A Hydroclimatological Analysis of Severe Flood Events: A Case Study of Whitesburg, KY

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ABSTRACT

Floods are the most common occurring natural disasters that affect humans and their surrounding environment. Severe flooding poses a threat to communities in flood prone areas. In July 2022, Eastern Kentucky experienced severe flooding across 13 counties which included the city of Whitesburg, KY. This study focuses on the historical significance of this event in comparison to previous record high floods using 3 different processes: a flood impact analysis, flood frequency analysis, and a flood hydroclimatological analysis. The results show that the magnitude of the July 2022 flood event was significantly greater than the magnitude of historical floods for the watershed due to temporal differences in the atmospheric mechanisms present at the time of major flood events in Whitesburg. The July 2022 flood event was the only major flood to occur in Whitesburg during tropical storm season, and the atmospheric mechanisms present were greater in both amount and duration. This suggests that this significant difference in magnitude when compared to other major floods in Whitesburg is a result of the type, duration, and amount of atmospheric mechanisms present at the time of these major flood events.

RECENT FLOODING IN EASTERN KENTUCKY

Between July 26th-July 30th, 2022, Eastern Kentucky experienced historic flooding across 13 counties. During this event, the city of Whitesburg experienced a large amount of precipitation in a short time period. On July 25th, Whitesburg received a total of 0.67 inches of rain and on July 28th the daily total was 6.2 inches. This put the total precipitation for this 4 day period at 8.40 inches. In Whitesburg, the highest annual maximum liquid precipitation for a single day in the past 10 years was 3.24 inches (NOAA NWS 2022). The objective of this study is to identify the historical significance of the July 2022 flood event.

FLOODING IN THE U.S.

Floods are the most common occurring natural disasters that affect humans and their surrounding environment (Hewitt 1997). Floods occur all over the U.S. in varying frequencies and magnitudes. Some areas are more prone to flooding than others and not all flood prone areas experience the same types of flooding. Flooding is defined as the overflowing or failing of the normal confines of a river, stream, lake, sea or accumulation of water as a result of heavy precipitation and the exceeding of the discharge capacity in areas not normally submerged (Douben and Ratnayake 2005).

The types of flooding experienced by a watershed can depend on many factors such as elevation, precipitation, land cover, and soil conditions. Dramatic changes in elevation can impact the discharge velocity. A significant drop in the elevation of a watershed can make an area prone to certain flood events such as flash flooding (Li et al. 2020). Flooding is simply an overflow of water onto normally dry land whereas flash flooding is caused by heavy or excessive rainfall in a short period of time, generally less than 6 hours (NOAA NWS 2015).

Precipitation plays a role in flooding concerning the resulting volume and frequency. If a watershed experiences a high volume of precipitation in a short period of time, this can result in a flood event. If a watershed experiences a high frequency of precipitation, once infiltration of the land cover decreases this will result in higher surface runoff which can result in a flood event (Guzha et al. 2018). Land cover can impact a watershed due to how different surfaces transport water. Urban areas will transport water on surfaces such as asphalt or concrete with little infiltration or vegetation dense areas with high infiltration (FEMA 2019). Different soil types also have different capillary action and adhesion, the ability of water molecules to attach to surface area of pore spaces, which can result in an increase or decrease in surface runoff.

FLOOD HYDROCLIMATOLOGY

The analysis of recent or current natural disasters such as floods is crucial to provide information about impacts of these disasters and for efficient response and recovery (Barz et al. 2019). Flood hydroclimatology and flood frequency analyses are two methods used to better understand the significance and reasons behind major flood events. Hydroclimatology provides a systematic structure for analyzing how the climate system causes time and space variations (both global and local) in the hydrologic cycle as a function of atmospheric mechanisms operating over an area (Shelton 2018). Many of the factors responsible for changes in flood frequency and magnitude remain constant throughout a given year, such as elevation and soil conditions, but one factor that does have annual changes is climate. A climatological analysis is useful in determining the significance of a flood event by providing a possible explanation for the rapid increase in discharge and can be compared to the climatological or atmospheric mechanism of previous flood events.

FLOOD FREQUENCY ANALYSIS

Flood frequency analysis is the estimation of how often a specified flood event of a particular magnitude will occur based on historical events (Hosking and Wallis 1997). The concept of probability is introduced in flood frequency models and the resulting magnitude return period relationships (Cunnane 1989). A flood frequency analysis is often performed after flood disasters to identify and/or update the return period. The return period is a probabilistic criterion used to measure and communicate the random occurrence of geophysical events such as floods in risk assessment studies (Bateni et al. 2022). Flood frequency, flood hydroclimatology, and flood impact analysis assist in finding the source of major flooding events which is useful in implementing proper flood prevention and flood warning systems for future flood events.

RESEARCH QUESTION AND HYPOTHESIS

How will the magnitude of the July 2022 flood compare to the magnitude of other historical floods for the city of Whitesburg, Kentucky? I hypothesize that the magnitude of the July 2022 event was significantly greater than the magnitude of historical floods for the watershed.

SIGNIFICANCE

Floods are hazards which poses immense threat to life and property. Identifying flood-prone areas will enhance flood mitigation and proper land use planning of affected areas (Ghansah et al. 2021). This type of study can be used to identify possible reasons for a flood and in the prevention and preparation of future flood events. The analysis of flood hydroclimatology involving the use of a flood frequency analysis is used in providing an accurate flood risk assessment of impacted areas and the atmospheric mechanisms responsible for severe flooding (Hirschboeck 1987). The flood impact analysis finds impacted areas at each flood stage and at historic crests which can be used in the development of flood warning systems as the issuance of flood warnings is linked to flood stage (NOAA 2004). Flood warnings are a crucial non-structural approach to flood mitigation (Chen and Yu 2007).

