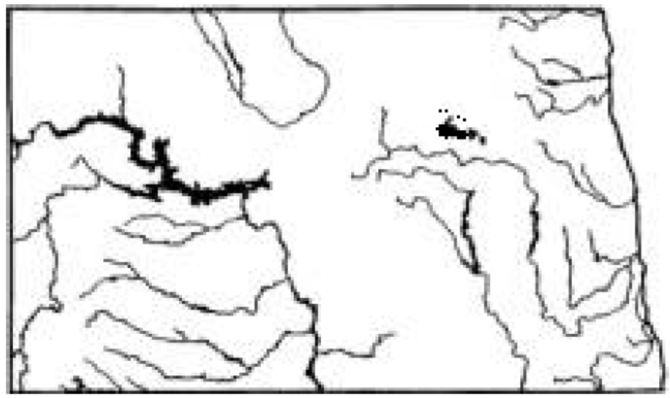

Technical Report No: ND12-04

TECHNIQUES OF ASSESSING CHANGES IN RIVER FLOODING PATTERNS IN THE UPPER MIDWEST

by

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TECHNIQUES OF ASSESSING CHANGES IN RIVER FLOODING PATTERNS IN THE UPPER MIDWEST

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The work upon which this report is based was supported in part by federal funds provided by the United States of Department of Interior and in part by the North Dakota State Water Commission in the form of ND WRRI Graduate Research Fellowship for the graduate student through the North Dakota Water Resources Research Institute

Project Period: March, 2011 - December 15, 2011

North Dakota Water Resources Research Institute
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ABSTRACT

In recent decades the Upper Midwest has experienced increased precipitation, temperature increase, and influence of climatic factors such as El Nino and La Nina, resulting in more flooding. This research is conducted to detect flooding trend changes in river stations throughout the Upper Midwest and update the flood frequency statistics based on the flooding trend changes.

Peak annual flows are the first type of data analyzed for flooding trend changes. Initially the Mann-Kendall trend test is used to determine if an increasing trend exists overall in the entire time series of flows up to the present year. For stations that show an overall increasing trend, two additional statistical methods are performed on the peak annual flow series: the moving average method and the ratio of means method. These two methods are used to identify when the trend changes might have occurred, in preparation for the two tailed t-test. The two tailed t-test results determine if the flooding increase is considered significant enough to be classified as an increasing trend change. For all stations showing a trend change in the two tailed t-test, the flood frequency statistics of those stations are updated using the trend change year found from the moving average and ratio of means methods.

Next, daily flow data is analyzed to study the flooding trends more closely. Wavelet analysis is used to detect trend changes in daily flow data. Wavelet coefficient plots are made at cycle pattern lengths (time scales) that show the most increasing trend. The moving average method and ratio of means method are used again to analyze the wavelet coefficient plots. Once the moving average and ratio of means method are run, the two tailed t-test is utilized to determine when the trend changes occurred in each scale of the wavelet coefficients. The 1-year scales represent annual flooding patterns, and the 2 to 8-year cycles represent El Nino and La Nina climatic cycles. The trend change year of the climatic cycles 6 to 8 years in length are analyzed for flood frequency statistical updates.

The flood frequency diagram from the peak annual flow trend change year is then compared with the flood frequency diagram from the 6 to 8 year scale trend change year to determine which diagram shows the largest percentage of flow increase in the low exceedance probabilities (long return periods). Whichever trend change year yields the highest percentage of flow increase is the year used in the updated flood frequency diagram. The updated flood frequency diagrams for the Upper Midwest may be beneficial in future flood preparation or flood protection measures.

ACKNOWLEDGEMENTS

Partial stipend support for the 2011 Research Fellow, Kyle Hafliger, was provided by the North Dakota Water Resources Research Institute. The fellowship program allows me to share and present the research of my project to others on the NDWRRI website.

