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ASSESSMENTS OF STREAM FLOW AND FLOODING ALONG THE PERE MARQUETTE RIVER, WEST MICHIGAN

Kenneth Ferrell, Jr.
Dr. Eric Portenga, Mentor

ABSTRACT

Understanding how stream flow in rivers across Michigan is responding to climate change is important because rivers are used for hydroelectricity, recreation, fisheries, and many people own property along them. Michigan's annual rainfall has increased by three inches since 1940 and is expected to increase by 0.036 inches/year through the 21st century due to climate change. In this study, I test the hypothesis that increased rainfall will lead to more frequent flooding along Michigan's rivers. I do so by analyzing river discharge data and flow-duration curves from a stream gaging station on the Pere Marquette River, the largest undammed river in Michigan. Results from this study show that the discharge on the Pere Marquette River was ≥1,643 cfs for 27 days and increased 6-fold to 164 days in the 1990s and 2000s. It is likely that other natural rivers in Michigan might also show increases in the historical 1.5 year discharge associated with them and that discharge with the 1% exceedance probability might also increase.

INTRODUCTION

Rivers drain rainfall and runoff from Earth's surface and carry sediments and nutrients to lakes, seas, coasts, and wetlands worldwide. As rivers flow across landscapes, they can erode or deposit sediments on their streambed and banks, driving landscape evolution by shaping landscapes and transporting and delivering sediment and nutrients to downstream rivers, lakes, estuaries, deltas, and coasts (Singh et al., 2007; Anthony et al., 2015; Merritt et al., 2003; Walling, 2009). When rivers exceed bankfull conditions and spill onto their floodplains, they deliver sediment and key nutrients, such as nitrogen and phosphorus, to local ecosystems (Kroes et al., 2015).

Rivers provide a large variety of habitats for many different species, both in channels and in the riparian corridor. Riparian forests help regulate food webs, stream flow and discharge, and water quality by retaining sediments and contaminants trapped within those sediments from surrounding regions (dos Santos et al., 2015; del Tánago and de Jalón, 2011; Fernandes et al., 2013).

The evolution of human settlement has historically revolved around river systems in prehistoric times (Liu et al., 2019; Jotheri et al., 2015; Wang and Chiou, 2019). Then and now, rivers are important sources of fresh water for farming and irrigation practices, delivering key nutrients needed for growing successful crops (Yin et al., 2017; Kroes et al., 2015). Additionally, rivers are important sources of fresh drinking water for humans (Karr and Chu, 2000). Since every region in the world is not easily accessible by road or air, rivers are also used for means of commercial travel and the transportation of goods (Ilham et al., 2020; Banerjee et al., 2012; Heydari and Othman, 2013). Some regions in the world are heavily reliant on tourism, particularly water sports and recreation, in order to stimulate their economy, and rivers allow these places to develop, or maintain, a stable economy (Rahmafitria et al., 2017; Sun et al., 2014). Stormwater infrastructure plays a vital role in flood management in populated areas because it handles the water that would cause flooding during a precipitation, or snowmelt, event and drains this excess water into a local river or lake nearby (Grigg, 2012; McPhillips and Matsler, 2018).

All rivers have a specific geometry that reflects a balance between the river's sediment load, its discharge, and its steepness (Lane, 1955). When the sediment load, discharge, and steepness are in balance with one another, a river is considered to be in equilibrium. Lane (1955) described a working model that explains how a river will respond to any change in its equilibrium flow conditions, including discharge; this model is best illustrated through the use of a diagram of a balance (Fig. 1). The "Lane Diagram" illustrates how a river's flow changes when it is pushed out of equilibrium by a change in river steepness, stream discharge, how much mass a river is transporting, or the size (e.g., the coarseness) of the sediment it is transporting. Geomorphologists use Lane's (1955) concepts of balance to understand the equilibrium dynamics of a river, which involves aggradation and incision on the river's bed.

Additionally, geomorphologists analyze patterns and changes in each of the parameters of the Lane Diagram (e.g., sediment size, sediment load, and discharge) to better understand rivers and stream flow behavior. Understanding discharge is particularly important because it may have an impact on water quality (Hillel et al., 2015; Van Vliet et al., 2013). One way of studying patterns in a river's discharge is the construction of a flow-duration curve, which shows the probability, expressed as a percentage, that a river's discharge will be met or exceeded (i.e., an exceedance probability; Fig. 2; Searcy, 1969).

Not all rivers reach equilibrium, and those that do may not remain in equilibrium if bedload characteristics, slope, or discharge are altered. The effects of climate change can be observed on a global and regional scale with changes in precipitation patterns, sea levels, ocean acidification, and increase in annual air temperature (Hayhoe et al., 2010; Mishra, 2018; Climate Change Science Program (U.S.), 2014). Earth's climate changes naturally without the interactions of humans (Blois et al., 2013; Shakun and Carlson, 2010; Shakun et al., 2012), but human-caused climate change, mainly through emissions of carbon dioxide (CO2), is warming Earth's atmosphere beyond natural climate patterns (Höök and Tang, 2013; Berrang-Ford et al., 2011). One of the noticeable effects of these climatic changes is linked to prolonged droughts in some regions, which in turn affect the quantity of available groundwater and reduce agricultural productivity (Cheng et al., 2016; Famiglietti, 2014). Since droughts decrease the amount of available water entering river systems, those rivers' discharge may decrease (Blöschl et al., 2019). Other rivers, however, may experience an increase in water due to climate change-driven increases in precipitation, causing the discharge to increase (Mirza, 2011).

