Human Influences and Decreasing Synchrony between Meteorological and Hydrological Droughts in Wisconsin since the 1980s

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Abstract

Hydrological droughts are important for agriculture and other human activities such as navigation and groundwater pumping, therefore it is necessary to understand their characteristics at various temporal and spatial scales. This study aims to examine the characteristics of hydrological droughts and their propagation from meteorological droughts across Wisconsin. Hydrological droughts were identified for 24 US Geological Survey streamflow monitoring sites using the 20th percentile threshold level for each calendar day. Meteorological droughts were identified in the same way using daily precipitation data. Drought events of both types were identified for the period 1980-2018, and the drought in 2012 was examined in detail. Our results indicate that (1) unlike meteorological droughts, hydrological droughts tend to occur more frequently in recent years; (2) characteristics of hydrological droughts are not correlated with those of meteorological droughts or annual precipitation; (3) there are generally three drought regions in Wisconsin showing different drought trends and propagation characteristics; and (4) groundwater withdrawal from unconfined aquifers have exacerbated hydrological droughts. In conclusion, hydrological droughts have become less synchronous with meteorological droughts, which will make drought early warning more challenging. The study sheds light on drought characteristics and propagation in relation to catchment characteristics and human activities.

Keywords: drought, paired catchment, synchrony, drought propagation, human impact

Introduction

As a hazard, droughts can impact any part of the world inhabited by human beings in a variety of ways such as devastating agricultural production, paralyzing navigation, reducing domestic water supply, and harming ecosystems. The Sahel drought of West Africa caused major environmental and humanitarian crises in the late 20th century (Cook 2019), and the drought in the Fertile Crescent is thought to have contributed to the occurrence of civil wars in Syria (Kelley et al. 2015). Drought is an interdisciplinary research subject but is very geographic in nature. Drought is fundamentally about water (or lack thereof), which is widely implicated in earth system processes and human activities. Therefore, drought research can be valuable for a range of applications such as agricultural, ecological, and hydrological (Robeson 2008). The diversity in the occurrence, processes, and impacts of drought calls for active research in the field of geography.

Droughts generally start with a lack of precipitation over a prolonged time, which is called a meteorological drought (American Meteorological Society 2013). Meteorological droughts propagate over time to other sectors of the hydrological system such as soil moisture, streamflow, and groundwater (Mishra and Singh 2010), and a prolonged lack of surface and subsurface waters is referred to as a hydrological drought (Wilhite and Glantz 1985, Van Loon 2015). The propagation of meteorological to hydrological drought is influenced by climate conditions (Van Loon et al. 2014, Apurv, Sivapalan, and Cai 2017, Gevaert, Veldkamp, and Ward 2018) and catchment characteristics (Haslinger et al. 2014).

Propagation of meteorological to hydrological droughts has been actively studied during the last decade in terms of processes and spatial and temporal characteristics (see relevant references in Choi 2020). In general, hydrological droughts follow meteorological droughts with time lags and take longer to terminate (Van Loon 2015, Choi et al. 2018, Wu et al. 2018, Liu et al. 2019). Precipitation events naturally recharge water stocks such as soil moisture and groundwater over time, and it takes time for water stocks to fall significantly after precipitation has ended. Even after precipitation has resumed, it takes time for water stocks to return to normal levels. Such propagation characteristics are highly variable between drought events and across regions, depending largely on the characteristics of individual drought events, catchment characteristics, and climate regimes. However, there is some synchrony between meteorological and hydrological droughts, and a hydrological drought is expected when a meteorological drought persists.

Human beings now modify the environment at an unprecedented scale, and active human roles are integrated into drought research (Van Loon et al. 2016a, Van Loon et al. 2016b). Droughts have been generally perceived as "natural" hazards because a meteorological drought, precursor to a hydrological drought, is caused mostly by anomalous atmospheric circulation and sea-surface temperature conditions (Shelton 2009, Cook 2019). However, human beings impact the surface and subsurface conditions of catchments, influencing soil moisture and hydrological droughts and reducing the degree of synchrony between meteorological and hydrological droughts. Human activities that influence hydrological droughts include irrigation (Wada et al. 2013), reservoir operation (Firoz et al. 2018, Rangecroft et al. 2019), and water abstraction (Wan et al. 2017, Margariti et al. 2019). Such influences occur differently in different regions; therefore region-specific studies are needed.

Approaches for investigating human impacts on hydrological drought can be grouped into hydrological modeling, modeling-observation pairing, paired-catchment studies, and before-after comparisons as summarized in the works of van Loon et al (2019) and Kakaei et al (2019). Approaches involving hydrological modeling quantify human impacts by isolating processes and applying scenarios. They allow one to do controlled experiments but are time-consuming in implementation. On the other hand, observation-driven approaches are easier to implement but require care in selecting sites and controlling for other factors. Both approaches may be seen as complementary. This study uses the paired-catchment approach proposed by van Loon et al (2019) whereby two catchments with very similar geophysical characteristics are selected, of which only one has received substantial human impacts. If the catchments are selected adequately, they can be compared regardless of climate variability between pre- and post-disturbance periods (van Loon et al 2019). While examining dozens of catchments for drought, we identified a pair of catchments suitable for the paired-catchment approach (see Materials and Methods).

