5%	65.4
4	13,924	196	1.4%	13.0
5	26,724	935	3.5%	42.3

Kinnickinnic River

The Kinnickinnic River Watershed is 25 square miles with 24 miles of streams, and 1.5% (238 acres) are wetlands and 78% is urban. With this high percentage of urban landscape and significantly polluted runoff, including the drainage of deicing fluid (glycol) from Mitchell airport, the opportunity for beavers to survive, breed, and build dams is marginal at best. Despite the harsh conditions of the watershed, beaver cuttings and other signs have been found along the Kinnickinnic River. However, after evaluating the watershed we determined that a sustained recovery is currently not likely.

Figure 4.13 Kinnickinnic River subwatershed

Table 4.10 Wetland areas and river miles of the Kinnickinnic River subwatershed

Sub-Basin	Sub-Basin Area (Acre)	Wetland Area (Acre)	Wetland Percentage	River Miles
1	15,938	238	1.5%	24.4

4.2.3 Recommended, 14 beaver restoration reestablishment sites

These sites are selected as initial reintroduction sites. They could serve as breeding area hubs, for colony establishment to facilitate dispersal to rebuild the population. A successful colony with good forage will quickly increase the population. As the population grows it creates internal dispersal pressure to create new territories. Normally 2-year-old beavers leave the natal colony in spring to find a mate and will establish a new colony in good habitat. Over time, those dispersing beavers will establish their own territories and create ponds and dams that would mitigate flooding throughout the basin. To facilitate recovery and dam building, reestablishing quality habitat forage and building materials will expedite the recovery. For example: planting patches of aspens and willows groves at the 52 dam sites identified in the report, will create habitat incentives for beaver to use at those locations. In addition, "Beaver Dam Analogs" (BDAs) are a proven tool to initiate dam building at a given site or area. BDAs are a low-tech method of driving wooden posts into the streambed, that serve as a starter structure that beavers will sometimes use to build a dam.

The recovery of a species takes some time and it's best if expectations approach this with the long view. With protection, and the cooperation of agencies and partners, good results with numerous dams would be seen in 5 years. Similar larger scale habitats have seen a substantial recovery in 25 to 35 years. (Hood 2008) In a matured system in the Milwaukee watershed you would expect to see hundreds of beaver dams.

The following sites are selected because they currently have existing habitat characteristics and enough acreage and area to support a breeding beaver colony (see Figure 4.14). Relocating sexed beaver pairs to these locations would give the beavers a much higher chance of surviving during their first few years. Their offspring will disperse to areas where they can build new ponds, and they can be encouraged to build in strategic locations by planting forage and building BDAs where new ponds would create beneficial water storage. Aerial photos and field pictures of the 14 recommended sites are presented in Appendix E. The green shaded wetland areas in the aerial photos of each of the recommended sites illustrate the large scale of available wetlands in the surrounding area for the creation of ponds with dams.

Those habitat land characteristics are as follows:

1. These areas have larger ponded water sites or the stream volume is large enough to support over winter water depth.
2. These areas are within or have access to large adjoining wetland areas to support breeding and the potential for population expansion to establish new territories. Areas have unobstructed water connection to stream channels.
3. These areas have existing forage of aquatic plants and woody material to provide colony establishment.

Sites selected:

1. Mud Lake, Dundee;
2. Mud Lake, Cedarburg Bog;
3. Mink Creek;
4. Mauthe Lake;
5. Kewaskum, North;
6. Jackson Marsh;
7. Random Lake Ponds;
8. North Branch;
9. Lake Twelve Marsh;
10. Kewaskum South East;
11. Ulao Creek;
12. Ashford;
13. Batavia Creek; and
14. Watercress Creek.

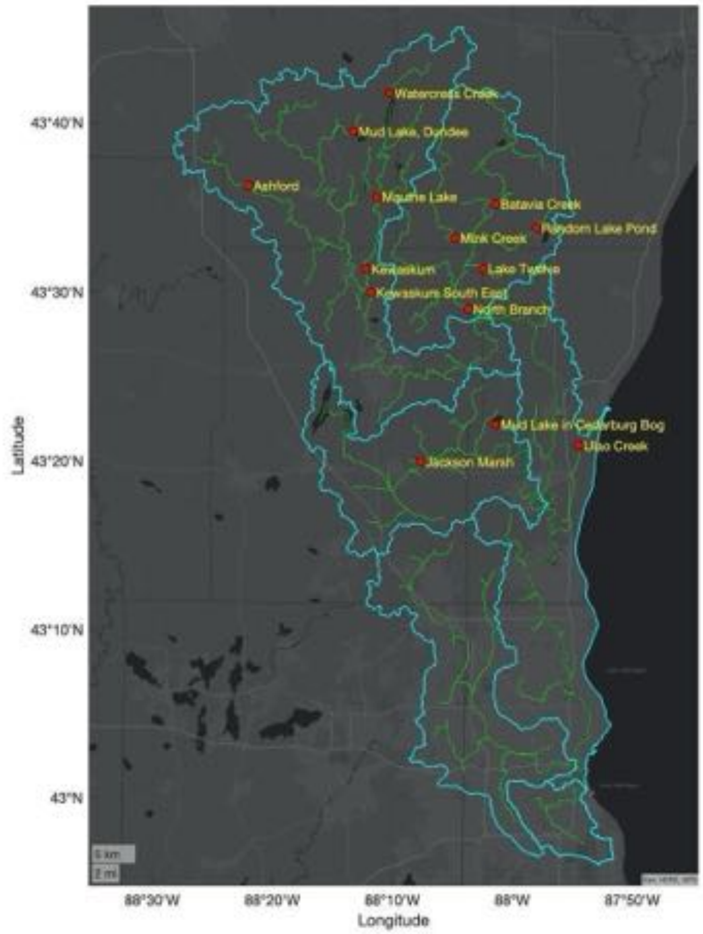

Figure 4.14 Locations of 14 recommend beaver restoration sites

5 Conclusions, discussions, and recommendations

A suite of models has been developed for the assessment of potential beaver habitat restoration and impacts of beaver dams on river flows in the Milwaukee River watershed. Models include a set of Matlab and Python programs that automates geophysical and hydrological data pre- and post-processes for the BRAT model, which assesses beaver restoration potential for a watershed; and for the HEC-HMS model which evaluates effects of beaver dams on river hydrographs in response to storm events. Since data required for models are publicly available for all geographic locations across the United States, the set of models can be applied to any watershed in the States. The primary objective of the modeling study is to test the hypothesis that restoration of beaver habitats in the Milwaukee River watershed can significantly mitigate river flood flows, even for urban areas at the lower end of the watershed.

5.2 Summary of beaver restoration model (BRAT) results and future improvement

The BRAT model was successfully adapted for the Milwaukee River watershed, by revising the hydrological module that estimates baseflow and flood flow stream powers based on drainage area; and by revising the maximum beaver capacity per unit stream length according to literature studies on watersheds that are similar to the Wisconsin landscape, the BRAT model simulation suggested that:

- Hydrologic conditions in the Milwaukee River watershed are favorable for beavers to establish colonies, as the landscape is generally flat and river slopes are mild for the most part of the watershed. Therefore, riparian vegetation type is the primary factor that determines the potential of beaver habitat restoration.
- Considering vegetation cover and hydrologic conditions, the three northern sub-basins including the East-West branch Milwaukee River, the North branch Milwaukee River and the Cedar Creek, are more suitable for beaver restoration. Model predicted maximum beaver dam capacities are greater than 6 dams/km on average in the three sub-basins. Despite a significant portion of land developed as urban landscape, the Menomonee River sub-basin and the Milwaukee River South sub-basin can moderately support beaver habitations. Model predicted maximum dam capacities are greater than 4 dams/km on average, and higher capacities can be found in the northern suburban areas of the two sub-basins. The Kinnickinnic River sub-basin is generally not suitable for beaver restoration due to extensive developed land areas, and lack of vegetation supporting beavers along the streams. Modeled maximum beaver capacity is about 1 dam/km.

Model predicted dam capacity should only be interpreted as a measure of relative importance, since it has not been calibrated with ground-truthed data. Present beaver colonies are rare to none in the Milwaukee River watershed, which brings difficulties for model calibration or validation. Archaeological evidence may serve as another means of calibration, a task that is more challenging and costly. A better alternative is to conduct field surveys in watersheds with similar riverscapes and existing beaver habitats and dam complexes. Some areas in northern Wisconsin can be candidates for model calibration studies. Important parameters for field samples may include vegetation types, river width and slopes, dam numbers, heights, and lengths, etc.

5.3 Summary of hydrological model (HEC-HMS) calibration results

Through this project, it was demonstrated that hydrological processes in the Milwaukee River watershed, including soil infiltration, groundwater interflow and baseflow, as well as stream flows, can be reproduced by HEC-HMS, which is a distributed continuous hydrologic model. Simulations of past storm and river flow events demonstrated that modeled hydrographs agreed fairly well with observed data, in terms of the peak flows and total discharge volume calculated over the period from late spring to early winter of each year. Geophysical data required for HEC-HMS, including SSURGO soil data, land cover, and vegetation type, etc., are all available in high spatial resolution. This allows the model to divide the watershed into more sub-basins to improve spatial resolution. The modeling process in this project showed that simulation results improved as the number of sub-basins increased (213 sub-basins in this study).

It was postulated that the main source of error of simulation was precipitation data. Precipitation inputs to the model were land based rain gauge data, which were interpolated to each sub-basin with the "inverse distance" method. Rain gauges are sparse, and the interpolation creates "smooth" variation of precipitation intensity over the watershed. This approach fails to represent the true spatial variability of a storm event, which is typically heterogeneous with rapidly moving "sharp" fronts. Therefore, it is expected that model performance will be improved if a "gridded" precipitation model is applied with radar image-based data.

5.4 Model predicted hydrologic impact of beaver dams

With the calibrated HEC-HMS model, hypothetical analysis was conducted to evaluate effects of beaver dams on hydrology of the watershed. Locations of beaver dams were identified based on BRAT model results and validated through field surveys. 52 beaver restoration sites were selected representing those with the highest potential for beavers according to the field survey. A Matlab program was developed to assist beaver dam reconstruction over high-resolution DEM data at selected sites. Through the reconstruction process, model parameters of dams were determined, including the height and length of dams, and the rating relations between water storage and water surface level behind dams. Reconstructed beaver dams were considered to be at their final stages of development (Stage 4). Three additional earlier stages (Stage 1~3) were also modeled with reduced dam number and dam heights. As a result, Stage 4 represented water impounded by 52 beaver dams with a total surface area of 3,793 acres and total storage volume of 5,266 acre-ft; and Stage 1 represented 777 acres of area and 789 acre-ft of storage volume impounded by 18 beaver dams.

With beaver dams added as "reservoir" components in HEC-HMS, model runs were conducted with both past storm events and synthetic frequency storms. Simulated hydrographs were extracted at eight observation locations: the outlets of five sub-basins excluding the Kinnickinnic river sub-basin, and river segments in three urban flood zones in the South Milwaukee River sub-basin.

5.4.2 Simulations of past storm events (2010~2019)

Simulation with realistic past storm events suggested that beaver dams can significantly reduce the peak flow and discharge volume at the eight observation locations. Two factors contribute to peak flow reduction: (1) flow interception by storage capacity of beaver dams makes the primary contribution; and (2) energy dissipation through dam overflow when the storage capacity is filled. Water evaporation from the impounded water is the primary loss that contributes to discharge volume reduction.

At the full stage of beaver development (Stage 4), averaged percentage of peak flow reduction ranged between 11% and 48%; and averaged percentage of volume reduction ranged between 15% and 48%. The minimum and maximum percentage reduction are at the outlet of the Menomonee River and the outlet of the Cedar Creek, respectively. At the earliest stage (Stage 1) the reduction rates decreased only slightly, i.e., 6% ~ 41% for average peak flow reduction, and 14% ~ 43% for average volume reduction. A further investigation indicated that most beaver dams were near their full capacity before the occurrence of major storms, due to water accumulation through prior flow events. Therefore, despite the vast disparity in potential storage among different beaver development stages, the total effective storage capacity may not be significantly different before a major storm. Among all the past storm simulation cases, the case with least flood flow reduction (7% average peak reduction) was observed for the October 2019 storm event. For this case, nearly all beaver dams were completely full due to a series of minor storms prior to the October peak event.

5.4.3 Simulations of synthetic frequency storms

Ten synthetic frequency storms were generated for simulation, they are standard 6-hour and 24-hour storms with recurrence intervals ranging from 10 years to 200 years. Total precipitation depth of these storms varied between 2.99 and 7.44 inches. Since synthetic storms were designed with a uniform spatial distribution over the entire watershed, all beaver dams were able to contribute to flow reduction at river reaches at the lower end of the watershed. Consequently, more significant flow reductions were reported at the eight observational locations. At Stage 1, average flood peak reduction ranged between 26% (24-hour 200-year storm) and 37% (6-hour 10-year storm). At the full Stage 4, the range of average peak reduction was 36% to 46%.

Modeling analysis with synthetic frequency storms approved the hypothesis that beaver dams that largely dispersed in the upper tributaries of the watershed may potentially mitigate flood flows in urban flood zones at the lower end of the watershed. Take the flood zone in the City of Glendale for example, model simulations suggested: a 100-year flood could potentially be downgraded to a 10-year flow (Stage 1 beaver dams) or even 5-year flow (Stage 4); and a 1,200-year flood could potentially be downgraded to an 80-year or 10-year flow, etc.

It should be noted that these conclusions are based on the assumption that storm precipitation was uniformly distributed over the entire watershed, and all beaver dams had at least 20% of their potential capacity for flow interception before the extreme but isolated storm event. For real storm events which are spatially inhomogeneous and may occur as a series of events, the effect of flood mitigation is expected to be less than that predicted by the synthetic storm simulation.

5.5 Model improvement and future research needs

It is considered that the main source of uncertainty that may affect model results and conclusions is associated with how beaver dams reconstructed in the model can represent realistic ones. In this study, each beaver site was assigned a single dam that is relatively large in height and length, such that impounded water is comparable to a large beaver dam complex. Most pervasive beaver colonies are a complex that consists of a series of smaller beaver ponds with multiple dam structures. Cumulative hydraulic performance of a large dam complex may or may not be comparable to that of a single large dam structure modeled in this study. To reduce the uncertainty, future research should focus on detailed modeling of beaver complex structures. Model simulations can be conducted in similar watershed with known existing beaver complexes, which allows model calibration with realistic dam structures. Field experiments in real beaver structures that measure change of water level, inflow and outflow during high and low flow events are also necessary to improve the simulation of hydraulic performance. These additional efforts may help to revise the current model that can better represent beaver effects on hydrology at the basin scale.

In the HEC-HMS model, groundwater storage and flow are treated for each sub-basin through a box model. Beaver dams (or reservoirs) are treated as hydraulic control nodes. Therefore, it is not able to account for the local pond-groundwater exchange, which is a rather important process that affects the water balance. This limitation needs to be acknowledged for future research considerations.

5.6 Habitat assessment conclusions

Based on calculations, the Milwaukee River Basin has the potential to support 4,563 beavers, in 840 colonies. This may be a surprisingly high number for many people to imagine, however, with 89,000 wetland acres, this also translates to about one family group of beavers for every 100 acres of wetlands across the watershed landscape. The early fur trade was an ecological disaster for wildlife populations throughout the western Great Lakes. Most of this happened prior to the early settlement of Wisconsin, which has resulted in lack of awareness of what the land was like prior to 1600. The historic shipping records and photos of the fur trade give a window to the past. Those historic records tallied that millions of beaver pelts were traded, and those pelts were the first currency of North America, helping to blaze the country's exploration. Conservation biologists refer to our current time period, with this loss of wildlife, as the 6th Extinction or the Anthropocene. ***Anthropocene*** refers to how human activity is the dominant influence on the environment affecting climate and the rapid loss of biodiversity globally. Restoring beavers can help restore some natural hydrology and the biodiversity of the planet.

Beavers are known as a keystone species that have many benefits for species richness. The dams they build create wetlands that are the most dynamic supporters of biodiversity in this bio-region. In the western Great Lakes, beaver ponds and their structured dams are akin to coral reefs and tropical rainforests in supporting biodiversity.

For a reference guide to the numerous benefits of beaver one can be referred to Chapter 1 of, ***The Beaver Restoration Guidebook, working with Beaver to Restore Streams, Wetlands, and Floodplains.*** This publication, prepared by the US Fish and Wildlife Service, National Oceanic and Atmospheric Administration, University of Saskatchewan, and the US Forest Service, can be downloaded from:
https://www.fws.gov/oregonfwo/Documents/BRGv.2.0_6.30.17_forpublicationcomp.pdf

The Guidebook is a blueprint for how to implement the restoration of beaver on a landscape. In Chapter 1, this publication discusses the hydrological benefits of increased water retention and base flows. It references studies that demonstrate how beaver activity decreased peak flows and how their expansion increases habitat area and complexity. This includes increasing wetland area and the resulting increase of groundwater recharge. Regarding water quality, it stated:

> *"Beaver have the ability to improve the water quality of streams by reducing suspended sediments in the water column, moderating stream temperatures, improving nutrient cycling and removing and storing contaminates."*

Beavers' works affect the geomorphology in many ways, and importantly their structures stabilize watersheds. These wetlands and ponds elicit a dynamic response from the many benefiting species. When beavers create wetlands, they are the keystone to a trophic cascade of increased biodiversity. Numerous studies have documented that these wetlands trigger increases in species diversity of plant communities, aquatic invertebrates, fish, amphibians, reptiles, and birds.

For example: great blue herons have a symbiotic relationship to beavers. When beavers flood timber they create conditions ideal for herons. Voyageurs National Park in Minnesota is about 525 square miles in size and has 31 great blue heron rookeries in it. 100% of the 31 rookeries are in beaver ponds. Similarly, 82% of osprey nests were also found in beaver ponds (Wendell's, Voyageurs NP communication).

Beavers have been documented in numerous studies as providing critical habitat for endangered and threatened species. Two endangered species, the swamp metalmark butterfly and the Hine's emerald dragonfly, are identified as endangered species in the Milwaukee Watershed. Beaver restored wetlands could provide critical habitat needs for both of these species.

Recovering and restoring beaver populations back to the basin could be a major benefit to flood mitigation, as well as water quality, and biodiversity. As detailed in the UWM modeling research, beaver ponds have the potential to reduce flood peak flows by as much as 26-46%. The economic value of protecting property and infrastructure by reducing peak flow levels is significant. Throughout the basin, there are hundreds of bridges and thousands of culverts. Reducing the peak flows means the wear and tear on that public investment is reduced and the functional life span is longer. Having beavers restore watersheds to reduce flooding is perhaps the most cost-effective method to mitigating peak flows.

Currently, in the northern upper Milwaukee River watershed areas, there is little evidence of beaver activity. They are functionally and locally extinct in the northern watershed. The protection of beavers is critical to allow these ecosystem engineers reestablish a population that could help mitigate flood levels and flatten flood peak flows. The habitat assessments of 163 representative wetland areas determined that sufficient habitat exists within the available 89,000 acres of wetlands to provide excellent habitat for recovery. Beaver populations can and will recover if protective measures are implemented.

5.7 Implementation Recommendations

To realize the water quality and flood mitigation benefits that beavers can provide us, they need to be protected to recover. To achieve protection, there needs to be a change in the game law policy for beavers and other aquatic mammals (otter, muskrat, and mink). This would allow aquatic mammal populations to recover and reestablish territories.

In Wisconsin, the beaver population game laws are managed by the WDNR. Currently, in this southern zone of beaver management (even with a functionally extinct population), the WDNR implements a five-month trapping season (November-March). All manners of lethal trapping and take are allowed during this time, with unlimited bag limits. Trapping licenses are sold by the WDNR and the fur can be sold. Trappers are not required to purchase tags or permits, and the WDNR does not collect data on how many beavers and aquatic mammals are taken each year. It is a wide open, no limit market. Ironically, the trappers have put themselves out of business because they have no beaver left to trap.

The team explored the process of changing the trapping laws in the Milwaukee River watershed (which is about 1.2% of the state area) to allow beaver recovery during several discussions with WDNR personnel, who estimated that changing trapping laws, even with full political support, might take five years.

The other effective way Wisconsin game laws can be changed is through direct legislation. This could be a much more effective and faster process (6 months to a year) for MMSD to explore, as it could include state support for implementing regional ordinances pertaining to flood management obligations as well as matching and supporting Greenseams project goals.

To move this change of a “Game Law” forward, MMSD could consider formally requesting a consultation with the WDNR and Governor Evers regarding the protection of beavers in the Milwaukee River Basin. Protecting the Milwaukee metro area from flooding and the negative effects of climate change is in the best interest of Wisconsin.

As stated earlier, there is a small remnant beaver population in Milwaukee County. In addition, north of Milwaukee County there are a few colonies in Ozaukee County such as at Trinity Creek Wetland in Mequon. This population and its genetics are extremely valuable, as they are the survivors of 300 years of exploitation and need full protection. If they were protected, and an incentive program (as part of the MMSD Greenseams program) with private landowners (via conservation easements or other land use agreements) was established to encourage beavers, the recovery could be rapid. With protection and habitat enhancements, such as aspen grove plantings at key locations, the 89,000 acres of wetlands (139 square miles) offers a large enough landscape to support a thriving beaver population. Many of the best habitat areas are already public lands such as the Jackson Marsh, Cedarburg Bog, and the Northern Kettle Moraine State Forest.

To create conditions to improve the likelihood that beavers will build dams, aspen groves could be planted at the 52 sites that the UWM study identified as potential dam sites. This will provide building materials and forage to encourage beavers to establish dams at or near those locations.

Identified potential locations for beaver dams can also guide the location selection process for Greenseams land acquisitions from landowners. The Greenseams program could also have an economic incentive program added to encourage private landowners to provide beavers with safety and security from human trapping and harassment. This could be similar to other “Conservation Reserve Projects” (CRP) or other federal programs that allow for payments to create economic incentives to landowners to promote wildlife habitat on their property. MMSD could also plant beaver forage on existing Greenseams properties.

Understanding beaver behavior and life cycle is imperative for partnering with beavers for assistance in flood mitigation. Security is key for beavers to thrive and breed, and as the offspring move out they will create new territories and repopulate the available habitat. Dispersing beavers leave their home colony in the spring, roaming to find new areas and mates to establish their own territory. Over a period of several years, it would lead to the reestablishment of dams and ponds throughout the subwatersheds.

The 400 miles of intermittent streams hold tremendous potential for additional flood mitigation. These are the small rivulets, the capillaries that drain wetlands as they swell and emerge during rain events. These intermittent streams are commonly running in the spring throughout the thaw and beavers will follow them upstream. They will commonly dam these intermittent wetland streams and create new ponds. Numerous ditched wetlands were observed in the rural, northern subwatersheds and smaller subwatersheds. These areas have significant potential for water storage by allowing beavers to create ponds and restore wetlands.

From a public relations and economic perspective, managing any nuisance flooding caused by beavers is important. There will need to be beaver management contractors in place who understand beavers and are skilled in installing flow devices and beaver deceiver stack pipes. This way any nuisance flooding problems can be managed quickly and effectively. This type of non-lethal beaver management has proven to be very cost effective. (Beaver Solutions, Mike Callahan)

Educating the public of the benefits of beavers as an ecosystem engineer is an important aspect with this program. Milwaukee Riverkeeper has begun preliminary conversations with the Milwaukee Public Museum and Milwaukee County Zoo on possible programs, exhibits or events highlighting beaver benefits. Because beaver cannot survive in captivity, one idea is to place a video camera inside a lodge and live stream it online and in a display at the Museum or Zoo.

Another important partner is the Ozaukee-Washington Land Trust, (OWLT). This program fits OWLT's mission and furthers their conservation goals for biodiversity, and OWLT staff have expressed interest in exploring how they can support the reintroduction of beavers. OWLT is an established land trust that could help coordinate land acquisitions and easements, and build partnerships with land owners.. Building trust and successfully negotiating land transactions is important for the long-term success of this program.

The Milwaukee Metropolitan Sewerage District's 2035 Vision and Strategic Objectives outlined an approach to Integrated Watershed Management. Beavers can be an ideal Green Infrastructure partner, helping MMSD achieve its 2035 objectives in a cost-effective manner.

As stated in the 2035 Vision:

Green infrastructure uses management approaches and technologies to infiltrate, evaporate, capture, and reuse water to maintain or restore natural hydrology. The preservation and restoration of natural landscape features, such as forests, floodplains and wetlands, are critical components of green infrastructure.

Specifically, beavers can help facilitate these stated integrated watershed flood mitigation goals from the 2035 Vision:

d. *Work with MMSD's partners to achieve zero homes in the 1% probability floodplain.*

e. *Acquire an additional 10,000 acres of river buffers through Greenseams and other regional programs.*
f. *Use green infrastructure to capture the first 0.5 inch of rainfall.*
g. *Harvest the first 0.25 gallons per square foot of area of rainfall.*

Beaver restoration is a natural fit for the following Integrated Watershed Management initiatives in the 2035 Vision.

c. Greenseams

1) *Expand the boundaries of the Greenseams program to match regional watershed boundaries.*
2) *Designate a percentage of annual Greenseams funding toward improving the rainwater storage capacity of the properties.*

d. Maximize MMSD's ability to deliver public educational programming to increase the general public's support and understanding of its operations.

e. Integrate green infrastructure with MMSD's grey infrastructure.

1) *Provide leadership and advocate for a change in the Federal, State, and local definitions of infrastructure to include green infrastructure.*
2) *Develop a plan that integrates the use of green infrastructure within the regional flood management program and municipal stormwater systems to maximize their effectiveness.*
3) *Establish performance measures for green infrastructure.*
4) *Establish regional ordinances that foster green infrastructure.*
5) *Prioritize by location the types and benefits of green infrastructure.*
6) *Establish implementation target levels for green infrastructure on five-year intervals.*
7) *Work with the M7 Water Council and local universities to develop a Great Lakes Center of Excellence for Green Infrastructure in Milwaukee.*

In addition, beaver restoration can help with the following Climate Mitigation & Adaptation initiative from the 2035 Vision:

c. *Expand green infrastructure to help to mitigate climate change and make the region more resilient in the face of intense storms.*

Beavers are very resilient and can recover if given protection. If efforts to support recovery are put into place, it can happen relatively quickly. Each new pond has functional characteristics similar to an engineered storm detention pond; however, beaver ponds are a more cost effective way of filtering water, creating habitat, recharging ground water, removing sediment, storing water, reducing peak flows, and flattening the hydrograph curve. Partnering with beavers is also much more cost effective than building storm detention structures. From a cost analysis, having beavers restore wetlands and create ponds is a win-win for flood mitigation.

In conclusion, Milwaukee Riverkeeper and University of Wisconsin-Milwaukee researchers have determined that partnering with beavers could help MMSD achieve a range of watershed restoration goals including habitat restoration, increasing biodiversity, and reducing flood peak flows. This would be especially beneficial in downstream urban areas. The 89,000 acres of wetland habitat in the Milwaukee River Basin would provide sufficient wetland habitat to support a recovered beaver population.

