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Recent Flooding Events on the Chagrin and Cuyahoga Rivers, Ohio

Kayley Martin
kmm382@uakron.edu

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Department of Geosciences, The University of Akron

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Abstract

From the 1910s through the 1980s, the number of intense daily precipitation events in the United States remained constant, however, since the 1980s there has been an increasing trend in intense single-day precipitation events (U.S Environmental Protection Agency, 2016). One outcome of intense precipitation events is river flooding, particularly in the upper Midwest region where floods have increased in magnitude and frequency (U.S Environmental Protection Agency, 2016). In this thesis project, recent flooding history on the Chagrin and Cuyahoga Rivers in Ohio was studied to expand on previous research that observed an abrupt increase in high magnitude flood events on the Cuyahoga River beginning in July 2003. Mean daily discharge data for the Cuyahoga and Chagrin Rivers (United States Geological Survey, 2021a) and daily precipitation data for the Chagrin River watershed (National Oceanic and Atmospheric Administration, 2021) were analyzed. The two-tailed t-test showed that the mean daily discharge and mean precipitation before and after July 22, 2003 were statistically significantly different. A higher number of top 1% floods and top 10 largest floods occurred after July 22, 2003 on both the Cuyahoga River and the Chagrin River. These results correspond with the observed trend of an abrupt increase in high magnitude river flooding on the Cuyahoga River as well as the trend of increasing flood magnitude and frequency in the upper Midwest region. Mean daily discharge was higher in the winter but lower in the summer while daily precipitation was lower in the winter and higher in the summer as a result of seasonal variations in evaporation, transpiration, runoff, and infiltration. Knowledge of the increasing trends in flood magnitude and frequency is important because this information can be used to help people prepare better, reduce the cost of spending on flood damage, and save lives.

1. Introduction

Floods are one of the deadliest natural disasters in the United States, with 57 recorded deaths caused by flooding in 2020 (National Weather Service, 2021). Flooding is also costly, with 3.75 billion dollars of flood-induced property and crop damage in 2019 (Statista, 2019). The number of intense daily precipitation events in the United States remained constant between 1910 through the 1980s, however, since the 1980s there has been an increasing trend in single-day precipitation events (U.S Environmental Protection Agency, 2016). As of 2016, 9 of the top 10 years for intense single-day precipitation events have occurred since 1990 (U.S Environmental Protection Agency, 2016). The increase in intense single-day precipitation events has been linked to climate change because the warming of the atmosphere increases its moisture carrying capacity and this moisture is released in intense precipitation events (Wing et al., 2018). This increase in intense precipitation events can lead to river flooding (U.S Environmental Protection Agency, 2016). The increased development of impervious surfaces, such as pavement and structures within watersheds enhances runoff and flooding. Approximately 41 million Americans presently live in an area that is at risk of top 1% river floods (Wing et al., 2018). These areas include 1.2 trillion dollars of assets that are at risk of top 1% river floods (Wing et al., 2018).

There has been an increase in precipitation in the upper Midwest region of the United States which has led to an increase in the magnitude and frequency of river floods (U.S. Environmental Protection Agency, 2016). This region includes northeastern Ohio where intense precipitation events significantly increased after July 2003 (Liberatore, 2013). Liberatore (2013) found that since July 2003 there has been an increase in high magnitude floods on the Cuyahoga River. This abrupt increase in the frequency of intense floods was also documented at Yellow

Creek by Delaney (2016). The Cuyahoga River and the Chagrin River are located in adjacent watersheds in northeast Ohio (Figure 1). The Cuyahoga River is approximately 100 miles long and flows into Lake Erie at Cleveland (Stewards of the Cuyahoga River, 2021). The Cuyahoga River watershed drains over 800 square miles and flows through Geauga, Portage, Summit, Stark, and Cuyahoga counties (U.S. Environmental Protection Agency, 2020). The Chagrin River is 47.9 miles long and discharges into Lake Erie at Eastlake (USGS, 2021b). The Chagrin River watershed drains 267 square miles and flows through Cuyahoga, Geauga, Lake, and Portage counties (Chagrin River Watershed Action Plan, 2011). As of 2000, the population in the watershed was 269,879 people (Chagrin River Watershed Action Plan, 2011). Flooding and flood-related damage has historically been a concern in the watershed and this concern continues to the present day (Chagrin River Watershed Action Plan, 2011). In recent years in the watershed, people have been moving from the urban cities to the less developed suburban and rural areas (Chagrin River Watershed Action Plan, 2011). The primary land use in the watershed is low-density residential impervious cover where the Chagrin River is less developed (Chagrin River Watershed Action Plan, 2011).

This study updates the Cuyahoga River flood history done by Liberatore (2013) and Delaney (2016). Their research documented an abrupt increase in flood magnitude and frequency that began in July 2003 that continued through 2016. This study extends the flood history through 2020 to understand the methods of flood analysis and tests the hypothesis that the increase in the frequency of large floods has continued since 2016. This study also tests the hypothesis that the Chagrin River has, also, experienced an abrupt increase in flood frequency since July 2003. It is expected that the two watersheds experienced the same change because they are nearby and have similar climates (Figure 1).

Understanding the flooding history of the Chagrin River is important because floods can have severe adverse impacts on people and property. Beyond the northeast Ohio watersheds in this study, it is also important to understand the risk of flooding as the world population increases and climate change is projected to further increase intense precipitation and flooding (Seneviratne et al., 2012; Wing et al., 2018). Increasing the awareness of where flooding has become more frequent and severe could help better prepare people. If people are better prepared for an increase in flooding, it could reduce the cost of spending on repairing flood damage and could save lives.

2. Methods

Mean daily discharge data of the Cuyahoga River was downloaded from the United States Geological Survey (USGS, 2021a) at two different sites: Old Portage, station 04290600, and Independence, station 0420800. Old Portage is located upstream of the Akron Water Reclamation Facility in Akron, Ohio, and Independence is located upstream of the Northeast Ohio Regional Sewer in Cleveland, Ohio. The download record spanned from 1986 to 2020, 17 years before and after the 2003 change in discharge observed by Liberatore (2013) and Delaney (2016). Mean daily discharge data of the Chagrin River was downloaded from the USGS at Willoughby, station 04209000 (USGS, 2021a). Willoughby is located downstream of two large wastewater treatment plants: The Meadow Lane Wastewater Treatment Plant in Chagrin Falls, Ohio, and the Central Wastewater Treatment Plant in Aurora, Ohio. Mean daily discharge was not recorded at Willoughby from 1984 to 1988, 1994 to 1995, and 1999-2001. To account for the 8 years of missing data, the record spanning from 1978 to 2020 was used. The Old Portage record was chosen to build on the previous research done by Liberatore (2013) and Delaney