In this article, we report results from an analysis of meteorological and hydrological droughts in Wisconsin with respect to their synchrony and human impacts. The occurrence of hydrological droughts and their relationship with meteorological droughts have been investigated for Europe in several studies (e.g. Lorenzo-Lacruz et al. 2013, Rahiz and New 2014, Heudorfer and Stahl 2017), but they did not explicitly address changing synchrony. Moreover, there has not been much research for the US Midwest like in Wisconsin where agriculture is an important economic sector. Irrigation has contributed to intensifying hydrological drought in the central United States (Wada et al. 2013) and has expanded widely during the last few decades in Wisconsin (Borchardt, Choi, and Han 2016). However, there is a lack of studies on the irrigation impacts on drought characteristics and synchrony. We presume that the synchrony between meteorological and hydrological droughts has been decreasing in Wisconsin based on some recent studies (Borchardt, Choi, and Han 2016, Borchardt 2019) and attempt to answer the following research questions: 1) How have the characteristics of meteorological and hydrological droughts and their synchrony been changing? 2) How are drought characteristics distributed across space and related to catchment characteristics? 3) What is the magnitude of irrigation impacts on hydrological droughts?

We analyze drought characteristics across the state for a number of catchments and quantify the irrigation impacts on hydrological droughts for a particular pair of catchments using the paired-catchment approach. By doing so we elucidate the relationship between meteorological and hydrological droughts in the US Midwest and explain it with respect to human activities and catchment characteristics. Because irrigation is widely practiced in the central United States, the approaches and findings of the study have broad implications.

Materials and Methods

Study area and data

The study was conducted in the state of Wisconsin. Wisconsin's land area is 140,663 km^2, and the population was more than 5.8 million in 2018. Large cities are mostly located in the southeastern part, whereas the north is mostly undeveloped and covered with forest (Figure 1). During the period 1971-2000, the statewide mean temperature was 6.2 °C, and the annual precipitation was 829 mm (Wisconsin State Climatology Office 2014). July is the warmest (20.6 °C), and January is the coldest (–10.4 °C). August is the wettest (108 mm), and February is the driest (25 mm). Monthly temperature strongly correlates with monthly precipitation. Snowfall is recorded except in June, July, August, and September. Wisconsin is rich in glacial landforms and has some distinct regions of landforms. One is the Central Sands region, an area of more than 7,000 km^2 in the center of the state, underlain by deposits left by glaciers. It has abundant groundwater in sand and gravel aquifers (Wisconsin Department of Natural Resources 2018). Another is the Driftless Area, which was not covered by glaciers during the Pleistocene and is different from the rest of the state in terms of geomorphology (Gebert and Krug 1996). The Driftless Area covers more than 62,000 km^2 and stretches over the states of Minnesota, Iowa, Wisconsin, and Illinois (U.S. Fish & Wildlife Service 2015).

Daily precipitation and streamflow data were collected across the state of Wisconsin from the PRISM Climate Group and the US Geological Survey (USGS), respectively. The PRISM (Di Luzio et al. 2008) precipitation data were retrieved for the latitude/longitude coordinates of the USGS streamflow measurement sites (Figure 1). The USGS sites were selected based on the length of their records. A total of 24 stations were selected and most of them have a continuous daily streamflow record from 1980 through 2018. The stations are clustered in the southeastern corner of the state where major cities of Wisconsin are located such as Milwaukee, Racine, and Kenosha (Figure 1). Six of the sites are in Milwaukee County. Other sites are scattered around the state except in the east-west band in the center of the state that encompasses the Central Sands region. The site identifiers, names, and coordinates are listed in Appendix 1.

Groundwater recharge was estimated using the USGS-developed software Groundwater Toolbox (Barlow et al. 2017). The toolbox contains the RORA recession-curve displacement method and associated RECESS program that reads annual streamflow data from the USGS Web site and produces annual recharge as depth. We ran the program for each catchment and averaged the annual outputs. The magnitude of groundwater recharge with respect to streamflow indicates the flashness of streamflow, with higher recharge meaning the streamflow is more baseflow dominated.

We delineated catchment boundaries using the USGS sites as outlet points. We downloaded the 1/3 arc-second digital elevation model (DEM) from the USGS National Map Web site and followed the standard catchment delineation process using the Esri® Arc Hydro tools. On average, the delineated catchment area is 99.7 percent of the drainage area found on the USGS Web site. The DEM was also used to calculate the mean slope of each catchment.