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Appendix A. Reconstruction of beaver dam models

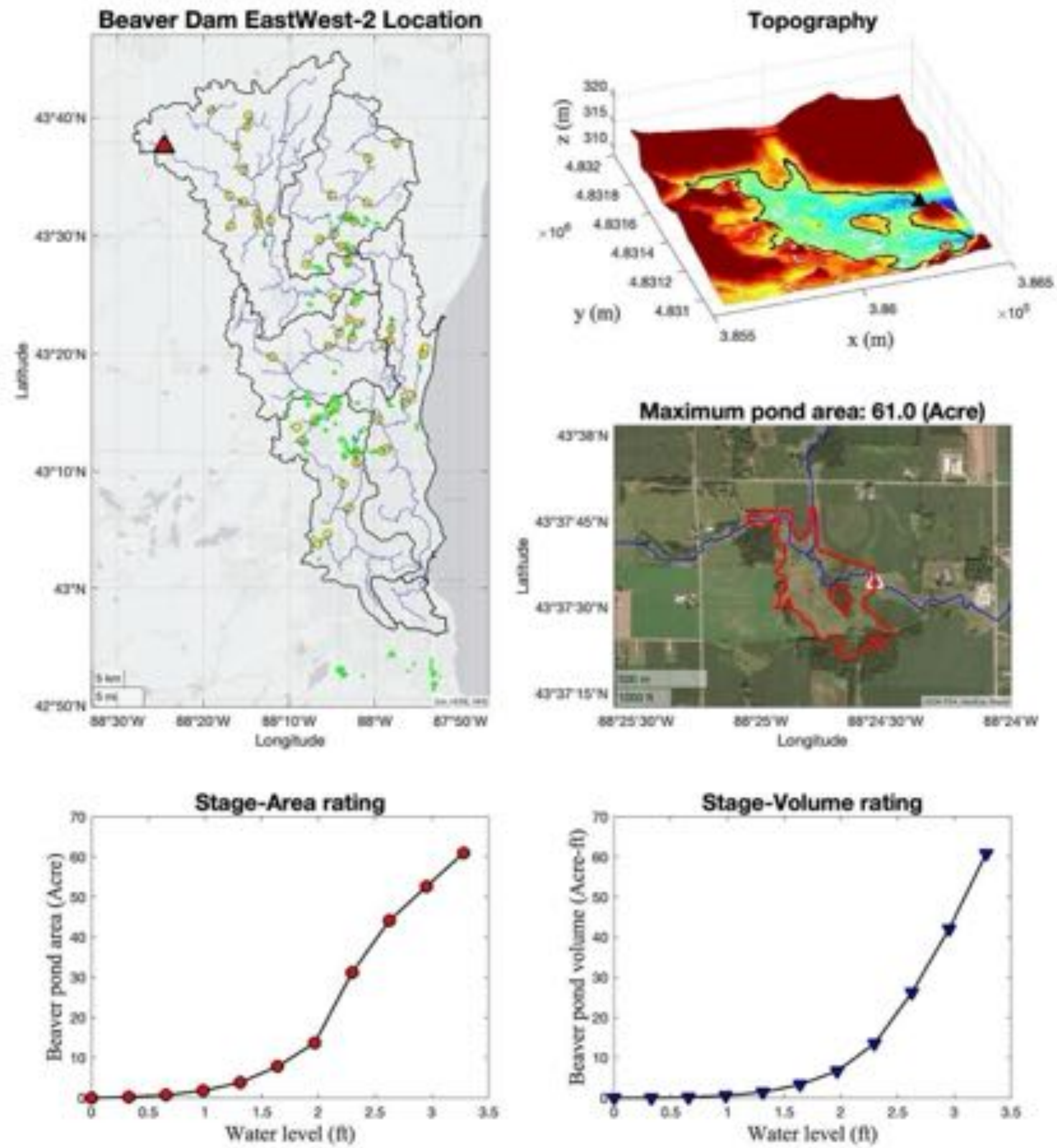


Figure A-1 Processes of beaver dam positioning and storage rating for dam ID: EastWest-2 in the East-West branch Milwaukee River sub-basin. Yellow circles in the location map represent all 52 identified dams; red triangle is the location of the current dam in process; black line in the 3D topography and red line in the satellite image represent the boundary line of water ponded with the maximum water depth (i.e., the dam height).

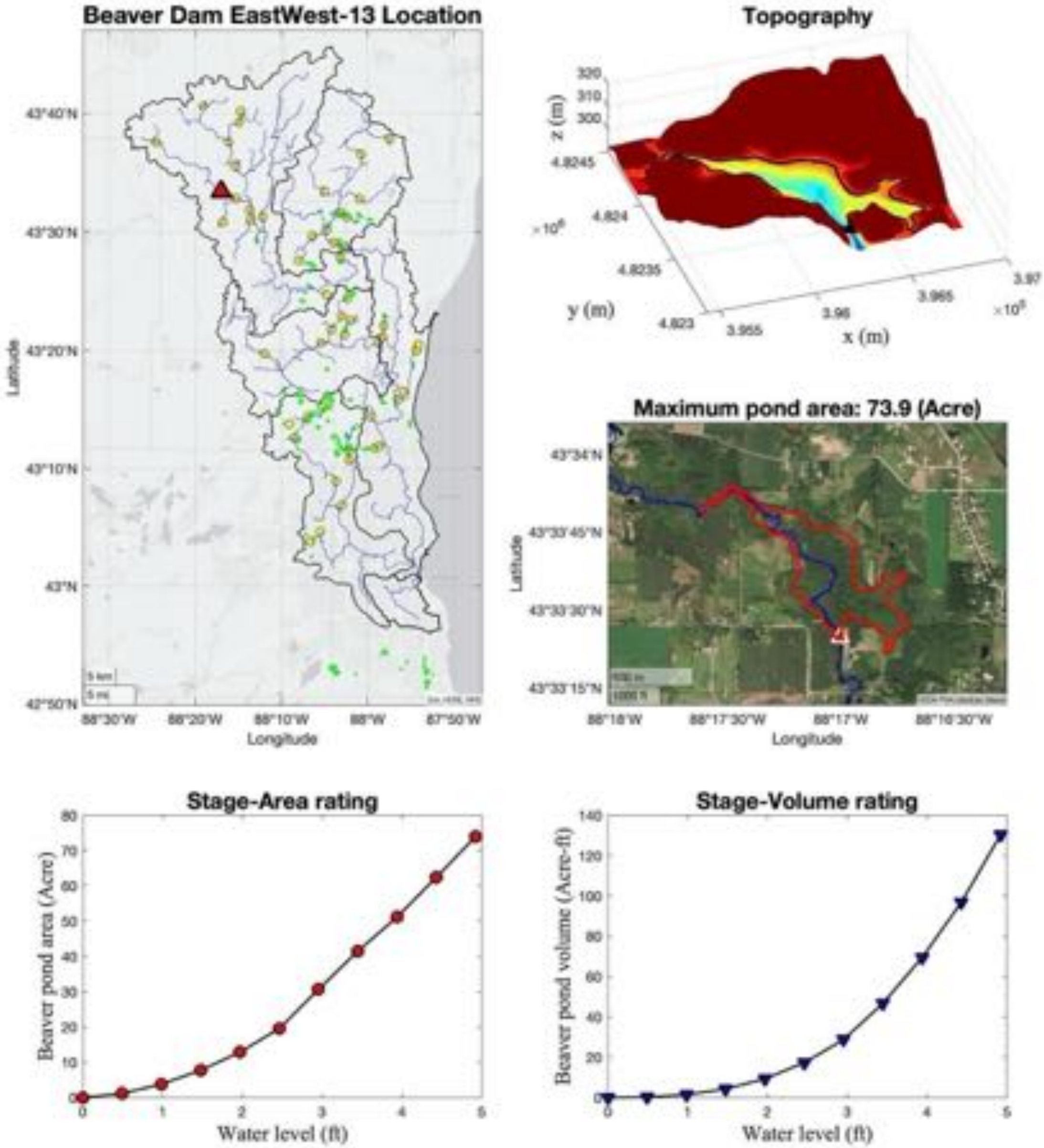


Figure A-2 Processes of beaver dam positioning and storage rating for dam ID: EastWest-13 in the East-West branch Milwaukee River sub-basin. Yellow circles in the location map represent all 52 identified dams; red triangle is the location of the current dam in process; black line in the 3D topography and red line in the satellite image represent the boundary line of water ponded with the maximum water depth (i.e., the dam height).

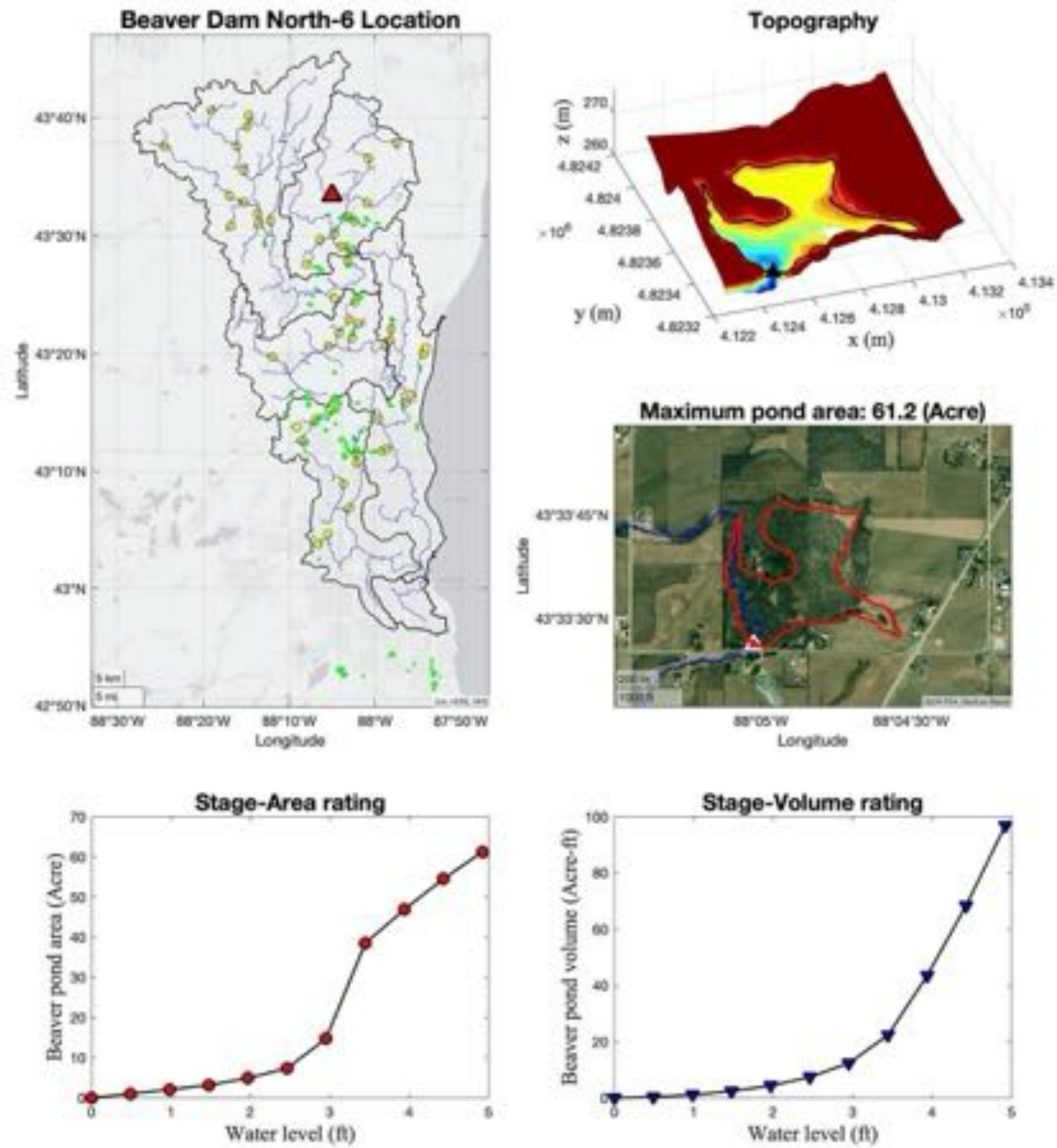


Figure A-3 Processes of beaver dam positioning and storage rating for dam ID: North-6 in the North branch Milwaukee River sub-basin. Yellow circles in the location map represent all 52 identified dams; red triangle is the location of the current dam in process; black line in the 3D topography and red line in the satellite image represent the boundary line of water ponded with the maximum water depth (i.e., the dam height).

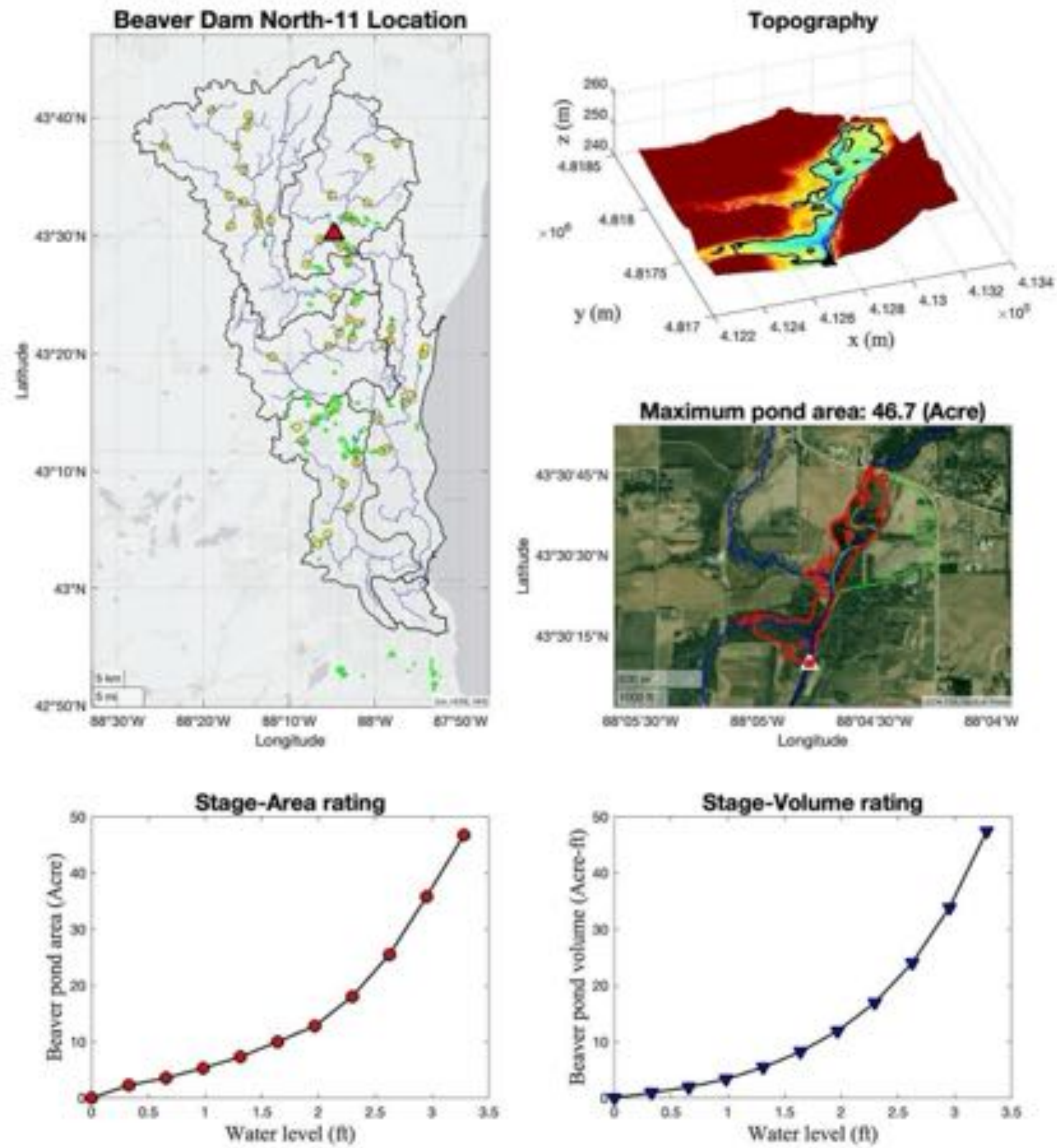


Figure A-4 Processes of beaver dam positioning and storage rating for dam ID: North-11 in the North branch Milwaukee River sub-basin. Yellow circles in the location map represent all 52 identified dams; red triangle is the location of the current dam in process; black line in the 3D topography and red line in the satellite image represent the boundary line of water ponded with the maximum water depth (i.e., the dam height).

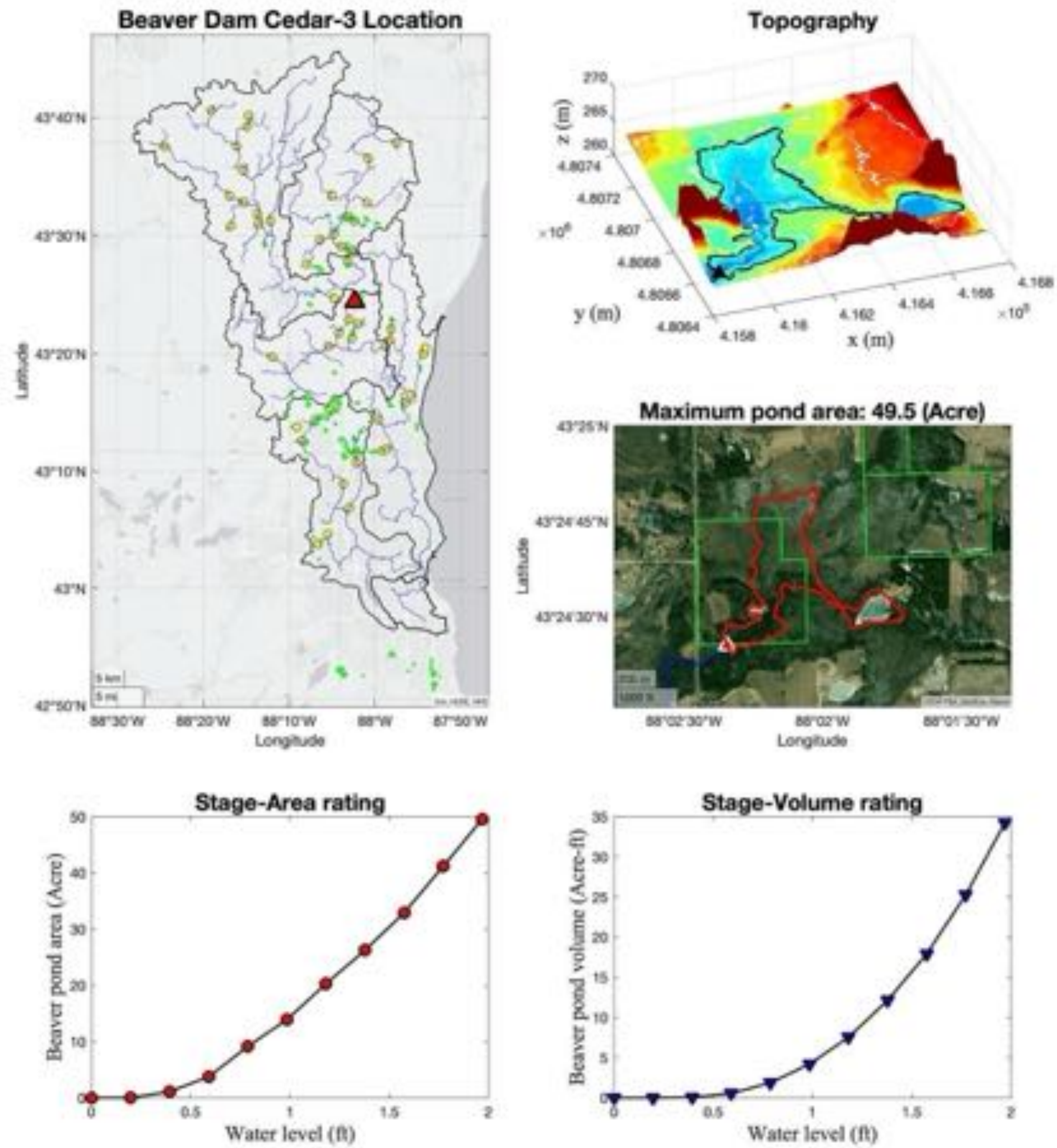


Figure A-5 Processes of beaver dam positioning and storage rating for dam ID: Cedar-3 in the Cedar Creek sub-basin. Yellow circles in the location map represent all 52 identified dams; red triangle is the location of the current dam in process; black line in the 3D topography and red line in the satellite image represent the boundary line of water ponded with the maximum water depth (i.e., the dam height).

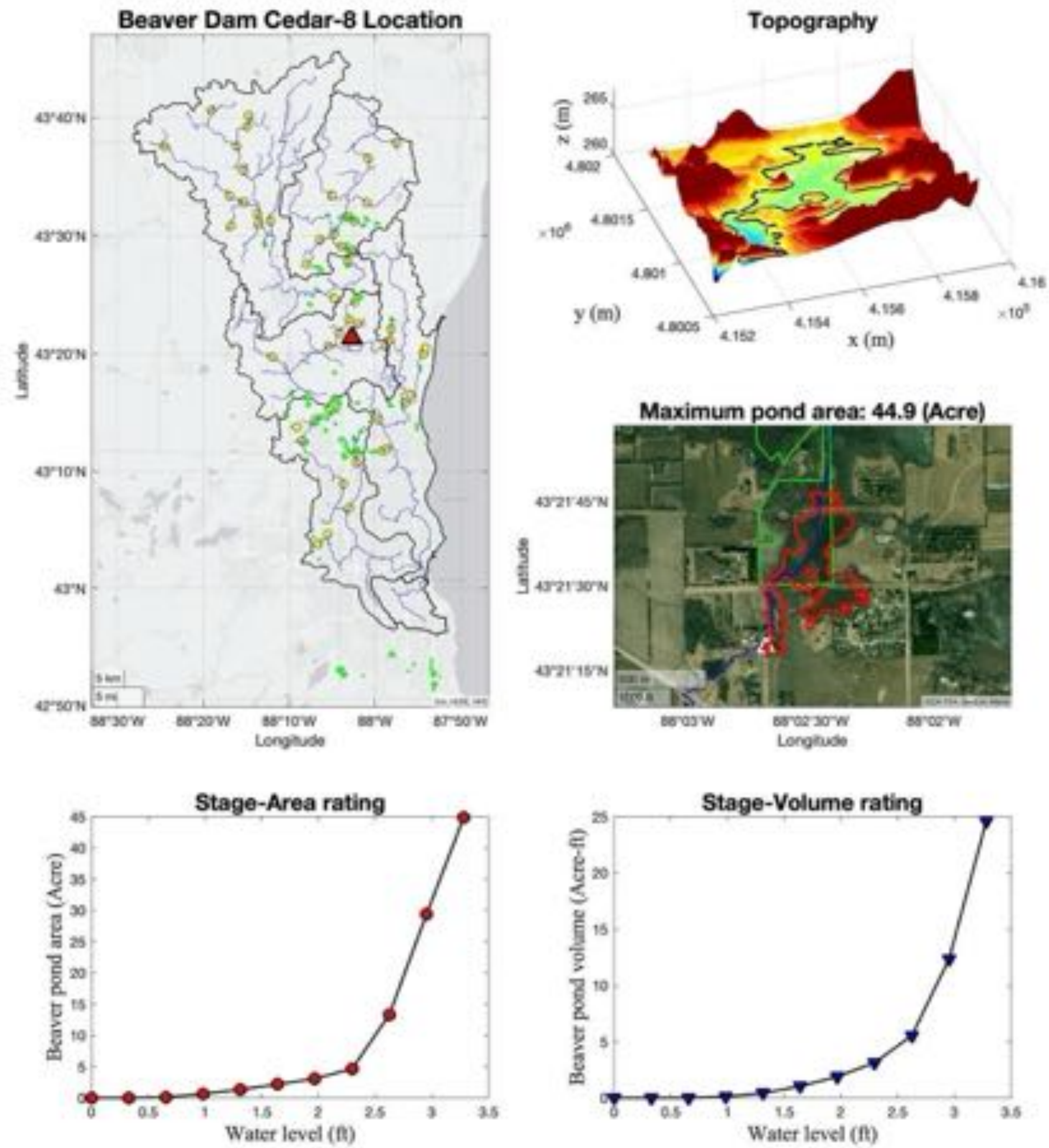


Figure A-6 Processes of beaver dam positioning and storage rating for dam ID: Cedar-8 in the Cedar Creek sub-basin. Yellow circles in the location map represent all 52 identified dams; red triangle is the location of the current dam in process; black line in the 3D topography and red line in the satellite image represent the boundary line of water ponded with the maximum water depth (i.e., the dam height).

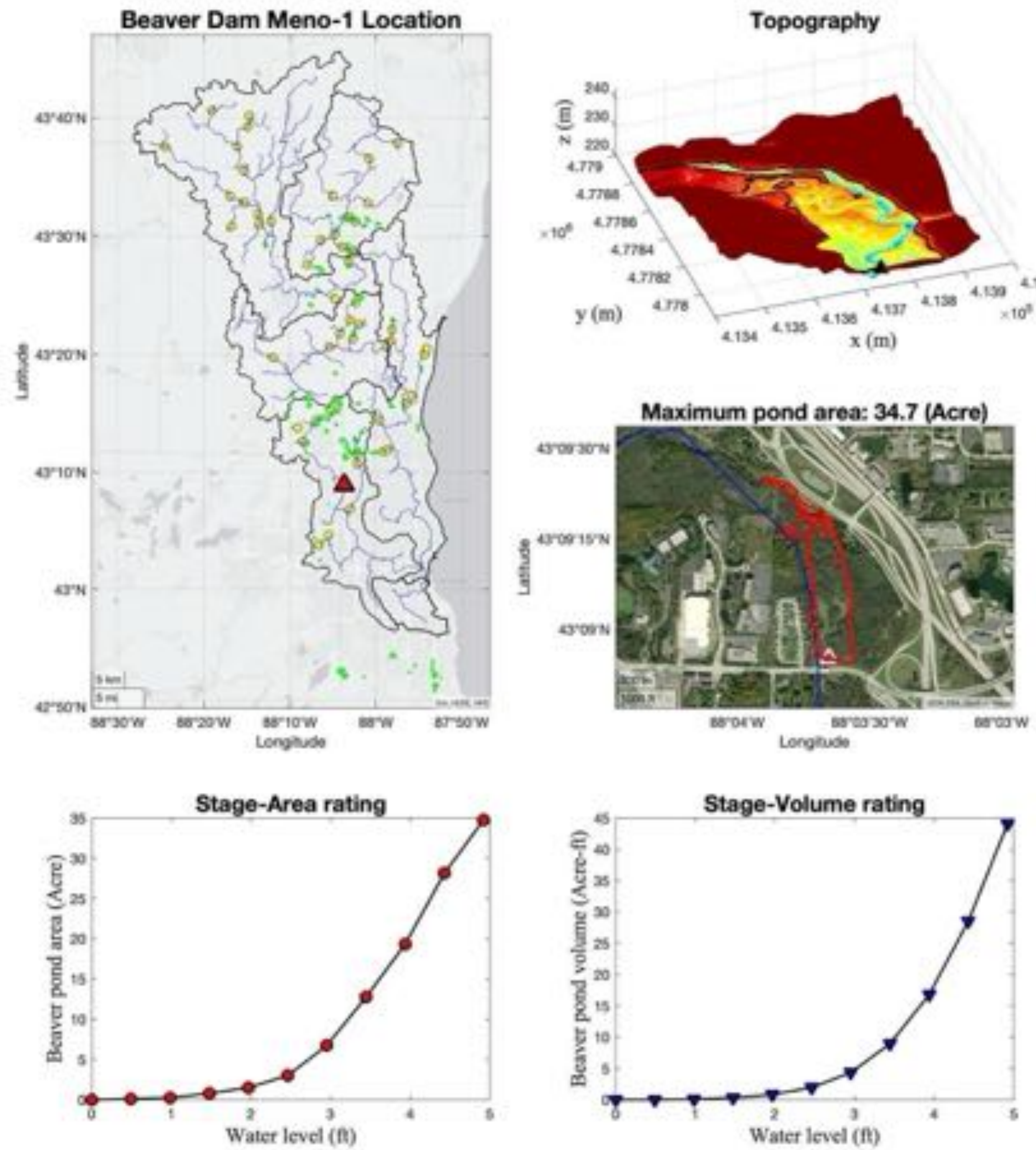


Figure A-7 Processes of beaver dam positioning and storage rating for dam ID: Meno-1 in the Menomonee River sub-basin. Yellow circles in the location map represent all 52 identified dams; red triangle is the location of the current dam in process; black line in the 3D topography and red line in the satellite image represent the boundary line of water ponded with the maximum water depth (i.e., the dam height).

