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Meteorological and Streamflow Droughts: Characteristics, Trends and Propagation in the Milwaukee River Basin

Woonsup Choi
University of Wisconsin - Milwaukee, choiw@uwm.edu

Hi-Ryong Byun

Claudio Cassardo

Jinmu Choi

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Woonsup Choi, Hi-Ryong Byun, Claudio Cassardo & Jinmu Choi

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Abstract

This study examined meteorological and streamflow droughts for the period 1951-2006 using the Milwaukee River basin in Wisconsin as the study area in an effort to improve the understanding of drought propagation. Specifically, this study aimed to answer the following research questions: (1) What are the temporal trends of meteorological and streamflow droughts identified by drought indicators? (2) How do the drought indicators manifest drought propagation? Meteorological droughts were identified using the Effective Drought Index (EDI), and streamflow droughts were identified using a threshold-level approach. The intensity and duration of both types of drought were found to have decreased over time most likely due to increasing precipitation. Therefore, in the study area, and likely in the larger region, drought has become of less concern. The propagation of meteorological drought into streamflow drought was detected generally after moderate and severe sequences of negative EDI that eventually led to extreme meteorological drought events. The study finds that both EDI and the threshold-level approach are effective in diagnosing meteorological and streamflow drought events of all durations.

Keywords: *drought index, drought propagation, hydrological drought, meteorological drought, runoff*

Droughts are causing alarming concern worldwide as they can cripple agricultural production, reduce the availability of drinking water, and harm ecosystems and wildlife. Syria is a good example of how a drought, combined with other factors, may even contribute to a civil war (Kelley et al. 2015). Due to diverse hydrometeorological variables and socioeconomic factors involved, there are a multitude of drought definitions (Mishra and Singh 2010). Meteorological droughts are defined in terms of the magnitude and duration of a precipitation shortfall (AMS 2013), and they can develop into other types of droughts as the precipitation shortage propagates through the hydrological system, such as soil moisture, streamflow, and groundwater (Feyen and Dankers 2009, Mishra and Singh 2010, Van Loon 2015). Deficits of soil moisture and surface/subsurface water against the seasonal normal are known as agricultural and hydrological droughts, respectively (Van Loon 2015). Meteorological droughts begin with anomalous atmospheric conditions, but the ensuing development of soil moisture and hydrological droughts also depends on terrestrial conditions such as land cover, water storage, and runoff pathways (Van Loon 2015). Identification of the relationship between meteorological and hydrological droughts is a relatively recent research agenda (Van Loon 2015), and it has the potential to be helpful for hydrological drought monitoring and early warning (Zhao et al. 2014). Because the propagation of meteorological drought to hydrological drought depends on terrestrial conditions, such research tends to be location-specific.

Drought indicators are used to quantify the magnitude and duration of drought events. Numerous indicators (>100 according to Lloyd-Hughes (2014)) have been proposed for different types of drought and require different variables to calculate. For meteorological drought, popular indicators include the Palmer Drought Severity Index

(PDSI), the Standardized Precipitation Index (SPI) and its variants, and the Effective Drought Index (EDI) among others (for details, see Shelton 2009). Such drought indices measure departure from the mean in standardized forms, and the index values are classified for different levels of drought intensity. For hydrological drought, the threshold-level approach (originally proposed by Yevyevich (1967)) and the Standardized Runoff Index, a standardized index like SPI, are widely used. In the threshold-level approach, the variable of interest is considered to be in a drought condition when it falls below the predetermined threshold. Because the magnitude and duration of drought events are defined based on drought indicators, examining drought propagation involves using such indicators. For example, indicators for meteorological and hydrological droughts are correlated at different time scales such as one month, three months, six months, etc. (e.g. Liu et al. 2012, Lorenzo-Lacruz et al. 2013, Rahiz and New 2014, Zeng et al. 2015, Barker et al. 2016, Zhao, Wu, and Fang 2016). Because droughts develop slowly, monthly scales can be sufficient; however, droughts can terminate abruptly with a large rainfall event or last for a short period, which can be difficult to detect with monthly-scale indices (Byun et al. 2008). Therefore, it is necessary to examine drought at finer scales using indicators that work at such scales. In addition, we find it necessary to examine how often and how soon individual meteorological drought events lead to streamflow drought events. Once a meteorological drought begins, questions may arise regarding whether and when a streamflow drought will begin.

When it comes to the location of drought, those occurring in California or the Great Plains receive much of the attention of the research community in the United States. However, the Midwest's agricultural and industrial activities are also highly influenced by drought. For example, corn and soybean yields in some Midwestern states show increasing sensitivity to drought (Lobell et al. 2014).

In this study, we selected a river basin in a Midwestern state to analyze both meteorological and streamflow droughts to examine the following research questions: (1) What are temporal trends of meteorological and streamflow droughts identified by drought indicators? (2) How do drought indicators manifest drought propagation? We diagnosed meteorological and streamflow droughts using daily-scale drought indicators for a 56-year period and examined precipitation and the indicators of meteorological and streamflow droughts in detail for a two-year period when both strong meteorological and streamflow droughts occurred. Our findings reveal the general trend of drought for the region, shed light on drought propagation, and provide a gauge of the usefulness of the selected methods for diagnosing drought.

Study area

The Milwaukee River basin (Fig 1; US Geological Survey Hydrological Unit Code 04040003) was selected mainly due to the lengthy streamflow record and its importance as a habitat for a wide range of plants and animals (http://dnr.wi.gov/water/basin/milw/, last accessed 17 November 2016). The Milwaukee River basin has an area of approximately 2330 km^2 and a population of about 1 million. It is nested in the Lake Michigan basin. The topography of the basin consists of rolling moraine over bedrock, sloping downward mostly from northwest to southeast, and the elevation ranges from 177 to 415 m above sea level (Wisconsin Department of Natural Resources 2001). The basin has three major rivers, namely Milwaukee, Menomonee, and Kinnickinnic, which merge just before the outlet of the basin.

The Milwaukee River basin is divided into six catchments by the Wisconsin Department of Natural Resources: Cedar Creek, East and West Branches Milwaukee River, Kinnickinnic River, Menomonee River, Milwaukee River South, and North Branch Milwaukee River (http://dnr.wi.gov/water/basin/milw/, last accessed 23 December 2015; Fig 1). The Milwaukee River and its tributaries drain four catchments (Cedar Creek, East and West Branches, Milwaukee South, and North Branch). Regarding land cover, Kinnickinnic and Menomonee are most urbanized followed by Milwaukee South, and the remaining three catchments have mostly non-urban land covers (Choi et al. 2016). Kinnickinnic receives the most annual precipitation (Table 1) with 841 mm, followed by North Branch (818 mm). Precipitation for other catchments is quite similar to that for North Branch. Given the large interannual variability and the similar rainfall in the six catchments, the catchments do not have significantly different annual precipitation.