Figure 1. US Geological Survey streamflow gages used in the study. Station IDs associated with the serial numbers are found in Appendix 1. The benchmark station and the human-impact station in Table 2 are enclosed in a circle and a triangle, respectively. The southeastern part of Wisconsin is expanded in the upper-right corner.

The National Land Cover Database data were downloaded from the Multi-Resolution Land Characteristics Consortium (Homer et al. 2020) for the year 2016. The data has a resolution of 30m and contains 16 classes of land cover. The layer was reclassified after download to reduce the number of classes to eight: water, developed, barren, forested, shrubland, herbaceous, agriculture, and wetland. The layer was then clipped to the area of each delineated catchment. Percentages of the three most prominent land covers—forested, agricultural, and urban—were calculated for each basin.

The data about soil properties, including available water storage and soil drainage class, were obtained as geographic information system layers from Esri®. Available water storage was calculated as the difference between the field capacity and the permanent wilting point and then adjusted for salinity and fragments at four different depths, the top 25cm, 50cm, 100cm, and 150cm of soil. The layer used in the study was produced from the 2014 Soil Survey Geographic Database (SSURGO) from the US Department of Agriculture Natural Resources Conservation Service dataset representing the top 150cm of soil. The available water-storage mean was calculated for each delineated catchment. Soil drainage class is a classification of the drainage conditions of the soil in the dominant soil components of the map unit (Esri 2020). The drainage classes are divided into seven conditions from excessively drained to very poorly drained. The layer was created from the 2019 version of the gridded SSURGO and downloaded from Esri (2020). Each drainage class was classified numerically from 1 (excessively drained) to 7 (very poorly drained), then the mean was calculated for each delineated catchment.

Data regarding high-capacity wells and groundwater withdrawal were obtained from the Wisconsin Department of Natural Resources via email communication with Robert A. Smail on the 10th of September 2018. A GIS layer of well locations is available at Anonymous (2019).

Variables describing catchment physical characteristics are listed in Table 1 along with their units. Their numbers are presented for each catchment in Appendix 2.

Table 1. List of variables of catchment physical characteristics.

Name	Data description	Unit
AREA	Drainage area of the USGS site	km^2
SLOPE	Mean slope	%
AS_150	Available water storage in top 150 cm of soil	mm
DRAIN	Soil drainage class	N/A
FORE%	Percent of forest land cover	%
AGRI%	Percent of agricultural land cover	%
URBA%	Percent of urban land cover	%
WELLS	Number of high-capacity wells	None
RUNOFF	Annual runoff	mm
RECHA	Annual recharge	mm
PRECI	Annual precipitation	mm

Threshold-level approach for drought diagnosis

The diagnosis for both meteorological and hydrological droughts was conducted using the threshold-level approach originally conceived by Yevyevich (1967). In this approach, when the water level (e.g., precipitation or streamflow) falls below a predefined threshold level, a drought is considered to have commenced (Figure 2). Conversely, the drought ends when the water level rises above the threshold. Another approach to diagnosing droughts is using standardized indices such as the Palmer Drought Severity Index and Effective Drought Index (for details, see Shelton 2009). They are unitless by nature, and we did not use them because we wanted to express deficits along with water balance terms.

The threshold level is generally determined based on percentiles, and the 20th percentile (smaller than 80 percent of the data) is widely used in the literature (e.g. Wong et al. 2011, Heudorfer and Stahl 2017, Rivera, Araneo, and Penalba 2017, Choi et al. 2018, Rangecroft et al. 2019). The 20th percentile threshold indicates that the water shortage occurs for 20% of the time. The percentile threshold can be determined for the entire dataset (Figure 2A), or seasonal variability can be considered (Figure 2B). In the former case, the threshold is fixed over time; therefore droughts occur when the water level, for example streamflow, is very low relative to the rest of the data. In the latter case, the magnitude of the threshold varies over time (e.g., calendar day, month, or season, depending on specification); thus it is higher in high-flow seasons than in low-flow seasons. A drought means that the water level is low for the given time. The fixed and variable threshold levels are complementary rather than hierarchical.