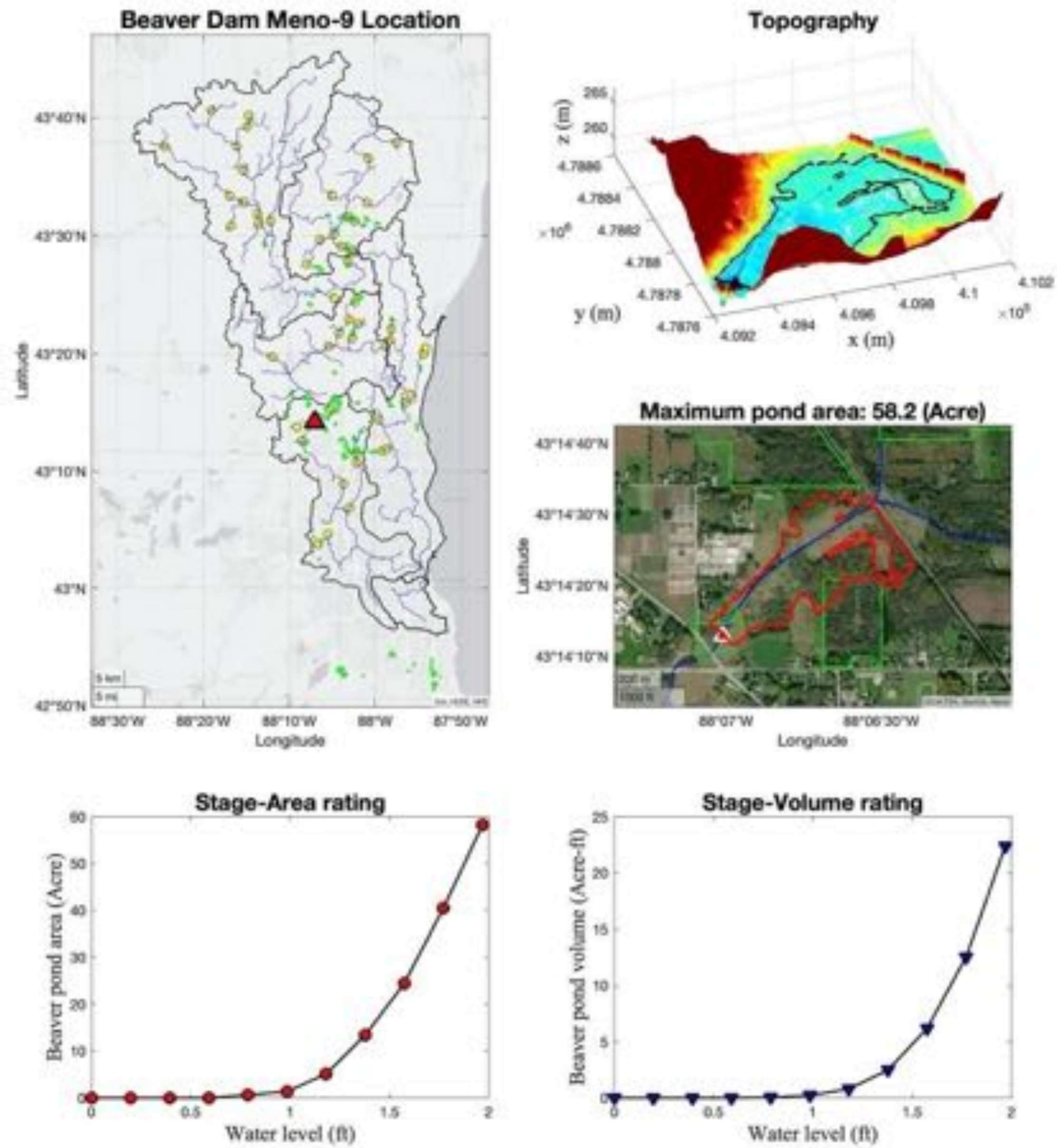


Figure A-8 Processes of beaver dam positioning and storage rating for dam ID: Meno-9 in the Menomonee River sub-basin. Yellow circles in the location map represent all 52 identified dams; red triangle is the location of the current dam in process; black line in the 3D topography and red line in the satellite image represent the boundary line of water ponded with the maximum water depth (i.e., the dam height).

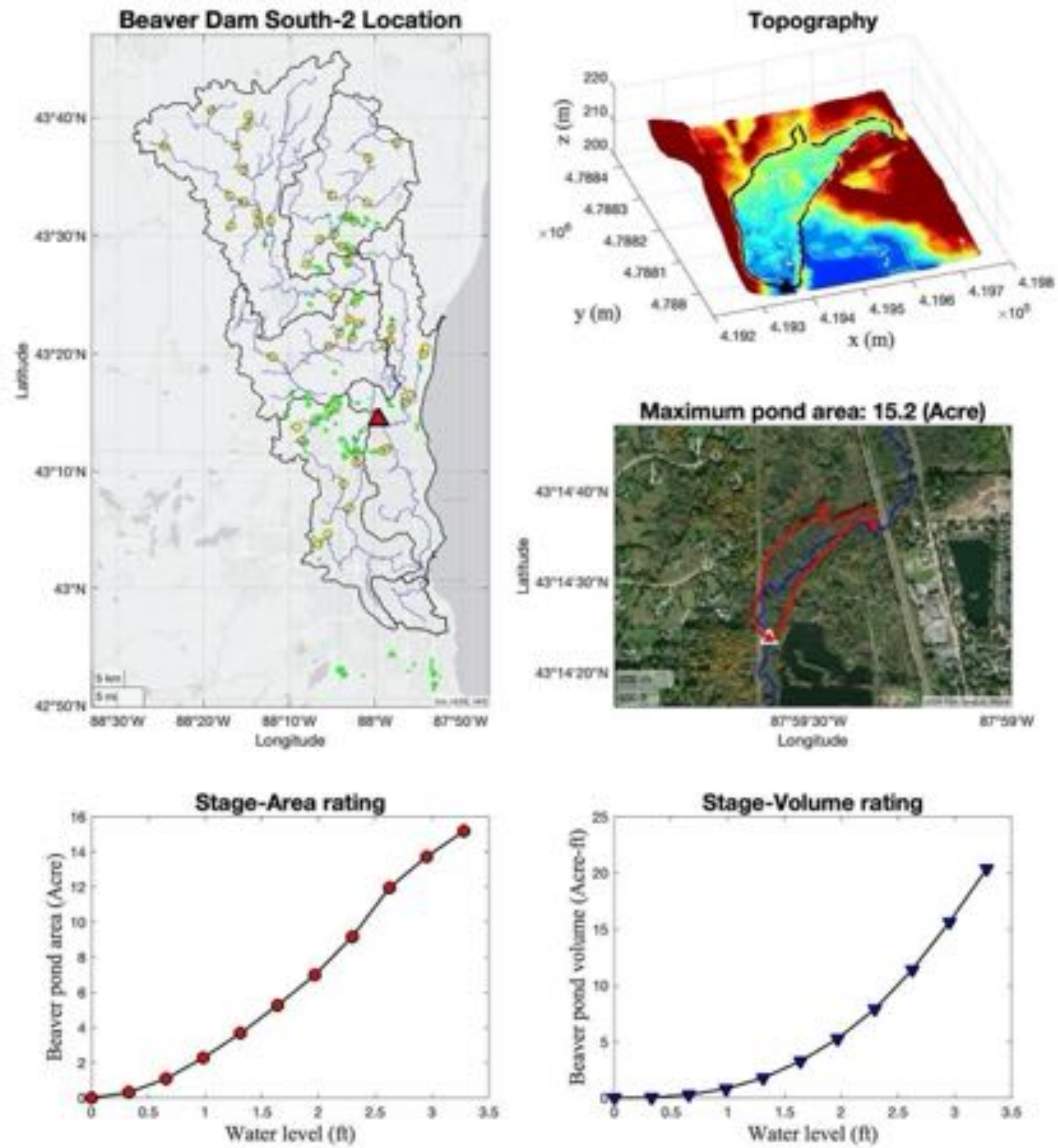


Figure A-9 Processes of beaver dam positioning and storage rating for dam ID: South-2 in the Milwaukee River South sub-basin. Yellow circles in the location map represent all 52 identified dams; red triangle is the location of the current dam in process; black line in the 3D topography and red line in the satellite image represent the boundary line of water ponded with the maximum water depth (i.e., the dam height).

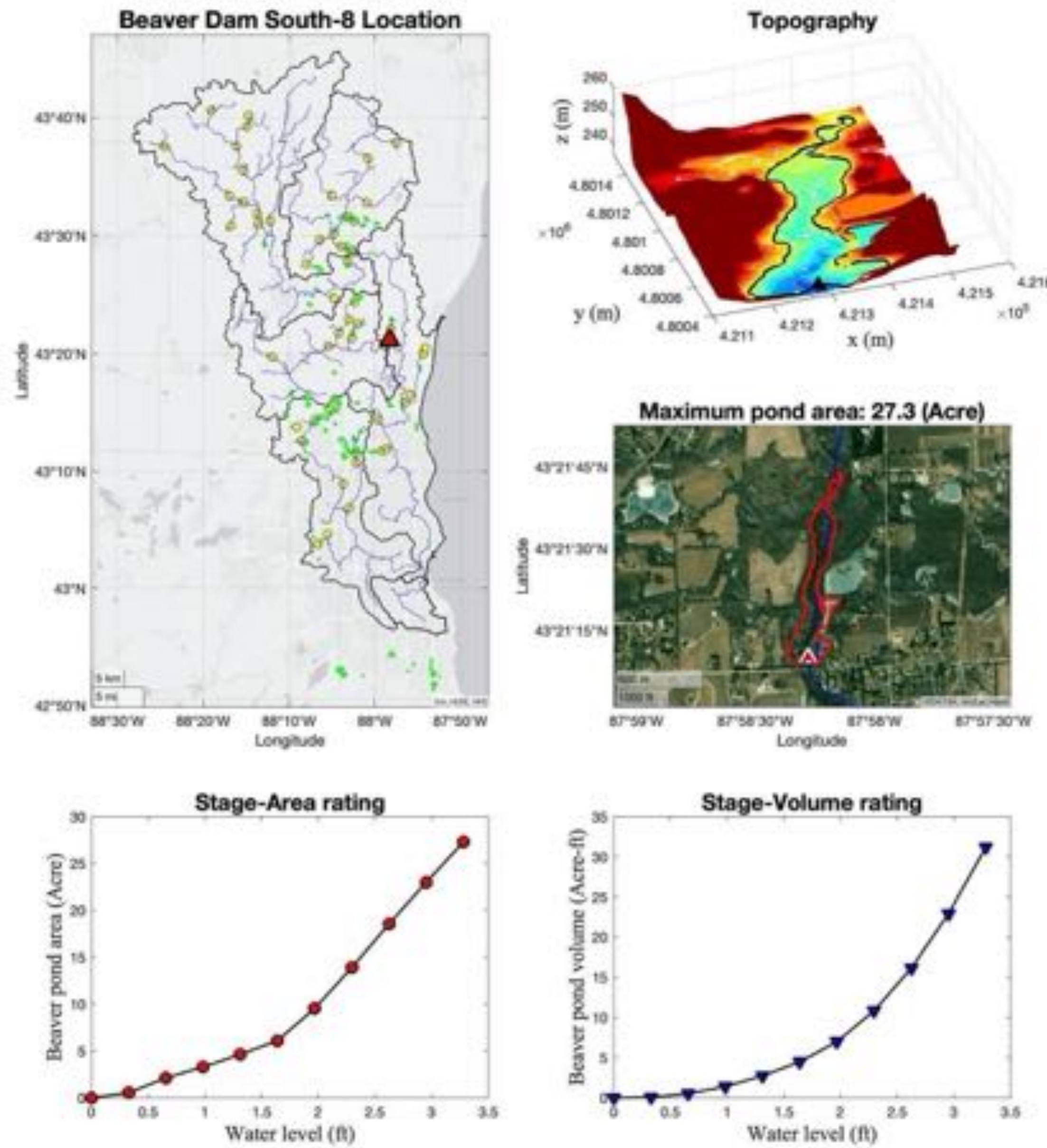


Figure A-10 Processes of beaver dam positioning and storage rating for dam ID: South-8 in the Milwaukee River South sub-basin. Yellow circles in the location map represent all 52 identified dams; red triangle is the location of the current dam in process; black line in the 3D topography and red line in the satellite image represent the boundary line of water ponded with the maximum water depth (i.e., the dam height).

Appendix B. HEC-HMS model calibration resutls

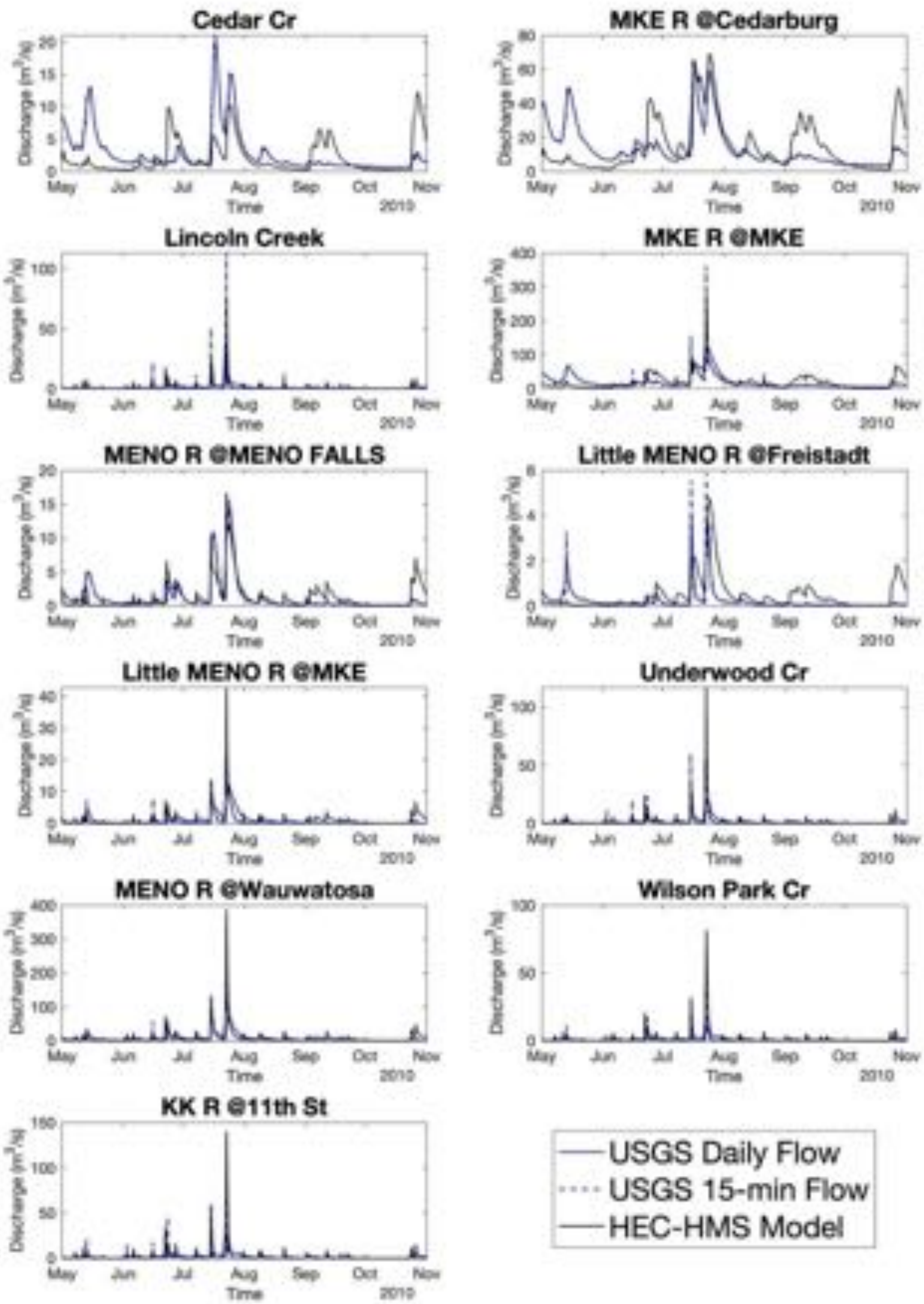


Figure B-1 Modeled hydrograph and observed discharge time series between May 1st and Nov 30th, 2010 at 11 USGS stream stations

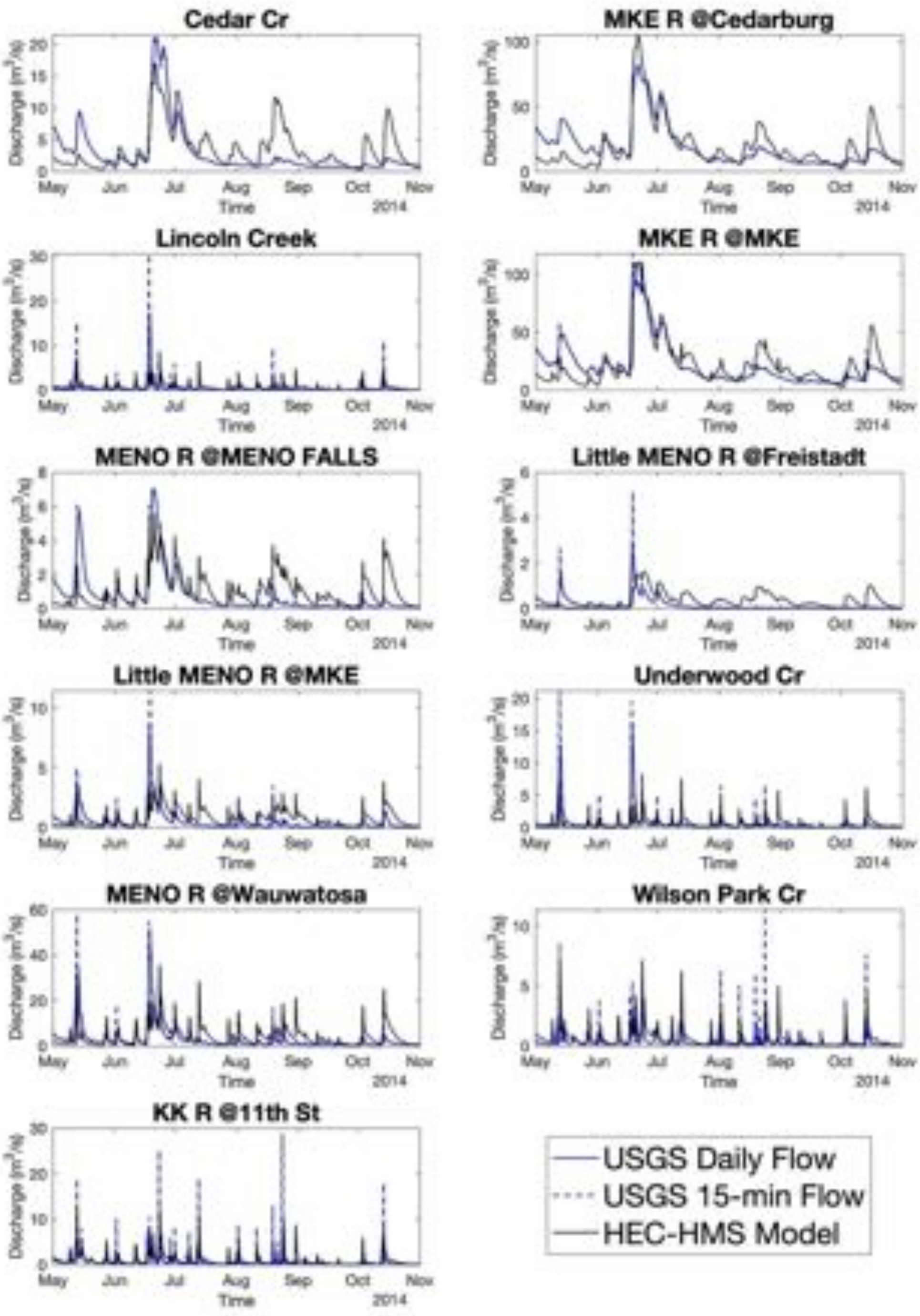


Figure B-2 Modeled hydrograph and observed discharge time series between May 1st and Nov 30th, 2014 at 11 USGS stream stations

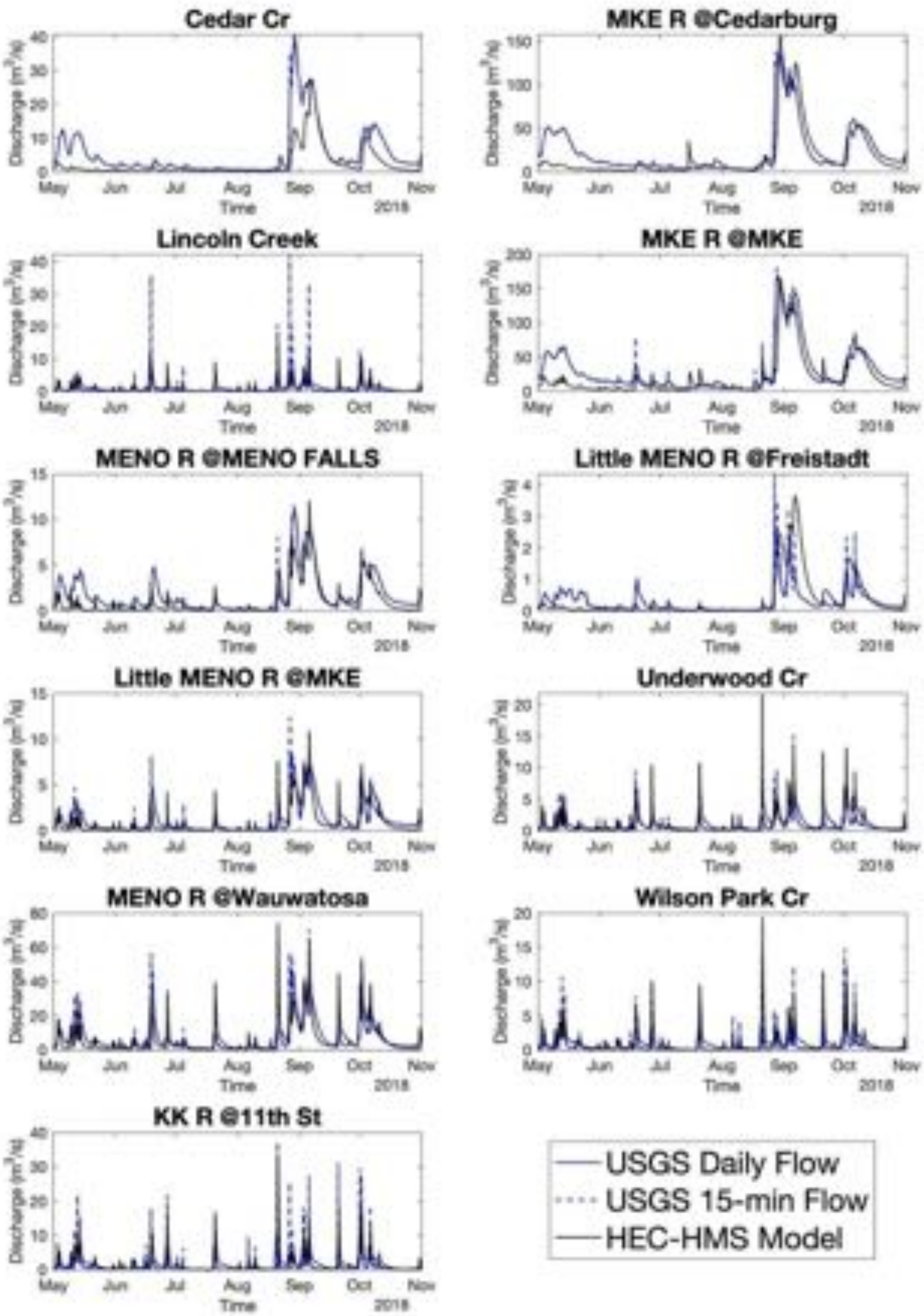


Figure B-3 Modeled hydrograph and observed discharge time series between May 1st and Nov 30th, 2018 at 11 USGS stream stations

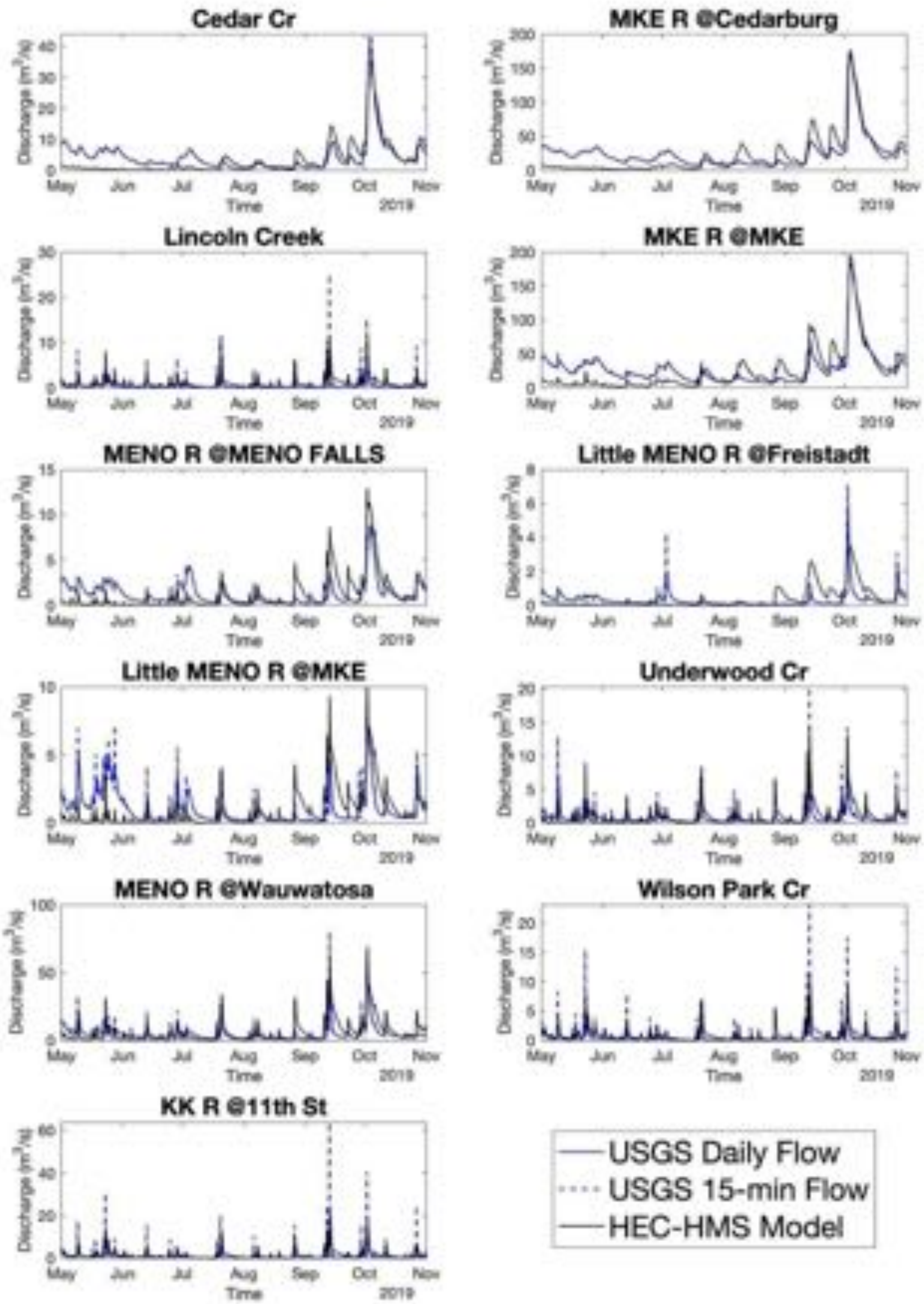


Figure B-4 Modeled hydrograph and observed discharge time series between May 1st and Nov 30th, 2019 at 11 USGS stream stations

Appendix C. Beaver impacts hydrological model results: past storms

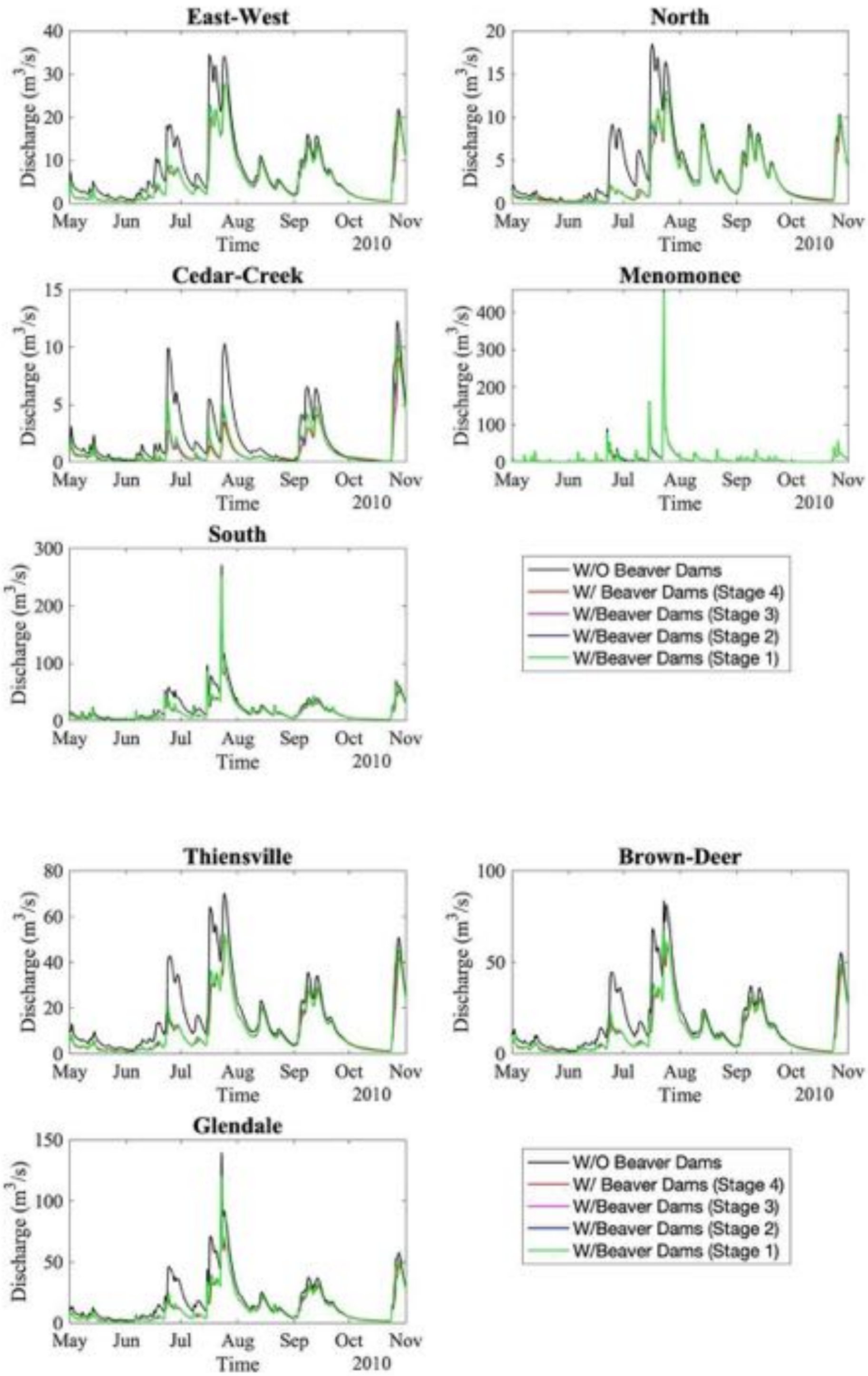


Figure C-1 Simulated hydrographs between May 1st and November 30th, 2010 at the outlets of five sub-basins and three flood zone river reaches in the South Milwaukee River sub-basin