The study region has warm, humid summers and cold winters (Fig 2). Precipitation is large from April to September, exceeding 70 mm/month. Mean monthly temperature exceeds 20°C in July and August and falls to –4°C or lower in December, January, and February.

Meteorological drought determination

Of the popular indicators for meteorological drought mentioned previously, we chose EDI for this study. PDSI is complex to calculate and requires insufficiently measured variables (e.g., evaporation). SPI requires only precipitation, but measures the departure of precipitation for different accumulation periods (e.g., 3-month, 6-month, etc.). Therefore, if a three-month accumulation period is selected (i.e., SPI-3), SPI-3 does not account for precipitation that occurred more than three months before present. Consequently, it is possible that SPI-3 indicates a drought whereas SPI-4 does not. Unlike PDSI and SPI, EDI explicitly takes the time of precipitation into account, giving more weight to more recent precipitation than to earlier precipitation. EDI works at the daily scale and requires only precipitation.

EDI was calculated using the following equations (Byun and Wilhite 1999):

$$EP_i = \left[\frac{(\sum_{m=1}^{n} P_m)}{n}\right] \quad \text{(Equation 1)}$$

$$DEP = EP - MEP \quad \text{(Equation 2)}$$

$$EDI = \frac{DEP}{ST(DEP)} \quad \text{(Equation 3)}$$

where P_m is the precipitation for m days before a particular date, n is a dummy index denoting the duration of preceding period, and i is the duration of aggregate precipitation. MEP is the mean of the EP over a 30-year period for the calendar day, and DEP is the deviation from EP, showing the deficiency or surplus of water resources for the date. EDI is computed by dividing DEP by the standard deviation of DEP.

Here i = 365 is used first, meaning effective precipitation is calculated considering precipitation over a year's period. As a result, EP_{365}, which is the effective precipitation over the last 365 days from the date, is given by:

$$P_1 + \frac{P_1 + P_2}{2} + \frac{P_1 + P_2 + P_3}{3} + \ldots + \frac{P_1 + \ldots + P_{365}}{365} \qquad \text{(Equation 4)}$$

where the denominator of each term corresponds to n. It indicates the aggregate precipitation over a year discounted by time, based on the premise that precipitation in the near past is more important than that in the distant past to understanding conditions in current water resources.

If DEP is negative (or positive) for k consecutive days, i changes to i_2 that is 365 + k – 1, and with i_2, EP, DEP, and MEP are recalculated. Whenever DEP changes between negative and positive, i_2 returns to 365. The resulting negative EDI values express the standardized deficiency, and positive values express the standardized surplus of water resources stored over many years, respectively.

This study used a daily historical gridded precipitation dataset covering the whole of Wisconsin. It was produced by spatially interpolating weather-station data across the state and available for 1950-2006 with 8-km grid spacing (Serbin and Kucharik 2009). As shown in Fig 1, each catchment contains several grid points, thus the spatial resolution of the data is deemed adequate for the analysis. The grid points falling in the Milwaukee River basin were selected, and the precipitation data were spatially averaged for each of the six catchments to calculate EDI. Therefore, the study did not take full advantage of the high spatial resolution of the precipitation data. Precipitation was averaged for each catchment in part because the spatial variability of precipitation was not large and in part because the study focused on the correspondence between meteorological and streamflow droughts. Wet and dry days were similar among the grid points for each catchment, therefore averaging did not significantly influence the wet-dry sequences. Total annual precipitation averaged for each catchment is presented in Table 1. The first year's data cannot produce the same year's EDI, thus EDI was calculated for the years 1951-2006.

Examples of meteorological droughts identified by EDI are shown in Fig 3a for a hypothetical year. In the graph, days with positive EDI are wet periods and those below zero are dry periods. A sequence of days with negative EDI is considered a drought event, and its intensity is determined by the minimum EDI value during that period. Drought intensity was classified (e.g. moderate, severe, and extreme) according to Oh, Byun, and Kim (2014) as shown in Table 2. In Fig 3a, a moderate drought (minimum EDI above −1.5 and below −0.7) began approximately on Day 5 and ended approximately on Day 70 when EDI turned positive. Another moderate drought occurred approximately from Day 130 to Day 165. An extreme drought event (minimum EDI below −2.5) commenced on approximately Day 180 and continued to the next year.

We also examined the temporal trends of annual minimum EDI because the intensity of meteorological drought is classified based on the minimum EDI value of the event. The monotonic trend was analyzed using the Mann-Kendall test for trend, and the periodicity was examined using spectral analysis. The spectral analysis was performed using the function spec.pcgram (https://stat.ethz.ch/R-manual/R-devel/library/stats/html/spec.pgram.html) of R software, which calculates the periodogram using a fast Fourier transform. To avoid a misinterpretation of the spectra results, the data were initially detrended series by series.

Streamflow drought determination

We employed the threshold-level approach for streamflow drought. As mentioned before, it was widely adopted for hydrological drought research, particularly for drought propagation (Vrochidou et al. 2013). For the streamflow time-series $x(t)$, the deficit volume (D) below the threshold for a particular drought is calculated as

$$D = \int_{t_b}^{t_e} \left(T - x(t)\right) dt \quad \text{(Equation 5)}$$

where T is an appropriate threshold level, and t_b and t_e are the start and end date of the drought; thus, drought duration (in days) can be defined as $L = t_e - t_b$. In accordance with previous studies (e.g. Wong et al. 2011, Van Lanen et al. 2013), we selected the 20th percentile (the value exceeded 80% of the time) of the streamflow data as the threshold, T.

Streamflow droughts were determined using the observed streamflow data at the Milwaukee River U.S. Geological Survey (USGS) site (Fig 1). It became operational in 1914 and is located close to the outlet of the Milwaukee South catchment. Therefore, the discharge from Cedar Creek, East and West Branches, and North Branch is part of the streamflow measured here. We analyzed the streamflow data for 1951-2006 to match the EDI data and used 30-day moving means to smooth the daily streamflow data. We also converted the unit of the streamflow data from cubic feet per second to millimeters to express streamflow as depth over the entire catchment. The Menomonee River site became operational since the 1960s, so its data were used as auxiliaries. Other UGSG sites within the basin were not used in this study because their records are much shorter than the precipitation data. If the study was extended to a larger area, it would be conducted for selected river basins scattered over the region because of the wide range of lengths of operation of streamflow measurement sites.

We determined the 20th percentile streamflow values for each calendar day (from 1 January to 31 December, excluding 29 February) of the data period, which resulted in a time series of 365 entries. Then we calculated 30-day moving means to smooth the threshold line. The 20th percentile was applied to the daily streamflow series to determine streamflow deficit. Continuous days with below-threshold streamflow constitute a drought event. Drought events lasting three days or less were ignored as in other studies (e.g. Vrochidou et al. 2013). When there is a short non-drought period between two drought events, the two drought events are considered mutually dependent droughts (Fleig et al. 2006). In this study, mutually dependent droughts were pooled when the non-drought period between them was shorter than three days. Means of deficit values for the preceding and following days of the non-drought days were assigned to the non-drought days.

