Hydroclimate Variability in the Great Miami River Watershed and Southwestern Ohio

Final Project Report

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Objective

Changes and variability in the hydroclimatology of the region surrounding the Great Miami River Watershed have been observed for several decades. Studies have shown increases in total annual precipitation as well as in the frequency and magnitude of heavy precipitation, particularly in the warm season, for the Central and Midwestern US. Fewer studies have sought to describe regional changes in light and moderate precipitation, which may have consequences in water resources and droughts when coupled with observed increases in temperature. Therefore, understanding the variability in precipitation magnitudes and temperature patterns is crucial for effective water resource management, such as that administered by the Miami Conservancy District (MCD) for the Great Miami River Watershed. However, a thorough investigation of hydroclimatic variability in the Great Miami River Watershed or southwestern Ohio does not currently exist. This research investigates and describes past and present variability in precipitation and temperature in southwestern Ohio to provide information that is beneficial for MCD's effective and proactive management of the watershed and flood control infrastructure. This objective will be achieved through three research aims, investigating:

- 1. Variability in maximum and minimum daily temperatures,
- 2. Spatially continuous precipitation patterns across the Great Miami River Watershed and southwestern Ohio.
- 3. Long-term variability in precipitation measured in the region, including hourly precipitation.

This research culminates in this three-part report, providing local data and interpretation that will be directly applicable to the mission of MCD.

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²Section 2: Spatial variability in precipitation

³Section 3: Long-term precipitation variability

Section authors contributed to the data collection, data analysis, and interpretation of the results.

Report Summary

This report examines hydroclimatic variability in the Great Miami River Watershed using gridded climate data and long-term station records. The findings indicate that there may be changes in temperature, precipitation distribution, and long-term precipitation patterns that may have implications for the Miami Conservancy District.

Temperature trends (1981-2023)

- Minimum temperatures are increasing, particularly in summer, fall, and early winter months. The increase of these minimum temperatures, typically nighttime temperatures, without similar increases in maximum temperature suggests reduction in the diurnal temperature range. Reductions in monthly temperature ranges were observed.
- Average temperature is increasing in September, suggesting summertime temperatures may extend into the fall months.

Precipitation distribution by magnitude (1981-2023)

- Daily dry areas are becoming smaller overall, particularly in summer.
- Light precipitation areas are covering more of the watershed, particularly in summer.
- Trends diverge for moderate precipitation, with these events affecting smaller areas in summer and larger areas in winter.

Long-term precipitation changes (1899-2024)

- Total annual and seasonal precipitation have increased at nearly all stations, particularly in fall and spring, though trends in daily precipitation intensity are mixed.
- The number of wet days per year has generally increased at locations throughout the watershed, and the length of the longest dry period per year has decreased.
- Trends in extreme daily precipitation and hourly precipitation are mixed, with some local increases but no emerging watershed-wide trends.

Implications

This collection of results suggests that the watershed is becoming warmer and wetter, with seasonal variability. Warmer nights, suggested through increased minimum temperatures, and longer summers, reflected in increased September temperatures, may increase evaporative demand. However, as light precipitation becomes more widespread across the watershed, soil moisture may become more consistent across the basin. The localized findings for heavy precipitation may complicate flood management in the region, as infrastructure and residents in different areas may be exposed to differing conditions.

Recommended next steps

Further exploration of these findings may reveal their significance to the operations of the Miami Conservancy District. Suggested next steps include:

- Soil and atmospheric moisture analysis: The increase in light precipitation and the potentially higher evaporative demand from warmer minimum temperatures present conflicting signals for water management. An analysis of soil moisture and relative humidity may indicate which of these changes has greater implications for MCD operations.
- Storm morphology analysis: The shifting size of precipitation events and the diverging signals in heavy precipitation events suggest that the mechanisms of precipitation delivery are shifting. An analysis of changes in the types, characteristics, and effects of the storms affecting the area may provide MCD with additional insight during the different storm seasons.

Geographical Context and Background

Increases in total annual precipitation have been observed across much of the United States in the 20th century (e.g., Karl and Knight 1998, Easterling et al. 2000, Hayhoe et al. 2018). These increases have also been observed in southwestern Ohio and the surrounding region. Notably, significant increases in the average annual precipitation and warm-season precipitation (May-October) have been observed in the Central US, including Ohio (Kunkel et al. 2020). The increases in this region are among the largest observed in the contiguous US (Kunkel et al. 2020).

The Midwest is also among the regions with the largest increasing trends in *heavy* precipitation, annually and in the summer (Li et al. 2022). The frequency of nearly all durations of heavy precipitation (1-day to 30-day) from 1- to 20-year return intervals increased significantly from 1949-2016, with largest increases observed in the most extreme events (Kunkel et al. 2020). This pattern was observed annually and in the warm season, but not the cold season, for the Central US including Ohio.

Recent work has shown that the increases in heavy precipitation may not extend across all magnitudes of precipitation. Li et al. (2022) show increases in the amount and frequency of all precipitation types, including increases in light precipitation totals. This contrasts with earlier findings that show decreases in light precipitation totals in the Ohio River Valley region from 1951-2013 (Wu 2015). These differences emphasize the importance of continued investigation of the changing character of precipitation magnitudes at the regional scale.

Numerous studies agree that the proportion of annual precipitation attributed to the heavy tail of precipitation is increasing. This includes the proportion of annual precipitation attributed to less-extreme, short-duration events such as 1–3-day events with a 1-year recurrence interval, particularly those in the warm season in the central US (Kunkel et al. 2020). A smaller proportion of annual total precipitation is attributed to light precipitation events in recent decades in the continental US, indicating that the increases in frequency and number of heavy precipitation events have been outpacing those in light precipitation events, shifting the distribution of the annual precipitation climatology (Li et al. 2022). Understanding these shifts in the distribution of precipitation magnitudes at the regional and watershed scale, as well as changes in the frequency of extreme events, is important for the management of water resources on seasonal and annual timescales.

Studies show these trends in intensification of precipitation in the Midwest to continue through the 21st century, with a range of expected negative impacts including enhanced erosion, degraded water quality, and additional stresses on flood control infrastructure (Pryor et al. 2014). These observed and projected changes have implications in agricultural contexts in the Ohio region when combined with changes in temperature (e.g., Wang et al. 2016, Hatfield et al. 2016) as well as urban and suburban flooding and flood control (Moore et al. 2016). However, the exploration of mitigation actions must be grounded in local or regional assessment of climate variability.

While changes in precipitation may be most closely related to watershed management, changes in temperature have consequences in local hydrology, particularly as they relate to drought and soil moisture. Increases in annual average temperature have been observed and projected for

the United States (Hayhoe et al. 2018). Globally, increases in minimum temperature have been larger than increases in maximum temperature (Vose et al. 2005). This pattern has been observed in the Midwest, with spring dominated by larger increases in minimum temperature and late summer seeing larger increases in maximum temperature (Dai et al. 2015). These changes to the growing season may have consequences in evapotranspiration rates, soil moisture, and other variables that directly or indirectly impact streamflow and flooding. For example, despite observed increases in precipitation in many regions, the frequency of drought has also increased (Easterling et al. 2007), attributed to increases in temperature. This shows that examination of precipitation patterns in a region is best coupled with an analysis of temperature variability, particularly in minimum and maximum temperatures, when conducted for watershed monitoring and management contexts.

Variability in regional hydroclimatology, such as increased heavy precipitation and rising temperatures, pose threats to the water resources and hydrology of southwestern Ohio. Understanding the evolving nature of precipitation magnitudes and temperature patterns is crucial for effective and proactive water resource management.

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Section 1: Temperature

The objective of this section is to assess the variability of temperature in the Great Miami River Watershed. Mean, maximum, and minimum daily temperatures averaged for the watershed are analyzed at the monthly and seasonal scales. Temperature range is also assessed at the monthly scale.

Data and Methods

Data

Daily temperature data was acquired from January 1, 1981 through December 31, 2023. This dataset is generated by ingesting in-situ measurements where and when available into PRISM (Parameter elevation Regression on Independent Slopes Model) statistical mapping, producing gridded climate variables that are continuous across space and time rather than at discrete sampling locations and times. Daily precipitation data were downloaded at a 4 km spatial resolution and trimmed to the watershed boundary.

Methods

Variables of interest (t_{min}, t_{max}, t_{mean}) were averaged across the watershed giving one watershed-wide value for each variable each day. For monthly analyses, the average was taken over the days of the month, producing one value for each month (e.g., one value for January 1981, one value for January 1982, etc.) For seasonal analyses, the mean was calculated over each month in the season, following climatological seasons (spring: MAM; summer: JJA; fall: SON; winter: DJF).

Changes over time were assessed at monthly and seasonal time scales using linear regression, with changes reported as significant at p<0.05.

Anomalies, or deviations from normal conditions, were calculated based on the baseline conditions of 1991-2020, following current climatological normal as defined by NOAA (https://www.ncei.noaa.gov/products/land-based-station/us-climate-normals). Negative values indicate conditions that are cooler than the 1991-2020 average; positive values indicate conditions that are warmer than the 1991-2020 average.

The following variables were analyzed for changes:

- Monthly and seasonal mean temperature (t_{mean}) anomalies
- Monthly and seasonal average minimum temperatures (t_{min}) and anomalies
- Monthly lowest minimum temperatures (t_{min}) and anomalies
- Monthly and seasonal average maximum temperatures (t_{max}) and anomalies
- Monthly highest maximum temperatures (t_{max}) and anomalies
- Monthly temperature range, as the difference between the highest t_{max} and lowest t_{min} values in one month.
- Number of days ≥90°F per year, both the watershed average maximum temperature as well as local maximum temperatures.