(2016) at this location. The Independence record was chosen because it is located in the lower Cuyahoga River and may be comparable to the Willoughby site on the lower Chagrin River. Daily precipitation data was downloaded from the National Oceanic and Atmospheric Administration (NOAA, 2021) at Chardon, station GHCND:USC00331458 in the Chagrin River watershed. The precipitation data record spanned from 1978 to 2020 and the dates that were missing from the Willoughby discharge data were removed to make the precipitation and discharge records comparable. There were also several dates in the Chardon precipitation record where data was not recorded, mostly between 2011 to 2012. Each dataset was brought into Microsoft Excel 2019 and sorted from highest value to lowest. The largest 1% values out of the total number of data points were then determined for each dataset. Next, each dataset was divided into before July 22, 2003, and July 22, 2003, and later. July 22, 2003, was used as the cutoff date because Liberatore (2013) found that the discharge at Old Portage had low and moderate flow before July 22, 2003, and frequent large floods July 22, 2003, and later. The mean of each dataset before and after July 22, 2003, was calculated. A two-tailed t-test with unequal variance was done on each dataset using Microsoft Excel 2019 to test if the mean discharge and precipitation before and after July 22, 2003, were statistically significantly different. Lastly, the monthly frequency of the top 10 discharge events at each site and the top 10 precipitation events were tallied. The monthly frequency of all 1% discharge and precipitation events from July 22, 2003, and later were also tallied.

3. Results

3.1. Cuyahoga River at Old Portage, Ohio

The mean daily discharge record of the Cuyahoga River at Old Portage from 1986 to 2020 downloaded from the USGS included 12783 daily values (Figure 2). For the entire length of the record, a top 1% flood on the was calculated to be 74.8 m^3/s (Table 1). The length of the record before July 22, 2003, was 6411 days and the length after July 22, 2003, was 6372 days (Table 1). The before and after lengths of the records are essentially the same. 8 of the top 10 biggest floods occurred after July 22, 2003, and only 2 occurring before (Table 1). When all top 1% floods are considered, 104 occurred after July 22, 2003, and only 26 occurred before July 22, 2003 (Table 1). The mean discharge was 13.0 m^3/s and 16.8 m^3/s before and after July 22, 2003, respectively (Table 1). The two-tailed t-test gave a p-value less than 0.05, indicating a significant difference in the mean discharge before and after July 22, 2003 (Table 1). There is a seasonal change in floods at this location (Tables 2, 3, 4, and 5; Figure 3). There are more top 1% floods after July 22, 2003, in the winter months, with March having the most top 1% floods (Table 5). In the summer months after July 22, 2003, there are fewer top 1% floods (Table 5). Even though there are few top 1% floods in the summer, six of the top ten largest floods after July 22, 2003, occurred in the summer in May through July (Table 4).

3.2. Cuyahoga River at Independence, Ohio

On the Cuyahoga River at Independence, the mean daily discharge record included 12784 daily values (Figure 4). A top 1% flood was found to be 165.1 m^3/s (Table 1). 6411 dates were before July 22, 2003, and 6373 were after July 22, 2003 (Table 1), making the before and after records approximately equal. 8 of the top 10 largest floods in this record occurred after July 22, 2003, and 2 occurred before July 22, 2003 (Table 1). When considering all top 1% floods, 86

occurred after July 22, 2003, and 41 occurred before July 22, 2003 (Table 1). There was a difference between the means, with the record before July 22, 2003, having a mean of 26.6 m^3/s and the record after July 22, 2003, having a mean of 33.6 m^3/s (Table 1). The two-tailed t-test yielded a p-value less than 0.05, which indicates a significant change in mean discharge before and after July 22, 2003 (Table 1). Discharge changes seasonally between the winter and summer months (Tables 2, 3, 4, and 5; Figure 3). There are more top 1% floods in the winter months, with March being the highest and having the highest amount (Table 5). In the summer, there are fewer top 1% floods (Table 5). Despite this, there is still high magnitude flooding at this location during the summer, with 5 of the top 10 floods after July 22, 2003, occurring during the summer in May through July (Table 4).

3.3. Chagrin River at Willoughby, Ohio

The mean daily discharge record of the Chagrin River at Willoughby, Ohio included 13341 daily values (Figure 5). A top 1% flood was calculated to be 102.0 m^3/s (Table 1). The record before and after July 22, 2003, is approximately equal with 6968 daily values before July 22, 2003, and 6373 daily values after July 22, 2003 (Table 1). 8 of the top 10 largest floods in the discharge record occurred after July 22, 2003 (Table 1). When all top 1% floods in the record are considered, 84 occurred after July 22, 2003, and 49 occurred before July 22, 2003 (Table 1). The mean discharge before July 22, 2003, was different than the mean discharge after July 22, 2003, 10.6 m^3/s and 13.6 m^3/s, respectively (Table 1). The two-tailed t-test calculated a p-value less than 0.05 which indicated that the mean discharge before July 22, 2003, and the mean discharge after July 22, 2003, are significantly different (Table 1). Seasonally, there is a change from more floods to fewer floods on the Chagrin River (Tables 2, 3, 4, and 5; Figure 3). The winter months have more flooding, with the most top 1% floods occurring in January (Table 5). The summer

months have less flooding (Table 5). However, there is still high magnitude flooding in the summer, with the 3rd highest discharge in the record occurring in May and the 7th highest occurring in July.

3.4. Chagrin River Watershed Precipitation at Chardon, Ohio

The daily precipitation record at Chardon, Ohio included 13136 daily values (Figure 6). A top 1% precipitation event was calculated to be 3.7 cm (Table 6). The record before July 22, 2003, included 6944 days, and the record after included 6192 days (Table 6). The records are approximately equal. 7 of the top 10 extreme precipitation events occurred after July 22, 2003, with only 3 occurring before July 22, 2003 (Table 6). When looking at all top 1% precipitation events, 77 occurred after July 22, 2003, and 54 occurred before July 22, 2003 (Table 6). The mean precipitation before July 22, 2003, was 0.3 cm and the mean precipitation after was 0.4 cm (Table 6). The two-tailed t-test calculated the p-value to be less than 0.05, indicating a difference in mean precipitation before and after July 22, 2003 (Table 6). There is a seasonal change in extreme precipitation events at Chardon (Tables 2, 3, 4, and 5; Figure 3). There are more precipitation events in the summer and fewer precipitation events in the winter (Figure 3). This seasonal change in extreme precipitation is the opposite of the seasonal change in flooding events on the Chagrin River (Figure 3). The summer months have a high number of top 1% precipitation events, with the most occurring in July (Figure 3). The winter months have a lower number of top 1% precipitation. There is still a possibility of extreme precipitation events in the winter, however, with 2 of the top 10 precipitation events in the record occurring in December through March (Table 2).

