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Articles

Modelling the impact of snowmelt in flows in the Mansfield Hollow Lake Watershed in Connecticut, USA

Modelación del impacto del deshielo en lo caudales en la cuenca del lago Mansfield Hollow en Connecticut, EUA

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Abstract

Storm runoff predictions are essential for minimizing flood hazards and increasing resilience to extreme weather events. In this study, an analysis was conducted to simulate snowmelt runoff in the Mansfield Hollow Lake Watershed, which is a tributary of the Thames River watershed in Connecticut, New England. The United States Army Corp of Engineers (USACE) model HEC-HMS was applied to simulate snowmelt runoff during the winter-spring of 2010 and 2019. The Mansfield Hollow Lake

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Watershed is composed of three main tributaries, namely the Fenton, Mount Hope, and Natchaug rivers. These runoff simulations and the watershed response to snowmelt are crucial for evaluating the potential impacts of watershed management decisions, particularly during high-flow periods. The HEC-HMS model was calibrated during the 2010 event and validated for the 2019 events. The study found that for the snow storms during 2010 and 2019 events, HEC-HMS model provided highly accurate predictions of snowmelt runoff with R-squared and, Nash-Sutcliffe correlation values exceeding 0.76. These findings highlight the efficacy of HEC-HMS model for simulating snowmelt runoff and demonstrate the utility of such model in predicting and managing flood risks. The results of this study provide valuable insights into the potential impacts of snowmelt runoff and will inform future watershed management decisions in the Mansfield Hollow Lake Watershed and similar regions.

Keywords: Connecticut, HEC-HMS, Mansfield Hollow Lake, snowmelt, thermodynamics.

Resumen

Las predicciones de escorrentía son esenciales para minimizar los peligros de inundación y aumentar la resiliencia ante eventos climáticos extremos. En este estudio se realizó un análisis para simular la escorrentía del deshielo en la cuenca del lago Mansfield Hollow, que es un afluente de la cuenca del río Támesis en Connecticut, Nueva Inglaterra, EUA. El modelo HEC-HMS del Cuerpo de Ingenieros del Ejército de los Estados Unidos (USACE, por sus siglas en inglés) se aplicó para simular la escorrentía del deshielo durante el invierno-primavera de 2010 y 2019. La cuenca del

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lago Mansfield Hollow se compone de tres afluentes principales: Fenton, Mount Hope y Natchaug. Estas simulaciones de escorrentía y la respuesta de la cuenca al deshielo son cruciales para evaluar los impactos potenciales de las decisiones de manejo de la cuenca, particularmente durante los periodos de alto caudal. El modelo HEC-HMS fue calibrado durante el evento de 2010 y validado para los eventos de 2019. El estudio encontró que para las tormentas de nieve durante los eventos de 2010 y 2019, el modelo HEC-HMS proporcionó predicciones muy precisas de la escorrentía del deshielo con R^2 y valores de correlación de Nash-Sutcliffe superiores a 0.76. Estos hallazgos resaltan la eficacia de los modelos HEC-HMS para simular la escorrentía del deshielo, y demuestran la utilidad de dicho modelo para predecir y gestionar los riesgos de inundación. Los resultados de este estudio brindan información valiosa sobre los impactos potenciales de la escorrentía del deshielo e informarán las futuras decisiones de gestión de cuencas hidrográficas en la cuenca del lago Mansfield Hollow y regiones similares.

Palabras clave: Connecticut, deshielo, HEC-HMS, lago Mansfield Hollow, termodinámica.

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Introduction

In the mountainous USA, rain-on-snow events are common on slopes within the snow transition zone. The Sierra Nevada Mountains are known for experiencing high flow rates in their rivers when warm winter storms combine with extensive snow cover, as noted Kattelmann (1997). However, the effects of such rainfall on snowmelt can significantly increase the risk of flooding and associated damages. According to the U.S. Army Corps of Engineers (USACE), the primary source of energy for snowmelt during rainfall is the transfer of sensible and latent heats from the atmosphere to the snow through convective processes (Allard, 1957). This phenomenon can cause rapid melting and lead to excess water that cannot be absorbed by the snowpack, resulting in runoff and potential flooding. Allard (1957) findings underscore the importance of understanding the mechanisms behind rainfall-induced snowmelt in order to mitigate flood risks in mountainous regions and, provides valuable insights into the factors that contribute to these events, which can inform efforts to manage and mitigate flood hazards in these areas.

According to Sarmad *et al*. (2022), Earth's climate is gradually becoming hotter, leading to the phenomenon of global warming. The rise in surface temperatures can have a significant impact on the hydrological cycle, particularly in regions where melting snow or ice is the primary source of water. As a result, hydrological modelling has become a widely used method for estimating a watershed hydrological response to precipitation. Sarmad *et al*. (2022) and Verdhen, Chahar and Sharma (2013) highlight the critical role of hydrological modelling systems in predicting and managing the impact of precipitation on hydrological

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systems. As global temperatures continue to rise and the hydrological cycle is increasingly affected, the use of such models will become ever more important for ensuring the resilience and sustainability of water resources in the years to come. According to Verdhen *et al*. (2013), HEC-HMS is a widely used modelling system that can simulate the impact of precipitation on hydrological systems. The system is particularly useful in predicting snowmelt and rainfall runoff in areas where these events are the primary sources of water. Additionally, by better understanding the hydrological cycle and the impact of global warming on water resources, researchers can work to develop effective strategies for managing and conserving these critical resources.

The accurate simulation of storm runoff in river watersheds is critical for assessing and mitigating flood risks. Teng, Huang and Ginis (2018) used two hydrological models, HEC-HMS, and the Precipitation-Runoff Modelling System (PRMS), to simulate storm runoff in the Taunton River Watershed, which spans the states of Rhode Island and Massachusetts. The study focused on a specific storm event in 2010, which brought approximately 5 inches of rainfall in March and 11 inches of snowfall in December and used the models to predict the resulting runoff. The results of the study indicate that both HEC-HMS and PRMS accurately predict rainfall runoff, with correlation values above 0.95. The simulation of the extreme storm scenario, which combined the maximum historical snowfall of 36.7 inches in early February with the March-April rainstorm in 2010, predicted a substantial increase in flow of about 50 % or more. These findings are significant for assessing and mitigating flood risks in the Taunton River Watershed. The use of hydrological models like HEC-HMS and PRMS provides valuable insight into the complex

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interactions between precipitation, snowmelt, and runoff in river watersheds.

Şengül and İspirli (2022) considered that predicting the runoff from snowpack accumulated in snowmelt-dominated watersheds is essential for managing water supply and flood control in mountainous regions. In particular, during melting periods, it is important to accurately predict the amount and timing of runoff from these watersheds to ensure that water resources are properly managed, and flood risks are minimized. To simulate snowmelt Şengül and İspirli (2022) employed HEC-HMS which uses the temperature index method in the Kırkgöze–Çipak watershed. The temperature index method is based on the principle that snowmelt is primarily driven by air temperature and solar radiation, which are used to estimate the amount of snowmelt and subsequent runoff. The Kırkgöze–Çipak watershed is located in Turkey, with an elevation ranging from 1 823 to 3 140 m above sea level. By using HEC-HMS and the temperature index method, the researchers were able to simulate snowmelt runoff in this watershed, providing critical information on the amount and timing of runoff during the melting period. Overall, the study by Şengül and İspirli (2022) highlights the importance of accurately predicting snowmelt runoff in snowmelt-dominated watersheds for managing water resources and mitigating flood risks.

Snowmelt runoff is a critical source of streamflow, which regulates water availability in spring and summer months (Verdhen *et al*., 2013). To better understand the snowmelt process, HEC-HMS was applied to the Beas sub-basin in the Pirpanjal range of the lower Himalayas above the Manali at an altitude of 1 900 m, using a temperature index method. In this study, the researchers performed spatiotemporal analysis of process

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parameters and variables to calibrate and validate the model. The daily and weekly simulations showed a satisfactory correlation with a square-r above 0.7. The study concluded that using ATI Cold/Melt rate functions and the meteorological model Index were crucial for successful model simulations. This finding highlights the importance of using appropriate model parameters for accurate simulation of snowmelt runoff.

Hu, Kreymborg, Doeing, Baron and Jutila (2006) employed HEC-HMS and the Corps Water Management System (HEC-CWMS) to model floods and mitigate future damages in the Red River of the North Basin, particularly in St. Paul District. CWMS was utilized to simulate the real-time operation of reservoirs and regulate their outflows. To enhance reservoir operational forecasting, which is a crucial aspect of the CWMS model, the authors used the Distributed Snow Process Model (DSPM) and HEC-HMS to create gridded snowmelt and rainfall-runoff models. The study involved setting up, calibrating, and verifying the model. The operational forecasting of the dam was examined in both cold and warm conditions.

Understanding snowmelt's contribution to runoff is essential for various reasons related to hydrology, ecology, water management, and climate science. Snowmelt is a major water source, especially in mountainous regions. It helps predict water availability for agriculture, drinking, and industry in warmer months. Knowledge of snowmelt timing and volume aids in managing reservoirs and dams for flood control and water storage, as rapid snowmelt can cause floods. This understanding helps in flood risk prediction and mitigation. Snowmelt influences stream flows, affecting aquatic ecosystems, fish spawning, plant growth, and habitats. It also maintains wetlands, which are vital for biodiversity and

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act as natural water filters. Changes in snowmelt patterns indicate climate change, revealing trends in temperature and precipitation. Understanding snowmelt helps model future climate scenarios and potential impacts on global water cycles. Snowmelt affects hydropower generation timing and capacity, crucial for energy planning. It also influences tourism activities like skiing and fishing, impacting local economies. In snowmelt-dependent regions, it aids equitable water distribution among competing needs.

In summary, understanding snowmelt's role in runoff is vital for effective water resource management, mitigating environmental impacts, adapting to climate change, and supporting economic activities. As climate patterns evolve, this knowledge will become increasingly important for sustainable water management practices. The aims of this research are:

1. Develop a HEC-HMS model to simulate runoff resulting from snowmelt in the Mansfield Hollow Lake Watershed in Connecticut.

2. Calibrate the model using observed discharge and stage data from the 2010 winter event at USGS gauge stations located on the Fenton, Mount Hope, and Natchaug rivers at Old Turnpike Bridge, Warrenville, Chaplin, and a USACE gauge at the Mansfield Hollow Lake Dam.

3. Validate the model with data from the 2019 winter event, focusing on discharges and stages at the same locations.

4. Perform simulations for the 2010 and 2019 events, both with and without snowmelt scenarios, to compare the resulting peak discharges and accumulated volumetric discharges under these conditions.

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Results shows that the snowmelt process can have an important contribution to instant discharges and the total volume of water delivery by the Mansfield Hollow Lake Watershed.

Materials and methods

Characteristics of the watersheds

The Mansfield Hollow Lake Watershed (MHL-W) is mainly fed by three rivers: the Fenton, Mount Hope, and Natchaug, which are all part of the larger Thames River watershed, according to Stella (2021). The Fenton River has a total length of 23 kilometers and a drainage area of 89 square kilometers (Stella, 2022). Since October 2006, a stream flow discharge gauge has been installed at the Old Turnpike Road bridge, marked as USGS gage # 01121330, Tolland County, with coordinates of latitude 41° 49' 59.50" and longitude 72° 14' 34.01" in the NAD83 coordinate system (USGS, 2022a). The Mount Hope River has a total length of 23 kilometers and a drainage area of 74.1 square kilometers, with a stream gauge marked as USGS gage # 01121000 located near Warrenville, with coordinates of latitude 41° 50' 37" and longitude 72° 10' 10" in the NAD27 coordinate system (USGS, 2022b). The Natchaug River has a total length of 31 km and a drainage area of 172.2 km^2 as it enters Mansfield Hollow Lake and has since 2006 a USGS gauge # 01120790 near Chaplin, latitude 41° 48' 58.21”, longitude 72° 06' 22.21" NAD83 (USGS, 2022c). The Mansfield Hollow Lake Dam (MHL-D) located at Windham County, latitude 41° 48' 58.21”, longitude 72° 06' 22.21" NAD83 has a usable capacity of 63 996 073 m^3, top and bottom elevations of 83.3 and 59.5 m NGVD,

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respectively, five rectangular culverts, Ogee weir with a 210.3 m length and 78.3 NGVD elevation (USACE, 2019) and has recorded stages since 1997 (USACE, 2022a). Figure 1 shows the Mansfield Hollow Lake Watershed and the East of the State of Connecticut, USA.

