ARCADIS

Michigan Department of Transportation

Infrastructure Protection and Rehabilitation Response to High Lake Levels

MDOT OR21-013

Appendix D: Inundation Duration Analysis Methodology

March 2022 (Final)

Infrastructure Protection and Rehabilitation Response to High Lake Levels

MDOT OR21-031

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March 2022 (Final)

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1 Duration Water Level Analysis

This Appendix describes the water level analysis performed on Algonac and Ludington NOAA monitoring stations. These stations observe water levels and meteorological data including winds, air temperature, barometric pressure, and relative humidity. The Ludington station (9087023) is located on the eastern bank of Lake Michigan within Pere Marquette Lake. The Algonac station (9014070) is located on the western bank of the St. Clair River north of the divergence between the North and South Channels of the St. Clair River. The St. Clair River empties into Lake St. Clair which is situated south of Lake Huron and north of Lake Erie. Relative location of these stations within the watershed are shown in Figure 1. Details of both stations are provided as insets with Ludington shown on the left and Algonac to the right in the figure.

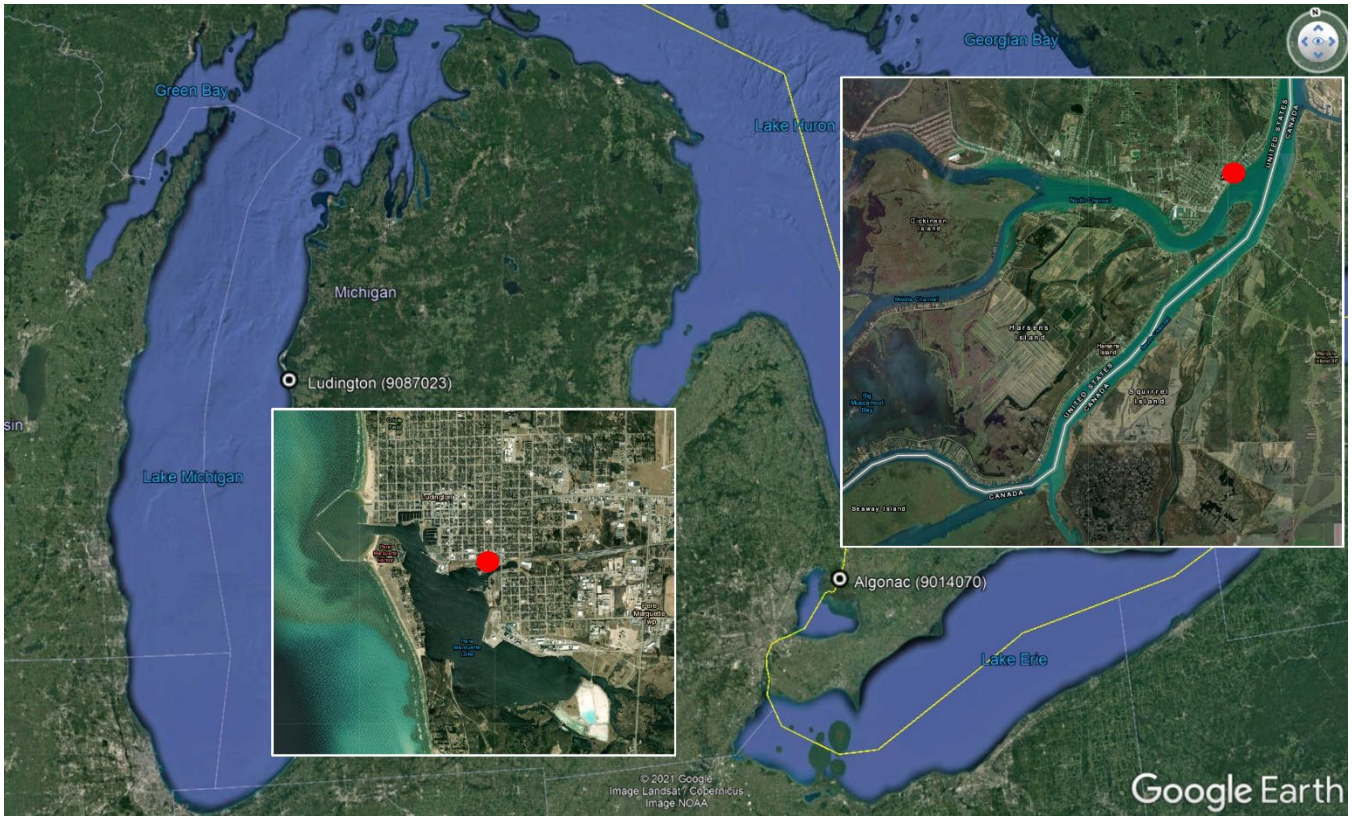

Figure 1. Ludington and Algonac NOAA station locations. Insets: Ludington (left), Algonac (right).

This work leverages a unique 51-year hourly water level time series from both stations spanning January 1971 to the start of April 2021. The goals of this analysis are 1) determine the number of exceedance events and 2) compute the duration this threshold is exceeded. Threshold elevations include the edge of pavement and bottom of subgrade for both stations.

An additional design elevation was also included. These threshold elevations (Table 1) were developed collaboratively with the Arcadis team and MDOT established in June 2021.

Table 1. Threshold Elevations (ft, IGDL).

	Algonac (St. John's Marsh)	Ludington (Frankfort/Elberta)
Edge of Pavement (At Shoulder)	577.3	581.2
Bottom of Subgrade	574.5	578.2
Design Elevation	579.8	582.9

The results of this analysis support further risk and cost benefit analysis as days of exceedance per year.

1.1 Methodology

Data processing workflow is depicted in the following chevron chart Figure 2 and each process will be discussed in the following sections.

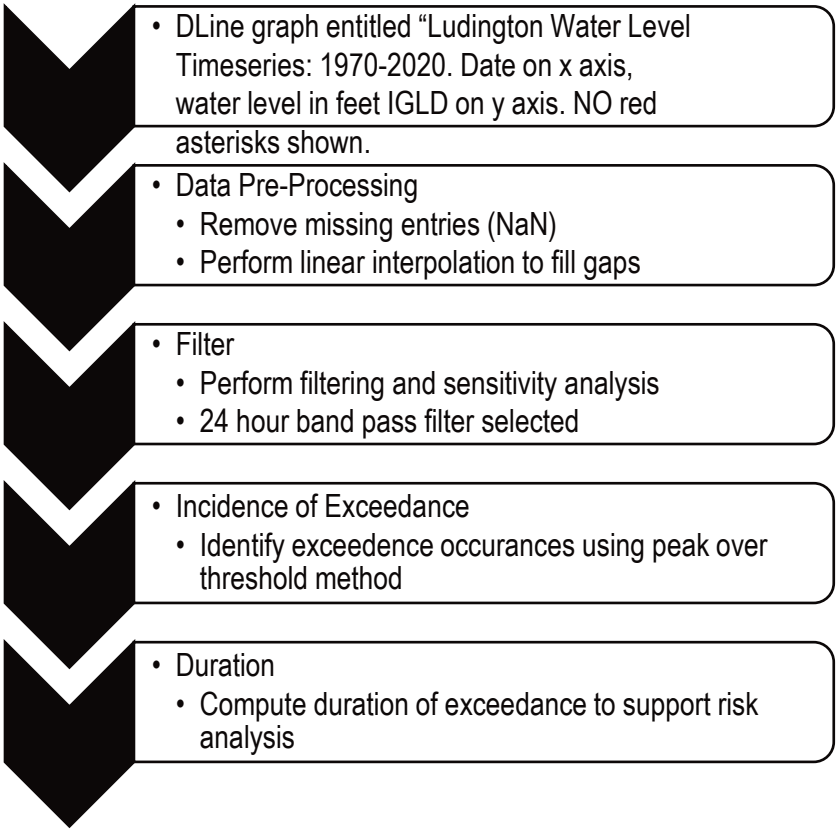

Figure 2. Data processing workflow.