4. Discussion

4.1. Interpretation of the Flooding History of the Cuyahoga and Chagrin Rivers

When visually comparing the mean daily discharge records on Figures 2, 4, and 5 the extreme floods become more pronounced after July 22, 2003. At all three locations, there are more frequent extreme floods which are shown by the increase in the number of high peaks on the mean daily discharge graphs (Figures 2, 4, and 5). The height of these peaks also increases after July 22, 2003 (Figures 2, 4, and 5). This visual change on the graphs is supported by the increase in mean discharge at each location after July 22, 2003, the low p-value calculated by the two-tailed t-test for each location, and the higher frequency of the top 10 largest floods and the top 1% floods after July 22, 2003, at each location (Table 1). The data supports the hypotheses that the increase in flooding on the Cuyahoga River has continued since the studies done by Liberatore (2013) and Delaney (2016) and that the Chagrin River has experienced a similar increase in flooding since July 22, 2003.

The daily precipitation record at Chardon also visually shows the change since July 22, 2003 (Figure 6). There are more intense precipitation events after July 22, 2003, as shown by the increase in the number of high peaks (Figure 6). The quantity of rainfall during these intense precipitation events also increased as shown by the higher height of the peaks after July 22, 2003 (Figure 6). The visual change in the frequency and intensity of single-day precipitation events shown in Figure 6 is supported by the high mean precipitation after July 22, 2003, the low p-value calculated, and the higher number of top 10 extreme precipitation events and top 1% precipitation events after July 22, 2003 (Table 6). The more frequent and intense precipitation at Chardon after July 22, 2003, is the cause of the increase in discharge of the Chagrin River at that time.

It is possible that illegal dredging also caused an increase in flooding on the Chagrin River at Willoughby. In 2007, 1.5 miles of Chagrin River streambed in Kirtland Hills was dug up and the sediment was piled on the streambank in an attempt to control flooding and erosion (O'Donnell, 2007). The dredging was done without a permit from the Ohio Environmental Protection Agency or the Army Corps of Engineering (O'Donnell, 2007). Kirtland Hills is located upstream of Willoughby and EPA inspectors found that the dredging would likely increase flooding danger for Willoughby and other areas downstream (O'Donnell, 2007). Because flood water can no longer flow onto the floodplains due to the sediment piled on the streambank, it continues downstream and enhances flooding downstream (O'Donnell, 2007). The director of the Chagrin River Watershed Partners Inc. stated that this dredging would cause significant long-term problems for the river (O'Donnell, 2007). Figure 5 reveals that since 2007 there are more numerous high discharge days at Willoughby compared to before 2007.

There is a possibility that flooding on the Chagrin River at Willoughby is enhanced in the winter months between January and March by ice dams. Ice dams in the lower Chagrin River limit discharge into frozen Lake Erie and enhance river flooding. 4 of the top 10 largest floods in the entire record occurred between January and March (Table 2). 36 of the top 1% floods after July 22, 2003, occurred in January through March (Table 5; Figure 3). Ice damming is not a concern for the Cuyahoga River stream gauge locations because they are further from Lake Erie. On December 31, 2004, the Daniels Park Dam on the Chagrin River at Daniels Park in Willoughby, Ohio failed as a result of a heavy influx of rain and snow-melt (Frischkorn, 2005). The park was closed for a few days, but no flood damage occurred downstream of the failed dam and an evacuation order was not placed (Frischkorn, 2005). The Daniels Park Dam did not reach the requirements set by the Ohio Division of Water's dam safety unit because the dam did not

reach the height requirement to be under the jurisdiction of the Ohio Department of Natural Resources (Frischkorn, 2005). The USGS stream gaging station at Willoughby is located downstream of the dam (Figure 7) and after the failure of the dam, there was a large increase in mean daily discharge as the former dam pool emptied (Table 7). January 12, 2005 was the 10th largest flood within the entire record. The high discharge value after the dam failed contributed in small part to the increased mean discharge of the Chagrin River after July 22, 2003. However, the dam failure discharge increase only contributed several weeks to a 17-year post July 2003 record. The remains of the Daniels Park Dam can be seen in the present day (Figure 8).

The mean daily discharge of the Cuyahoga River at both locations and the mean daily discharge of the Chagrin River at Willoughby is high in the winter and lower in the summer (Tables 2, 3, 4, and 5; Figure 3). The daily precipitation at Chardon is high in the summer and low in the winter (Tables 2, 3, 4, and 5; Figure 3). In the winter, river discharge is higher because of snowmelt and low temperatures (Dettinger and Diaz, 2000). When the snow on the ground melts, the water will drain into the river (Dettinger and Diaz, 2000). When the temperature is low, the ground is frozen and any precipitation that occurs cannot infiltrate into the ground and will runoff into the river instead (Dettinger and Diaz, 2000). In the summer, precipitation is higher because temperatures are higher (Dettinger and Diaz, 2000). When the temperature is higher, there is more convection which results in thunderstorms (Dettinger and Diaz, 2000). River discharge is lower in the summer despite the increase in precipitation because of enhanced evaporation and transpiration (Dettinger and Diaz, 2000). When the temperature is higher more water is evaporated from Earth’s surface (Dettinger and Diaz, 2000). During the summer, plants are no longer dormant and can take up water through their roots and release it through their leaves (Dettinger and Diaz, 2000).

The Midwest region of the United States has experienced an increase in surface temperature corresponding with the average trend of increasing surface temperature in the contiguous United States (U.S. Environmental Protection Agency, 2016). This increase in temperature has been caused by the increasing concentrations of greenhouse gases in the atmosphere (U.S Environmental Protection Agency, 2016). As surface temperatures rise, more evaporation and convection occur which increases overall precipitation (U.S. Environmental Protection Agency, 2016). The warmer air can hold moisture and when that moisture heavy air moves over land it produces heavy rain (U.S Environmental Protection Agency, 2016). This region has also experienced an increase in precipitation as well as intense single-day precipitation (U.S. Environmental Protection Agency, 2016). When these intense single-day precipitation events become larger and more frequent, they can lead to river flooding including the increase in flooding on the Cuyahoga River and Chagrin River determined in this study. It is projected that warm-season temperatures in the Midwest will increase more than any other region of the United States (Angel et al., 2018). The frost-free season is projected to increase by 10 days from 2016 to 2044 and increase by possibly a month from 2036 to 2065 (Angel et al., 2018). An increase in humidity during the spring is projected which could lead to an increase in precipitation (Angel et al., 2018). The soil moisture is projected to fluctuate between excessive levels in the spring caused by an increase in precipitation to insufficient levels caused by an increase in temperatures (Angel et al., 2018).