INTRODUCTION

Flooding has become a serious problem in many areas of the Upper Midwest in recent decades, especially since the 1990s (Christopherson, 2011). The increase in flooding is caused by several natural factors, such as an increase in precipitation and temperature, and oceanic climatic patterns such as El Nino and La Nina. Precipitation is the main cause of an increase in flooding, since most runoff entering into the rivers comes from precipitation either in the form of rain or melted snow. Flooding caused by temperature increases has mainly occurred in the northern Upper Midwest, where most of the flooding is caused by snowmelt. Higher temperatures increase the snowmelt rate, which allows for more runoff to enter into the river system at one time (Voelker, 2010). Temperature increases in areas of the southern Upper Midwest that receive less snowfall normally do not have much effect on flooding. Precipitation trends in North America have been increasing in the past 50 years (IPCC, 2007). Figure 1 shows the average annual temperature and total annual precipitation (NCDC, 2011), and Figure 2 shows the peak annual flow at the Red River at Fargo, ND (USGS, 2011). Figure 1 indicates an increasing trend in both temperature and precipitation which lead to an increase in flooding, as shown in Figure 2. Climatic factors such as El Nino and La Nina can affect both temperature and precipitation levels, which in turn affect flooding. El Nino's cause an increase in average temperature and La Nina's cause an increase in average precipitation and a decrease in temperature. In the Upper Midwest, La Nina's have a stronger effect on flooding due to the increase in precipitation.

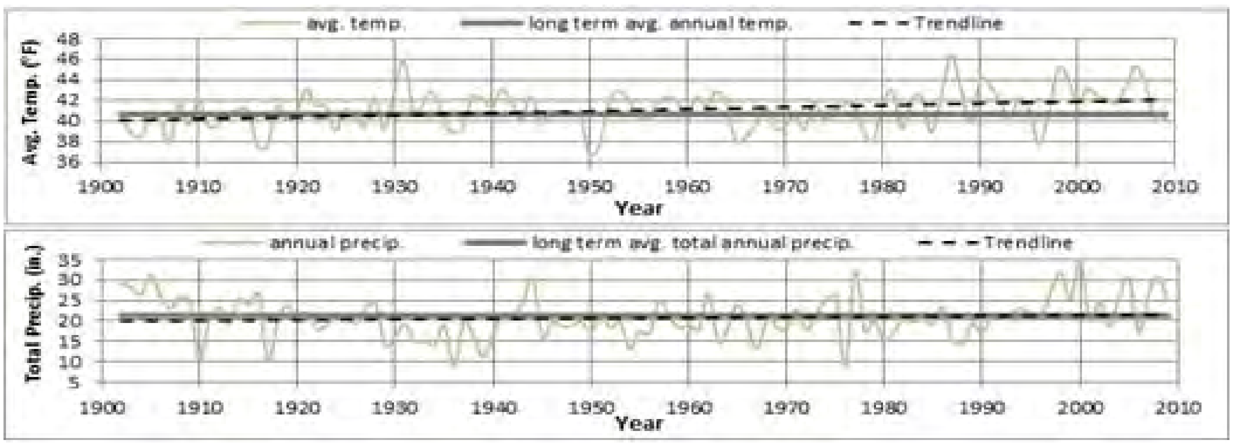

Figure 1: Precipitation and temperature data for Fargo, ND (1902-2009)

The purpose of this research is to study changes in the flooding patterns of rivers or streams in the Upper Midwest. Several different statistical tests are performed on the daily flow data and peak annual flow data series of numerous river stations in the Upper Midwest to detect any changes in flooding patterns. These tests are conducted to update flood frequency diagrams for the various river stations. When flooding patterns change, the return periods of certain flows in a river will also change. Monitoring these changes is extremely important in order to update requirements for flood preparation or flood protection measures such as dams or diversions. Many of those structures are built using design flows with certain return periods (Cahill, 1985).

OBJECTIVES

The objectives in this study were to:

1.) Analyze peak annual flow and daily flow time series data of numerous stations in the Upper Midwest to determine if there is an increasing flooding trend and an increasing change in the flooding trends by using several statistical methods.
2.) Determine when the trend changes occurred in stations showing an increasing change in flooding trends using statistical analysis.

3.) Perform flood frequency analyses on stations that indicate an increasing flooding trend using the data from the year of the trend change up to the present year.
4.) Compare the two different flood frequency diagrams for each station (one diagram using the trend change year from peak annual flow analysis, and the other diagram using the trend change year caused by climatic factors, found from wavelet analysis) to determine the flood frequency diagram that shows the largest percentage flow increase for the low exceedance probabilities (0.04 or lower).