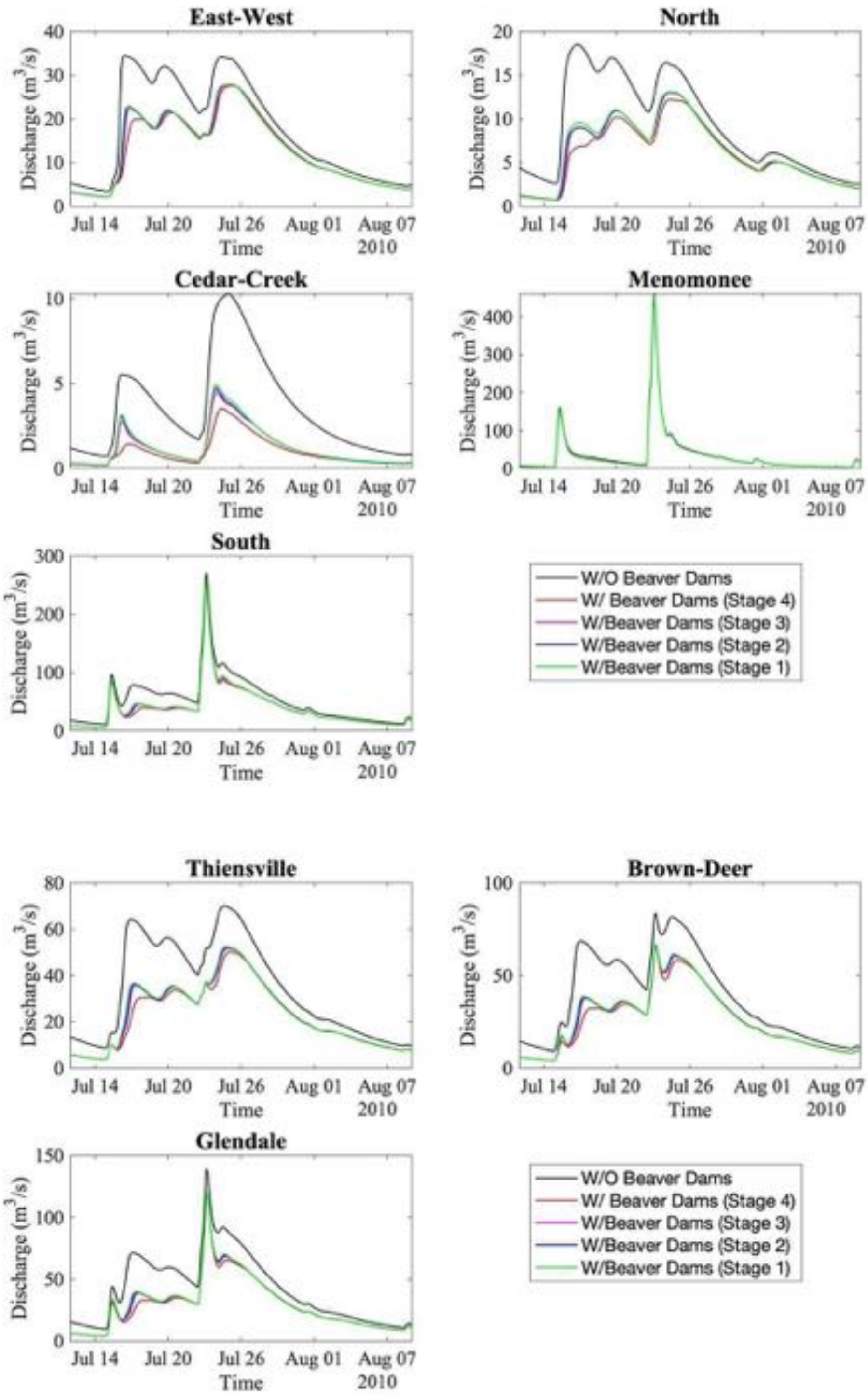


Figure C-2 Simulated hydrographs during the major storm events in 2010 (July 13th ~ August 7th) at the outlets of five sub-basins and three flood zone reaches in the South Milwaukee River sub-basin

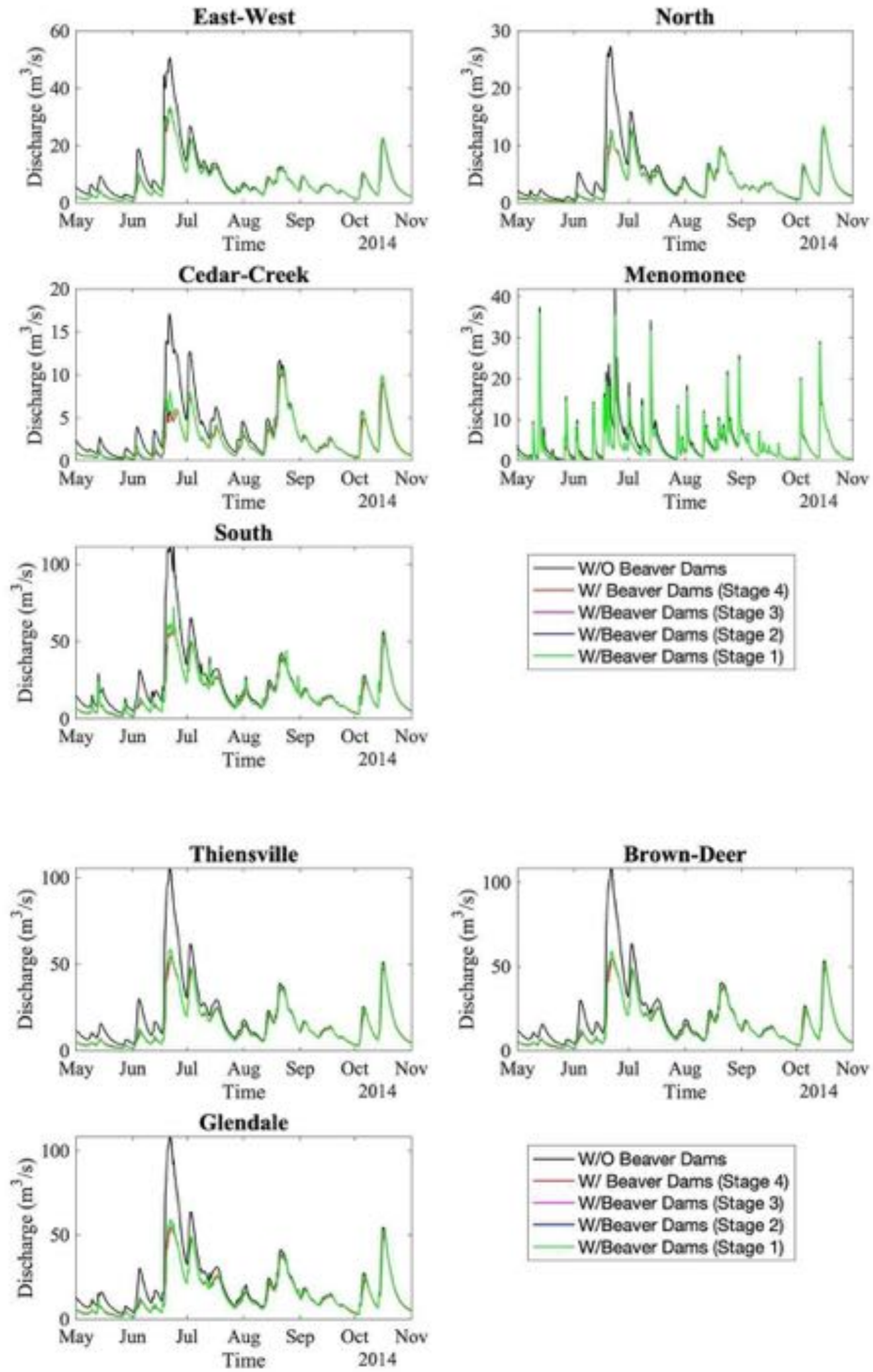


Figure C-3 Simulated hydrographs between May 1st and November 30th, 2014 at the outlets of five sub-basins and three flood zone river reaches in the South Milwaukee River sub-basin

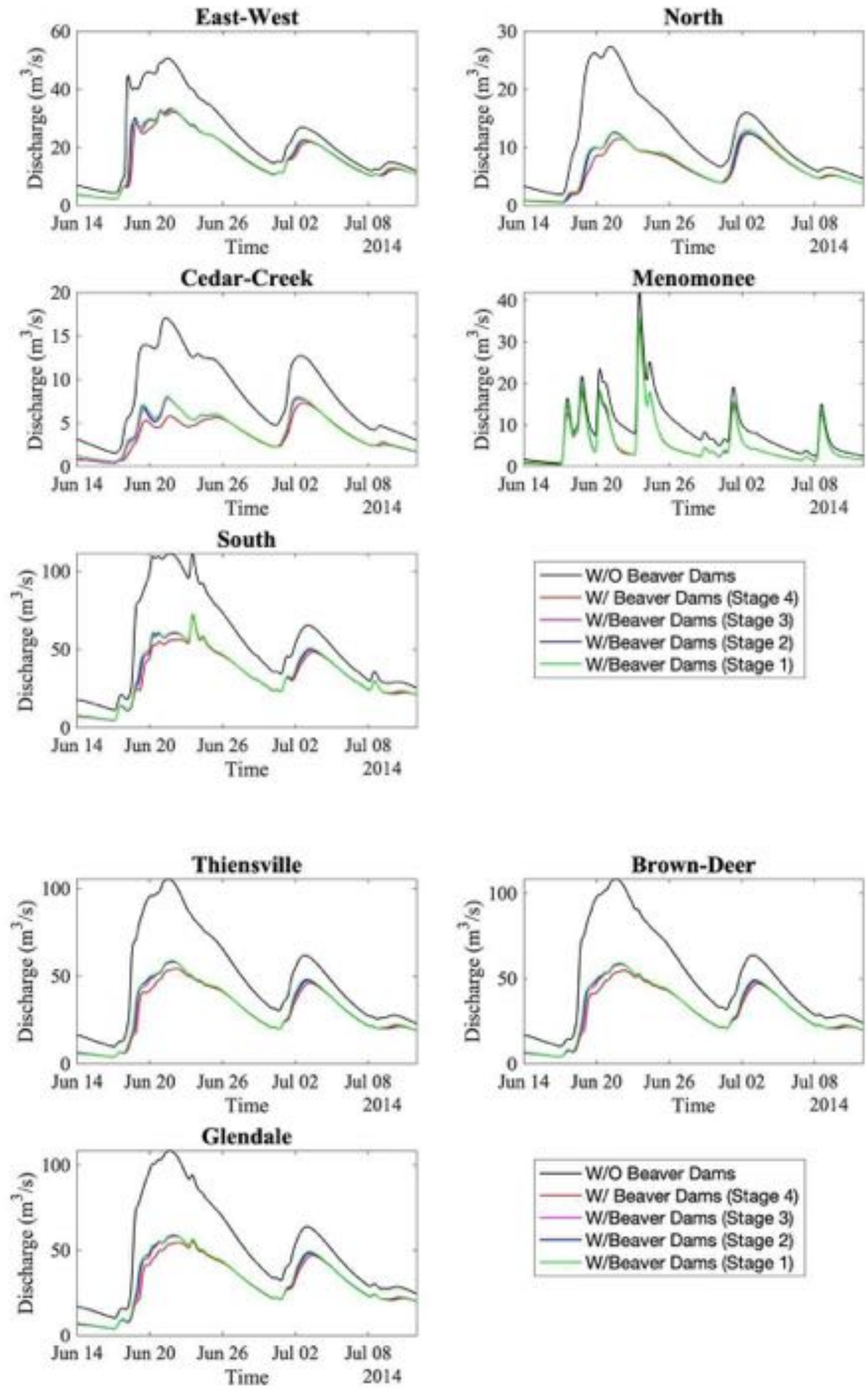


Figure C-4 Simulated hydrographs during the major storm events in 2014 (June 14th ~ July 12th) at the outlets of five sub-basins and three flood zone river reaches in the South Milwaukee River sub-basin

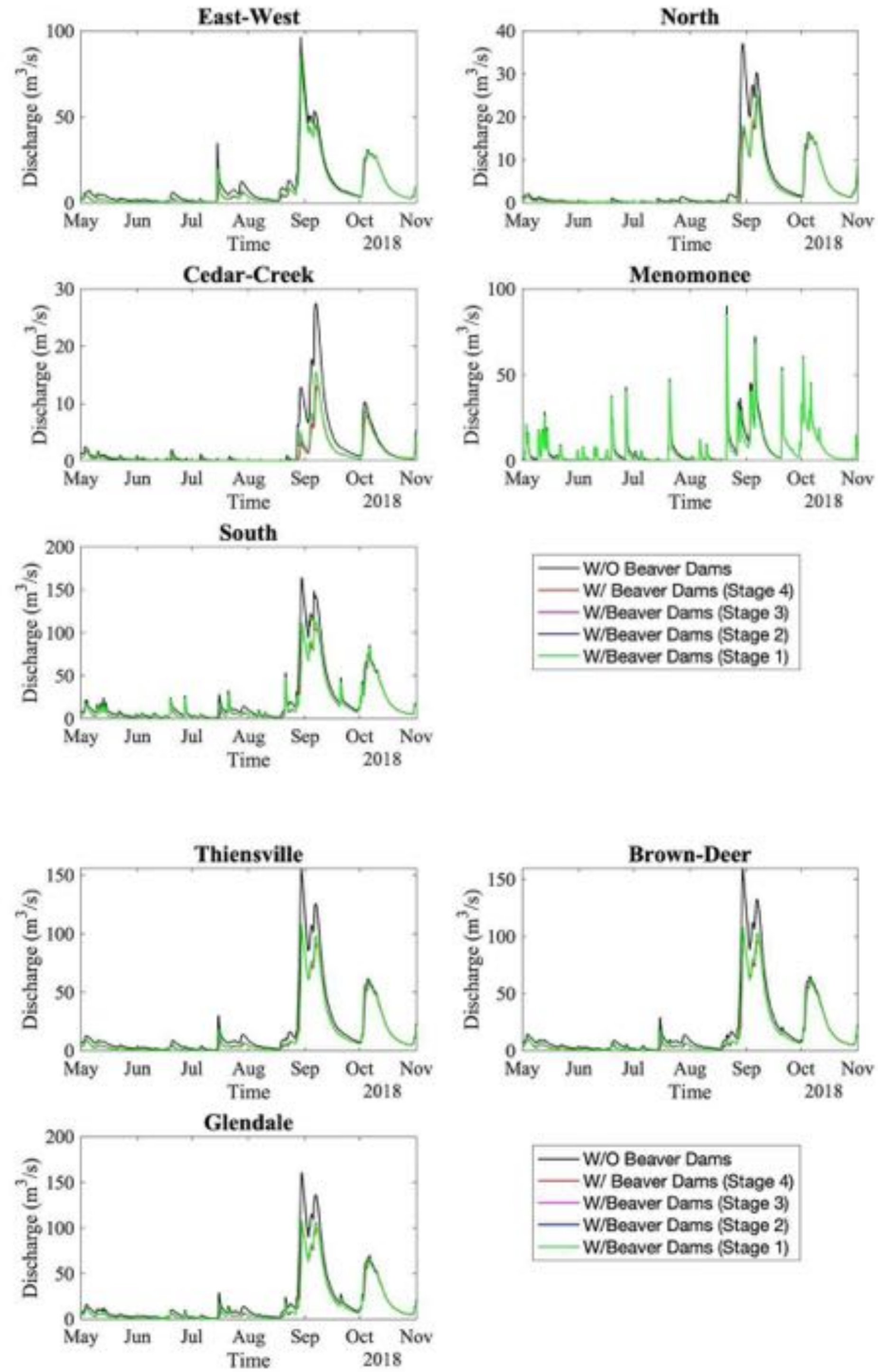


Figure C-5 Simulated hydrographs between May 1st and November 30th, 2018 at the outlets of five sub-basins and three flood zone river reaches in the South Milwaukee River sub-basin

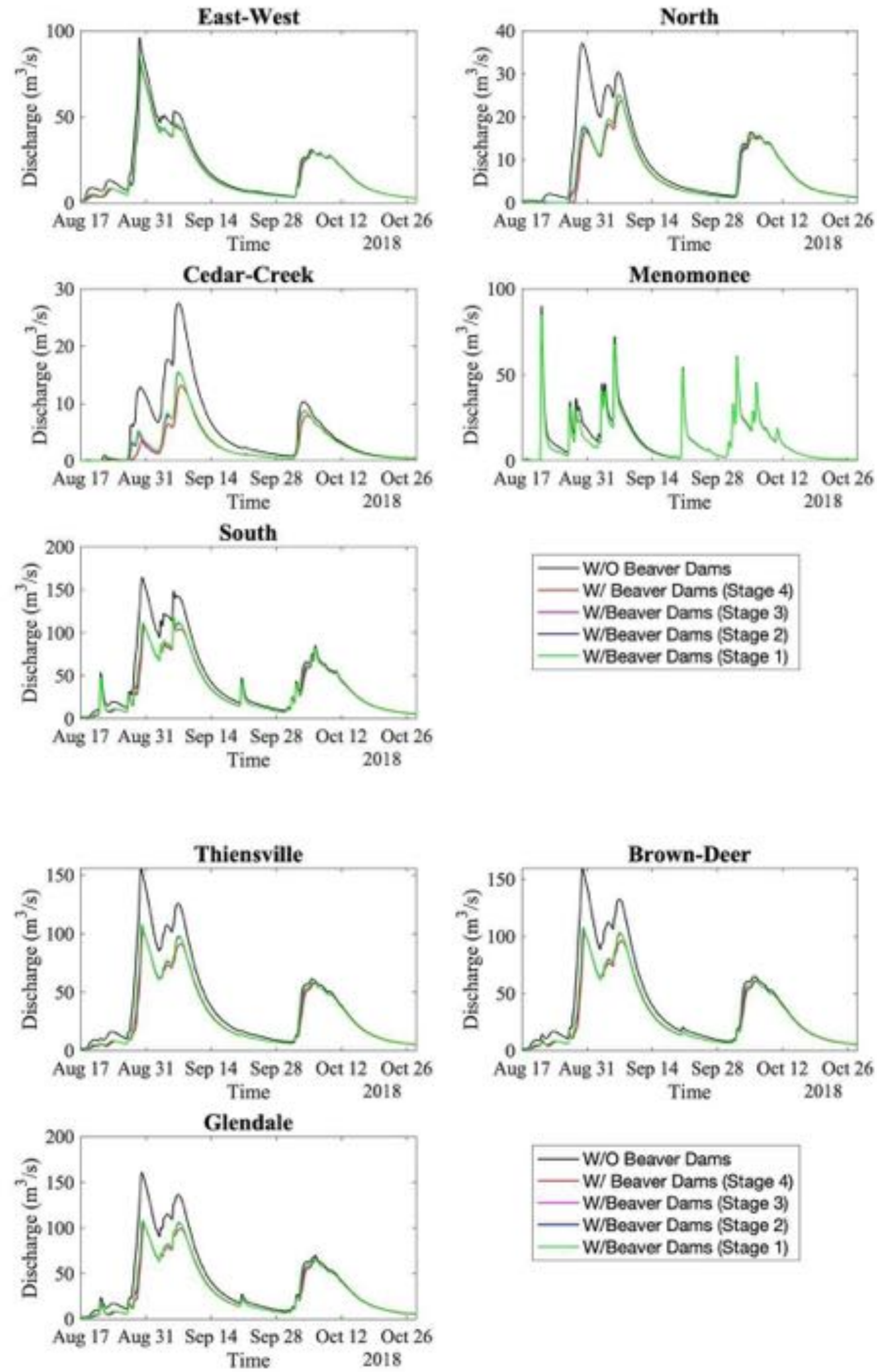


Figure C-6 Simulated hydrographs during the major storm events in 2018 (August 17th ~ October 26th) at the outlets of five sub-basins and three flood zone river reaches in the South Milwaukee River sub-basin

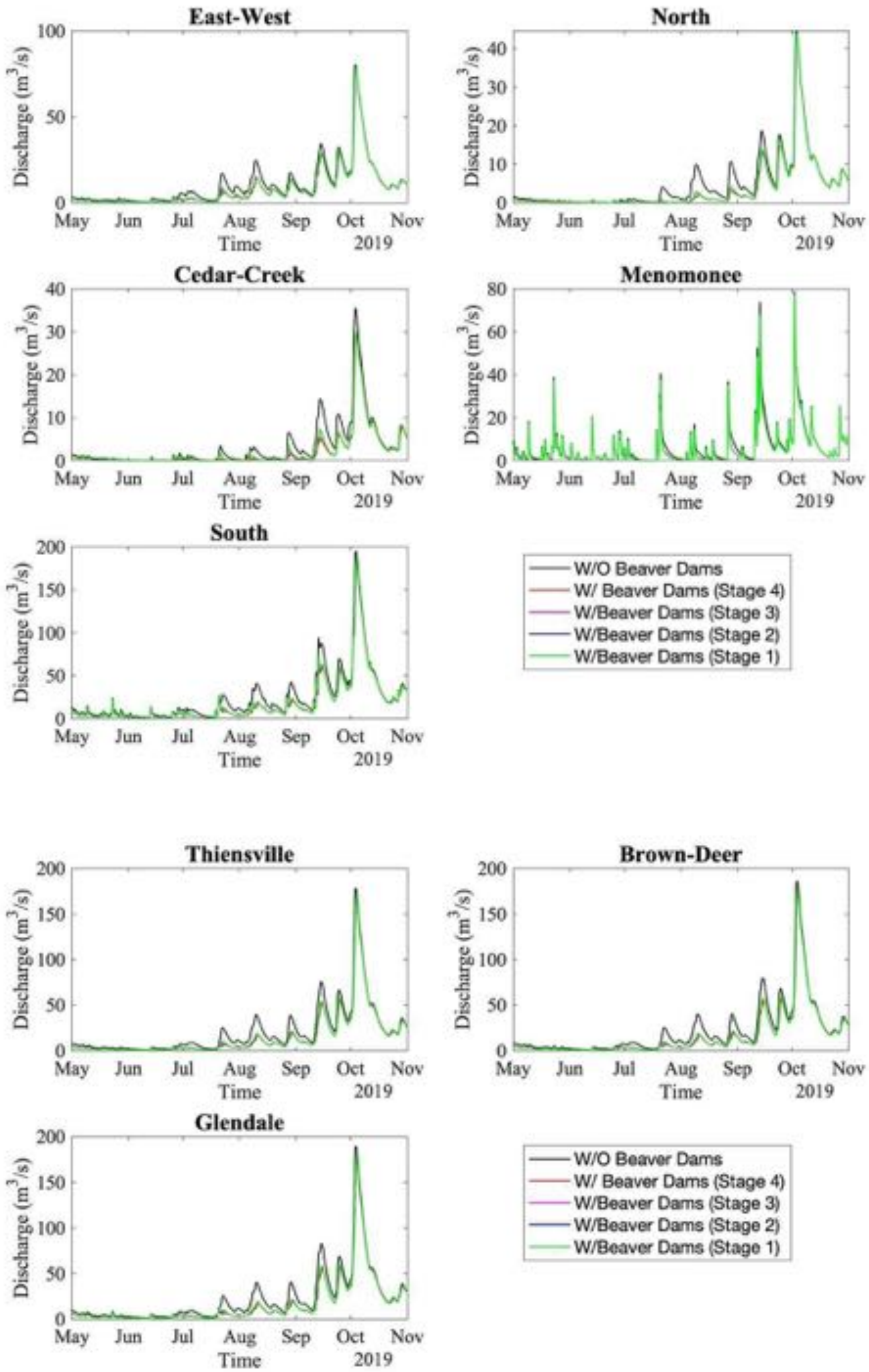


Figure C-7 Simulated hydrographs between May 1st and November 30th, 2019 at the outlets of five sub-basins and three flood zone river reaches in the South Milwaukee River sub-basin

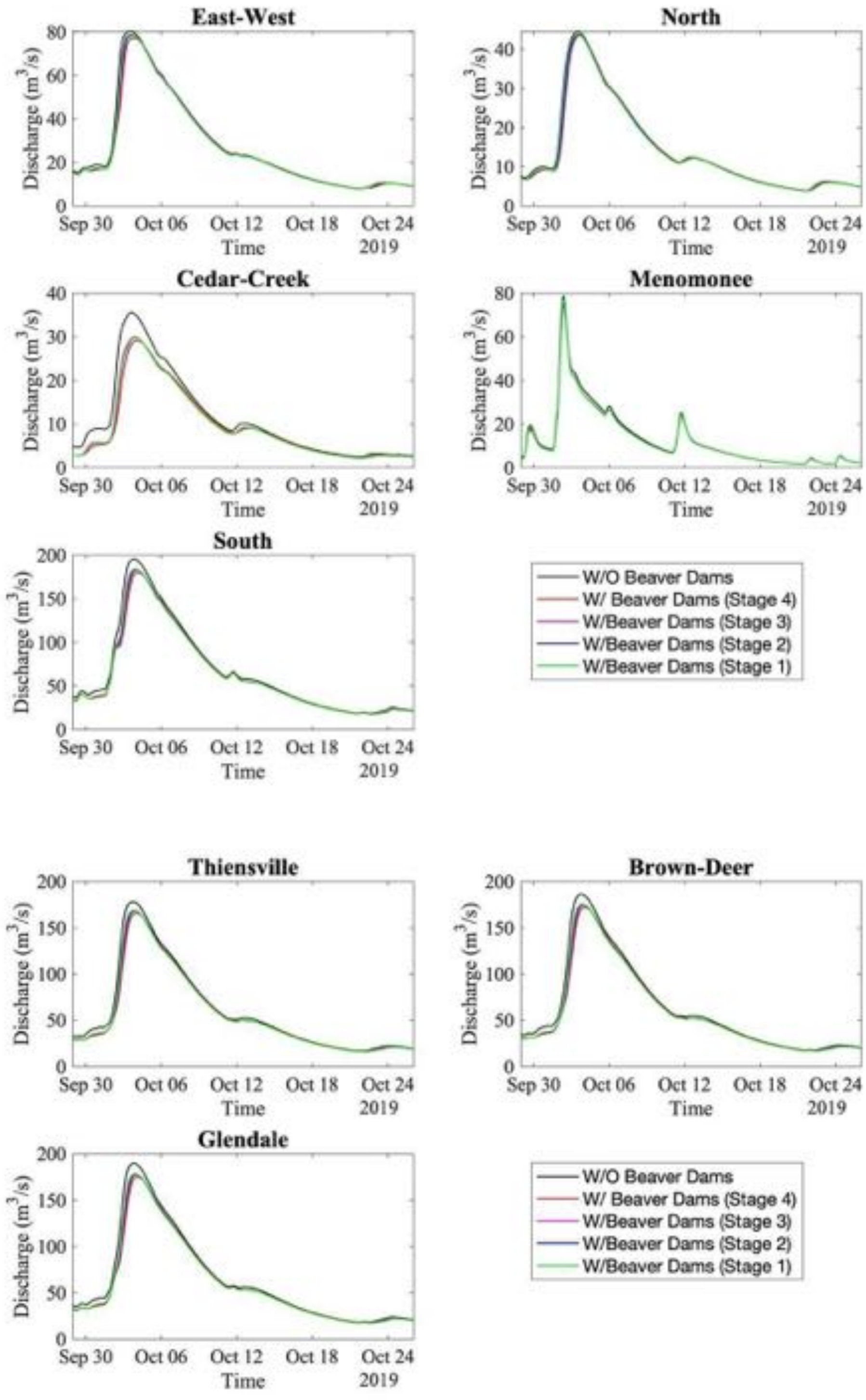
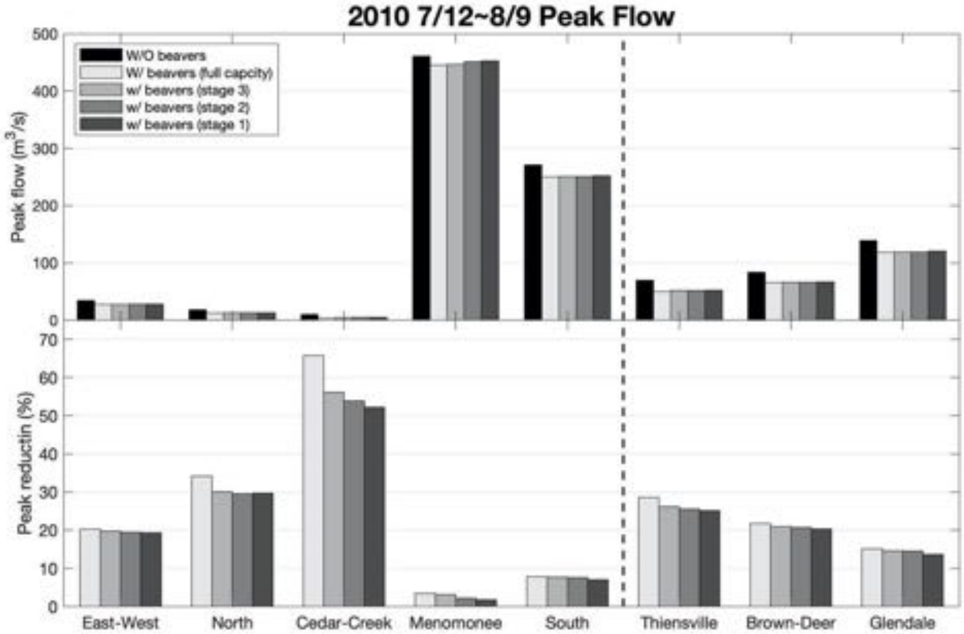


