

1 Meteorological and Streamflow
2 Droughts: Characteristics, Trends and
3 Propagation in the Milwaukee River
4 Basin

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11

12 **Abstract**

13

14 This study examined meteorological and streamflow droughts for the period 1951-2006
15 using the Milwaukee River basin in Wisconsin as the study area in an effort to improve the
16 understanding of drought propagation. Specifically, this study aimed to answer the
17 following research questions: (1) What are the temporal trends of meteorological and
18 streamflow droughts identified by drought indicators? (2) How do the drought indicators
19 manifest drought propagation? Meteorological droughts were identified using the Effective
20 Drought Index (EDI), and streamflow droughts were identified using a threshold-level
21 approach. The intensity and duration of both types of drought were found to have decreased

22 over time most likely due to increasing precipitation. Therefore, in the study area, and
23 likely in the larger region, drought has become of less concern. The propagation of
24 meteorological drought into streamflow drought was detected generally after moderate and
25 severe sequences of negative EDI that eventually led to extreme meteorological drought
26 events. The study finds that both EDI and the threshold-level approach are effective in
27 diagnosing meteorological and streamflow drought events of all durations.

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

32

33 Droughts are causing alarming concern worldwide as they can cripple agricultural
34 production, reduce the availability of drinking water, and harm ecosystems and wildlife.
35 Syria is a good example of how a drought, combined with other factors, may even
36 contribute to a civil war (Kelley et al. 2015). Due to diverse hydrometeorological variables
37 and socioeconomic factors involved, there are a multitude of drought definitions (Mishra
38 and Singh 2010). Meteorological droughts are defined in terms of the magnitude and
39 duration of a precipitation shortfall (AMS 2013), and they can develop into other types of
40 droughts as the precipitation shortage propagates through the hydrological system, such as
41 soil moisture, streamflow, and groundwater (Feyen and Dankers 2009, Mishra and Singh
42 2010, Van Loon 2015). Deficits of soil moisture and surface/subsurface water against the
43 seasonal normal are known as agricultural and hydrological droughts, respectively (Van
44 Loon 2015). Meteorological droughts begin with anomalous atmospheric conditions, but
45 the ensuing development of soil moisture and hydrological droughts also depends on
46 terrestrial conditions such as land cover, water storage, and runoff pathways (Van Loon
47 2015). Identification of the relationship between meteorological and hydrological droughts
48 is a relatively recent research agenda (Van Loon 2015), and it has the potential to be helpful
49 for hydrological drought monitoring and early warning (Zhao et al. 2014). Because the
50 propagation of meteorological drought to hydrological drought depends on terrestrial
51 conditions, such research tends to be location-specific.

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

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

76 When it comes to the location of drought, those occurring in California or the Great
77 Plains receive much of the attention of the research community in the United States.
78 However, the Midwest's agricultural and industrial activities are also highly influenced by

79 drought. For example, corn and soybean yields in some Midwestern states show increasing
80 sensitivity to drought (Lobell et al. 2014).

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

91 **Study area**

92
93 The Milwaukee River basin (Fig 1; US Geological Survey Hydrological Unit Code
94 04040003) was selected mainly due to the lengthy streamflow record and its importance as
95 a habitat for a wide range of plants and animals (<http://dnr.wi.gov/water/basin/milw/>, last
96 accessed 17 November 2016). The Milwaukee River basin has an area of approximately
97 2330 km² and a population of about 1 million. It is nested in the Lake Michigan basin. The
98 topography of the basin consists of rolling moraine over bedrock, sloping downward
99 mostly from northwest to southeast, and the elevation ranges from 177 to 415 m above
100 sea level (Wisconsin Department of Natural Resources 2001). The basin has three major

101 rivers, namely Milwaukee, Menomonee, and Kinnickinnic, which merge just before the
102 outlet of the basin.

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

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

119 **Meteorological drought determination**

120

121 Of the popular indicators for meteorological drought mentioned previously, we chose EDI
122 for this study. PDSI is complex to calculate and requires insufficiently measured variables

123 (e.g., evaporation). SPI requires only precipitation, but measures the departure of
124 precipitation for different accumulation periods (e.g., 3-month, 6-month, etc.). Therefore,
125 if a three-month accumulation period is selected (i.e., SPI-3), SPI-3 does not account for
126 precipitation that occurred more than three months before present. Consequently, it is
127 possible that SPI-3 indicates a drought whereas SPI-4 does not. Unlike PDSI and SPI, EDI
128 explicitly takes the time of precipitation into account, giving more weight to more recent
129 precipitation than to earlier precipitation. EDI works at the daily scale and requires only
130 precipitation.

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

132

133

$$134 \quad EP_i = \left[\frac{(\sum_{m=1}^n P_m)}{n} \right] \quad \text{(Equation 1)}$$

135

$$136 \quad DEP = EP - MEP \quad \text{(Equation 2)}$$

$$137 \quad EDI = \frac{DEP}{ST(DEP)} \quad \text{(Equation 3)}$$

138

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

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

147

$$148 \quad P_1 + \frac{P_1 + P_2}{2} + \frac{P_1 + P_2 + P_3}{3} + \dots + \frac{P_1 + \dots + P_{365}}{365} \quad (\text{Equation 4})$$

149

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

154 If DEP is negative (or positive) for k consecutive days, i changes to i_2 that is $365 +$
155 $k - 1$, and with i_2 , EP, DEP, and MEP are recalculated. Whenever DEP changes between
156 negative and positive, i_2 returns to 365. The resulting negative EDI values express the
157 standardized deficiency, and positive values express the standardized surplus of water
158 resources stored over many years, respectively.