METHODOLOGY

Multiple statistical tests in this study are used to analyze both the annual peak flow and daily flow time series data of various rivers or streams in the Upper Midwest to detect trend changes in flooding patterns. The study area analyzed includes the states of: North Dakota, South Dakota, Nebraska, Kansas, Minnesota, Iowa, Missouri, Wisconsin, Illinois, Indiana, and Michigan. Flow time series data from numerous USGS river gage stations is analyzed to determine if there are increases in flooding trends. Stations are only analyzed if there is continuous historical data without any missing gaps with the data, spanning at least 80 years or longer.

Peak Annual Flow Analysis

Annual peak flow data is used first to determine whether there is an increase in the flooding trends in rivers. A number of different statistical tests are performed on the time series. If the time series that is being tested for flooding trends happens to show a generally increasing trend in flooding throughout the entire time series, then the time series is split into two time periods. The year at which the data is split is the year in which the change occurs in the flooding patterns. Several different statistical tests and methods are used to determine which year is best used to split the river time series into two periods. The statistical test that is used to analyze if there is an overall increasing trend in the peak annual flow data is the Mann Kendall test. The statistical methods that are used to detect a trend change in the time series are the moving average method, the ratio of means method, and the two tailed t-test.

The Mann Kendall test is used first to determine if there is an overall increasing trend in the flooding trends. The Mann Kendall test is a non-parametric test, comparing the rank of values in the time series dataset and not the magnitude of the values. The Mann Kendall test is advantageous to use to detect an overall trend because the test is not affected by outliers in the data. The main parameter to check in the Mann Kendall test is the Z parameter, and it must be greater than 1.645 (indicating a confidence level greater than 95 percent) for the flow time series to have an overall increasing trend.

Stations that show an overall increasing flooding trend from the Mann Kendall test are analyzed using both the moving average method and ratio of means method. The moving average plot is made first, showing the moving average with the time series plot of the peak annual flows. The average is taken over a time window of certain length. For example, if the moving average time window is five years, then the first data point in the plot is the average of the first five years of the data. Then the five year window moves forward one year for the second point. The window keeps moving year by year until the last point of the graph is the average of the last five years of the time series. A time window of 7 to 15 years is usually used when analyzing peak annual flows. The moving average method smoothes out the time series plot, which will lessen the up and down fluctuations of the plot. This will help make the trends stand out more in the time series plot, in order to determine when the trend changes have occurred by observing the graph.

Next, the ratio of means method is used, which compares the data after a certain point in time with the data before that same point in time. When the ratio at a certain period of time is greater than 1, the flooding trend is increasing, and when the ratio is less than 1, the flooding trend is decreasing. The time frames that show a peak in the ratio of means graph is the time frames that are selected for the change in flooding trends. The highest of the peaks is usually selected. The ratio of means graph is visually compared with the time series and moving average plot to determine the time of the change in flooding trends more easily. The peak annual flow time series and moving average plot along with the ratio of means plot for the Red River at Fargo, ND is shown in Figure 2 for example. Based on the results, the largest trend change occurred around 1942, by observing the major peak in the mean ratio graph and the sudden rise in the moving average.