Figure C-8 Simulated hydrographs during the major storm events in 2019 (September 27th ~ October 26th) at the outlets of five sub-basins and three flood zone river reaches in the South Milwaukee River sub-basin



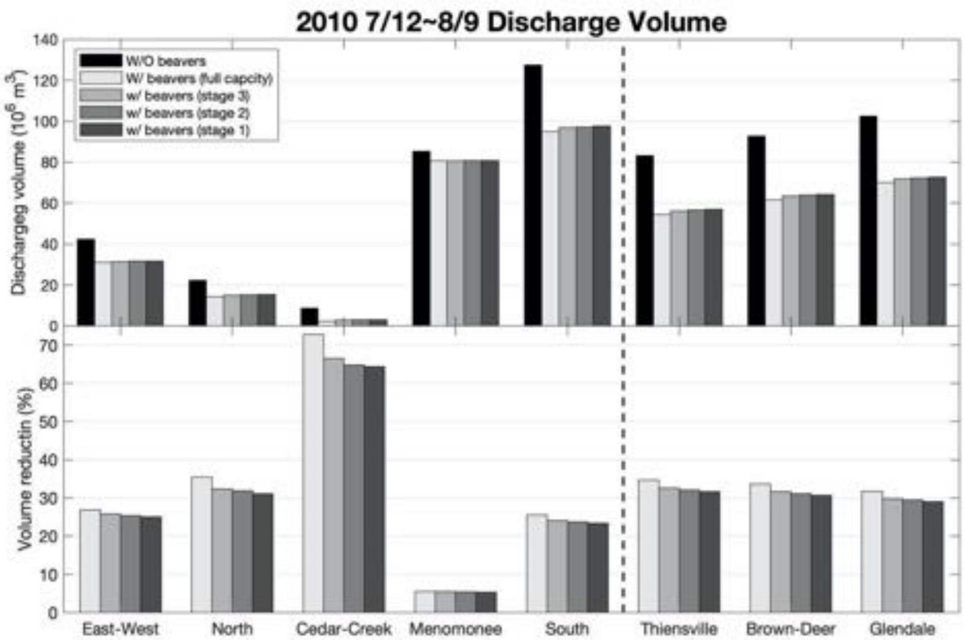
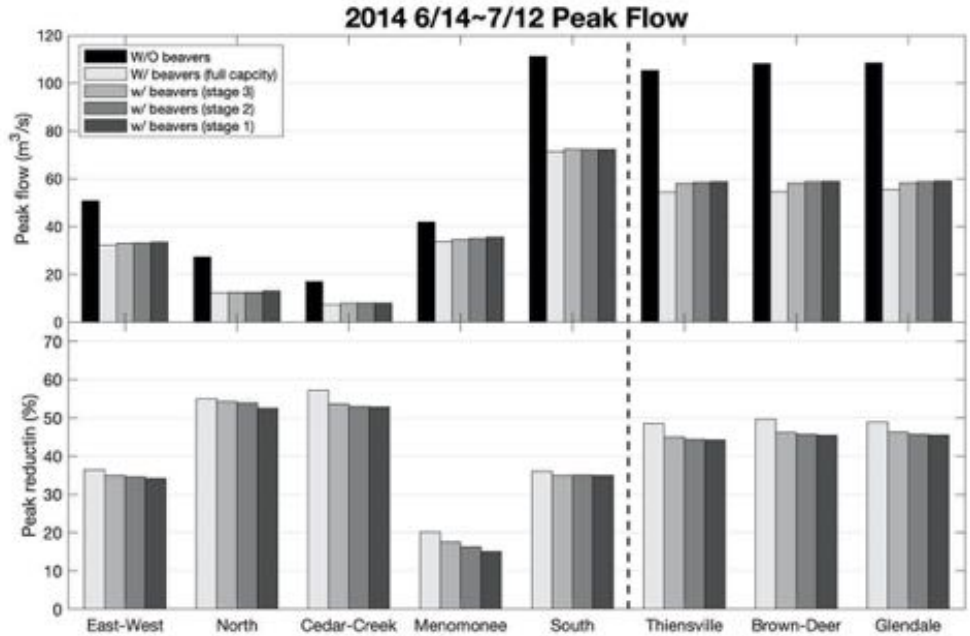


Figure C-9 Peak flow rate and discharge volume, and percentage of peak and volume reduction due to beaver dams during the major storm events in 2010, at the outlets of five sub-basins and three flood zone river reaches in the South Milwaukee River sub-basin



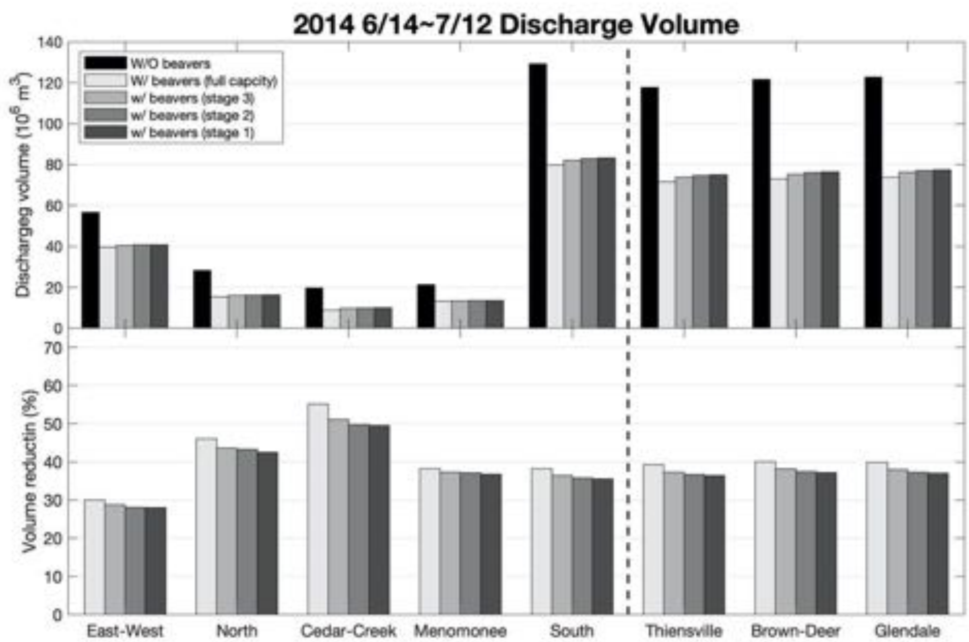
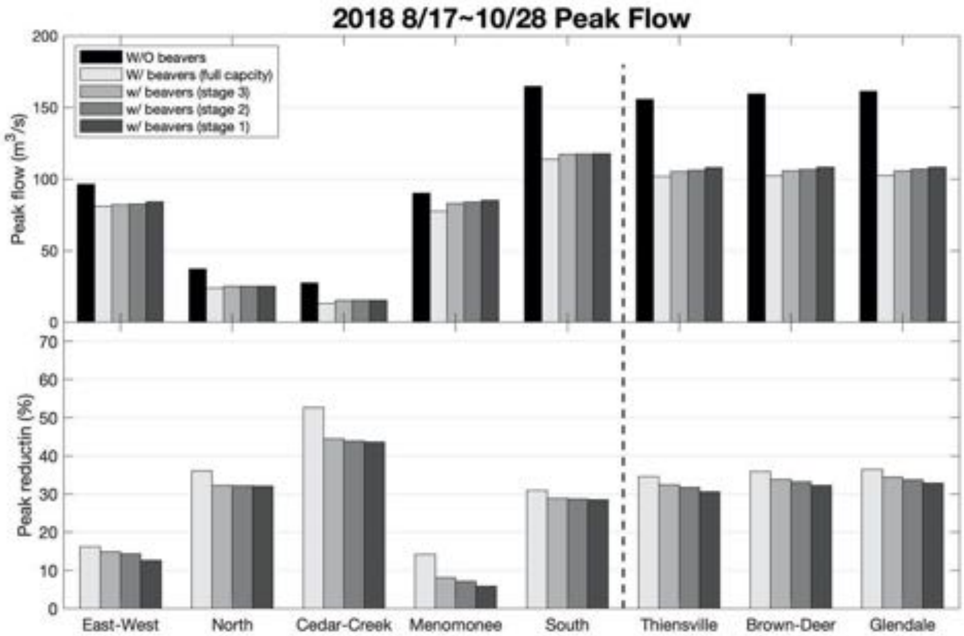


Figure C-10 Peak flow rate and discharge volume, and percentage of peak and volume reduction due to beaver dams during the major storm events in 2014, at the outlets of five sub-basins and three flood zone river reaches in the South Milwaukee River sub-basin.



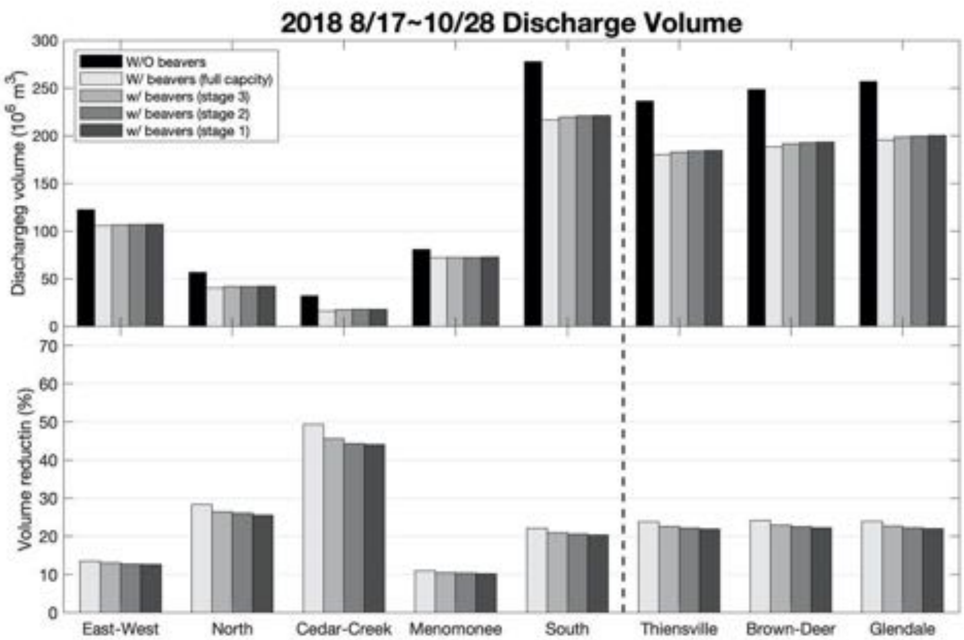


Figure C-11 Peak flow rate and discharge volume, and percentage of peak and volume reduction due to beaver dams during the major storm events in 2018, at the outlets of five sub-basins and three flood zone river reaches in the South Milwaukee River sub-basin

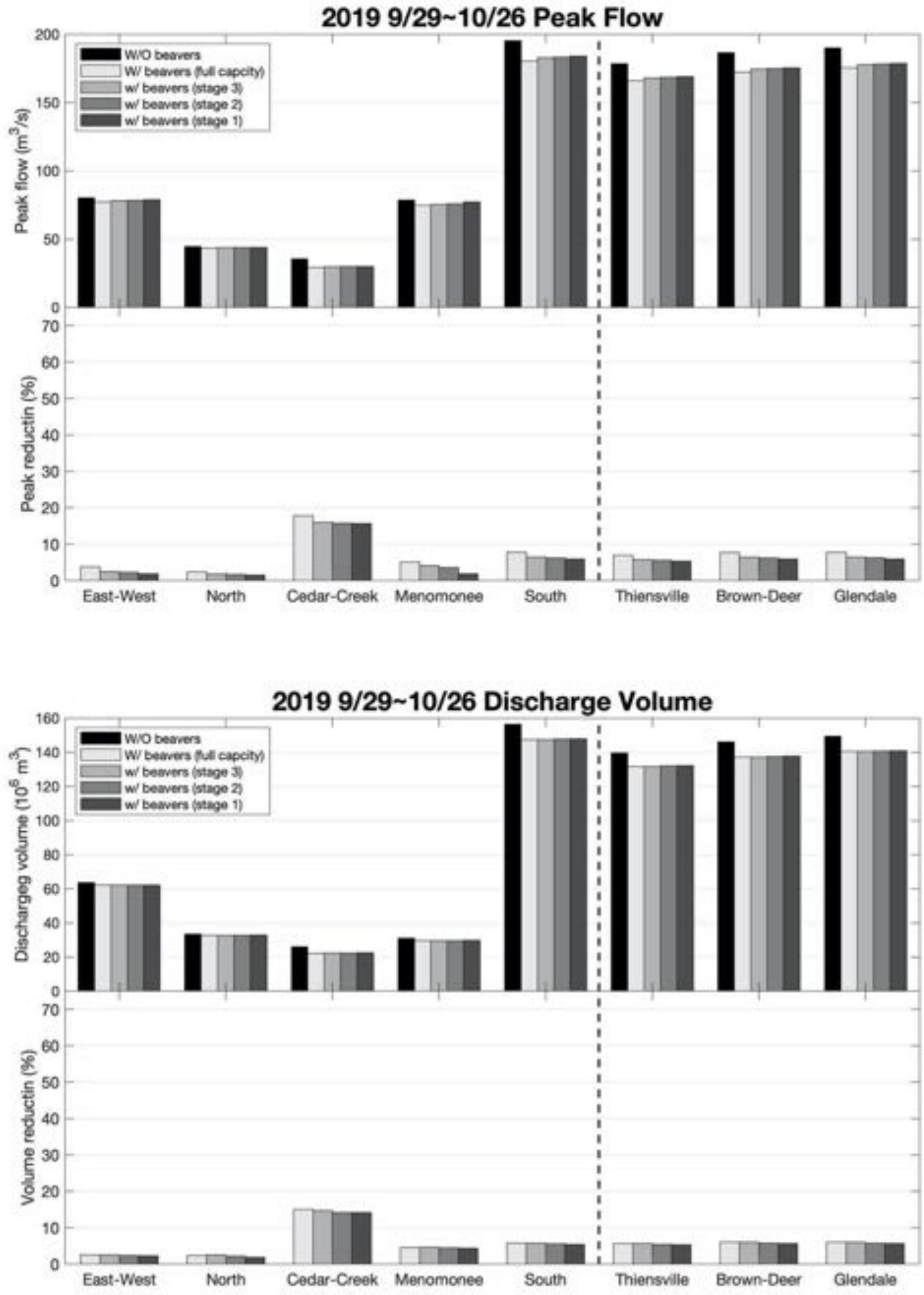


Figure C-12 Peak flow rate and discharge volume, and percentage of peak and volume reduction due to beaver dams during the major storm events in 2019, at the outlets of five sub-basins and three flood zone river reaches in the South Milwaukee River sub-basin

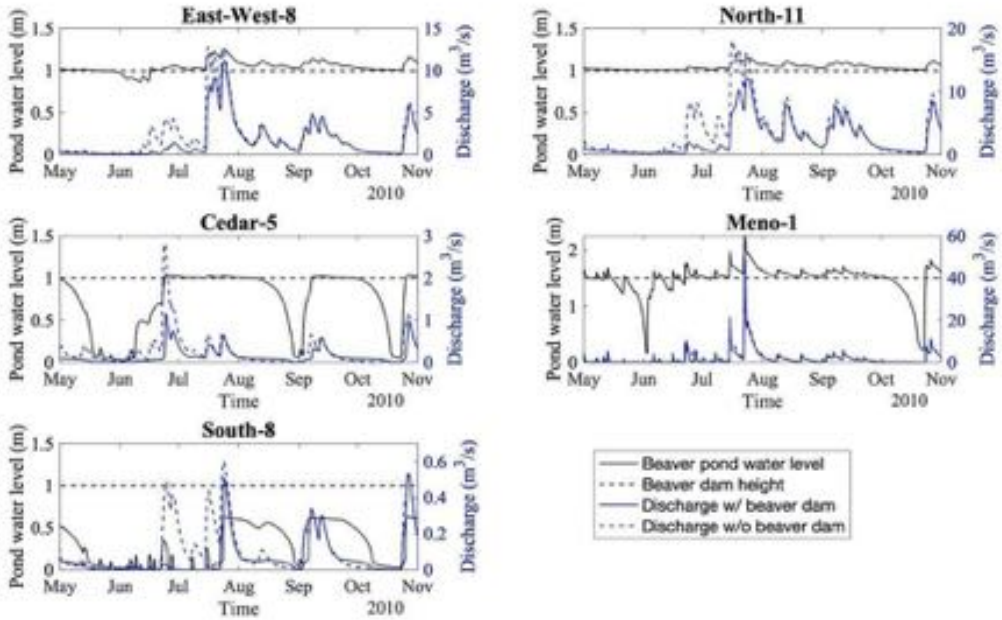


Figure C-13 Pond water level variation and hydrograph with or without beaver dams (stage 4) between May 1st and Nov 30th, 2010 at five selected beaver dam locations

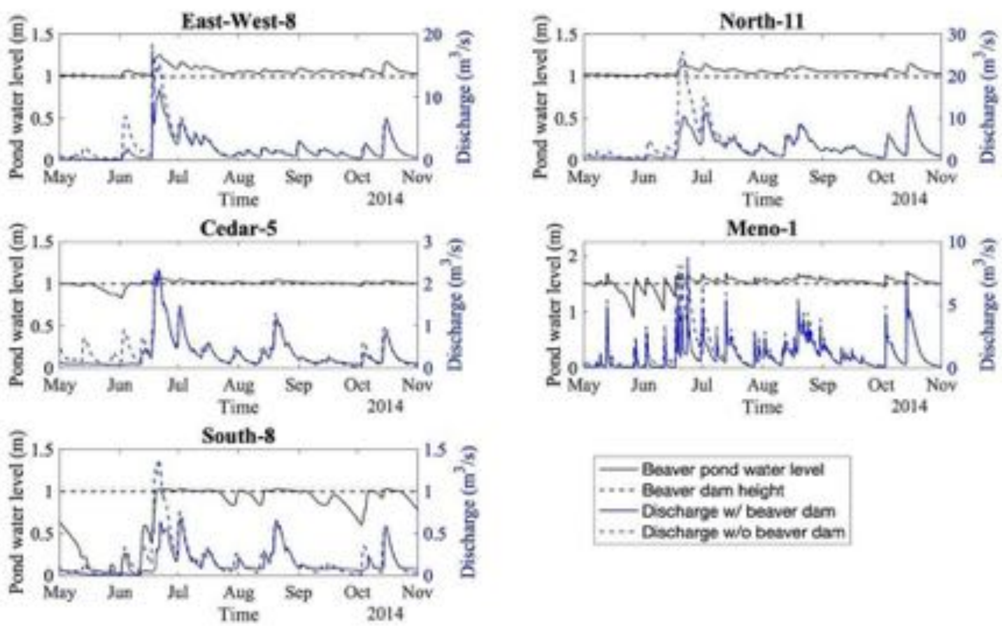


Figure C-14 Pond water level variation and hydrograph with or without beaver dams (stage 4) between May 1st and Nov 30th, 2014 at five selected beaver dam locations

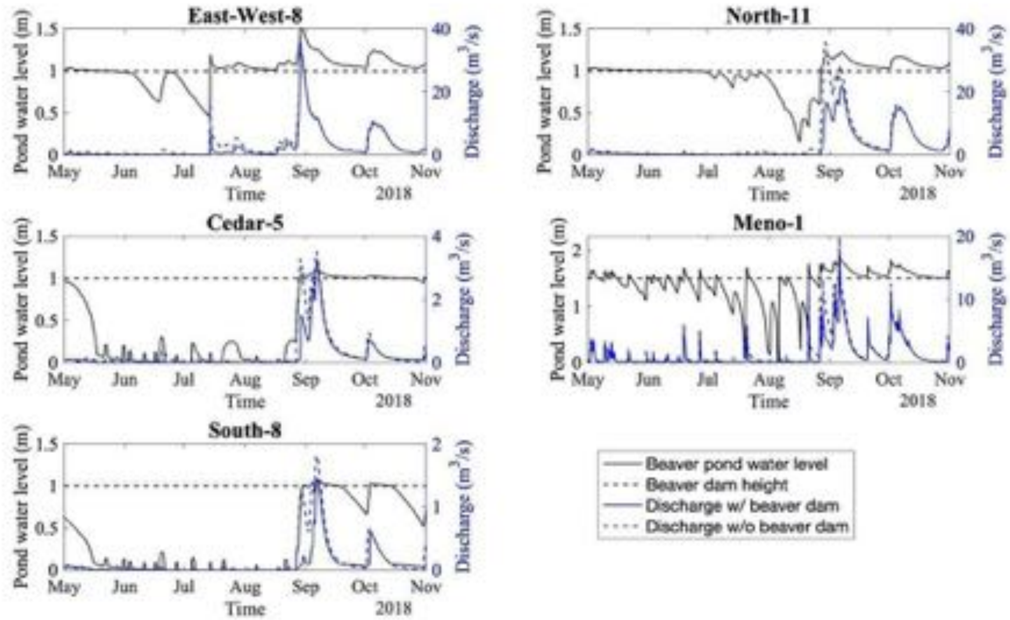


Figure C-15 Pond water level variation and hydrograph with or without beaver dams (stage 4) between May 1st and Nov 30th, 2018 at five selected beaver dam locations

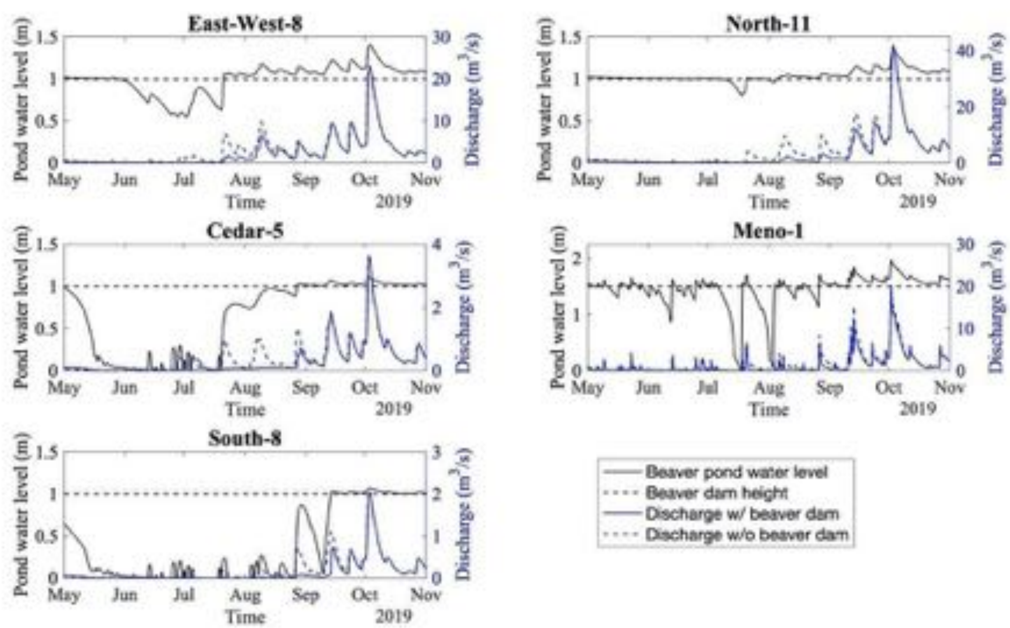


Figure C-16 Pond water level variation and hydrograph with or without beaver dams (stage 4) between May 1st and Nov 30th, 2019 at five selected beaver dam locations

Appendix D. Beaver imapcts hydrological model results: synthetic frequenc storms

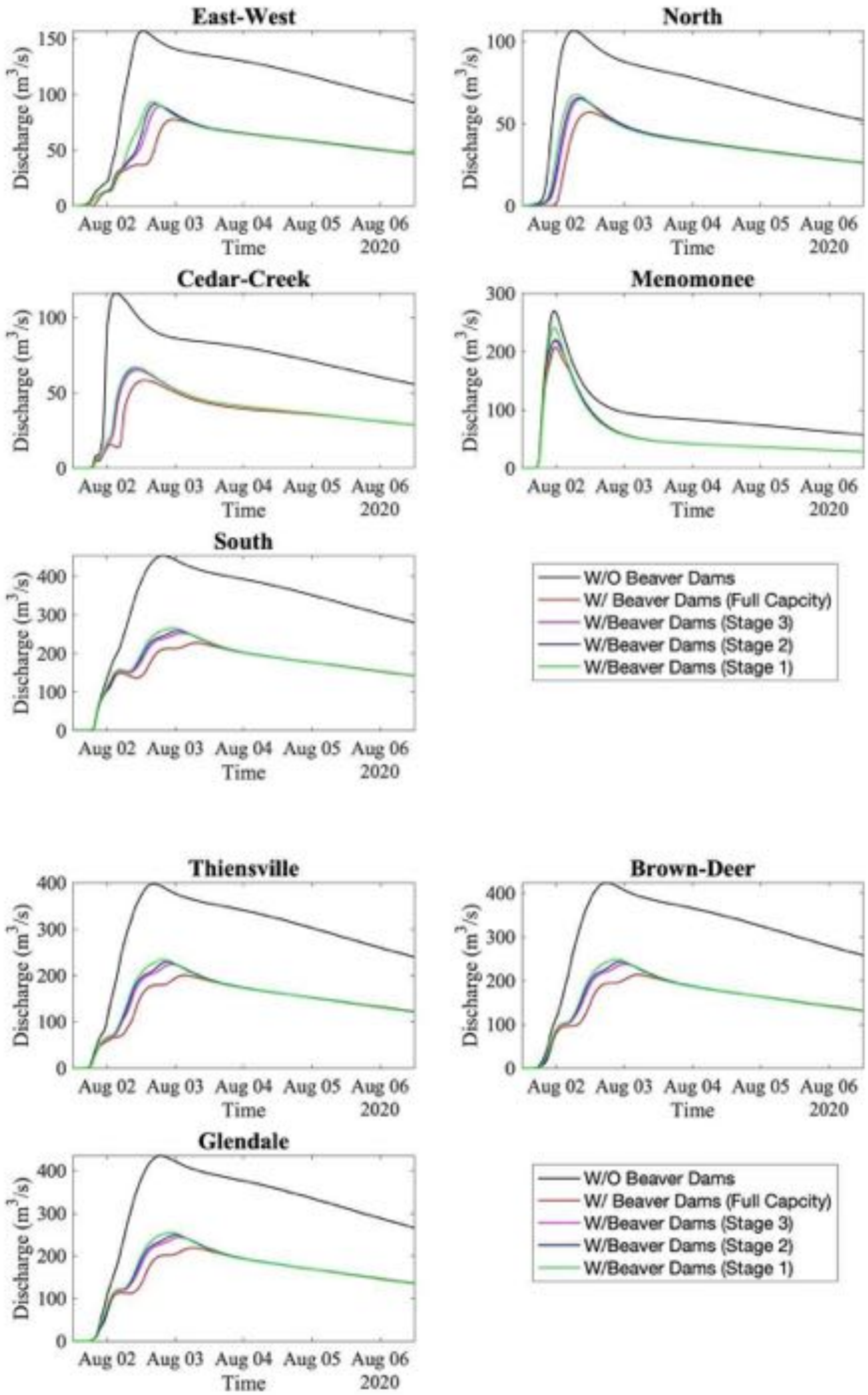


Figure D-1 Simulated hydrographs at the outlets of five sub-basins and three flood zone river reaches in the South Milwaukee River sub-basin in response to a 10-year 6-hour synthetic storm