159 This study used a daily historical gridded precipitation dataset covering the whole
160 of Wisconsin. It was produced by spatially interpolating weather-station data across the
161 state and available for 1950-2006 with 8-km grid spacing (Serbin and Kucharik 2009). As
162 shown in Fig 1, each catchment contains several grid points, thus the spatial resolution of
163 the data is deemed adequate for the analysis. The grid points falling in the Milwaukee River
164 basin were selected, and the precipitation data were spatially averaged for each of the six
165 catchments to calculate EDI. Therefore, the study did not take full advantage of the high
166 spatial resolution of the precipitation data. Precipitation was averaged for each catchment

167 in part because the spatial variability of precipitation was not large and in part because the
168 study focused on the correspondence between meteorological and streamflow droughts.
169 Wet and dry days were similar among the grid points for each catchment, therefore
170 averaging did not significantly influence the wet-dry sequences. Total annual precipitation
171 averaged for each catchment is presented in Table 1. The first year's data cannot produce
172 the same year's EDI, thus EDI was calculated for the years 1951-2006.

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

183 We also examined the temporal trends of annual minimum EDI because the
184 intensity of meteorological drought is classified based on the minimum EDI value of the
185 event. The monotonic trend was analyzed using the Mann-Kendall test for trend, and the
186 periodicity was examined using spectral analysis. The spectral analysis was performed
187 using the function `spec.pgram` ([https://stat.ethz.ch/R-manual/R-](https://stat.ethz.ch/R-manual/R-devel/library/stats/html/spec.pgram.html)
188 [devel/library/stats/html/spec.pgram.html](https://stat.ethz.ch/R-manual/R-devel/library/stats/html/spec.pgram.html)) of R software, which calculates the periodogram

189 using a fast Fourier transform. To avoid a misinterpretation of the spectra results, the data
190 were initially detrended series by series.

191 **Streamflow drought determination**

192

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

197

$$198 \quad D = \int_{t_b}^{t_e} (T - x(t)) dt \quad \text{(Equation 5)}$$

199

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

204 Streamflow droughts were determined using the observed streamflow data at the
205 Milwaukee River U.S. Geological Survey (USGS) site (Fig 1). It became operational in
206 1914 and is located close to the outlet of the Milwaukee South catchment. Therefore, the
207 discharge from Cedar Creek, East and West Branches, and North Branch is part of the
208 streamflow measured here. We analyzed the streamflow data for 1951-2006 to match the
209 EDI data and used 30-day moving means to smooth the daily streamflow data. We also
210 converted the unit of the streamflow data from cubic feet per second to millimeters to

211 express streamflow as depth over the entire catchment. The Menomonee River site became
212 operational since the 1960s, so its data were used as auxiliaries. Other UGSG sites within
213 the basin were not used in this study because their records are much shorter than the
214 precipitation data. If the study was extended to a larger area, it would be conducted for
215 selected river basins scattered over the region because of the wide range of lengths of
216 operation of streamflow measurement sites.

217 We determined the 20th percentile streamflow values for each calendar day (from 1
218 January to 31 December, excluding 29 February) of the data period, which resulted in a
219 time series of 365 entries. Then we calculated 30-day moving means to smooth the
220 threshold line. The 20th percentile was applied to the daily streamflow series to determine
221 streamflow deficit. Continuous days with below-threshold streamflow constitute a drought
222 event. Drought events lasting three days or less were ignored as in other studies (e.g.
223 Vrochidou et al. 2013). When there is a short non-drought period between two drought
224 events, the two drought events are considered mutually dependent droughts (Fleig et al.
225 2006). In this study, mutually dependent droughts were pooled when the non-drought
226 period between them was shorter than three days. Means of deficit values for the preceding
227 and following days of the non-drought days were assigned to the non-drought days.

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

233 **Results and Discussion**

234 **Trend of annual minimum EDI**

235

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

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

253 The significant periodicity, emerging in all six catchments, was the one of 6.67
254 years, but also periodicities of 4.62 years and 3 years were found in five and four
255 catchments, respectively. An example is presented in Fig 5 for Cedar Creek. The lowest

256 minima in several series are observed in the years 1958 and 1964 (Fig 4), which are
257 separated by 6 years. In other periods, shorter periodicities (3 and 4.62 years) are also
258 evident, especially in the most recent years. Therefore, the region needs to prepare for
259 severe and extreme meteorological drought events every 4-6 years.

260 **Characteristics of drought events**

261

262 During 1951-2006, the Milwaukee South catchment had 9 and 21 meteorological drought
263 events (Table 3) classified as extreme and severe, respectively (see Table 2 for
264 classification). More intense droughts tended to occur less frequently and with longer
265 durations. The duration was as short as seven days and many events lasted for less than a
266 month. It indicates the usefulness of EDI in diagnosing both short- and long-duration
267 droughts. The total number of events was 95 (1.7 per annum). According to the
268 classification scheme used for this study, meteorological drought is a phenomenon
269 occurring more than once a year on average. The average frequency of 1.7 per annum is
270 slightly higher than previous studies that used EDI for different regions. For example, Lee
271 et al. (2014) report 75 events for South Korea during 1952-2007 (1.34 per annum), and Oh
272 et al. (2014) report 29-50 events for different subregions of East Asia during 1962-2004
273 (0.7-1.2 per annum). Having more than one drought event per annum sounds incompatible
274 with the general perception that droughts occur every once in a while. We doubt that the
275 moderate drought events identified in this study would be recognized as drought by the
276 general public. The results suggest that only extreme and severe events deserve to be
277 recognized as drought in the study area.

278 Six of the nine meteorological drought events classified as extreme for the
279 Milwaukee South catchment occurred before 1970 (Table 4). The 1950s and 1960s had

280 three events each, and the 1990s had none. All the extreme drought events lasted at least
281 four months, and the one that began in 1962 lasted for nearly two years. Except for the one
282 that began in November 1967, all the events commenced in spring or summer months. The
283 extreme drought events tended to terminate in late spring and summer when precipitation
284 was generally abundant.

