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Mapping Floods of Fenton River, an Ungauged Stream in Connecticut

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Abstract

The study describes the modeling of flood events of an ungauged river by using recorded data from a neighboring watershed. The Fenton and Mount Hope Rivers are two tributaries of the Thames River in Northwest Connecticut, New England. The Fenton River was an ungauged stream until 2006, the Mount Hope River has stream discharges measurements since 1940. Due to the lack of discharge measurements in the Fenton River during the XX century, there is a huge uncertainty about the characteristics of past flood events. An analysis was conducted to map the most important floods in the Fenton River around the pump wells of the University of Connecticut (UConn) with simulated peak discharges applying the drainage-area ratio methodology using recorded peak discharges from the Mount Hope River in 1955, 2005 and, 2008. Flood maps of the Fenton River were generated applying a one-dimensional (1D) HEC-RAS model for the 1955, 2005, 2008 events and a simulated 2022 flood. The methodology shows that it is possible to simulate flood maps of past events using a neighboring watershed discharges.

Keywords

Floodmaps, HEC-RAS Model, Drainage-Area Ratio Method, Connecticut

1. Introduction

Hydrological studies are useful in designing, planning, and managing water resources, infrastructure, and ecosystems. However, the danger of natural hazards due to their very extreme probability of occurrence cannot be completely avoided, and water engineers often face major challenges in estimating the impact of these events [1].

The most accurate way of obtaining information on streamflow discharges at any location is to measure them for an extended period, but sometimes this is not possible. The alternative is to estimate them by modelling methods from measurements at other locations in the region [2].

The Fenton, Mount Hope and Natchaug Rivers are part of the Thames River watershed in Connecticut [3]. The USGS (United States Geological Survey) has been taking measurements of discharges in the Fenton River at Old Turnpike Bridge since October 2006 [4] and in the Mount Hope River at Warrenville since 1940 [5]. The University of Connecticut (UConn) pumps water from four different wells along the Fenton River (Wells A, B, C and D) to supply the UConn Campus at Storrs. Well A was installed in 1926, B and C were installed in 1949 and D in 1959 [6].

The drainage-area ratio method has been tested by the USGS [7] and applied where discharge measurements were not recorded. Due to the lack of stream flow measurements in the Fenton River during the twentieth century and the availability of daily and instantaneous stream flow measurements for a long period of time in the neighboring watershed the Mount Hope River from 1940 to the present, the Mount Hope River discharges were used to identify flood events in this watershed and simulate discharges from Mount Hope to the Fenton watershed. Due to the fact that in the year 2008 was the first recorded flood in Fenton River, this year was used to calibrate the drainage-area ratio coefficient with observed discharges in the Fenton River. Then, this method was applied to simulate peak flow discharges during the two biggest unrecorded flood events, in 1955 and 2005, in the Fenton River with the calibrated coefficient. Then, a one dimensional (1D) HEC-RAS model was applied for the Fenton River downstream of the Old Turnpike Bridge to map the floods in 1955, 2005, 2008 and a simulated 2022 event. The study area for the evaluation of the flood plain for these events is around the location of UConn wells that includes the two main roads inside the study area, the Pumping Road that connects Wells A, B and C, from Well C to Old Turnpike Bridge that crosses the place known as the Meadows (the Countryside Road), and the five bridges that cross the Fenton River.

2. Methods

2.1. Characteristics of the Watersheds

The Fenton River has a total length of 23 km and a drainage area of 89 km^2 [6] as it enters Mansfield Hollow Lake and has since October of 2006 a gagging station for the estimation of daily stream flow discharges located at the bridge of Old Turnpike Road, USGS gage # 01121330, Tolland County, Latitude 41˚49'59.50", Longitude 72˚14'34.01" NAD83 [4] with a drainage area of 47.4 km^2. The Mount Hope River has a total length of 23 km and a drainage area of 74.1 km^2 at the USGS gage # 01121000, Windham County, located at Warrenville, Latitude 41˚50'37", Longitude 72˚10'10" NAD27 [5]. The distance between USG-Warrenville to USGS-Old Turn Pike is 7.52 km. **Figure 1** shows the location of the Fenton and Mount Hope watersheds within the State of Connecticut, in New England, USA. **Figure 2** shows the Fenton and Mount Hope Rivers and points of interest.