As the effects of climate change are being studied worldwide, studies show that annual air temperatures are projected to increase in the Great Lakes Region by 1.4 ± 0.6°C over the years 2010–2039, by 2.0 ± 0.7°C under lower greenhouse gas emissions scenarios, and 3 ± 1°C under high greenhouse gas emissions scenarios over the mid-century, 2040–2069 (Fig. 3; Hayhoe et al., 2010). Warmer air has the capability to hold 7% more water vapor as the planet is warmed by 1°C, which would cause an increase in intense rainfalls when precipitation events occur (Mishra, 2018).

Just as annual air temperatures in the Great Lakes region have increased since 1940, the decadal air temperature in Michigan has been steadily increasing by 0.3°F per decade in the years 1940–2019 (Fig. 4). Accompanying increased temperatures is an increase in decadal precipitation of 0.52 inches/decade occurring in the same years, 1940–2019 (Fig. 5). Local rainfall patterns in the Pere Marquette region also follow the statewide temperature and precipitation trends (Fig. 6). Another consequence of climate change in Michigan is decreased ice coverage on the Great Lakes from 1963 to 2001, which impacts winter evaporation and lake levels (Bartolai et al., 2015).

Since increased precipitation for a region can lead to increased discharge for the region's rivers, climate change-induced increases in precipitation for the Great Lakes region could mean that flow conditions of Michigan's rivers may change. In this study, I test the hypothesis that an increase in rainfall will result in more frequent flooding events along Michigan rivers, specifically along the Pere Marquette River. I test this hypothesis using the Pere Marquette River in West Michigan as a case study. Here, daily discharge measurements from 1940–2019 are analyzed to create decadal flow-duration curves. I assess changes in flow conditions at the Pere Marquette River by calculating the discharge associated with bankfull flow conditions, which are those commonly associated with a flood that has a 1.5 year recurrence interval (Edwards et al., 2019), and analyze trends in the exceedance probability across each decade on record. I also assess how discharge changes along the same low (1%) exceedance probability throughout the decades 1940–2019.

The Pere Marquette was chosen for this study because it is one of the 16 rivers that the Michigan Department of Natural Resources (DNR) has designated as a Natural River system (DNR, 2021; Fig. 7). The Pere Marquette River (Fig. 7) is the largest undammed river in Michigan (~64 miles in length, 740 mi^2) and drains fine-grained glacial till and outwash in the areas of Mason, Newaygo, and Oceana counties into Lake Michigan.

METHODS

The amount of water that is flowing through a stream, its discharge (Q), is given by the following relationship:

$Q = V\ D\ W$

Here, Q is discharge (cubic feet per second, ft^3/s, or cfs), V is the stream flow velocity (ft/s), D is the stream depth (ft), and W is the stream width (ft). Discharge is calculated via a gauging station that continually records the stream stage, a water level with respect to a set reference height, or datum. The United States Geological Survey (USGS) measures discharge and other stream flow conditions at >8,500 different rivers across the U.S. on a daily basis. The USGS derives relationships between stream stage and discharge using a ratings curve (Fig. 8), which relates discharge to stage. Ratings curves allow hydrologists to easily estimate the discharge of a stream based solely off of its stage (USGS, 2021).

Though measuring discharge is important, understanding the probability that a specific discharge may be equalled or exceeded is important for stream hydrologists, land owners and land managers, and those who use rivers for recreation. Flow-duration curves for the Pere Marquette River were created following standard methods (Oregon State University, 2005) using daily mean discharge from the USGS stream gauging station located on the Pere Marquette River at Scottville, MI (USGS Station Number 04122500; Fig. 7). Daily mean discharge values, measured in cfs, are used from January 1, 1940, through December 3, 2019, and binned into decadal intervals (e.g., 1940–49, 1950–59, etc.). Within each decade, daily mean discharge data were sorted from highest discharge to lowest discharge and ranked (1 = highest daily mean discharge). Following the ranking of the daily mean discharge data, they were then separated into 20 classes of equal ranges in discharge.

When the class range is determined, the number of occurrences with the discharge falling in between those ranges was recorded. The cumulative number of days must also be calculated, which involves summing the number of values greater than the lowest class boundary for each successive class. Since the flow-duration curve is a plot of the percent of time discharge was equaled or exceeded (x-axis) and discharge (y-axis), the percent of time flow is not exceeded must be determined. This is done by taking the cumulative number of days for each class and dividing them by the highest number of cumulative days. Once the cumulative number of days is completed, subtracting the percent of time flow is not exceeded from 100 for each class, producing the percent of time flow is exceeded.

In this study, decadal trends of flooding along the Pere Marquette River are analyzed in two ways: first, I calculated the historical 1.5 year discharge (i.e., bankfull discharge) and analyzed the exceedance probability associated with this discharge. Second, I chose a low exceedance probability, 1%, and analyzed how decadal discharges associated with that rarity changed over time. This exceedance probability was chosen to get a better understanding of how the discharge of equally rare flooding events changes across all decades.

