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Relationship between Drought Characteristics and the Extent of Urban Land Cover: The Case of the Milwaukee River Basin in Wisconsin (USA)

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Abstract : It is well known that land covers significantly influence hydrological processes, particularly in urban catchments. However, it is less well known how urban land covers affect hydrological (streamflow) drought. This study investigated how streamflow drought characteristics vary along with the extent of urban land cover and compared them to precipitation drought characteristics. The Milwaukee River basin was chosen as the study area to build on previous research related to streamflow characteristics and urban land cover. Three catchment areas (Cedarburg, Menomonee, and Kinnickinnic) that have different extents of urban land cover in the Milwaukee River basin were examined. Streamflow and precipitation droughts were diagnosed using the variable threshold level method and daily streamflow and precipitation data for the period 1983-2022. For streamflow drought, the maximum and mean durations were longest in the Cedarburg catchment, which is the least urbanized. On the other hand, they were shortest in the Kinnickinnic catchment, more than 98% of which is urban. The mean deficit relative to the mean annual runoff was largest in Cedarburg and smallest in Kinnickinnic. Not surprisingly, the characteristics of precipitation drought were very similar between the catchments. From this exploratory study, I speculate that highly urbanized catchments are likely to experience shorter but less intense streamflow droughts than less urbanized ones largely because of increased variability and magnitude of streamflow.

Key Words : drought, streamflow, precipitation, urban land cover, Milwaukee River

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1. Introduction

Drought means "the naturally occurring phenomenon that exists when precipitation has been significantly below normal recorded levels, causing serious hydrological imbalances" (United Nations, 1994), and as such, streamflow drought refers to a condition where streamflow is significantly below normal over an extended time. Streamflow drought has adverse impacts on various sectors such as hydropower generation, municipal water supplies, river navigation, and river ecology. Drought has been traditionally viewed as a 'natural' disaster, but there is growing recognition that human activities affect streamflow drought (e.g., Van Loon *et al.*, 2016; Choi *et al.*, 2022; Van Loon *et al.*, 2022; Wang *et al.*, 2023; Senbeta *et al.*, 2024). In urban areas, streamflow drought is more likely to be affected by human activities and also could affect more people than in non-urban areas. Streamflow drought in urban areas, or runoff-induced urban drought (Zhang *et al.*, 2019), deserves more attention for its socio-economic impacts.

Human activities affecting streamflow drought include water abstraction, water transfer, reservoir release, land use/cover change, and pipe leaks and sewage return (Wan *et al.*, 2017; Brunner, 2021; Van Loon *et al.*, 2022). Van Loon *et al.* (2022) extensively examined human impacts on streamflow drought by collating cases from around the world and comparing observation data between human-influenced and benchmark time series (paired catchments approach, Van Loon *et al.* 2019). In their work, only two cases were included regarding land use changes, which show both alleviation and aggravation of drought events. The dearth of cases regarding land use change in their study necessitates more case studies, but it could be in part due to the difficulty in finding adequate pairs of catchments for the paired catchments approach in streamflow drought research.

There are numerous studies regarding land cover change impacts on streamflow characteristics where streamflow characteristics were compared among catchments with different degrees of urbanization (e.g., Chang, 2007; Choi, 2008; Dixon and Earls, 2012; Choi *et al.*, 2016; Bhaskar *et al.*, 2020). Such studies generally find larger magnitude and variability of streamflow in catchments with more urban land cover. When one extends these findings of increasing streamflow variability, one could hypothesize that streamflow drought will be exacerbated by increasing urban land covers. However, there are few empirical studies (if any) regarding how urban land covers influence the characteristics of streamflow drought. On the other hand, impacts of urban land cover on precipitation drought (i.e., lack of precipitation over an extended time) were investigated in several studies (e.g., Huang *et al.*, 2022; 2024a; 2024b). A better understanding of how urban land covers affect streamflow drought may help better prepare for streamflow drought and mitigate its impacts.