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

298 The frequency of streamflow drought events (~1 per annum) is quite comparable to
299 previous studies that used the threshold approach. For example, Vrochidou et al. (2013)
300 report 23 streamflow drought events during 1974-1999 (0.88 per annum) for a Greek basin
301 using the 20th percentile threshold, and Liu et al. (2016) report 27 events using the 30th-
302 percentile monthly threshold during 1980-2009 for a northern Chinese basin (0.9 per

303 annum). Because streamflow drought was defined using pre-determined thresholds,
304 drought-like conditions, regardless of duration or severity, may have been left uncounted.
305 This limitation applies to virtually all studies diagnosing drought quantitatively, and we are
306 not aware of any reasonable alternatives.

307 **Drought time series**

308

309 Meteorological droughts appeared to be quite common and severe in the 1950s and 1960s
310 and much less so in the 1980s and 1990s (Fig 8). Droughts somewhat rebounded in the
311 2000s, with multiple events with minimum EDI values below -1.5 during 2000-2006.
312 Similar trends are reported for nearby states of Illinois and Indiana (Mishra, Cherkauer,
313 and Shukla 2010), suggesting a regional-scale phenomenon. Annual total precipitation
314 increased in the Milwaukee area during the time with varying degrees and levels of
315 confidence (Kucharik et al. 2010, Keuser 2014, Choi et al. 2016), to which the
316 meteorological drought trend is attributable. An abrupt termination of drought was also
317 found in the graph in the middle of September 1961. An exceptionally large rainfall event
318 (>120 mm during 15-17 September) helped abruptly push the EDI value above zero. This
319 would not have been detected with monthly-scale indices such as SPI or PSDI. Similar
320 results were found for Menomonee (not shown).

321 Streamflow droughts were much less frequently observed after the 1970s (Fig 7).
322 Only three events were observed during the 1980s, two during the 1990s, and slightly more
323 in the 2000s, reflecting the meteorological droughts. The reduced occurrence of streamflow
324 droughts since the 1970s is also found in another study for several Midwestern states, and
325 such changes suggest that the long term (decadal or longer) process in the atmospheric
326 general circulation somewhat changed after the 1970s (Changnon 1996). It should be noted

327 that the Milwaukee River basin was not included in that study, and streamflow drought was
328 determined differently from this study. Compared with the EDI time series (Fig 8), the
329 streamflow deficit time series appeared to hide many minor events that did not exceed the
330 threshold. During the 1980s and 1990s, several severe meteorological drought events were
331 identified, but very few streamflow drought events were identified according to the 20th
332 percentile threshold. This is due to the inherent difference between a standardized-index
333 approach like EDI and a threshold approach. If streamflow remained quite low for a while
334 but above the threshold, it would not count as a drought event. On the other hand, a
335 meteorological drought consists of any sequence of days with negative daily EDI values
336 with the minimum lower than -0.7 .

337 Comparison of the extreme meteorological drought events listed in Table 4 with
338 the streamflow deficit time series in Fig 7 provides a picture of correspondence between
339 meteorological and streamflow droughts. Most of the events listed in Table 4 correspond
340 to streamflow drought events in Fig 7 with varying lag times. For example, the extreme
341 meteorological drought for Milwaukee South that commenced on 16 August 1953 is
342 followed by a streamflow drought from 31 August, which lasted for 157 days. The extreme
343 meteorological drought events in 2003 for Milwaukee South were followed by streamflow
344 droughts in late August with a lag of about ten weeks. On the other hand, a fairly significant
345 streamflow drought occurred in the spring of 2003, but it was preceded by a severe, though
346 not extreme, meteorological drought from November 2002 (see Fig 8). Actually, the year
347 2003 was in a meteorological drought condition for most of the year with only days
348 separating different events (see Fig 8). Despite that, streamflow drought was not
349 remarkable, particularly in the second half of the year.

350 The propagation of meteorological drought to streamflow drought for the
351 Milwaukee River USGS site is portrayed in Fig 9 for the years 1976-1977. An unusual
352 statewide agricultural drought occurred in 1976 (Mitchell 1979), and an emergency was
353 declared by Federal Emergency Management Agency on 17 June 1976. During this period,
354 an extreme meteorological drought event commenced and terminated (Table 4). In Fig 9,
355 daily precipitation (top panel) is shown with mean daily precipitation during the record
356 period. Precipitation was generally below the average from late May of 1976 through
357 February of 1977 and was quite abundant in 1977. After briefly falling below zero in mid-
358 June, EDI remained below zero continuously from late June of 1976 through late July of
359 1977. A few large rainfall events in the summer of 1976 brought EDI close to but still
360 below zero in August 1976. Precipitation was abundant in April 1977 as well and brought
361 EDI up again, but EDI still remained below zero. EDI began to fluctuate around zero from
362 late July due to the abundant summer precipitation and remained positive for the rest of the
363 year from September 1977. Streamflow drought became evident only in September 1976,
364 whereas EDI was negative from late June. There was a short (lasting six days) streamflow
365 drought in July with a very small deficit. Streamflow drought disappeared in late February
366 1977 when EDI began to increase. From April to May 1977, streamflow drought was very
367 intense in response to falling EDI. The drought terminated at the beginning of June 1977.
368 Similar results were found for Menomonee (not shown).

369 The intense streamflow drought in May 1977 contrasted with the longer and less
370 intense event during the winter of 1976-1977. The 20th percentile threshold is much lower
371 in magnitude during the winter than in May. Because winter is a low flow season, the room
372 for streamflow deficit is quite small. In May, much more flow is expected than in January

373 or February. Even though the absolute flow level in May 1977 was larger than that of the
374 winter of 1976-1977, the deficit was much larger, making the drought even more intense.
375 After June 1977, the streamflow drought was no longer observed with increasing
376 streamflow and decreasing threshold.

377 **Conclusions**

378

379 We examined meteorological and streamflow droughts for the period 1951-2006 for the
380 Milwaukee River basin in Wisconsin in an effort to improve the understanding of drought
381 propagation. Specifically, we aimed to answer the following research questions: (1) What
382 are the temporal trends of meteorological and streamflow droughts identified by drought
383 indicators? (2) How do the drought indicators manifest drought propagation? We employed
384 the Effective Drought Index and the threshold-level approach for diagnosing
385 meteorological and streamflow drought events, respectively. In addition, we examined in
386 detail daily time series of precipitation and drought indicators for a two-year period of
387 1976-1977 that saw significant drought events.