RESULTS

The nominal average peak discharge per decade for the Pere Marquette River has increased from 1,692 cfs in the 1940s to 2,541 cfs in the 2010s, an overall increase of 121 cfs (Fig. 9). During this time, the nominal average peak discharge per decade dropped from 2,520 cfs in the 1980s to 2,006 cfs in the 1990s. Though the nominal average peak discharge per decade has increased by 849 cfs from the 1940s to the 2010s, all average peak discharges per decade are within the uncertainties of the others. A ratings curve for the Pere Marquette River (Fig. 10), based on the stage height and discharge associated with the stage height, shows that the overall height of the river's water level of the average peak discharge per decade has increased 0.7 feet since the 1940s.

The discharge associated with bankfull discharge for the Pere Marquette River (i.e., the 1.5-recurrence interval) is 1,643 cfs and is derived from the entire historical record of discharge (Fig. 10). The fact that flow-duration curves for each decade do not overlap is an indication that flow conditions of the Pere Marquette River are different for each decade on record. Flow-duration curves from 1940–2010 show that the exceedance probability of the 1.5-year flood (e.g., 1,643 cfs) increased from a minimum of 0.75% in the 1940s to a maximum of 4.5% in the 1990s and 2000s (Fig. 11). In the 2010s, the exceedance probability of the 1.5-year flood discharge dropped below those of the 1970s, 1990s, and 2000s (Fig. 12).

The discharge associated with a 1% exceedance probability is not constant over time and has been gradually increasing. In the 1940s, the discharge associated with a 1% exceedance probability was 1,562 cfs. Flood discharges with the same rare 1% probability of occurring or being met or exceeded, increased to 2,000 cfs in the 2010s, which resulted in a change in stage height by 0.5 feet from the 1940s to the 2000s (Fig. 10).

DISCUSSION

This study of flow conditions and flood exceedance probability is the first to assess changes in discharge over the decades ranging from the 1940s to 2010s for the Pere Marquette River, or from any of Michigan's designated Natural Rivers. New data presented in this study show that the frequency of achieving or exceeding bankfull discharge (i.e., the 1.5-year flood) has increased since the 1940s. In the 1940s, discharge on the Pere Marquette River was ≥1,643 cfs for 27 days and increased 6-fold to 164 days in the 1990s and 2000s. Furthermore, data presented here show that the discharge associated with a 1% exceedance probability has increased from 1,562 cfs in the 1940s to 2,262 cfs in the 2010s (Figs. 11–13). In relation to the changes in flow height, this equates to a change in flow height of floods with a 1% exceedance probability from 4.62 feet in the

1940s to 5.35 feet in the 2010s, an overall increase of 0.7 ft.

This study assessed the hypothesis that an increase in precipitation will result in more frequent flooding events because the more water entering the river, the more frequently a flooding event may occur. This hypothesis is supported by new flow data presented here when comparing discharge and flooding on the Pere Marquette River to both statewide and local trends in precipitation (Figs. 5, 6). It appears that flooding along the Pere Marquette River has become more frequent, accompanied by an increase in the discharge of the rare floods, a 1% exceedance probability (Fig. 6). This suggests that there is a relationship between climatic changes and precipitation trends that ultimately affects the frequency of flooding events and the discharge associated with those floods.

Though trends in decadal exceedance probability and flooding are being compared to annual rainfall patterns, they are not directly related to one another due to the different timescales from which the different measurements are made. A full understanding of the relationship between rainfall patterns and exceedance probabilities requires a more detailed water budget and land-use analysis. Doing so requires, at least, an analysis of evapotranspiration within the watershed area and ground water inflow and outflow rates. Such a detailed water budget analysis is not a part of this project.

Since most of the Pere Marquette River watershed is located within the Manistee National Forest, it is possible that changes in stream flow and flooding could be attributed to deforestation and land-use changes. Deforestation due to road construction, power-line installation, and communication facilities has recently been documented (USDA Forest Service, 2021); however, this deforestation and land-use change has occurred on a small scale and is therefore unlikely to have a large impact on the discharge of the Pere Marquette River.

Michigan's climate is projected to continually change, with an increase in average air temperature by 0.3°F/decade, and precipitation is projected to increase by 0.036 inches/year (Figs. 4, 5). If the parallel trends of increasing precipitation and increasing frequency of high-discharge flows of the Pere Marquette River continue, the geomorphology of the river will respond by adjusting to the new climate conditions.

The discharge associated with the 1% exceedance probability is increasing. In other words, floods that occur 36 days out of every decade are getting larger. In the 1940s this meant a discharge of 1,562 cfs was met or exceeded. In the 2010s a discharge of 2,000 cfs was met or exceeded. Following river flow relationships described by Lane (1955), it is likely that the Pere Marquette River will erode the streambed and banks until equilibrium is re-established. Equilibrium may be achieved once more by increasing the volume of the river's bedload and/or increasing the coarseness of the river's bedload. Additionally, an increase in flood discharges over time could likely be balanced by the Pere Marquette River flattening its slope by depositing sediments onto the streambed (Fig. 1). Overall, it is likely that, over time, the bedload of the Pere Marquette River will become coarser. In addition, more frequent and larger flooding events along the Pere Marquette River could also contribute to the erosion of the finer sediments on the river bed, at least during floods.