This study tests the hypothesis by examining streamflow drought characteristics against urban land covers among catchments. Specifically, the streamflow drought characteristics of three catchments of the Milwaukee River basin (MRB) in Wisconsin were examined and compared with precipitation drought characteristics. The catchments have distinct proportions of urban land cover and almost identical temperature and precipitation regimes (details in the next section). The key questions addressed here are (1) What are the characteristics of streamflow drought in the three catchments of the MRB and how do they compare to precipitation drought? and (2) How do the streamflow drought characteristics vary by the extent of urban land cover? To answer the questions, daily precipitation and streamflow data were used for the years 1983-2022 and precipitation and streamflow drought events were identified. Drought events were identified for the three catchments each of which is referred to as Cedarburg, Menomonee, and Kinnickinnic, respectively. Then the drought characteristics were examined against the extent of urban land cover.

2. Materials and Methods

1) Study area

The Milwaukee River basin is located in the southeastern corner of Wisconsin (Figure 1). There are three major rivers in the basin, namely Milwaukee, Menomonee, and Kinnickinnic, and they merge right before discharging to Lake Michigan. The Milwaukee River is the longest, stretching from north to south, and the Kinnickinnic is the shortest. There are no dams known to affect the streamflow. The basin's overall size is

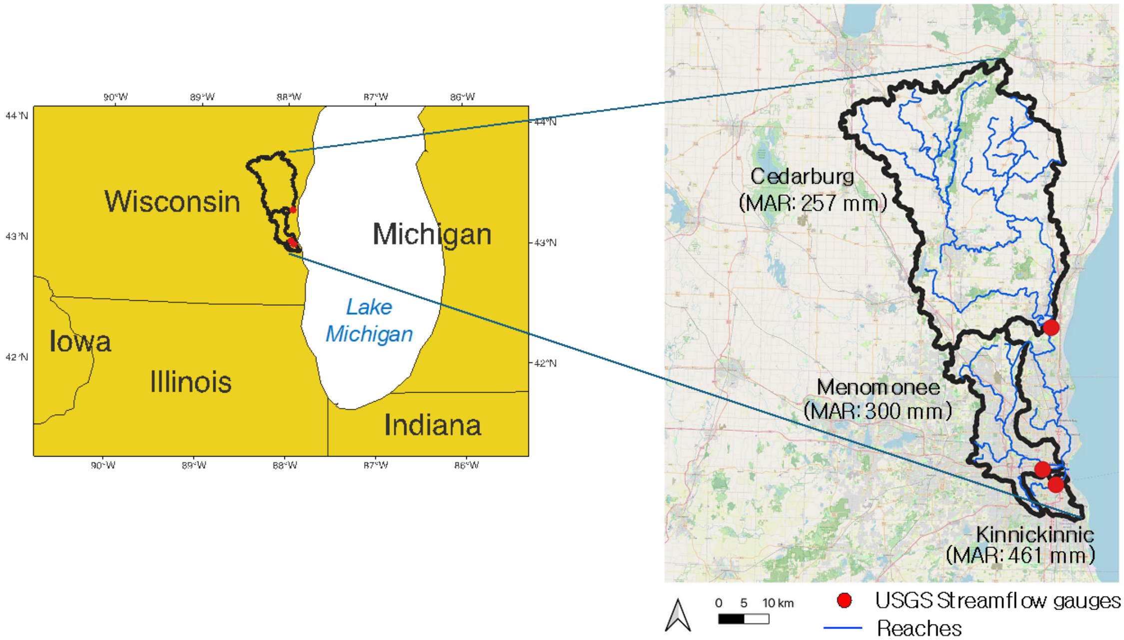

Figure 1. The three catchments selected for the study. Also shown are major reaches of the river and the USGS streamflow gauge for each catchment. MAR stands for mean annual runoff.

Table 1. Characteristics of the three catchments in the Milwaukee River basin analyzed in this study.