STUDY AREA

Whitesburg is a small, rural city located in Letcher County and part of Kentucky's Appalachian Mountain region. The terrain of Whitesburg is comprised of ridges and valleys mostly ranging between about 320 to 610 meters. On the southern edge of Whitesburg is the Appalachian Mountains where elevation is as high as 999 meters (*Figure 1*).

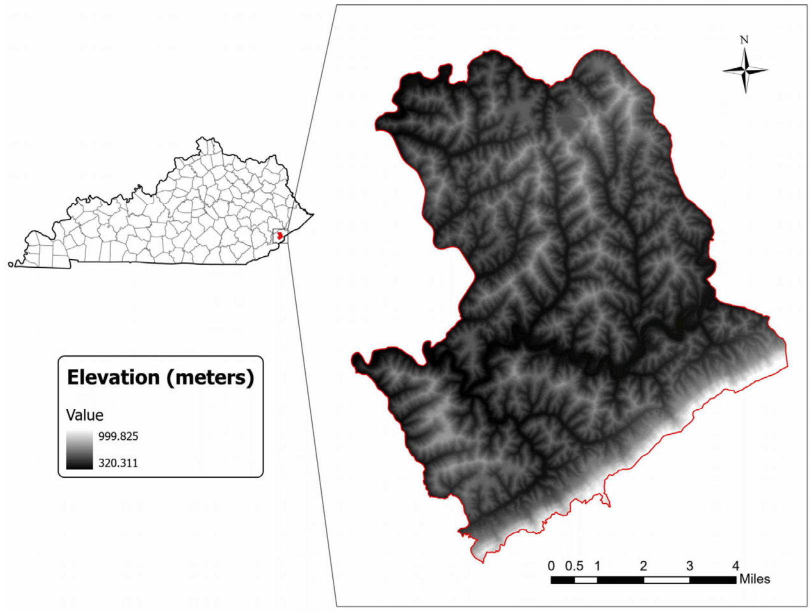

Figure 1. Elevation of Whitesburg, KY.

Whitesburg has thin soils and impermeable rock associated with shales. The geology of Whitesburg mainly consists of sandstone, siltstone, shale, and coal rock types. In the areas with higher elevation there are also limestone and underclay (Carey et al. 2007). On average, Whitesburg receives about 55.8 inches of liquid precipitation annually (NOAA NWS 2022).

This study will focus on the North Fork of the Kentucky River, specifically the part that runs through the city of Whitesburg (*Figure 2*). The United States Geological Survey (USGS) stream gage associated with this area of the river is 03277300. This stream gage has has a drainage around of 66.4 square miles and discharge records dating back to 1957 (USGS 2022).

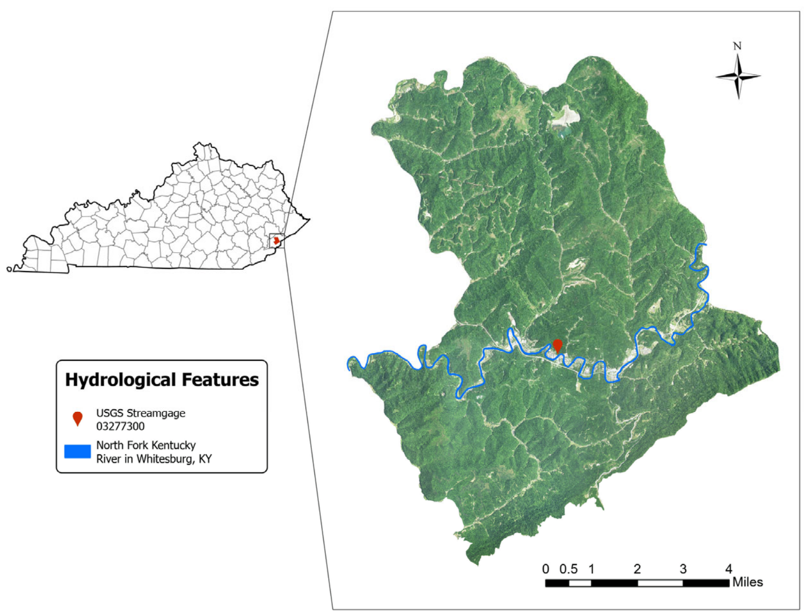

Figure 2. Orthoimagery and Hydrological Features of Whitesburg, KY.

DATA

In order to answer the research question this study required the following datasets:

- The stream gage data was sourced from the USGS National Water Information System for the USGS 03277300 NORTH FORK KENTUCKY RIVER AT WHITESBURG, KY stream gage. This data provided the annual peak streamflow data by discharge and height, as a table of the highest recorded streamflow in each year, that was used in the flood frequency analysis.
- The flood stage data was sourced from the NOAA NWS Advanced Hydrologic Prediction Service. This data provided the gage height, which is the height of the water in the stream above a reference point, at each flood stage as a table. This data was used in the flood impact analysis to map the area of Whitesburg impacted at each flood stage, at the peak stream gage height of the July 2022 flood, and for two other historic flood events (January 1957 & March 1963). Flood stages are established gage heights categorized into 4 stages of flooding based on their impact to people. The 4 flood stages from least to most impact are: action stage, flood stage, moderate stage, and major stage. A historic flood stage is a flood that reached the highest level since the records began.
- Elevation data in the form of a raster image was sourced from the USGS National Mapper. This imagery is a 1 Arc-second DEM displaying the elevation across the study area. This data was used in the flood impact analysis to calculate the areas impacted by flooding based on their elevation.
- The US Census data used in this study was a shapefile of Kentucky subcounty boundaries. This data was used in the flood impact analysis to obtain the boundary of the study area in order to clip other data layers to that extent.
- The orthoimagery was sourced from the National Agriculture Imagery Program (NAIP). This data was used in the flood impact analysis as a base map to provide a reference of the land cover impacted by flood events.
- The climatological data used is sourced from the NOAA Daily Weather Report. This data was used in the hydroclimatological analysis to find what atmospheric mechanisms were occurring in the study area during the July 2022 flood, and for the two other historic flood events (January 1957 & March 1963).