The frequency of flooding on the Pere Marquette River is not just of interest to fluvial geomorphologists. Spawning salmon in the Pere Marquette River rely on coarse-grained sediments on the streambed, and with more flooding events, these conditions could become more suitable if the Pere Marquette were to deposit coarser-grained sediments in order to re-establish equilibrium (Hassan et al., 2008). Furthermore, coho salmon, one of the most common fish species in the Pere Marquette River, rely on streams with low turbidity; coho salmon growth rates may be impeded if more frequent, larger-magnitude flooding increases the suspended load of the Pere Marquette River (Araujo et al., 2015). More frequent flooding events also affect trout populations by more stream bank erosion occurring, which may lead to more sand being deposited on top of the gravel, mainly in areas that have lower turbidity, providing necessary stream beds for trout spawning nests (Tarzwell, 1931; Workman et al., 2004). In addition to impacts on fish populations, the riparian corridor may be negatively affected by more frequent flooding since stream discharge is an important factor in the maintenance of a riparian ecosystem (Primack, 2000; Parsons, 2019).

Additionally, property owners along the Pere Marquette River may also be affected by these changes in flooding patterns. Property owners along the Pere Marquette River may experience personal and economic losses due to the increasing frequency and size of the flooding events, such as structural damage and property loss due to river bank collapse (Lewis et al., 2008; Parsons, 2019). An increase in flooding frequency and size can also negatively affect recreational activities along the Pere Marquette River. Because these flooding events are larger, the discharge during the events is also larger, which can reduce the safety of recreational activities along the river (Talbot et al., 2018).

CONCLUSION

The potential for bankfull flow events on the Pere Marquette River has increased since the 1940s, specifically from occurring 27 days in the 1940s, increasing 6-fold to 164 days in the 1990s and 2000s. Additionally, the discharge associated with the 1% exceedance probability has increased from 1,562 cfs in the 1940s to 2,262 cfs in the 2000s. This is likely due to climate change in the Great Lakes region, which has seen temperature increases of 0.3°F/decade and rainfall increases of 0.52 inches/decade since the 1940s. Based on the flood exceedance probability trends shown in this study, an increase in more frequent and larger flooding events may also be occurring along other Natural Rivers in Michigan. As a result, recreational activities, property values, and some species of fish may be negatively affected by increasingly-frequent and larger flooding events.

Figure 1. *Diagram from the Vermont River Management Program (2005) showing the proportional relationships between the size of sediments deposited onto the bed and how that is connected to the grade of the river, developed by Lane (1955). For example, if the channel geometry were to steepen, the river could deposit more or coarser sediments on the bed in order to re-establish equilibrium.*

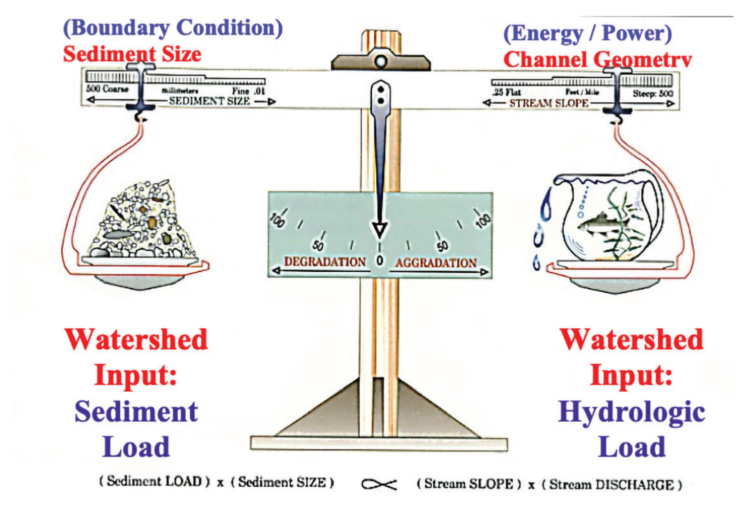


Figure 2. *Generic flow-duration curve, which plots discharge against the percent of time any specified discharge was equalled or exceeded during the period of discharge measurement (i.e., the exceedance probability; Searcy, 1969). Based on*

this example, this stream had a measured discharge ≥1,000 cfs for10% of the time during which discharge was measured.

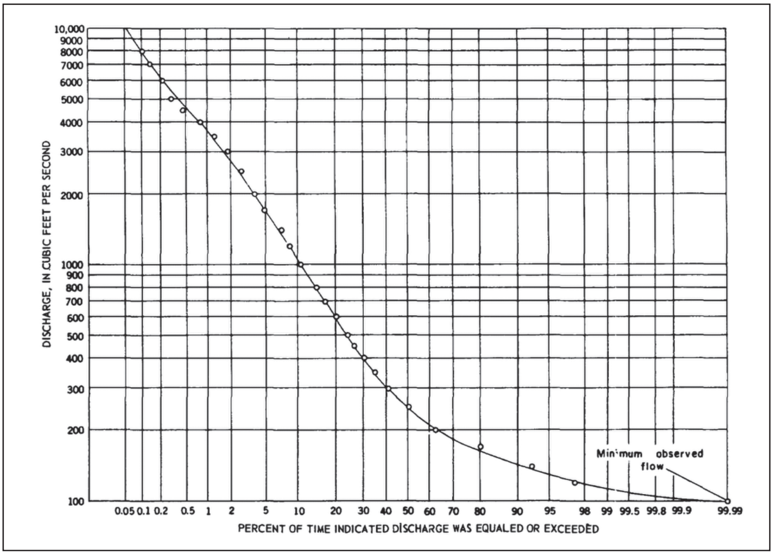


Figure 3. *Graph showing historical annual average temperature (black line) and projected annual average temperatures of the Great Lakes region; projected annual average temperatures under high greenhouse gas emissions model are shown in purple, and those under a low greenhouse gas emissions model are shown in orange (Hayhoe et al., 2010).*