1.1.1 Database Generation and Initial Inspection

This process includes initial evaluation of the data and building a Matlab (.MAT) database to facilitate analysis. This database can be converted into other data formats such as comma separated variables and text files for ease of distribution. Initial evaluation of the timeseries included examining the dataset for large gaps and repeated entries. Minor corrections were made to both timeseries. The long-term behavior of both signals are similar from a long term perspective however, the distinct signal behavior of each station can be best observed at shorter intervals. Figure 3 presents a comparison between the two gauges over approximately a year of observations.

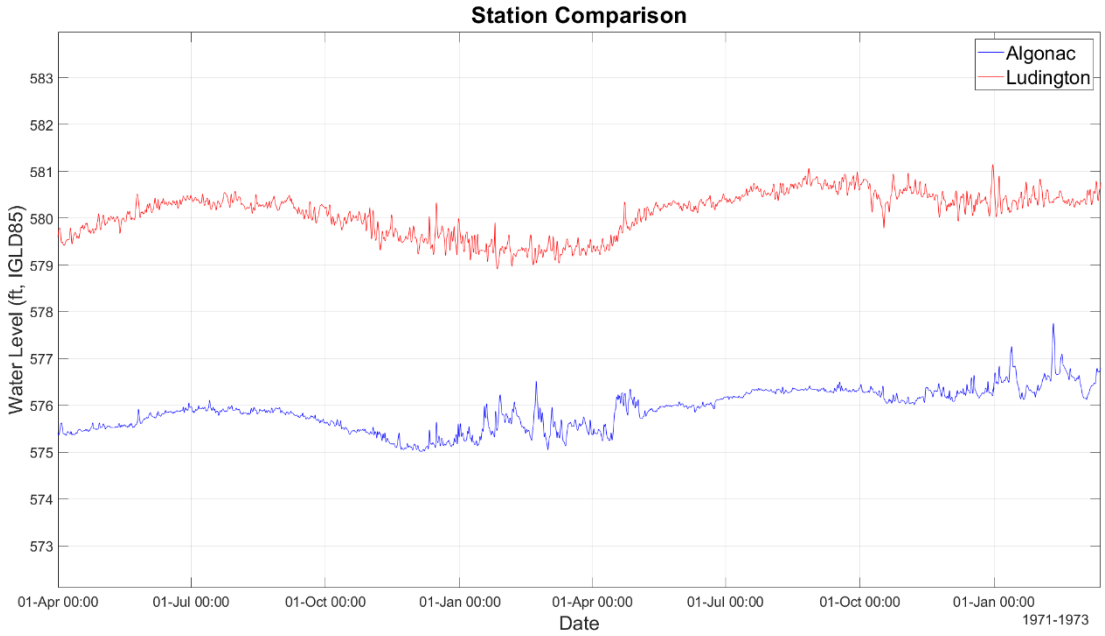

Figure 3. Algonac and Ludington timeseries comparison.

The Algonac station is represented by a blue line (lower) and the Ludington station is presented as a red line (upper). A similarity can be observed in the general trend however there is some variability between the two gauges on shorter time periods. During this observation period, the Algonac gauge experienced larger water level variations in April 1975 and again in January – February 1976 while the Ludington gauge had smaller variations during the same time. The offset between the records is due to the vertical difference between the stations. The conversion between NAVD88 and IGLD is provided in Table 2.

Table 2. Datum Conversions.

	Algonac (St. Johns)	Ludington (Elberta/Frankfort)
NAVD88 (ft)	577.5	581.5
IGLD (ft)	577.3	581.2

Table 3 provides descriptive statistics for both stations. It should be noted that all the elevations listed are below the design elevations in Table 1.

Table 3. Descriptive statistics.

	Algonac (ft, IGLD)	Ludington (ft, IGLD)
Maximum	578.34	582.91
Mean	575.38	579.17

1.1.2 Data Pre-Processing

This exercise includes removing missing entries (NaN) and perform linear interpolation to fill gaps with native matlab subroutines. Linear interpolation is performed between the neighboring, non-missing values (Matlab, 2021).

1.1.3 Filtering

The water level timeseries is filtered using a band pass approach to remove the daily oscillations and other high frequency variability in the hourly signal. A sensitivity analysis is performed to evaluate the effect of filtering the signal for varying time periods has on both the number of exceedance events and the duration of the exceedance. Figure 4 presents a comparison between 12, 24, 36 and 48 hours filtered timeseries to the raw dataset. The raw dataset is represented by a black dashed line while the filtered periods are represented by cyan, blue, green, and red respectively. Date is on the horizontal axis while the water level (ft, IGLD) is on the vertical axis. The 24-hour filter is selected for further analysis since it maintained the amplitude of the peak while removing much of the signal noise. Reduction in amplitude was on the order of 0.15 ft. This sensitivity exercise indicates that there were observable differences in the number of exceedance events between filtering time periods but no change in the total duration. Duration is the primary parameter to be incorporated into further risk analysis.

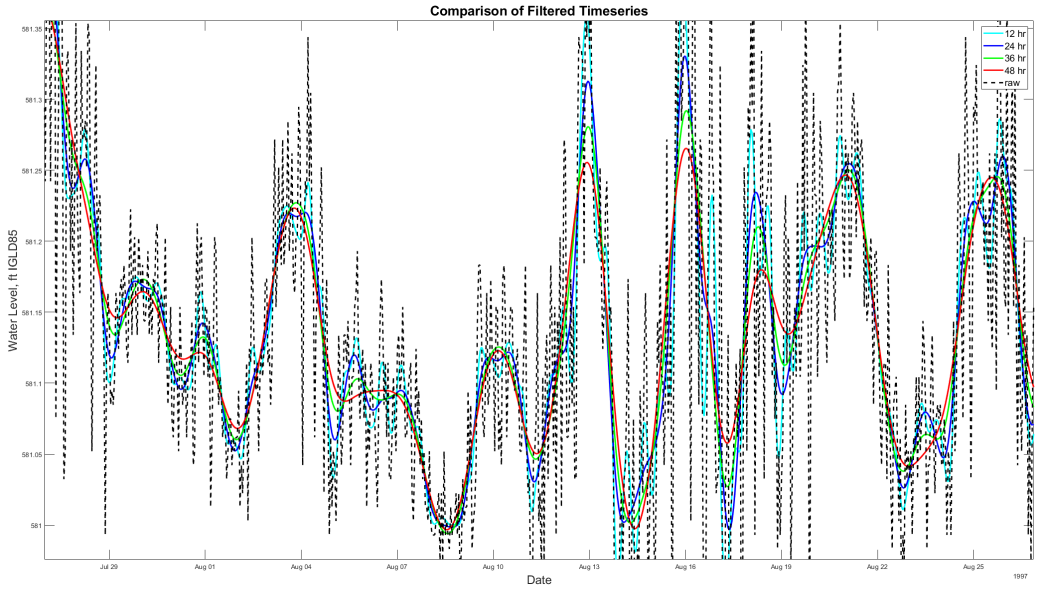

Figure 4. Comparison of Filtered Timeseries.