4.2. Human Impact of Flooding of the Chagrin River

In the winter, there is a greater risk of intense flooding (Tables 2, 3, 4, and 5; Figure 3). An intense flood happened at Daniels Park in Willoughby on February 27, 2011 (Morning Journal, 2011)(Figure 9). This flood was caused by the failure of a dam in Gates Mills, located

upstream of Willoughby (Morning Journal, 2011). The failure of this dam added an influx of water to the influx of rain and snowmelt causing it to flood (Morning Journal, 2011). February 28, 2011, the day following the flood, is the 5th highest recorded mean daily discharge of the Chagrin River at Willoughby during the entire record. Despite the high risk of flooding in the winter, there are also intense floods in the summer that should not be ignored (Tables 2, 3, 4, and 5; Figure 3). Yet another event occurred in 2006 when no dam failed. A flood classified as a "500-year flood" occurred in Lake County, Ohio, from July 27 through July 28, 2006, affecting the Chagrin River as well as other rivers in the county (Reardon, 2019)(Figure 10). This flood was caused by torrential rainfall across Northeast Ohio, which had already been inundated by frequent heavy rain earlier in July and in June (Reardon, 2019). Damage in Lake County from this flood cost around $30 million (Reardon, 2019). Hundreds of people were evacuated and one death was reported (Kropko, 2006). Power outages and sanitation problems were reported after the flood (Kropko, 2006). The mean daily discharge on July 28, 2006 was the 7th highest recorded on the Chagrin River at Willoughby for the entire record. This date was also the highest single-day precipitation event recorded in Chardon for the entire record. Many residents in Lake County can recount the events of this flood, as it affected them and the community greatly (Reardon, 2019; Sadler, 2016).

As single-day precipitation is projected to increase in the Midwest region of the United States, this could have adverse impacts on the people living within the region (Angel et al., 2018). The increase in precipitation could lead to an increase in soil erosion, lowering crop yields (Angel et al., 2018). Flooding has been a consistent concern on the Chagrin River (Chagrin River Watershed Action Plan, 2011), and the projected increase in single-day precipitation is expected to lead to more flooding events. Flooding on the Chagrin River has

previously led to property damage and the loss of homes of many residents (Reardon, 2019; Sadler, 2016). Floods carry contaminated water and other debris that can cause injuries and gastrointestinal illnesses if people are in contact with the contaminated water (U.S. Environmental Protection Agency, 2016). People with disabilities, pregnant women, low-income populations, first responders, and construction workers are at high risk of injury or death caused by flooding (U.S. Environmental Protection Agency, 2018). Heavy precipitation and flooding can damage infrastructure and make traveling on roads more difficult (Angel et al., 2018). Annual flood damage costs in the Midwest are projected to exceed $500 million by 2050 (Angel et al., 2018).

In areas across the Midwest, possible adaptations to increased precipitation and flooding are being put into practice and are well summarized by Angel et al. (2018). To reduce the effects of soil-erosion, soil-erosion suppression methods are being used in row-crop agriculture that experiences more extreme precipitation. These methods include cover crops, grassed waterways, water management systems, contour farming, and prairie strips. To reduce the effects of increased precipitation and flooding on human health, basic health services and an increase in surveillance and monitoring are being put into practice. Water treatment installations are also being used to reduce the risk of illness from contaminated groundwater. To reduce the effects of stormwater on infrastructure, the use of green infrastructure, plants, and open space to manage stormwater, is increasing. Rain gardens are used to collect and filter rainwater in the soil to slow the runoff into sewer systems. Permeable pavements also allow water to be stored in soil instead of entering sewer systems. Wetland restoration projects are being used to vegetate floodplains and increase their ability to hold water and prevent floodwaters from reaching people, property, or infrastructure.

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References

Angel, J., C. Swanston, B.M. Boustead, K.C. Conlon, K.R. Hall, J.L. Jorns, K.E. Kunkel, M.C. Lemos, B. Lofgren, T.A. Ontl, J. Posey, K. Stone, G. Takle, and D. Todey, 2018: Midwest. In Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II [Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 872–940. doi: 10.7930/NCA4.2018.CH21

Chagrin River Watershed Action Plan, 2011. Chagrin River Watershed Partners, Inc. Revised by Ohio Environmental Protection Agency. http://wwwapp.epa.ohio.gov/dsw/nps/WAPs/ChagrinR.pdf.

Delaney, A., 2016. Effects of Climate and Development on the Hydrology and Geomorphology of the Yellow Creek Watershed, Summit and Medina Counties, OH. M.S Thesis University of Akron. https://etd.ohiolink.edu/apexprod/rws_etd/send_file/send?accession=akron1479127682219327&disposition=inline.

Dettinger D. M. and Diaz F. H, 2000. Global Characteristics of Stream Flow Seasonality and Variability, Journal of Hydrometeorology, 1(4), 29-310. Retrieved Mar 28, 2021 from https://journals.ametsoc.org/view/journals/hydr/1/4/1525-7541_2000_001_0289_gcosfs_2_0_co_2.xml.

Frischkorn, Jeffrey L. "Dam Breaks." *The News-Herald*, 3 Jan. 2005, www.news-herald.com/news/dam-breaks/article_104822f0-2911-5541-9f35-a24ede9cd5fd.html.

Liberatore. S., 2013. Changes in Geomorphic Equilibrium on Furnace Run, Summit County, Ohio. M.S. Thesis University of Akron. https://etd.ohiolink.edu/apexprod/rws_etd/send_file/send?accession=akron1365872441&disposition=inline.

Morning Journal, 2011. https://www.morningjournal.com/news/swollen-chagrin-river-remains-on-flood-watch/article_5294f4ee-a9b4-5f79-ba81-dffbb6f1873a.html.

National Weather Service, 2021. "NWS Preliminary US Flood Fatality Statistics". Weather.gov. www.weather.gov/arx/usflood. Accessed 26 Jan 21.

NOAA, 2021. https://www.ncdc.noaa.gov/cdo-web/.

NOACO, 2021. https://www.noaca.org/regional-planning/water-quality-planning/watershed-planning.

O'Donnell, P. "Osborne Cited for Dredging River." *The Plain Dealer*, 1 Sept. 2007, https://web.archive.org/web/20110607135620/http://www.cleveland.com/whateverhappened/plaindealer/index.ssf?%2Fwhateverhappened%2Fmore%2Fosborne2.html.

Reardon, K. "Remembering the 500-year flood of Lake County: Cause, damage, and personal accounts". *Cleveland.com*, 19 May 2019, https://www.cleveland.com/weather/blog/2017/07/remembering_the_500-year_flood.html.

Sadler, C. "10 years later: Memories of the 2006 flood in Lake County". *The News-Herald*, 27 Sept. 2018, https://www.news-herald.com/news/ohio/10-years-later-memories-of-the-2006-flood-in-lake-county/article_13088d7e-848a-5ac1-9394-c4b5c78c29dc.html.