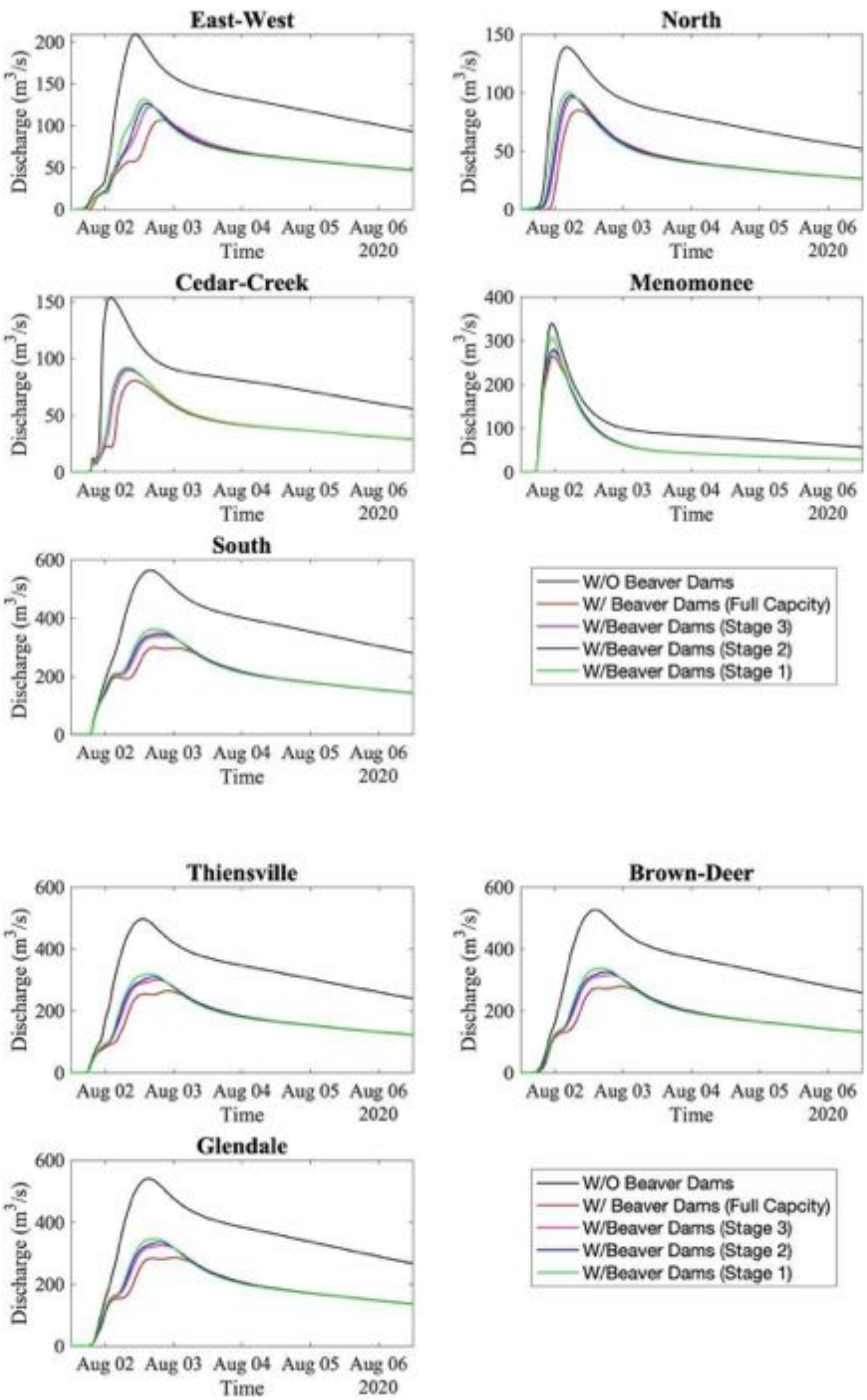


Figure D-2 Simulated hydrographs at the outlets of five sub-basins and three flood zone river reaches in the South Milwaukee River sub-basin in response to a 25-year 6-hour synthetic storm

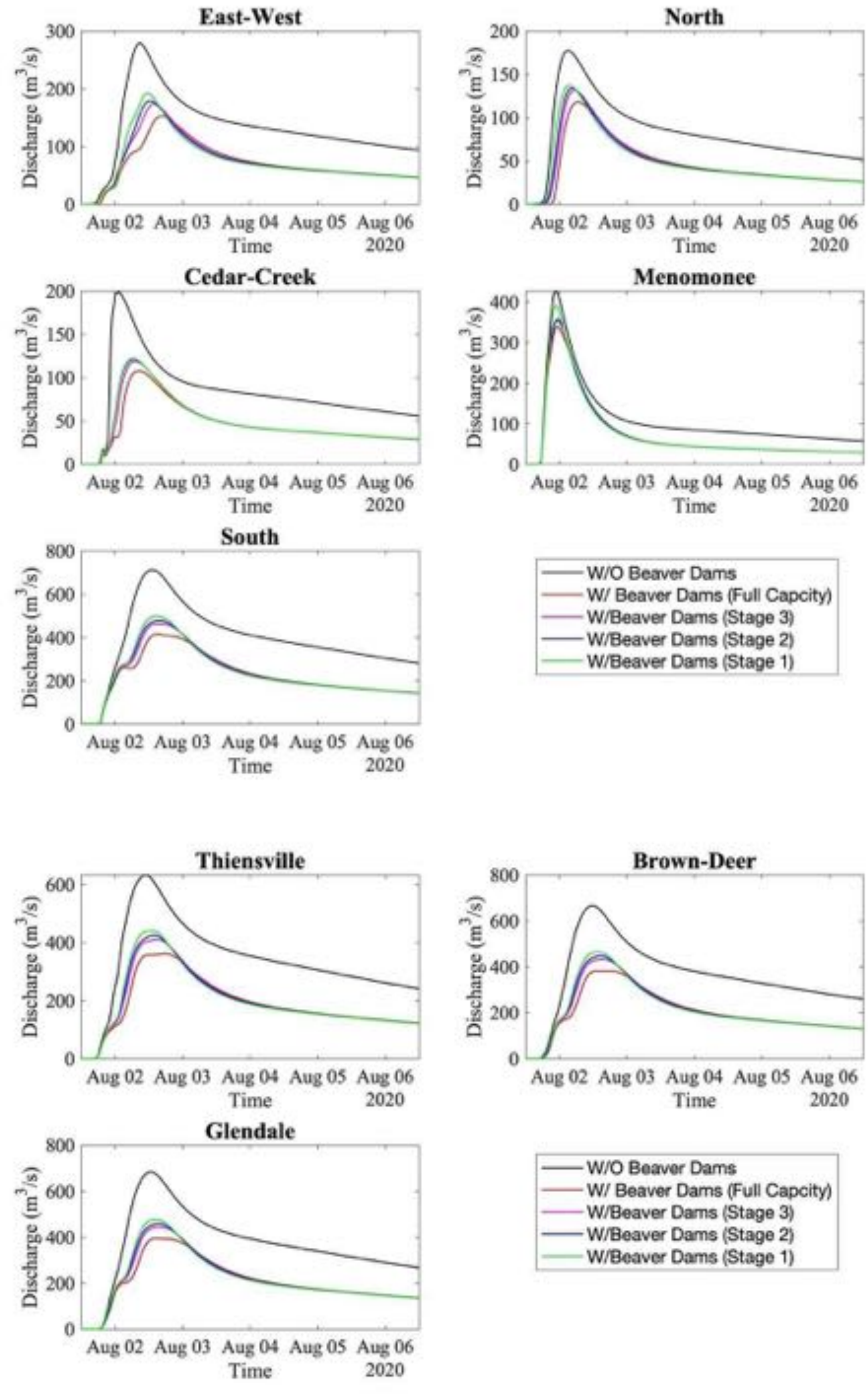


Figure D-3 Simulated hydrographs at the outlets of five sub-basins and three flood zone river reaches in the South Milwaukee River sub-basin in response to a 50-year 6-hour synthetic storm

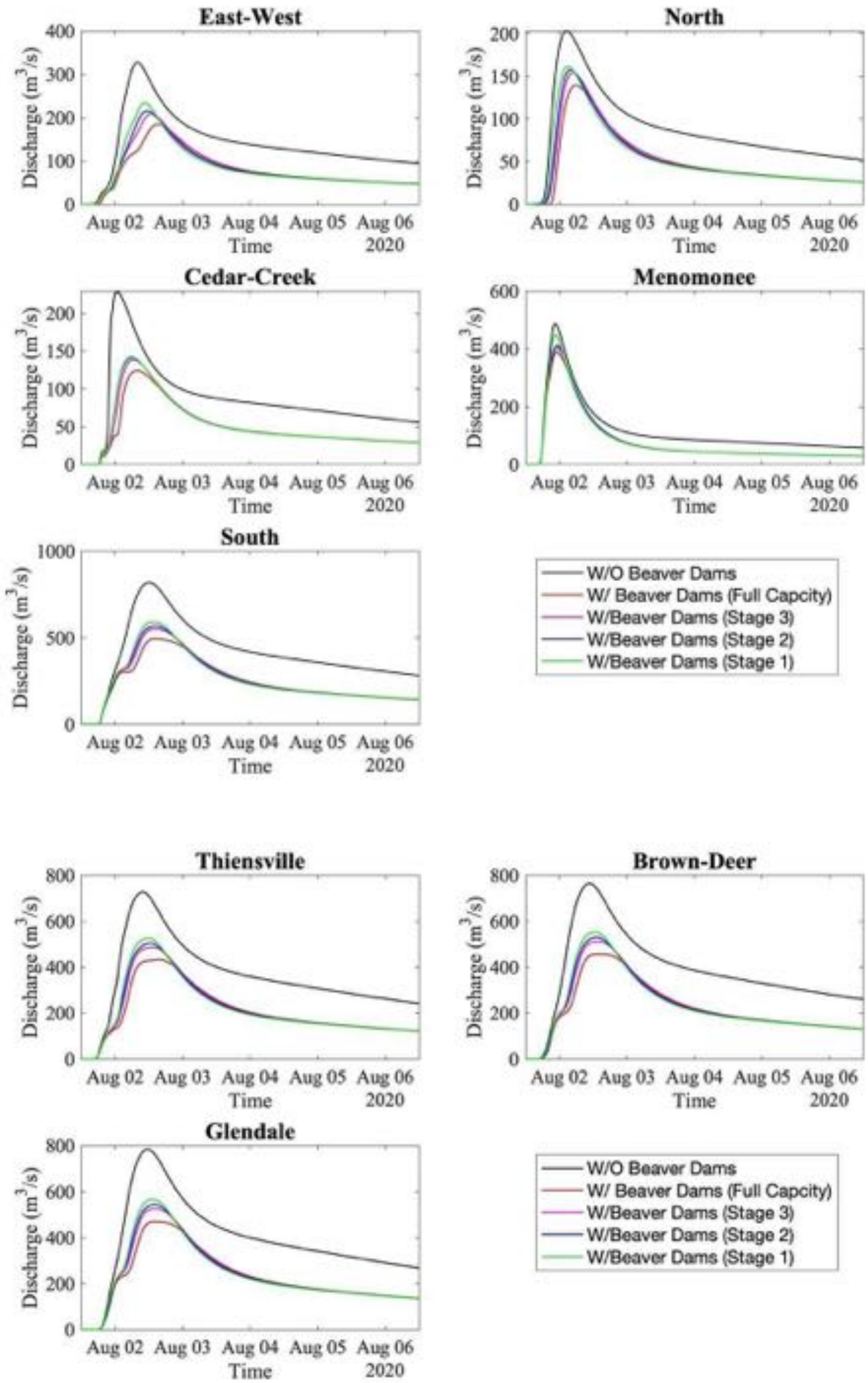


Figure D-4 Simulated hydrographs at the outlets of five sub-basins and three flood zone river reaches in the South Milwaukee River sub-basin in response to a 100-year 6-hour synthetic storm

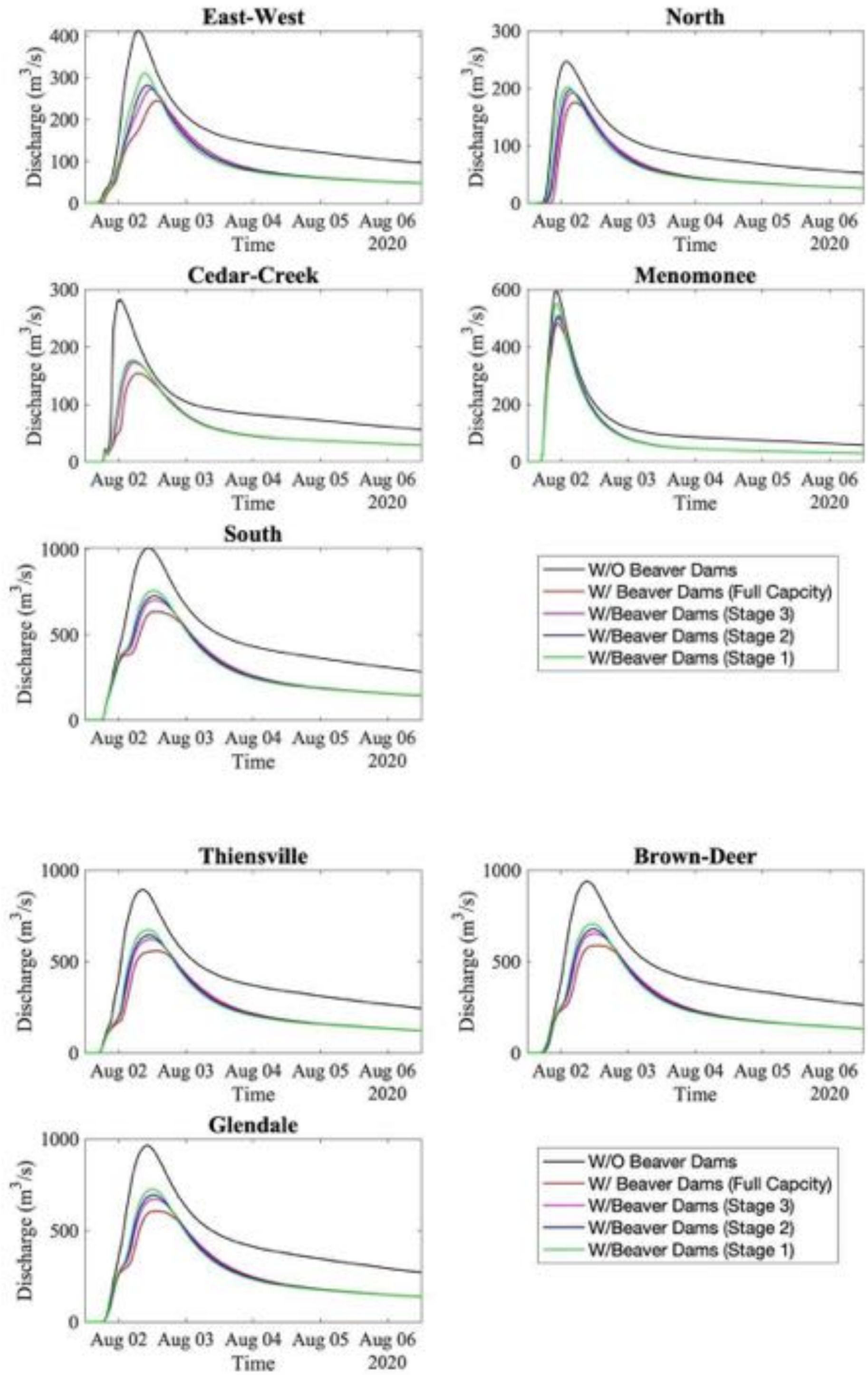


Figure D-5 Simulated hydrographs at the outlets of five sub-basins and three flood zone river reaches in the South Milwaukee River sub-basin in response to a 200-year 6-hour synthetic storm

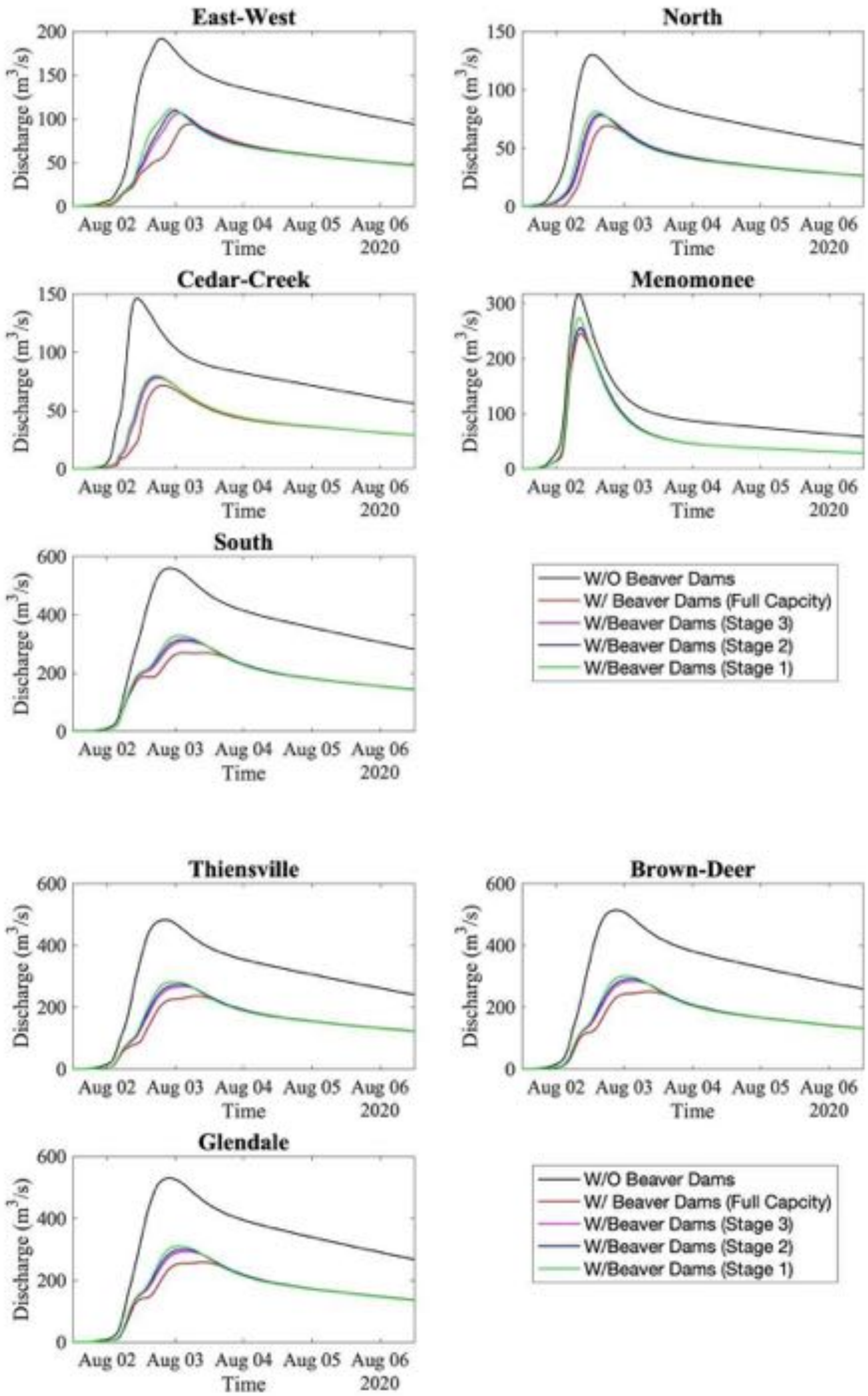


Figure D-6 Simulated hydrographs at the outlets of five sub-basins and three flood zone river reaches in the South Milwaukee River sub-basin in response to a 10-year 24-hour synthetic storm

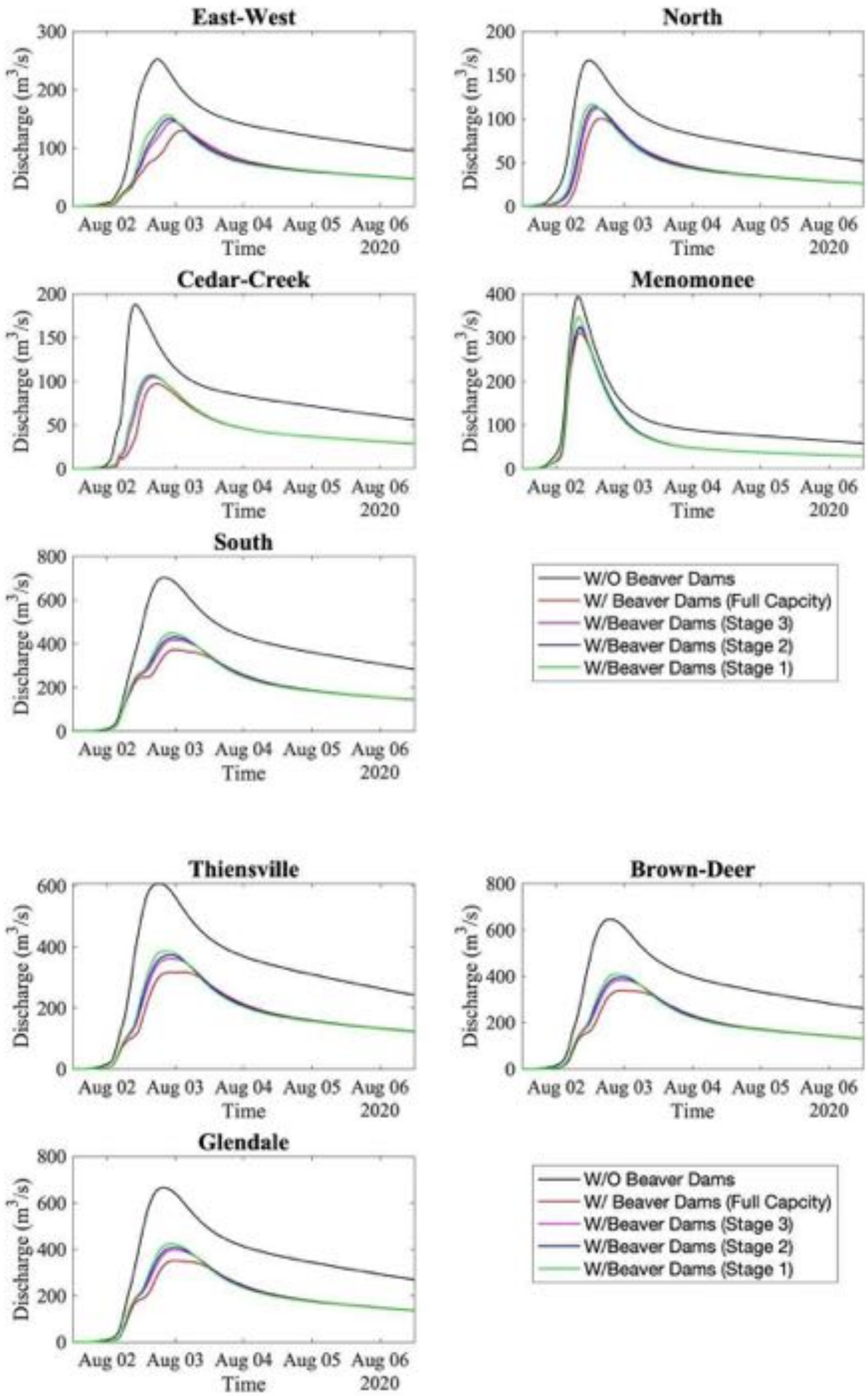


Figure D-7 Simulated hydrographs at the outlets of five sub-basins and three flood zone river reaches in the South Milwaukee River sub-basin in response to a 25-year 24-hour synthetic storm

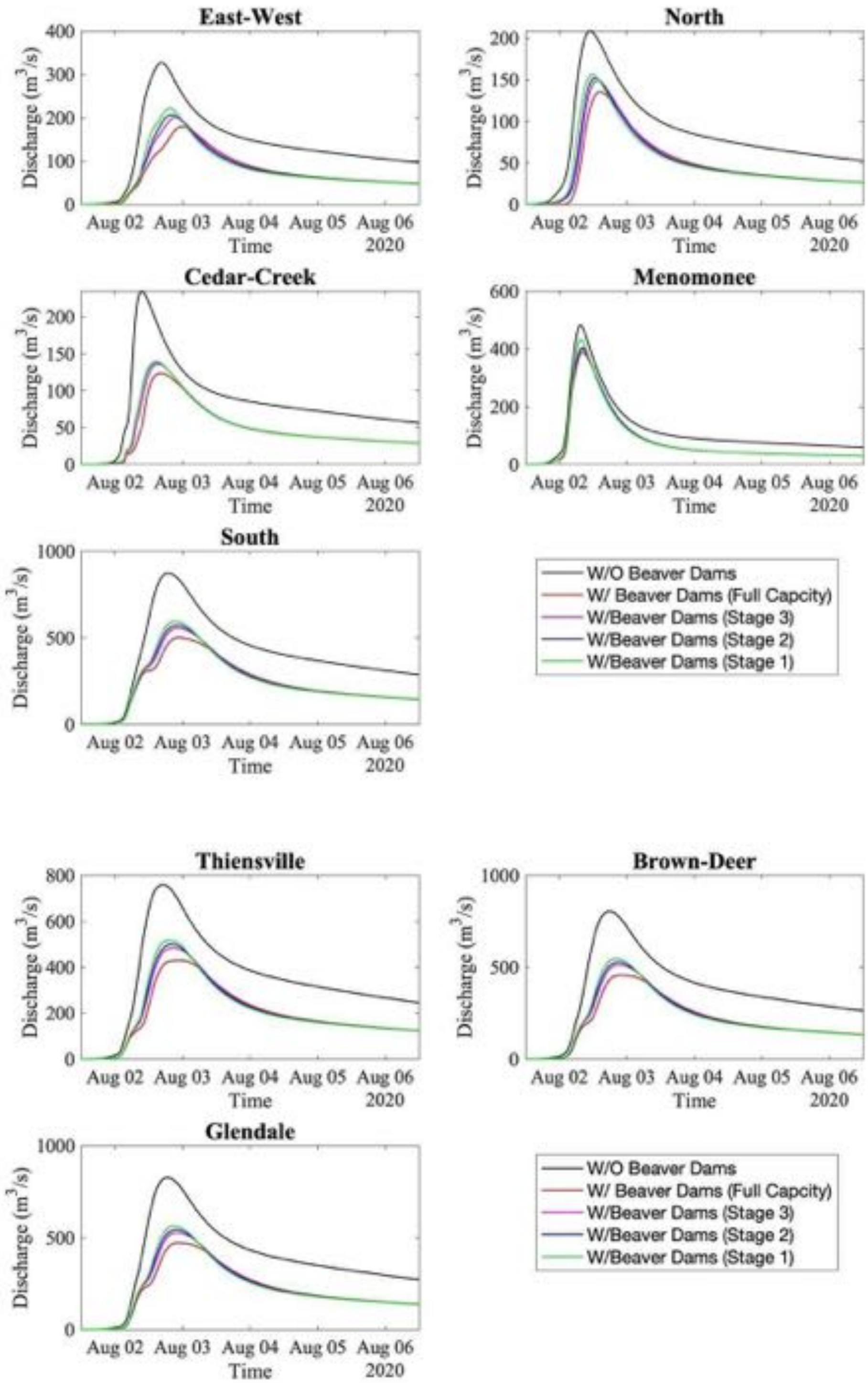


Figure D-8 Simulated hydrographs at the outlets of five sub-basins and three flood zone river reaches in the South Milwaukee River sub-basin in response to a 50-year 24-hour synthetic storm