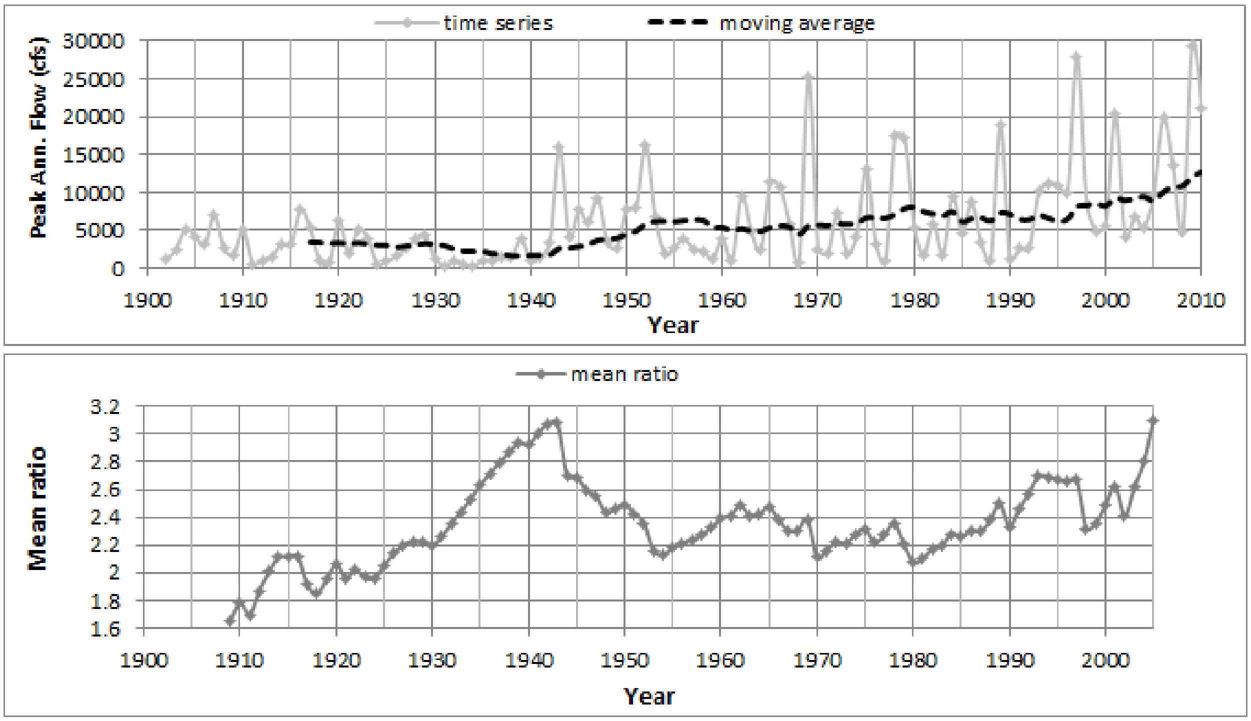

Figure 2: Peak annual flow time series and moving average plot and the mean ratio plot for the Red River at Fargo, ND

Lastly, the two tailed t-test is used to determine if the change in flooding trends is significant. The two tailed t-test is performed using the computer program MINITAB. Not all river stations that show an overall increasing trend in flooding trends will have a significant change in flooding trends. The time series is split into two time periods, split at the year that appears to have a change in flooding trends, found from the combination of the moving average and ratio of means methods. If the p value from the two tailed t-test results is less than 0.05, then it is assumed that there is a change in the flooding trends.

Daily Flow Analysis

After the annual peak flow data is analyzed, additional statistical analysis is then conducted on the average daily flow data for stations showing an increasing flooding trend change using peak annual flow data. Daily flow data is analyzed to study the pattern more closely. Wavelet analysis is the principal statistical method that is used in analyzing daily flow data. Wavelet analysis is used to focus on different flooding patterns that can reoccur at various cycle lengths. Wavelets analyze the time series in more detail compared to the cumulative volume of flow method.

There are several different varieties of wavelets, varying in shape. The computer program MATLAB is used to prepare the wavelet diagram, using a Morlet-shaped wavelet. The wavelet plot shows the time (in years for this study) on the x-axis and the time scale on the y-axis, in days. The time scales shown range from 2 days up to 4,096 days or slightly over 11 years, plotted in powers of 2. The time scale of 4,096 days at the bottom of the y-axis represents 2^{12} days. The scales on the vertical axis represent time periods where patterns repeat themselves. The wavelet plot not only shows the years in which a greater trend for flooding occurs compared to other years, but it also shows common cycle lengths where the patterns usually repeat themselves during different years of the time series. Figure 3 shows the wavelet plot used for daily flow statistical analysis, using the Red River at Fargo, ND station as an example (Torrence and Gompo, 1998).