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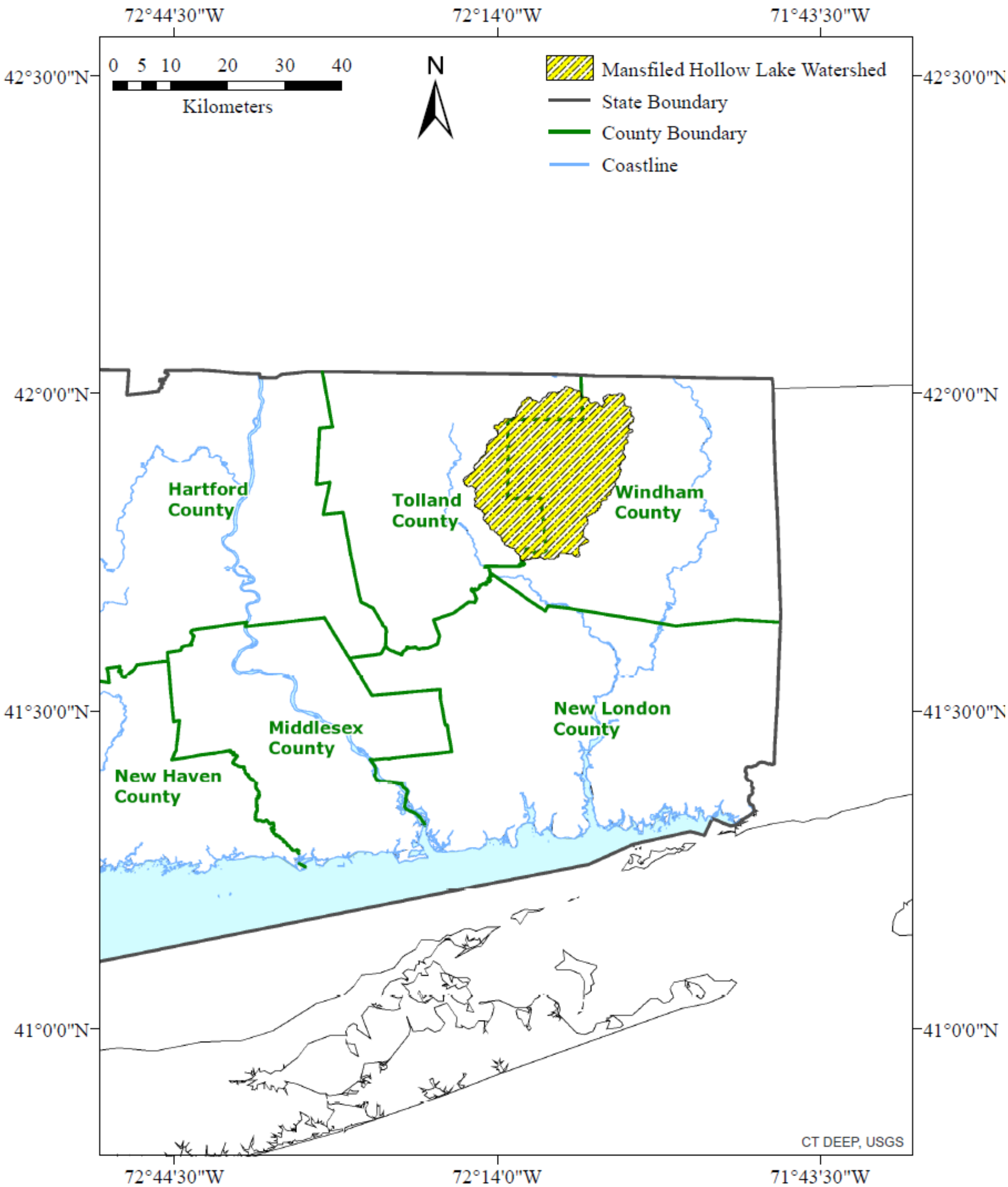

Figure 1. MHL watershed and State of Connecticut.

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Figure 2 shows an elevation map of the MHL-W, the location of the USGS stream gauges, Mansfield Hollow Lake and Windham Waterworks Dams, and the Fenton, Mount Hope, and Natchaug rivers.

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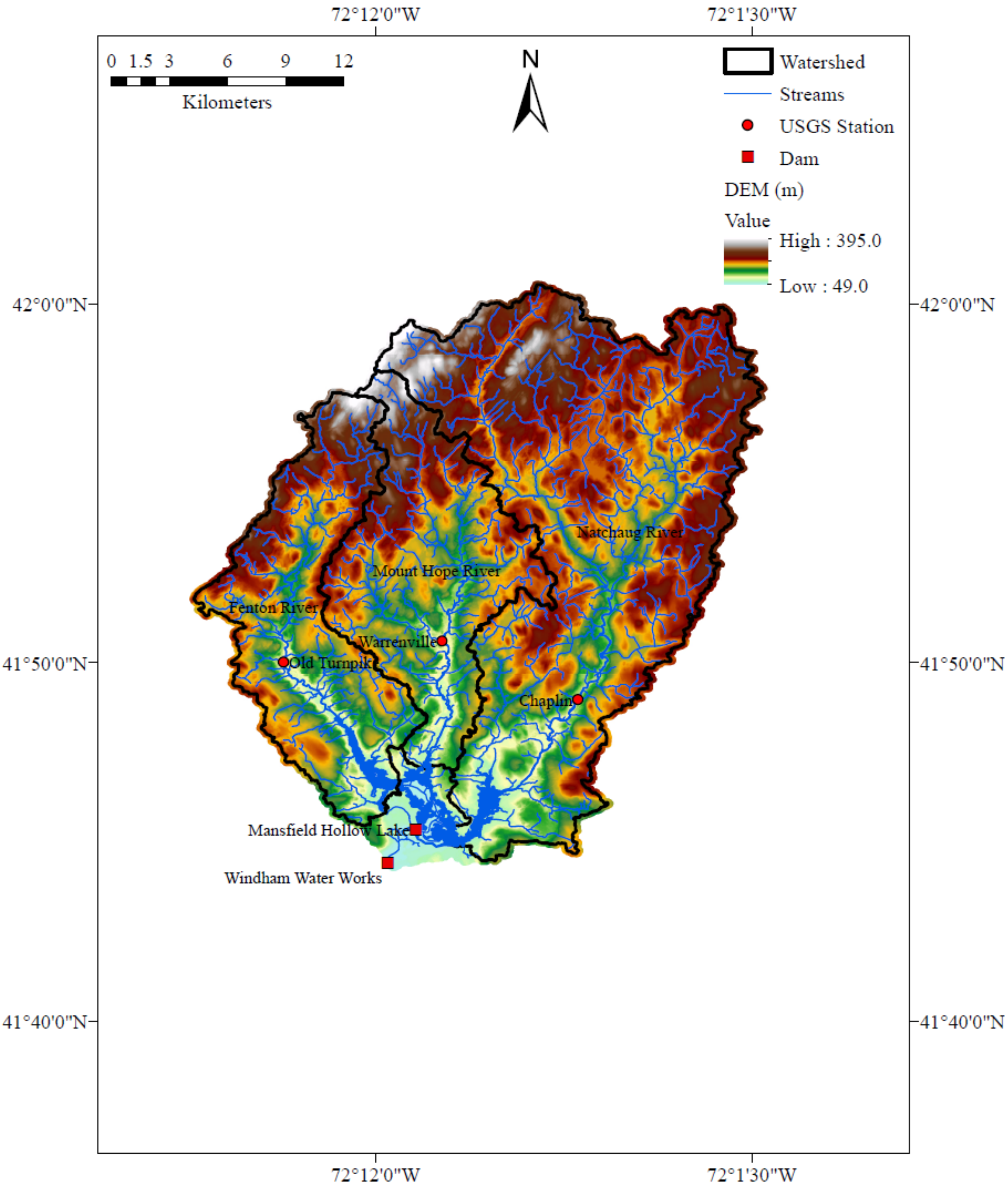

Figure 2. DEM of the MHL-W, Fenton, Mount Hope and Natchaug rivers.

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Table 1 summarize stream order and identification number of the Fenton, Mount Hope and Natchaug rivers (NOAA, 2022).

Table 1. Stream order and identification numbers by river.

Parameter	Fenton	Mount Hope	Natchaug
Stream order	2	2	3
Stream ID	6162579	6162583	6162939

According to the United States Geological Survey (USGS), the Fenton River has a mean discharge of 0.37 m^3/s, with a minimum of 0.070 m^3/s and a maximum of 1.61 m^3/s (USGS, 2022a). The Mount Hope River has a mean discharge of 1.08 m^3/s, with a minimum of 0.071 m^3/s and a maximum of 6.91 m^3/s (USGS, 2022b). The Natchaug River has a mean discharge of 3.40 m^3/s, with a minimum of 0.71 m^3/s and a maximum of 16.17 m^3/s (USGS, 2022c). Ahearn (2008) estimated the 7Q10 (the lowest 7-day average flow that occurs on average once every 10 years) to be 0.01 m^3/s, 0.03 m^3/s, and 0.25 m^3/s for the Fenton, Mount Hope, and Natchaug rivers, respectively. Table 2 provides a summary of the hydrological characteristics of these rivers within the Mansfield Hollow Lake Watershed (Stella, 2021).

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Table 2. Hydrologic watershed characteristics by river.

River	Area (km^2)	Mean (m^3/s)	7Q10 (m^3/s)	Minimum (m^3/s)	Maximum (m^3/s)
Fenton	47.4	0.37	0.01	0.070	44.46
Mount Hope	74.1	1.08	0.03	0.076	74.76
Natchaug	172.2	3.66	0.25	0.020	151.78

The MHL-D has a usable capacity of 63 996 073 m^3 (64 million of m^3) including a recreation pool (USGS, 2022d). The minimum, mean and maximum precipitation in the State of Connecticut are: 787, 1 138 and 1 627 mm's, respectively (Miller, Warner, Ogden, & DeGaetano, 2002).

The land cover of the Fenton Mount Hope and Natchaugh watersheds is principally forested (84 %) with some non-forested vegetation (8.3 %) and urban areas (2.8 %) (Stella, 2013). Table 3 summarizes the land cover of the watershed (Stella, 2013).

Table 3. Land cover attributes of the watershed.

Land cover	(%)
Forest	84.4
Non-forested vegetation	8.3
Stratified drift	4.2
Urban	2.8
Open water	2.1
Barren land	1.4
Wetland	1.0

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HEC-HMS model

HEC-HMS offers multiple methods for simulating snowmelt. These methods include the Temperature Index, Radiation-Derived Temperature Index, and Energy Balance methods, as well as two options for snowmelt modelling: The gridded temperature index method and the temperature index method (USACE, 2022b).

The method used in this study, the Gridded Temperature Index method, uses the same principles as the Temperature Index method, but applied on a cell-by-cell basis across the entire grid, as opposed to averaging over the entire watershed. This approach allows for a more detailed and accurate assessment of snowmelt patterns across the area being modeled (USACE, 2022b). Figure 3 provides a summary of the Temperature Index method used in HEC-HMS. This method assumes that the rate of snowmelt is directly proportional to the difference between the air temperature and a base temperature, known as the melting temperature. The model calculates the degree-day factor, which is the number of degrees above the melting temperature that a given day's temperature exceeds. This factor is then used to estimate the amount of snowmelt that will occur on that day (USACE, 2022b).