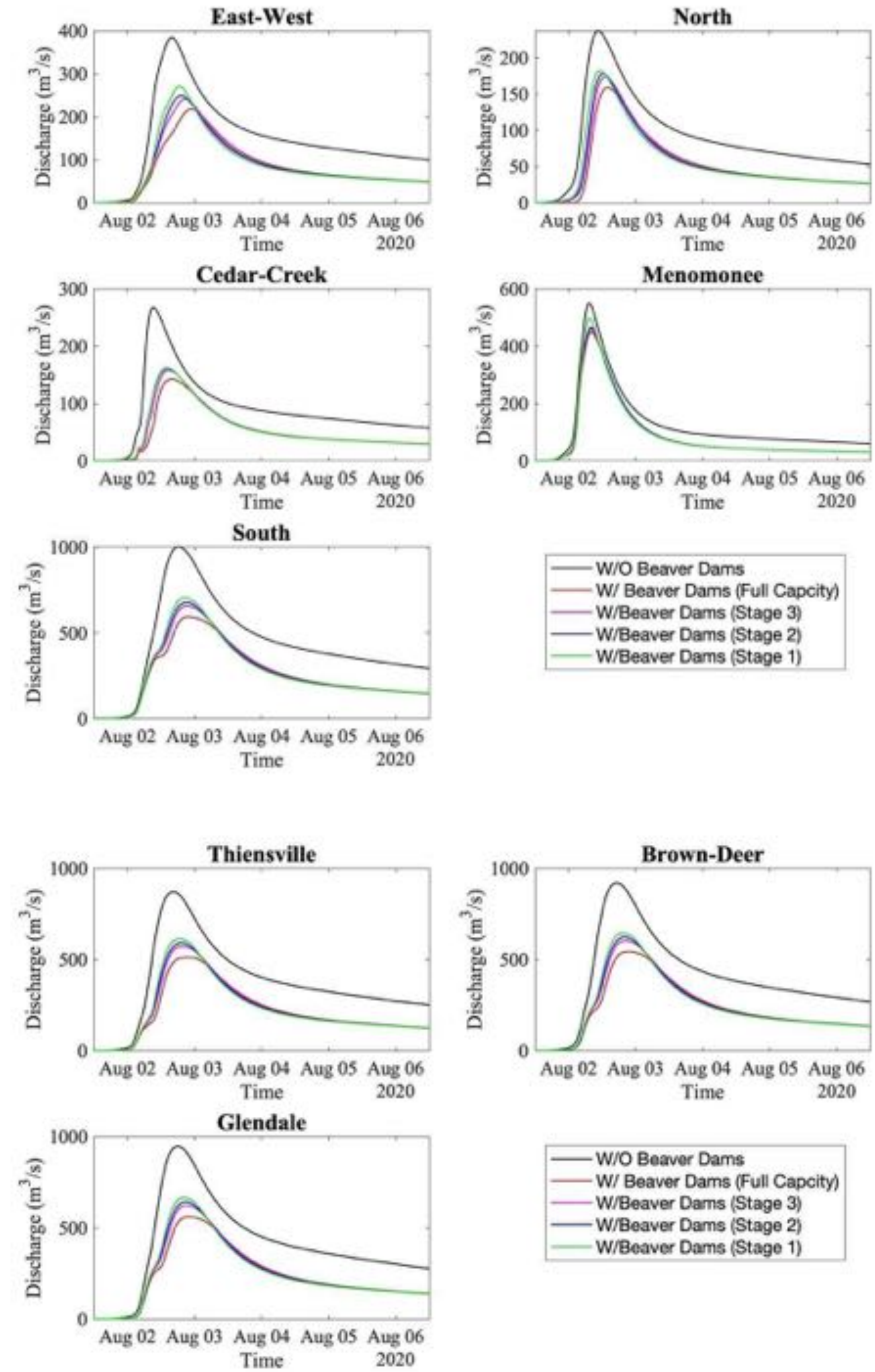


Figure D-9 Simulated hydrographs at the outlets of five sub-basins and three flood zone river reaches in the South Milwaukee River sub-basin in response to a 100-year 24-hour synthetic storm

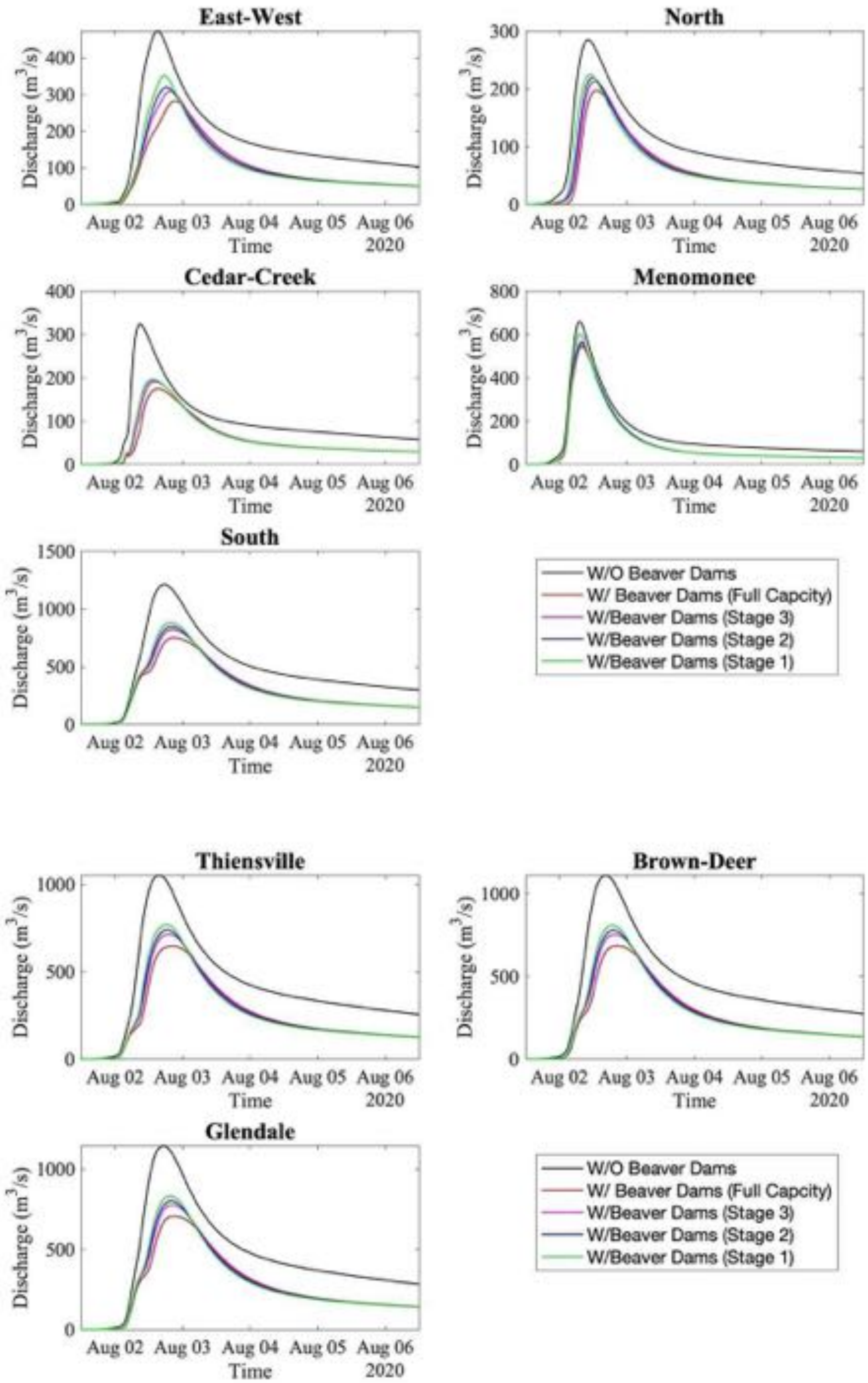


Figure D-10 Simulated hydrographs at the outlets of five sub-basins and three flood zone river reaches in the South Milwaukee River sub-basin in response to a 200-year 24-hour synthetic storm

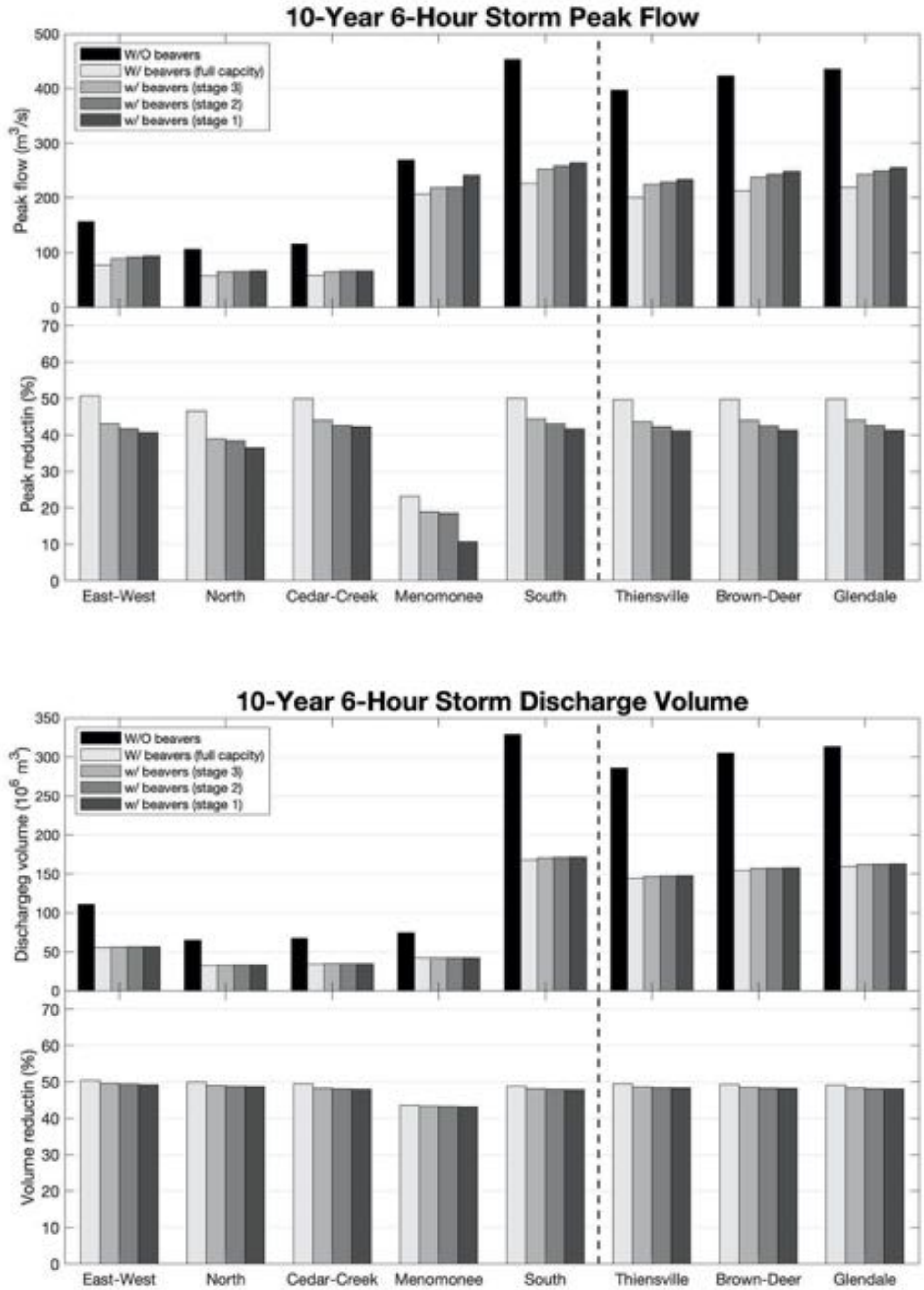


Figure D-11 Peak flow rate and discharge volume, and percentage of peak and volume reduction due to beaver dams at the outlets of five sub-basins and three flood zone river reaches in the South Milwaukee River sub-basin in response to a 10-year 6-hour synthetic storm

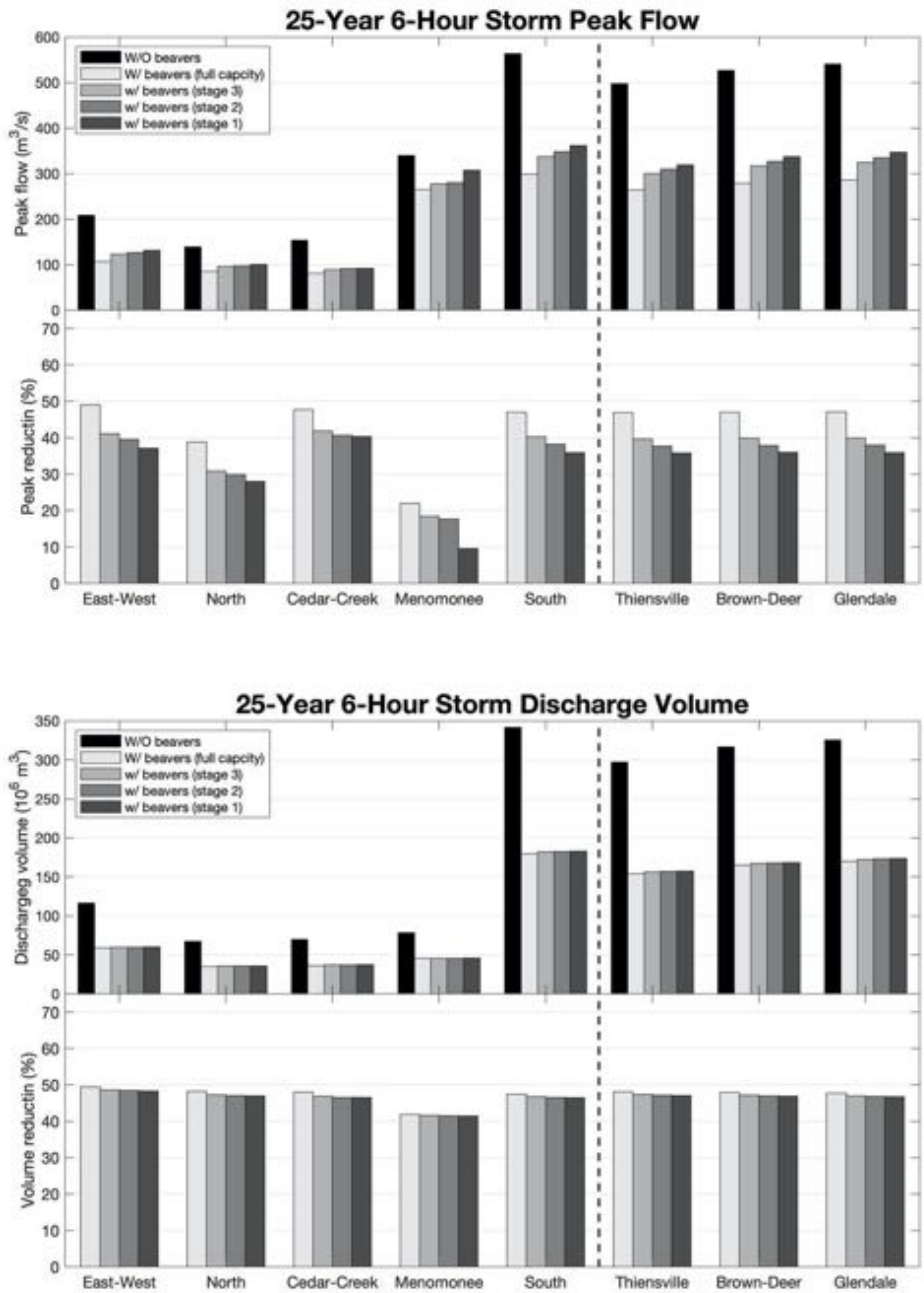
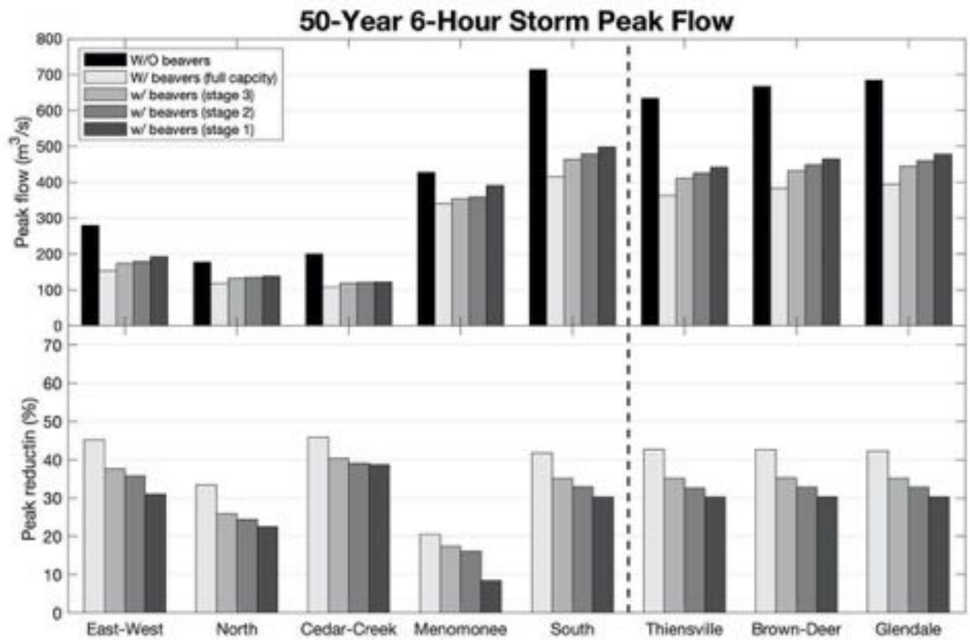


Figure D-12 Peak flow rate and discharge volume, and percentage of peak and volume reduction due to beaver dams at the outlets of five sub-basins and three flood zone river reaches in the South Milwaukee River sub-basin in response to a 25-year 6-hour synthetic storm



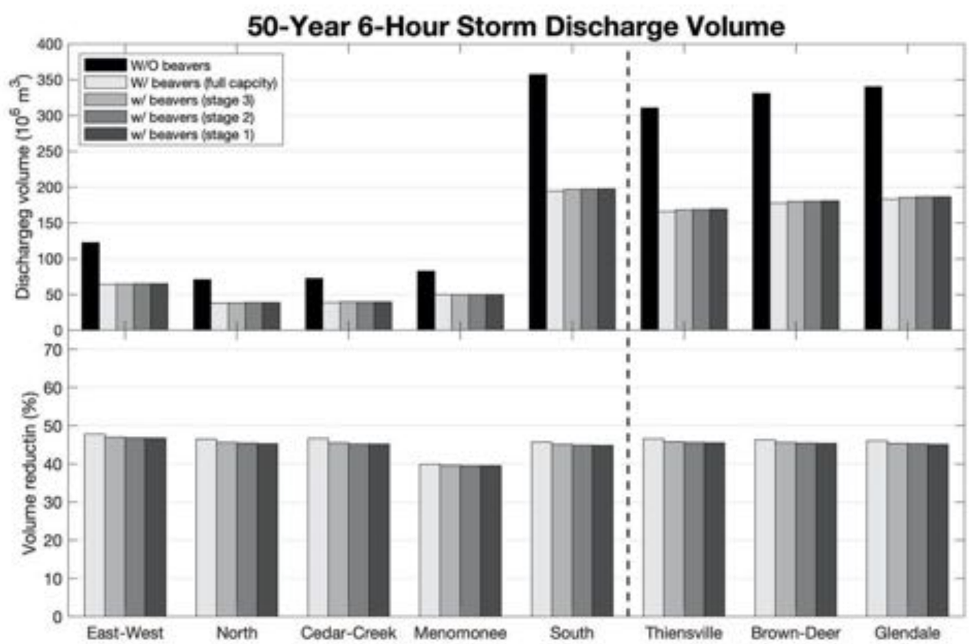


Figure D-13 Peak flow rate and discharge volume, and percentage of peak and volume reduction due to beaver dams at the outlets of five sub-basins and three flood zone river reaches in the South Milwaukee River sub-basin in response to a 50-year 6-hour synthetic storm

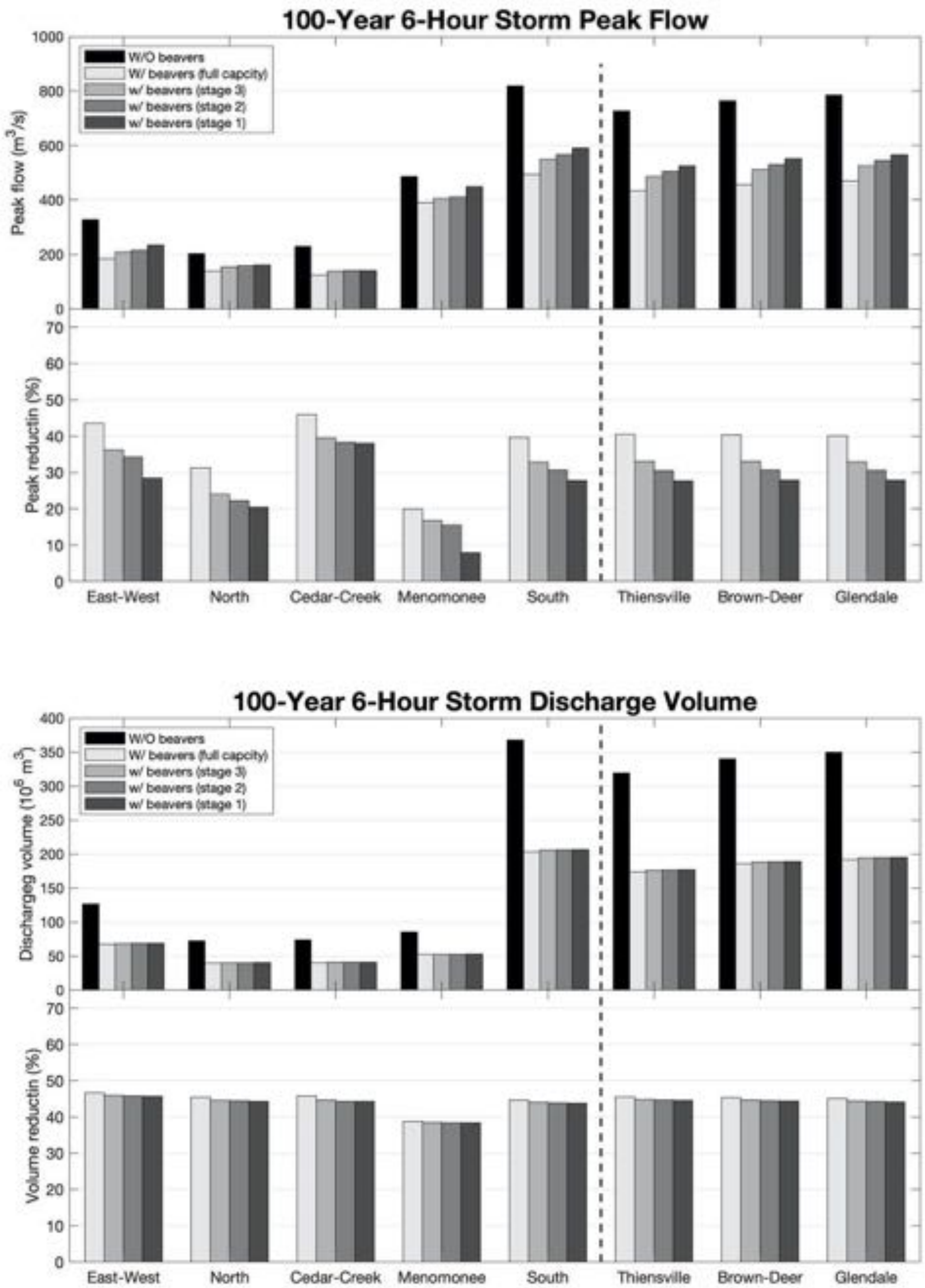


Figure D-14 Peak flow rate and discharge volume, and percentage of peak and volume reduction due to beaver dams at the outlets of five sub-basins and three flood zone river reaches in the South Milwaukee River sub-basin in response to a 100-year 6-hour synthetic storm

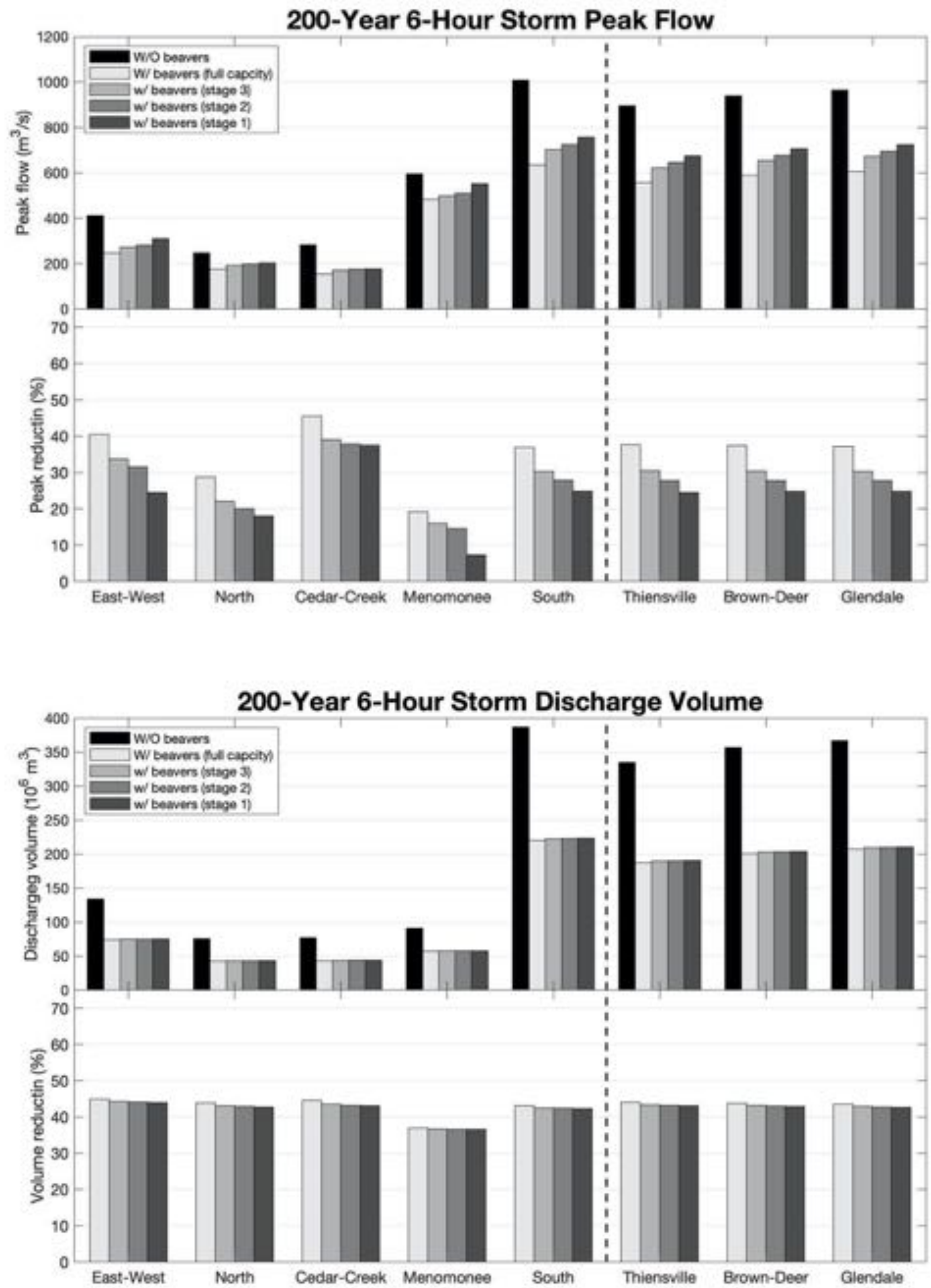
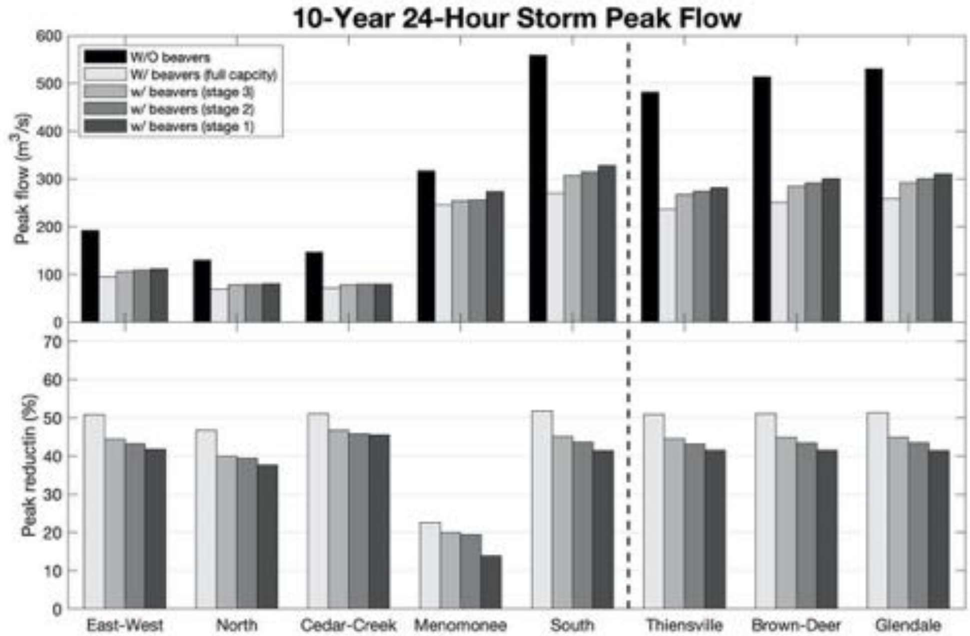