388 In conclusion, the magnitude and duration of drought generally decreased during
389 the 56-year period in the study area most likely due to increasing precipitation. Therefore,
390 in the study area and likely in the larger region, drought has become increasingly less of a
391 concern. With respect to the propagation of meteorological drought to streamflow drought,
392 streamflow droughts were detected generally after moderate and severe sequences of
393 below-normal precipitation that eventually led to extreme meteorological drought events.
394 Streamflow was generally responsive to precipitation events but it took sustained

395 precipitation shortage from days to weeks for streamflow drought to manifest itself.
396 Termination of streamflow drought in this approach accompanied large rainfall events.
397 However, the termination of streamflow drought does not mean that water is available at a
398 normal level but rather that water recovery just has commenced.
399

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492 **Tables**

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496 **Table 1.** Selected information on the six catchments of the Milwaukee River basin. The
497 coordinates are means of the climate data grid points falling in the basin. The mean
498 annual precipitation is for the period 1950-2006 and shown with \pm standard deviation of
499 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 \pm 123
Menomonee	43.125, -88.098	241.4	807 \pm 127
Kinnickinnic	42.960, -87.889	308.6	841 \pm 152
East and West Branches	43.574, -88.223	308.6	803 \pm 113
Cedar Creek	43.342, -88.131	281.1	809 \pm 120
North Branch	43.569, -88.042	281.2	818 \pm 122

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

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504 **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

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507 **Table 3.** Summary characteristics of meteorological drought by class for the Milwaukee
508 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

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519 **Table 4.** Characteristics of extreme meteorological drought events for the Milwaukee
520 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

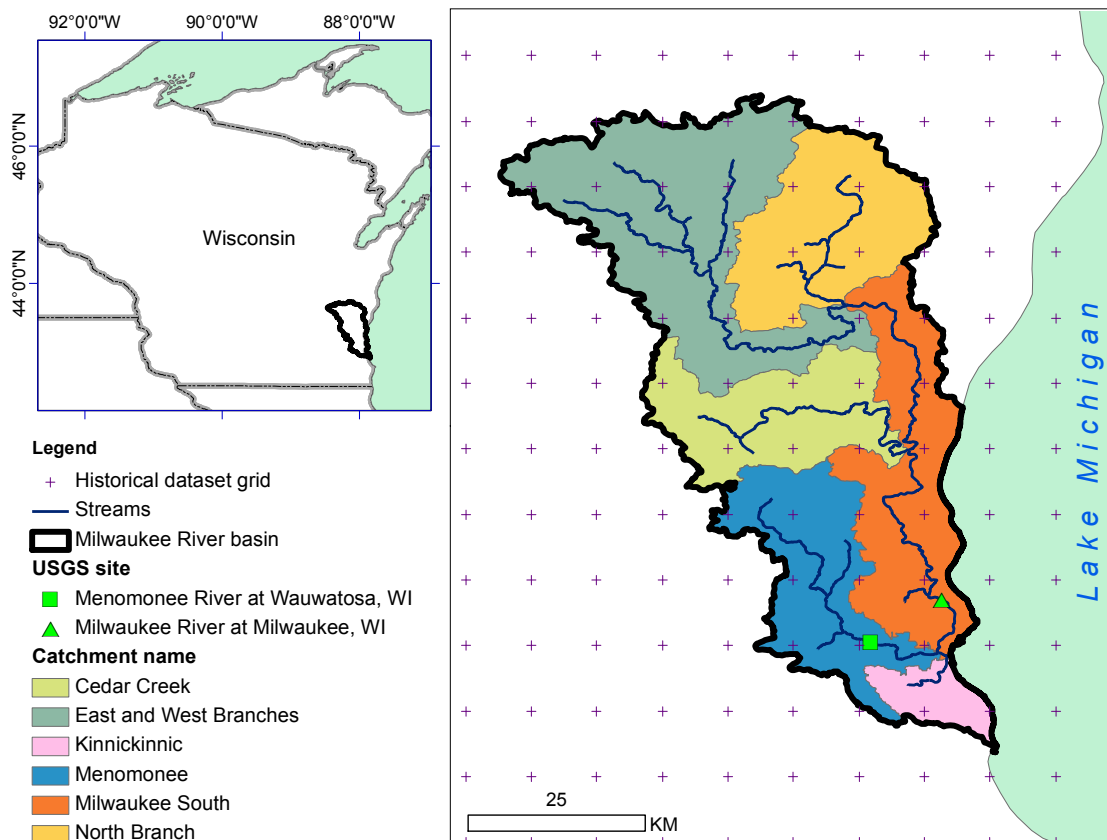
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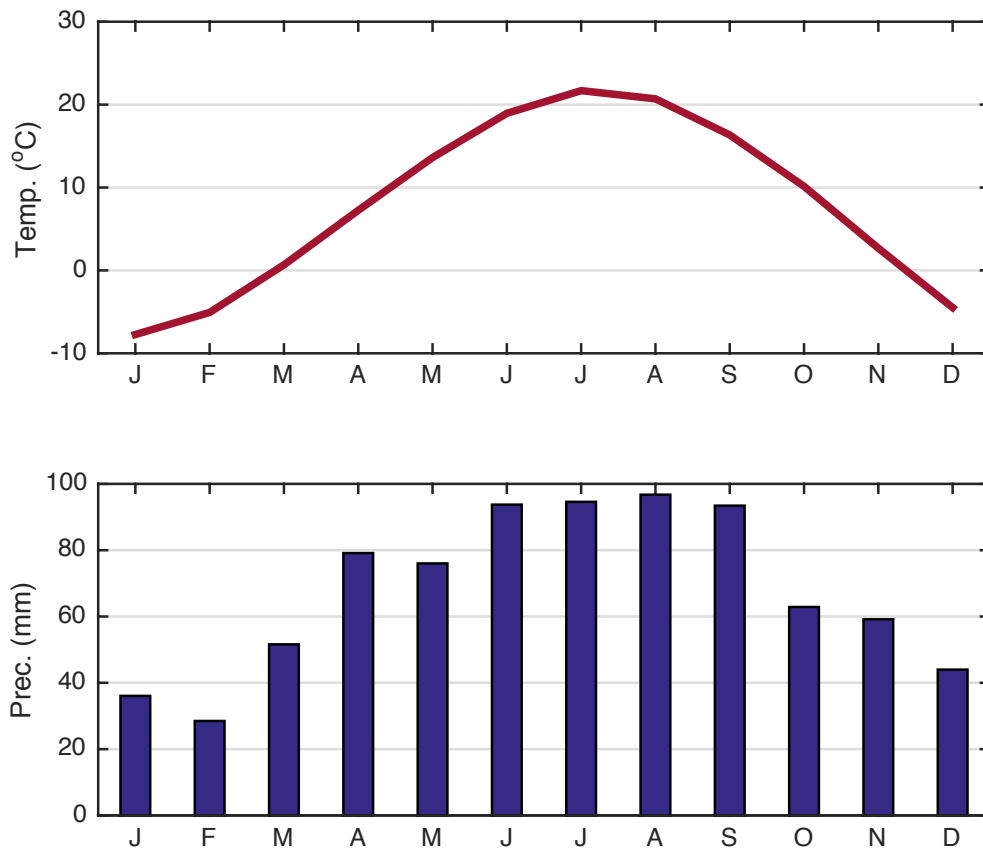
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525 **Figures**