	Cedarburg	Menomonee	Kinnickinnic
USGS site ID	04086600	04087120	04087159
Drainage area (km^2)*	1,572.12	318.57	48.69
Mean elevation ± standard deviation (m above sea level)	291.4 ± 30.0	241.2 ± 23.6	208.6 ± 12.7
Mean daily maximum temperature (°C)*	13.2	13.6	13.3
Mean daily minimum temperature (°C)*	2.6	2.9	3.5
Developed[#] land cover (%) in 2021	13.3	70.8	98.7

* data from Choi *et al*. (2016); [#]NLCD classification codes 21-24 (https://www.mrlc.gov/data/legends/national-land-cover-database-class-legend-and-description)

approximately 2,330 km^2 measured upstream of the US Geological Survey (USGS) site ID 04087 000 (Milwaukee River at Milwaukee, WI), and it has about 1.3 million inhabitants in it (Wisconsin Department of Natural Resources, 2001). The City of Milwaukee, the largest city in the state, is nested in the basin. The land use/cover is generally agriculture in much of the basin, but there is dense urban land cover in the southern corner.

Three USGS streamflow gauge sites (Table 1) were used for streamflow data analysis. For the Milwaukee River, the site in the town of Cedarburg was chosen (ID 04086600) instead of the one mentioned above to select the mostly rural part of the basin. The catchment boundary (referred to as Cedarburg hereafter) was delineated upstream of the site. The boundaries of Menomonee and Kinnickinnic were obtained from the National Hydrography Dataset, and the USGS sites are located close to the respective outlet.

2) Data

Daily mean streamflow data (in cubic feet per second) were obtained from USGS (https://waterdata.usgs.gov) for the three gauges for the period of 1983-2022 and converted to mm/day. Daily precipitation (in mm) data were obtained from the PRISM climate dataset (Di Luzio *et al*., 2008) for the same period. The precipitation data were downloaded for the 4-km resolution grid box containing each streamflow gauge. The streamflow and precipitation time series were loaded to RStudio for processing and analysis.

3) Drought diagnosis

The threshold level approach was used to identify both precipitation and streamflow drought events. The approach originates from the run theory (Yevyevich, 1967) and identifies drought events when the variable of interest (precipitation or streamflow in this study) continuously stays below the predefined threshold level (Figure 2). When the measured variable falls below the threshold level, a drought is considered to have commenced, and the drought ends when the measured variable rises above the threshold level. The duration refers to the number of consecutive days when the variable falls below the threshold, and the deficit volume refers to the sum of deviations from the threshold during the drought event. The 20th percentile (smaller than 80% of the data) was used as the threshold following many previous studies (e.g., Wong *et al*., 2011; Rivera *et al*., 2017; Rangecroft *et al*., 2019; Choi *et al*., 2022). The variable threshold approach was adopted, meaning the 20th percentile varies, not remain constant throughout the year (see the undulating dashed line in Figure 2). Here the 20th percentile was found for each calendar day from the dataset. In the variable threshold level approach, the threshold is higher in a wet (or high-flow) season and lower in a dry (or low-flow) season.

Droughts were diagnosed using an R package adopted from Van Loon (2019). The package calculated 10-day moving averages of the entire dataset to reduce inter-daily variability and determined the 20th percentile for each calendar day. Drought events separated by ten days or less were deemed dependent events and pooled together following Choi *et al*. (2022). For example, in Figure 2, if the gap between the first and the second events is ten days or less, they are pooled as one event. Drought events lasting for 15 days or less were discarded as minor events following Choi *et al*. (2022). First, the basic statistics of drought characteristics such as mean and maximum deficit volume (in mm) and mean and maximum duration (in days) were examined. They were calculated from all drought events of the respective drought type. Then the timing of drought occurrence was examined by counting the number of events that commenced in each month from January to December. The time series of drought events were also examined based both on deficit volume and duration.