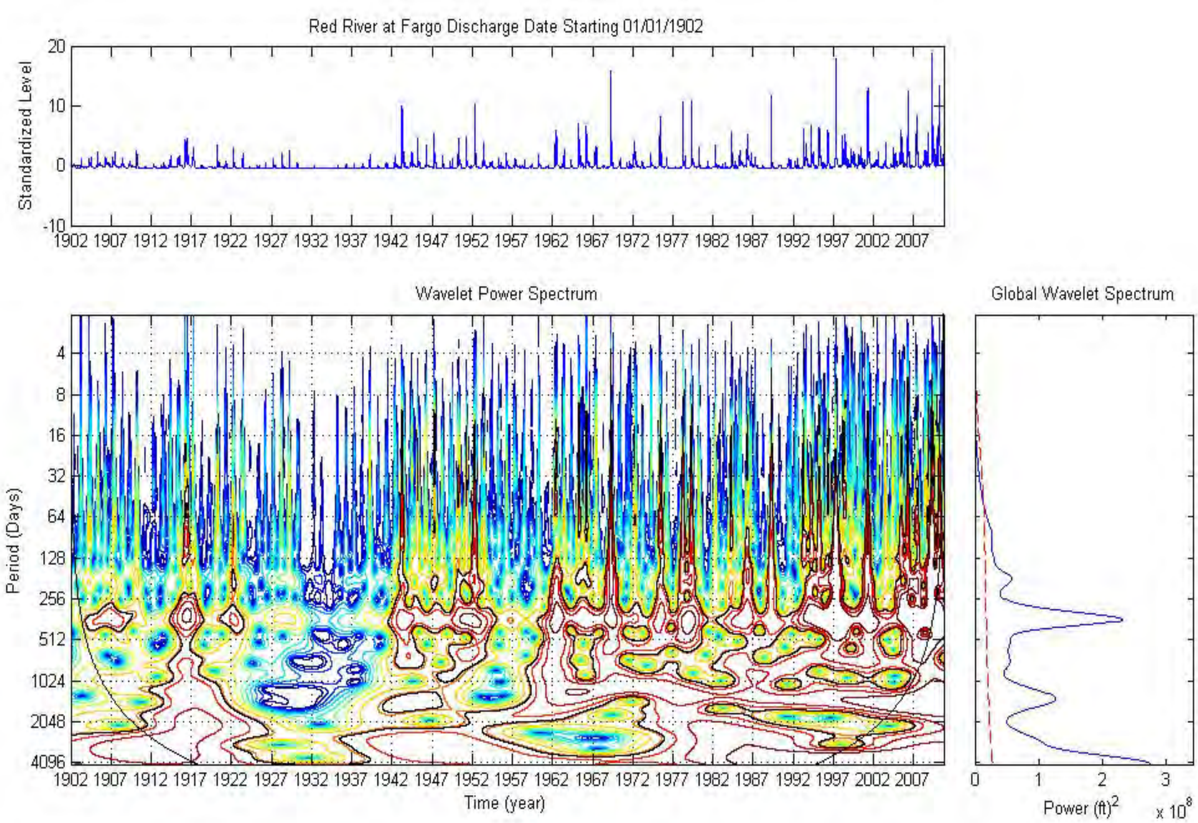

Figure 3: Wavelet plot used for statistical analysis of daily flow data

Once the wavelet plot of the time series is completed, a plot of the wavelet coefficients is made for different time scales that appear to have repeating patterns. The statistical analysis that is conducted on the coefficients of the wavelet plots is done using the moving average method, the ratio of means method, and the two tailed t-test.

The highest coefficients determine when the flooding trends are at a maximum. The wavelet coefficients can either have a positive or a negative value. The farther the coefficients depart from zero, the more change there is in the discharge. The time frames with the biggest flooding trend changes will usually have coefficients significantly above zero or significantly below zero. A coefficient near zero means there is not much change in the pattern. Since all of the positive coefficient and the negative coefficient values are nearly the same departure from zero throughout the time series, they average out to be zero overall. For example, if the positive coefficients are 1000, the negative coefficients in that time frame will be near -1000. This balance is a problem when analyzed with the two tailed t-test, since the average will be zero on both the first and second data sets. In order to analyze the coefficients using the two tailed t-test, the absolute value of the coefficients must be used.