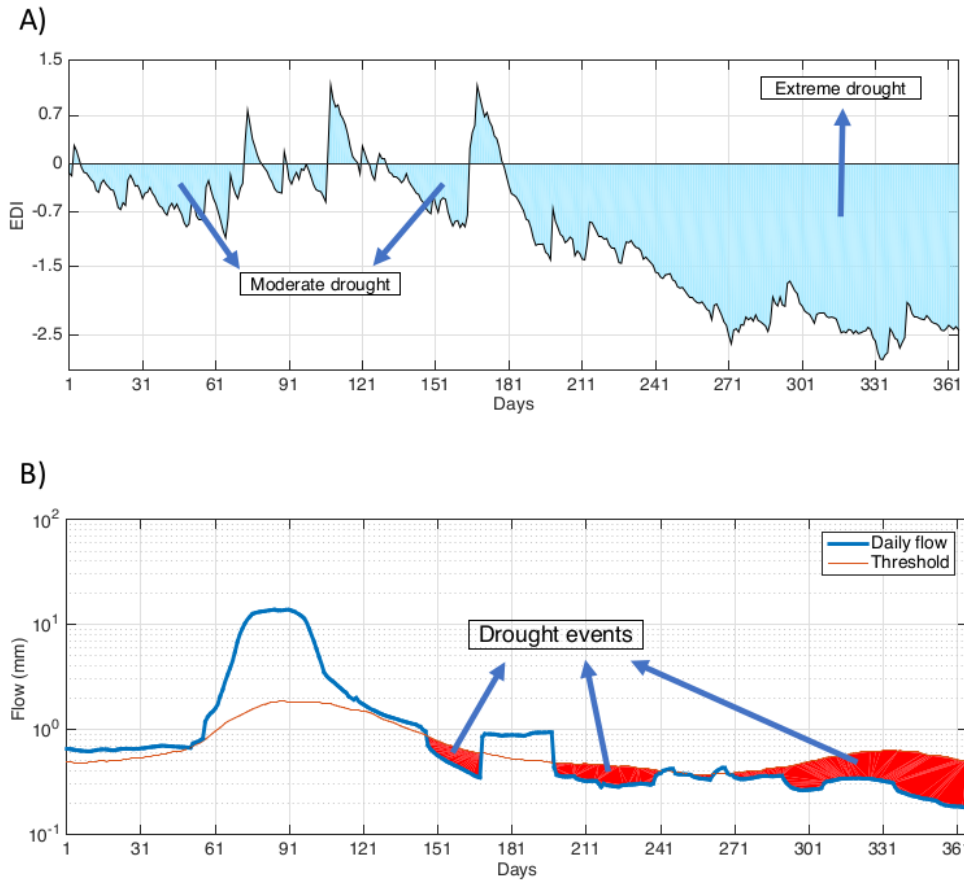


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527 **Fig 1** Study area: boundary of the Milwaukee River basin, boundaries of six nested
 528 catchments, major streams, grid points of historical precipitation dataset, and the two U.S.
 529 Geological Survey (USGS) streamflow measurement sites.

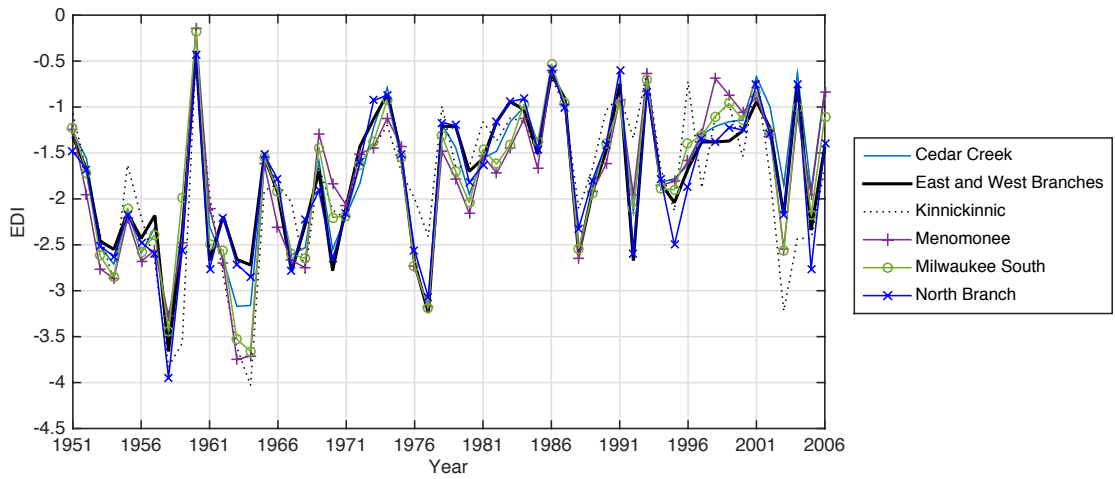


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 531 **Fig 2** Mean monthly temperature (upper panel) and precipitation (lower panel) for the
 532 entire Milwaukee River basin calculated from the historical gridded data (Serbin and
 533 Kucharik 2009)