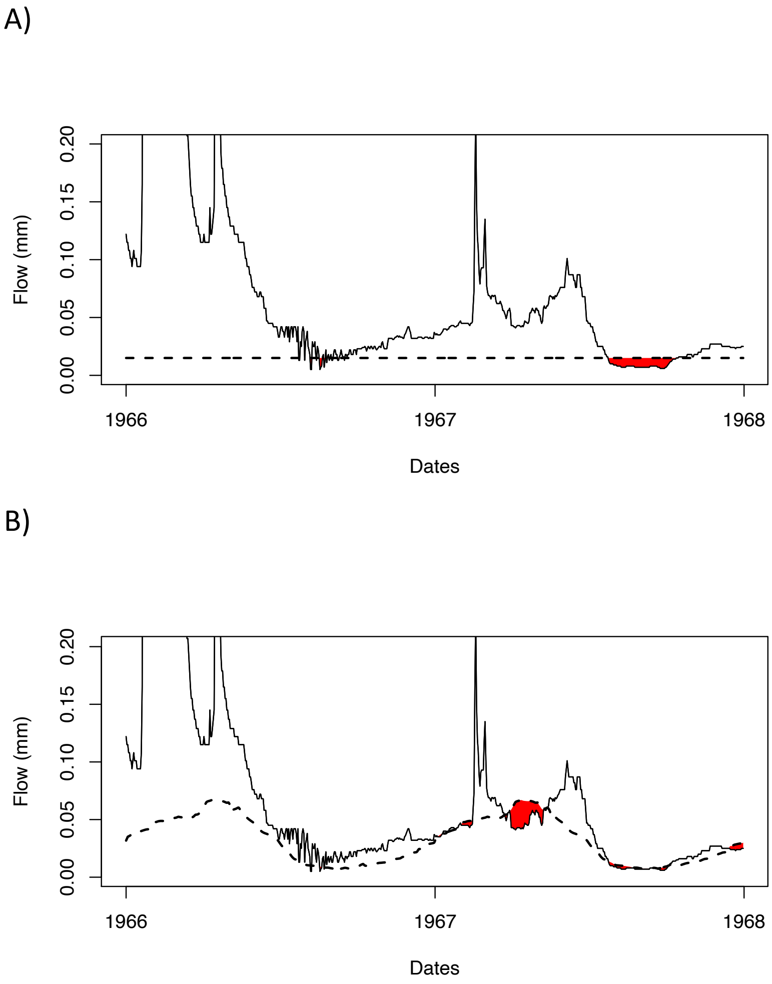

Figure 2. Illustrations of drought diagnosis using the (A) fixed and (B) variable threshold level methods from the same hypothetical dataset. Solid lines indicate the water level (e.g., streamflow) and the dashed lines indicate threshold levels. Red areas indicate the deficit volumes of the drought events.

We adopted the 20th percentile threshold both in fixed and variable methods. Higher or lower percentiles could be used as well, but they did not make much difference according to our preliminary analysis. We used the R package developed by van Loon (2019) for drought diagnosis. Some scripts were revised for additional functionality and are available from the lead author upon request. For the variable threshold, each calendar day's 30-day moving average of streamflow record is used to determine the 20th percentile for the day. Once a drought event is identified, dependent droughts (separated by 10 days or less) are pooled, and minor ones (lasting for 15 days or less) are removed. The R package calculates the deficit volume (mm) and the duration (days) of each drought event. The duration tells how long the drought event lasted, and the deficit volume is the sum of deviations of the water level from the threshold during the event (the size of each red area in Figure 2). Therefore, the deficit volume depends on how far the water level falls below the threshold as well as how long the below-normal condition continues. The deficit volume may be understood as water-shortage volume normalized by the catchment size. Such characteristics of meteorological and hydrological droughts were presented as choropleth maps.

Correlation analysis

We correlated major catchment characteristics (see Appendix 2) with drought characteristics across the catchments (n = 24). The drought characteristics used in the correlation analysis are median durations and deficit volumes of both meteorological and hydrological droughts for each catchment. The Pearson correlation analysis was performed using the "rcorr" function embedded in the "Hmisc" package of R, and the results were presented as a correlation table.

Drought propagation

The drought in the year 2012 was selected for drought propagation analysis. The 2012 drought is the most recent major drought event that affected much of Wisconsin. At some point in 2012, twenty percent of Wisconsin's land experienced "extreme drought" (U.S. Drought Portal 2020), which led to major crop losses and widespread water shortages or restrictions. Time-series plots of precipitation and streamflow for the period 2011-2013 were closely examined for select catchments. We also compared the binary state of hydrological drought to maps from the US Drought Monitor (National Drought Mitigation Center 2020) to examine the correspondence between our results and USDM's. USDM is a joint effort of several public agencies to map drought conditions of the country. It shows snapshots of drought in five categories (from abnormally dry to exceptional drought) by blending a range of drought indicators for precipitation, soil moisture, and streamflow.

Paired-catchment approach

Two catchments associated with USGS sites 05394500 (Prairie River) and 05397500 (Eau Claire River) were selected for quantifying human impacts on hydrological droughts using the paired-catchment approach. In this approach, the Prairie River (number 7 in Figure 1) is regarded as a benchmark catchment and the Eau Claire River is a human-impact catchment (number 9 in Figure 1). The drought threshold is determined using the streamflow data for the benchmark catchment and applied both for the benchmark and human-impact catchment. Then the differences between the drought metrics of the benchmark and human-impact catchments are deemed due to human activities. The changes in drought metrics due to human activities are quantified using the following equation:

$$\text{Changes (percent) due to human activities} = \frac{Human - Benchmark}{Benchmark} \times 100 \qquad (1)$$

The pair was selected following the steps in van Loon et al (2019). In summary, the pair has similar annual precipitation, soil characteristics, and land cover but very different numbers of high-capacity wells and withdrawal rates. The comparison is presented in Table 2. The annual precipitation is almost identical, but the annual discharge is substantially different suggesting the effect of terrestrial processes. The benchmark catchment has a higher percentage of forest land cover and a lower percentage of agricultural land cover. The percentage of urban land cover is quite similar. Both catchments lie above aquifers that are well connected to surface water (Borchardt 2019). Most importantly, the human-impact catchment has many more high-capacity wells and much more groundwater withdrawal than the benchmark catchment.