By visualizing the one-dimensional plot of the wavelet coefficients of a certain scale, the year when the flooding patterns change can be easily determined. Scales of one year for repeating patterns of rivers in the Northern Plains usually represent repeating cycles of spring runoff. The scales ranging from two to eight years often represent repeating patterns of El Nino and La Nina climatic cycles (Torrence and Gompo, 1998). When analyzing the wavelet coefficients, it is possible to determine when the flooding trend changes have occurred, either caused by annual spring runoff patterns or by climatic patterns such as El Nino or La Nina. A moving average is used in the time series plot of the wavelet coefficients of a certain scale and is compared with the mean ratio graph of the wavelet coefficients of that same scale. In order to smooth out the wavelet coefficient time series to help make the trends stand out more, a moving average window of 3 to 6 years is used. The comparison of the time series and moving average graph with the mean ratio graph will aid in determining when the trend changes have occurred for that certain time scale. Results from the one year scale of the Red River at Fargo, ND are shown below as an example. Figure 4 shows the one-year scale wavelet coefficient time series with the moving average, and Figure 5 shows the mean ratio graph of the one-year scale wavelet coefficients.

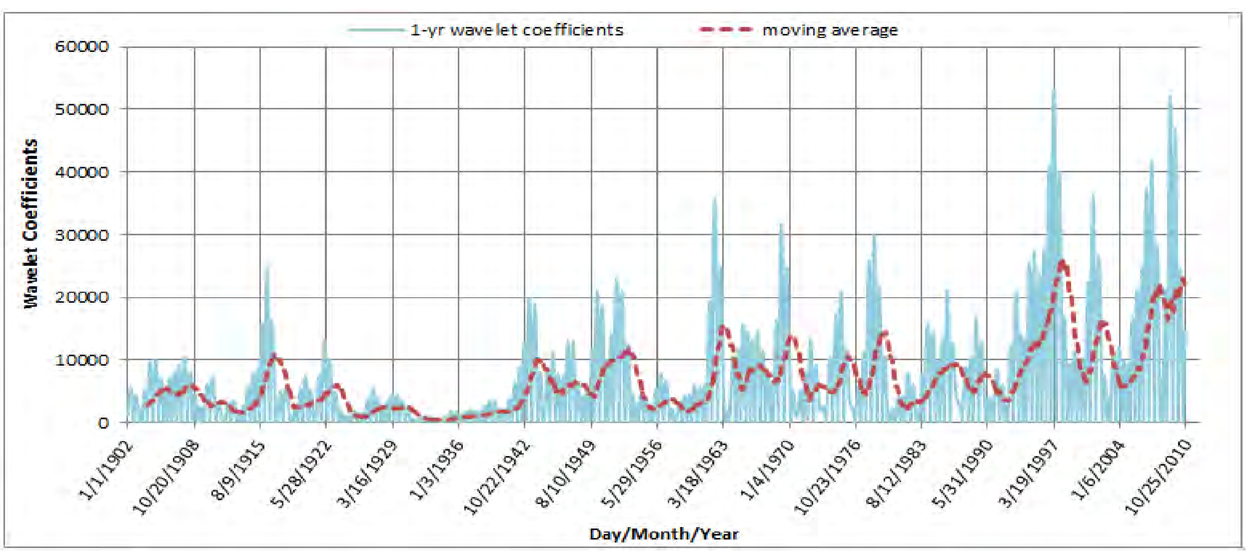

Figure 4: 1-year Scale Wavelet Coefficients of Daily Discharge for the Red River at Fargo, ND (1902-present)

These wavelet coefficients are based off of the wavelet diagram shown in Figure 3. The two tailed t-test is used to determine if the trend change is significant or not. It is assumed that a flooding trend change has occurred if the *p* value from the two tailed t-test is less than 0.05.