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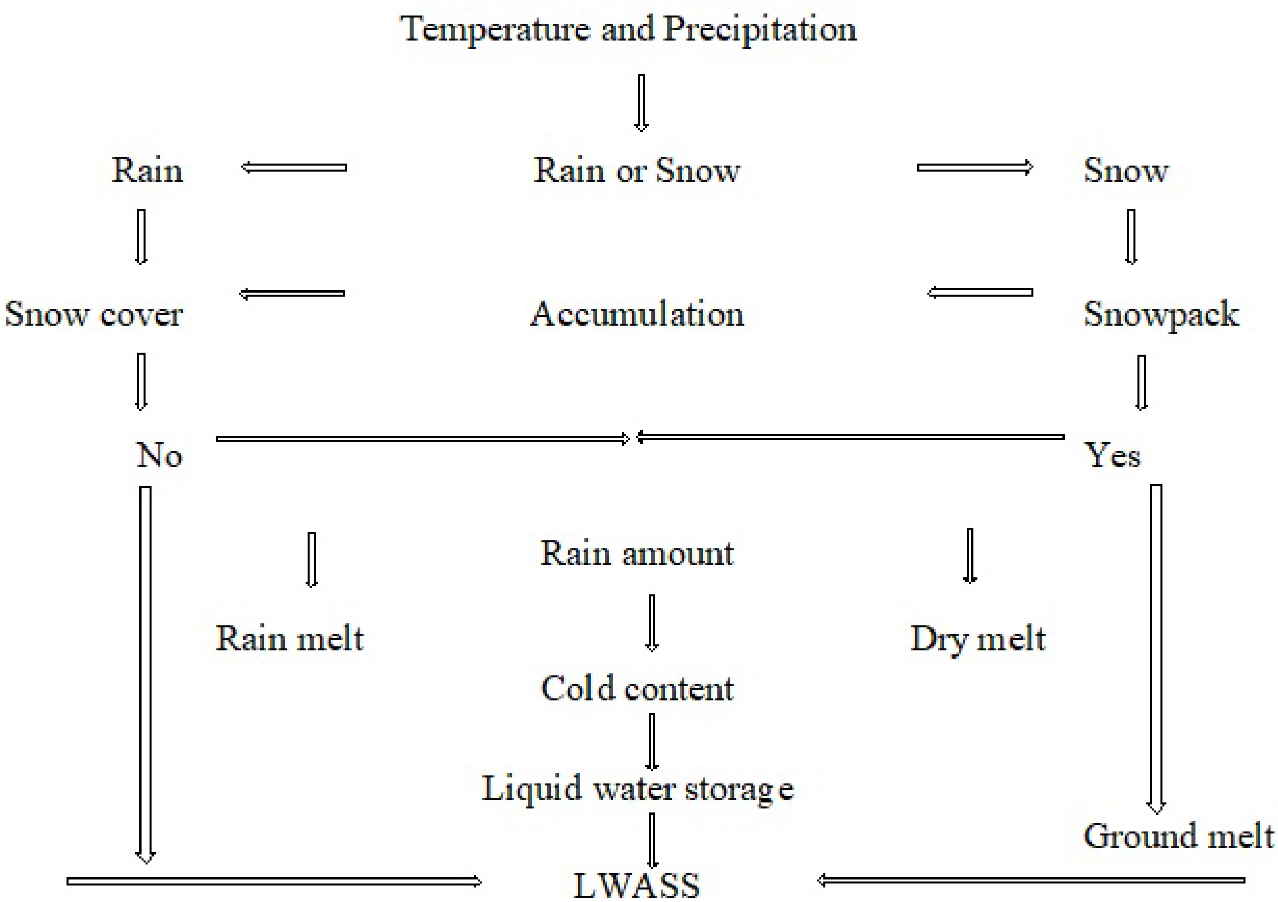

Figure 3. HEC-HMS gridded temperature index method model.

The Gridded Temperature Index has to be used in conjunction with the ModClark Unit Hydrograph Transform method (Scharffenberg, Ely, Daly, Fleming, & Pak, 2010).

Data for the application of HEC-HMS model such as Digital Elevation Model (DEM) were obtained from the United States Geological Service (USGS, 2022d) with 1x1 m of resolution, Land Cover from the National Land Cover Database (NLCD, 2022) and soil type from the United States Department of Agriculture (USDA, 2022) both with 30 x 30 m of resolution

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and all of them with ArcGIS online. Discharges and, stages were obtained from the United States Geological Service at Old Turnpike Bridge (USGS, 2022a), Warrenville (USGS, 2022b), and Chaplin (USGS, 2022c), MHL-D has recorded stages since 1997 (USACE, 2022a) with 15 minutes time step. Grid precipitation was obtained from the PRISM© Climate Group, Oregon State University (PRISM©, 2022) with 4 000 m resolution and 1 Day time step and Snow Water Equivalent (SWE) from the National Snow and Ice Data Center (NSIDC, 2022). The HEC-HMS model grid has 2 000 x 2 000 m of resolution and 15 minutes time step. Table 4 summarize the sources of data.

Table 4. Data sources for DEM, land cover, soil type discharges, stages, and precipitation.

Data	Data source
DEM	USGS (2022d) with ArcGIS online
Land cover	NLCD (2022) with ArcGIS online
Soil type	SSURGO (2022) with ArcGIS online
Precipitation and Temperature	PRISM© (2022)
SWE	NSIDC (2022)
Discharges	USGS (2022a), USGS (2022b) and USGS (2022c)
Stages	USACE (2022a)

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Evaluation coefficient

The observed discharges of the Fenton River at Old turnpike Bridge, Mount Hope at Warrenville and Natchaug at Chaplin were used to conduct the calibration of HEC-HMS model applying the evaluation coefficients: R-squared (r-square), Nash-Sutcliffe (NS) model of efficiency, Root Mean Square Error (RMSE) by the standard deviation of observations and Mean Absolute Error (MAE).

R-squared regression coefficient of determination is the most used statistics to assess the degree of fit of a model, the value measures how much variation the trendline has (Akossou & Palm, 2013), given by Equation (1):

$$r^2 = \frac{SCE_P}{SCE_{tot}} \quad (1)$$

Where:

SCE_p = Sum of squares related to regression.

SCE_{tot} = Total sum of squares.

Nash-Sutcliffe (NS) model of efficiency (Nash & Sutcliffe, 1970), given by Equation (2):

$$NS = 1 - \frac{\sum_{i=1}^{n}(O_i - S_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O}_i)^2} \quad (2)$$

Where:

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O_i = Observed discharges.

Ô = Mean of observed discharges.

S_i = Simulated discharges.

n = Number of steps modeled.

Table 5 summarize coefficient evaluation criteria for R-squared (r-square) and, Nash-Sutcliffe (NS) by Da Silva *el at*. (2015), and Chicco, Warrens and Jurman (2021).

Table 5. Criteria for evaluating the performance of the hydrological model.

Model	Value	Performance	Reference
r-square	+1	Best value	Chicco *et al*. (2021)
	- infinite	Worst value	
NS	0.75 < NS < 1.0	Very good	Da Silva *et al*. (2015)
	0.65 < NS < 0.75	Good	
	0.50 < NS < 0.65	Satisfactory	
	0.4 < NS < 0.50	Acceptable	
	NS < 0.4	Unsatisfactory	

Results and discussion

A HEC-HMS model was developed to simulated discharges, accumulated discharges, stages, and snowmelt of the Mansfield Hollow Lake Watershed. The model was calibrated using data from 2010 and validated with data from the 2019 events.

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The Mansfield Hollow Lake watershed was divided into seven sub-basins: two each for the Fenton, Mount Hope, and Natchaug rivers, and one for the Mansfield Hollow Lake reservoir. Figure 4 displays the HEC-HMS model schematic of the Mansfield Hollow Lake Watershed. The model utilized the Simple Canopy as the Canopy Method, the SCS Curve Number as the Loss Method, Mod Clark as the Transform Method, Linear Reservoir as the Baseflow Method, Gridded Temperature Index as the Snowmelt Method, and Muskingum as the Routing Method.

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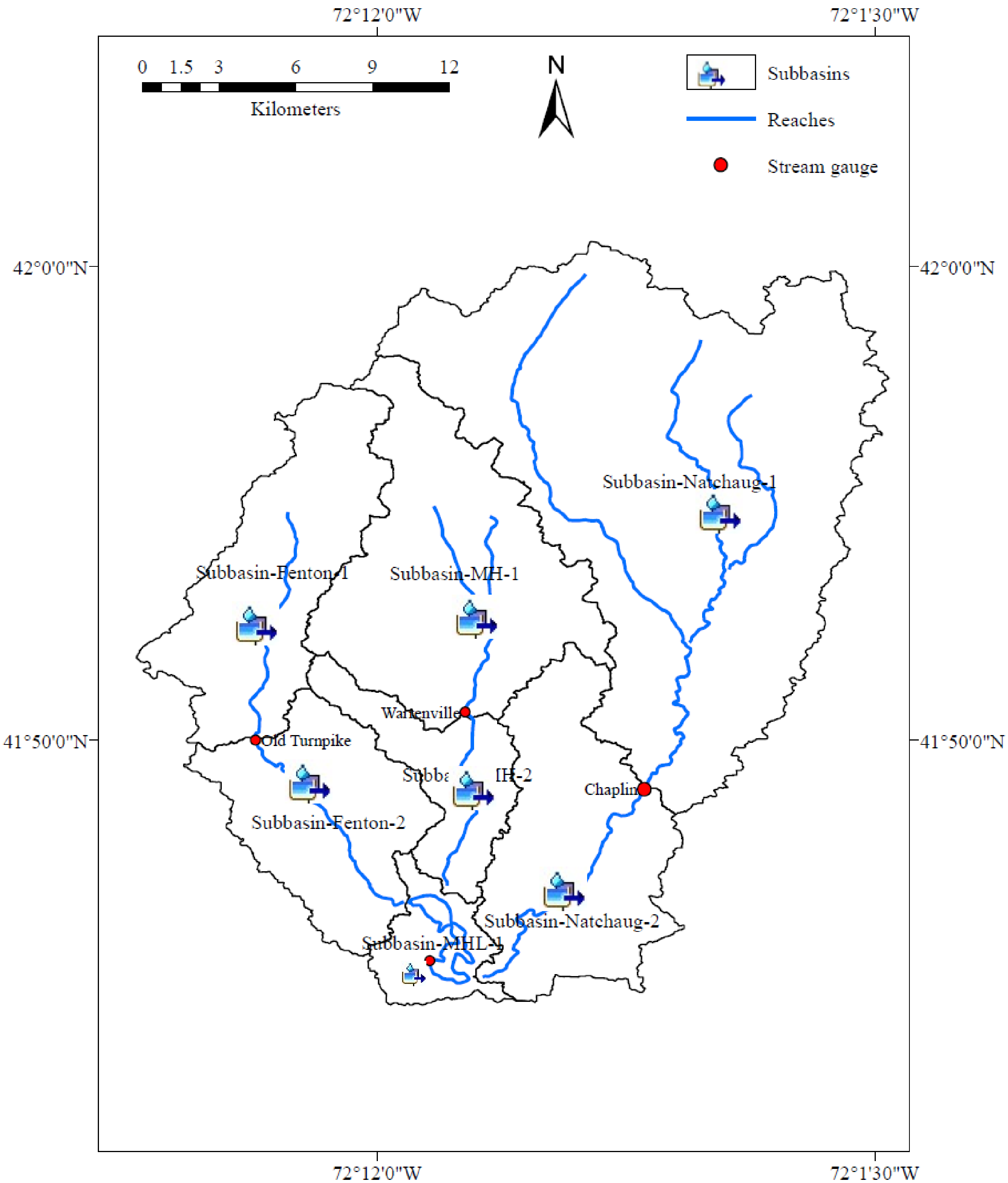

Figure 4. HEC-HMS schematic of the MHL-W.

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The temperature index snow model in HEC-HMS requires temperature and snowpack data at each timestep, along with initial snow conditions at the model's first timestep.

Daily precipitation and temperature gridded data were sourced from the Prism Climate Group (PRISM©, 2022). The Snow Water Equivalent (SWE), which indicates the volume of liquid water in the snowpack, was obtained from NSIDC (2022) for the simulated events. Temperature data serve as an index for all energy fluxes into the snowpack, and they help determine whether precipitation falls as rain or snow, if snow melts, and the rate at which melting occurs.