Results

Summary

Generally, temperatures are increasing in the watershed, particularly in the minimum temperatures in the summer and fall seasons. The temperature range (the difference between the highest and lowest temperatures in a month) is decreasing, mostly in spring and summer seasons, suggesting that the lowest temperatures, likely at night, are warming faster than the maximum daytime temperatures. This may be related to changes in humidity (not analyzed in this study.) This upwardshift in temperatures may have implications on evaporative demand in the watershed.

Table 1.1. Summary of significant trends in temperature by month and season.

Month or Season	Average mean temperature	Average maximum temperature	Highest maximum temperature	Average minimum temperature	Lowest minimum temperature	Temperature range
January						
February						
March						\downarrow
April						\downarrow
May			↑			
June				1	↑	
July			\downarrow		↑	\downarrow
August					↑	\downarrow
September	↑			1	↑	\downarrow
October				1	↑	
November						
December					↑	
Spring				↑		
Summer				1	1	
Fall				1	1	
Winter					↑	

Mean temperature

Mean temperatures for each month were plotted and analyzed. Monthly average temperature anomalies show only September with statistically significant change from 1981-2023 (p=0.0035), suggesting that summer temperatures are extending further into September than they had in previous decades.

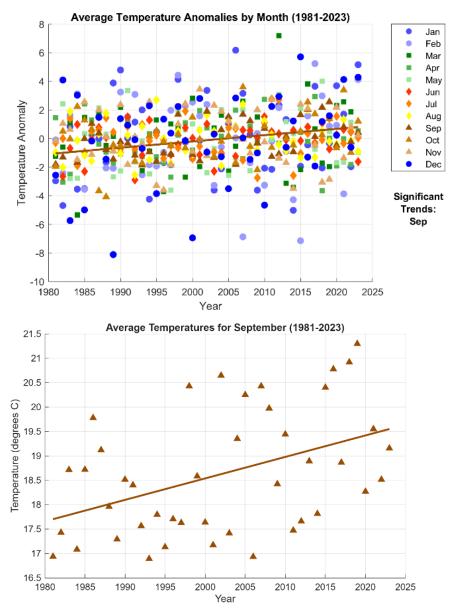


Figure 1.1. Top: Average temperature anomalies (°C) for each month, with significant trend shown and with seasons indicated by marker shape. Bottom: Monthly average temperatures for September with significant trend, 1981-2023.

Average temperatures for each climatological season were also analyzed. Symbols in Figure 1.1 refer to each season (winter, DJF = circles; spring, MAM = squares; summer, JJA = diamonds; fall, SON = triangles). There are no significant changes in seasonal mean temperatures.

Maximum temperature

Maximum temperatures were analyzed in two forms: as the average of all maximum temperatures in a month, and as the single highest temperature of all the daily maximum temperature values in a month.

There are no significant changes in monthly or seasonal average maximum temperatures, which is when monthly t_{max} is the average of all daily t_{max} values.

When considering the *highest* daily monthly maximum temperature and comparing that to the average (1991-2020) monthly maximum temperature, May shows significantly increasing "highest high" temperatures (p=0.0311) while July shows significantly decreasing "highest high" temperatures (p= 0.0397) (Figure 1.2). This suggests that the maximum May temperatures are increasing relative to 1991-2020, while the highest July temperatures are not as high as those experienced 1991-2020. Note that these trends are analyzed at the daily scale only; while the highest temperature may be decreasing or unchanging, a cluster of very warm days (but not the warmest overall) may still have substantial impacts on human health, soil moisture, and water resources. There are no significant trends in highest t_{max} at seasonal scale (i.e., when the highest daily temperature of a season is compared to average seasonal highest high temperature).

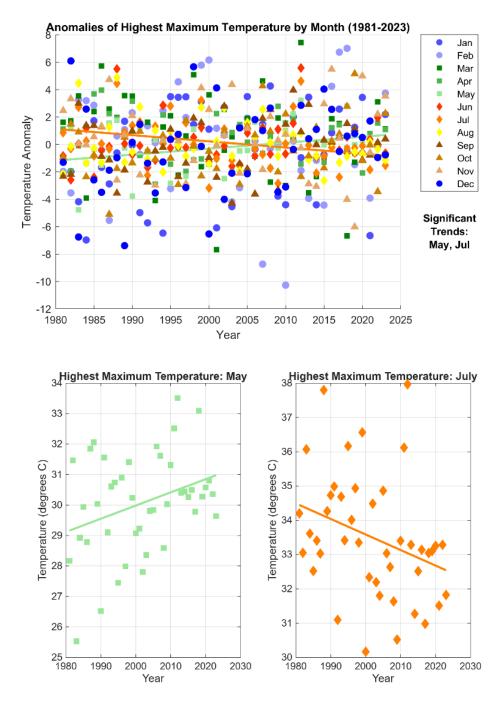


Figure 1.2. Top: Highest monthly maximum temperature anomalies (°C) for each month, with significant trends shown and with seasons indicated by marker shape. Bottom: Monthly highest temperatures for May (left) and July (right) with significant trends, 1981-2023.

Minimum temperature

Minimum temperatures were analyzed in two forms: average minimum temperature (the average of all daily low temperatures in a month), and lowest minimum temperature (the single lowest temperature in a month). The monthly average minimum temperature is increasing significantly in June (p=0.0102), September (p<0.001), and October (p=0.0248) (Figure 1.3).

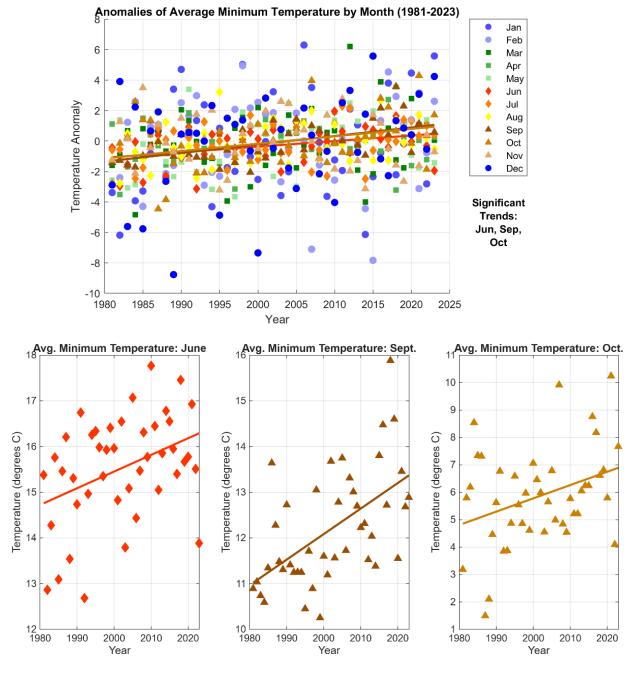


Figure 1.3. Top: Average minimum temperature anomalies (°C) for each month, with significant trends shown and with seasons indicated by marker shape. Bottom: Monthly minimum temperatures for June, September, and October with significant trends, 1981-2023.

The seasonal average minimum temperature is increasing significantly in spring (p=0.0255), summer (p=0.0025), and fall (p= 0.0103), with each showing warming at a similar rate (Figure 1.4).

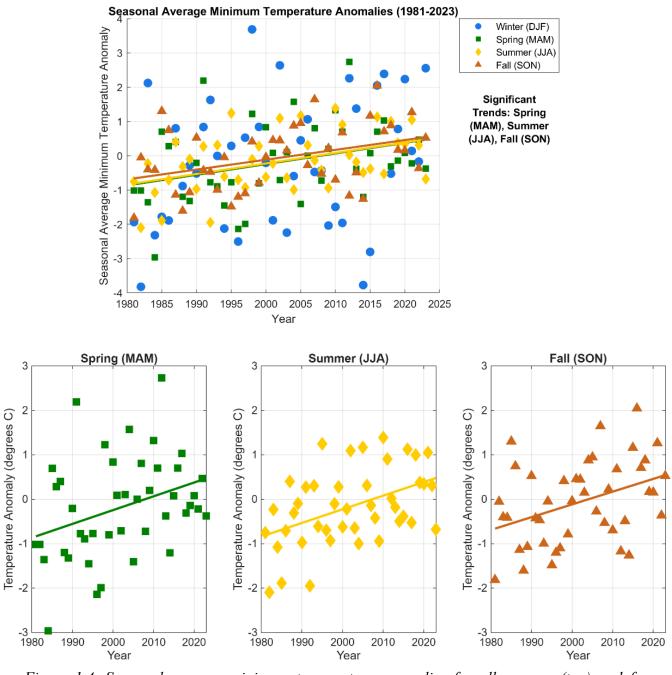
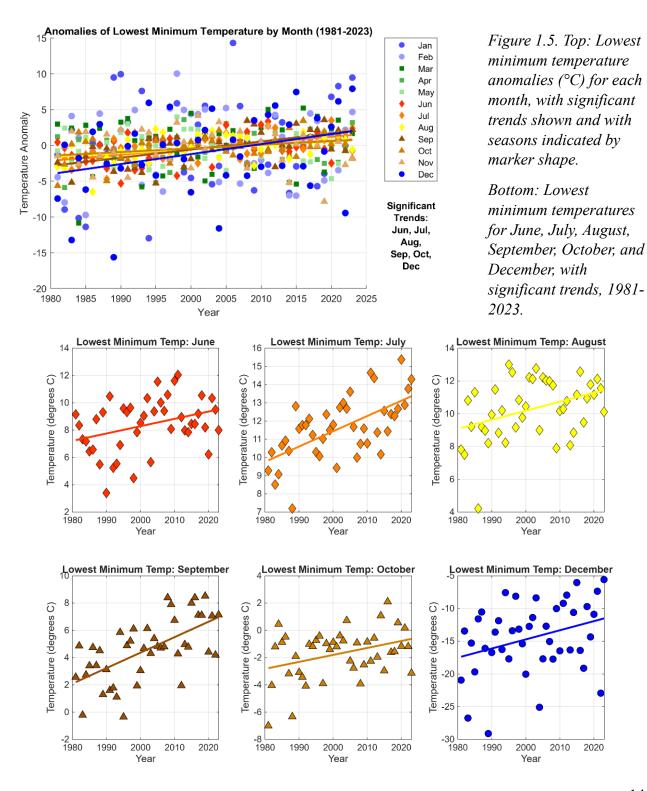


Figure 1.4. Seasonal average minimum temperature anomalies for all seasons (top) and for seasons with significant trends (bottom).