METHODOLOGY

The flood impact analysis was performed using ArcGIS Pro. In ArcGIS Pro, the extract my mask, raster calculator, and mosaic raster geoprocessing tools were used to create the flood impact map. The resulting data of these processes and the resulting map were then used to analyze the impact of flooding events in Whitesburg, KY.

The NAD 1983 State Plane Kentucky FIPS (Meters) coordinate system was used for the flood impact map. The map boundary was set to the study area using US Census TIGER/Line shapefile and creating a new layer with only the subcounty of Whitesburg within Letcher County. This new shapefile was used as a mask to extract the USGS 1 Arc Second DEM raster data for the study area.

The stream gage data utilizes the NGVD29 elevation datum and the USGS 1 Arc Second DEM utilizes the NAVD88 elevation datum. A datum conversion factor was calculated to adjust for the difference in elevation between the datums (*Appendix A*). The datum conversion factor was then be added to the NGVD29 datum elevation resulting in the corrected gage elevation. The corrected gage elevation was then converted from feet to meters. The flood category depth was collected from the NOAA NWS Advanced Hydrologic Prediction Service in feet, then converted to meters. The corrected flood category elevation was found by adding the converted flood category depths in meters to the corrected gage elevation in meters for each flood category.

Each flood category was mapped using a raster calculator tool to output 2 values: non-flooded cells (0) and flooded cells (1). A flooded cell is defined as the area with an elevation less than or equal to the corrected flood category elevation. A non-flooded cell is defined as the areas with an elevation greater than the corrected flood stage elevation. The non-flooded cells will be made transparent leaving only the flooded cells within the study area. The percent of the study area flooded was calculated by dividing the flooded cell count by the sum of both the non-flooded and flooded cell counts. The non-flooded cell counts, flooded cell counts, and percent of study area flooded were then recorded.

NAIP orthoimagery was used as a base map for the flood impact map. The purpose of the base map in this analysis was to give a visual of the type of land cover impacted in different levels of flooding. The high resolution of the NAIP orthoimagery made it the preferred imagery for this analysis. The imagery is provided in 3.75 x 3.75 minute quarter quadrangle tiles which required the use of multiple tiles to cover the city of Whitesburg, KY. The 16 tiles were merged in a mosaic to deliver one cohesive raster.

The program R Studio was used for the flood frequency analysis. In R Studio, an R code was run to perform the analysis (*Appendix B*). This R code retrieved and plotted the peak historical discharge for the stream gage and generated an output plot for each time period showing the return interval (T) and discharge for each annual flood (annual peak flow in cfs) using a standard Gumbel graph scale for the return interval. This graph was then used to find the return interval of the January 1957, March 1963, and July 2022 flood events using the peak flow of the event and the return interval (*Equation 1*).

$$RI = \frac{(n\ +1)}{m}$$

n = number of floods in record
m = rank of each flood

Equation 1. Return Interval Formula

The NOAA Daily Weather Reports used were for the July 2022, January 1957, and March 1963 flood events. These daily weather charts show both the surface-level and upper, 500 millibar pressure level, atmospheric conditions for each day of the week. I used these weather reports to find the atmospheric conditions of the study area during these 3 major flood events, then used a Flood Hydroclimatology Decision Tree (Hirschboeck 1987) to identify the atmospheric mechanism(s) responsible (*Appendix C*).