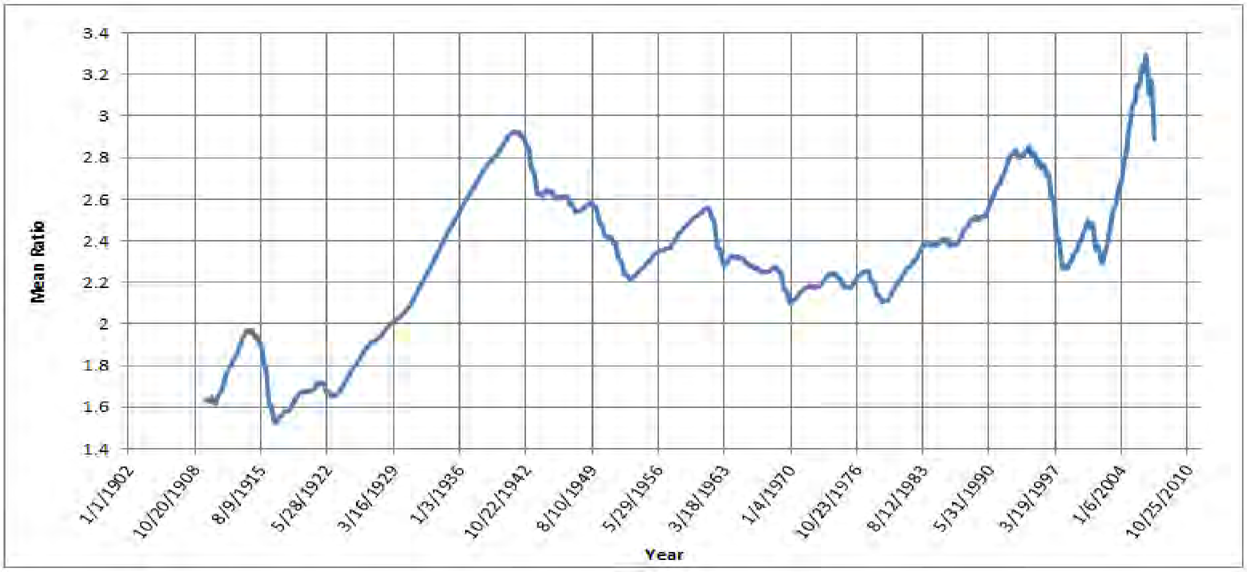

Figure 5: Mean Ratio graph for the 1-year scale coefficients for the Red River at Fargo, ND (1902-present)

Flood Frequency Analysis

Once the peak annual flow data and daily flow data are analyzed, updated flood frequency diagrams are prepared for each station showing a trend change. The flood frequency analysis is performed using the USGS program PKFQWin, which uses a Bulletin 17B, Log Pearson Type III fitting curve for the data (Ponce, 1989; Water Resources of the United States, 2008). Flood frequency diagrams are prepared for both the trend change year found in the peak annual flow analysis and the daily flow analysis. The updated flood frequency diagrams use data starting at the year in which the trend change is found under statistical analysis up to the present day. The flood frequency diagrams in this study compares the flood frequency curve using the time period after the trend change with the curve using the entire time series since the start of records. The two curves are compared to determine percentage flow increase for different exceedance probabilities for the time period after the trend change. Shown in Figure 6 is the flood frequency diagram used in this study, showing the Red River at Fargo, ND station as an example. The trend change year in this example diagram was from peak flow analysis. In this example, the trend change occurred in 1942, indicated by the legend in the diagram.

A flood frequency diagram is first made for each station using the trend change year found from peak annual flow analysis. This trend change year usually is from changing annual flooding patterns, such as spring runoff from snowmelt or heavy summer rainfall. Next, a flood frequency diagram is made for each station using the trend change year found from wavelet analysis of daily flows. The trend change year found at a scale of six to eight years is used to split the time series for flood frequency analysis of the daily flows. A scale of six to eight years is usually the longest cycle length of repeating patterns of El Nino or La Nina. Flood frequency analysis on the six to eight year scale trend change year may show how much the El Nino and La Nina climatic patterns affect flooding patterns.