Parameters for gridded snowmelt method were selected from HEC-HMS user's manual (USACE, 2022b) Table 6 summarize the major calibrated parameters' value of HEC-HMS model, curve number, time of concentration (h), storage coefficient (h) and GW 1 initial (m^3/s) during the 2010 event.

Table 6. HEC-HMS parameters.

Subbasin	**Curve number**	**Time of concentration (h)**	**Storage coefficient (h)**	**GW 1 initial**
Subbasin-Fenton 1	52	4.54	8.4	2.5
Subbasin-Fenton 2	52	2.54	4.7	0.85
Subbasin-MHL 1	30	1.83	3.4	1.0
Subbasin-MH 1	85	3.73	6.9	1.0
Subbasin-MH 2	30	3.16	5.9	0.85
Subbasin-Natchaug 1	58	5.60	10.4	7.5
Subbasin-Natchaug 2	30	2.97	5.5	7.5

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Figure 5, Figure 6, Figure 7 and Figure 8 shows observed and simulated discharges and stages by the HEC-HMS during the 2010 event in the Fenton, Mount Hope, Natchaug rivers at Old Turnpike, Warrenville, Chaplin, and MHL-D from 02/14/2010 00:00 to 03/18/2010 23:45.

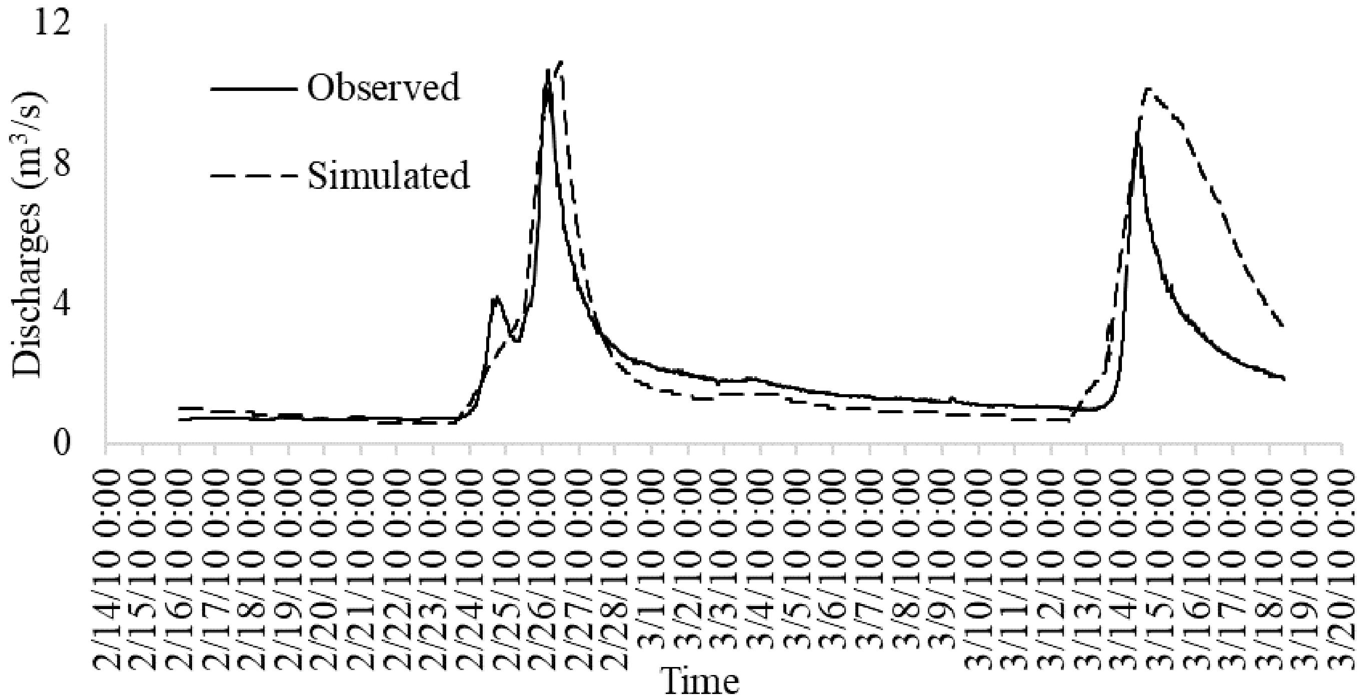

Figure 5. Observed and simulated discharges by HEC-HMS at Old Turnpike.

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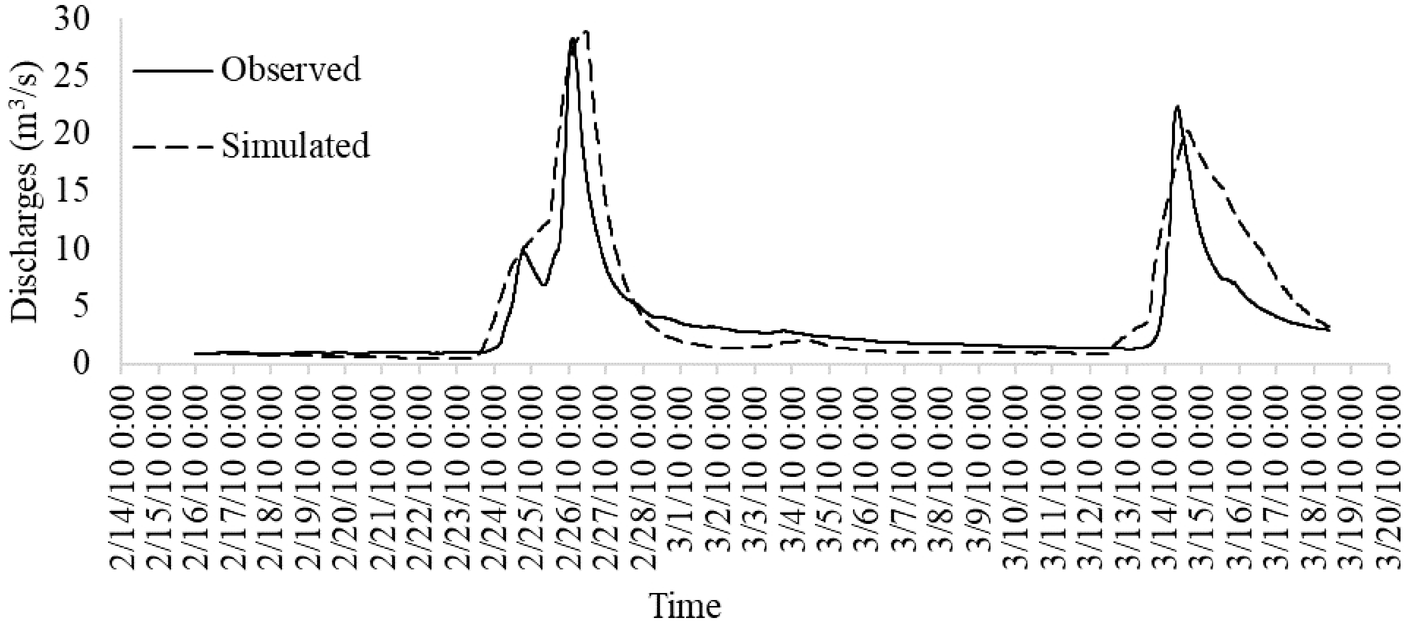

Figure 6. Observed and simulated discharges by HEC-HMS at Warrenville.

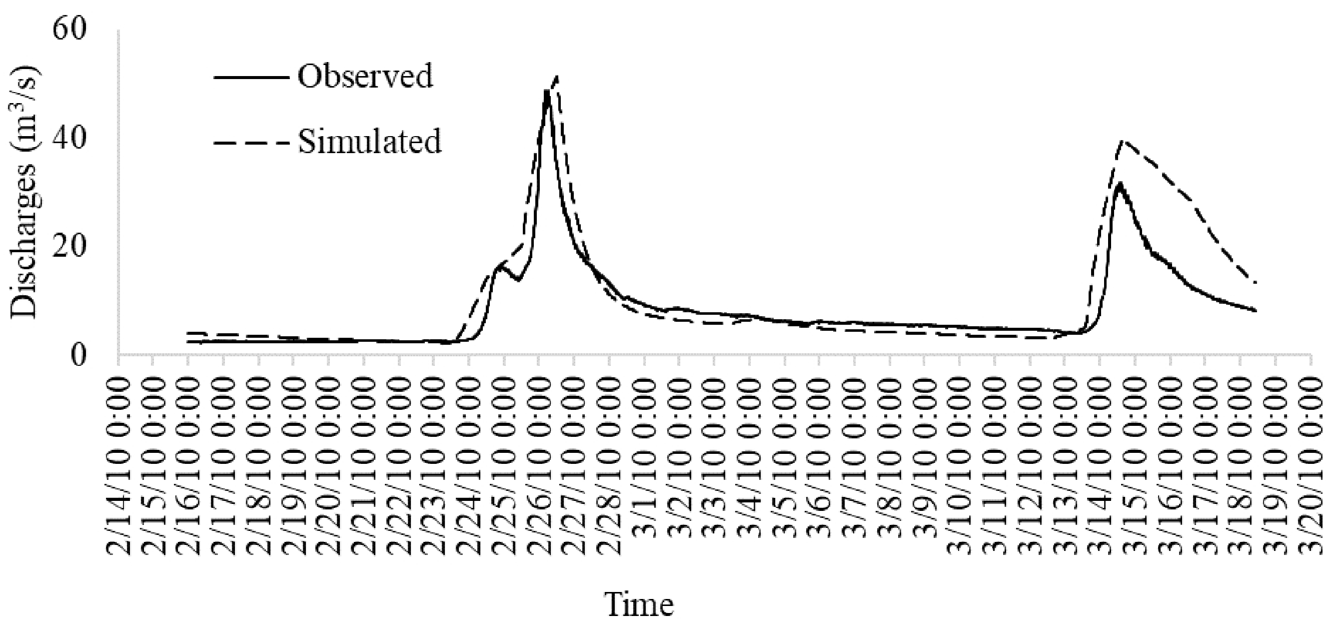

Figure 7. Observed and simulated discharges by HEC-HML at Chaplin.

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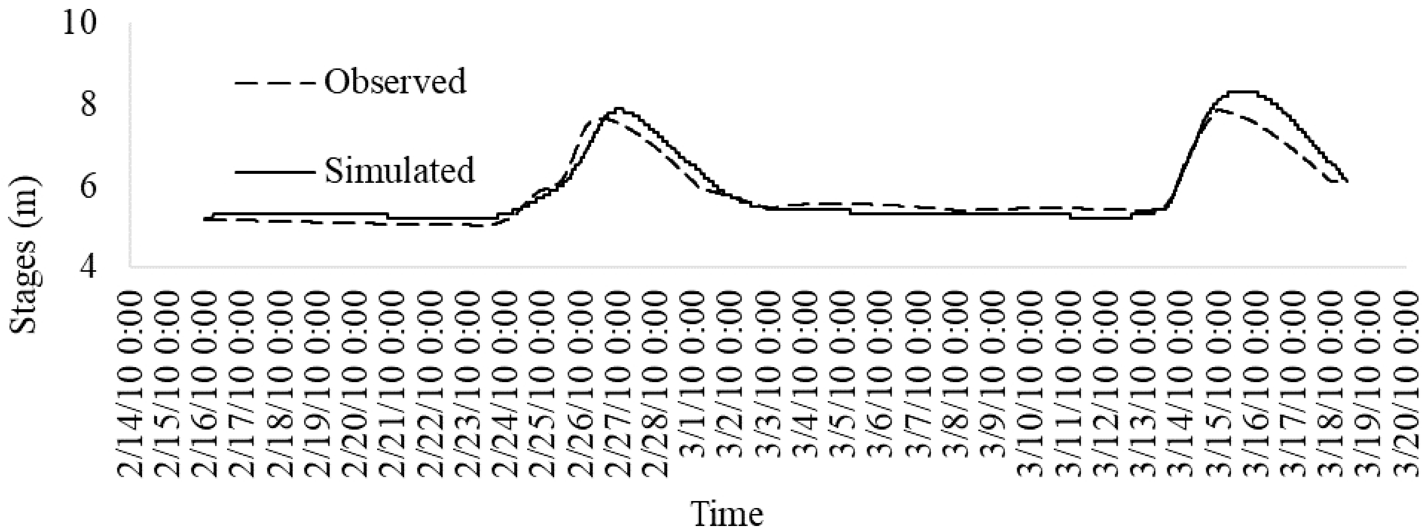

Figure 8. Observed and simulated stages by HEC-HML at the MHL-D.