An example of streamflow drought is illustrated in Fig 3b for the same hypothetical year as the meteorological drought examples. Three events are easily visible, and they commenced on approximately Day 145, Day 195, and Day 268. The last event continued to the following year. The solid area below the streamflow line for each event is considered as cumulative deficit of the event.

Results and Discussion

Trend of annual minimum EDI

Annual minimum EDI showed an increasing trend (Fig 4) for the six catchments ($p < 0.01$). There is only one year with minimum EDI above −0.7 (threshold between normal and moderate drought) before 1980, but several thereafter. The graph also demonstrates the periodicity of annual minimum EDI to some extent. A few years of increase are followed by a few years of decrease. Troughs were found at most catchments with intervals ranging from 2 to 8 years. The EDI calculated from precipitation data measured at the Milwaukee Airport weather station showed a trough in 2012 (not shown), seven years after the trough in 2005. When it comes to minimum EDI below −2.5 (threshold between severe and extreme drought), troughs were found for the years 1958, 1964, 1967, 1970, 1977, 1988, and 1992 for most catchments.

Some discrepancies were also found in the graph between the catchments. Kinnickinnic, which is the most urbanized basin and also receives the largest amount of precipitation, tended to diverge from other catchments several times. For example, its minimum EDI was much higher than the others in 1955, 1977, and 1996 and much lower in 1964, 1997, and 2003. The catchments diverged from each other to a large extent in the years 1964, 1996, 1998, and 2003. Such results suggest a need for more investigation of the spatial variability of drought, even for a mid-size basin with simple topography.

The significant periodicity, emerging in all six catchments, was the one of 6.67 years, but also periodicities of 4.62 years and 3 years were found in five and four catchments, respectively. An example is presented in Fig 5 for Cedar Creek. The lowest minima in several series are observed in the years 1958 and 1964 (Fig 4), which are separated by 6 years. In other periods, shorter periodicities (3 and 4.62 years) are also evident, especially in the most recent years. Therefore, the region needs to prepare for severe and extreme meteorological drought events every 4-6 years.

Characteristics of drought events

During 1951-2006, the Milwaukee South catchment had 9 and 21 meteorological drought events (Table 3) classified as extreme and severe, respectively (see Table 2 for classification). More intense droughts tended to occur less frequently and with longer durations. The duration was as short as seven days and many events lasted for less than a month. It indicates the usefulness of EDI in diagnosing both short- and long-duration droughts. The total number of events was 95 (1.7 per annum). According to the classification scheme used for this study, meteorological drought is a phenomenon occurring more than once a year on average. The average frequency of 1.7 per annum is slightly higher than previous studies that used EDI for different regions. For example, Lee et al. (2014) report 75 events for South Korea during 1952-2007 (1.34 per annum), and Oh et al. (2014) report 29-50 events for different subregions of East Asia during 1962-2004 (0.7-1.2 per annum). Having more than one drought event per annum sounds incompatible with the general perception that droughts occur every once in a while. We doubt that the moderate drought events identified in this study would be recognized as drought by the general public. The results suggest that only extreme and severe events deserve to be recognized as drought in the study area.

Six of the nine meteorological drought events classified as extreme for the Milwaukee South catchment occurred before 1970 (Table 4). The 1950s and 1960s had three events each, and the 1990s had none. All the extreme drought events lasted at least four months, and the one that began in 1962 lasted for nearly two years. Except for the one that began in November 1967, all the events commenced in spring or summer months. The extreme drought events tended to terminate in late spring and summer when precipitation was generally abundant.

The duration and intensity of streamflow drought generally decreased over time (Fig 6). Here intensity is represented by the deficit below the threshold (in mm) which indicates the depth of water evenly spread over the basin, not just the river. Each bar in the graph represents an individual event sorted by time. Upward bars indicate duration and downward bars deficit of the event. There were 58 events during 1951-2006 (~1 per annum). When averaged, it looks as if drought occurred almost every year, but the occurrences are unevenly distributed (see Fig 7). Fig 7 suggests that even after pooling of mutually dependent droughts, some events still were counted separately. We found a median duration of 17 days, a median deficit of 0.37 mm, and a strong correlation between the deficit and the duration ($r < -0.7$; $p < 0.05$). The results are similar for the Menomonee River site (not shown). Its median duration was 22 days and median deficit was 2.25 mm. The Menomonee catchment is much more urbanized than the Milwaukee and its upstream catchments, and their streamflow characteristics appear to manifest it.

The frequency of streamflow drought events (~1 per annum) is quite comparable to previous studies that used the threshold approach. For example, Vrochidou et al. (2013) report 23 streamflow drought events during 1974-1999 (0.88 per annum) for a Greek basin using the 20th percentile threshold, and Liu et al. (2016) report 27 events using the 30th-percentile monthly threshold during 1980-2009 for a northern Chinese basin (0.9 per annum). Because streamflow drought was defined using pre-determined thresholds, drought-like conditions, regardless of duration or severity, may have been left uncounted. This limitation applies to virtually all studies diagnosing drought quantitatively, and we are not aware of any reasonable alternatives.

Drought time series

Meteorological droughts appeared to be quite common and severe in the 1950s and 1960s and much less so in the 1980s and 1990s (Fig 8). Droughts somewhat rebounded in the 2000s, with multiple events with minimum EDI values below −1.5 during 2000-2006. Similar trends are reported for nearby states of Illinois and Indiana (Mishra, Cherkauer, and Shukla 2010), suggesting a regional-scale phenomenon. Annual total precipitation increased in the Milwaukee area during the time with varying degrees and levels of confidence (Kucharik et al. 2010, Keuser 2014, Choi et al. 2016), to which the meteorological drought trend is attributable. An abrupt termination of drought was also found in the graph in the middle of September 1961. An exceptionally large rainfall event (>120 mm during 15-17 September) helped abruptly push the EDI value above zero. This would not have been detected with monthly-scale indices such as SPI or PSDI. Similar results were found for Menomonee (not shown).

Streamflow droughts were much less frequently observed after the 1970s (Fig 7). Only three events were observed during the 1980s, two during the 1990s, and slightly more in the 2000s, reflecting the meteorological droughts. The reduced occurrence of streamflow droughts since the 1970s is also found in another study for several Midwestern states, and such changes suggest that the long term (decadal or longer) process in the atmospheric general circulation somewhat changed after the 1970s (Changnon 1996). It should be noted that the Milwaukee River basin was not included in that study, and streamflow drought was determined differently from this study. Compared with the EDI time series (Fig 8), the streamflow deficit time series appeared to hide many minor events that did not exceed the threshold. During the 1980s and 1990s, several severe meteorological drought events were identified, but very few streamflow drought events were identified according to the 20th percentile threshold. This is due to the inherent difference between a standardized-index approach like EDI and a threshold approach. If streamflow remained quite low for a while but above the threshold, it would not count as a drought event. On the other hand, a meteorological drought consists of any sequence of days with negative daily EDI values with the minimum lower than –0.7.