Table 2. Characteristics of the benchmark and human-impact catchments.

	Benchmark	Human-impact
Site ID	05394500	05397500
Site name	Prairie River near Merrill, WI	Eau Claire River at Kelly, WI
Latitude (decimal degrees)	45.236	44.919
Longitude (decimal degrees)	–89.650	–89.552
Aquifer type	Unconfined	Unconfined
AREA	476.6	971.2
SLOPE	4.627	2.758
AS_150	20.50	20.06
DRAIN	4.347	4.153
FORE%	48.9	37.0
AGRI%	9.0	30.5
URBA%	2.8	5.1
WELLS	6	239
RUNOFF	323	225
RECHA	272	166
PRECI	827	835
Annual withdrawal (10^5 m^3)	0.41	69.75

Results

General characteristics of drought

The geographical distributions of the median deficits and durations of meteorological droughts are depicted in Figure 3, and the variability is not large. The median deficits tend to be smaller in the north and larger in the south, but the range is just about 6.4 mm, 1/3 of the minimum. The geographical distribution of the deficit largely mirrors that of the precipitation amount in the state (see Serbin and Kucharik 2009), i.e., larger deficits with larger precipitation. The distribution of median durations is very similar to that of median deficits. Here the range is three days with a minimum of 29 days. Overall, meteorological drought characteristics do not vary widely across the state like the precipitation amount.

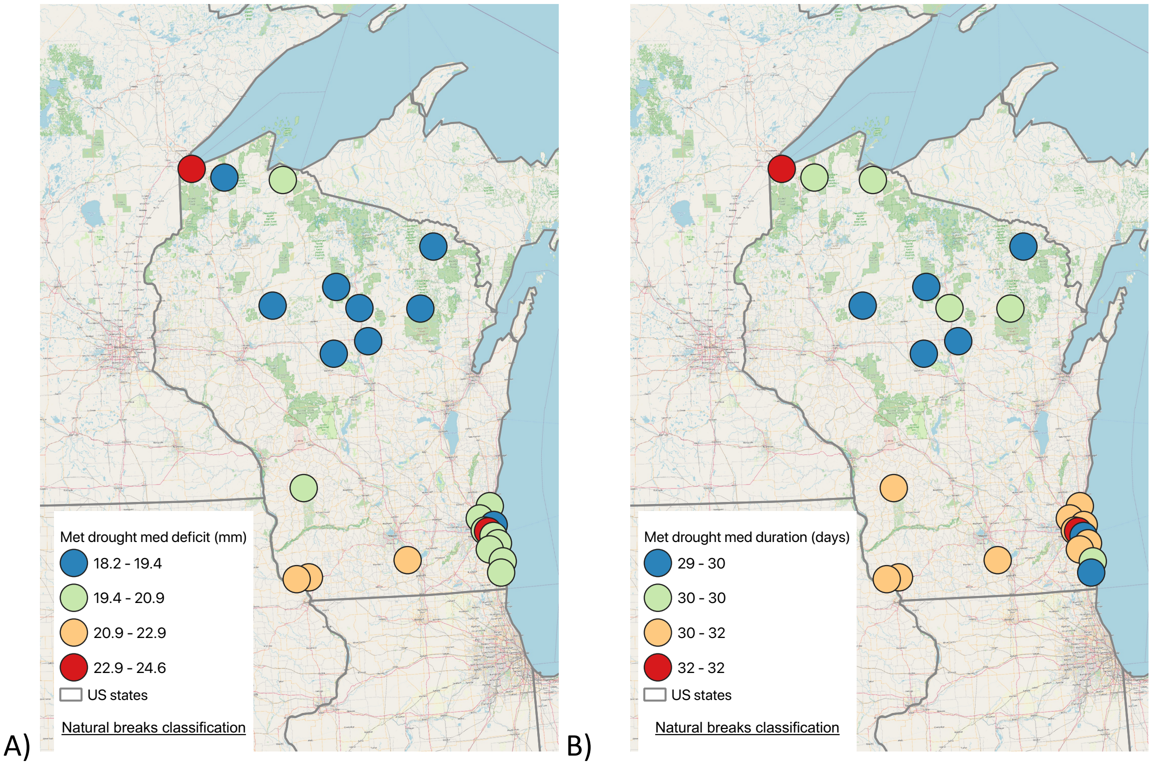

Figure 3. Median deficit (A) and duration (B) of meteorological droughts from the variable threshold approach.