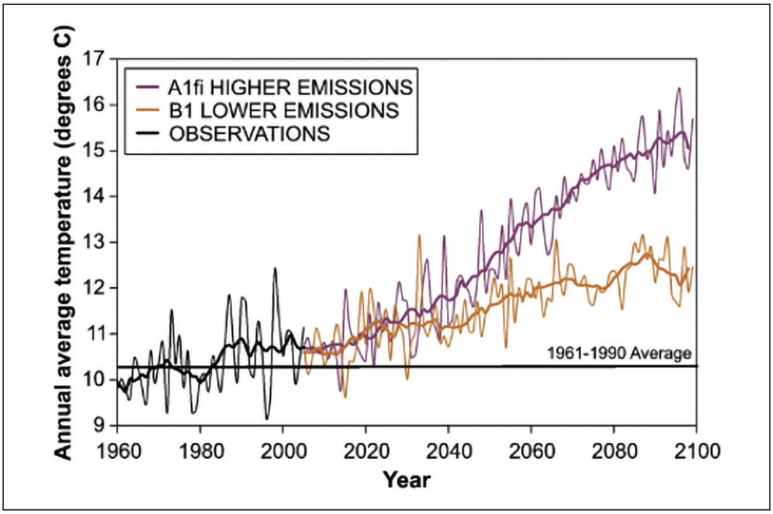


Figure 4. *Annual average temperature trends for Michigan between 1940–2019 (National Oceanic and Atmospheric Association (NOAA), 2021). The horizontal gray line shows the average temperature for the period of record (1901–2000). Temperatures have increased 0.3°F/decade (blue line).*

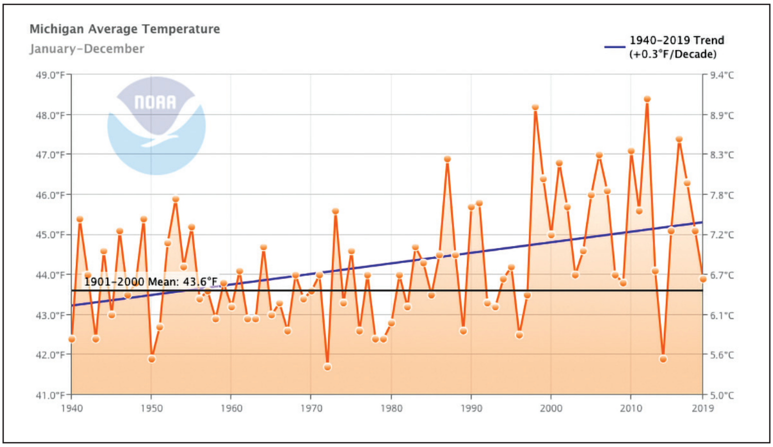


Figure 5. *Annual precipitation totals for Michigan between 1940–2019 (NOAA, 2021). The horizontal gray line shows the average precipitation for the period of record (1901–2000). Precipitation increased 0.52 inches/decade over the period of record (blue line).*

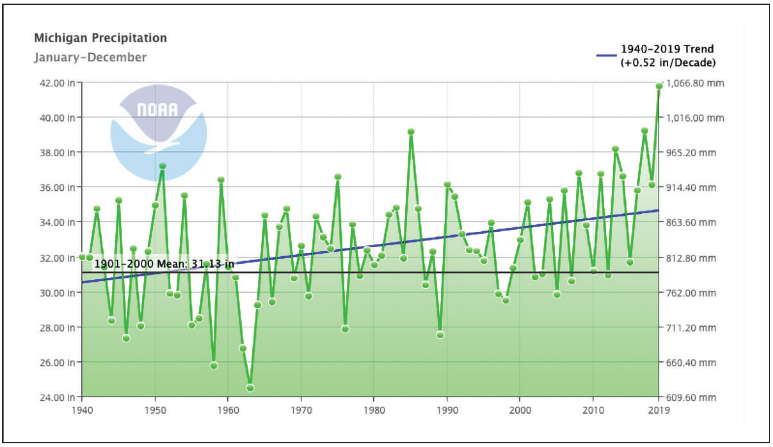


Figure 6. *Local average annual precipitation data along the Pere Marquette region with the 1940 to 2019 mean of 32.6 inches indicated by the solid black line with a rate of increase of 0.11 inches/year indicated by the solid orange line. Precipitation data come from seven stations within the immediate vicinity of the Pere Marquette River: Scottville 2SE, MI; Scottville 1NE, MI; Ludington 4 SE, MI; Baldwin, MI;*

Luther, MI; Reed City WWTP, MI; and Big Rapids Water Treatment Plant, MI (Cli-MATE, 2021).