Figure 9, Figure 10, Figure 11 and Figure 12 shows observed and simulated discharges and stages by the HEC-HMS during the 2019 event in the Fenton, Mount Hope, Natchaug rivers at Old Turnpike, Warrenville, Chaplin, and MHL-D from 01/01/2019 00:00 to 01/12/2019 23:45.

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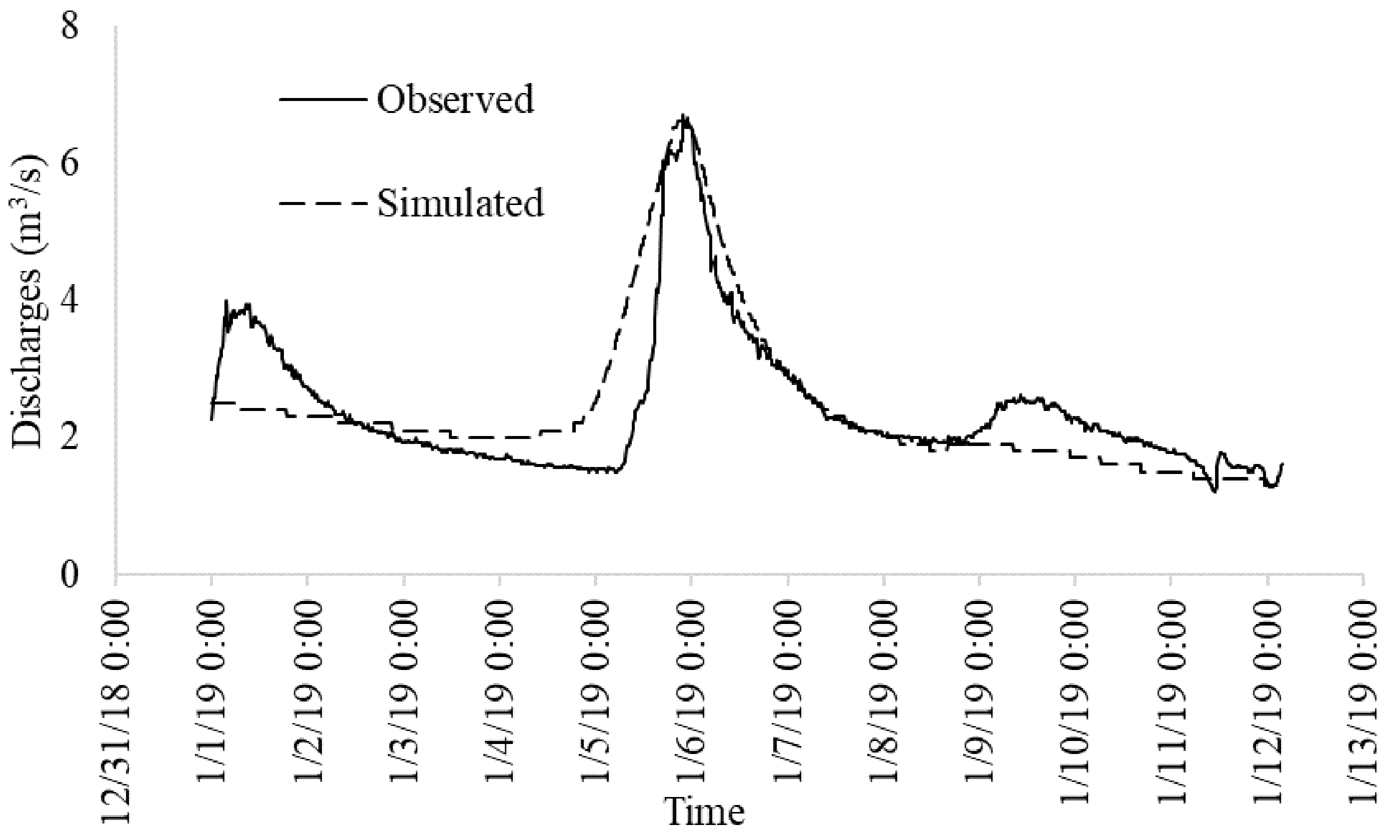

Figure 9. Observed and simulated discharges by HEC-HMS at Old Turnpike.

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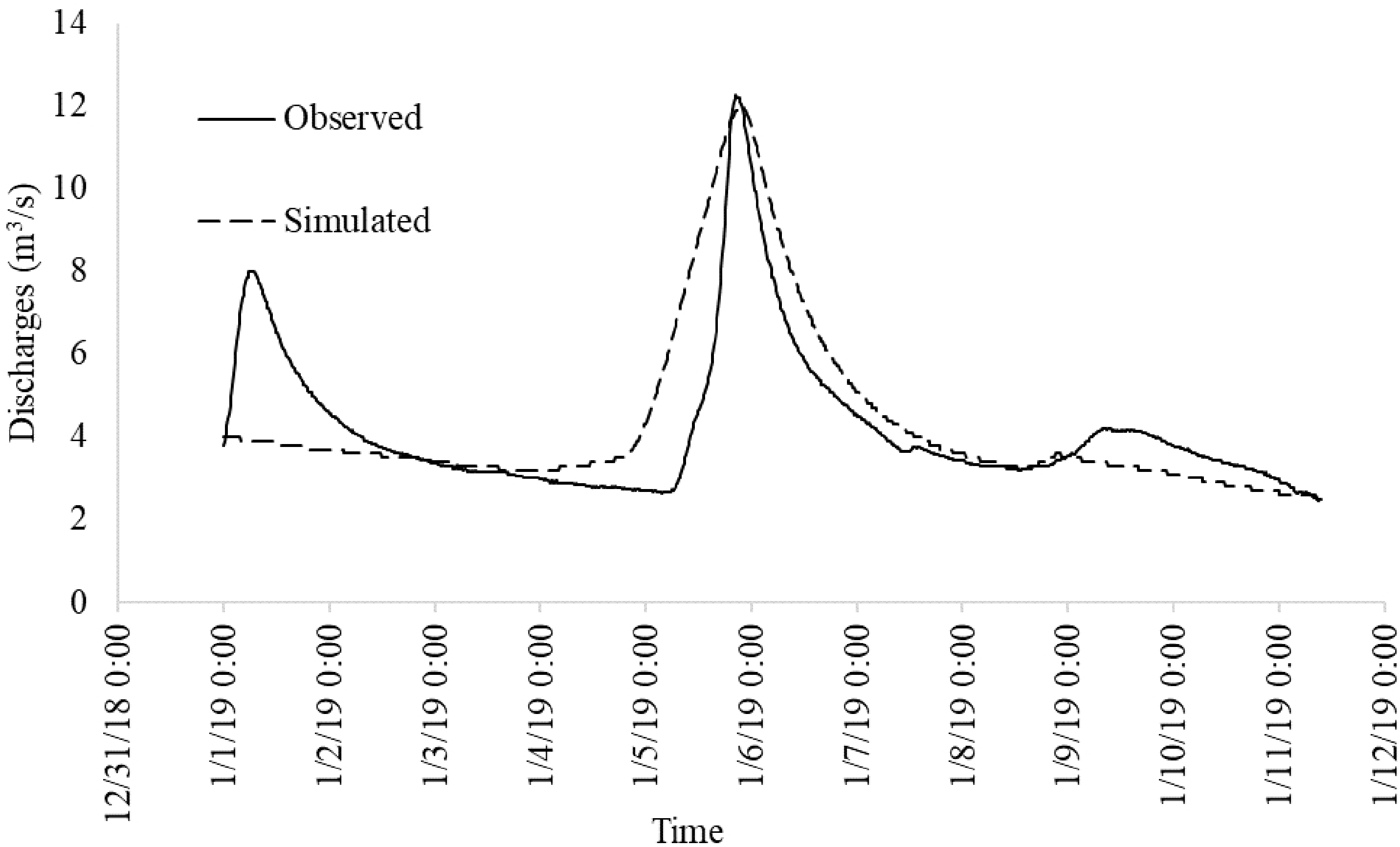

Figure 10. Observed and simulated discharges by HEC-HMS at Warrenville.

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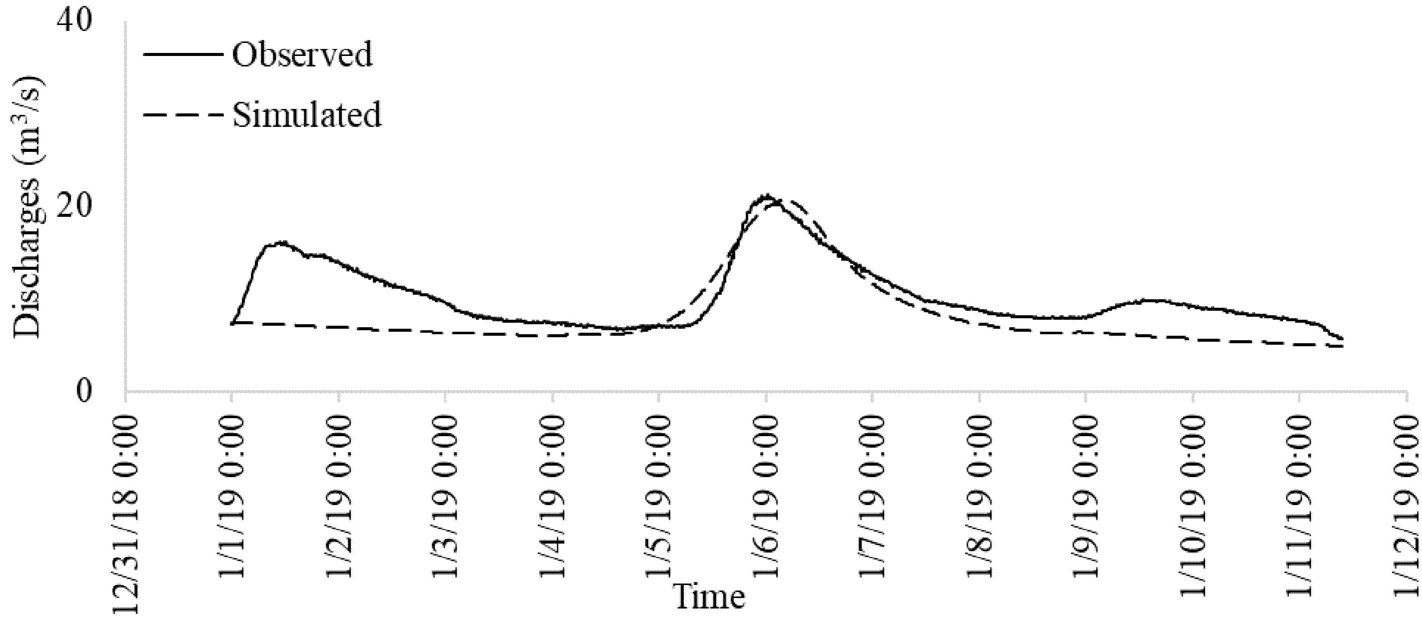

Figure 11. Observed and simulated discharges by HEC-HMS at Chaplin.