1.1.4 Incidence of Exceedance

A Peak-Over-Threshold (POT) method is used to identify exceedance occurrences throughout the water level timeseries. This is a method to model extreme values in a dataset and establishes a threshold to identify values that exceed this threshold. A graphical example of POT is shown in Figure 5 where the threshold is represented by a horizontal red line and the filtered time series is represented by a blue line. Date is shown on the horizontal axis and water level in ft, IGLD is on the vertical axis. The POT method identifies the peak at the center of the exceedance and recorded. An event is defined by an up crossing past a defined threshold and closed by a down crossing below the threshold.

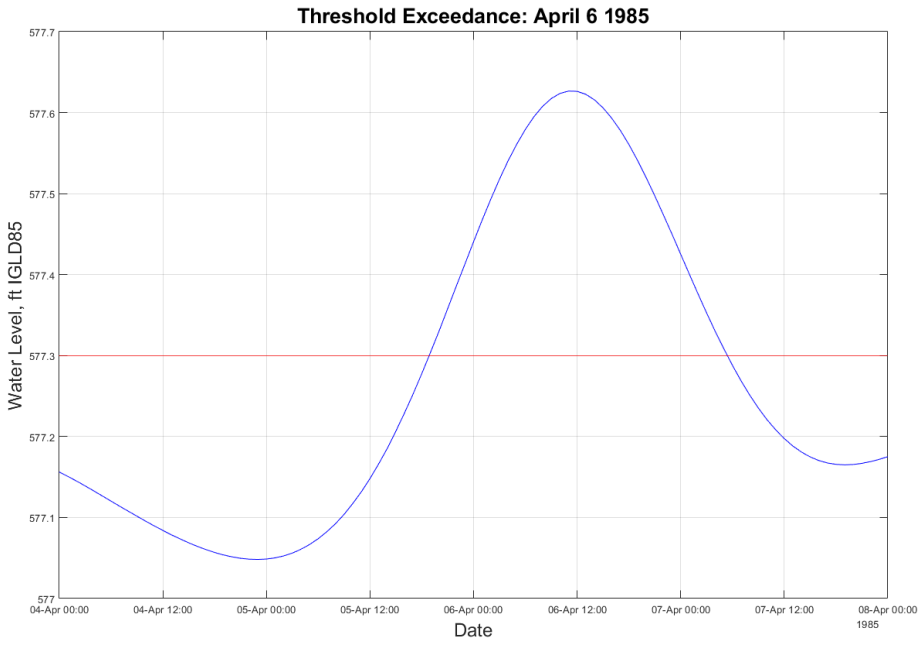

Figure 5. Example of Threshold of Exceedance.

1.1.5 Duration of Exceedance

Duration of exceedance is computed at each identified peak from the POT method throughout the timeseries. The time and date of both the initial up cross past the threshold and the final down cross below the threshold were identified and the difference between these two time and dates were computed.

1.2 Results

Results of this analysis will be presented for each threshold for both stations.

1.2.1 Algonac: Edge of Pavement (At Shoulder)

The incidence of exceedance for the Algonac water level record 66 for the edge of pavement threshold of 577.3 ft, IGLD. The incidences of occurrence are clustered during periods of elevated water conditions in the following time periods; 1973 – 1974, 1985 – 1987, and 2019 – 2021. A single incident of exceedance is observed in 1997. A summary of occurrences is tabulated in Table 4. It should be noted that 2021 is a partial year of record and only includes the first three calendar months.

Table 4. Algonac Station Incidences of Exceedance: Edge of Pavement (At Shoulder).

Year	Incidence
1973	2
1974	2
1985	6
1986	21
1987	5
1997	1
2019	17
2020	11
2021*	1
-	-

* Indicates partial year

The incidences of exceedance are plotted with the timeseries in Figure 6 with the timeseries represented by a solid blue line and incidence of exceedance represented by red stars. A horizontal line plotted at the 577.3 threshold for the edge of pavement elevation.

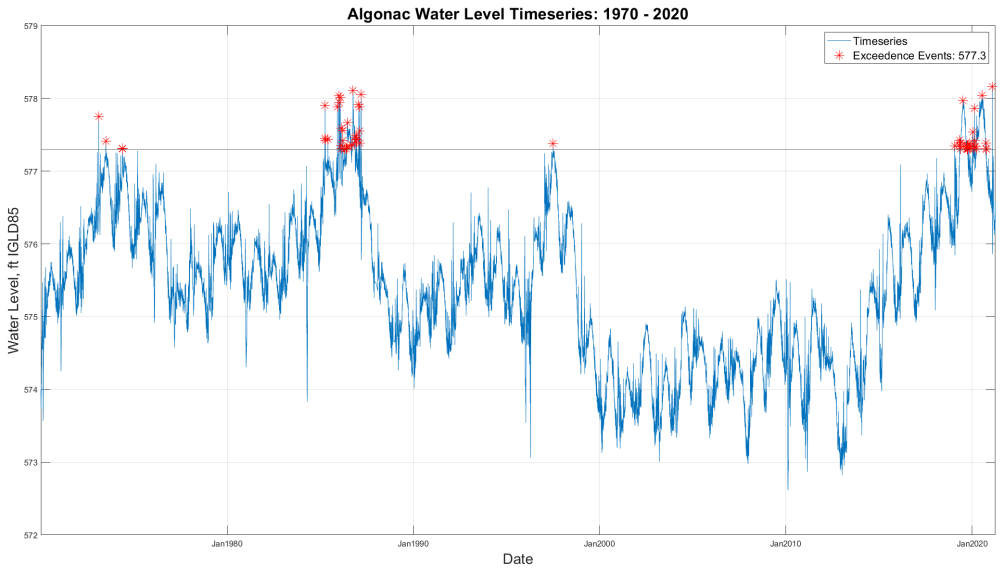

Figure 6. Algonac Timeseries and Edge of Pavement Incidence of Exceedance.

The duration of exceedance at this threshold for the entire timeseries was 582 days with a maximum duration of 179 days and a minimum of 1 hour. The average duration of exceedance was 9 days. The duration of threshold exceedance for the Edge of Pavement elevation is plotted graphically in Figure 7. Duration in hours is displayed on the vertical axis and year is on the horizontal axis.