The median deficits and durations of hydrological droughts have much wider variations than those of meteorological droughts (Figure 4). It is difficult to find a pattern for median deficits because the deficit classes are found across the state from north to south except the outlier (red circle), which is the Kinnickinnic River catchment (number 17 in Figure 1). The range of the data is larger than 43 mm, compared to 6.4 mm for meteorological droughts. Median durations show a clearer pattern than median deficits with longer durations found in the south. The maximum is about five times longer than the minimum, and it is also found at the Kinnickinnic River catchment. The Kinnickinnic River catchment is not an outlier with respect to meteorological drought but clearly one with respect to hydrological drought. The catchment is highly urbanized (Appendix 2) unlike any other catchment, and its streamflow shows much more extreme characteristics than other urbanized catchments (Choi et al. 2016). Therefore, the Kinnickinnic River catchment should be treated as a group of its own.

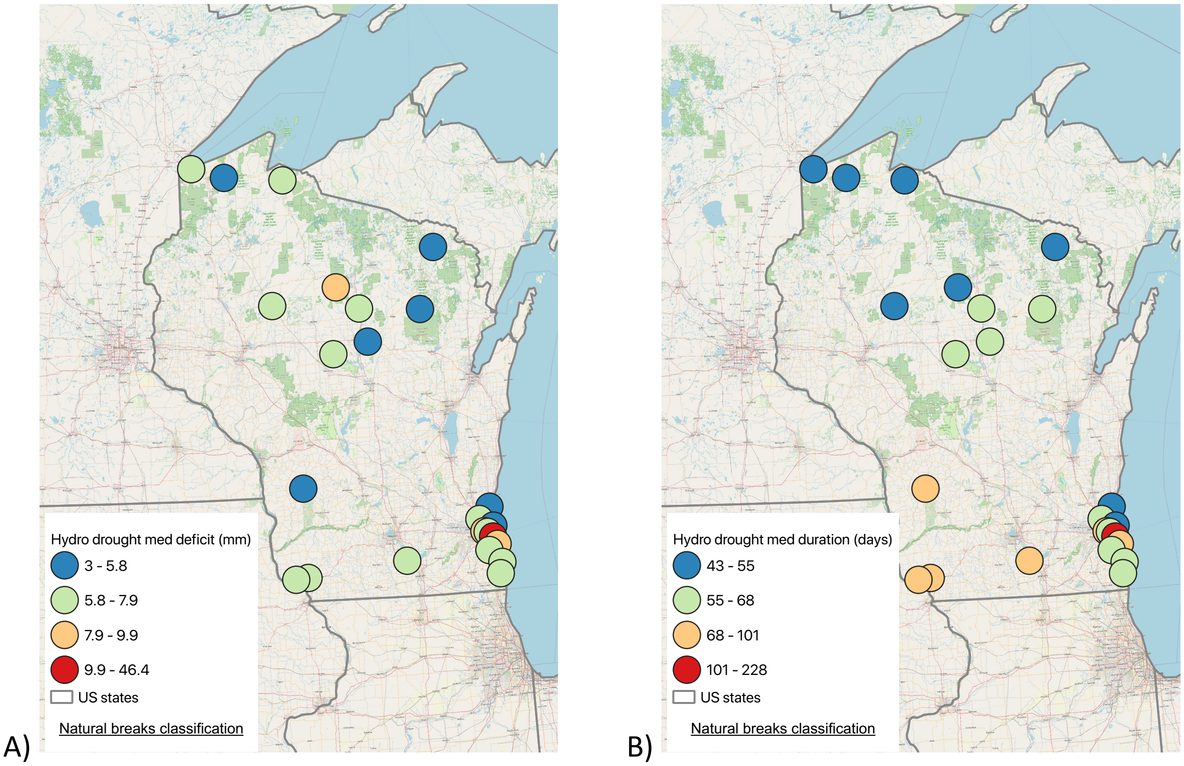

Figure 4. Same as Figure 3 but for hydrological droughts.

When it comes to the number of days below the fixed threshold, meteorological and hydrological droughts show considerable differences in magnitude and trend (Figure 5). For meteorological drought, a few major drought years (e.g., 1988, 2003, and 2012) mildly stand out. The number of days varies to a much larger extent in hydrological drought, being close to zero and exceeding 300 depending on year and catchment. The same drought years stand out as well but much more vividly than those of meteorological drought. The year 1988 particularly caught our attention because the variability was quite large across the catchments. Some of them in the south (numbers 22 and 23 in Figure 1) had around 300 days below the threshold but those in the middle had much fewer. These two catchments had more days of meteorological drought than any other catchment but with much smaller margins. The numbers for hydrological drought are also generally larger in the second half of the period indicated by more abundant greenish and yellowish pixels in the chart. Overall, the occurrence of meteorological and hydrological droughts diverged over time. The same trends were found with the variable thresholds.