The monthly *lowest* minimum temperature is increasing significantly in June (p=0.0233), July (p<0.0001), August (p= 0.0109), September (p<0.0001), October (p=0.0199), and December (p=0.0355) (Figure 1.5). These changes are also seen at the seasonal scale in summer (p<0.0001), fall (0.0012), and winter (p=0.0444) (Figure 1.6).



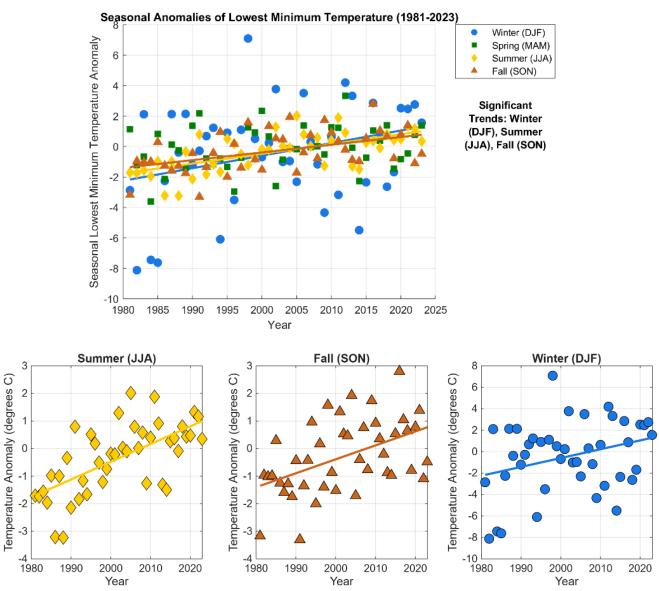


Figure 1.6. Seasonal lowest minimum temperature anomalies for all seasons with significant trends shown (top) and for seasons with significant trends (summer, fall, and winter) individually (bottom).

Temperature range

The difference between highest maximum temperature and lowest minimum temperatures was calculated for each month, providing a monthly temperature range. Temperature ranges are generally greatest in the winter and spring months and smallest in summer and fall months, though exceptions abound (Figure 1.7). Temperature ranges decreased over time for all months except May, which showed an insignificant increase in temperature range. Significant decreases in the temperature range were detected in March (p=0.0368), April (p=0.0473), July (p<0.0001), August (p<0.0001), and September (p=0.0234).

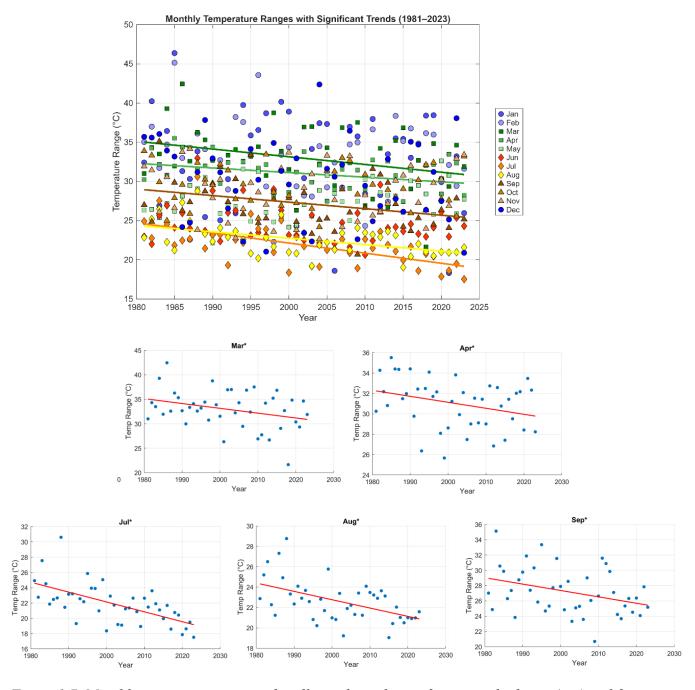


Figure 1.7. Monthly temperature ranges for all months with significant trends shown (top) and for March, April, July, August, and September with significant trends in temperature range, 1981-2023.

Frequency of ≥90°*F days*

The number of days equal to or exceeding 90°F was calculated for each year. This was calculated on two variations of the maximum temperature data: as an *average* of maximum temperatures across the watershed (i.e., how often was the daily high temperature 90°F or greater averaged across the whole watershed?), and as *local* high temperatures (i.e., how often was the daily high temperature 90°F or greater for at least part of the watershed?). Linear regression was used to determine if trends from 1981-2023 were statistically significant.

Overall, there are no statistically significant trends in the number of days $\geq 90^{\circ}F$ annually (Figure 1.8). There is an insignificant negative trend in the number of days in which the average high temperature of the watershed is $\geq 90^{\circ}F$, likely influenced in part by two years of high $\geq 90^{\circ}F$ frequencies in the 1980s as well as declines in $\geq 90^{\circ}F$ days after 2013. In contrast, the number of local $\geq 90^{\circ}F$ days has increased (insignificantly) since 1981. This may mean that the warmest temperatures are becoming more heterogeneous across the watershed; individual locations may experience $\geq 90^{\circ}F$ days while the watershed average is below $90^{\circ}F$.

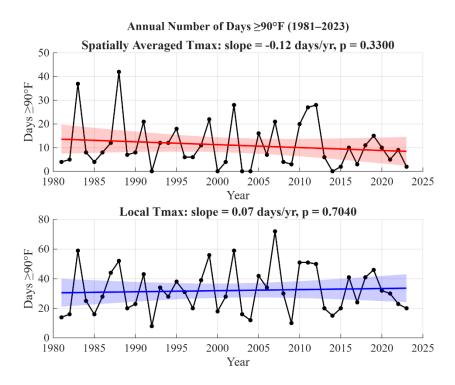


Figure 1.8. Number of ≥ 90 °F days per year for both watershed-average daily high temperatures (top) and local daily high temperatures (bottom). Note that while trendlines are shown, neither variation of the metric shows statistically significant changes from 1981-2023.

Section 2: Precipitation Magnitude

The objective of this section is to examine the spatial distribution of precipitation of varying magnitudes across the watershed. This analysis identifies and examines the spatial area of precipitation (the spatial "footprint" of precipitation on individual rainy days) with the goal of identifying if precipitation of a given magnitude is impacting a larger or smaller portion of the watershed on a given day.

Data & Methods

Data

Daily precipitation data were obtained from PRISM data, from January 1, 1981 to December 31, 2023. This dataset is generated by ingesting in-situ measurements where and when available into PRISM (Parameter elevation Regression on Independent Slopes Model) statistical mapping, producing gridded climate variables that are continuous across space and time. Daily precipitation data were downloaded at a 4 km spatial resolution and trimmed to the watershed boundary. For each 4km grid cell within the watershed, daily precipitation in was classified into one of the following categories:

Table 2.1. Precipitation magnitude categories

Category	Threshold (mm)
No precipitation	0 mm
Light precipitation	0 <x<12.7< td=""></x<12.7<>
Moderate precipitation	12.7≤x<25.4
Heavy precipitation	25.4≤x<57.9
Recurrence interval: 1-yr	57.9≤x<69.6
Recurrence interval: 2-yr	69.6≤x<85.1
Recurrence interval: 5-yr	x ≥85.1

Analysis

The number of grid cells receiving each category of precipitation was summed on a daily basis and converted to a percentage of the watershed as a measure of the spatial area (size) of the precipitation event. These values were tested for significant changes over time using the Mann-Kendall test with a significance level of p<0.05. Note that because precipitation is extremely noisy, the coefficient of determinations (r²) for these relationships are not particularly useful; therefore, only the statistical significance and direction of the trend is reported here. These analyses were done overall (including all days from 1981-2023) as well as seasonally, in which the dates were filtered by climatological seasons (DJF, MAM, JJA, SON).

Results

Results summary and interpretation

Overall, Great Miami River Watershed has experienced increased spatial area receiving light precipitation over time. This contrasts with the decrease in area under dry conditions (no precipitation). The size of moderate precipitation events increased in area in winter months but no other months, and the size of moderate and heavy precipitation events decreased in spatial footprint in summer months and overall, respectively, indicating that precipitation of greater than 0.5 inches has become more consolidated and localized over recent decades.

Table 3.2. Direction of significant trends in spatial area receiving precipitation of varying magnitudes.