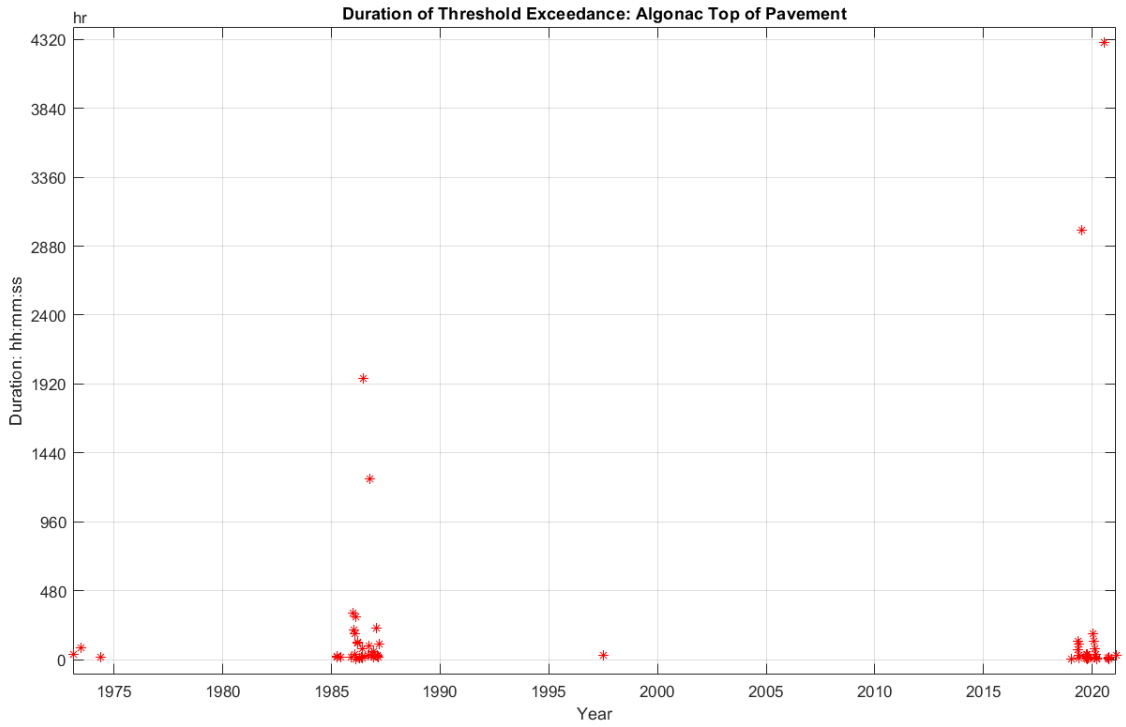

Figure 7. Duration of Threshold Exceedance: Algonac Edge of Pavement.

Examining the exceedance duration for the length of the record at this threshold indicates that while the number of exceedance events occurring between 2019 and 2020 are similar to the period between 1986 and 1987, the duration of exceedance has increased in the more recent events. Figure 8 plots the duration of exceedance for the Algonac station at the Edge of Pavement threshold in a histogram format. The histogram is plotted with a binning method of days and is independent of date of occurrence. Count of incidence is on the vertical axis while duration in hours is presented on the horizontal axis. The majority of exceedance duration is on the shorter end of the spectrum (left of the figure) while the longer duration events are occur less frequently.

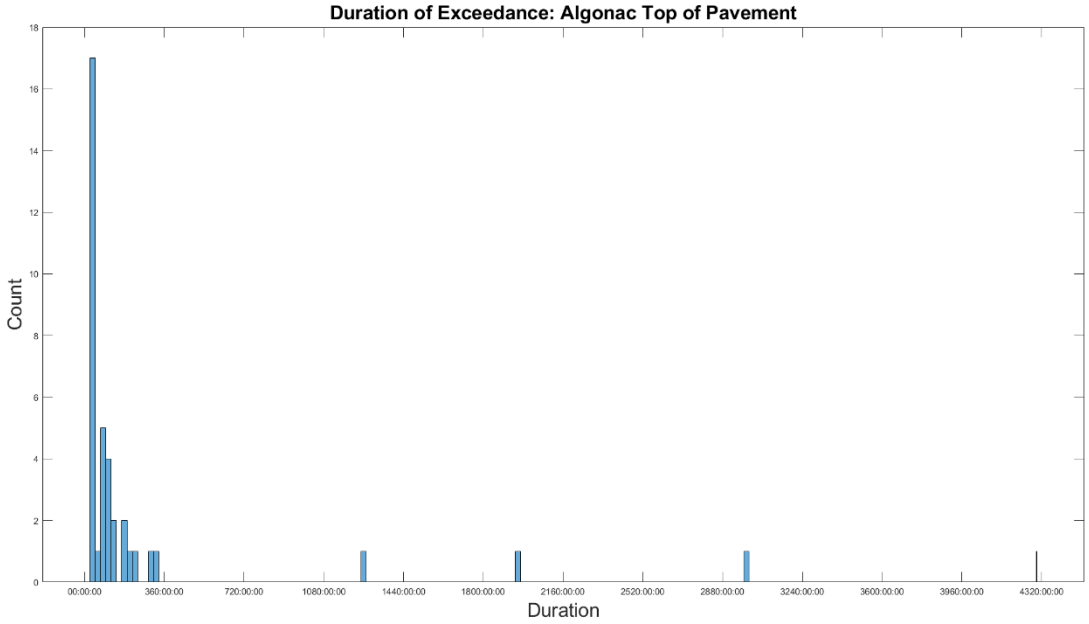

Figure 8. Duration of Exceedance: Algonac Edge of Pavement.

1.2.2 Algonac: Base of Subgrade

The base of subgrade elevation for the Algonac station is 2.8 ft lower in elevation than the edge of pavement. Therefore, the number of incidences of exceedance is likely to increase. The number of exceedance events for the Algonac station at the base of subgrade elevation was 229. Incidences of exceedance at base of subgrade are shown in Figure 9 represented by a red star at the peak of the event.

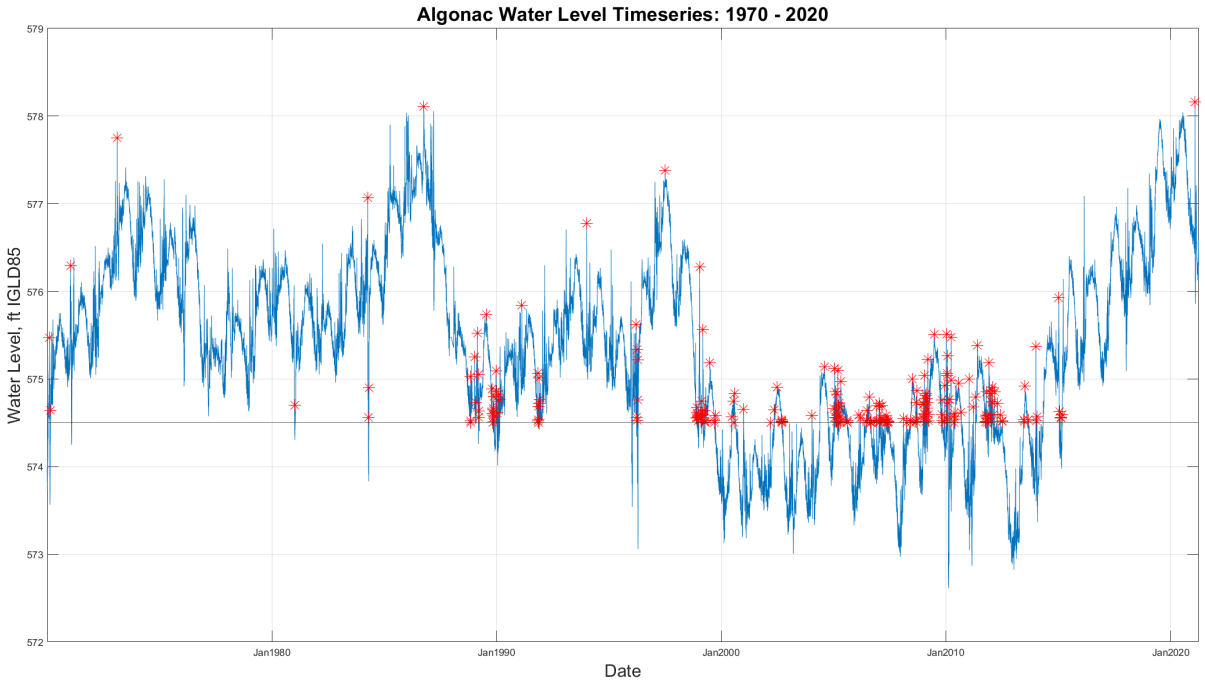

Figure 9. Algonac Timeseries and Base of Subgrade Incidence of Exceedance.