RESULTS

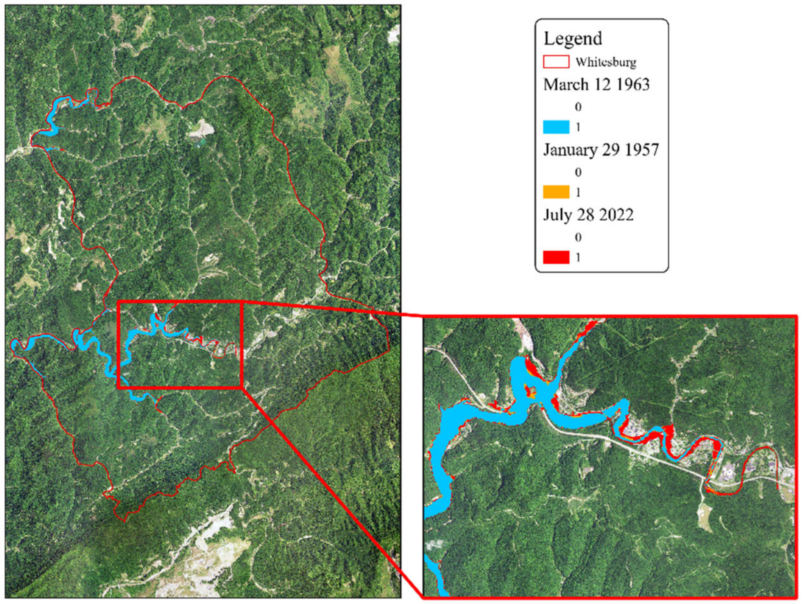

Figure 3. Flood Impact Map – Historic Floods

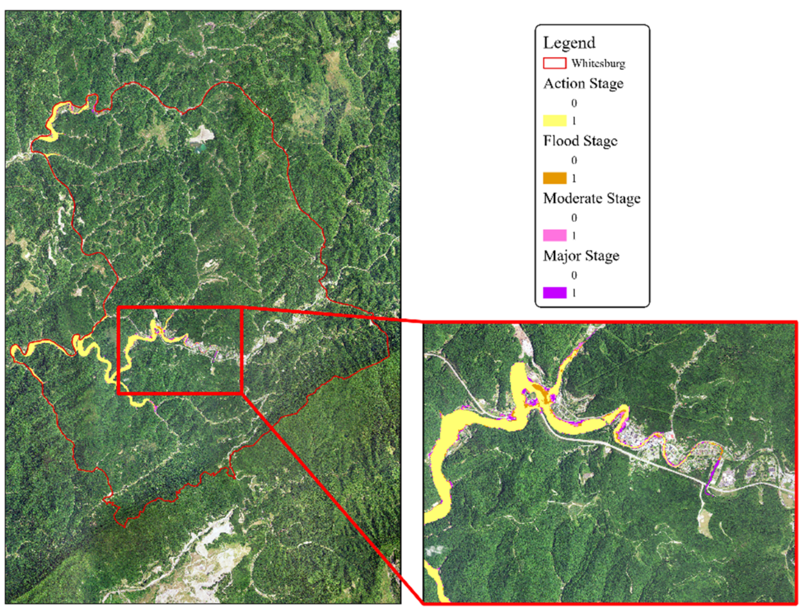

Figure 4. Flood Impact Map – Flood Stages

The flood impact analysis was used to find the impact that historic floods (*Figure 3*) and each flood stage (*Figure 4*) have on Whitesburg, KY. The flood impact analysis showed that the July 2022 flood had a greater impact on Whitesburg than previous floods. The Eastern part of the North Fork Kentucky River in Whitesburg shows the greatest amount of change in comparison to previous flood events. In this Eastern part the impact is significantly larger and the impact extends further East than any of the previous floods.

Stage	Flooded Cell Count
Action	33566
Flood	35399
Moderate	37151
Major	39020
1/29/1957	39665
3/12/1963	38144
7/28/2022	47085

Table 1. Flood Impact Cell Counts

The flood impact analysis flooded cell counts (*Table 1*) show that the July 2022 flood event having a significantly larger impact when compared to the major flood stage, the January 1957 flood event, and the March 1963 flood event. The large, 7420 flooded cell count difference between the July 2022 and January 1957 flood events shows that the July 2022 flood event impacted area that haven't been impacted before in recent history.

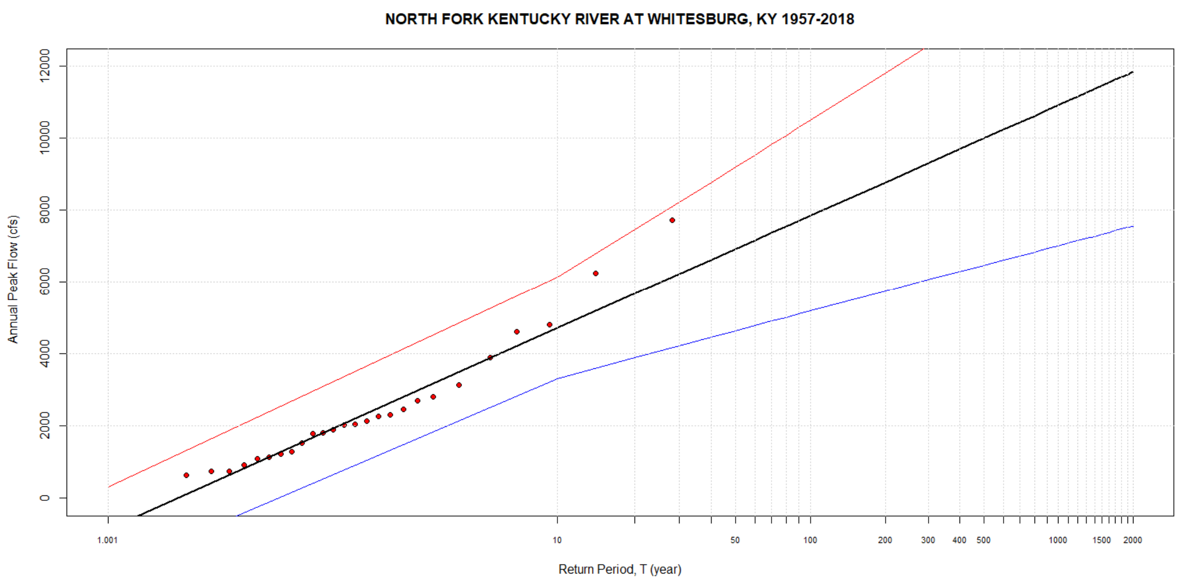

Figure 5. Flood Frequency Graph

Date	Discharge (cfs)	Return period (yrs)	Gage Height (ft)
1/29/1957	7,730	200	14.70
3/12/1963	6,240	60	13.05
7/28/2022	9,830	1700	22.03

Table 2. Return Interval of Historic Floods in Whitesburg, KY

The flood frequency analysis was used to find the return interval of the January 1957, March 1963, and July 2022 flood events using their peak discharge (*Figure 5*). This analysis showed that the July 2022 flood event had a significantly larger return interval than the January 1957 and March 1963 flood events (*Table 2*). Using the flood frequency graph, we find that the return period of the July 2022 flood event is 1700 years. To account for the large margin of error associated with a flood of this magnitude, the July 2022 flood event can safely be considered a 1000-year flood. Even when considered a 1000-year flood, this flood is significantly larger than previous historic floods in Whitesburg as the January 1957 flood was a 200-year flood and the March 1963 flood was a 60-year flood.

Date	Atmospheric Conditions
1/29/1957	• Stationary Front (surface) over study area • Cold Front (surface) over study area • Precipitation
3/12/1963	• Warm Front (surface) forming Southeast of study area • Complete overcast • Precipitation
7/28/2022	• Stationary Front (surface) over study area • Low Pressure • Through to the West of study area on July 27th • Through to the West and East of study area on July 28th • Complete overcast • Precipitation

Table 3. Atmospheric Conditions of Historic Floods in Whitesburg, KY

The flood hydroclimatological analysis was used to find the atmospheric conditions of the study area during the January 1957, March 1963, and July 2022 flood events, then used a Flood Hydroclimatology Decision Tree (*Appendix C*) identify the atmospheric mechanism(s) responsible. This analysis showed the atmospheric mechanisms responsible for each flood event (*Table 3*), along with a possible explanation for the significant difference in severity between these flood events.