Comparison of the extreme meteorological drought events listed in Table 4 with the streamflow deficit time series in Fig 7 provides a picture of correspondence between meteorological and streamflow droughts. Most of the events listed in Table 4 correspond to streamflow drought events in Fig 7 with varying lag times. For example, the extreme meteorological drought for Milwaukee South that commenced on 16 August 1953 is followed by a streamflow drought from 31 August, which lasted for 157 days. The extreme meteorological drought events in 2003 for Milwaukee South were followed by streamflow droughts in late August with a lag of about ten weeks. On the other hand, a fairly significant streamflow drought occurred in the spring of 2003, but it was preceded by a severe, though not extreme, meteorological drought from November 2002 (see Fig 8). Actually, the year 2003 was in a meteorological drought condition for most of the year with only days separating different events (see Fig 8). Despite that, streamflow drought was not remarkable, particuarly in the second half of the year.

The propagation of meteorological drought to streamflow drought for the Milwaukee River USGS site is portrayed in Fig 9 for the years 1976-1977. An unusual statewide agricultural drought occurred in 1976 (Mitchell 1979), and an emergency was declared by Federal Emergency Management Agency on 17 June 1976. During this period, an extreme meteorological drought event commenced and terminated (Table 4). In Fig 9, daily precipitation (top panel) is shown with mean daily precipitation during the record period. Precipitation was generally below the average from late May of 1976 through February of 1977 and was quite abundant in 1977. After briefly falling below zero in mid-June, EDI remained below zero continuously from late June of 1976 through late July of 1977. A few large rainfall events in the summer of 1976 brought EDI close to but still below zero in August 1976. Precipitation was abundant in April 1977 as well and brought EDI up again, but EDI still remained below zero. EDI began to fluctuate around zero from late July due to the abundant summer precipitation and remained positive for the rest of the year from September 1977. Streamflow drought became evident only in September 1976, whereas EDI was negative from late June. There was a short (lasting six days) streamflow drought in July with a very small deficit. Streamflow drought disappeared in late February 1977 when EDI began to increase. From April to May 1977, streamflow drought was very intense in response to falling EDI. The drought terminated at the beginning of June 1977. Similar results were found for Menomonee (not shown).

The intense streamflow drought in May 1977 contrasted with the longer and less intense event during the winter of 1976-1977. The 20th percentile threshold is much lower in magnitude during the winter than in May. Because winter is a low flow season, the room for streamflow deficit is quite small. In May, much more flow is expected than in January or February. Even though the absolute flow level in May 1977 was larger than that of the winter of 1976-1977, the deficit was much larger, making the drought even more intense. After June 1977, the streamflow drought was no longer observed with increasing streamflow and decreasing threshold.

Conclusions

We examined meteorological and streamflow droughts for the period 1951-2006 for the Milwaukee River basin in Wisconsin in an effort to improve the understanding of drought propagation. Specifically, we aimed to answer the following research questions: (1) What are the temporal trends of meteorological and streamflow droughts identified by drought indicators? (2) How do the drought indicators manifest drought propagation? We employed the Effective Drought Index and the threshold-level approach for diagnosing meteorological and streamflow drought events, respectively. In addition, we examined in detail daily time series of precipitation and drought indicators for a two-year period of 1976-1977 that saw significant drought events.

In conclusion, the magnitude and duration of drought generally decreased during the 56-year period in the study area most likely due to increasing precipitation. Therefore, in the study area and likely in the larger region, drought has become increasingly less of a concern. With respect to the propagation of meteorological drought to streamflow drought, streamflow droughts were detected generally after moderate and severe sequences of below-normal precipitation that eventually led to extreme meteorological drought events. Streamflow was generally responsive to precipitation events but it took sustained precipitation shortage from days to weeks for streamflow drought to manifest itself. Termination of streamflow drought in this approach accompanied large rainfall events. However, the termination of streamflow drought does not mean that water is available at a normal level but rather that water recovery just has commenced.

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Tables

Table 1. Selected information on the six catchments of the Milwaukee River basin. The coordinates are means of the climate data grid points falling in the basin. The mean annual precipitation is for the period 1950-2006 and shown with ± standard deviation of annual total precipitation.

Catchment name	Latitude, longitude (d.d.)	Mean elevation (m.a.s.l.)	Mean annual precipitation (mm)
Milwaukee South	43.236, −87.959	223.0	809±123
Menomonee	43.125, −88.098	241.4	807±127
Kinnickinnic	42.960, −87.889	308.6	841±152
East and West Branches	43.574, −88.223	308.6	803±113
Cedar Creek	43.342, −88.131	281.1	809±120
North Branch	43.569, −88.042	281.2	818±122

Note: d.d. = decimal degrees; m.a.s.l. = meters above sea level

Table 2. Classification of drought intensity by EDI values (Oh, Byun, and Kim 2014)

Effective Drought Index	Classification
2.5 or higher	Extremely wet
Above 1.5 and below 2.5	Severely wet
Above 0.7 and below 1.5	Moderately wet
Above 0 and below 0.7	Weakly wet (normal)
Above −0.7 and 0	Weakly dry (normal)
Above −1.5 and below −0.7	Moderately dry
Above −2.5 and below −1.5	Severely dry
Below −2.5	Extremely dry

Table 3. Summary characteristics of meteorological drought by class for the Milwaukee South catchment

Drought class	Number of events	Duration (days)		
		Maximum	Median	Minimum
Extreme	9	724	260	120
Severe	21	361	157	38
Moderate	65	175	39	13

Table 4. Characteristics of extreme meteorological drought events for the Milwaukee South catchment

Onset date	Duration (days)	Minimum EDI	Date of minimum EDI
1953 August 16	260	-2.85	1954 January 18
1955 July 26	286	-2.58	1956 February 11
1957 June 29	469	-3.44	1958 August 21
1962 April 17	724	-3.66	1964 January 18
1967 July 8	120	-2.6	1967 September 14
1967 November 9	196	-2.65	1968 April 4
1976 June 29	391	-3.19	1977 February 27
1988 May 13	142	-2.54	1988 September 10
2003 May 30	171	-2.57	2003 September 14