Some incidences of exceedance are long periods during elevated water conditions. The POT method requires that the exceedance event have both an initial upward cross and closed by a down cross past the threshold to define an event. Therefore, a single marker in Figure 9 may indicate a long period of threshold exceedance. Persistent elevated water levels were observed for most of the 1970s and 1980s at this threshold. Water elevations exceeding this threshold have persisted since March of 2015 and continue to the end of the observation record. The total duration of exceedance is 14,477 days (~40 years) at the base of subgrade threshold with a maximum of 3,624 days (~10 years) and an average of 63 days. Figure 10 plots the duration of exceedance for the Algonac station at the base of subgrade threshold. Year is plotted on the horizontal axis while duration in hours is on the vertical axis.

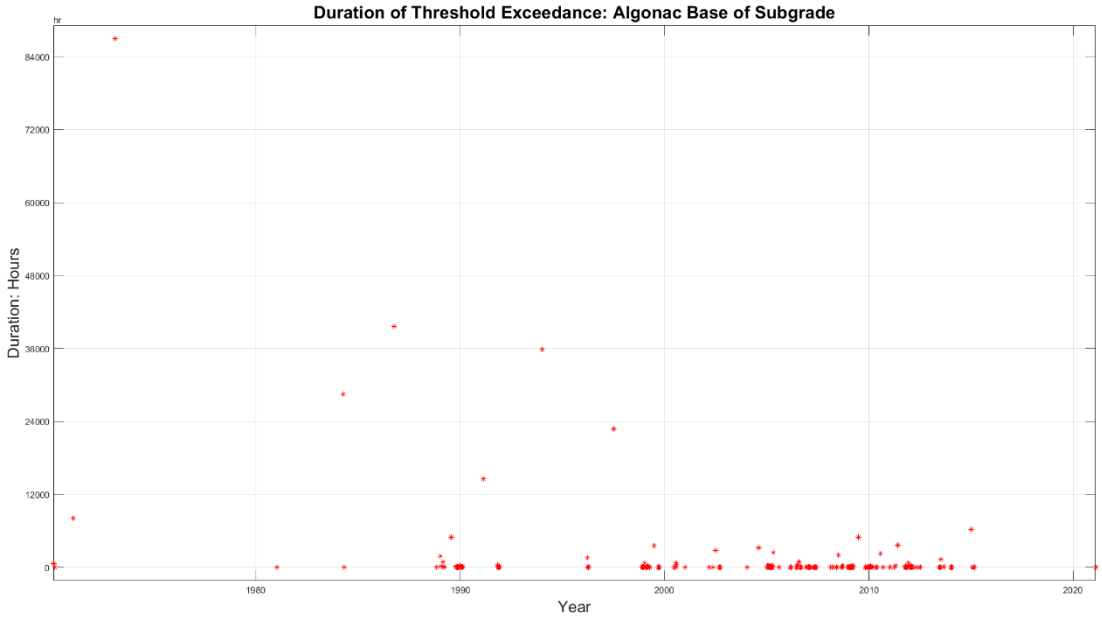

Figure 10. Duration of Threshold Exceedance: Algonac Base of Subgrade.

The duration of exceedance is dominated by the persistent elevated water conditions early in the signal while most of the other incidents of exceedance occurred at much lower durations. Short durations of exceedance are observed between 1990 through 2015. Figure 11 plots the duration of exceedance for the Algonac station at the Base of Subgrade threshold in a histogram format. The histogram is plotted with a binning method of days and is independent of date of occurrence. Count of incidence is on the vertical axis while duration in hours is presented on the horizontal axis. The majority of exceedance duration is on the shorter end of the spectrum (left of the figure) while the longer duration events are occur less frequently.

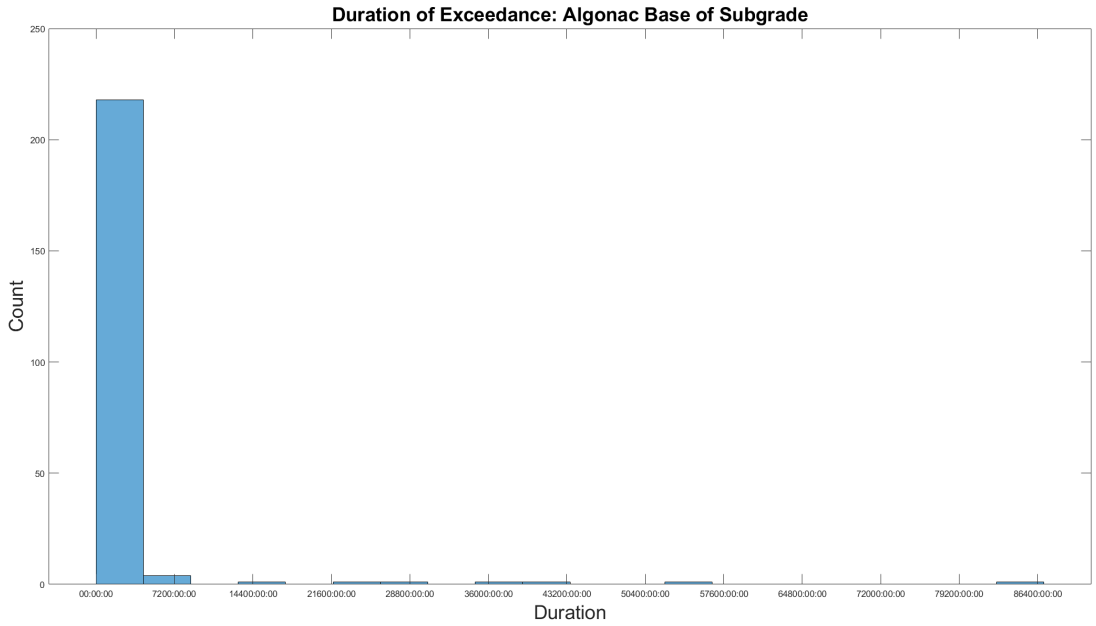

Figure 11. Duration of Exceedance: Algonac Base of Subgrade.

1.2.3 Algonac: Design Elevation

A design elevation of 579.8 ft IGLD is evaluated to observe incidence of exceedance at this threshold. As shown in Figure 12, no incidence of exceedance occurred during the observation period at the Algonac station.

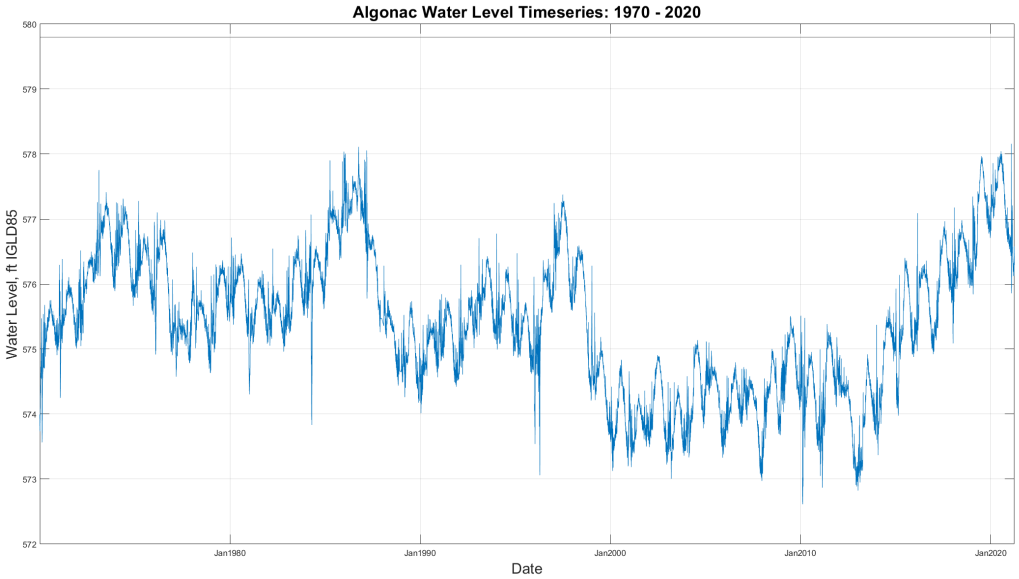

Figure 12. Algonac Timeseries and Design Elevation Threshold.