During the January 1957 flood there was a stationary front and a cold front over Whitesburg with heavy precipitation (*Appendix D*). Using the Flood Hydroclimatology Decision Tree we can identify that the major atmospheric condition associated with this flood event was a front giving it a classification of F.

During the March 1963 flood there was a warm front forming Southeast of Whitesburg, complete overcast, and heavy precipitation (*Appendix E*). Using the Flood Hydroclimatology Decision Tree we can identify that the major atmospheric condition associated with this flood event was a front giving it a classification of F.

The atmospheric mechanisms of the July 2022 flood are more complex than the previous 2 major floods. During the July 2022 flood there was a stationary front over Whitesburg, low pressure, complete overcast, heavy precipitation, a through to the West of Whitesburg on

July 27th, and then a through to the West and East of Whitesburg on July 28th (*Appendix F*). Using the Flood Hydroclimatology Decision Tree we can identify that the major atmospheric condition associated with this flood event was a combination of 3 factors: tropical storm season, cutoff low, and front. This gives the July 2022 flood event a classification of TCF.

The increase in both amount of duration of flood related atmospheric mechanisms in the July 2022 flood in comparison to the January 1957 and March 1963 floods is a major factor in the significant difference in the magnitude of these floods. Another explanation for the difference in magnitude of these flood events is the temporal difference and the difference in the types of atmospheric mechanisms present in different seasons. The January 1957 flood occurred in Winter, March 1963 in Spring, and July 2022 in Summer. The July 2022 flood event was the only major flood event in Whitesburg's history to have taken place during tropical storm season.

CONCLUSION

Looking at a flood using a flood impact, flood frequency, and flood hydroclimatological analysis can help identify flood-prone areas, provide an accurate flood risk assessment of impacted areas, and identify the atmospheric mechanisms responsible for severe flooding. This is important in implementing flood mitigation, proper land use planning of affected areas, and the implementation of effective flood warning systems.

The magnitude of the July 2022 flood event was significantly greater than the magnitude of historical floods for the watershed. The July 2022 flood event impacted a greater amount of area, had a significantly larger return interval, and had different atmospheric mechanisms present in greater amount and duration in comparison to other major floods in Whitesburg. The temporal difference between the July 2022 flood event and other major floods in Whitesburg gives a possible explanation to the reason behind this significant difference in magnitude.

Future research could focus on changes in the magnitude of flooding in each season over the recorded years in Whitesburg rather than on major flood events alone. This could give some insight into the how smaller flood events differ across seasons, as well as if there have been changes in magnitude across time. This could help to find if temporal differences in atmospheric mechanisms are linked to more minor levels of flooding in Whitesburg. Another aspect that would benefit from further research would be a study that looks into other factors that could be impacting the landscape of Whitesburg and pose the risk of an increased frequency of larger flood events such as land cover change due to strip mining. This type of study could give more information on if floods could be worsening in Whitesburg unrelated to atmospheric conditions.

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APPENDIX A

Conversion Factors and Datums

Conversion Factors and Datums

(U.S. Geological Survey 2010)

Multiply	By	To obtain
foot (ft)	0.3048	meter (m)
foot per year (ft/yr)	0.3048	meter per year (m/yr)
meter (m)	3.281	foot (ft)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)

Datums

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88). Vertical coordinate information for historical data collected and stored as National Geodetic Vertical Datum of 1929 (NGVD 29) has been converted to NAVD 88 for this publication. Conversion between NAVD 88 and the commonly used NGVD 29 varies spatially; however, over most of the study area the following conversion can be used:

NGVD 29 = NAVD 88 – 0.515 ift

This conversion generally is accurate within about ± 0.5 feet for 95 percent of the study area. The reader is directed to either the National Geodetic Survey Web site for VERTCON at http:// www.ngs.noaa.gov/TOOLS/Vertcon/vertcon.html or the U.S. Army Corps of Engineers Web site for Corpscon at http://crunch.tec.army.mil/software/corpscon/corpscon.html for more accurate conversions.

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83). Horizontal coordinate information for historical data collected and stored as North American Datum of 1927 (NAD 27) has been converted to NAD 83 for this publication. Conversion between NAD 83 and the commonly used NAD 27 varies spatially, and the difference in lateral positions can be greater than 300 feet. For assistance with conversions, the reader is directed to either the National Geodetic Survey Web site for NADCON at http://www.ngs.noaa.gov/TOOLS/ Nadcon/Nadcon.html or the U.S. Army Corps of Engineers Web site for Corpscon at http:// crunch.tec.army.mil/software/corpscon/corpscon.html.

Elevation, as used in this report, refers to distance above the vertical datum.