Precipitation category	Annual	Spring (MAM)	Summer (JJA)	Fall (SON	Winter (DJF)
No precipitation	\downarrow		\downarrow		
Light precipitation	↑		↑		
Moderate precipitation			\downarrow		↑
Heavy precipitation	\downarrow				

Overall, the slight decrease in spatial area receiving no precipitation on a daily basis coupled with slight increase in area receiving light precipitation shows that weather systems that may have delivered precipitation in localized areas may be delivering precipitation more broadly. This may have impacts in soil moisture and water resources across the Great Miami River Watershed.

The slight decrease in portion of the watershed receiving moderate precipitation on rain days in the summer suggests that systems delivering precipitation are depositing rain in a more localized manner. One explanation could be if an increase in small convective storms (thunderstorms) has resulted in more isolated rain events in recent decades compared to earlier decades, or that moderate precipitation is being delivered more frequently in small thunderstorms rather than large weather systems that would encompass larger portions of the watershed. The increase in the portion of the area receiving precipitation in winter months may be due to changes in weather patterns that cause more precipitation to be delivered to the area. A frequency analysis may discern if this is the case.

With each of these magnitudes of precipitation, it is important to note that changes within a category may indicate a subtle shift in precipitation delivery. One potential example of this could be if summertime moderate precipitation (0.5 to 1 inch) is becoming less localized; that is, if some storms are maturing over a wider area, resulting in an increased footprint of light precipitation with a decreased footprint of moderate precipitation.

The area receiving very heavy precipitation, at the level of 2-year and 5-year RIs, has increased (insignificantly) in the fall months. This may be related to post-tropical storm activity, as remnants

of tropical systems dissipate over the continent. A separate analysis on the behavior of post-tropical storm remnants may determine if these systems are of importance to the water resource management of southwestern Ohio. The increasing footprint of this very heavy precipitation may also be associated with stronger extratropical cyclones, which are most common in late fall to early spring. An analysis on the storm morphology associated with these events, and a meteorological review of those events, may demonstrate if certain storms pose flood risks at an increasing rate in the watershed.

No Precipitation Area

The area receiving no precipitation, overall, decreased slightly but significantly (p=0.0486) from 1981-2023, indicating that precipitation has become more widespread over the watershed, though only marginally (Figure 2.1). At the seasonal scale, the area receiving no precipitation decreased significantly (p=0.0001) in the summer months (JJA) (Figure 2.2). This suggests that summer precipitation is becoming more widespread over the watershed. The portion of the watershed receiving no precipitation also decreased in the fall months (SON), but the trend was not statistically significant. Overall, these results show that precipitation is falling slightly more widely over the watershed than it did in the early portion of the study period.

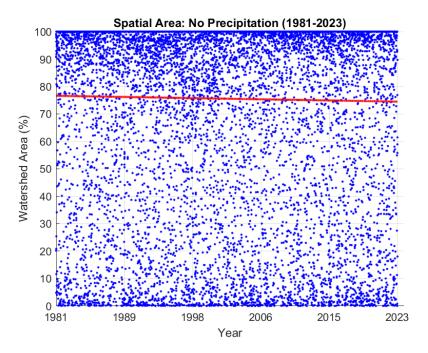


Figure 2.1. Percentage of the watershed receiving no precipitation daily from 1981-2023. Significant trend indicated by red line.

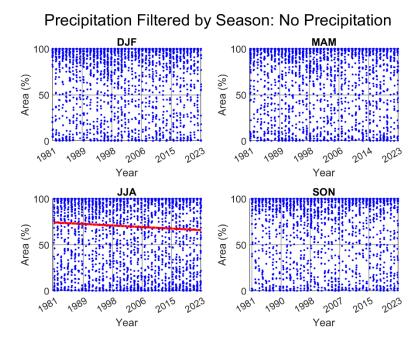


Figure 2.2. Percentage of the watershed receiving no precipitation daily filtered by season. Significant trend indicated by red line.

Light Precipitation Area

The watershed area receiving light precipitation, up to 0.5 inch per day, increased significantly (p=0.0153) from 1981-2023 (Figure 2.3). This increasing trend is also statistically significant in summer months (JJA, p=0.0177) (Figure 2.4). While winter and spring (DJF and MAM, respectively) both show increasing trends in the percentage of the area receiving light precipitation, these trends are not statistically significant.

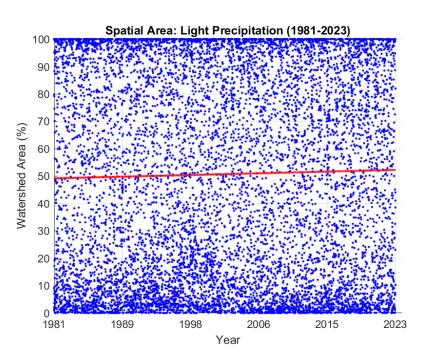


Figure 2.3. The percentage of the watershed receiving light precipitation from 1981-2023. Significant trend indicated by red line

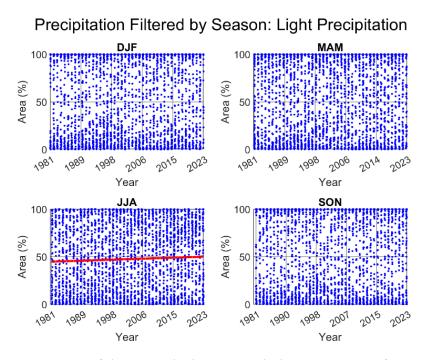


Figure 2.4. The percentage of the watershed receiving light precipitation from 1981-2023 filtered by season. Significant trend indicated by red line.

Moderate Precipitation Area

The portion of the watershed receiving moderate precipitation (between 0.5 and 1 inches of precipitation in a day) did not change significantly from 1981-2023. However, subtle yet statistically significant shifts are detectable at the seasonal level (Figure 2.5). In winter months, there is a statistically significant increase in the portion of the watershed receiving precipitation (p=0.0267). In summer, there is a slight yet significant decrease in the portion of the watershed receiving precipitation (p=0.0359). This may indicate that moderate summer precipitation is becoming more localized over time, or is becoming less intense and is contributing to the increasing size of light precipitation events.

Precipitation Filtered by Season: Moderate Precipitation DJF Area (%) Area (%) Year Year JJA SON 100 100 Area (%) Area (%) 50 50 1990 Year Year

Figure 2.5. The percentage of the watershed receiving moderate precipitation filtered by season. Significant trends indicated by red line.

Heavy Precipitation Area

Overall, the portion of the watershed receiving heavy precipitation has decreased over time (p=0.0300; Figure 2.6). This trend is not influenced by significant trends in any season, though heavy precipitation is most common in summer months. It should be noted that this decrease may not be representative of the full picture: if heavy precipitation has become more frequent but in small areas, such as that delivered by small but intense thunderstorms, compared to a few but widespread heavy precipitation events early in the timeseries, this apparent decline in the portion of the watershed receiving heavy precipitation may only be showing part of the story that is relevant to water resources. A frequency analysis would discern if heavy precipitation is becoming more frequent, even if it less widespread when it occurs, as such a trend would have impacts on water resource and flood management.

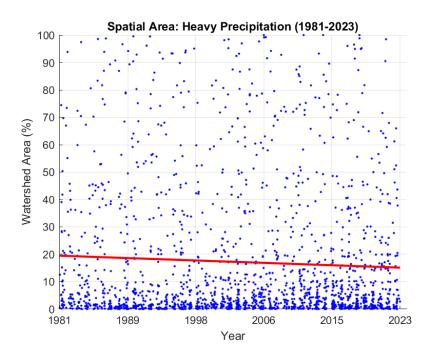


Figure 2.6. The percentage of the watershed receiving heavy precipitation from 1981-2023. Significant trend indicated by red line.

Recurrence Interval Areas: 1-year, 2-year, 5-year

While there are no statistically significant changes in the portion of the watershed receiving precipitation exceeding the 1-year, 2-year, and 5-year recurrence intervals, visual inspection of the data reveals useful patterns. Notably, it appears that the area of the watershed receiving 2-year and 5-year values (69.6-85.1mm, and ≥85.1mm, respectively) has increased in the fall months. In the first half of the dataset, the 5-year RI value was recorded only once in the watershed in fall months (SON); in the latter half of the timeline, this value was experienced in at least some portion of the watershed 15 times. While there are not enough data points for statistical significance in the portion of the study area receiving 2-year RI precipitation in the fall, it appears that these areas are on an upward trajectory and should be monitored for water resources purposes.

Precipitation Filtered by Season:

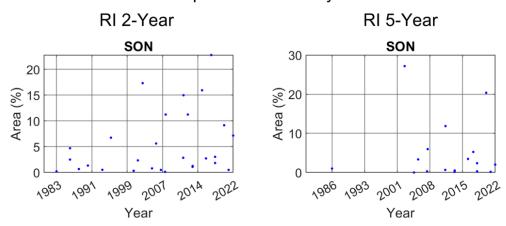


Figure 2.7. The percentage of the study area receiving precipitation exceeding the 2-year recurrence interval (left) and 5-year recurrence interval (right) in the fall months. No significant trends are detected, likely due to low sample sizes.