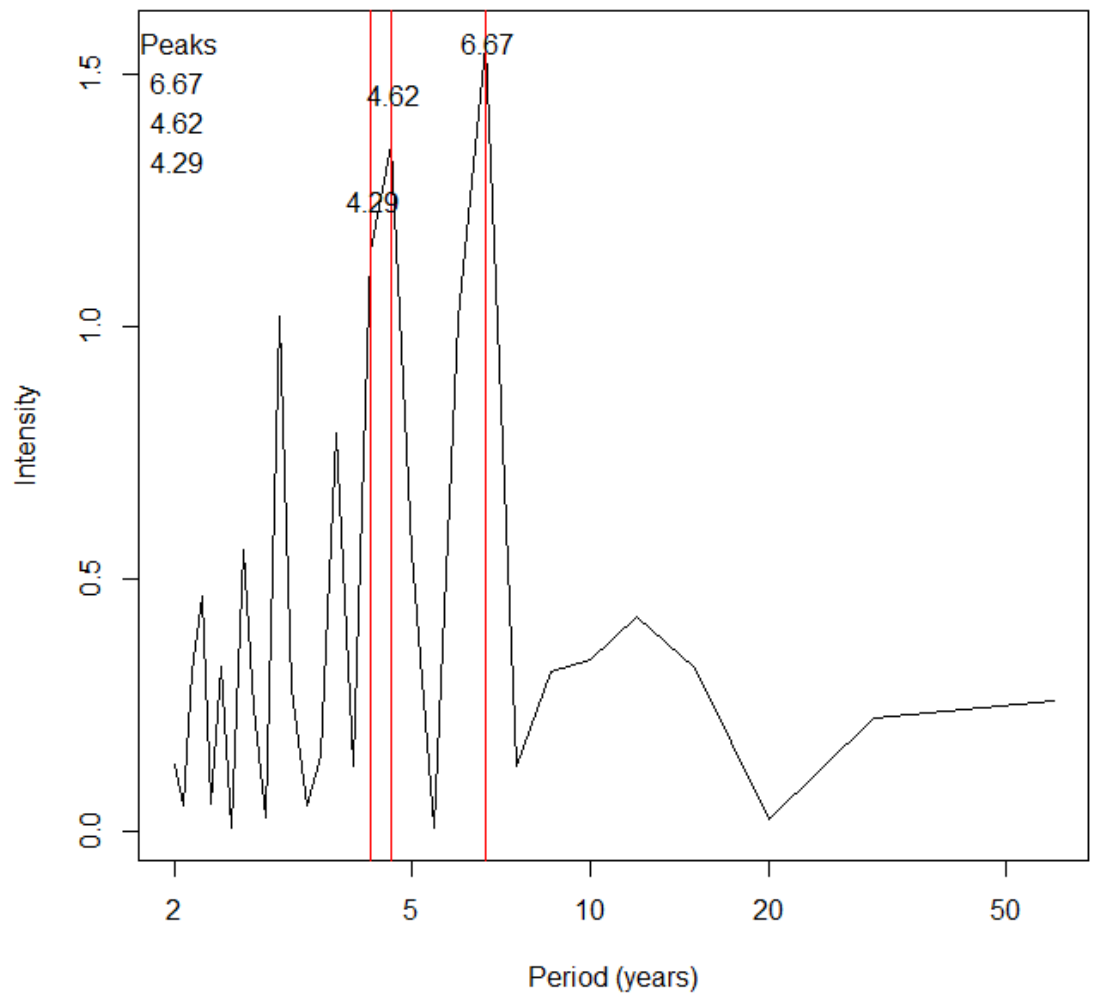
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535 **Fig 3** Illustration of meteorological drought events (upper panel) and streamflow drought
 536 (lower panel) using drought indicators over a one-year period

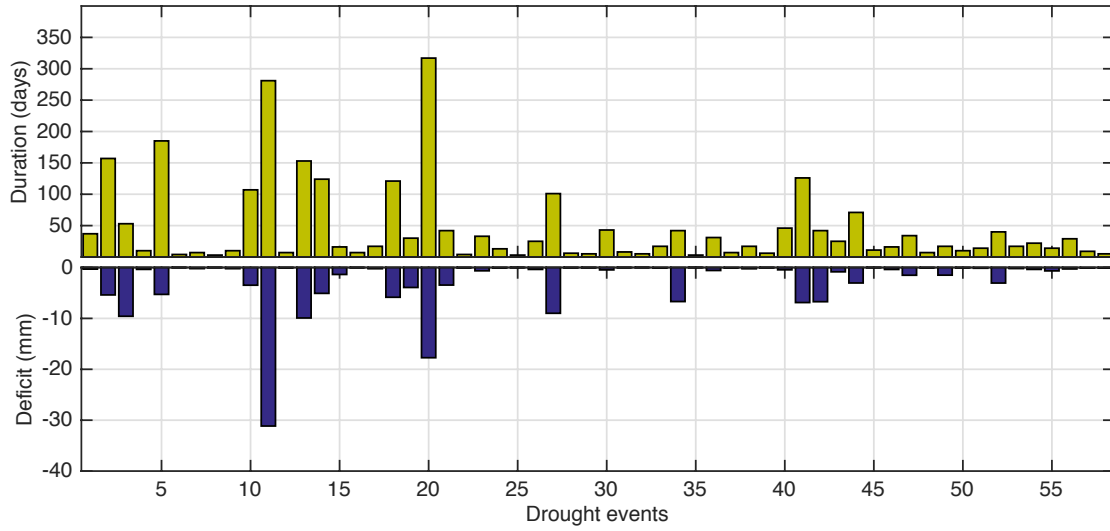


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Fig 4 Annual minimum Effective Drought Index series for the six catchments of the Milwaukee River basin