The land cover of the Fenton and Mount Hope watersheds is principally forested (84%) with some non-forested vegetation (8.3%) and urban areas (2.8%), [8]. There are 5 bridges that cross the Fenton River from Old Turnpike Road to the outlet in Mansfield Hollow Lake, Old Turnpike was built in 1970, Gurleyville (1970), Stonemille (2012), Chaffeville (1950), and Warrenville Road (1950). Table 1 summarizes the main structural parameters and the year of construction of the Fenton River Bridges [9].

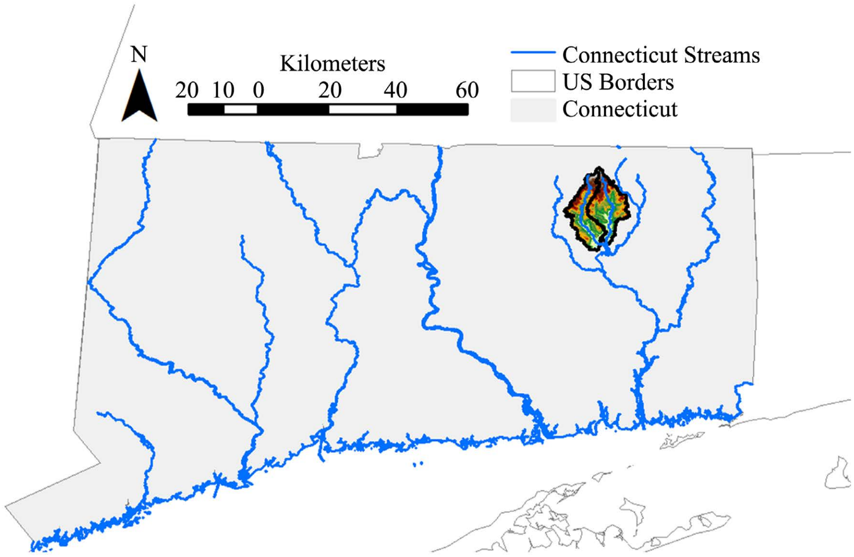

Figure 1. Mount hope and Fenton watersheds within the state of Connecticut, New England.