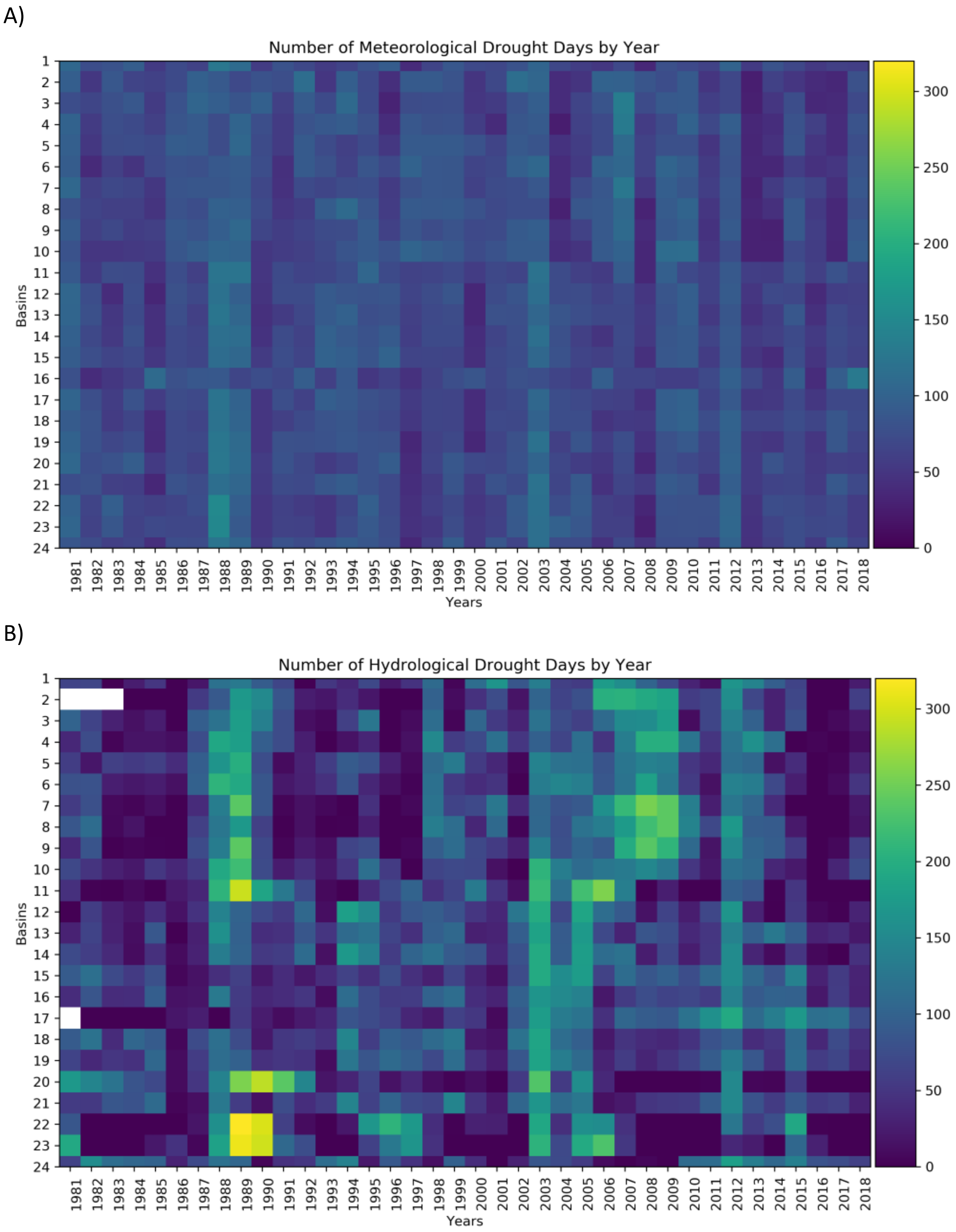

Figure 5. Number of days per year below the fixed threshold for meteorological (A) and hydrological (B) drought by catchment. The basin numbers are the same as those in Figure 1.