Seneviratne, S.I., N. Nicholls, D. Easterling, C.M. Goodess, S. Kanae, J. Kossin, Y. Luo, J. Marengo, K. McInnes, M. Rahimi, M. Reichstein, A. Sorteberg, C. Vera, and X. Zhang, 2012. Changes in climate extremes and their impacts on the natural physical environment. In: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge, UK, and New York, NY, USA, pp. 109-230.

Statista, 2019. "Economic Damage Caused by Foods in the U.S. 1995-2019". https://www.statista.com/statistics/237420/economic-damage-caused-by-floods-and-flash-floods-in-the-us/#:~:text=In%202019%2C%20floods%20caused%20approximately,damage%20across%20the%20United%20States. Accessed 26 Jan 21.

Stewards of the Cuyahoga River, 2021. "Fast Facts about the Cuyahoga River". *Friends of the Crooked River*. http://cuyahogariver.net/resources/facts/.

USGS, 2021a. https://waterdata.usgs.gov/oh/nwis/rt.

USGS, 2021b. https://geonames.usgs.gov/apex/f?p=GNISPQ:3:::NO::P3_FID:1070711.

U.S. Environmental Protection Agency, 2016. Climate change indicators in the United States. Fourth edition. EPA 430-R-16-004. www.epa.gpv/climate-inidcators.

U.S. Environmental Protection Agency, 2020. Cuyahoga River AOC. https://www.epa.gov/great-lakes-aocs/cuyahoga-river-aoc. Accessed 25 Mar. 2021.

Wing, O. E. J., Bates, P.D., Smith, A.M., Fargione, C.J., and Morefield, A., 2018. Estimates of present and future flood risk in the conterminous United States, Enviro. Res. Lett., 3, 1-7.

Table 1. Summary table of hydrologic variables of the Cuyahoga and Chagrin Rivers.

Hydrologic Variable	Units	Willoughby, OH	Old Portage, OH	Independence, OH
USGS Station #	-	4209000	4206000	4208000
Length of record before 7/22/03	Days	6968	6411	6411
Length of record after 7/22/03	Days	6373	6372	6373
Top 1% Discharge	m^3/s	102.0	74.8	165.1
# of top 1% discharge before 7/22/03	Days	49	26	41
# of top 1% discharge after 7/22/03	Days	84	104	86
# of top 10 floods before 7/22/03	Days	2	2	2
# of top 10 floods after 7/22/03	Days	8	8	8
Mean discharge before 7/22/03	m^3/s	10.6	13.0	26.6
Mean discharge after 7/22/03	m^3/s	13.6	16.8	33.6
P-value from t-test	-	< 0.05	< 0.05	< 0.05

Table 2. Monthly frequency of top 10 floods at Willoughby, Old Portage and Independence as well as top 10 extreme precipitation at Chardon.

Month	Willoughby, OH	Old Portage, OH	Independence, OH	Chardon, OH
January	2	2	0	0
February	2	0	2	0
March	0	2	1	1
April	0	1	1	0
May	1	1	1	0
June	0	1	1	0
July	1	2	1	3
August	0	0	0	3
September	0	0	0	1
October	2	0	1	1
November	0	0	0	0
December	2	1	2	1

Table 3. Monthly frequency of top 10 floods before 7/22/03 at Willoughby, Old Portage, and Independence Ohio. Monthly Frequency of top 10 precipitation at Chardon, Ohio.

Month	Willoughby, OH	Old Portage, OH	Independence, OH	Chardon, OH
January	0	2	1	0
February	2	0	0	1
March	0	0	0	1
April	0	4	0	0
May	2	0	1	1
June	1	0	2	1
July	0	2	2	0
August	1	0	0	4
September	1	0	1	2
October	0	0	0	0
November	0	0	0	0
December	3	2	3	0

Table 4. Monthly frequency of top 10 floods after 7/22/03 at Willoughby, Old Portage, and Independence Ohio. Monthly Frequency of top 10 precipitation at Chardon Ohio.

Month	Willoughby, OH	Old Portage, OH	Independence, OH	Chardon, OH
January	2	2	0	0
February	2	0	2	0
March	2	2	2	0
April	0	0	1	0
May	0	2	2	0
June	0	2	1	2
July	1	2	1	3
August	0	0	0	2
September	0	0	0	1
October	2	0	1	1
November	0	0	0	0
December	1	0	0	1

Table 5. Monthly frequency of top 1% floods after 7/22/03 at Willoughby, Old Portage, and Independence Ohio. Monthly Frequency of top 1% precipitation at Chardon, Ohio.

Month	Willoughby, OH	Old Portage, OH	Independence, OH	Chardon, OH
January	16	24	17	1
February	8	10	7	4
March	12	38	23	3
April	7	6	5	5
May	8	7	9	4
June	5	9	7	10
July	5	8	5	18
August	1	0	1	11
September	1	0	2	9
October	8	0	4	4
November	5	0	1	3
December	8	2	5	5

Table 6. Summary table of precipitation at Chardon, Ohio.

Variable	Units	Chardon, OH
NOAA Station #	-	GHCND:USC00331458
Length of record before 7/22/03	Days	6944
Length of record after 7/22/03	Days	6192
Top 1% precipitation	cm	3.7
# of top 1% precipitation before 7/22/03	Days	54
# of top 1% precipitation after 7/22/03	Days	77
# of top 10 extreme precipitation before 7/22/03	Days	3
# of top 10 extreme precipitation after 7/22/03	Days	7
Mean precipitation before 7/22/03	cm	0.3
Mean precipitation after 7/22/03	cm	0.4
P-value from t-test	-	< 0.05

Table 7. Mean daily discharge of the Chagrin River at Willoughby, Ohio before and after the failure of the Daniels Park Dam on 12/31/2004 (USGS, 2021a).

Date	Discharge (m^3/s)	Date	Discharge (m^3/s)
12/1/2004	25.57296	1/1/2005	154.6272
12/2/2004	39.0816	1/2/2005	91.7568
12/3/2004	20.44704	1/3/2005	163.6896
12/4/2004	8.94912	1/4/2005	145.5648
12/5/2004	5.97552	1/5/2005	85.8096
12/6/2004	4.8144	1/6/2005	114.1296
12/7/2004	4.98432	1/7/2005	94.3056
12/8/2004	6.82512	1/8/2005	68.8176
12/9/2004	7.30656	1/9/2005	65.136
12/10/2004	13.1688	1/10/2005	65.7024
12/11/2004	15.49104	1/11/2005	75.048
12/12/2004	20.1072	1/12/2005	228.2592
12/13/2004	20.90016	1/13/2005	139.9008
12/14/2004	20.532	1/14/2005	125.1744
12/15/2004	14.55648	1/15/2005	52.392
12/16/2004	11.27136	1/16/2005	24.44016
12/17/2004	10.0536	1/17/2005	12.48912
12/18/2004	8.04288	1/18/2005	10.62
12/19/2004	7.6464	1/19/2005	9.94032
12/20/2004	7.3632	1/20/2005	10.56336
12/21/2004	7.02336	1/21/2005	54.3744
12/22/2004	7.788	1/22/2005	86.9424
12/23/2004	17.92656	1/23/2005	88.0752
12/24/2004	51.8256	1/24/2005	88.9248
12/25/2004	43.3296	1/25/2005	89.4912
12/26/2004	33.984	1/26/2005	89.4912
12/27/2004	26.3376	1/27/2005	85.2432
12/28/2004	20.9568	1/28/2005	83.2608
12/29/2004	22.656	1/29/2005	82.6944
12/30/2004	25.488	1/30/2005	81.2784
12/31/2004	164.256	1/31/2005	77.5968