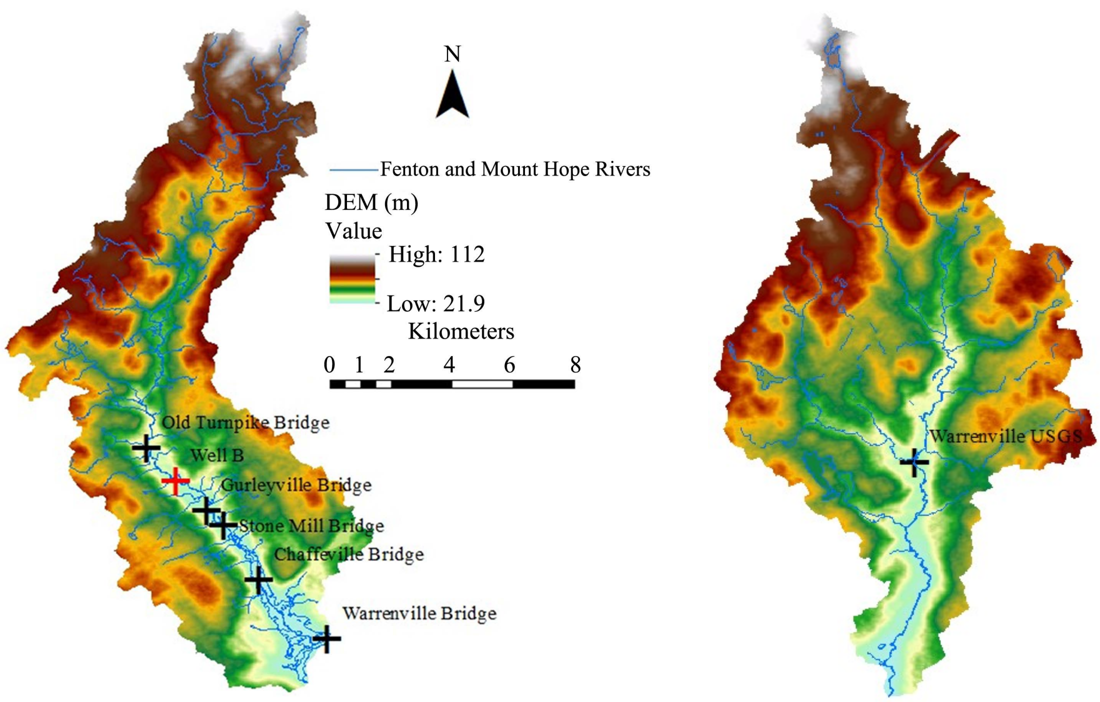

Figure 2. Fenton River (left) and Mount Hope River (right).

Table 1. Bridges over the Fenton River.

Bridge name	Year built	Length (m)	Width (m)	Design	Road
Old Turnpike	1970	9.1	6.2	slab	Old Turnpike
Gurleyville	1970	13.1	7.2	slab	Gurleyville
Stonemill	2012	23.8	7.2	frame	Stonemill
Chaffeville	1950	8.8	7.2	culvert	Chaffeville
Warrenville	1953	7.6	7.2	culvert	89

2.2. Hydrologic Engineering Center-River Analysis System (HEC-RAS)

HEC-RAS is a hydraulic model developed by the Hydrologic Engineering Center (HEC) of the U.S. Army Corps of Engineers [10] that can create a fully functional modeling environment which allows to cope with virtually all types of problems concerning river networks, including flood maps [11]. HEC-RAS uses several input parameters for hydraulic analysis and includes a geographic information system interface called RAS Mapper [12] [13].

2.3. Drainage-Area Ratio Method

The drainage-area ratio method is a technique that transfers same-day streamflow information from one location to another based on the drainage areas of the two locations. The method is mathematically simple and requires little data [14]. The drainage-area-ratio equation is as follows:

$$Q_2 = \left(\frac{DA_2}{DA_1}\right)^b * Q_1 \tag{1}$$

where:

Q_2 : is the discharge for the selected ungauged station

Q_1 : is the discharge for the selected gagged station

DA_1 : is the drainage area at the ungauged site,

DA_2 : is the drainage area at the gaged site, and

b: Is the exponent of the drainage-area only for regional regression equations given by Equation (2):

$$b = \frac{\log_{10}\frac{Q_1}{Q_2}}{\log_{10}\frac{DA_1}{DA_2}} \tag{2}$$

where:

Q_1 : is the discharge at the gagged site

Q_2 : is the discharge at the ungauged site

DA_1 : is the drainage area at the gagged site

DA_2 : is the drainage area at ungauged site

Usually the drainage-area method has been applied with an exponent of $b = 1$, but research conducted by USGS shows that this parameter can vary between 0.74 and 1.343 with contributing drainage areas from 1.01 to 107,256 km^2 [15].

2.4. Nash and Sutcliffe Coefficient

The observed discharges of the Mount Hope and Fenton Rivers were used to calibrate the parameter b of the drainage-area ratio method by optimizing the Nash-Sutcliffe (NS) model of efficiency [16], given by Equation (3).

$$NS = 1 - \frac{\sum_{i=1}^{n}(O_i - S_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2} \quad (3)$$

where:

O_i: Observed discharges

$\bar{O}$: Mean of observed discharges

S_i: Simulated discharges

n: Number of steps modeled

The Nash-Sutcliffe (1970) model's value of NS can range from −∞ to 1. The closer the model NS is to 1, the more accurate the model is. If NS < 0, it means that the observed data mean is a better predictor than the model [17].