4) Trend analysis

The Mann-Kendall test for trend (McLeod,

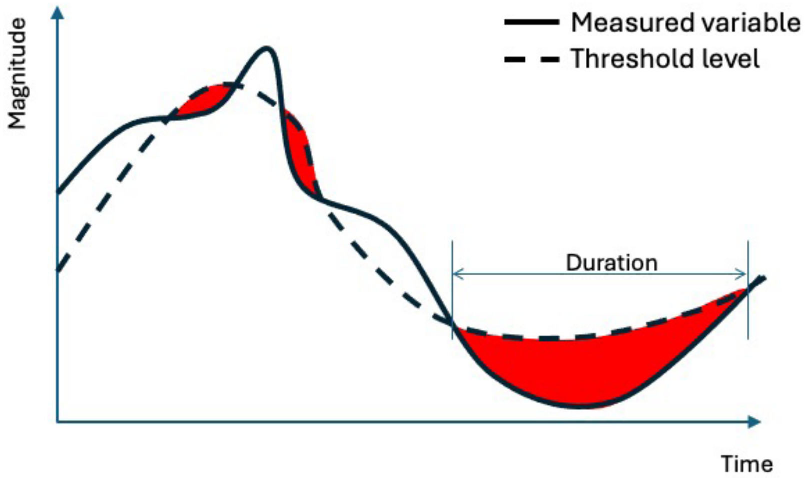

Figure 2. Variable threshold level approach. The dashed line represents the pre-defined threshold level, and the solid line represents the measured variable for the given time. Three drought events are shown in the figure indicated by the colored areas. The size of the colored areas indicates the deficit volume of the drought.

2011) was employed to find the direction and significance of temporal trends in drought characteristics. It is a non-parametric statistical test used to assess the presence of a monotonic trend in a time series or a set of data. It starts by calculating S as follows (equation 1):

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sign(y_j - y_i) \qquad (1)$$

where y is the variable of interest, i and j denote subsequent times, and $sign$ is 1 if $y_j - y_i$ is > 0, 0 if $y_j - y_i$ is 0, or −1 otherwise. When the series has a random order, S is expected to be 0. The z statistic is found from S and its variance and used to determine the trend and its significance.

3. Results

1) General characteristics of droughts

Overall, the three catchments have very similar precipitation and somewhat dissimilar streamflow characteristics (Table 2 top panel). Mean annual precipitation hovers around 880 mm, but mean annual runoff varies from 282 (Cedarburg) to 461 mm (Kinnickinnic) with Menomonee (351 mm) in between. Similar to many previous studies (see Introduction), catchments with more urban land cover have higher runoff ratios in MRB. Kinnickinnic's runoff ratio is more than 60% higher than that of Cedarburg.

The catchments also show very similar precip-

Table 2. General characteristics of precipitation, runoff, and drought for the three catchments.

	Cedarburg	Menomonee	Kinnickinnic
Precipitation and runoff			
Mean annual precipitation (mm)	883.0	874.0	883.0
Mean annual runoff (mm)	282.0	351.0	461.0
Annual runoff ratio[1]	0.32	0.40	0.52
Precipitation drought			
Mean deficit volume (mm)	20.2	20.6	19.6
Maximum deficit volume (mm)	82.6	127.0	125.0
Deficit-to-mean annual precipitation (%)[2]	2.3	2.4	2.2
Mean duration (days)	30.2	30.3	29.0
Maximum duration (days)	106.0	121.0	121.0
Streamflow drought			
Mean deficit volume (mm)	5.7	6.0	7.0
Maximum deficit volume (mm)	50.4	44.3	30.9
Deficit-to-mean annual runoff (%)[3]	2.0	1.7	1.5
Mean duration (days)	48.5	39.8	32.3
Maximum duration (days)	240.0	179.0	100.0

[1] mean annual runoff / mean annual precipitation; [2] mean deficit volume / mean annual precipitation × 100; [3] mean deficit volume / mean annual runoff × 100

itation drought characteristics in terms of mean deficit volume and mean duration (Table 2 middle panel). Menomonee's mean deficit volume (20.6 mm), largest of the three, is 5.1% larger than the smallest (Kinnickinnic, 19.6 mm), and Menomonee's mean duration (30.3 days) is just 4.5% longer than that of Kinnickinnic (29.0 days). The variabilities are much larger for maximum deficit and duration.