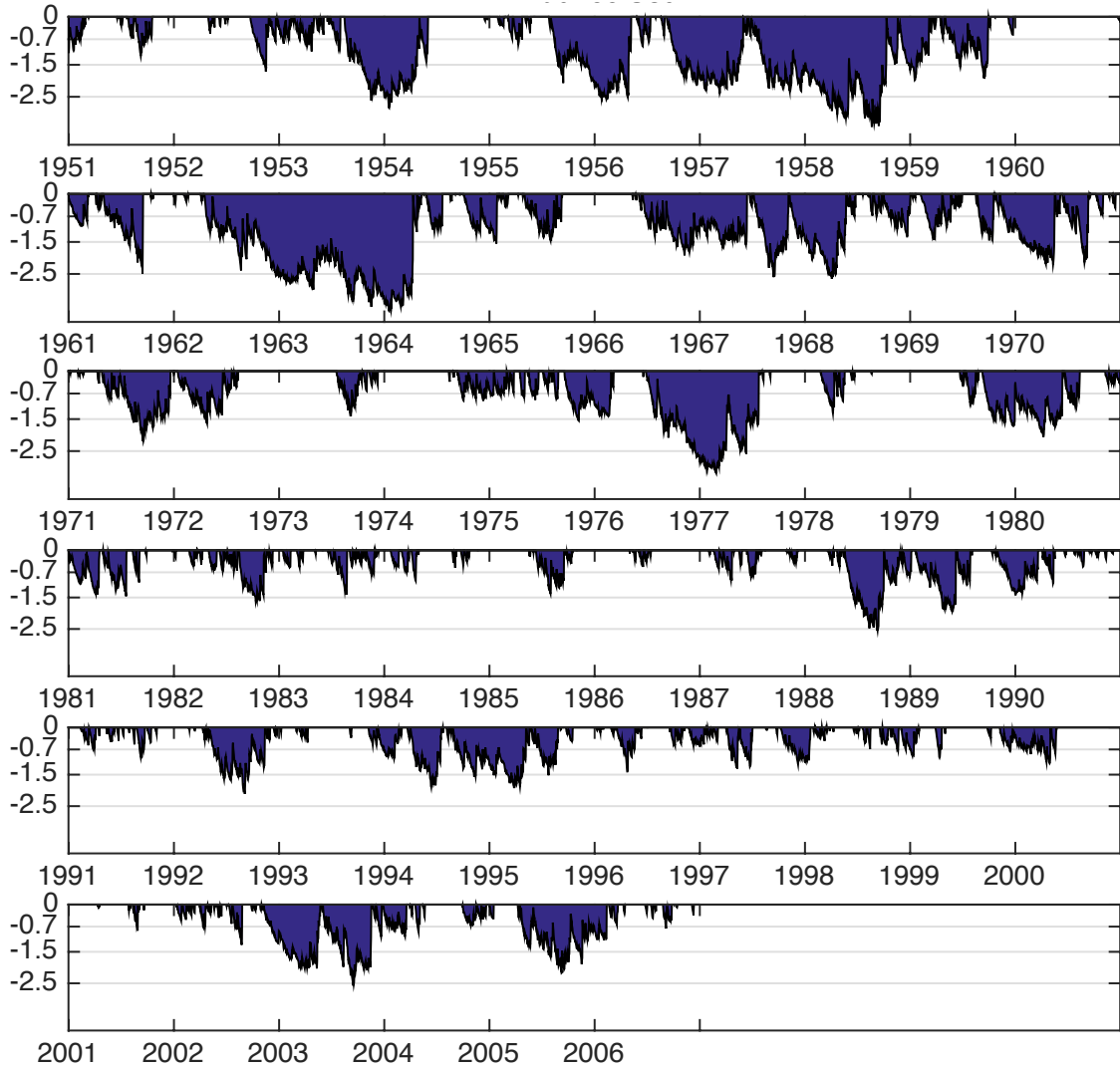


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 541 **Fig 5** Spectral analysis of annual minimum Effective Drought Index calculated for Cedar
 542 Creek