3. Results and Discussion

3.1. Fenton and Mount Hope Rivers Peak Discharge Relationship

Figure 3 shows the linear regression and the r-squared, between the daily average discharges of the Mount Hope and Fenton Rivers from 10/01/2006 to 11/30/2020 [4] [5].

Figure 4 shows the linear regression and the r-squared, between instantaneous annual peak discharges of the Mount Hope and the Fenton Rivers from 01/01/2009 to 12/31/2020 [4] [5].

Table 2 summarizes the correlation coefficients r-squared between daily discharges and annual maximum discharges between the Fenton River and the Mount Hope Rivers.

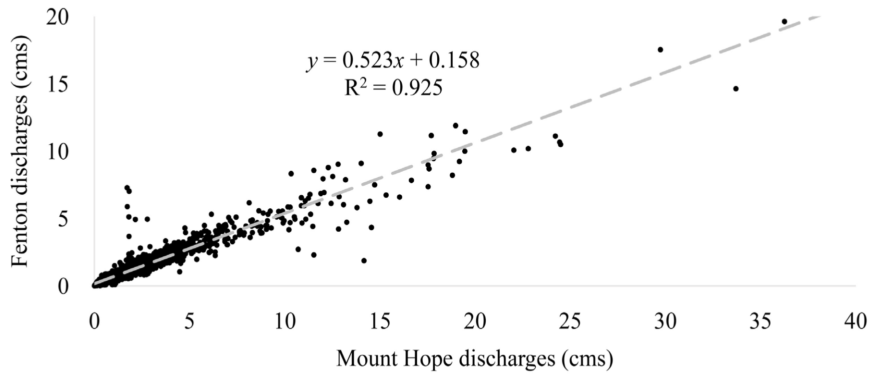

Figure 3. Mount Hope and Fenton Rivers daily discharges from 2006 to 2020.

Table 3 shows the annual peak discharges in the Fenton and Mount Hope Rivers from 2007 to 2020 (the Fenton River started to be recorded on 07/11/2006 and the peak discharge in the Mount Hope was on 06/25/2006). In gray are shown the entries for the days when the peak discharges occur on the same day [4] [5].

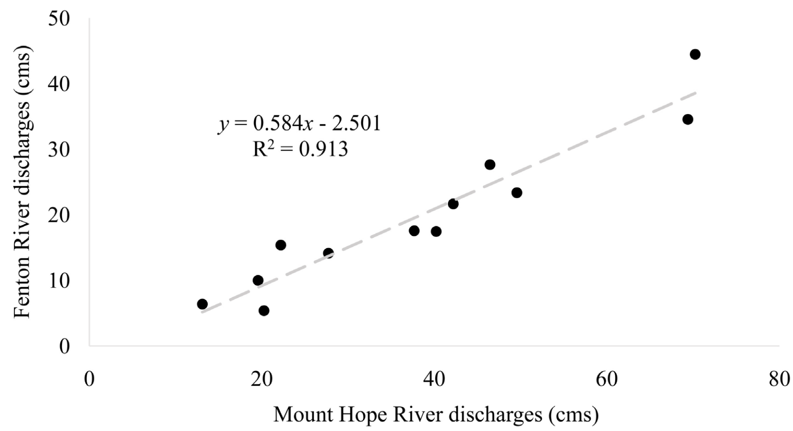

Figure 4. Mount Hope and Fenton Rivers instantaneous annual peak discharges from 2007 to 2020.

Table 2. Correlation coefficients for the Mount Hope-Fenton Rivers.

Watersheds	Daily discharges	Annual daily Maximum discharges
Mount Hope-Fenton	0.9259	0.9138

Table 3. Annual Peak discharge by date and by river from 2007 to 2020. The data is colored in gray, when the discharges of both rivers occurred on the same day.