Streamflow drought characteristics show larger variabilities between the catchments than precipitation drought characteristics (Table 2 bottom panel). The mean deficit volume is the largest in Kinnickinnic with 7.0 mm and smallest in Cedarburg with 5.7 mm, and the former is about 23% larger than the latter. When compared to the respective mean annual runoff, the order is reversed. The mean deficit is 1.5% of mean annual runoff in Kinnickinnic and 2.2% in Cedarburg, with Menomonee in the middle. The more urbanized catchments have larger deficits relative to the mean annual runoff. The maximum deficit is the largest in Cedarburg (50.4 mm) and smallest in Kinnickinnic (30.9 mm). When it comes to durations, both mean and maximum durations were the longest in Cedarburg (48.5 days and 240.0 days, respectively) and shorted in Kinnickinnic (32.3 days and 100.0 days, respectively). In summary, more urbanized catchments show shorter durations and smaller deficit relative to the mean annual runoff.

2) Timing of drought onsets

The month when the drought event commenced varied considerably between the catchments (Figure 3). In Cedarburg, April, February, and September were the months when streamflow drought commenced most frequently. In Menomonee, it commenced most frequently in October, followed by August. In Kinnickinnic, December, September, and October were the

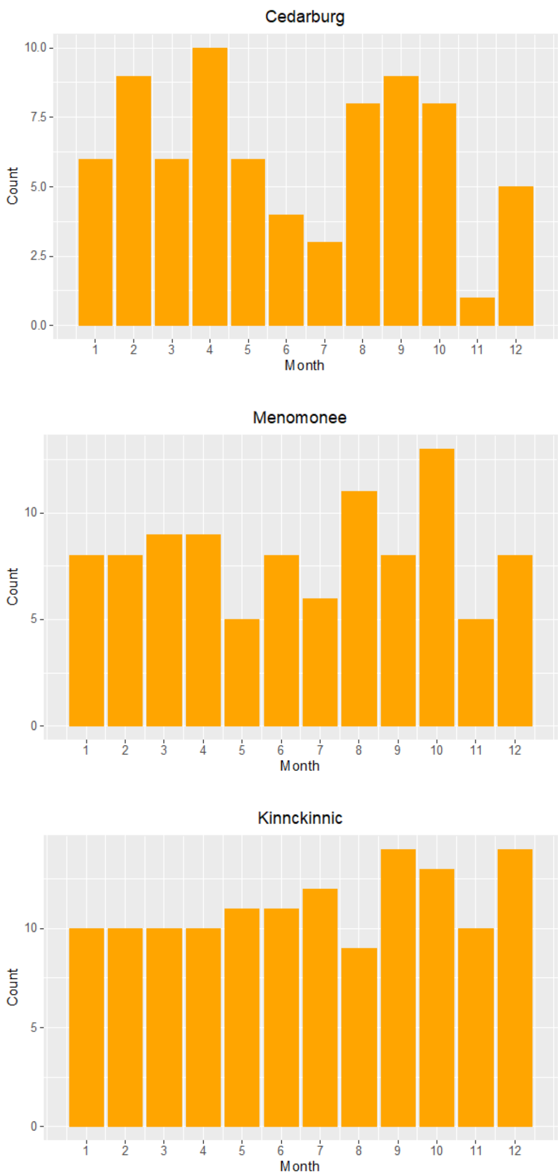

Figure 3. Counts of streamflow drought events that started in each month.

months when streamflow drought started most frequently. Cedarburg shows the largest range of counts between the months, from 10 in April to 1 in November, whereas Kinnickinnic shows the smallest range. In Kinnickinnic, streamflow drought began to occur practically in any month of the year. The graphs suggest that the onset timing is evener in more urbanized catchments.

3) Trends of streamflow drought characteristics

The occurrence of drought over time shows different trends between precipitation and streamflow droughts and between the catchments for streamflow drought (Figure 4). Precipitation drought was more severe in the first half of the period, particularly in 1988 (Figure 4a) when a large swath of the U.S. suffered from drought (Shelton, 2009). Drought events with deficit larger than 50 mm occurred five times before 2005 but only once thereafter. However, the trend for the annual total precipitation drought deficit was found to be statistically insignificant (p = 0.21) according to the Mann-Kendall test.