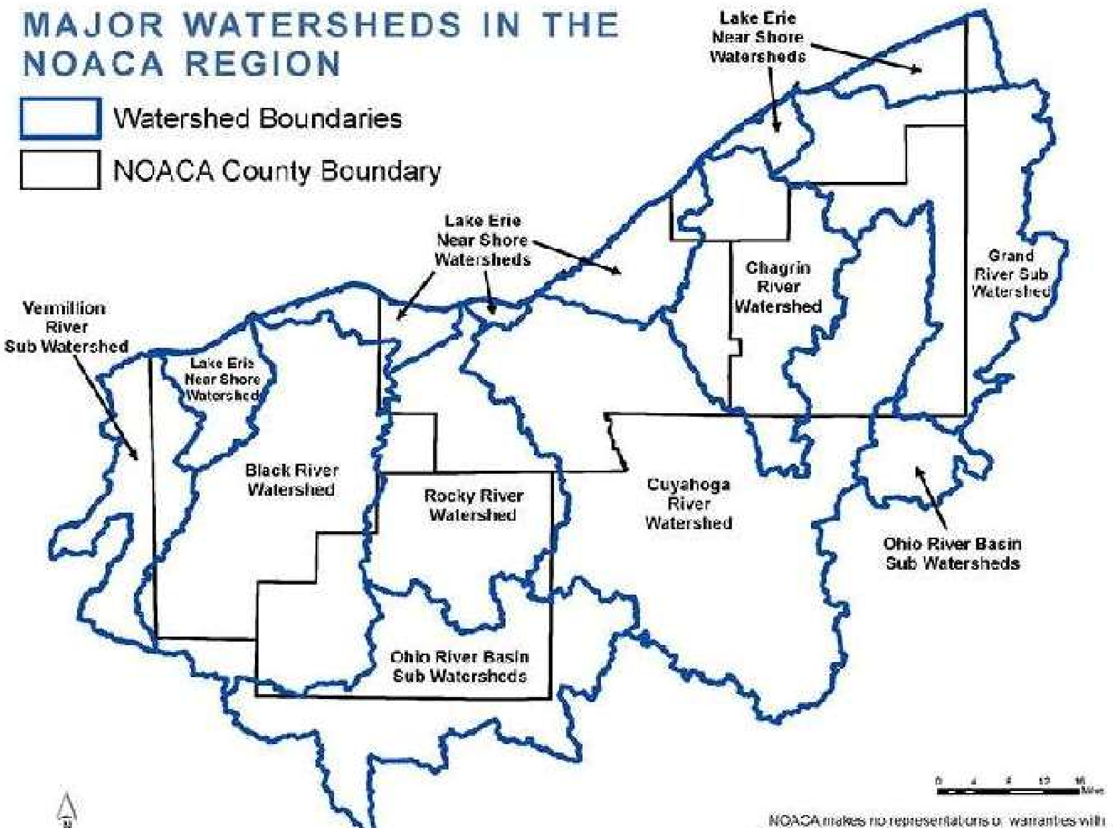

Figure 1. Map of watersheds in northeast Ohio showing the adjacent Cuyahoga River and Chagrin River watersheds. From the Northeast Ohio Areawide Coordinating Agency (NOACO, 2021).

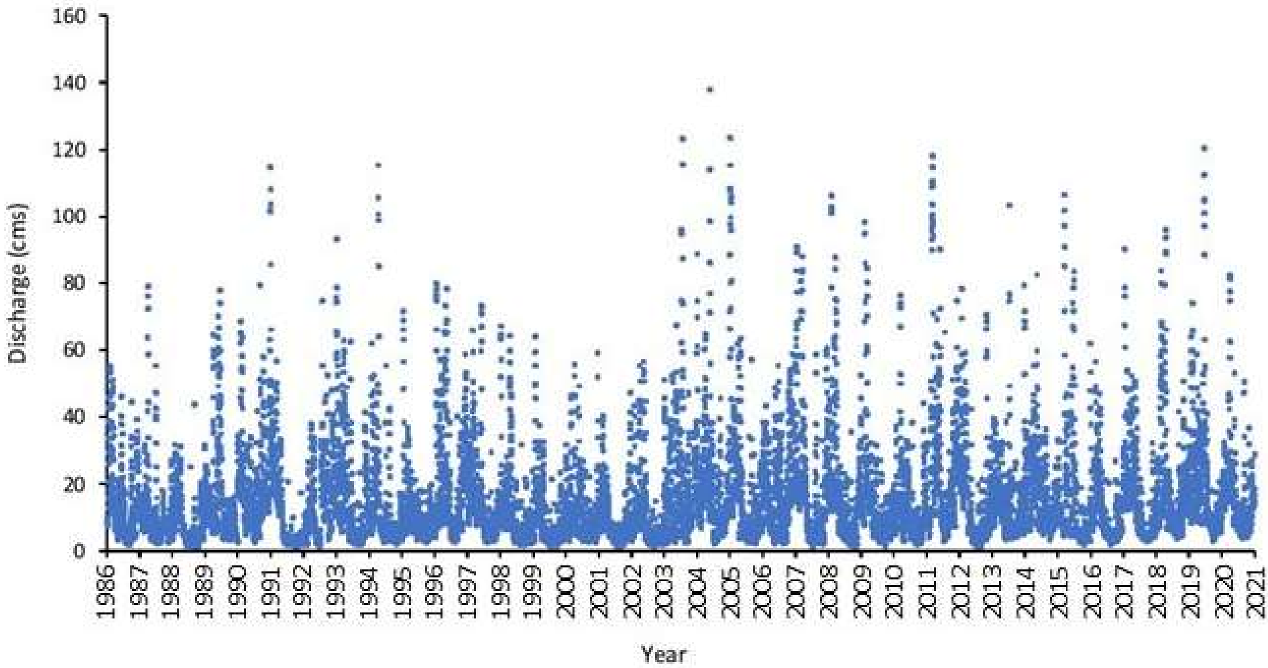

Figure 2. Mean daily discharge of the Cuyahoga River at USGS station 04290600 at Old Portage, Ohio from 1/1/1986 to 12/31/2020. This hydrograph shows the pronounced change to more frequent intense floods after July, 2003 (USGS, 2021a).