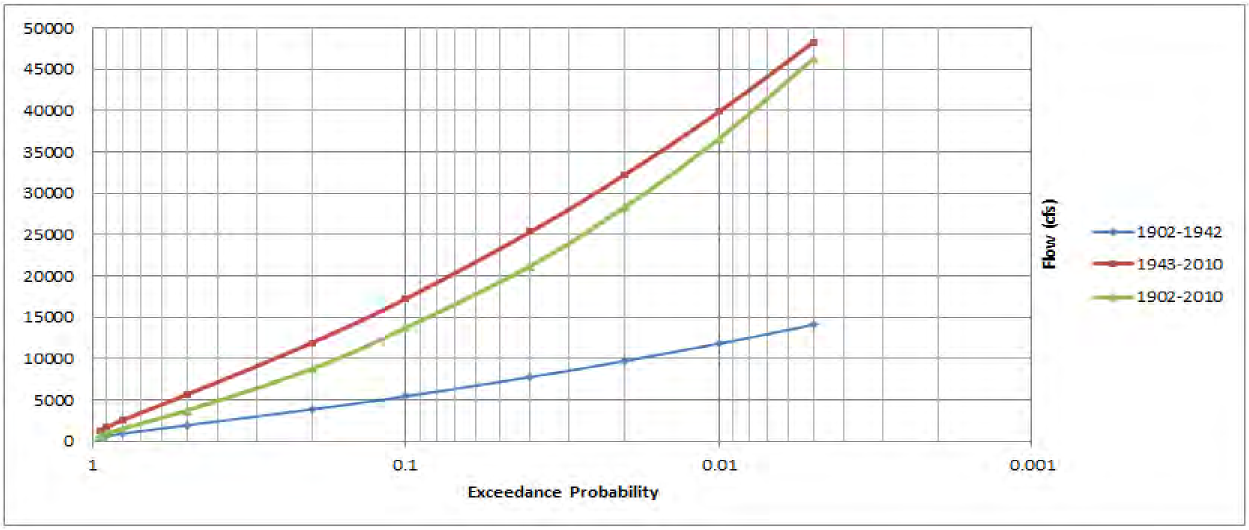

Figure 6: Flood frequency diagram comparison of the entire time series, before the trend change, and after the trend change for the Red River at Fargo, ND using the peak annual flow change year

The two diagrams are then compared with one another to determine which diagram shows the largest percentage of increase in flow of the low exceedance probabilities of 0.04 and lower. Those lower exceedance probabilities are more important to consider than the high exceedance probabilities, since the low exceedance probabilities are used for design standards for flood protection such as dams or diversions (Cahill, 1985). The diagram showing the largest percentage flow increases in the low exceedance probabilities is the diagram to be used as a basis for flood preparation and flood protection.

CONCLUSION

The results of this study indicate the statistical methods used are very effective in detecting increasing trends and changes in trends, but are not completely accurate when the peak annual flow is analyzed. Outlying values in the flows can significantly affect trend patterns in a river, and including the outlying values in the analysis under most of the peak annual statistical tests will affect when the trend change occurs. Outlying flow data does not affect the results of the Mann Kendall test, which is why that test is the most appropriate indicator of an overall trend in the peak annual time series. The moving average method, ratio of means method, and the two tailed t-test results can be affected by outliers, which indicate that these statistical methods are not totally accurate when detecting a trend change. Daily flow data is less affected by outlying flows since times with high peaks usually occur in periods only lasting a few days up to a few weeks. Annual data still needs to be used, despite its lesser accuracy, in order to perform flood frequency analysis. The smaller effect of outlying values in daily flow data is one of the main reasons that daily data is considered in this study, in addition to annual data, to detect trend changes.

This research also detects the reason for pattern changes in the flooding of rivers in the Upper Midwest, whether caused by a change in the annual flooding patterns or caused by El Nino or La Nina climatic changes. Based on trend changes observed at many stations in the Upper Midwest, the occurrence of a sudden trend change in annual peak flows is not always the best time to split the time series for updating the flood frequency statistics. Sometimes climatic factors such as El Nino or La Nina might have a stronger influence on the flooding trend change and must be considered.

The flood frequency results of several stations show that the percentage increase of flow is usually affected mostly on the high exceedance probability flows rather than the low exceedance probability flows. This is not always true, as was the case in the Red River at Fargo, ND diagram shown in Figure 6. Despite the smaller influence on the low exceedance probability flows, the influence is still significant enough to affect the flood quantiles. If the flood frequency quantiles of a river were not updated in an area that has experienced significant changes in flooding trends, the existing flood frequency quantiles would be unreliable to use as a guide for flood preparation or protection. A 100-year flood risk could become a 25-year flood risk. Such a potential change in flooding risk demonstrates why it is important to study the flooding trends of rivers. This study of the rivers in the Upper Midwest will provide a basis for future research in analyzing flooding trends of rivers or streams in other areas of the United States or the world.

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