Fenton	Mount Hope
4/16/2007	4/16/2007
12/12/2008	12/12/2008
7/24/2009	7/24/2009
3/30/2010	3/30/2010
3/7/2011	3/7/2011
4/23/2012	4/23/2012
6/8/2013	6/8/2013
3/30/2014	3/30/2014
4/21/2015	4/4/2015
2/25/2016	2/25/2016
10/30/2017	10/30/2017
4/16/2018	9/26/2018
1/24/2019	1/24/2019
12/25/2020	12/25/2020

Figure 3 and Figure 4 and Table 2 and Table 3 show a strong relationship between the Fenton and Mount Hope discharges, with a correlation coefficient of 0.9259 for average daily discharges and of 0.9138 for instantaneous annual peak discharges with a 92% of possibility that these discharges happen on the same day, validating the transfer of discharge data from one watershed to the other.

Table 4 shows the eight biggest instantaneous peak flow events by ranking, in the Mount Hope River from 1940 to 2020 [5].

From Table 4 it can be seen that the biggest instantaneous peak flow for both the Fenton and Mount Hope Rivers was recorded in 2008. The drainage-area ratio method was applied, and the parameter b was calibrated using the observed discharges during the 2008 flood event. Applying the Nash-Sutcliffe coefficient for the optimization, a parameter $b = 1.34$ was obtained for a Nash-Sutcliffe value of NS = 0.94. Then discharges for the Fenton River on 08/18/1955 and 10/15/2005 were simulated. Figure 5 shows the 2008 flood event observed and the simulated discharges, and the simulated discharges for the 1955 and 2005 flood events for the Fenton River.

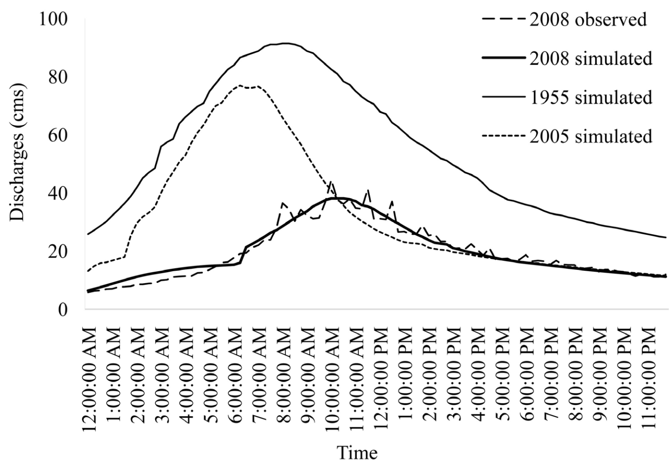

Figure 5. Fenton River discharges every 15 minutes for the flood events during 08/19/1955, 10/15/2005, simulated and observed during 12/12/2008.

Table 4. The 8 biggest recorded instantaneous peak discharges in the Mount Hope River.

#	Date	Flow (cms)
1	08/19/55	158.3
2	10/15/05	141.6
3	09/11/54	92.0
4	04/16/96	91.2
5	01/25/79	87.2
6	03/09/98	79.0
7	06/06/82	77.0
8	12/12/08	70.2

3.2. Flood Maps of the Study Area

Flood maps were simulated for the Fenton River from Old Turnpike Road Bridge to Warrenville Bridge with a length of 9.82 km applying a 1D HEC-RAS model with a Digital Elevation Model (DEM) obtained from the USGS website [18] with a resolution of 1 × 1 meters for the flood events of 08/19/1955, 10/15/2005 and 12/12/2008 and a simulated event with 1955 discharges and 2022 border conditions (5 bridges). The Manning's parameter applied was n = 0.05, corresponding to pit and gravel for the whole stream and an estimated normal depth of 0.00025.