Section 3: Long-term precipitation characteristics

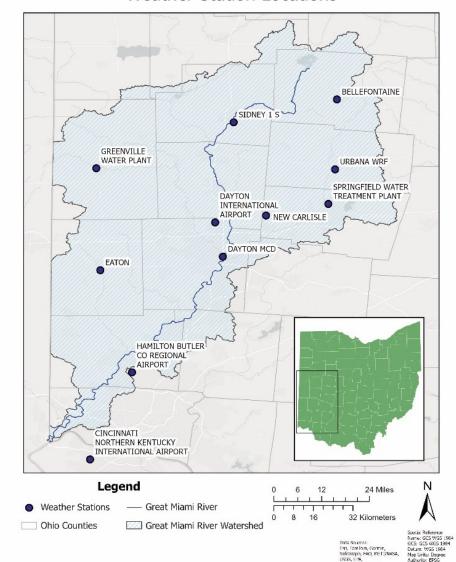
This collection of analysis examines daily precipitation at individual stations within the watershed. The objective of this section is to identify long-term characteristics and changes in precipitation patterns within the watershed where long-term records exist. A brief analysis of hourly precipitation is also provided in this section.

Data & Methods:

Data acquisition and cleaning

Weather station data was acquired from NOAA's National Centers for Environmental Information (NCEI) Climate Data Online database (https://www.ncei.noaa.gov/cdo-web/search). Stations located in the Great Miami River Watershed that have a relatively complete precipitation record

Weather Station Locations



greater than 50 years were chosen for this analysis (Figure Table 1). Cincinnati Northern Kentucky International Airport and Hamilton Butler Co Regional Airport are located just outside of the watershed and the Hamilton Butler Regional Airport record is less than 50 years. Station locations shown in Map 3.1.

Map 3.1. Names and locations of long-term precipitation records used in this analysis.

Data flags were screened to ensure data quality. The precipitation observation for 03/31/1952 was removed from the Bellefontaine record as 0" precipitation was recorded here and precipitation >1" was recorded at other stations. Records were trimmed to ensure all station records began at the start of the calendar year and end on the last day of 2024 (Table 3.1). The percentage of days per year that have an associated precipitation observation were calculated for each station and years that have < 85% coverage were excluded from analysis to avoid falsely low precipitation totals.

Table 3.1. Information about weather station records used in this study.

Station Name	Station ID	Latitude	Longitude	Start Date	End Date
Bellefontaine	USC00330563	40.3535	-83.7754	01/01/1930	12/31/2024
Cincinnati Northern Kentucky International Airport	USW00093814	39.04443	-84.67241	01/01/1948	12/31/2024
Dayton International Airport	USW00093815	39.90638	-84.21853	01/01/1948	12/31/2024
Dayton MCD	USC00332067	39.78175	-84.19025	01/01/1934	12/31/2024
Eaton	USC00332485	39.7328	-84.6353	01/01/1922	12/31/2024
Greenville Water Plant	USC00333375	40.1032	-84.6504	01/01/1899	12/31/2024
Hamilton Butler Co Regional Airport	USW00053855	39.36119	-84.52063	01/01/1999	12/31/2024
New Carlisle	USC00335786	39.9317	-84.0329	01/01/1952	12/31/2024
Sidney 1 S	USC00337693	40.2705	-84.1507	01/10/1949	12/31/2024
Springfield Water Treatment Plant	USC00337935	39.9735	-83.8072	01/01/1970	12/31/2024
Urbana WRF	USC00338552	40.0991	-83.7823	01/01/1929	12/31/2024

Precipitation Analyses

Multiple precipitation parameters were calculated from these records. These parameters were calculated for each year, and all stations were analyzed separately. These parameters include total annual precipitation, total seasonal precipitation, annual maximum precipitation, number of wet days, average daily precipitation intensity, heavy precipitation days, heavy precipitation fraction, and consecutive dry days.

- Total annual precipitation was calculated by summing all daily precipitation observations in each year. Total seasonal precipitation was calculated by summing all daily precipitation observations in each season within each year. Note that because data were added and cleaned by calendar year, analyses could not use climatological seasons (for example, if 1954 was removed from a station, using climatological seasons would mean that the winter ending in 1954 as well as the winter ending in 1955 would be incomplete and thus unable to be used.) Therefore, seasons were delineated following a water year schedule (Fall = OND, Winter = JFM, etc.). Seasons are retained in the year in which the weather occurred; for example, October 1980 is part of Fall 1980 instead of 1981. Seasons were delineated by water year instead of standard climatological seasons to reduce the impact of missing years of data on seasonal analyses.
- Annual maximum precipitation is defined as the day with the highest amount of precipitation, or the largest daily precipitation observation.
- The number of wet days per year was calculated by counting the number of days per year that had a valid precipitation observation > 0"; because these data use "trace" to indicate unmeasurably light precipitation, applying an above-zero threshold was not necessary.
- Average daily precipitation intensity was calculated by dividing total annual precipitation by number of wet days.
- Heavy precipitation days was calculated by counting the number of precipitation observations in each year above Dayton MCD point precipitation frequency (PF) estimates (https://hdsc.nws.noaa.gov/pfds/). This analysis was conducted using both a 1-yr and 2-yr recurrence interval (RI) which is 2.28" and 2.74", respectively. The centrally located Dayton MCD RIs were used to facilitate comparison between sites. Years with valid precipitation observations but no observation above these thresholds was recorded as 0 heavy precipitation days.
- Heavy precipitation fraction was calculated by ranking all wet days in each year by precipitation observation value and summing the observations of days with the highest 1% of precipitation observations (always rounding up to the nearest whole day and ensuring there is at least one day), then calculating the percent of total annual precipitation delivered on the heaviest 1% of days.
- Consecutive dry days was calculated by determining the maximum number of consecutive days with no measurable precipitation for each year. The streak of days ended on days that had no precipitation observation and at year boundaries.

Simple linear regression models were created for all precipitation parameters to determine if there are temporal trends present in the watershed. These regressions were calculated separately for each station. Year of observation was used as the predictor and the calculated precipitation parameter was used as the response for each regression. Statistical significance is reported at the 0.05 level. The slope of the regression line was used to determine if there was an increasing or decreasing trend over time of record.

Table 3.2. Variables investigated and corresponding units.

Variable	Definition	Units
Total annual and seasonal	Sum of precipitation measured in	mm or in.
precipitation	one year and each season	
Annual maximum precipitation	Largest single-day precipitation	mm or in.
	event recorded per year	
Number of wet days	Number of days per year with	Days
	measurable precipitation*	
Average daily precipitation intensity	Sum of precipitation received in a	mm or in.
	year divided by number of wet days	
	in that year	
Heavy precipitation days	Number of days with precipitation	Days
	greater than a predefined threshold,	
	such as 10 mm, 1 inch, or another	
	value useful to MCD.	
Heavy precipitation fraction	Percentage of annual precipitation	Percent
	delivered in the heaviest 1% of	
	precipitation days	
Consecutive dry days	Maximum number of consecutive	Days
	days without measurable	
	precipitation* per year	
Maximum hourly precipitation	Largest magnitude of precipitation	mm or in. per
intensity	received in one hour per year	hour

Results

Summary results and interpretation

Over the watershed, the trends at most locations align with higher total precipitation and more frequent precipitation (Table 3.3). Variations exist between stations, even stations within relatively close proximity to each other. These differences may arise from differences in time period, as one station may have captured a significant event before another station was online. Similarly, perfect continuity of observations is relatively rare. Most stations have at least a few missing days. These missing days can arise from station relocation, or from sensor malfunction, which can happen during extreme events, causing those events to be "missed" in the record. While efforts were made to reduce these effects, such as by eliminating years with substantial missing data, artifacts of small amounts of missing data may impact the results.

Table 3.3. Direction and significance of trends at individual stations.

↑ Significant increase ↓ Significant decrease ✓ Insignificant increase ↓ Insignificant decrease - No change Station Name	Annual Precipitation	Spring (AMJ) precip	Summer (JAS) precip	Fall (OND) precip	Winter (JFM) precip	Maximum daily precip	Number of wet days	Average precip intensity	Number of 1-yr RI days	Number of 2-yr RI days	Heavy precip fraction	Consecutive dry days
Bellefontaine	↑	↑	↑	↑	↑	↑	↑	-	7	7	7	\downarrow
Cincinnati N. Kentucky Int. Airport	↑	↑	۲	↑	۲	۲	۲	↑	۲	7	7	7
Dayton International Airport	↑	7	7	↑	7	/	7	↑	7	7	K	/
Dayton MCD	↑	7	7	7	7	7	7	↑	7	7	7	\downarrow
Eaton	↑	↑	7	↑	7	7	↑	\downarrow	↑	↑	↑	\downarrow
Greenville Water Plant	7	7	7	7	7	7	↑	\downarrow	7	7	↑	\downarrow
Hamilton Butler Co Reg. Airport	7	7	7	7	7	7	↓	↑	7	7	7	7
New Carlisle	↑	7	7	↑	↑	7	↑	7	7	7	\rightarrow	7
Sidney 1 S	↑	↑	7	↑	7	7	↑	-	7	7	7	7
Springfield Water Treatment Plant	7	7	7	7	↑	7	↑	7	7	7	7	7
Urbana WRF	↑	↑	↑	↑	7	↑	↑	7	↑	↑	7	7

Overall, precipitation is increasing in the watershed. With both total annual precipitation and number of wet days showing significantly increasing trends at a majority of the locations, and average daily precipitation intensity showing diverging trends, it is likely that the increase in precipitation is the result of precipitation occurring on more days rather than a widespread increase in intensity on wet days. The lack of a similar significant trend at the majority of locations in annual maximum precipitation also supports this interpretation: there is not likely a widespread increase in the intensity of precipitation on the heaviest wet days, but rather an increase in the number of days on which precipitation is delivered. It should be noted that while precipitation is generally intensifying in the eastern United States, particularly in the extreme ranges, these changes may not be statistically significant at the individual station level, and that the highly spatially heterogeneous nature of intense precipitation (such as that delivered in mesoscale systems such as thunderstorms) increase variability between even nearby stations.