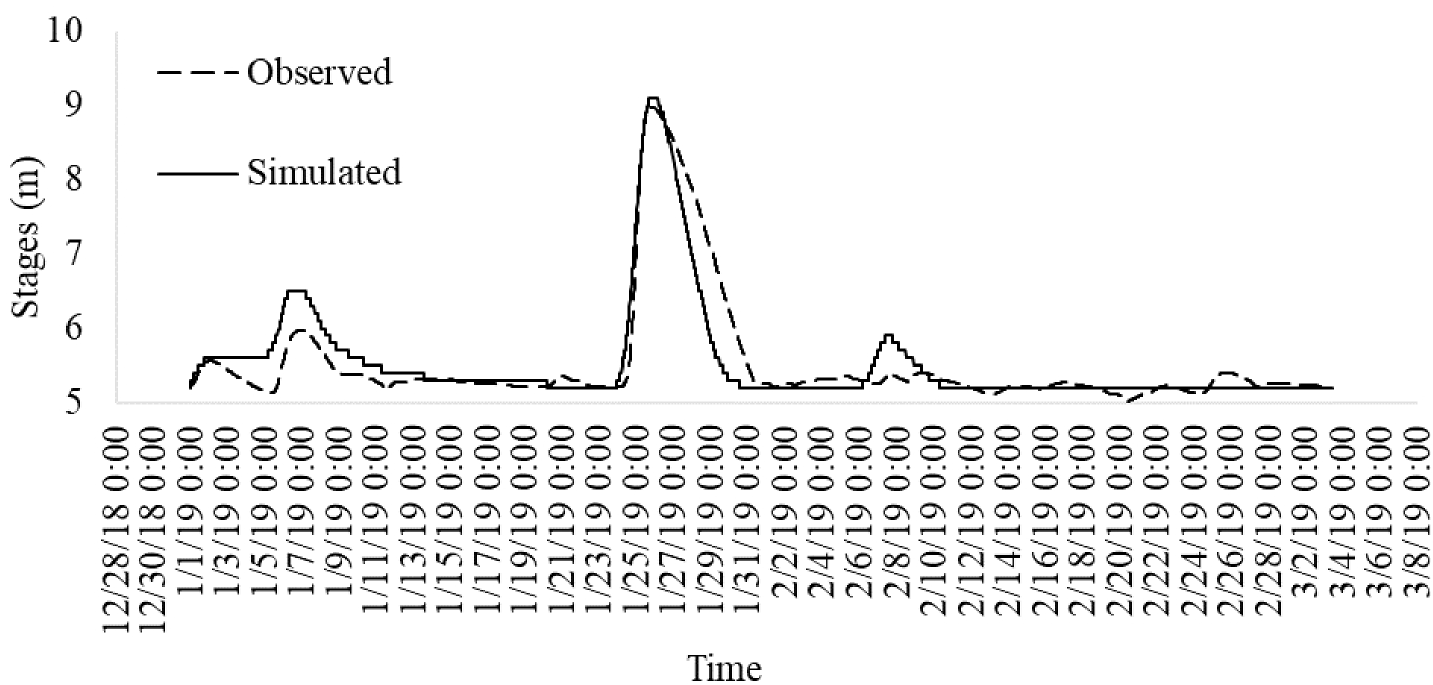

Figure 12. Observed and simulated stages by HEC-HML at the MHL-D.

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Table 7 summarize r-square and NS coefficients obtained after calibration of the simulated HEC-HMS model against observed discharges and stages during the 2010 event from 02/14/2010 00:00 to 03/18/2010 23:45 at USGS Old Turnpike, Warrenville, Chaplin, and USACE MHL-D hydrometric stations.

Table 7. r-square and NS coefficients for the 2010 event.

Location	r-square	NS
Old Turnpike	0.82	0.41
Warrenville	0.84	0.48
Chaplin	0.86	0.48
MHL-D	0.93	0.99

The best-performing location after calibration during the 2010 simulation was the Mansfield Hollow Lake Dam, with an R-squared value of 0.93 and an NS (Nash-Sutcliffe) coefficient of 0.99. The Old Turnpike in the Fenton River, while the worst-performing location, still produced satisfactory results, with an R-squared value of 0.82 and an NS coefficient of 0.41.

Table 8 summarizes the r-square and NS coefficients obtained after calibration of the simulated HEC-HMS model against observed discharges and stages during the 2019 event from 01/01/2019 00:00 to 01/12/2019 23:45 PM at USGS Old Turnpike, Warrenville, Chaplin, and USACE MHL-D hydrometric stations.

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Table 8. r-square and NS coefficients for the 2019 event.

Location	r-square	NS
Old Turnpike	0.85	0.76
Warrenville	0.78	0.77
Chaplin	0.77	0.81
MHL-D	0.85	0.99

The best-performing location after calibration during the 2019 simulation was Mansfield Hollow Lake Dam (MHL-D), with an R-squared value of 0.85 and an NS (Nash-Sutcliffe) coefficient of 0.99. The Warrenville location in the Mount Hope River was the worst-performing, but it still produced satisfactory results, with an R-squared value of 0.78 and an NS coefficient of 0.77.

To explore snowfall's contribution to the discharges and the performance of HEC-HMS during the 2010 and 2019 events, inflows to the MHL-D have been simulated under two scenarios, with snowpack (Scenario 1) and without snowpack (Scenario 2). The observed SWE, Air temperatures, and Precipitations were included in the analysis of the water balance.

Figure 13 shows the simulated inflows in the MHL-D during the 2010 event by HEC-HMS and precipitation.

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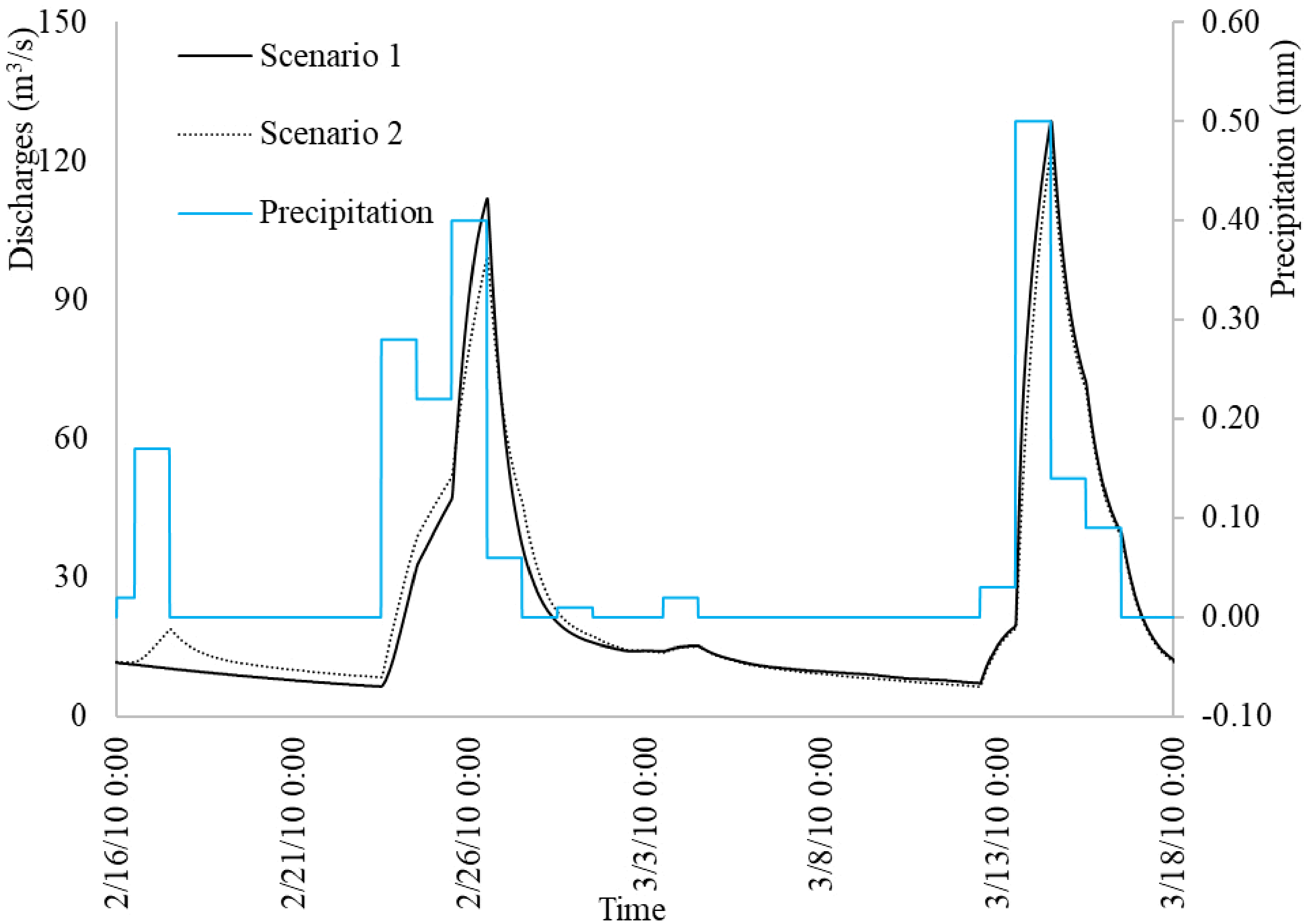

Figure 13. Simulated inflows at the MHL-D during the 2010 event.

Figure 14 shows the simulated accumulated inflow at the MHL-D with snowpack (Scenario 1) and without snowpack (Scenario 2) during the 2010 event by HEC-HMS.

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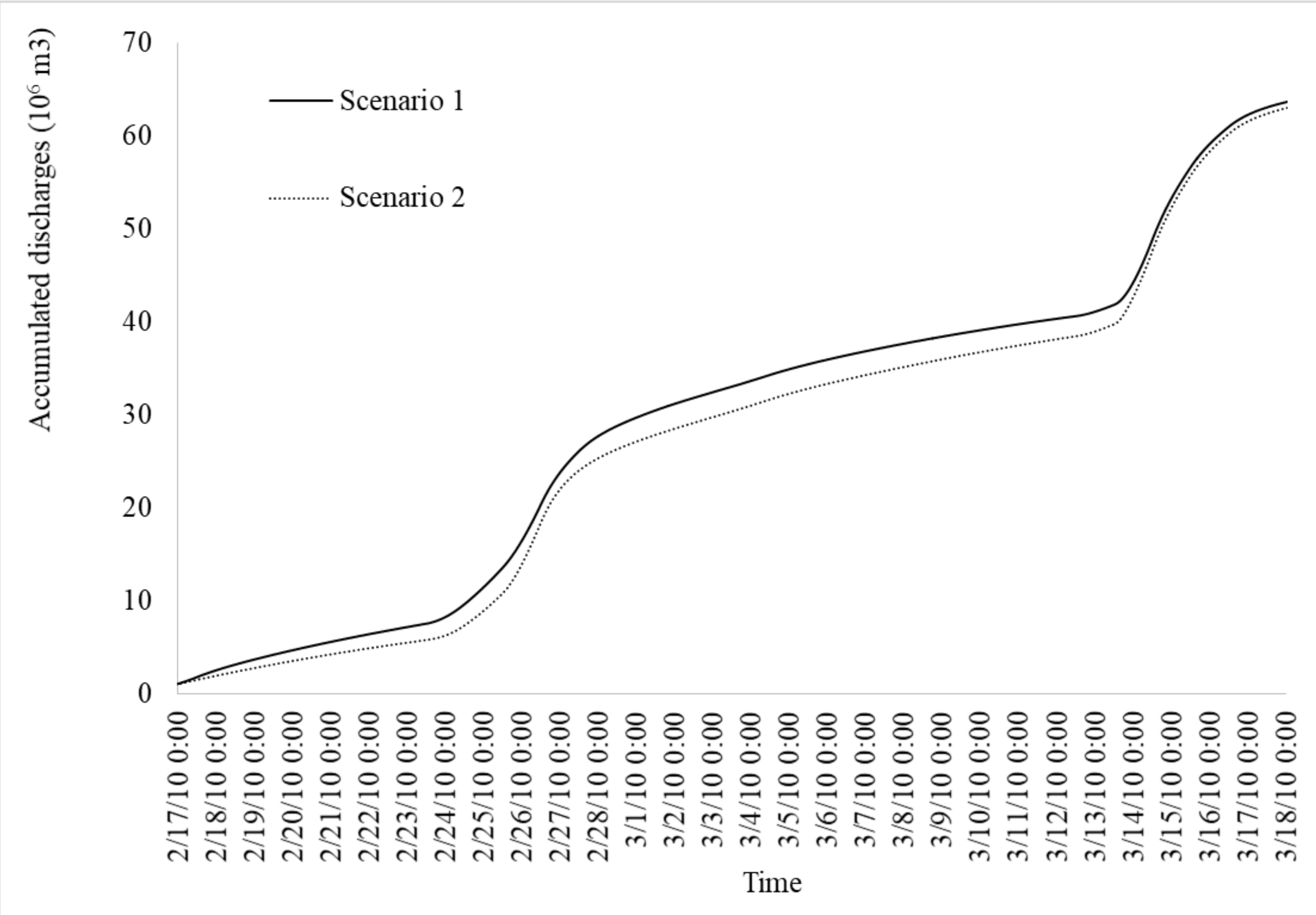

Figure 14. Simulated accumulated inflows at the MHL-D during the 2010 event.