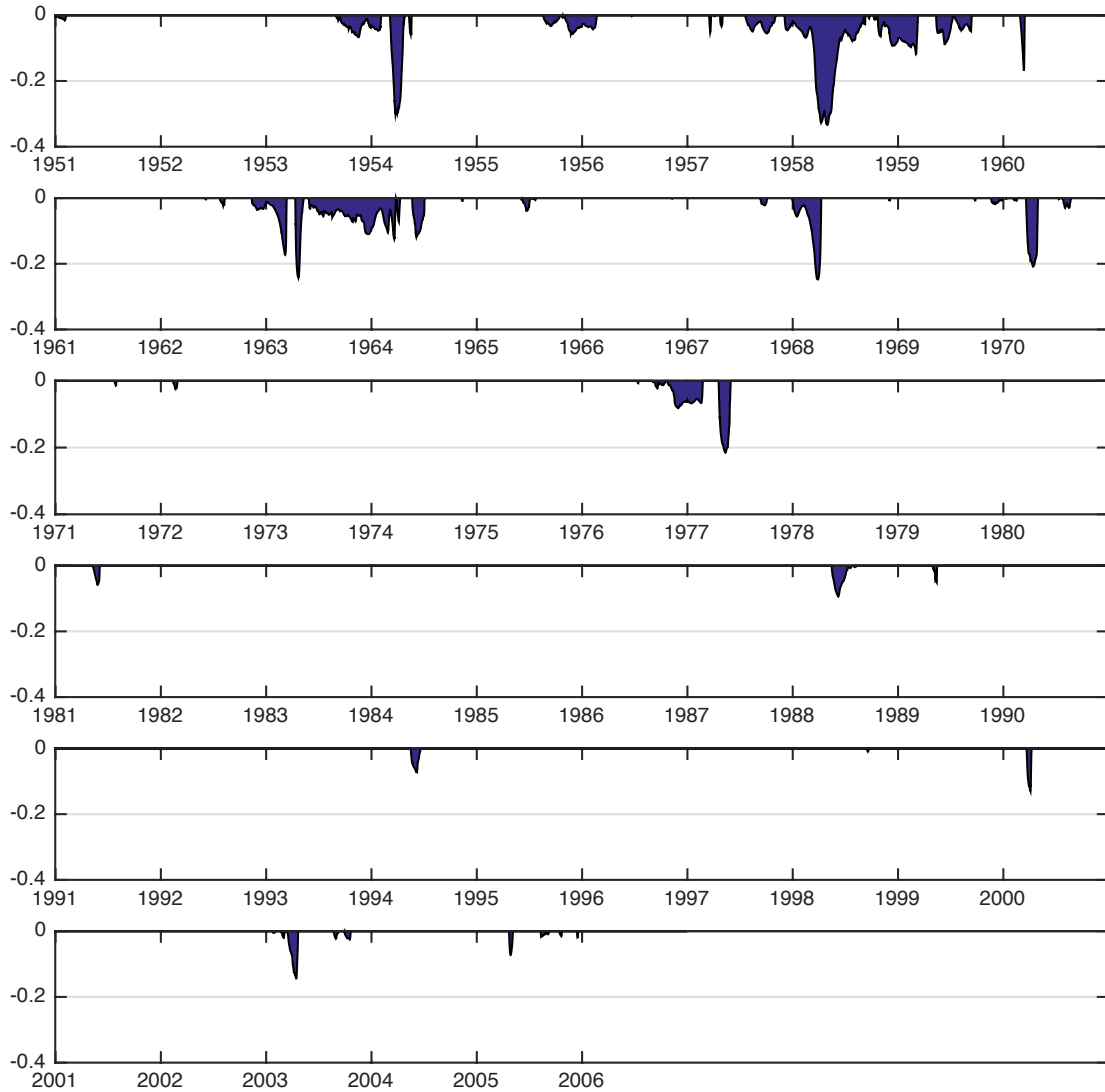
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Fig 6 Streamflow drought duration (upper panel) and cumulative deficit (lower panel) for each of the 58 events at Milwaukee during 1951-2006. The x-axis indicates each individual event (1: oldest, 58: most recent)



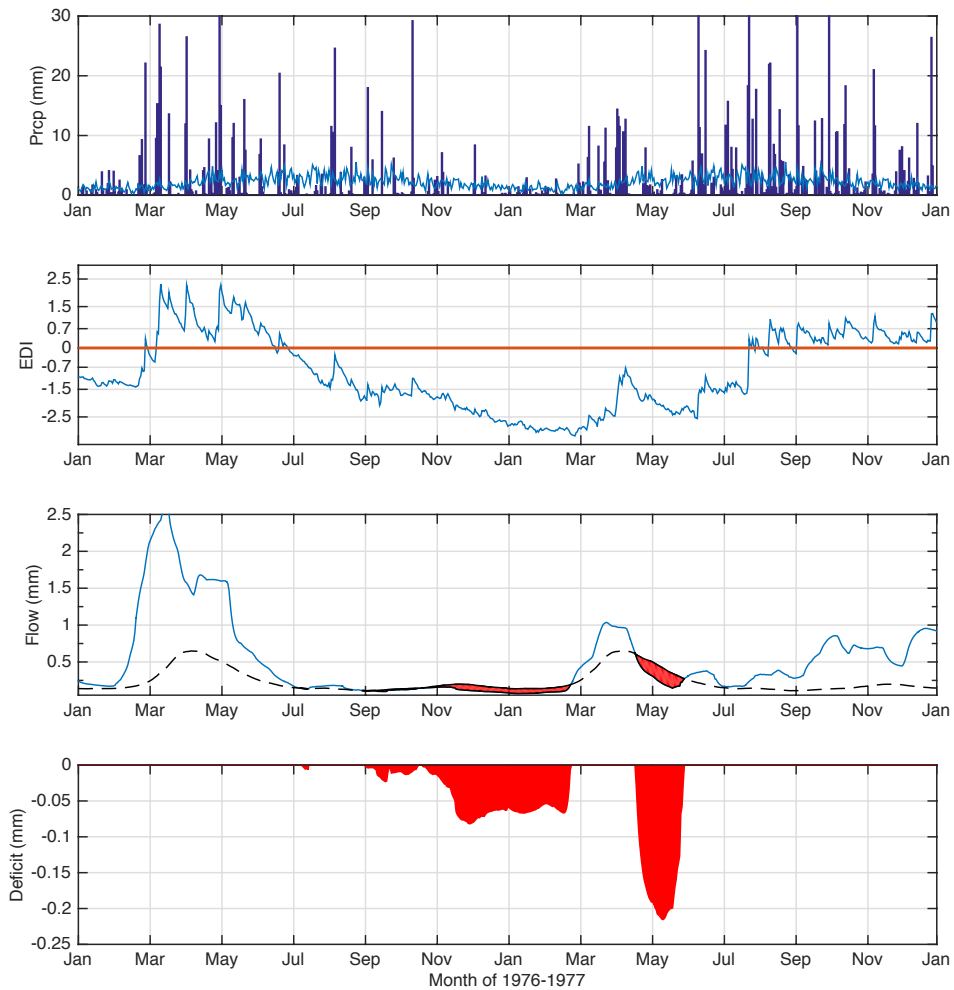
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Fig 7 Daily Effective Drought Index for the Milwaukee South catchment



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



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