1.2.4 Ludington: Edge of Pavement (At Shoulder)

The incidences of exceedance for Ludington edge of pavement elevation of 581.2 ft, IGLD was 158. The results are summarized annually in Table 5.

Table 5. Ludington Edge of Pavement Incidence of Exceedance.

Year	Incidence
1973	10
1974	10
1975	4
1976	4
1985	56
1986	22
1987	10
1997	10
2019	5
2020	15
2021*	2

Incidences of exceedance occurred in distinct clusters in the time periods between 1973 – 1976, 1985 – 1987, 1997 and 2019 – 2021. It should be noted that 2021 is a partial year that includes the first three months. These clusters can be observed in Figure 13. The timeseries is plotted in blue and incidences of exceeded determined using the POT method are represented as red stars. The horizontal line at 581.2 ft IGLD provides a reference of the edge of pavement elevation.

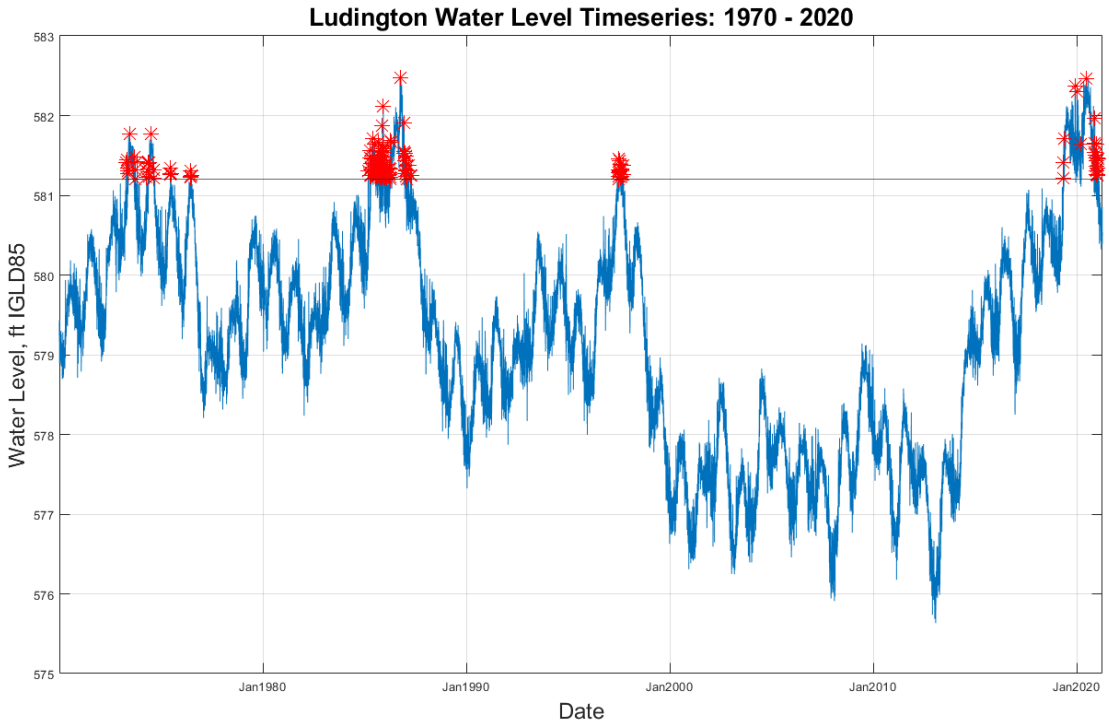

Figure 13. Ludington timeseries and Edge of Pavement incidence of exceedance.

The total duration of exceedance for the Ludington station at the edge of pavement threshold is 1,306 days (~3.5 years) with a maximum of 231 days (0.63 years), minimum of two hours and a mean of eight days. Figure 14 plots the duration of exceedance on the vertical axis through time on the horizontal axis.

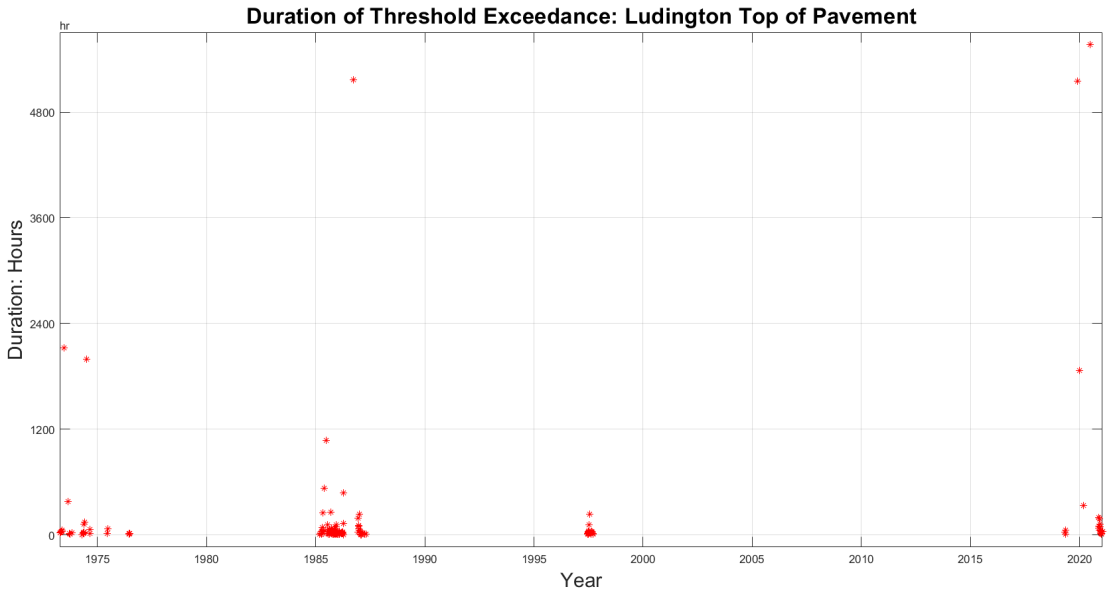

Figure 14. Duration of Threshold Exceedance: Ludington Edge of Pavement.

The duration of exceedance is largely below 1,200 hours however several outliers of far greater duration are observed throughout the observation period. One of the longest durations of exceedance occurs between 1985 and 1990 and two other long duration incidents are also observed later in the record around 2020. Figure 15 plots the duration of exceedance for the Ludington station at the Edge of Pavement threshold in a histogram format. The histogram is plotted with a binning method of days and is independent of date of occurrence. Count of incidence is on the vertical axis while duration in hours is presented on the horizontal axis. The majority of exceedance duration is on the shorter end of the spectrum (left of the figure) while the longer duration events are occur less frequently.