Figures

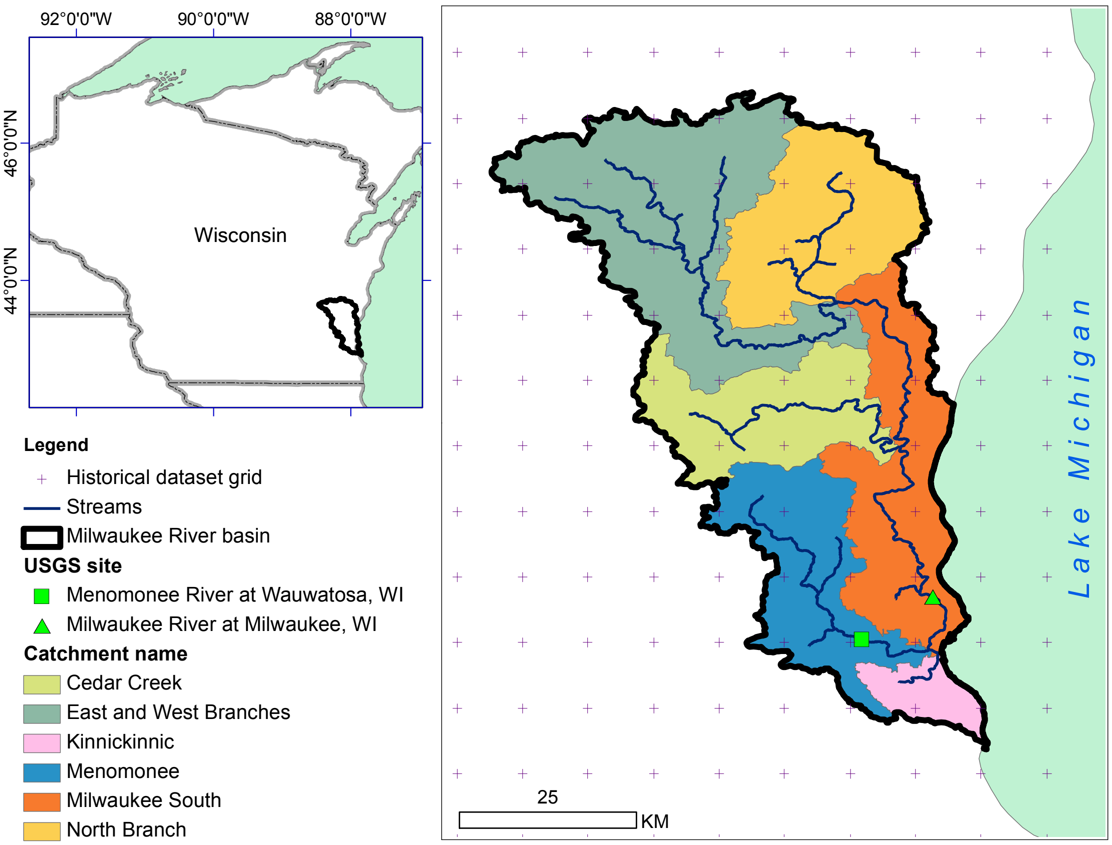


Fig 1 Study area: boundary of the Milwaukee River basin, boundaries of six nested catchments, major streams, grid points of historical precipitation dataset, and the two U.S. Geological Survey (USGS) streamflow measurement sites.

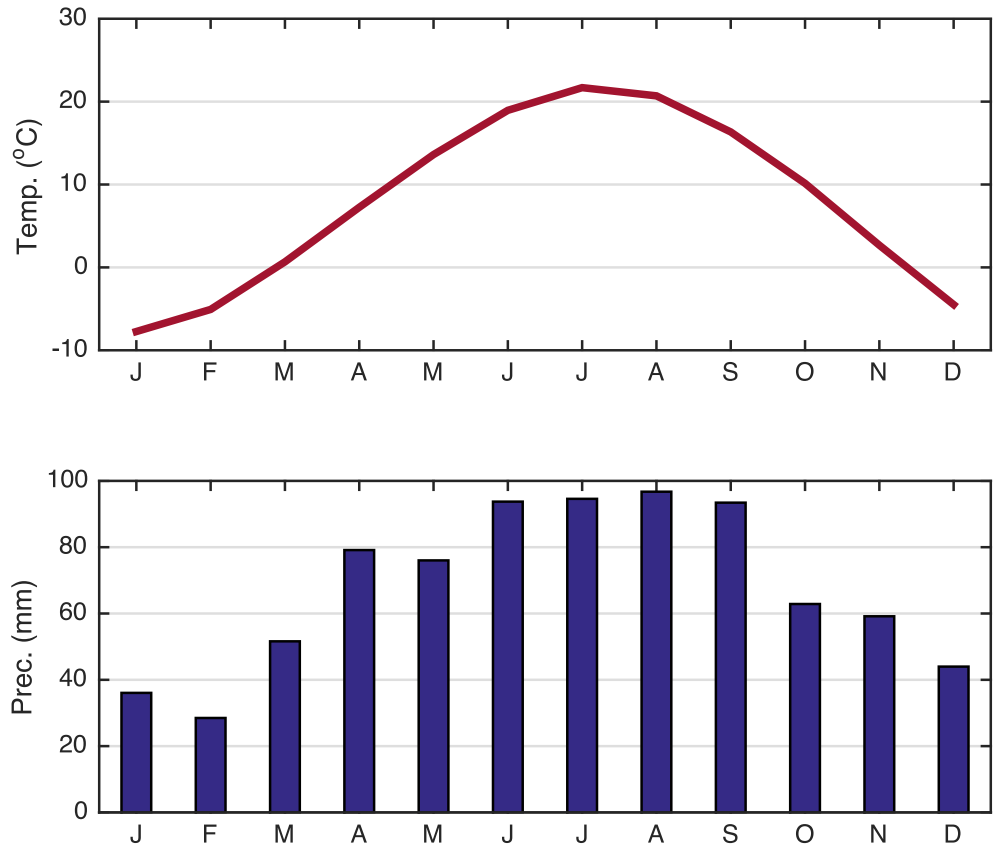


Fig 2 Mean monthly temperature (upper panel) and precipitation (lower panel) for the entire Milwaukee River basin calculated from the historical gridded data (Serbin and Kucharik 2009)