Figure D-15 Peak flow rate and discharge volume, and percentage of peak and volume reduction due to beaver dams at the outlets of five sub-basins and three flood zone river reaches in the South Milwaukee River sub-basin in response to a 200-year 6-hour synthetic storm



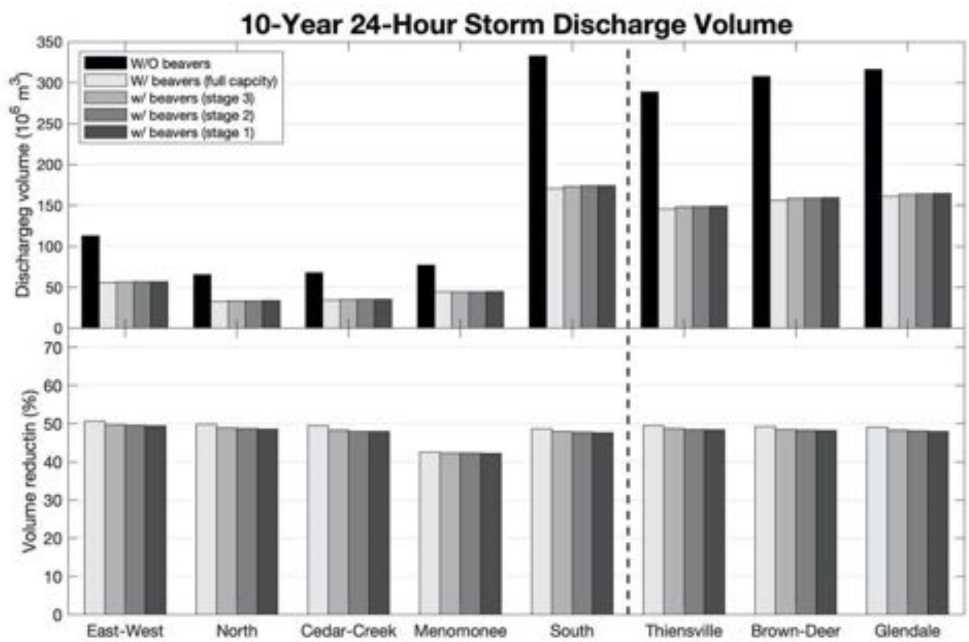


Figure D-16 Peak flow rate and discharge volume, and percentage of peak and volume reduction due to beaver dams at the outlets of five sub-basins and three flood zone river reaches in the South Milwaukee River sub-basin in response to a 10-year 24-hour synthetic storm

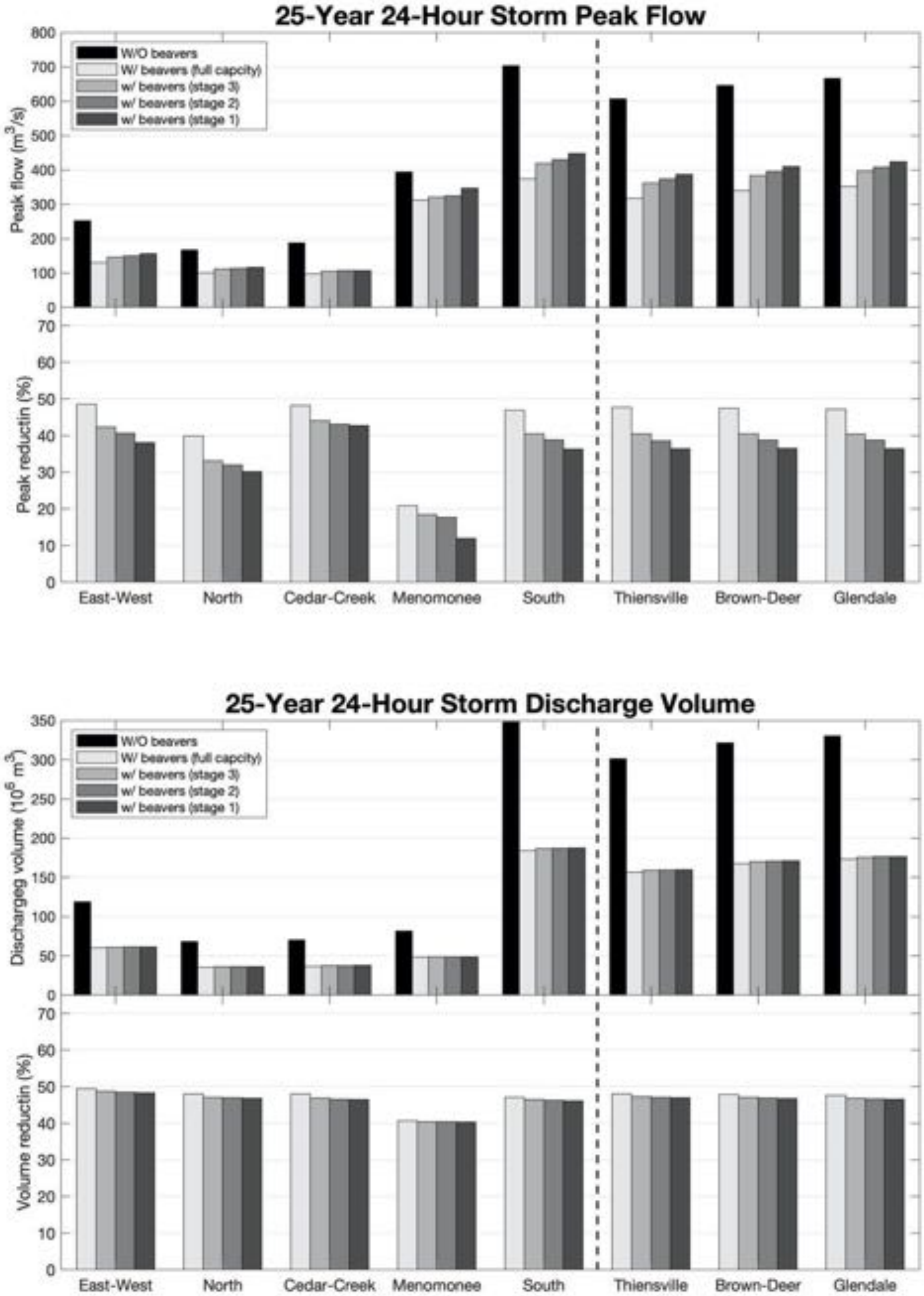


Figure D-17 Peak flow rate and discharge volume, and percentage of peak and volume reduction due to beaver dams at the outlets of five sub-basins and three flood zone river reaches in the South Milwaukee River sub-basin in response to a 25-year 24-hour synthetic storm

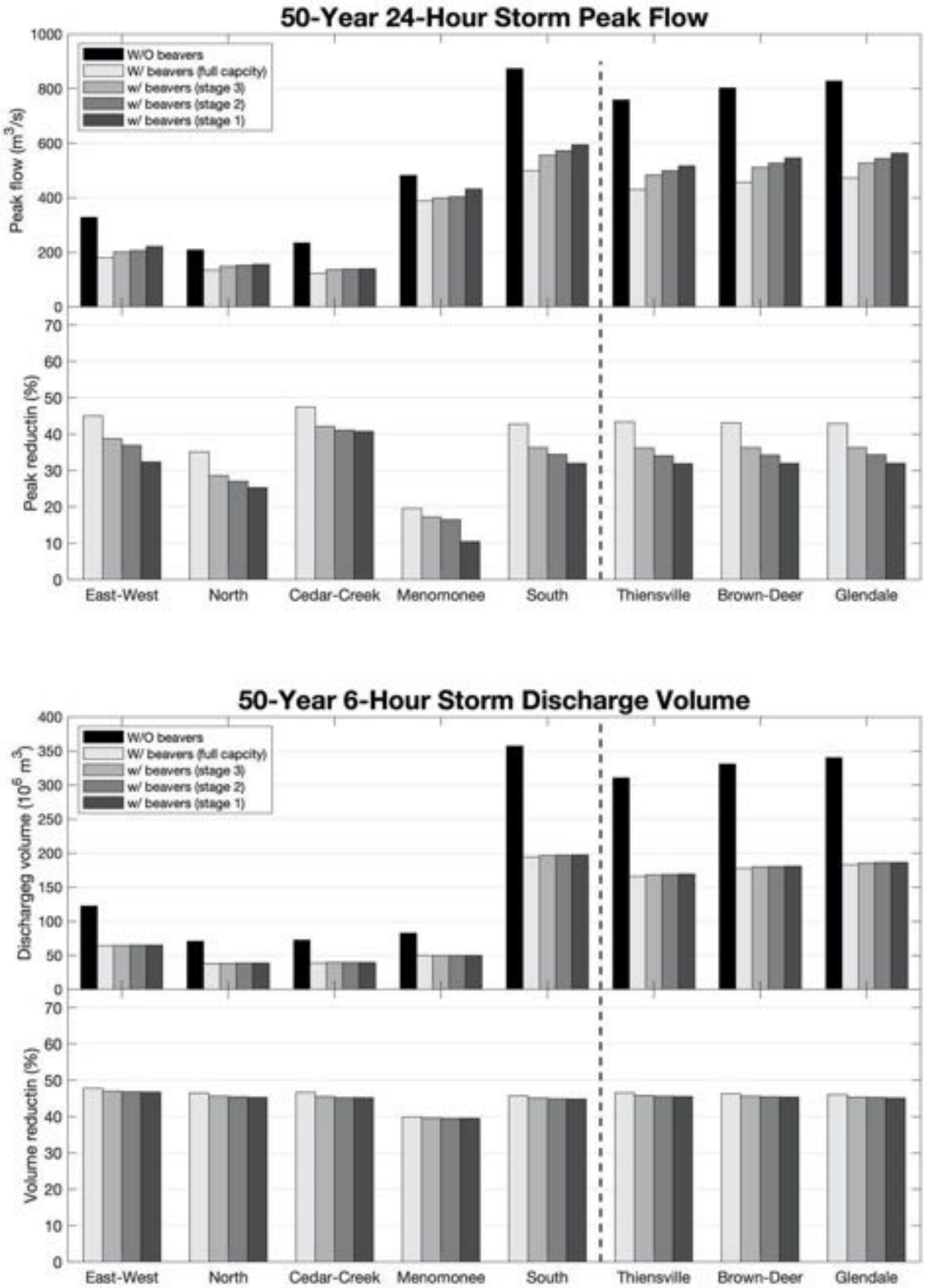


Figure D-18 Peak flow rate and discharge volume, and percentage of peak and volume reduction due to beaver dams at the outlets of five sub-basins and three flood zone river reaches in the South Milwaukee River sub-basin in response to a 50-year 24-hour synthetic storm

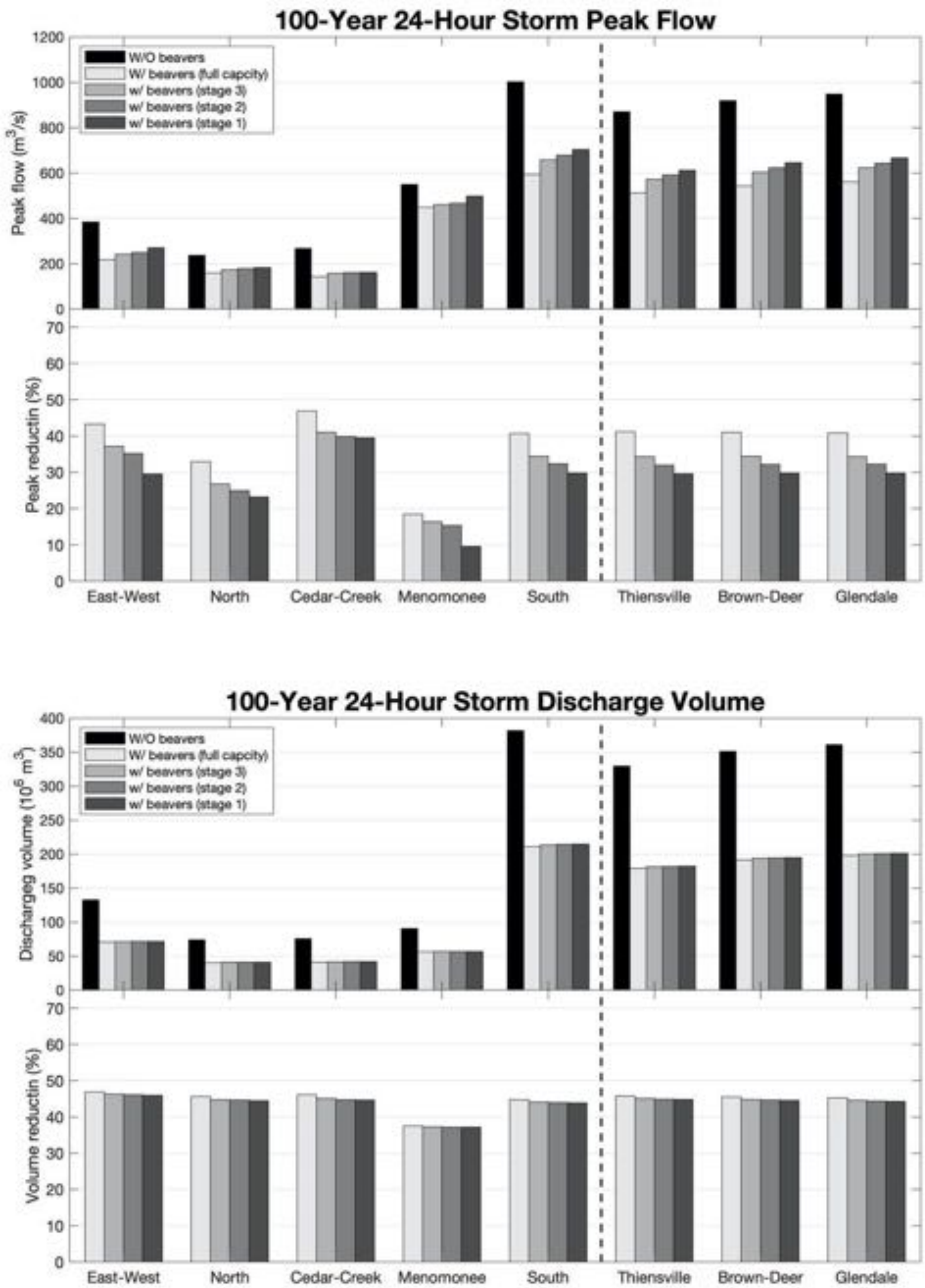


Figure D-19 Peak flow rate and discharge volume, and percentage of peak and volume reduction due to beaver dams at the outlets of five sub-basins and three flood zone river reaches in the South Milwaukee River sub-basin in response to a 100-year 24-hour synthetic storm

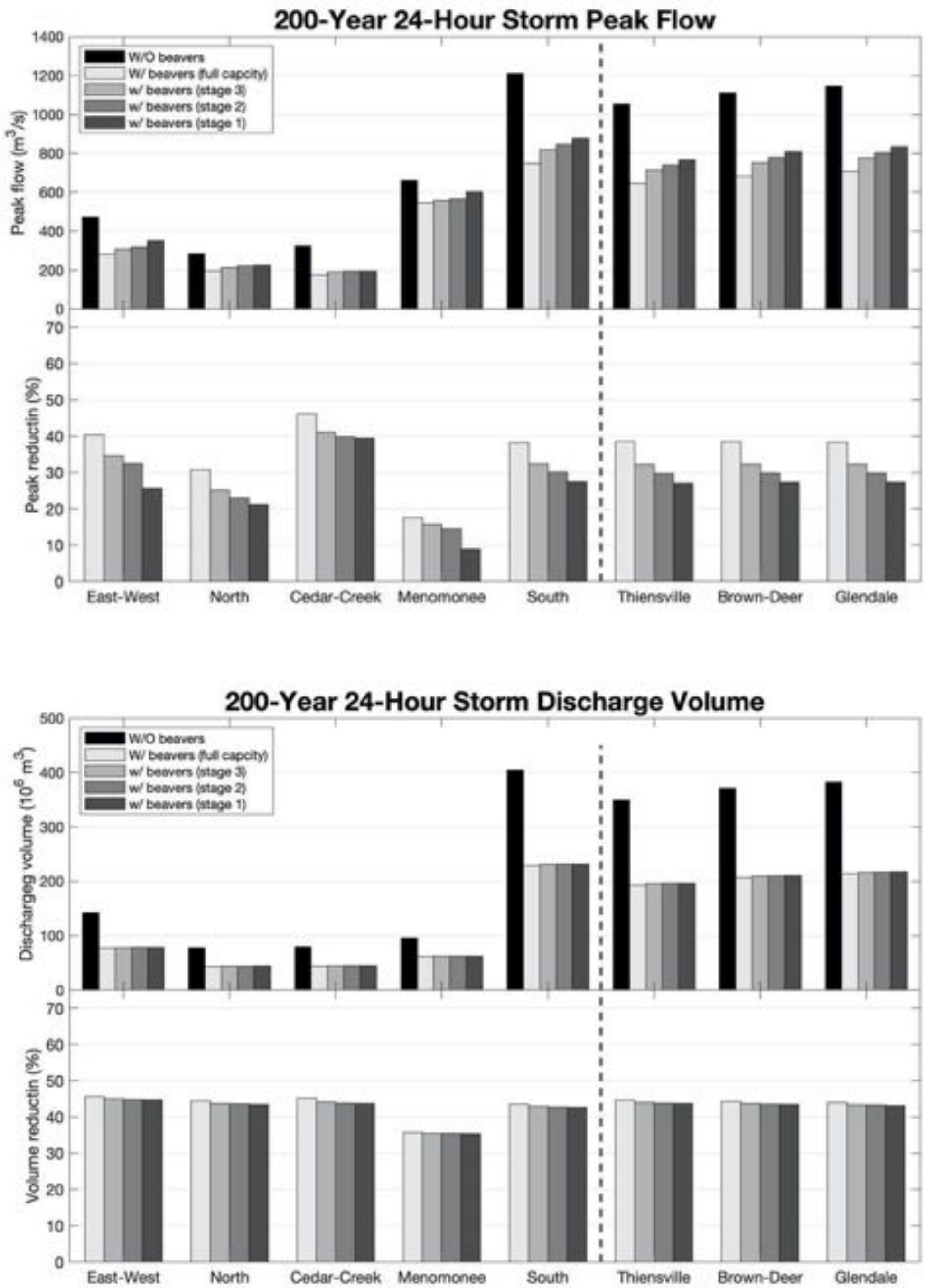


Figure D-20 Peak flow rate and discharge volume, and percentage of peak and volume reduction due to beaver dams at the outlets of five sub-basins and three flood zone river reaches in the South Milwaukee River sub-basin in response to a 200-year 24-hour synthetic storm

Appendix E. 14 Recommend sites for immediate beaver habitat restoration

Site 1: Mud Lake, Dundee

Mud Lake is just north of County Highway F, two miles west of Dundee, in Fond du Lac County, WI. Spruce Lake bog drains into it.

Figure E-1 Aerial photo and a field picture of Mud Lake, Dundee as one of the 14 recommended beaver restoration sites

Site 2: Mud Lake in Cedarburg Bog

Mud Lake is in the Cedarburg Bog State Natural area, just north-east of the intersection of County Highway Y and Cedar Sauk Rd. in Ozaukee County. It is approximately 4 miles west of Saukville, WI.

Figure E-2 Aerial photo and a field picture of Mud Lake in Cedarburg Bog as one of the 14 recommended beaver restoration sites

Site 3: Mink Creek

Mink Creek is a tributary of the North Branch and enters the river just east of the intersection of Highway 28 and Highway 144 in Sheboygan County.

Figure E-3 Aerial photo and a field picture of Mink Creek as one of the 14 recommended beaver restoration sites

Site 4: Mauthe Lake

Mauthe Lake is in the heart of the 34,000-acre North Kettle Moraine State Forest, in the southeast corner of Fond du Lac County. It was formed by damming a part of the East Branch of the Milwaukee River.

Figure E-4 Aerial photo and a field picture of Mauthe Lake in the North Kettle Moraine State Forest, as one of the 14 recommended beaver restoration sites

Site 5: Kewaskum, East Branch North of Highway 28

This area is about one mile east of Kewaskum and north of Highway 28. It is part of the East Branch, south of Mauthe Lake.

Figure E-5 Aerial photo and a field picture of an area near Kewaskum as one of the 14 recommended beaver restoration sites

Site 6: Jackson Marsh

Jackson Marsh is a State Wildlife Area that drains into Cedar Creek in Washington County

Figure E-6 Aerial photo and a field picture of Jackson Marsh as one of the 14 recommended beaver restoration sites

Site 7: Random Lake Ponds

The Random Lake ponds are north of Highway 144, northwest of the town and connect to Silver Creek which joins the North Branch.

Figure E-7 Aerial photo and a field picture of the Random Lake Pond as one of the 14 recommended beaver restoration sites

Site 8: North Branch

County Rd M, ½ mile north. of County A in Washington County, WI

Figure E-8 Aerial photo and a field picture of North Branch in Washington County as one of the 14 recommended beaver restoration sites

Site 9: Lake Twelve Marsh Area.

This large wetland complex is in the northwest corner of Washington County. It is mostly west of County Rd E on Jay Road, and is a part of the North Branch

Figure E-9 Aerial photo and a field picture of Lake Twelve Marsh as one of the 14 recommended beaver restoration sites

Site 10: South East of Kewaskum

This large wetland complex is a confluence of two subwatersheds. The photo is at County Road H between Highway 45 and Kettle Moraine Drive.

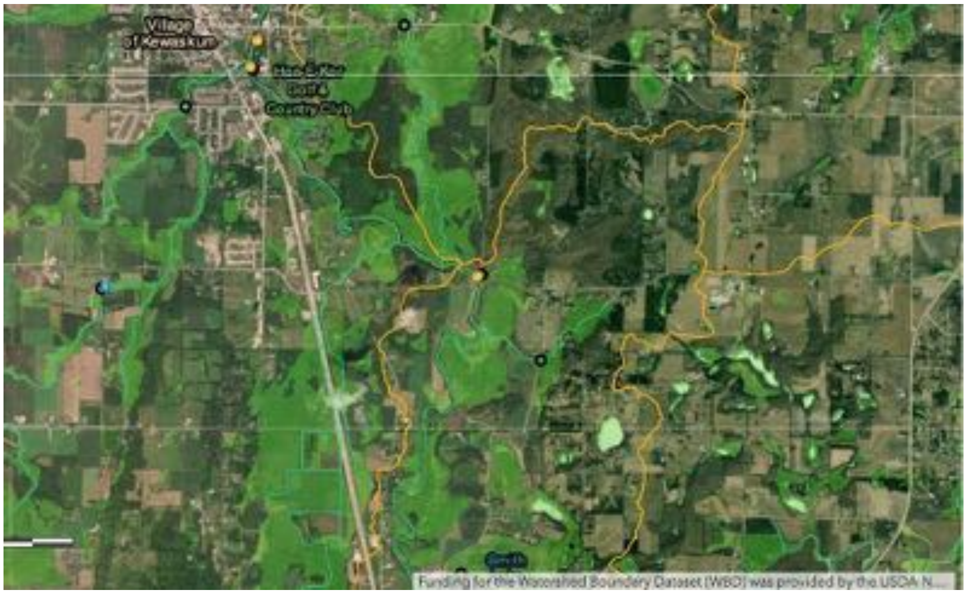


Figure E-10 Aerial photo and a field picture of an area southeast of Kewaskum as one of the 14 recommended beaver restoration sites

Site 11: Ulao Creek

This wetland area, despite having been ditched, has favorable habitat and has good potential for wetland restoration with beavers

Figure E-11 Aerial photo and a field picture of Ulao Creek as one of the 14 recommended beaver restoration sites

Site 12: Ashford West Branch

This area is north of the Town of Ashford in Fond du Lac County.

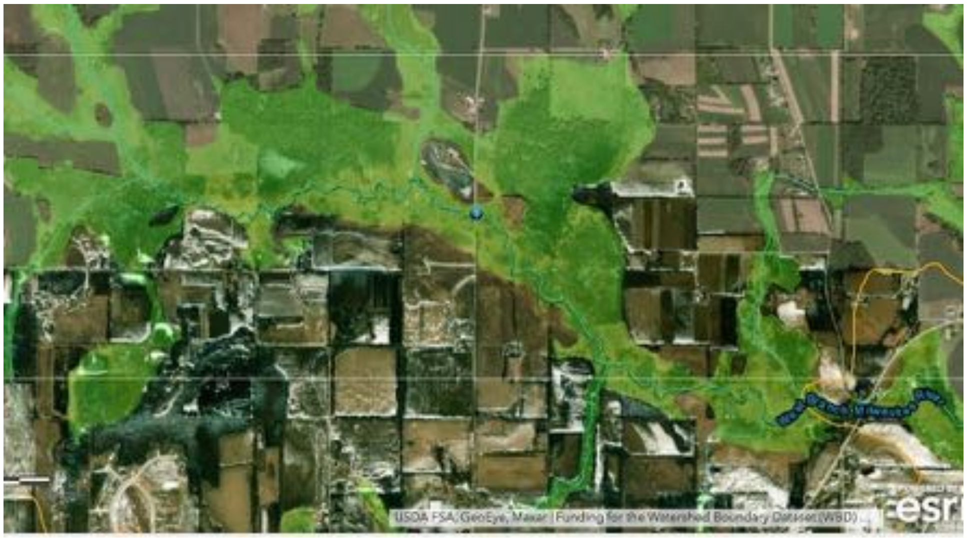


Figure E-12 Aerial photo and a field picture of an area north of Ashford as one of the 14 recommended beaver restoration sites (photo is taken from Drumlin Rd)

<u>**Site 13: Batavia Creek**</u>

Batavia Creek near County SS, and County A. It drains into the North Branch

Figure E-13 Aerial photo and a field picture of Batavia Creek as one of the 14 recommended beaver restoration sites

Site 14: Watercress Creek, North of Long Lake

Figure E-14 Aerial photo and a field picture of Watercress Creek as one of the 14 recommended beaver restoration sites (Photos was taken at the north end of Long Lake looking north towards Watercress Creek).

Appendix F. Resources for Beaver Food and Forage

Reference from Müller-Schwarze (2011)

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Appendix G. Resources for Beaver Population Estimates

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Appendix H. Beaver density and number of beavers per family (Müller-Schwarze, 2003)

Table 11.1 | Beaver Densities (Number of Colonies per Unit Stream Length) in Various Areas

Area	No./mile	No./km
Yellowstone National Park	0.37	0.23
Alaska	0.64	0.40
Fulton County, New York	0.87	0.54
Massachusetts	0.89	0.55
Western New York	0.93	0.58
Eastern South Dakota	1.30	0.81
Quabbin Reservation, Mass.	1.61	1.00
New Brunswick, N.J.	1.76	1.09

Sources: References 1-7, 10.

Table 11.2. | Numbers of Beavers per Family in Various Areas

Area	Average No. / Family
Alaska	4.1
Montana	4.1
Newfoundland	4.2
Adirondacks, N.Y.	4.3
Sagehen Creek, Calif.	4.8
Michigan	5.1
Allegany State Park, N.Y.	5.4
Ohio	5.9
Colorado	6.3
Isle Royale National Park, Mich.	6.4
Massachusetts	8.1
Nevada	8.2

Source: Reference 10.