The largest precipitation drought deficit in 1988 did not translate to the largest streamflow

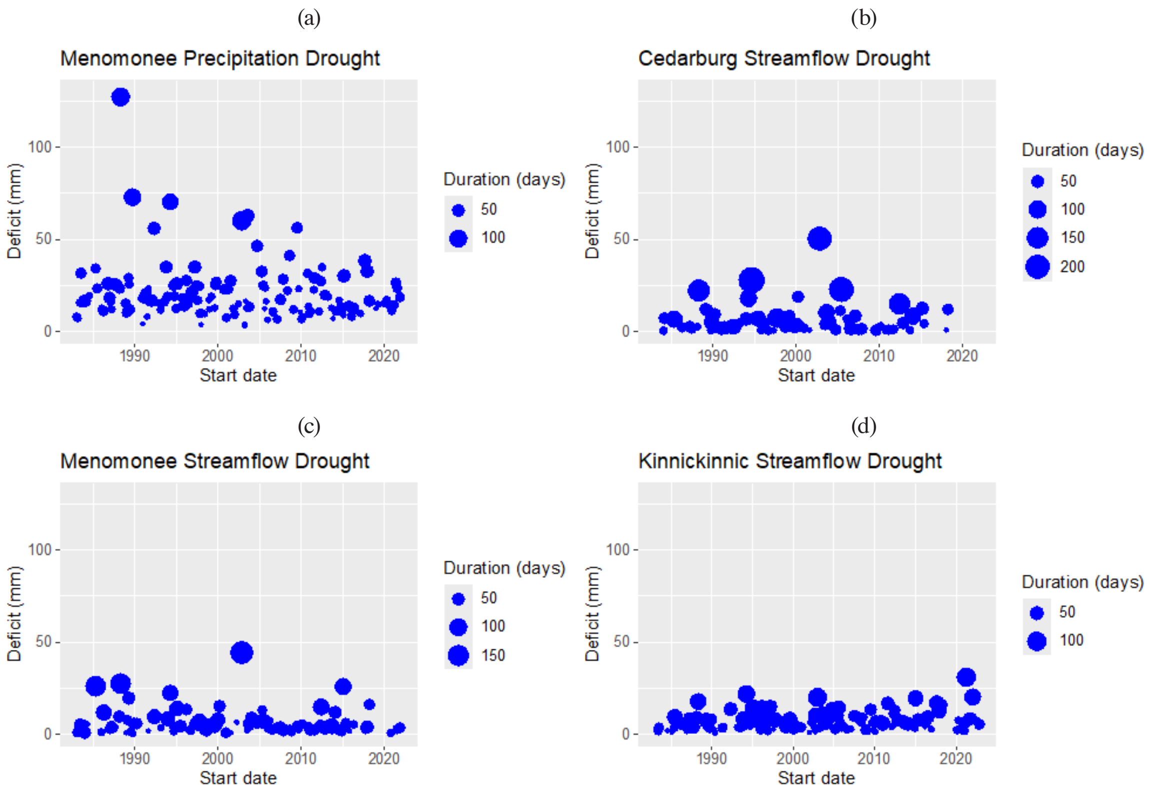

Figure 4. Deficit volume of each drought event over time. Each circle in the chart represents a drought event after pooling close events and discarding minor ones, and the size of the circle is proportional to the duration. (a) Precipitation drought in Menomonee (only Menomonee is shown because the others are very similar), (b)-(d) streamflow drought in Cedarburg, Menomonee, and Kinnickinnic, respectively.

drought deficit in the same or following year (Figure 4b-d). The largest streamflow drought deficit occurred in 2002 (Cedarburg and Menomonee) or 2021 (Kinnickinnic). The graphs suggest that streamflow drought relatively subsided after 2002 in Cedarburg and Menomonee whereas that is not the case for Kinnickinnic. The annual total deficit shows no statistically significant trend for Cedarburg or Menomonee, but a significantly increasing trend ($p = 0.039$) for Kinnickinnic. When it comes to the number of events, Kinnickinnic has the most, followed by Menomonee and Cedarburg.