The number of heavy precipitation days per year does not show a consistent trend among stations and therefore supports the interpretation that the intensity of daily precipitation has not increased significantly, despite the increase in the number of days with some precipitation. Heavy precipitation fraction also does not show trend agreement among stations, indicating the proportion of heavy precipitation days compared to number of wet days has not changed in the watershed. There is a consistent decreasing trend in maximum number of consecutive dry days per year among all weather stations, further supporting the interpretation that the increase in precipitation is the result of more wet days, rather than a strong increase in precipitation intensity on wet days. This increase in precipitation frequency may have implications in soil moisture and water resources.

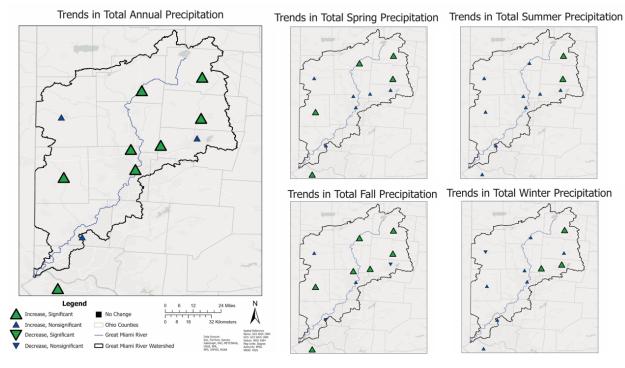
This precipitation increase generally occurs in all seasons, however, fall and spring show a higher number of stations with significantly increasing trends (7 and 5 stations, respectively) compared to winter and summer (3 and 2 stations, respectively). This may be interpreted to mean that the increase of precipitation in fall and spring is occurring at a higher magnitude or at a faster rate. Therefore, there is a seasonality component of the increase in precipitation, and it is not consistent throughout the entire year. Further work might examine whether weather patterns are shifting temporally (consolidating more precipitation events into the shoulder seasons) or if atmospheric circulation patterns and mesoscale systems are remaining consistent but producing larger increases in precipitation in the shoulder seasons than in summer and winter.

At Bellefontaine and Urbana, the most northwesterly locations included in the analysis, precipitation amounts and frequency increased the most consistently. Changes in precipitation patterns were the least conclusive at Hamilton Butler Regional Airport. While this record is consistent, with no missing years, it is a short record, beginning in 1999.

It should be noted that interpretations for the watershed are general, and that length of record is important in determining statistical significance. For example, the Greenville location has 125 years of data and often showed diverging signals with the Hamilton location, which only has 25 years of data. The Hamilton location therefore is highly influenced by conditions of the 21st century, while the Greenville trends are influenced heavily by conditions in the century prior to the establishment of the Hamilton records.

Total annual and seasonal precipitation

Total annual precipitation has an increasing trend at all stations, with 8 stations showing a significant increasing trend, and 3 showing a nonsignificant trend (Map 2). Total winter precipitation has an increasing trend at all but one weather station, with 3 stations having a significant increasing trend (Bellefontaine, New Carlisle, Springfield) and 7 having a nonsignificant increasing trend (Map 3.2). The one station with a decreasing winter precipitation trend (Greenville) is nonsignificant. Total spring precipitation has an increasing trend at all stations, with 5 stations showing a significant increasing trend, and 6 showing a nonsignificant but increasing trend (Map 3.2). Total summer precipitation has an increasing trend at all stations, with 2 stations showing a significant increasing trend (Bellefontaine, Urbana), and 9 showing a nonsignificant trend. Total fall precipitation has an increasing trend at 9 stations, with 7 stations showing a significant increasing trend, and 2 showing a nonsignificant trend. Two stations (Hamilton, Springfield) show nonsignificant decreasing trends in total fall precipitation (Map 3.2).



Map 3.2. Trend directions and significance in total annual precipitation and total seasonal precipitation.

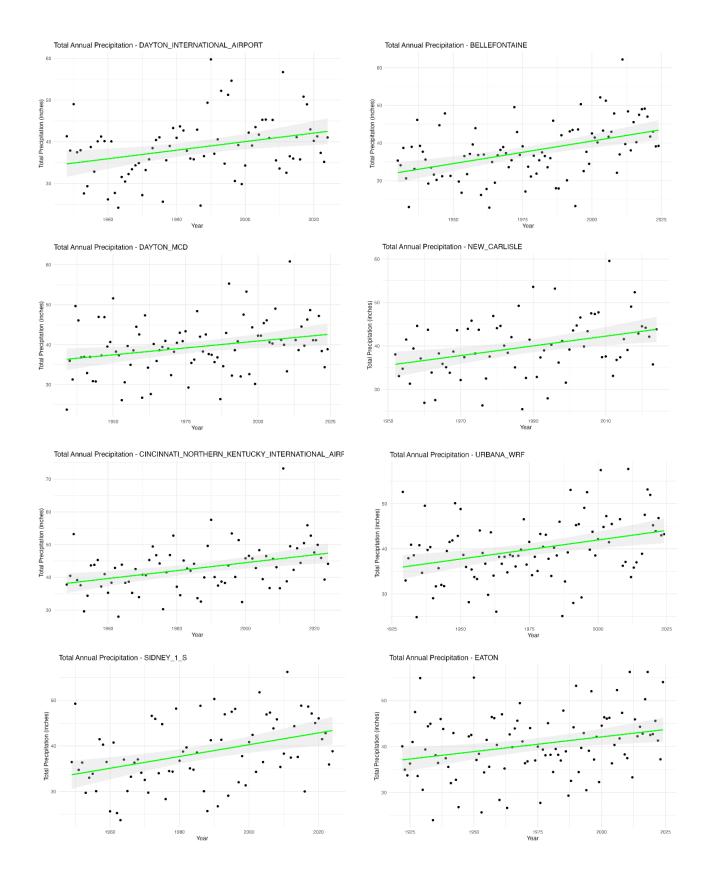


Figure 3.1. Significant trends in total annual precipitation.

Annual Maximum Precipitation

There is an increasing trend in annual maximum precipitation at 7 stations, with 2 of the northeast stations having a significant increase (Bellefontaine, Urbana; Figure 3.2) and 5 showing nonsignificant increases (Map 3.3). Four stations through the middle-range of the watershed and Hamilton display nonsignificant decreasing trends.

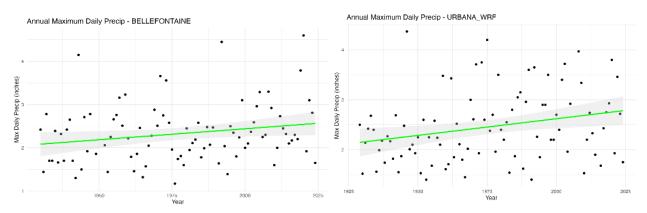
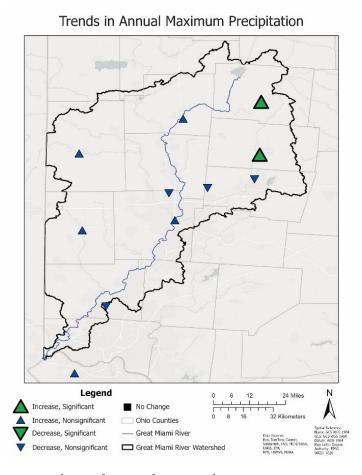


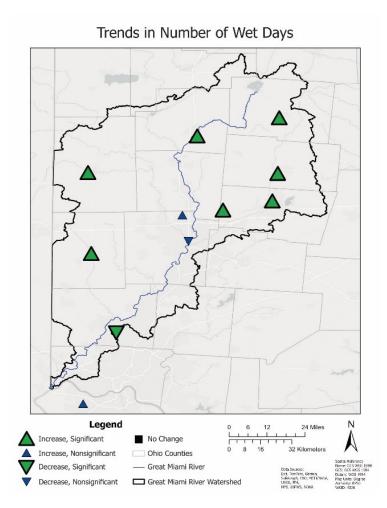
Figure 3.2 Significant trends in annual maximum daily precipitation.



Map 3.3. Trend directions and significance for annual maximum precipitation.

The Number of Wet Days

The number of days with non-zero precipitation shows a significant increasing trend at 7 locations, nonsignificant increasing trend at 2 locations, significant decreasing trend at 1 station (Hamilton), and a nonsignificant decreasing trend at 1 station (Map 3.4). The significant decreasing trend in the number of wet days at Hamilton may be an artifact of missing data near the end of the relatively short time period; fewer days included in the record results in fewer potential days for precipitation to be recorded.



Map 3.4. Directions and significance of trends in the number of wet days per year.