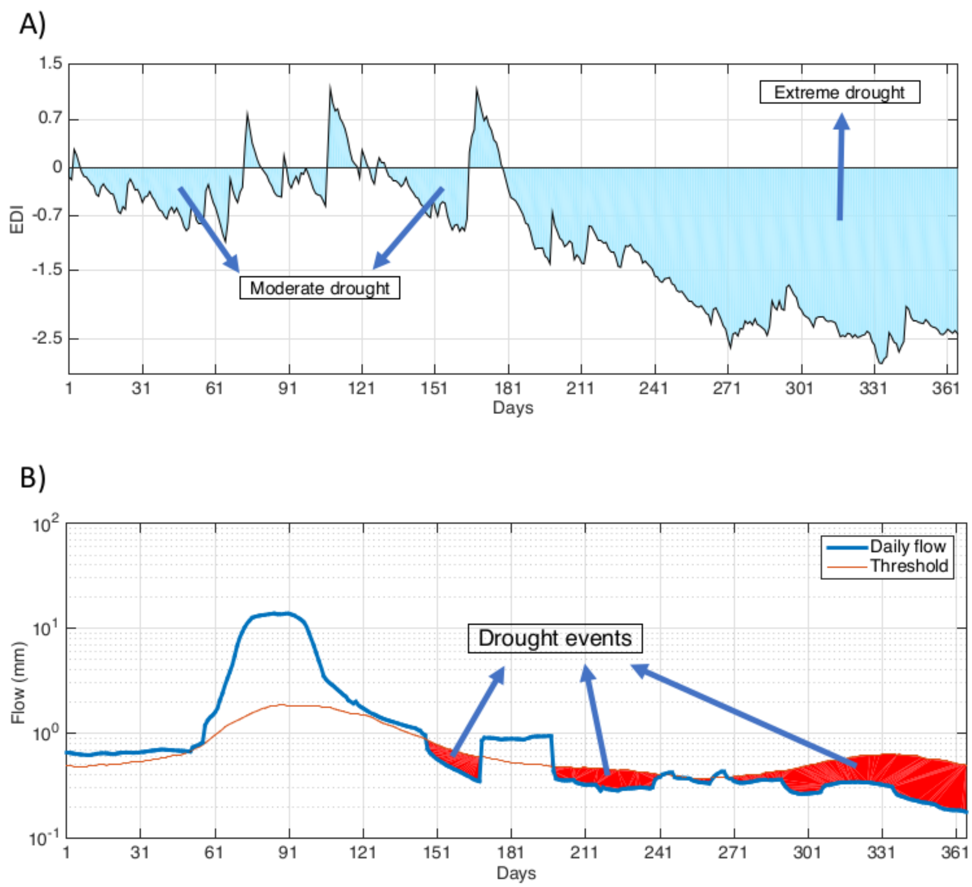


Fig 3 Illustration of meteorological drought events (upper panel) and streamflow drought (lower panel) using drought indicators over a one-year period

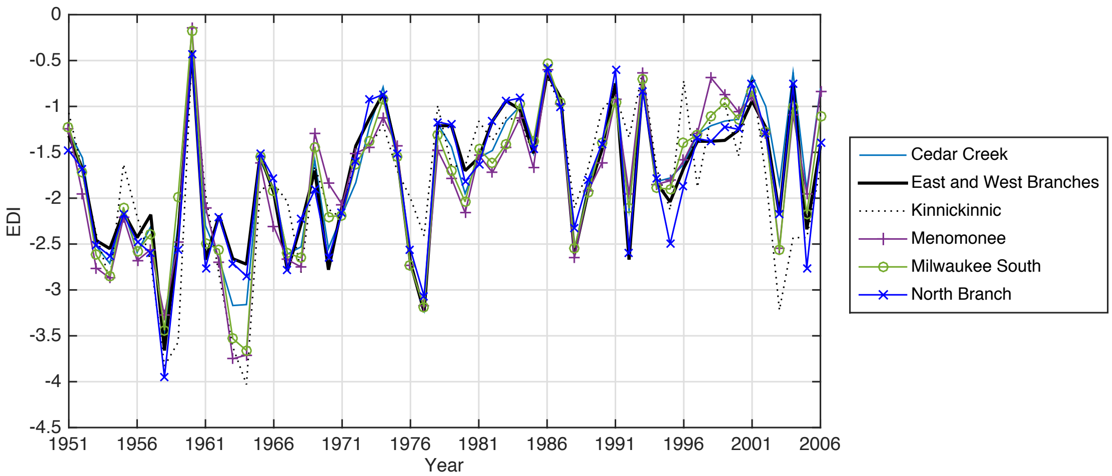
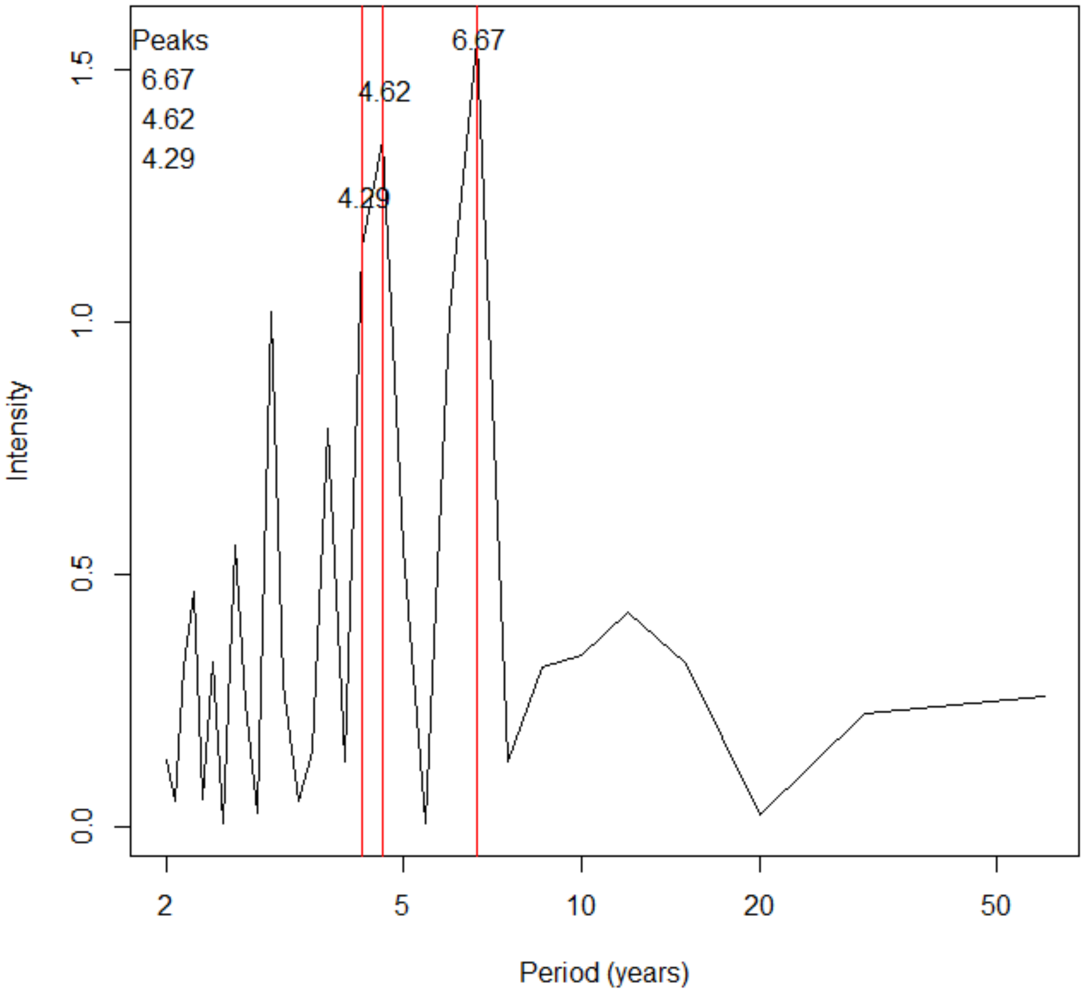