A detailed examination of drought events during 2011-2013 reveals a very similar picture for precipitation droughts and some differences in streamflow droughts between the catchments (Figure 5). In 2012, the precipitation drought did not stand out compared to other years, but the streamflow drought was significant (Figure 4). In this year, a wide swath of the U.S. Midwest and Great Plains experienced drought in the summer, which was investigated as a flash drought (Hoerling *et al.*, 2014; Pendergrass *et al.*, 2020). Here I take a close look at the drought in these catchments.

Cedarburg had quite large shortage of precipitation in the middle of 2012, which led to a sustained streamflow drought in the year. After pooling and discarding minor events, an event was identified in the middle of the year that lasted for 148 days with the deficit volume of 15 mm. Streamflow drought was minute in 2011 when the precipitation shortage was moderate. Menomonee also had a substantial streamflow drought in 2012 but with somewhat different

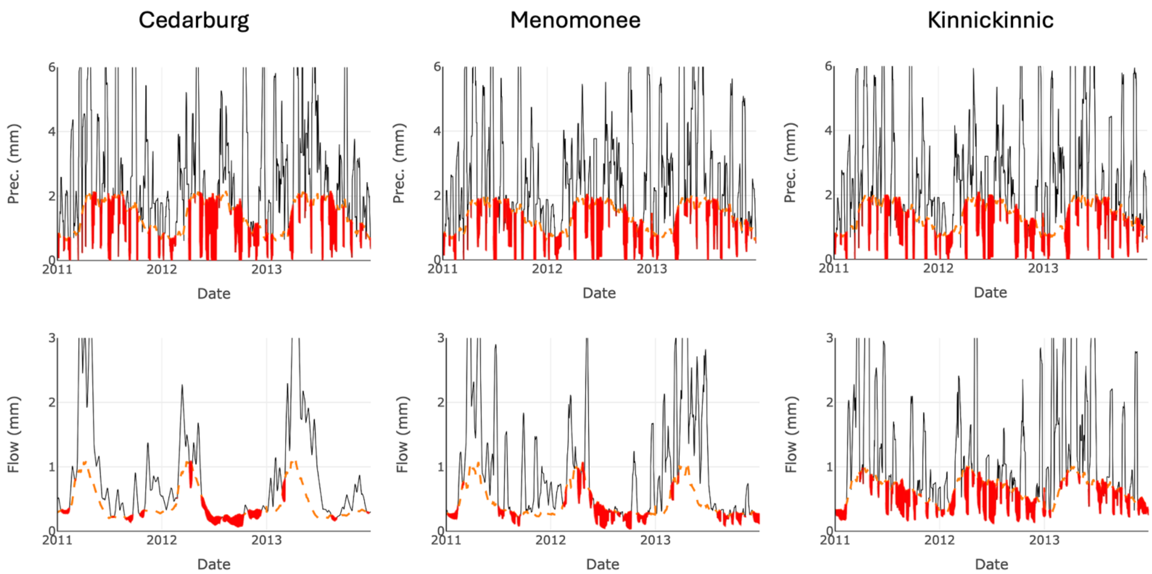

Figure 5. Precipitation (top row) and streamflow (bottom row) drought events in the three catchments during 2011-2013 before pooling close events and discarding minor ones. Solid lines indicate smoothed precipitation or streamflow and dashed lines threshold levels. When the solid line is below the dashed line, the area is filled and indicates a drought event.

deficits and durations from Cedarburg. The most significant event in the year lasted for 88 days with a deficit volume of 14.8 mm. Here it is noted that Menomonee's streamflow is somewhat more variable than Cedarburg. Menomonee also had quite small deficits and short durations of streamflow drought in 2011. Kinnickinnic shows the most striking picture. Its daily streamflow fluctuates to a much larger degree than the others, and its drought threshold is higher than the others due to its larger mean annual runoff, particularly during summer. The combination of larger streamflow variability and higher threshold makes the streamflow more likely to fall below the threshold. In 2012, the longest event lasted for 43 days (with a deficit of 7.8 mm), and the largest deficit was 13.1 mm (with a duration of 29 days). Kinnickinnic also experienced a significant streamflow drought in the summer of 2011 unlike the others.