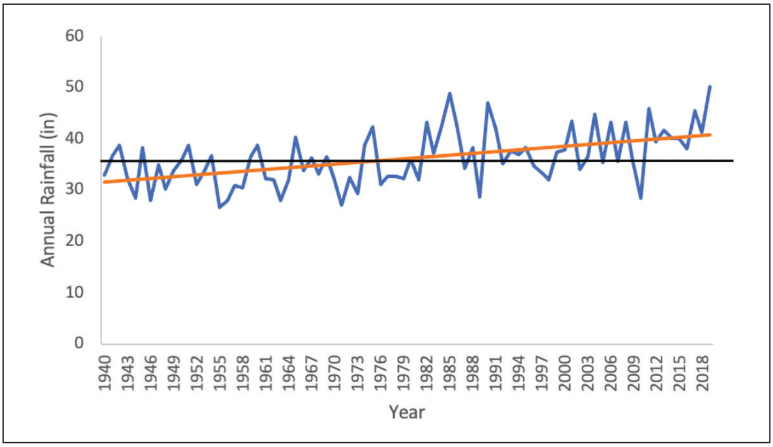
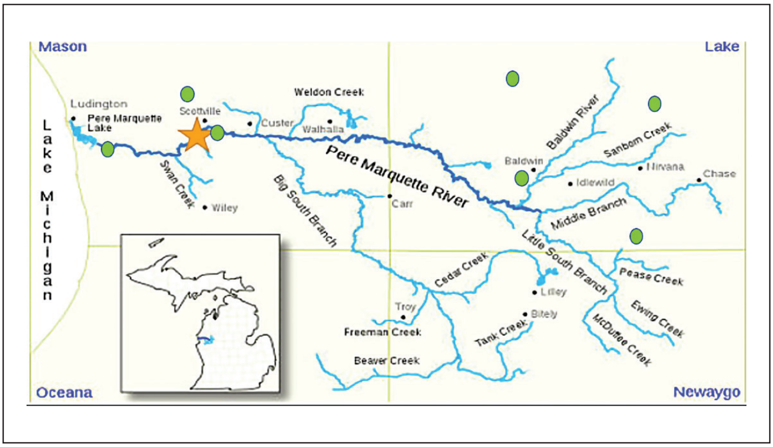


Figure 7. *A. Pere Marquette River main branch highlighted in blue, USGS stream gaging station #04122500 located by the star, and precipitation stations indicated by the green dots. B. All the rivers in Michigan that are considered natural rivers (DNR, 2021).*

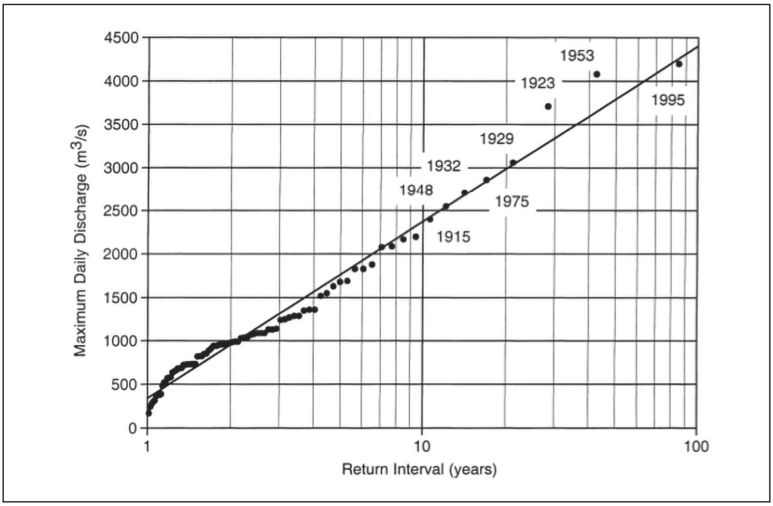
A



B

Figure 8. *A. Generic discharge versus return (recurrence) interval provided by Kalischuk et al. (2001), which plots discharge (cfs) against recurrence interval (years). B. Generic representation of a stream's ratings curve, which plots height of stream flow above a datum (ft) against discharge (cfs) (USGS, 2021).*

A



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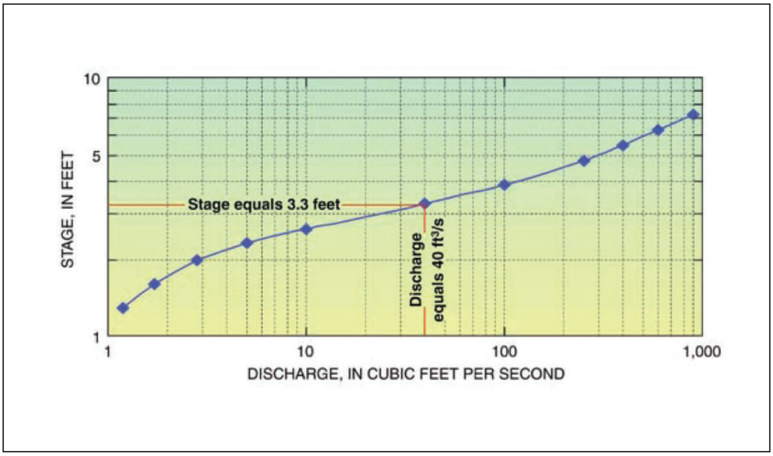


Figure 9. *Average decadal peak discharge values for the Pere Marquette River between 1940-2019 with standard deviations, averages, and corresponding decades shown in Table 1.*