The bridges included in the HEC-RAS model were for the 1955 event: Warrenville (1953) and Chaffeville (1950). For the 2005 and 2008 events: Warrenville, Chaffevile, Old Turnpike (1970) and Gurleyville (1970). For the simulated 2022 event: Stonemille Bridge (2012) plus the other four [9]. **Figure 6(a)-(d)** show the floodplains during the 1955, 2005, 2008 and 2022 events around the Meadows including UConn pumping stations A, B and C.

3.3. Maximum Area, Depth, and Velocity

For the study area during the 1955, 2005, 2008 and 2022 events, the maximum surface area flooded was 1.27, 1.21, 0.99 and 1.25 square kilometers, respectively. The maximum flood depth was 2.52, 2.94, 2.18 and 3.19 meters. The maximum velocity was 2.66, 4.49, 3.10 and 4.98 meters by second. The peak flow was 91.4, 76.9, 44.5 and 91.4 cubic meters by second. The total volume of water was 280, 170, 100 and 280 million of cubic meters. All these parameters are summarized in **Table 5**.

3.4. Roads, Wells and Bridges Flooded

For the 1955 flood event: the Pumping Station and the Countryside Roads were flooded. For the 2005 flood event: the Pumping Station, and Countryside Roads, and the Old Turnpike Bridge were flooded. For the 2008 flood event: the Countryside Road was flooded. For the simulated 2022 event: Pumping Station and Countryside Roads, Wells A, B, and C and Old Turnpike Bridge were flooded. **Table 6** summarizes the simulated flooded areas with infrastructure during the 1955, 2005, 2008 and 2022 flood events.

Table 5. Maximum area, depth, velocity, peak flow, and volume of water during the 1955, 2005, 2008 and 2022 flood events.

Event	1955	2005	2008	2022
Max. Area (Km^2)	1.27	1.21	0.99	1.25
Max. Depth (m)	2.52	2.94	2.18	3.19
Max. Velocity (m/s)	2.66	4.49	3.10	4.98
Peak flow (m^3/s)	91.4	76.9	44.5	91.4
Volume ($m^3 \cdot 10^6$)	280	170	100	280

Table 6. Summary of the simulated flooded areas.

Event	1955	2005	2008	2022
Roads	PS + CR	PS + CR	CR	PS + CR
Wells	None	None	None	A + B + C
Bridges	None	OT	None	OT

* OT: Old Turnpike Bridge; ** CR: Countryside Road; *** PS: Pumping Station Road; **** A, B, C, D: Well A, Well B and Well C.