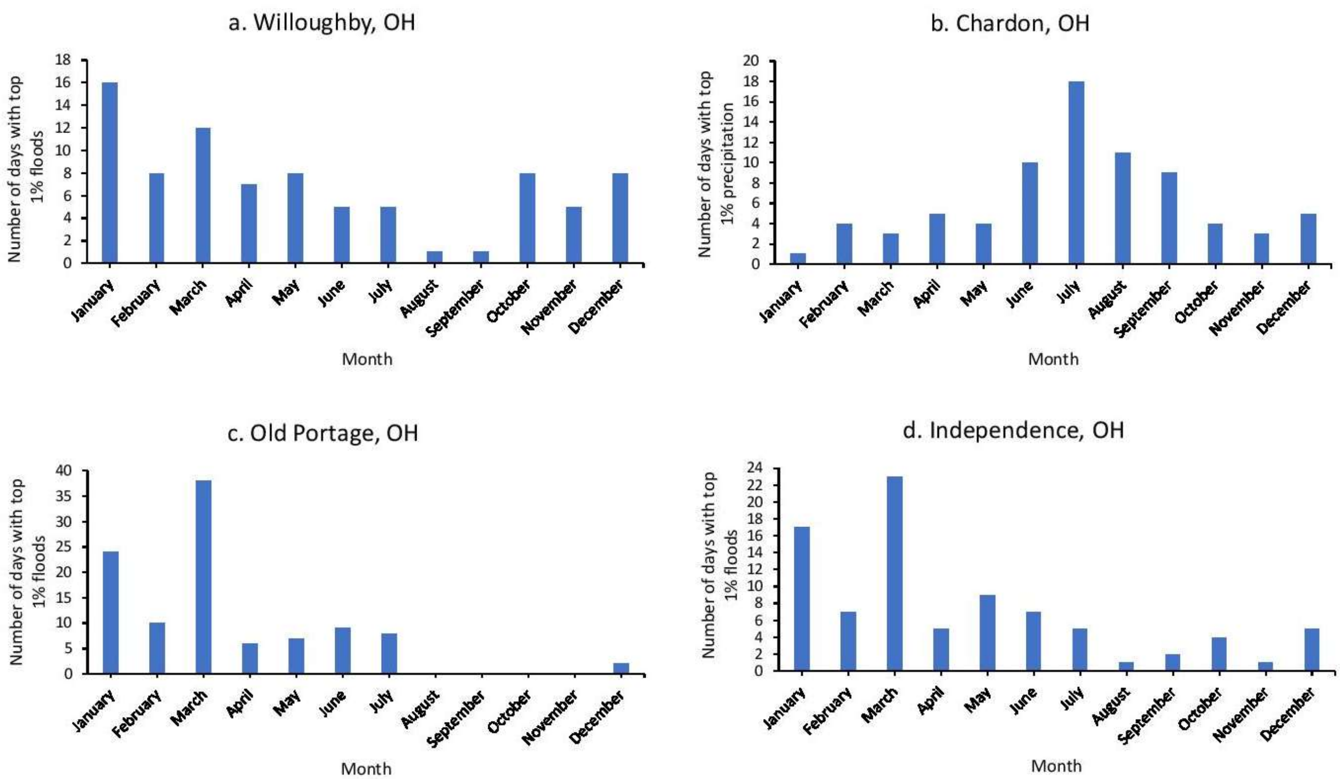

Figure 3. Monthly frequency of top 1% floods after 7/22/03 at a. Willoughby, c. Old Portage, and d. Independence. Monthly frequency of top 1% precipitation at b. Chardon.

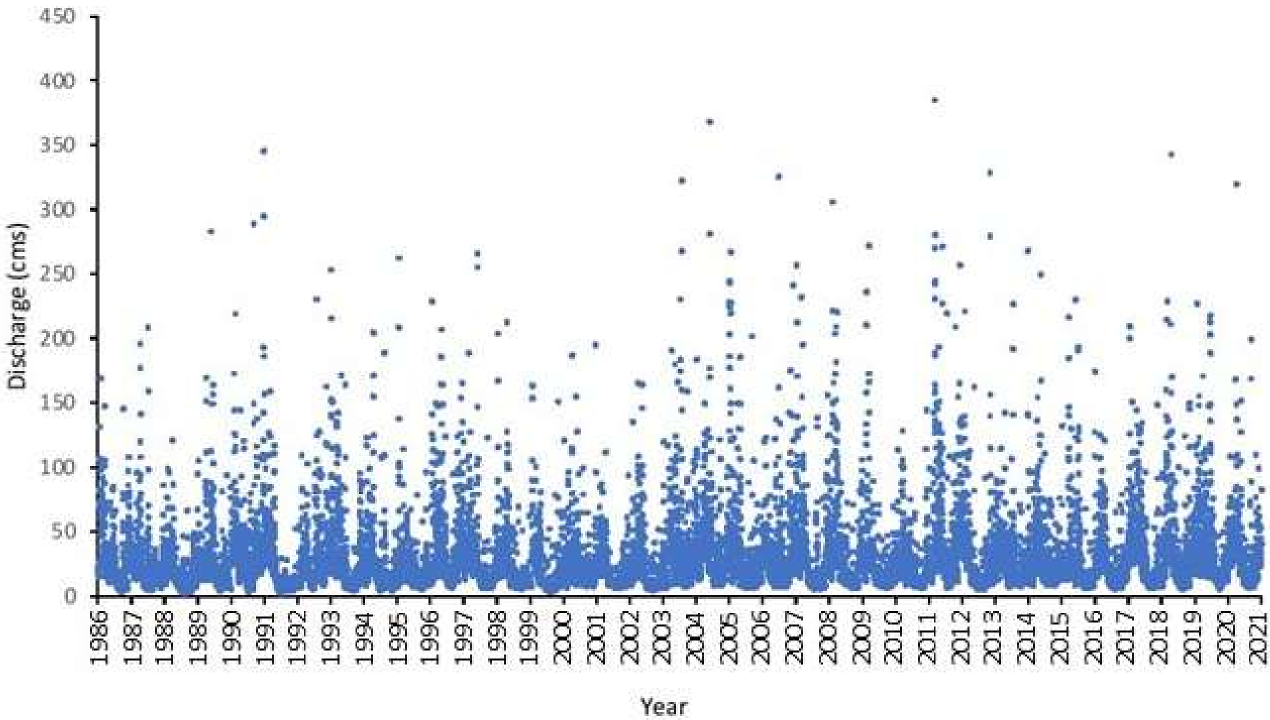

Figure 4. Mean daily discharge of the Cuyahoga River at USGS station 4208000 at Independence, Ohio from 1/1/1986 to 12/31/2020. This hydrograph shows the pronounced change to more frequent intense floods after July, 2003 (USGS, 2021a).