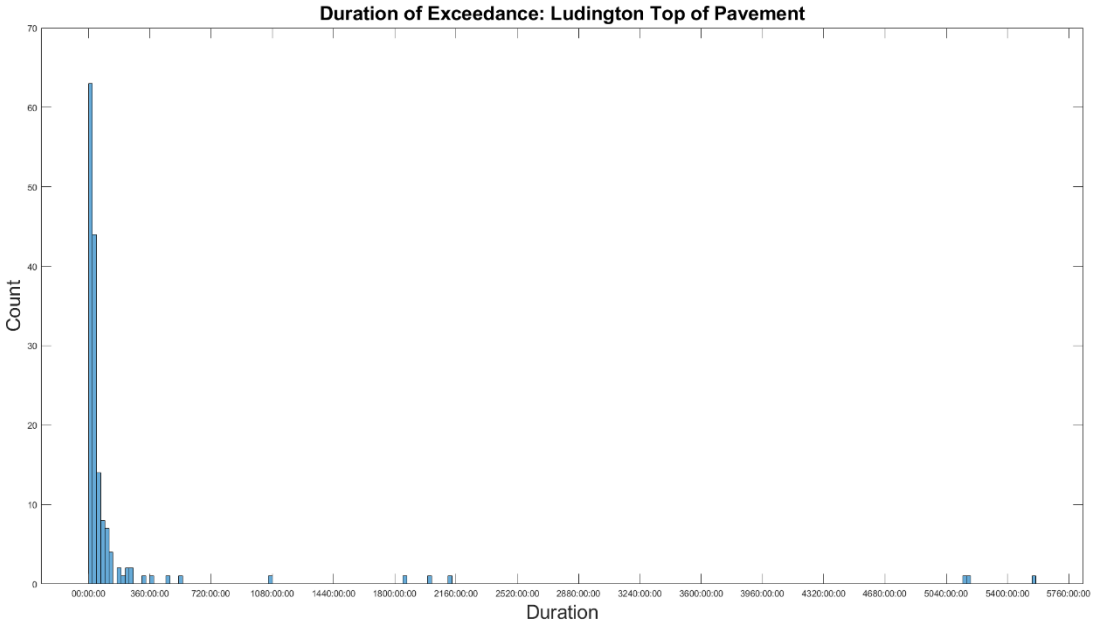

Figure 15. Duration of Exceedance: Ludington Edge of Pavement.

1.2.5 Ludington: Base of Subgrade

The bottom of subgrade is three feet lower than the edge of pavement elevation and the incidence of exceedance is likely to increase with a decrease in elevation. 210 incidences of exceedance were observed at this threshold for the Ludington water level record. Figure 16 plots the Ludington water level time series in blue with the identified incidences of exceedance as red starts. Date is provided on the horizontal axis and water level in ft, IGLD is on the vertical axis.

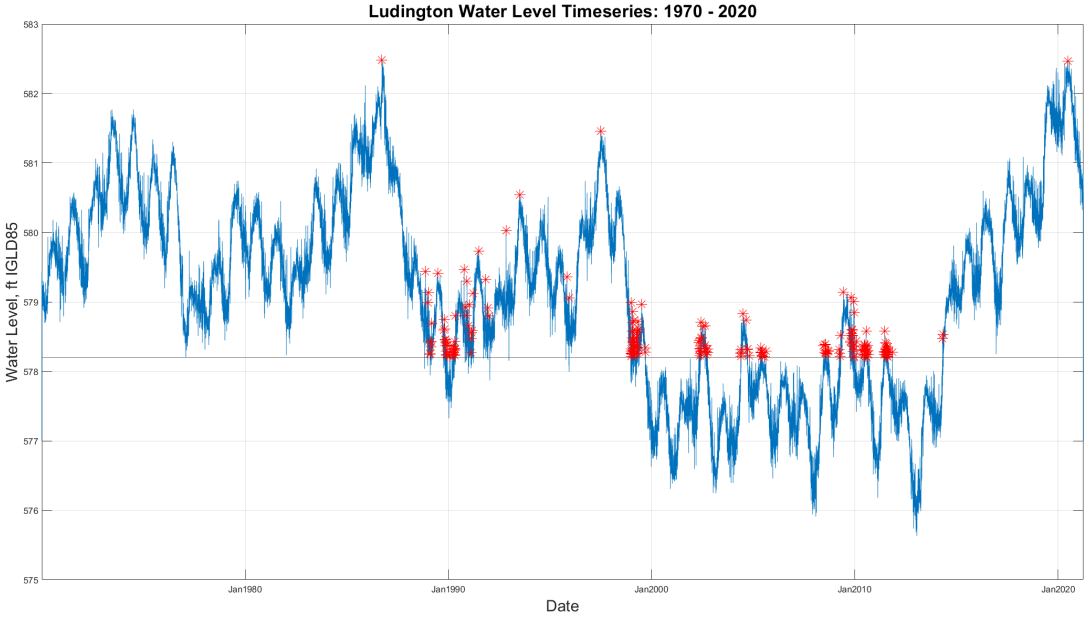

Figure 16. Ludington timeseries and Base of Subgrade incidence of exceedance.

A similar behavior is observed in Ludington Base of Subgrade incidence of exceedance to Algonac's at the same threshold (Figure 9). Some incidences are long time periods during elevated water conditions. In particular, the peak of the threshold exceedance event at the beginning of the observation period through the end of 1988 is represented by a single point. At this threshold, persistent elevated water levels are observed from January 1971 through December 1998. A lower water elevation is observed after this point ending in May of 2014. An elevated condition persists to the end of the observation record in 2021.

The total duration of exceedance is 6,875 days (~19 years) at the base of subgrade threshold. A minimum of 5 hours is observed with a mean of 1,565 hours (65 days). The total duration of exceedance for Ludington at the base of subgrade is 13,698 days (~37 years). The duration of exceedance is plotted graphically in Figure 17. Year is plotted on the horizontal axis while duration in hours is on the vertical axis and incidences are represented by red stars. Most incidences of exceedance had a low duration, but the signal is dominated by the longer periods of exceedance at the beginning and end of the observation record.

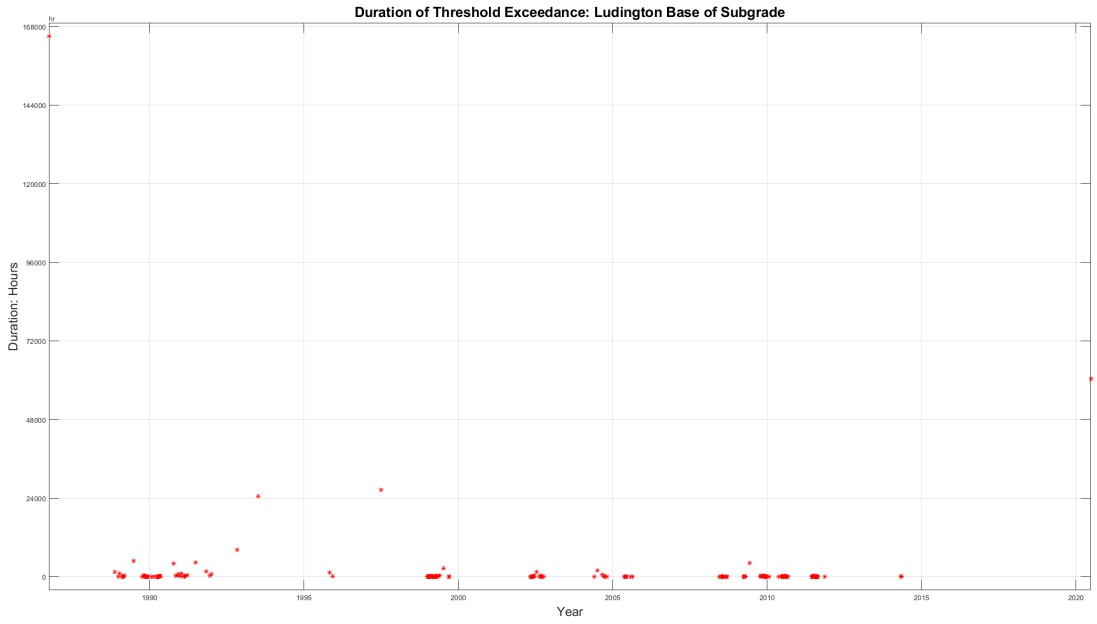

Figure 17. Duration of Threshold Exceedance: Ludington Base of Subgrade.