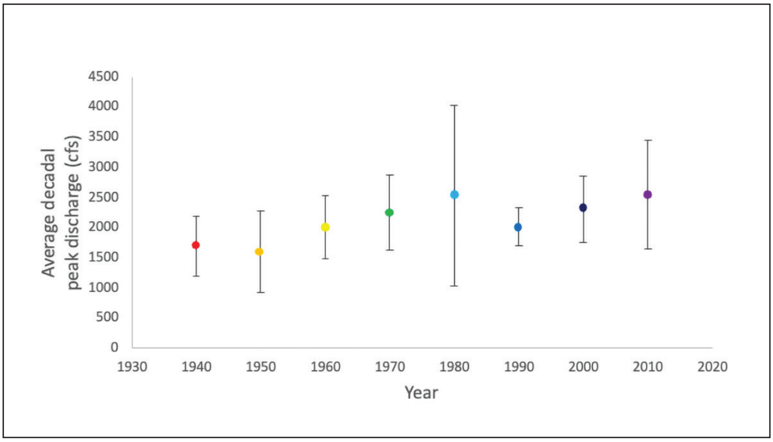
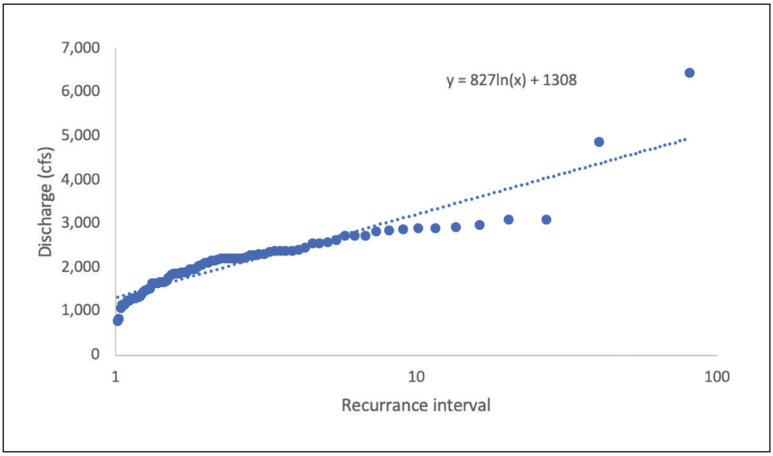


Figure 10. *A. Discharge versus recurrence interval graph for the Pere Marquette River. B. Accompanied by the ratings curve associated with the Pere Marquette River.*

A



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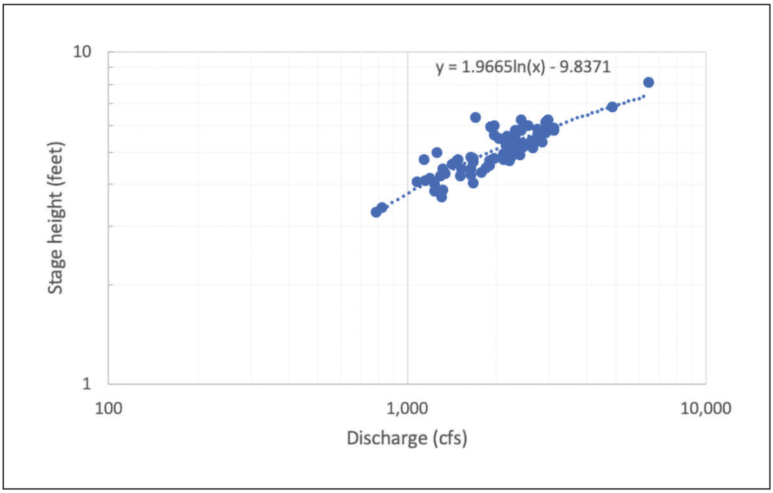


Figure 11. *A. Decadal flow-duration curves for the Pere Marquette River between 1940-2019. Horizontal black line shows discharge associated with bankfull flow conditions (i.e., the 1.5-year recurrence interval flood; Q = 1,643.3 cfs). B. Decadal flow-duration curves showing a more-limited range of discharge (Q < 3,000 cf) to aid in visualizing the 1.5-year flood conditions.*