4. Discussion

This study examined the characteristics of streamflow drought in the three catchments of the Milwaukee River basin against precipitation drought and the extent of urban land covers. It was found that he mean duration and deficit volume clearly covary with the extent of urban land cover. More urbanized catchments had shorter mean durations, and combined with the number of events, they have more frequent drought events with shorter durations than less urbanized catchments. The mean deficit volume was larger in more urbanized catchments, but when divided by mean annual runoff, it was smaller in more urbanized catchments. The relationship between the drought characteristics and the extent of urban land cover appears to be largely due to the streamflow magnitude and variability. First, when the streamflow is high, the threshold level is also high as it is determined by the percentile. When the threshold level is high, streamflow deviation from the threshold can be large, leading to large deficits. Second, the more variable the streamflow is, the more frequently it can fall below the threshold. Therefore, drought can have shorter durations and more frequency. The magnitude and variability of streamflow are exceptionally large in the Kinnickinnic catchment.

The Kinnickinnic River catchment is highly urbanized, and the channel was also highly modified. Some segments of the river were lined with concrete in the early 1960s as a way to address flooding (https://storymaps.arcgis.com/stories/340848cb046a449694059830d396c0f0). However, Milwaukee Metropolitan Sewerage District, in partnership with other entities, began to remove concrete and replace with a natural stream design in some segments of the river in the late 2000s. The project is in different stages in different segments of the river but is complete only in a small segment (https://storymaps.arcgis.com/stories/340848cb046a449694059830d396c0f0). Considering the data period 1983-2022, it is hard to think that the project has had any meaningful impact on the streamflow characteristics. It remains to be seen whether the magnitude and variability of streamflow will decrease in the future as the project continues.

As expected, precipitation drought did not vary with respect to the extent of urban land covers. Even though cities are known to affect precipitation (Liu and Niyogi, 2019) and it is empirically found in Milwaukee area (Keuser, 2014), the effects did not translate into drought characteristics at this scale. Overall, there is good synchrony between precipitation and streamflow droughts, but the degree of synchrony varies by catchment and time. The general trend of streamflow drought (Figure 4) does not much resemble that of precipitation drought, suggesting decreasing synchrony between the two drought types. Generally decreasing synchrony between the two types in Wisconsin is already known (Choi *et al.*, 2022), and this study explicitly shows it for MRB. The cause is elusive and warrants further research. What is clear is that it is necessary to be prepared for streamflow drought when there is not a significant precipitation drought event.

The study has some limitations. First, the sample size is just small. The study was conducted as a follow-up for existing ones, so it is limited to the same study domain which has a very small number of catchments. Therefore, it takes caution to generalize the findings from this study. Second, it was not conducted with a clear framework. There is not previous research that could serve as a framework, and the research was conceived and conducted in an exploratory mode. As there is little research that examined streamflow drought and urban land covers, it is expected that this research contributes to forming such a framework.

5. Conclusions

Even though the effects of urbanization on streamflow have been widely investigated, the effects on streamflow drought are barely known at best. In this study, the characteristics of streamflow drought were examined against those of precipitation drought and the extent of urban land covers for three catchments in the Milwaukee River basin for the period 1983-2022. The findings are summarized as follows: (1) The more urbanized the catchment was, the shorter the mean drought duration was; (2) The more urbanized the catchments was, the smaller the mean drought deficit was relative to the mean annual runoff; and (3) The characteristics of precipitation drought were very similar between the catchments. It should be noted that the most urbanized catchment has the highest threshold level in summer and autumn and the largest variability of streamflow, which led to streamflow fluctuating above and below the threshold frequently. Such streamflow characteristics led to different streamflow drought characteristics while precipitation drought characteristics remained almost identical. Therefore, if urbanization leads to higher and more variable streamflow, streamflow drought characteristics may change like this study. Even though urban land covers are known to exacerbate low flow, it is difficult to tell from this study whether that is the case for streamflow drought. Similar research for other catchments is desired for more general knowledge.

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