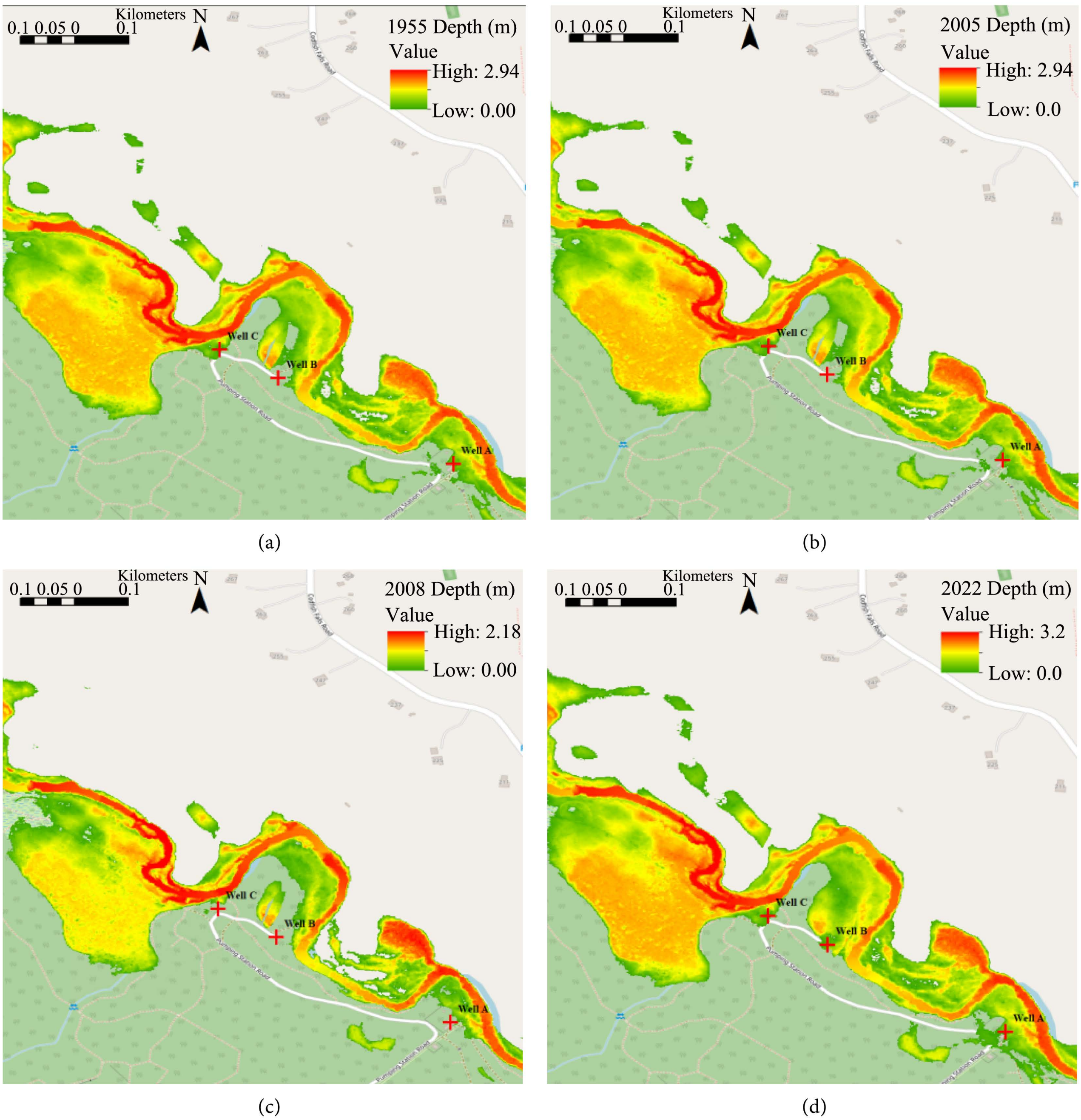

Figure 6. Simulated flood maps of the Fenton River for the flood events of (a) 08/19/1955; (b) 10/15/2005; and (c) 12/12/2008; (d) 31/19/2022 with Google OpenStreetMap© map as background.

4. Conclusions

A study was conducted to simulate flood events of an ungauged river by using recorded data from the neighboring watershed. Flood maps of the Fenton River were simulated using the neighboring Mount Hope River discharges during the most important flood events recorded in the Mount Hope River from 1940 to 2020.

The transfer of discharges from one watershed to the other was achieved, since the two rivers have similar characteristics with a strong correlation between both rivers' daily average discharges, instantaneous annual peak discharges. Also, the days of their peak discharges coincide.

The simulated discharges were used to simulate flood maps in the Fenton River from Old Turnpike Bridge to Warrenville Bridge, using different border conditions due to the construction of bridges preceding those events.

The results show that it is possible to simulate flood maps in an ungauged stream, if the neighboring watershed has a similar area, elevations, vegetative cover, and if the stream flow discharges from the neighboring watershed are available and the hydraulic parameters of the model are well known.

The main problem with the application of ratio-area drainage equation is that it includes the sizes of the watersheds, but does not include any parameter related to the shape of the watersheds. Take in consideration that the shape of the watershed gives physical meaning to the dispersion of the discharge over time, altering the peak flow and time of concentration at the outlet of the watershed. This is the main weakness in the application of the area-ratio drainage equation for this study.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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