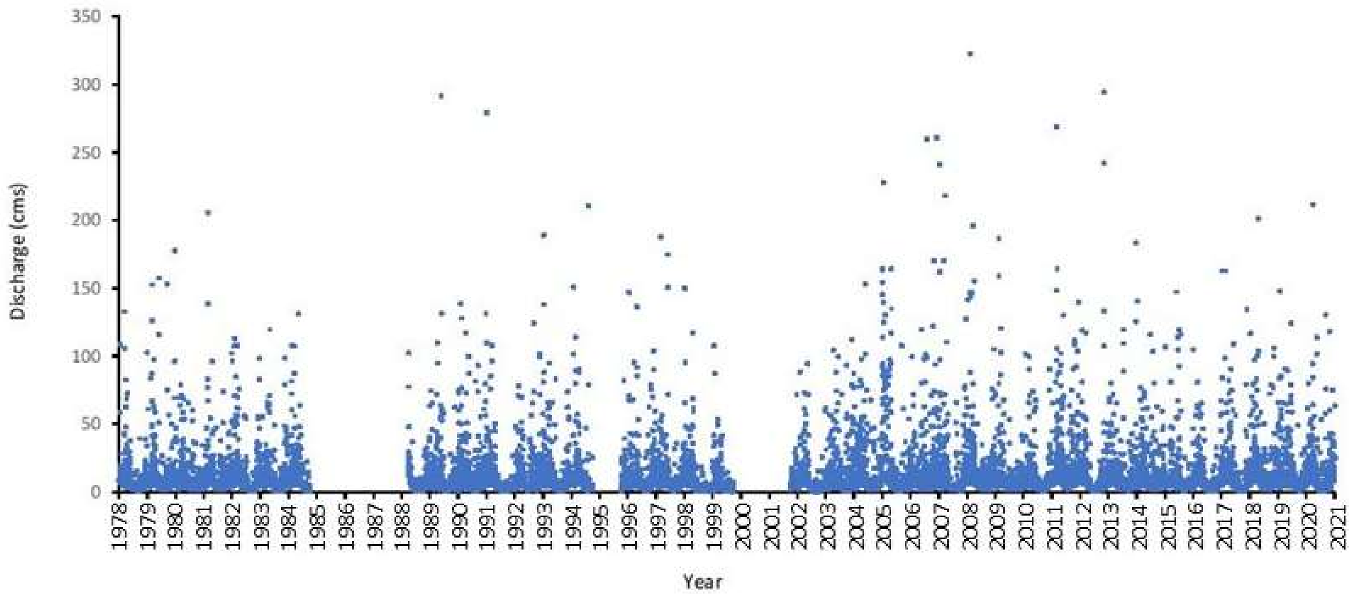

Figure 5. Mean daily discharge of the Chagrin River at USGS station 04209000 in Willoughby, Ohio from 1/1/1978 to 12/31/2020. Discharge was not recorded from October 1984 to March 1988, from September 1994 to September 1995, and from September 1999 to September 2001. This hydrograph shows the pronounced change to more frequent intense floods after July, 2003 (USGS, 2021a).

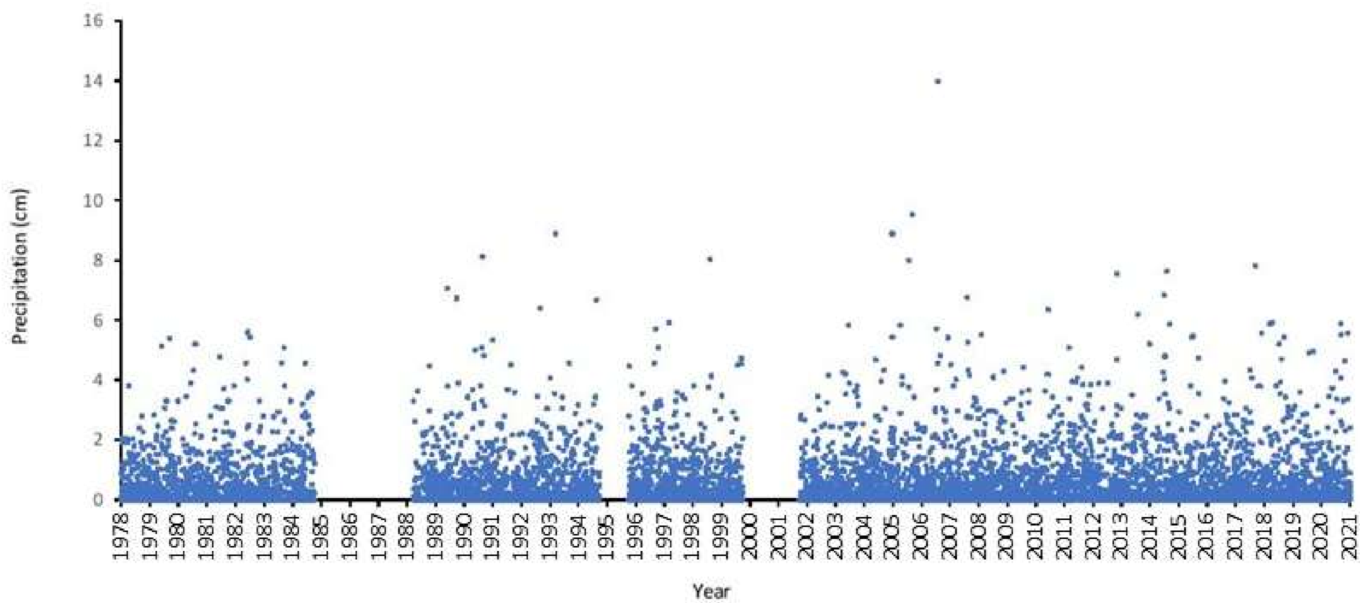

Figure 6. Daily precipitation in Chardon, Ohio at NOAA station GHCND:USC00331458 from 1/1/1978 to 12/31/2020. Data was removed from October 1984 to March 1988, from September 1994 to September 1995, and from September 1999 to September 2001 to make it comparable to the mean daily discharge of the Chagrin River (Figure 5). The precipitation graph the change to more frequent intense single day precipitation events after July, 2003 (NOAA, 2021).

Figure 7. USGS stream gaging station 04209000 on the Chagrin River at Daniels Park in Willoughby, Ohio on March, 2021.

Figure 8. Remains of the Daniels Park Dam on the Chagrin River at Daniels Park in Willoughby, Ohio on March, 2021. The dam failed on 12/31/2004.

Figure 9. Chagrin River flood at Daniels Park in Willoughby, Ohio February 27, 2011 (Morning Journal, 2011).

Figure 10. David Moyer, Eastlake resident, showing damage at his house in Eastlake caused by flooding of the Chagrin River July 27-28, 2006 (Sadler, 2016).