During the 2010 event, the peak discharge for Scenario 1 was 128.6 m^3/s, while Scenario 2 had a peak discharge of 122.5 m^3/s, representing a 5 % increase with the snowpack simulation. The accumulated discharge for Scenario 1 was 64.0 million m^3, compared to 63.3 million m^3 for Scenario 2, resulting in a total volumetric difference of 0.6 million m^3, or 1 % greater with the snowpack simulation.

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Figure 15 shows SWE, Zero-degree C temp and average air temperature during the 2010 event.

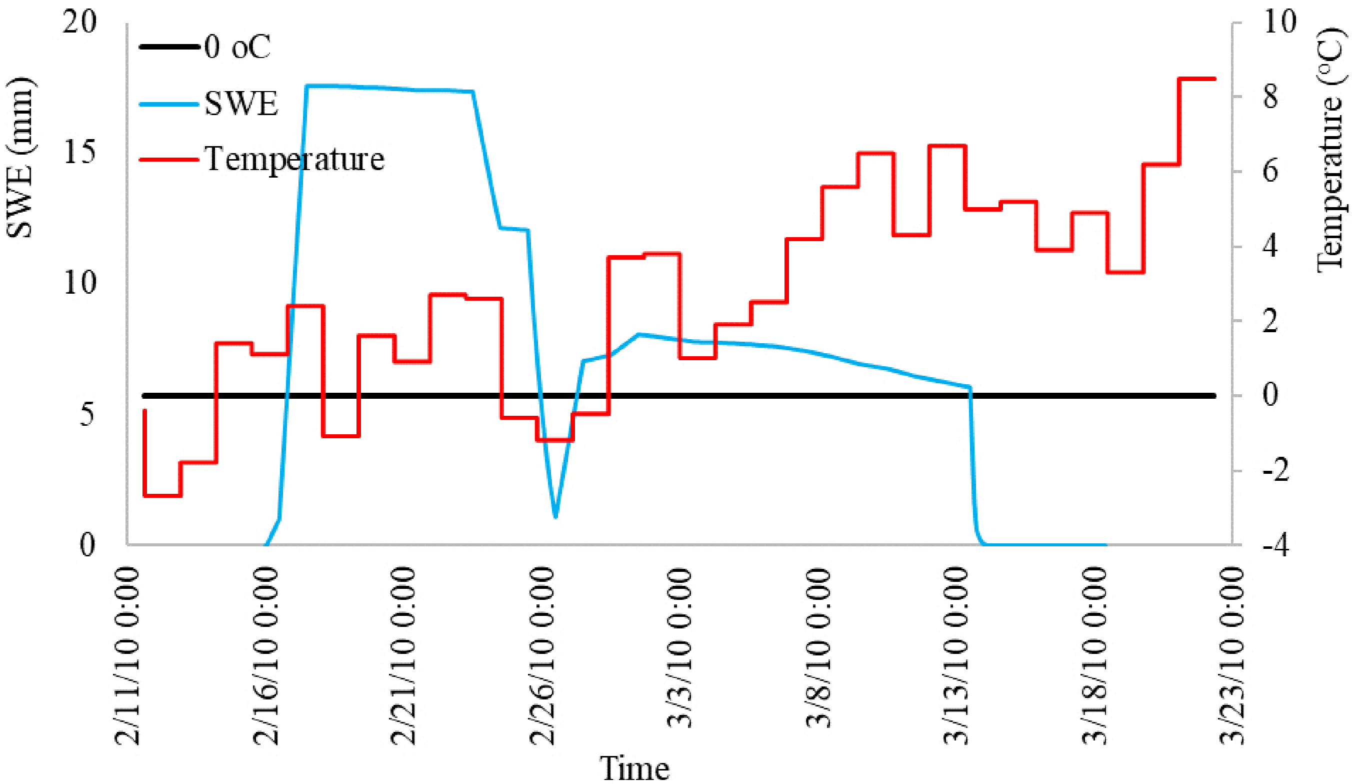

Figure 15. SWE, Zero-degree C temp and average air temperature during the 2010 event.

The melt rate of snow depends on the temperature and due to the fact that daily average air temperature rose above zero during almost all the 2010 event, the snow started to melt from the beginning of the simulation for Scenario 1, thus, there is not much difference in the hydrograph and the accumulated discharges between Scenario 1 and Scenario 2.

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Figure 16 shows the simulated inflow at the MHL-D with snowpack (Scenario 1) and without snowpack (Scenario 2) during the 2019 event by HEC-HMS and precipitation.

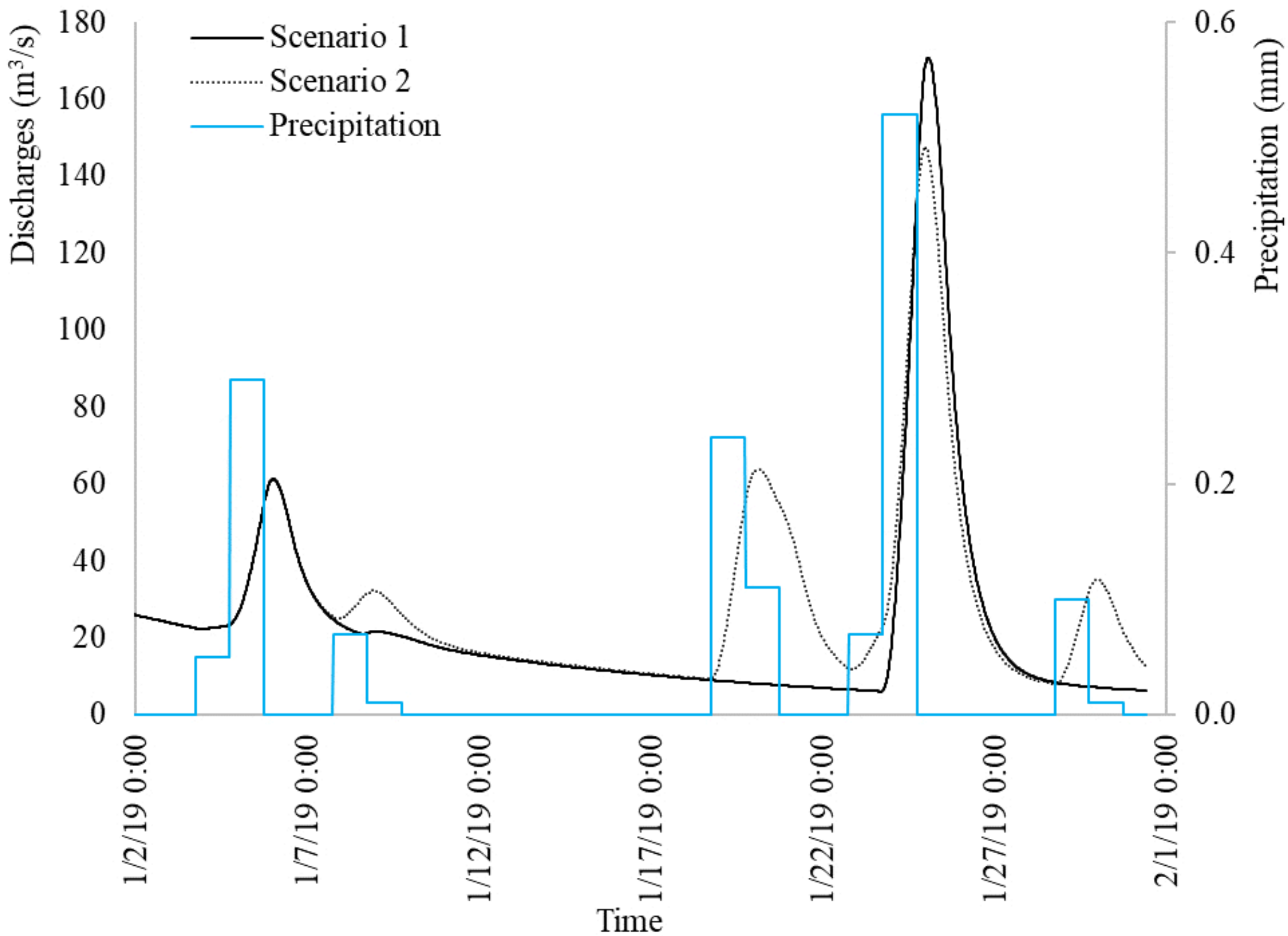

Figure 16. Simulated inflows at the MHL-D during the 2019 event.

Figure 17 shows the simulated accumulated inflow at the MHL-D with snowpack (Scenario 1) and without snowpack (Scenario 2) during the 2019 event by HEC-HMS.

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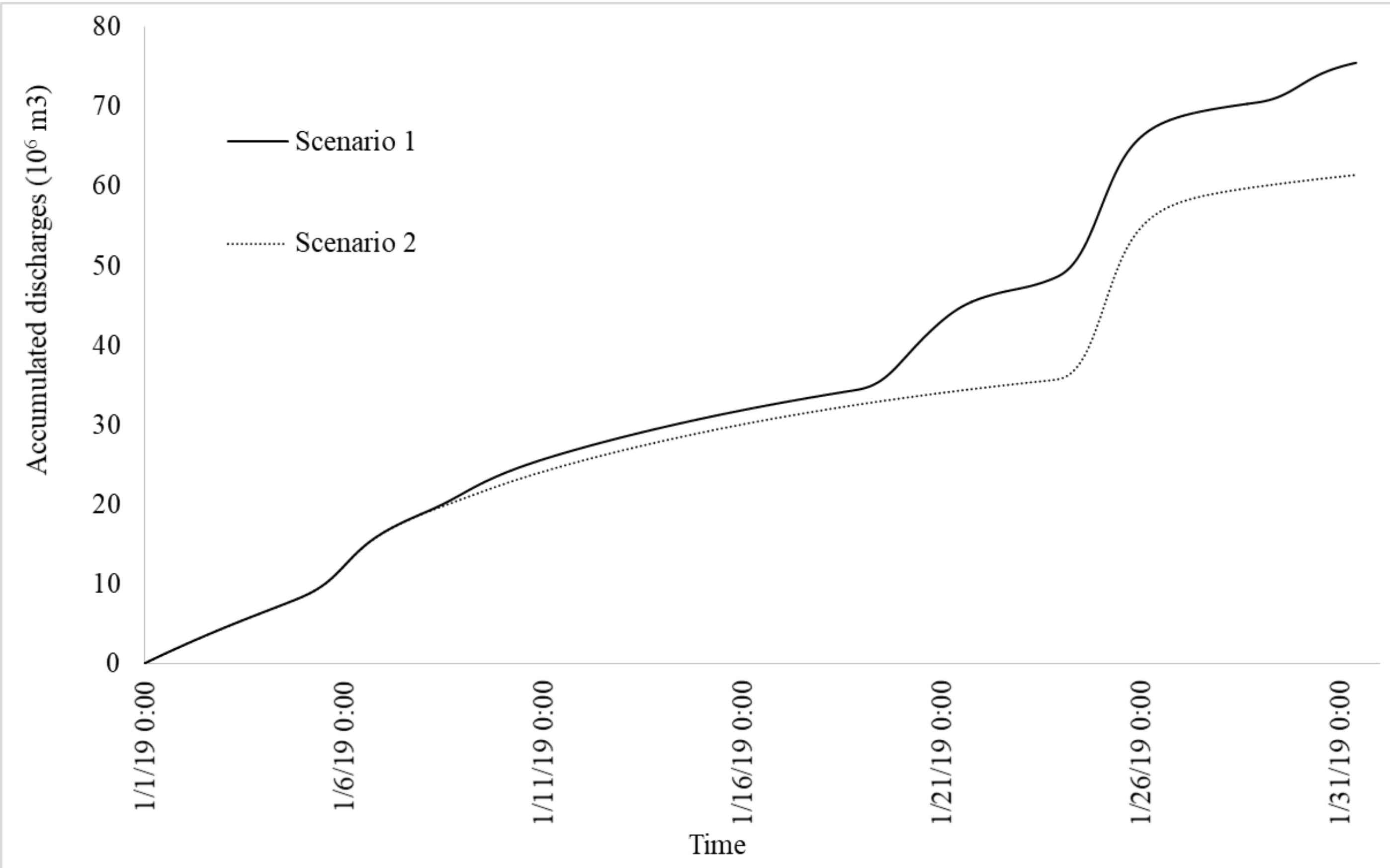

Figure 17. Simulated accumulated inflows at the MHL-D during the 2019 event.