APPENDIX B

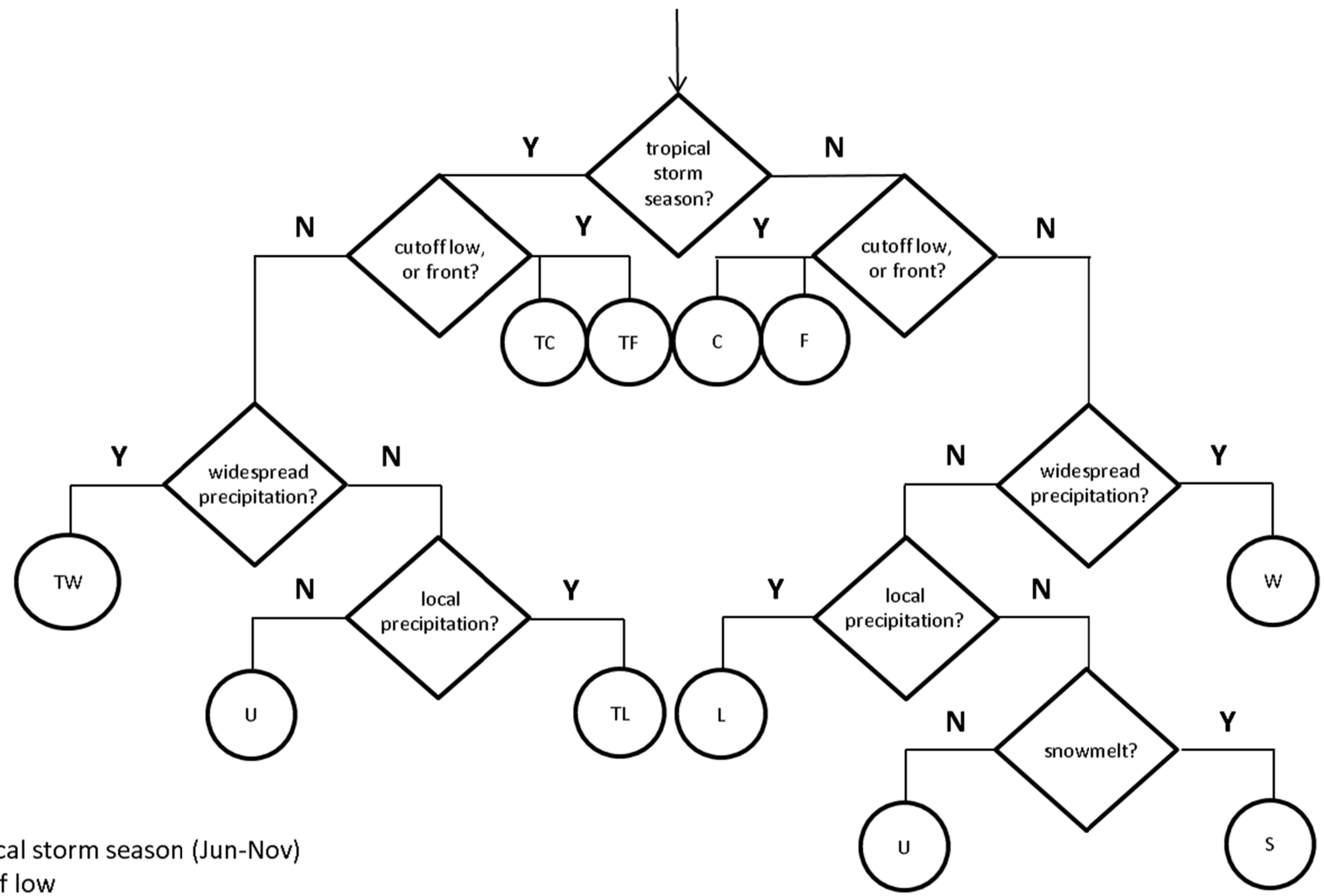
R Code for Flood Frequency Analysis

```
#Load USGS dataRetrieval library
library(dataRetrieval)

#Retrieve annual peaks for desired USGS gage number for required time period range (already set for first time period)
annualpeak<-readNWISpeak('03277300', startDate = "01-01-1957", endDate = "12-31-1983")

#Select column with peak runoff data and choose graph title using year range covered
Q = annualpeak[,c("peak_va")]
graphlab = "1957-2018"

#Generate plotting positions
n = length(Q)
r = n + 1 - rank(Q)  # highest Q has rank r = 1
T = (n + 1)/r

# Set up x axis tick positions and labels
Ttick =
c(1.001,10,20,30,40,50,60,70,80,90,100,200,300,400,500,600,700,800,900,1000,1100,1200,1300,1400,1500,1600,1700,180
0,1900,2000)
xtlab =
c(1.001,10,NA,NA,NA,50,NA,NA,NA,NA,100,200,300,400,500,NA,NA,NA,NA,1000,NA,NA,NA,NA,1500,NA,NA,NA,
NA,2000)
y = -log(-log(1 - 1/T))
ytick = -log(-log(1 - 1/Ttick))
xmin = min(min(y),min(ytick))
xmax = max(ytick)

# Fit a line by method of moments, along with 95% confidence intervals
KTtick = -(sqrt(6)/pi)*(0.5772 + log(log(Ttick/(Ttick-1))))
QTtick = mean(Q) + KTtick*sd(Q)
nQ = length(Q)
se = (sd(Q)*sqrt((1+1.14*KTtick + 1.1*KTtick^2)))/sqrt(nQ)
LB = QTtick - qt(0.975, nQ - 1)*se
UB = QTtick + qt(0.975, nQ - 1)*se
max = max(UB)
Qmax = 12000


# Plot peak flow series with Gumbel axis
plot(y, Q,
    ylab = expression( "Annual Peak Flow (cfs)" ) ,
    xaxt = "n", xlab = "Return Period, T (year)",
    ylim = c(0, Qmax),
    xlim = c(xmin, xmax),
    pch = 21, bg = "red",
    main = paste( "NORTH FORK KENTUCKY RIVER AT WHITESBURG, KY",graphlab )
)
par(cex = 0.65)
axis(1, at = ytick, labels = as.character(xtlab))

# Add fitted line and confidence limits
lines(ytick, QTtick, col = "black", lty=1, lwd=2)
lines(ytick, LB, col = "blue", lty = 1, lwd=1.5)
lines(ytick, UB, col = "red", lty = 1, lwd=1.5)
print(Ttick)
print(QTtick)

# Draw grid lines
abline(v = ytick, lty = 3, col="light gray")
abline(h = seq(2000, floor(Qmax), 2000), lty = 3,col="light gray")
```