Figure 18 plots the duration of exceedance for the Ludington station at the Base of Subgrade threshold in a histogram format. The histogram is plotted with a binning method of days and is independent of date of occurrence. Count of incidence is on the vertical axis while duration in hours is presented on the horizontal axis. The majority of exceedance duration is on the shorter end of the spectrum (left of the figure) while the longer duration events are occur less frequently. The duration data at this threshold has a similar behavior to the Algonac station and the other thresholds.

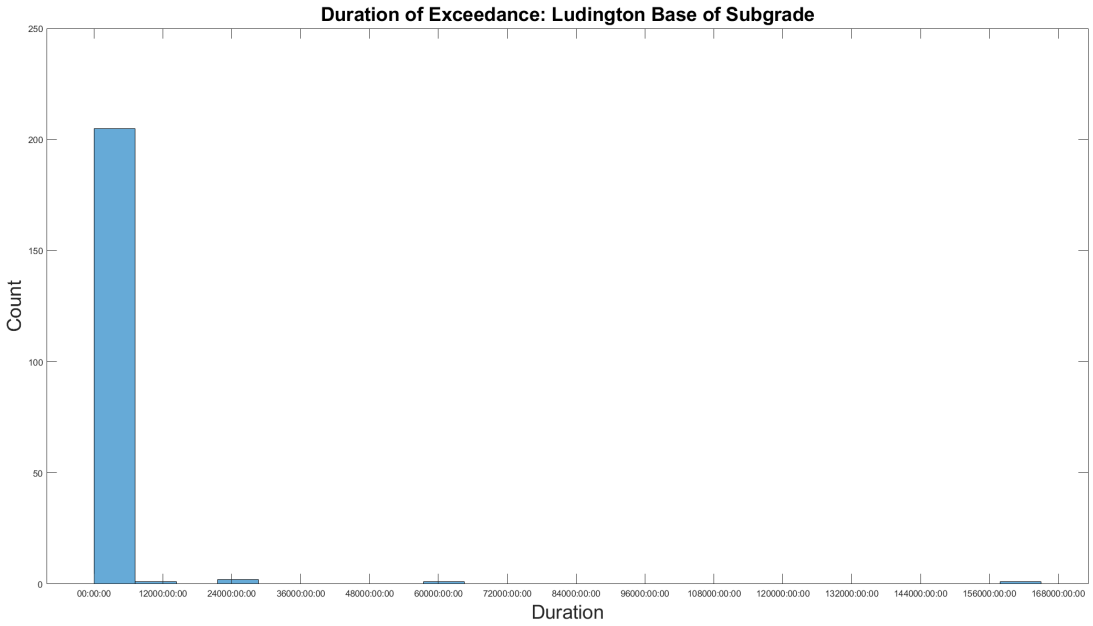

Figure 18. Duration of Exceedance: Ludington Base of Subgrade.

1.2.6 Ludington: Design Elevation

Ludington station exhibited a similar behavior at the design elevation to the Algonac station. A design elevation of 582.9 ft IGLD was evaluated to observe incidence of exceedance at this threshold. As shown in Figure 19, no incidence of exceedance occurred during the observation period at the Ludington station.

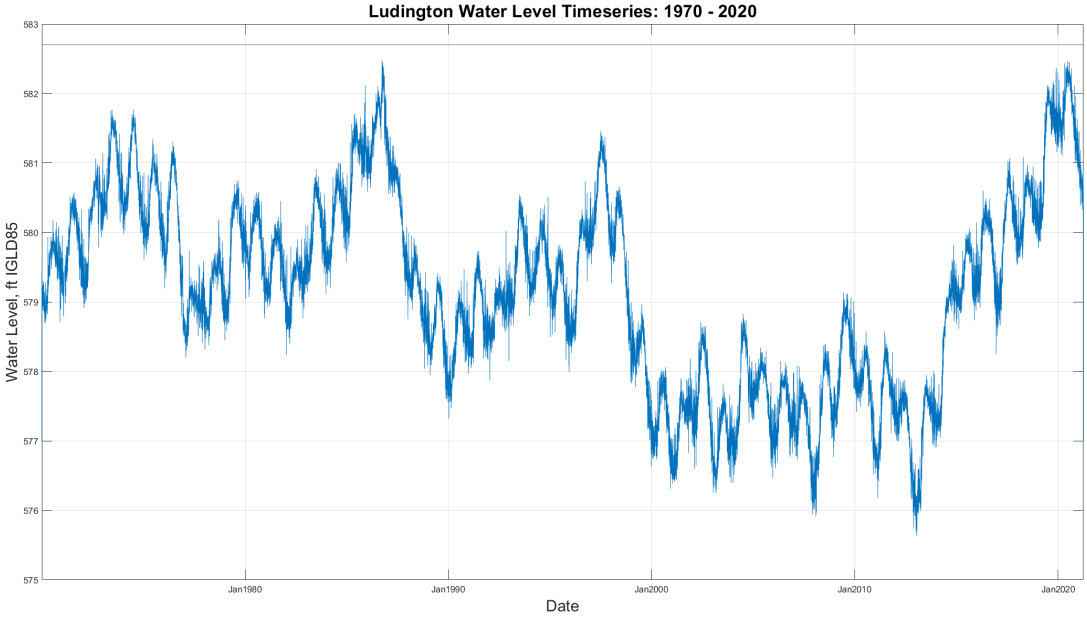

Figure 19. Ludington Timeseries and Design Elevation Threshold.

2 Discussion

A water level analysis determining both the incidence of exceedance and duration of exceedance at multiple threshold elevations is performed on a decadal water level timeseries for two locations in the Great Lakes region. Results of this analysis are summarized in Table 6 and Table 7.

Table 6. Summary of Results for Algonac

	Threshold Elevation (ft, IGLD)	Number of Exceedance Events	Total Duration, hours (days), *years*
Edge of Pavement (At Shoulder)	577.3	66	13970 (582) *1.6*
Bottom of Subgrade	574.5	229	347452 (14477) *40*
Design Elevation	579.8	0	0

Table 7. Summary of Results for Ludington

	Threshold Elevation (ft, IGLD)	Number of Exceedance Events	Total Duration, hours (days), *years*
Edge of Pavement (At Shoulder)	581.2	159	31354 (1306) *3.6*
Bottom of Subgrade	578.2	210	328757 (13698) *37.5*
Design Elevation	582.9	0	0

Neither station experienced incidence of exceedance above the design elevation.

3 References

MathWorks, 2021 *fillmissing* subroutine Available Online:
https://www.mathworks.com/help/matlab/ref/fillmissing.html

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