Fig 4 Annual minimum Effective Drought Index series for the six catchments of the Milwaukee River basin



540
541 **Fig 5** Spectral analysis of annual minimum Effective Drought Index calculated for Cedar
542 Creek

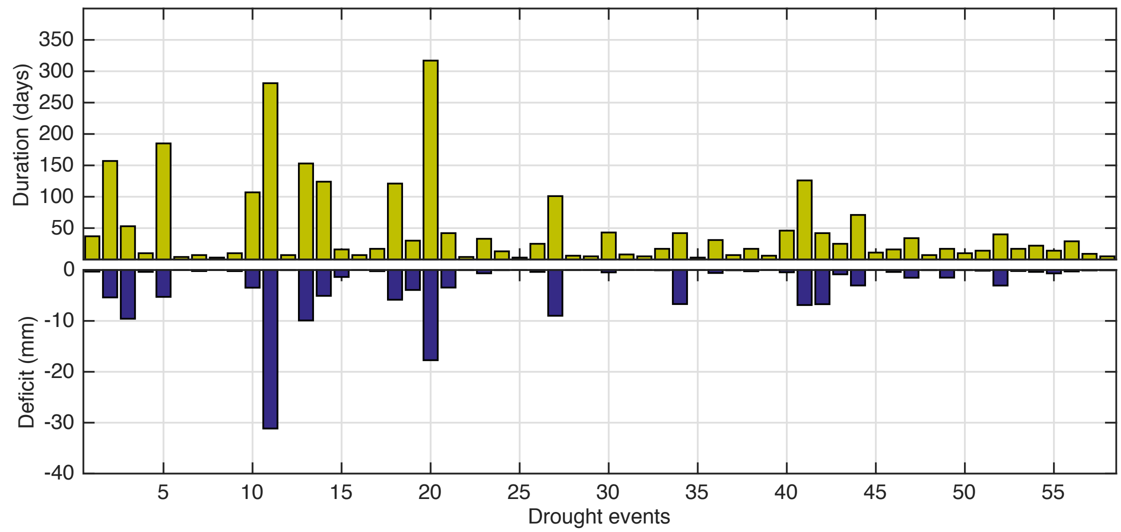
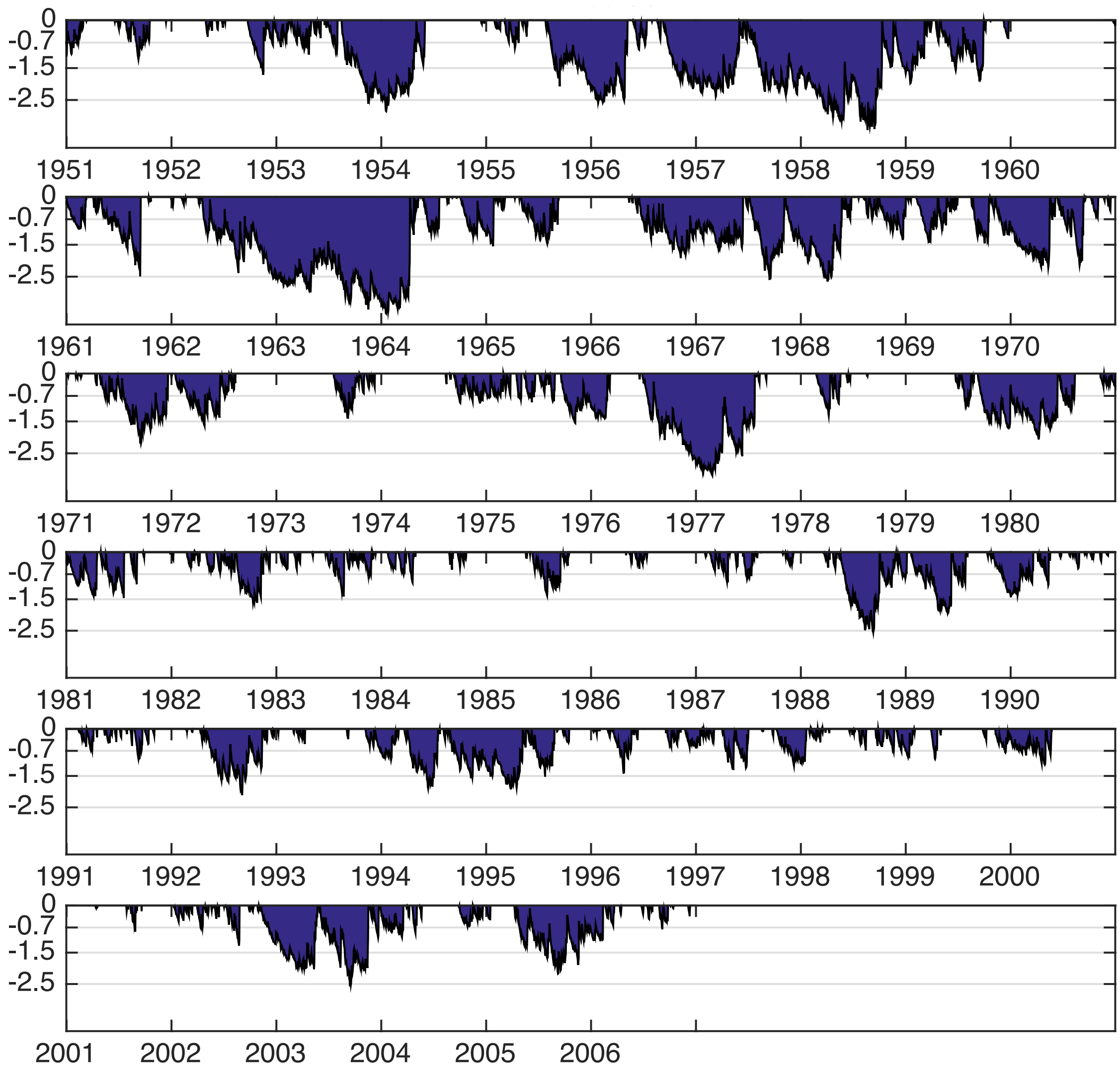


Fig 6 Streamflow drought duration (upper panel) and cumulative deficit (lower panel) for each of the 58 events at Milwaukee during 1951-2006. The x-axis indicates each individual event (1: oldest, 58: most recent)



547
548 **Fig 7** Daily Effective Drought Index for the Milwaukee South catchment