APPENDIX C

Flood Hydroclimatology Decision Tree

Decision Tree for Hydroclimatological Flood Classification



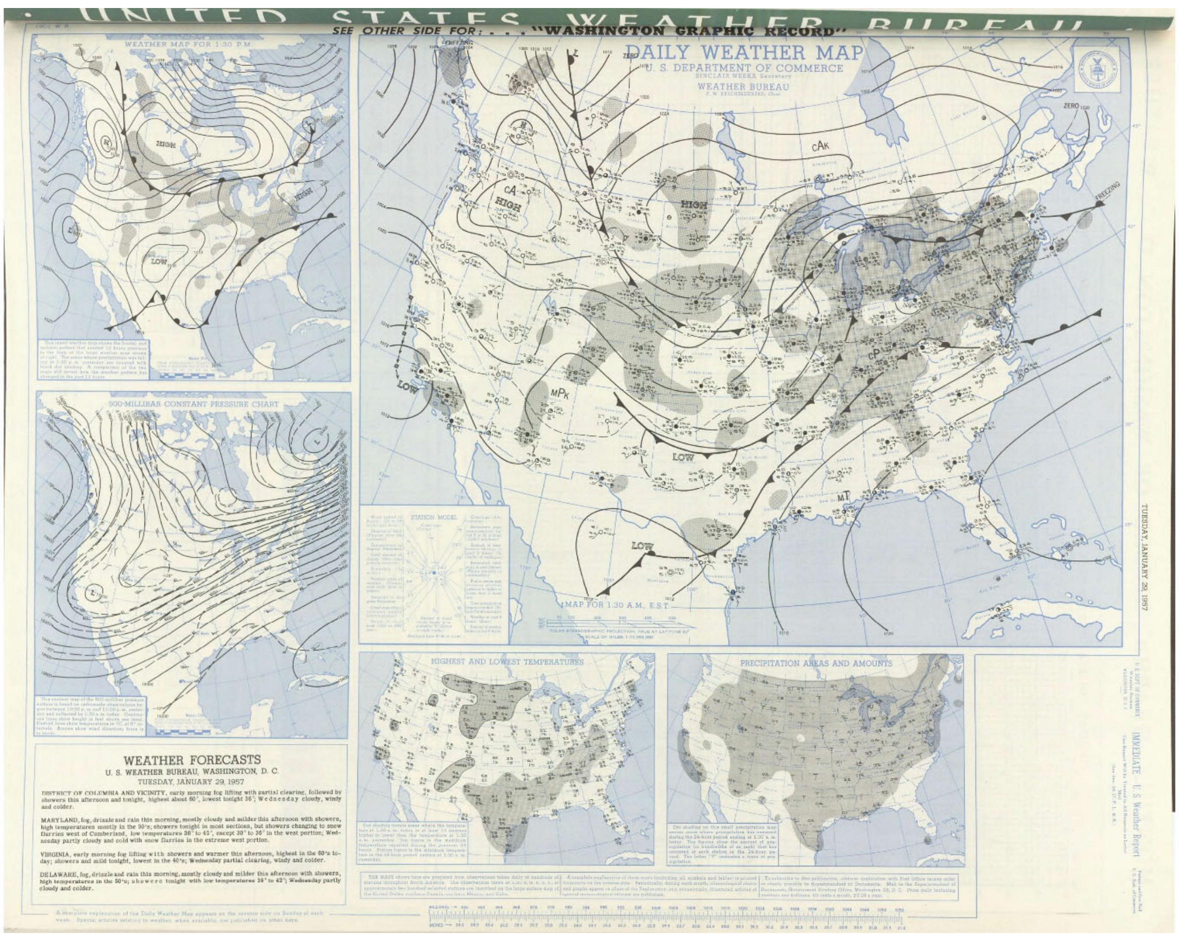
T = tropical storm season (Jun-Nov)
C = cutoff low
F = front
W = widespread synoptic precipitation
L = local convectional precipitation
S = snowmelt
U = undefined

Example: Peak flood occurs on 7/10/81. Does this occur during the tropical storm season? Yes (Y) so head left. Then look for evidence of a cutoff low or front. If you can see either you have identified the flood as either a tropical cutoff low (TC) or tropical frontal (TF) storm. If not then determine if it was widespread or local precipitation etc.

(adapted from Hirschboeck 1987)