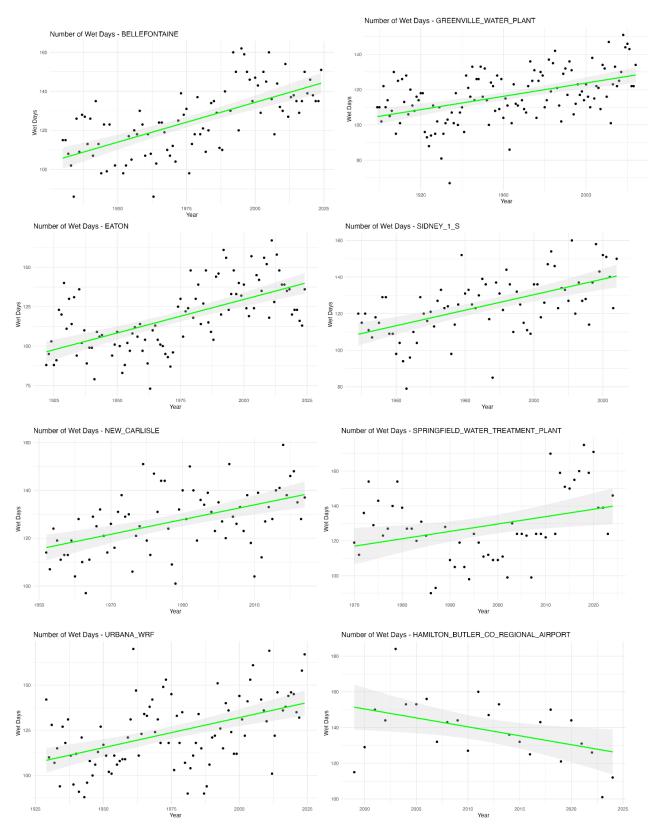
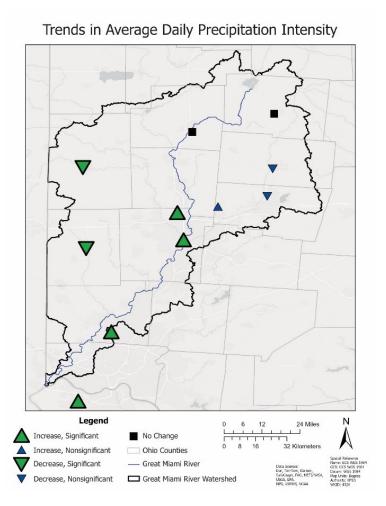


Figure 3.3. Significant trends in the number of wet days per year.

Average Daily Precipitation Intensity

Four locations through the south-center of the watershed (Cincinnati, Hamilton, both Dayton stations) show a significant increase in average daily precipitation intensity (precipitation per day relative to the number of wet days in that year) and one station shows a nonsignificant increasing trend. Two western locations show a significant decreasing trend (Greenville, Eaton) and two locations show a nonsignificant decreasing trend. The two northeastern stations show no change in average daily precipitation intensity (Map 3.5).



Map 3.5. Direction and significance of trends in average daily precipitation intensity.

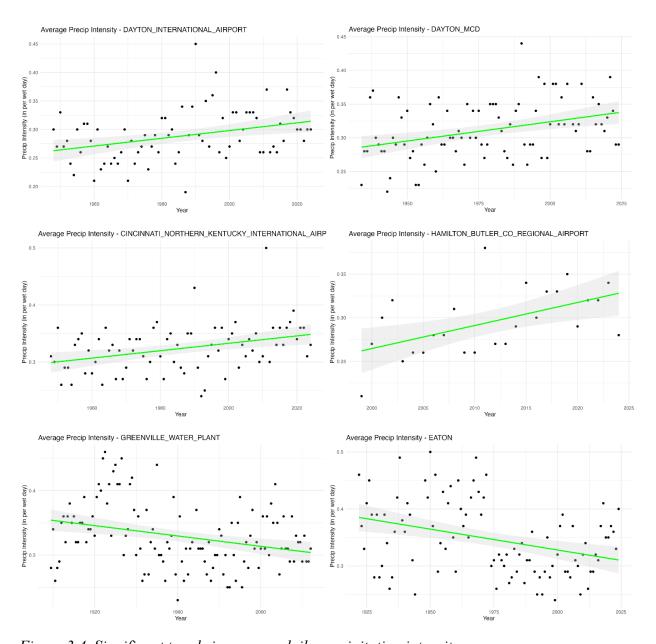
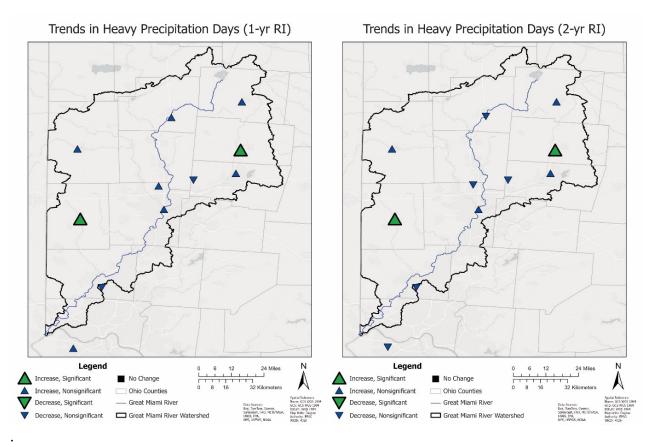


Figure 3.4. Significant trends in average daily precipitation intensity.

Heavy Precipitation Days

The number of heavy precipitation days per year greater than the 1-yr RI (>2.28") shows a significant increasing trend at 2 stations at opposite ends of the watershed (Eaton, Urbana), nonsignificant increase at 7 stations, and a nonsignificant decreasing trend at 2 stations (Map 3.6, Figure 3.5). The number of heavy precipitation days per year greater than the 2-yr RI (>2.74") shows a significant increasing trend at 2 stations (Eaton, Urbana), nonsignificant increase at 4 stations, and a nonsignificant decreasing trend at 5 stations (Map 3.6, Figure 3.6). It should be noted that the relative rarity of these events (0-4 instances per year, integers only) weakens the strength of these analyses, as they are highly sensitive to outliers or to single events near either

end of the time series. A percentile-based approach specific for each location (e.g., the number of events exceeding the 90th percentile of wet-day precipitation at that location) may provide sample sizes that are more conducive for quantitative analysis.



Map 3.6. Trend significance and direction of the number of 1-year recurrence interval events (left) and 2-year recurrence-interval events (right).

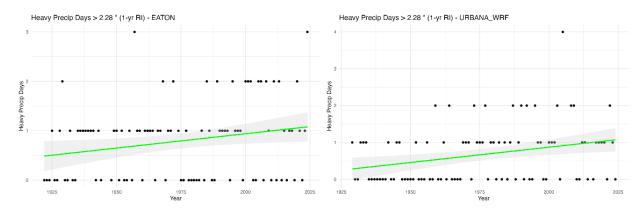


Figure 3.5. Significant trends in the number of events exceeding 2.28in at Eaton and Urbana WRF.

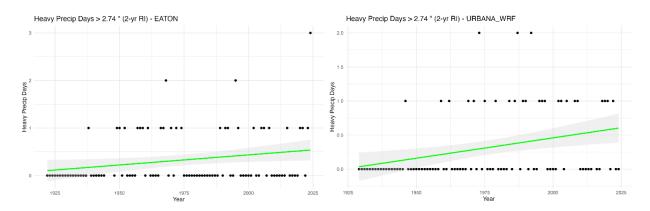


Figure 3.6. Significant trends in the number of events exceeding 2.74in at Eaton and Urbana WRF.

Heavy Precipitation Fraction

Decrease, Significant

Decrease, Nonsignificant

Heavy precipitation fraction, or the percentage of annual precipitation delivered in the heaviest 1% of precipitation days, has a significant increasing trend at 2 western stations (Greenville, Eaton), a

Trends in Heavy Precipitation Fraction Legend Increase, Significant Increase, Nonsignificant Ohio Counties No Change 0 6 12 24 Miles N 24 Miles N 32 Kilometers

Great Miami River Watershed

nonsignificant increasing trend at 3 weather stations, a significant decreasing trend at 1 station, and a nonsignificant decreasing trend at 5 stations (Map 3.7). This suggests that the heaviest precipitation events at these locations are having increasing impact annual on precipitation totals.

Map 3.7. Trend significance and direction of the percentage of annual precipitation falling in the heaviest 1% of precipitation days.

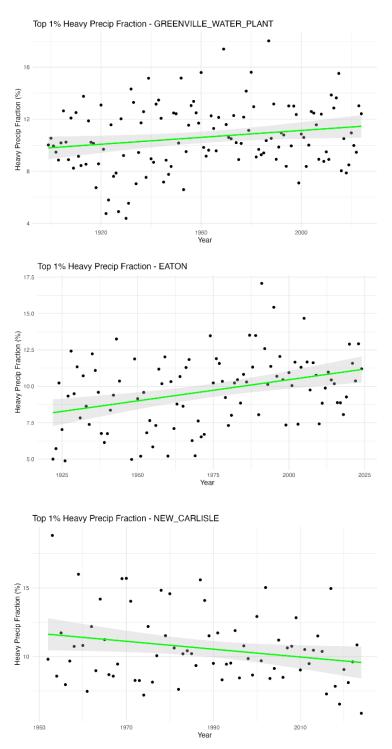
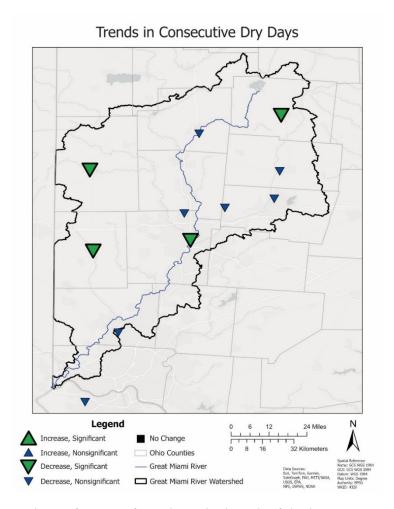


Figure 3.7. Significant trends in the percentage of heavy precipitation delivered in the heaviest 1% of precipitation events each year.