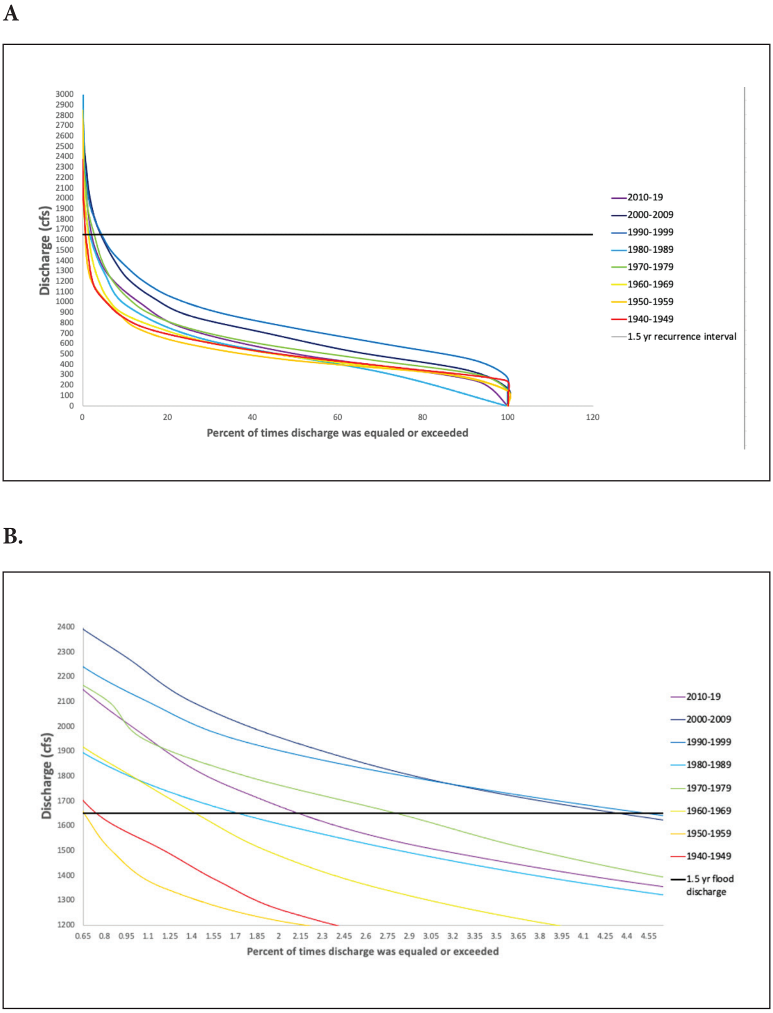


Figure 12. *Exceedance probability associated with the discharge of the 1.5-year flood (1,643.3 cfs) for each decade analyzed, based on Fig. 9.*

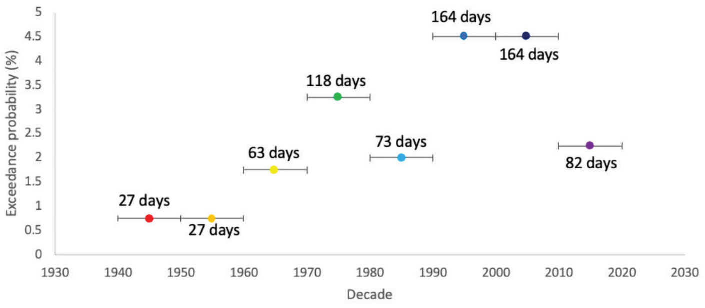
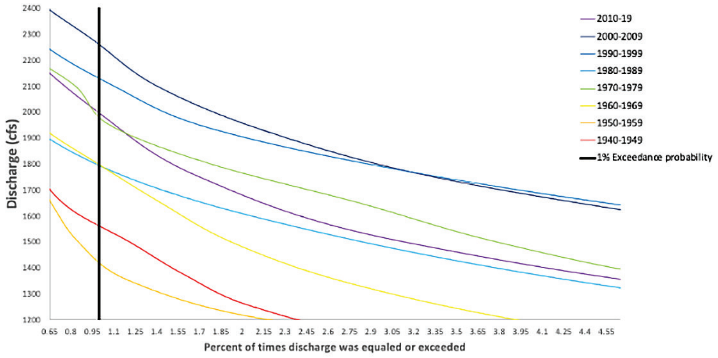


Figure 13. *A. Flow-duration curves previously shown in Fig. 10 but with decadal discharges of the 1% exceedance probability and zoomed in on the 1% exceedance probability. B. Decadal discharges associated with the 1% exceedance probability.*

A



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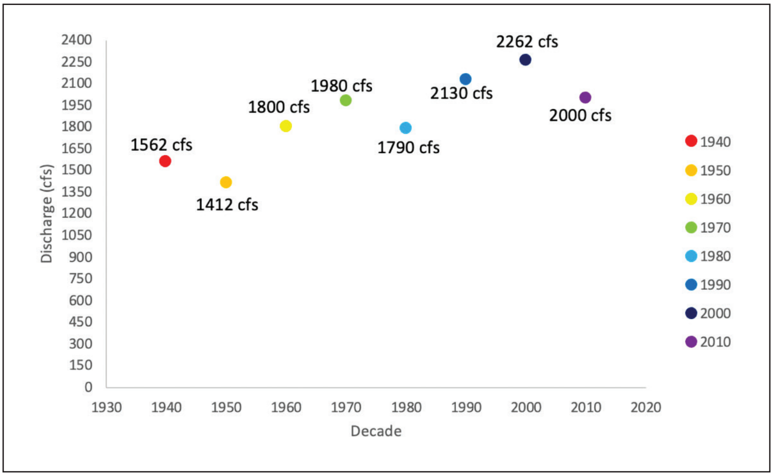

TABLES

Table 1

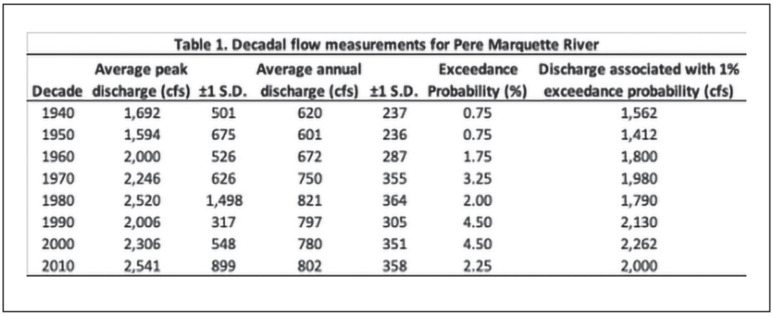

Table 1. Decadal flow measurements for Pere Marquette River

Decade	Average peak discharge (cfs)	±1 S.D.	Average annual discharge (cfs)	±1 S.D.	Exceedance Probability (%)	Discharge associated with 1% exceedance probability (cfs)
1940	1,692	501	620	237	0.75	1,562
1950	1,594	675	601	236	0.75	1,412
1960	2,000	526	672	287	1.75	1,800
1970	2,246	626	750	355	3.25	1,980
1980	2,520	1,498	821	364	2.00	1,790
1990	2,006	317	797	305	4.50	2,130
2000	2,306	548	780	351	4.50	2,262
2010	2,541	899	802	358	2.25	2,000

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