APPENDIX D

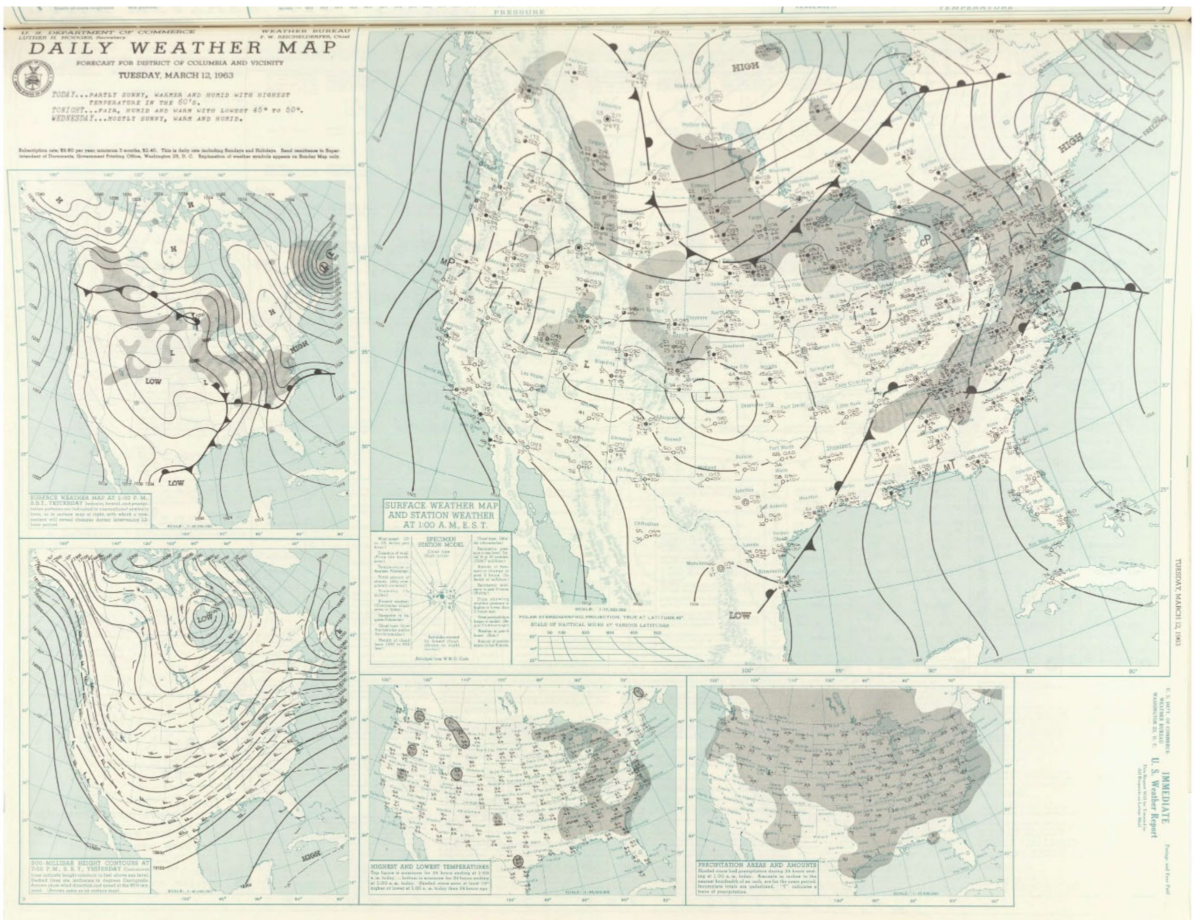
January 29th, 1957 Daily Weather Maps(



(NOAA Central Library Data Imaging Project 2022)

APPENDIX E

March 12th, 1963 Daily Weather Maps

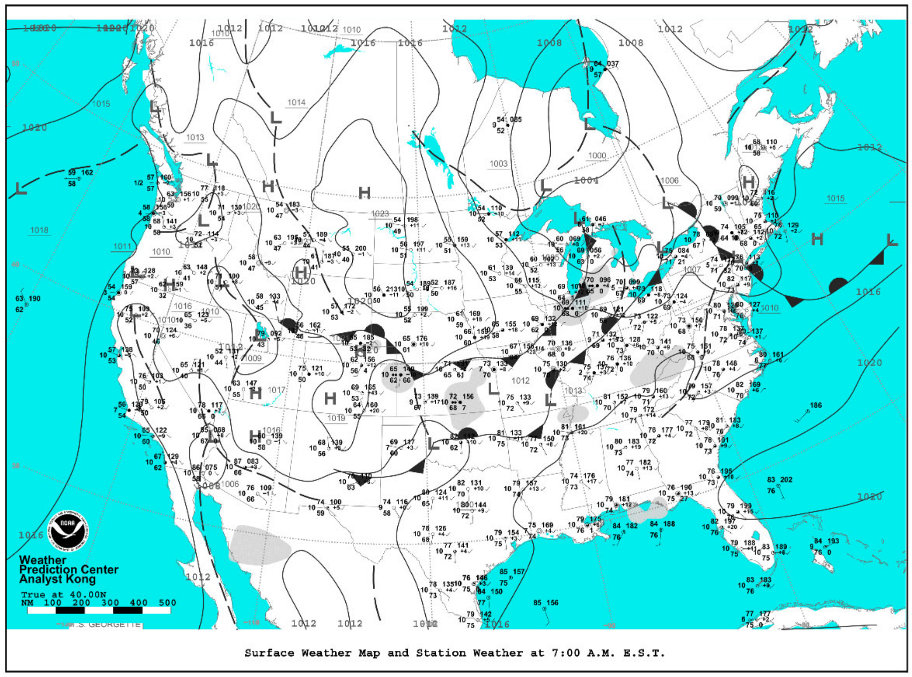


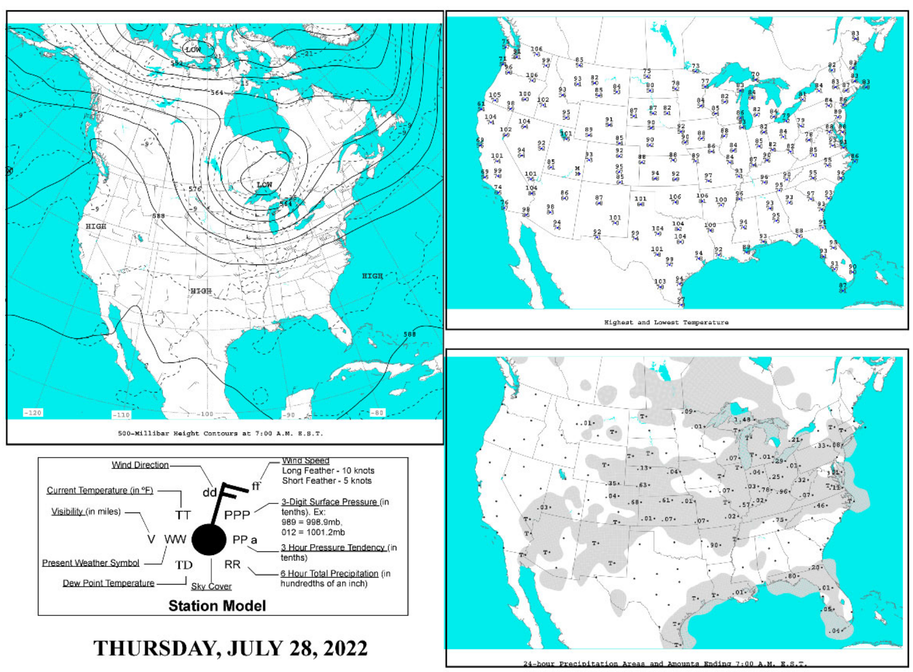
(NOAA Central Library Data Imaging Project 2022)

APPENDIX F

July 28th, 2022 Daily Weather Maps

THURSDAY, JULY 28, 2022





THURSDAY, JULY 28, 2022

(NOAA Central Library Data Imaging Project 2022)