Consecutive Dry Days

All stations show a decreasing trend of maximum length of consecutive dry days per year, with 4 stations (Greenville, Eaton, Dayton MCD, Bellefontaine) having a significant decreasing trend and 7 stations having nonsignificant trends (Map 3.8). While it is expected that the number of dry days per year must decrease in response to the increasing number of wet days, the decreases in the length of longest dry runs of the year indicate that the longest dry periods are also becoming shorter, or are being interrupted more frequently. This may have implications for water quality and water resources management



Map 3.8. Direction and significance of trends in the length of the longest consecutive dry run per year.

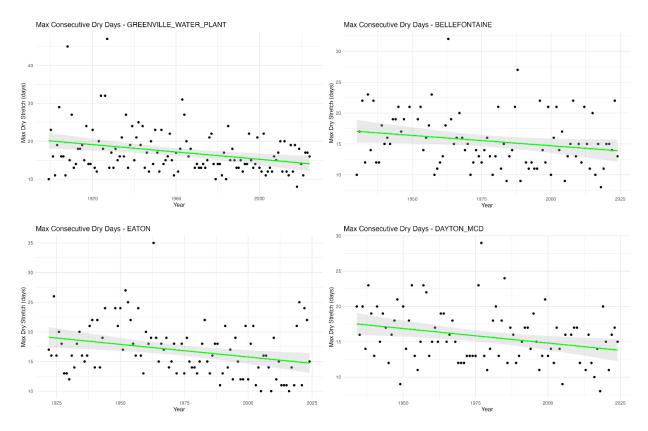


Figure 3.8. Significant trends in the length of the longest consecutive dry run per year.

Hourly precipitation

Hourly precipitation was analyzed for Piqua, Lebanon, Fairfield, and Springfield (Table 3.4). These locations had the longest and most complete records available.

Table 3.4 Stations and time periods used in hourly precipitation anal	Tahle	3 4 Stations	and time neriods 1	ised in hourl	ly precipitation anal	2924
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Station	Station code	Data used for analysis
Fairfield	USC00332651	1/1/1986 - 12/31/2023
Lebanon	USC00334459	11/7/1966 - 5/8/25
Piqua	USC00336650	8/1/1948 - 5/5/2025
Springfield	USC00337935	8/1/1948 - 5/1/2025

Because of changes in data acquisition and recording procedures, the data precision of the data changed over the decades for multiple stations. Changes in the precision of the data have the potential to create false trends in the data. For example, if a station recorded data at a tenth of an inch precision (0.1in), a rainfall amount of 0.04in may not be measurable and therefore may be recorded as 0in. If the station later updates sensor precision to hundredths of an inch, another 0.04in event would be recorded as 0.04in instead of 0in. This would show an increase in precipitation,

when in reality the increase was in data precision, not precipitation. Therefore, all hourly precipitation values were rounded to the nearest tenth of an inch for consistency.

Trends in hourly precipitation over time were assessed using a linear regression model, with results reported if the trend was significant at p<0.05, indicating that there is a <5% probability that the observed trend occurred by random chance. However, given the changes in data precision over time, these findings should be interpreted cautiously.

Maximum hourly precipitation intensity

There were no significant linear trends in maximum hourly precipitation intensity at Springfield or Piqua over the time periods.

At Fairfield, a linear regression detected significant increases (p<0.05) in precipitation at the annual scale (Figure 3.9). This increase was driven by a significant increase in maximum hourly precipitation intensity in the spring months (MAM; Figure 3.10). Other seasons did not show a significant change in hourly precipitation intensity over time.

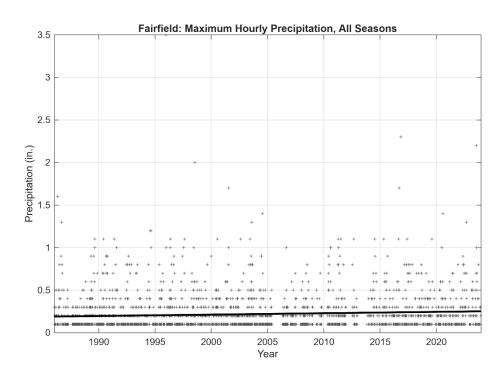


Figure 3.9. Maximum hourly precipitation recorded each day at Fairfield. Significant trend is shown with black line. Note that the high temporal resolution results in close spacing of data points.

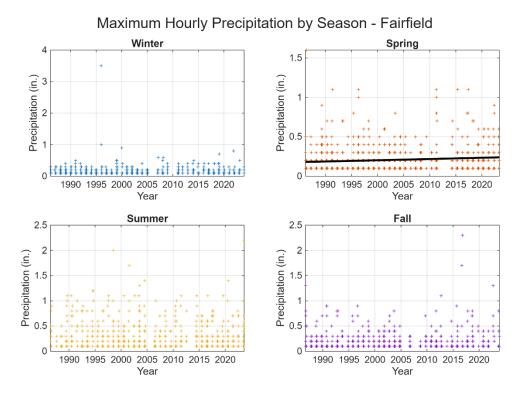


Figure 3.10. Maximum hourly precipitation recorded each day at Fairfield, filtered by season. Significant trend is shown with black line. Note that the high temporal resolution results in close spacing of data points.

At Lebanon, an opposite trend was detected, with a decrease in the maximum hourly precipitation intensity over time (Figure 3.11). This trend is strongest in the fall (note different scale bars on the seasonal subfigures), suggesting that short-term precipitation is becoming less intense over time (Figure 3.12).

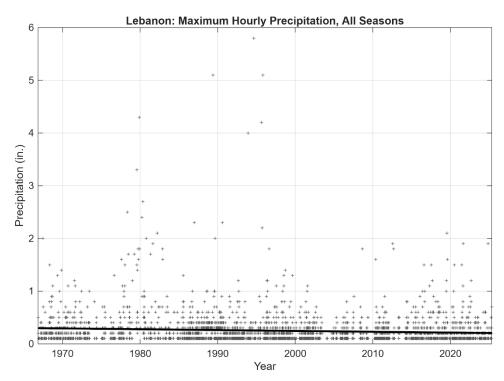


Figure 3.11. Maximum hourly precipitation recorded each day at Lebanon. Note that the high temporal resolution results in close spacing of data points.

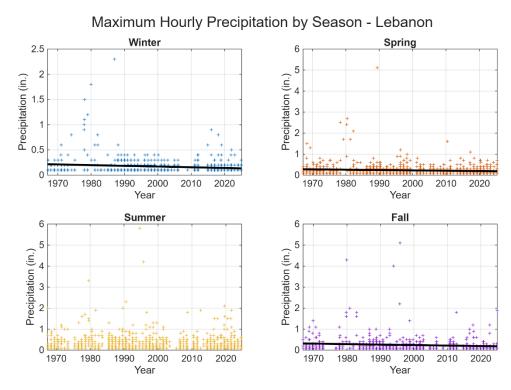


Figure 3.12. Maximum hourly precipitation recorded each day at Lebanon, filtered by season. Significant trend is shown with black line. Note that the high temporal resolution results in close spacing of data points

With these significant trends in maximum hourly precipitation at Fairfield and Lebanon, it is important to note that changes in station characteristics may impact measurements. Precipitation is highly spatially variable and can be affected by local environmental changes, such as wind patterns created by trees and buildings. The possibility of changes in the local environment or changes to the station, such as relocation or sensor upgrades, should be taken into account when considering these results. If variability in hourly precipitation is of interest to MCD, additional analyses should be taken, including investigations into when the data collection methods changed, what the potential impacts were, and potentially analyses excluding times when data records were less precise.

Concluding summary of key findings

Section 1: Temperature variability

- September shows a significant warming trend in average temperatures (1981–2023), suggesting summers extend later into fall.
- May shows increasing highest maximum temperatures; July shows decreasing highest maximum temperatures
- Average minimum temperatures are increasing significantly in June, September, October, and seasonally in spring, summer, and fall.
- Lowest monthly minimum temperatures are rising in June, July, August, September, October, December, and seasonally in summer, fall, and winter.
- Temperature ranges are declining in March, April, July, August, and September, suggesting a narrowing of temperature extremes.

Section 2: Precipitation distribution

- The size of the area receiving no precipitation daily is decreasing overall (1981-2023), especially in summer (June-August).
- The size of the area receiving light precipitation daily is increasing overall, especially in summer.
- The area experiencing moderate precipitation in winter is increasing, while moderate precipitation in summer is becoming more localized. This could mean that these systems are becoming smaller, or that they are de-intensifying and delivering a larger area of light precipitation rather than moderate precipitation.
- While there are no statistically significant trends in the size of the area receiving very heavy precipitation from 1981-2023, it appears that these events are expanding in the fall months.

Section 3: Long-term precipitation variability

- Total annual and seasonal precipitation amounts are increasing at nearly all locations, especially in spring (April-June) and fall (October-December).
- Trends in the annual maximum daily precipitation are mixed, though there are statistically significant increases at the northwesternmost locations.
- The number of wet days per year (precipitation frequency) is increasing throughout the watershed.
- The length of the longest dry spell per year is decreasing throughout the watershed as precipitation becomes more frequent.
- Trends in hourly precipitation intensity are mixed. Hourly precipitation intensity is increasing at Fairfield overall and especially in the spring (March-May), and is decreasing at Lebanon overall, including fall, winter, and spring. These emerging findings may be influenced by variations in data precision and collection methods.