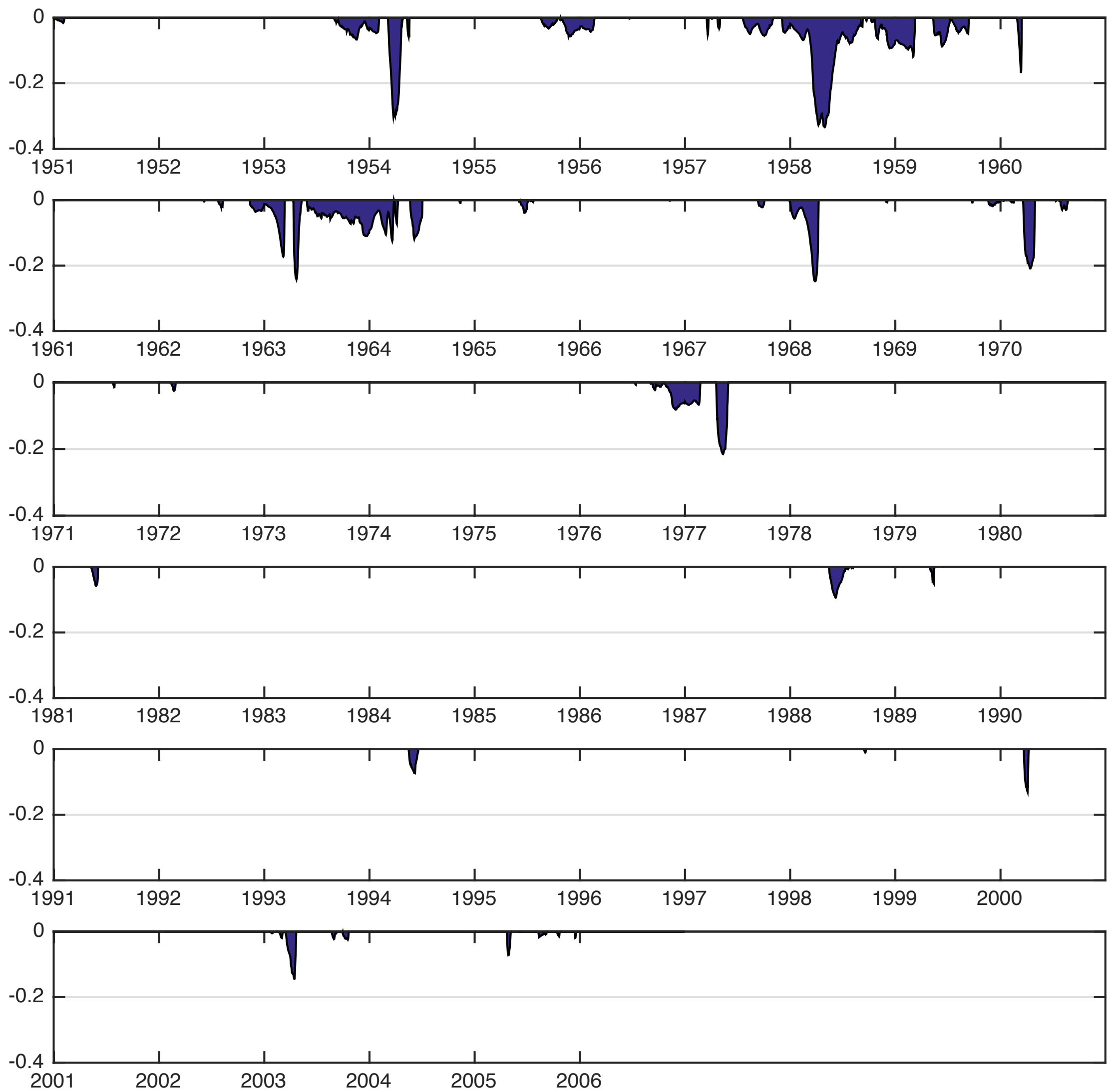


Fig 8 Daily streamflow deficit (mm) for the Milwaukee River streamflow measurement site

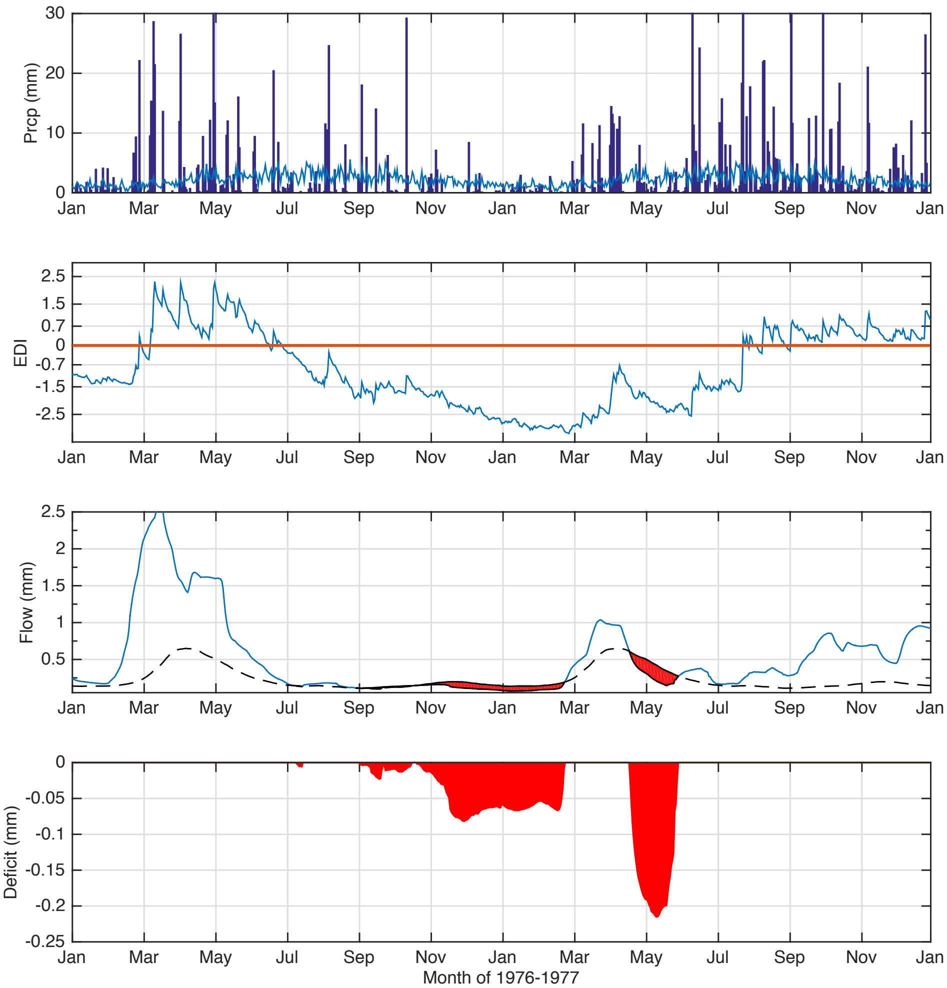


Fig 9 Drought propagation in the Milwaukee River basin for the years 1976-1977. Top panel: daily precipitation during 1976-1977 (bars) and mean daily precipitation for the record period (line). The y-axis is truncated. Second panel: Effective Drought Index. Third panel: smoothed daily streamflow (solid line) and the streamflow drought threshold (dashed line). Bottom panel: streamflow deficit.