During the 2019 event, the peak discharge for Scenario 1 was 170.7 m^3/s, while Scenario 2 had a peak discharge of 147.6 m^3/s, representing a 16 % increase with the snowpack simulation. The accumulated discharge for Scenario 1 was 75.5 million m^3, compared to 61.5 million m^3 for Scenario 2, resulting in a total volumetric difference of 14.0 million m^3, or 23 % greater with the snowpack simulation.

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Figure 18 shows SWE, Zero-degree C temp and average air temperature for the 2019 event.

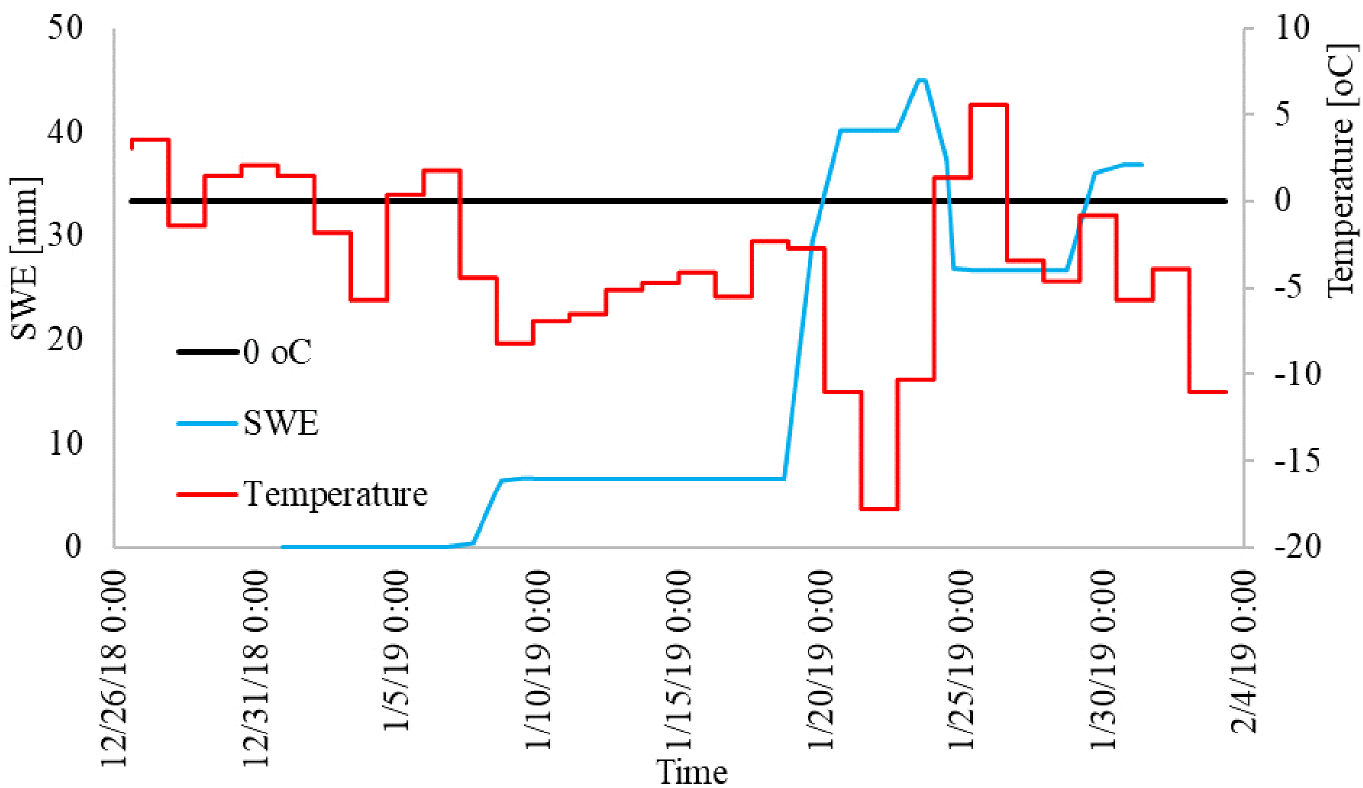

Figure 18. SWE, zero-degree C temperature and average air temperature during the 2019 event.

During the 2010 simulation the model calibration achieve coefficients r-square above 0.82 (very good) and NS above 0.41 (acceptable). During the 2019 simulation the model validation achieve coefficients r-square above 0.77 (very good) and NS above 0.76 (very good).

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Scenario 1 and 2 (with and without snowmelt process) have r-square of 0.98 for the simulated discharges and the accumulated discharges have a total volumetric difference of 8.81 million m^3 of water.

During the 2010 event, the model calibration achieves coefficients r-square above 0.82 (very good) and NS above 0.41 (acceptable).

During the 2019 event, the model validation achieves coefficients r-square above 0.77 (very good) and NS above 0.76 (very good).

During the 2010 event (with and without snowmelt process) peak discharges for Scenario 1 was 128.6 m^3/s and 122.5 m^3/s for Scenario 2, with an increase of 5 % with snowpack simulation. The accumulated discharges for Scenario 1 was 64.0 million of m^3 and 63.3 m^3 for Scenario 2, with a total volumetric difference of 0.6 million m^3 of water, 1 % greater with snowpack simulation.

During the 2019 event (with and without snowmelt process) peak discharges for Scenario 1 was 170.7 m^3/s and 147.6 m^3/s for Scenario 2, with an increase of 16 % with snowpack simulation. The accumulated discharges for Scenario 1 was 75.5 million of m^3 and 61.5 m^3 for Scenario 2, with a total volumetric difference of 14.0 million m^3 of water, 23 % greater with snowpack simulation.

Taking in consideration that the melt rate of snow depends on the temperature and due to the fact that daily average air temperature rose above zero during almost all the 2010 event, the snow started to melt from the beginning of the simulation for Scenario 1, thus, there is not much difference in the discharges between Scenario 1 and Scenario 2.

Meanwhile for the 2019 event the average daily air temperature remained below zero, the snow did not melt for a significant portion of

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the simulation. However, when it finally did melt, it resulted in an increased flow and the accumulated discharges in the watershed with a significant increase in the volume of water.

Taking in consideration that the water storage of the Mansfield Hollow Lake Reservoir is 64 million of m^3, 8.81 and 14.0 million of m^3 of water during a snowmelt process represents 14 and 21 % of the total water storage in the reservoir in just one month during 2010 event and one month and half during 2019.

Scenario 1 and 2 shows that the Snowpack works as water storage meanwhile temperatures are under zero and released as soon temperature is above zero, changing the water balance in the watershed creating increasing possibilities of flood.

Conclusions

The study aimed to assess the impact of snowmelt on water discharges and evaluate the performance of HEC-HMS during extreme weather events, specifically focusing on snowmelt runoff in the Mansfield Hollow Lake Watershed during the winter seasons of 2010 and 2019. To ensure the accuracy and reliability of the model, calibration was performed using observed discharges and stages from the 2010 event using discharges and stages recorded at USGS gauge stations on the Fenton, Mount Hope, and Natchaug rivers, and a USACE gauge at the Mansfield Hollow Lake Dam. Validation was then carried out with the 2019 data.

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Simulations were run both with (Scenario 1) and without the snowmelt process (Scenario 2) to compare peak discharges and accumulated water volumes for the 2010 and 2019 events.

The results indicate that snowmelt significantly affects instantaneous discharges and the total volume of water delivered by the Mansfield Hollow Lake Watershed. Snowmelt occurs when accumulated snowpack melts due to temperatures rising above freezing, resulting in water flowing downstream. Average air temperature is a crucial factor for predicting discharges, as snowpack acts as a water reservoir while temperatures are below 0 °C. However, rapid snowmelt combined with heavy rainfall can cause flooding and damage to infrastructure and human life. Climate change is accelerating snowmelt in many areas, potentially leading to water shortages later in the year.

In the 2010 event, the model calibration achieved an r-square value above 0.82, reflecting very good performance, and a Nash-Sutcliffe Efficiency (NS) coefficient above 0.41, which is acceptable. Peak discharges for Scenario 1 were 128.6 m^3/s and 122.5 m^3/s for Scenario 2, showing a 5 % increase with snowpack simulation. The accumulated volumetric discharges were 64.0 million m^3 for Scenario 1 and 63.3 million m^3 for Scenario 2, with a volumetric difference of 0.6 million m^3—1 % higher with snowpack.

During the 2019 event, the model validation achieved an r-square value above 0.77 and an NS coefficient above 0.76, indicating very good performance. Peak discharges for Scenario 1 were 170.7 m^3/s, compared to 147.6 m^3/s for Scenario 2, reflecting a 16 % increase with snowpack simulation. Accumulated volumetric discharges were 75.5 million m^3 for

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Scenario 1 and 61.5 million m³ for Scenario 2, with a volumetric difference of 14.0 million m³—23 % higher with snowpack.

The model demonstrated strong performance in both 2010 and 2019, showing robust calibration and validation, which highlights its reliability for hydrological simulations. The snowmelt rate depends on temperature, and during the 2010 event, where the average daily temperature remained above zero, snowmelt occurred early, resulting in minimal discharge differences between Scenarios 1 and 2. In contrast, during the 2019 event, with temperatures remaining below zero for much of the simulation, snowpack accumulated and led to significantly higher discharges once the snow melted.

The impact of snowmelt on discharge simulations was substantial, with a minimal volumetric difference of 0.6 million m³ in 2010 and a larger difference of 14.0 million m³ in 2019. This suggests that sudden snowmelt is a critical factor influencing water volume and peak discharges.

Given that the Mansfield Hollow Lake Reservoir's capacity is 64 million m³, the snowmelt influx of 0.6 million m³ during the 2010 event represented 1 % of the reservoir's total capacity, while the 14.0 million m³ influx in 2019 accounted for 21 % of the reservoir's capacity over one and a half months.

Understanding snowmelt's contribution to runoff is essential for various fields, including hydrology, thermodynamics, ecology, water management, and climate science. Snowmelt serves as a vital water source, especially in mountainous regions, and is crucial for predicting water availability for agriculture, drinking, and industry during warmer months. Insight into snowmelt timing and volume helps manage

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reservoirs and dams effectively, ensuring flood control and optimal water storage.

The high r-square and NS values in both scenarios underscore the importance of accurate snowmelt modeling, particularly in years with significant snowmelt contributions. The study confirms the model's effectiveness in simulating hydrological events and highlights snowmelt's critical role in discharge calculations. By employing modeling systems like HEC-HMS, researchers and decision-makers can better simulate extreme weather effects and make informed decisions on water management and flood control. The choice of snowmelt simulation method will depend on various factors, including data availability, model complexity, and research objectives. Accurate prediction of snowmelt and rainfall runoff is increasingly vital as climate change impacts snowmelt-dominated watersheds worldwide, ensuring the resilience and sustainability of water resources.

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