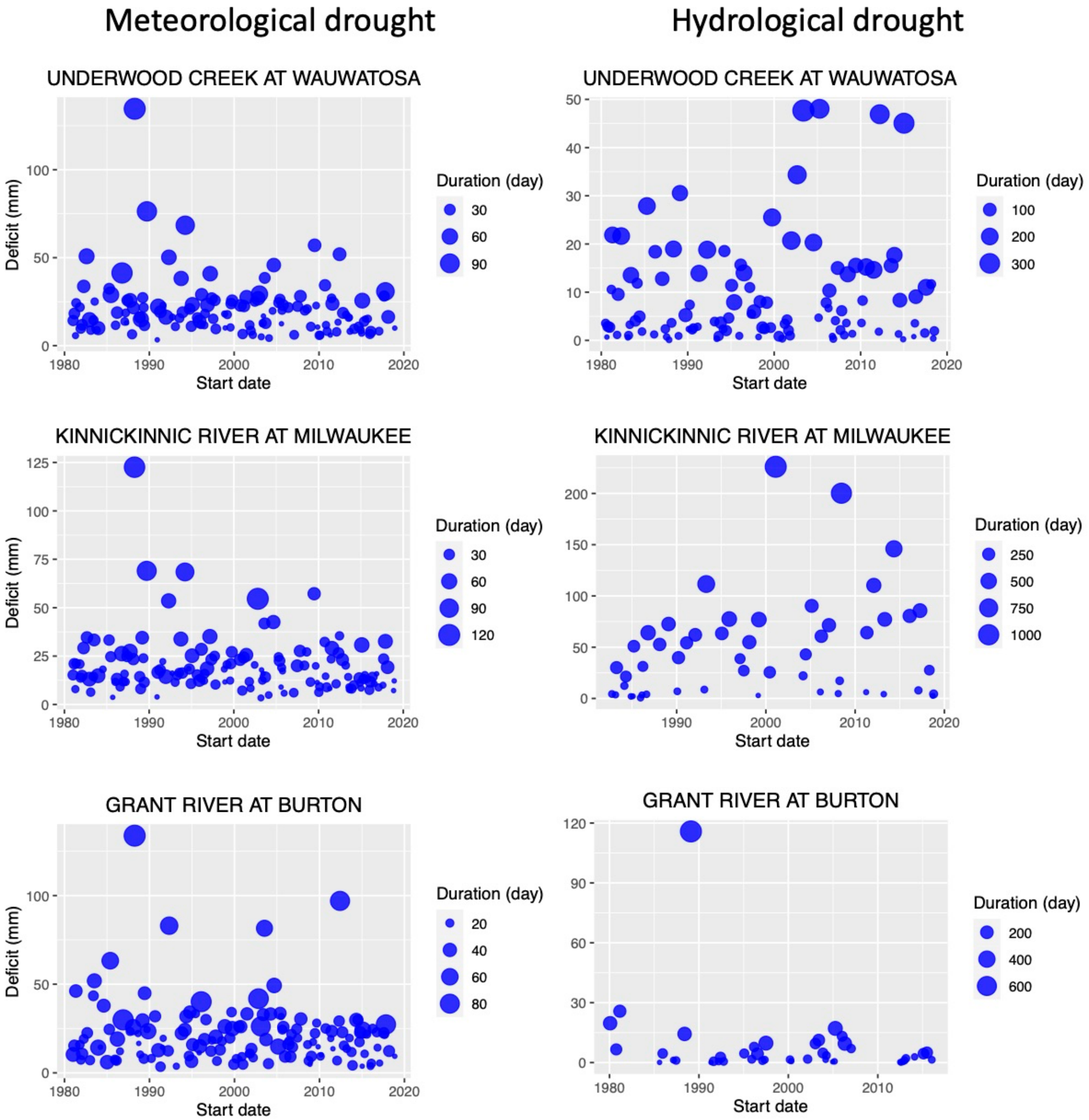

Figure 6. Deficits of meteorological (left) and hydrological (right) drought events from the variable threshold approach against the start dates of the events for select catchments. The size of the circles indicates duration. The data used for the graphs are available as online supplements.

When we focus on the year 2012, the contrast with previous and next years is more striking with hydrological drought than with meteorological drought. The number of meteorological drought days in 2012 is clearly more than those in 2011 and 2013 in most of the catchments, as indicated by the brighter color. Hydrological droughts show stronger contrast in color (e.g., between navy blue and green), indicating a pronounced response of the surface hydrology.

Many basins had similar numbers of hydrological drought days in 2013, meaning the drought carried over to the next year.

The temporal patterns of drought deficits and durations are similar across catchments for meteorological droughts but not for hydrological droughts (Figure 6). The figure shows each drought event's (circle) start day (along the horizontal axis), deficit (along the vertical axis), and duration (size of circle) for three representative catchments. For both types of droughts, deficits and durations generally show positive correlations. The frequency, duration, and deficit of meteorological droughts do not show noticeable differences between the first and the second halves of the time except for the major event in 1988. The drought in 1988 was the most outstanding event for precipitation for all the catchments shown in the figure, but smaller-deficit events occurred quite randomly over time. On the other hand, hydrological droughts show noticeable differences between the first and second halves of the time period and between the catchments as well. The Underwood Creek and Kinnickinnic River catchments have more large-deficit events in the second half whereas the Grant River catchment does not have major events in the second half. The hydrological drought in 1988 was the most outstanding only in Grant River and did not stand out much in Underwood Creek and Kinnickinnic River.

Correlation between the variables of catchment and drought characteristics

The hydrological drought characteristics show significant correlations with few catchment characteristics (Table 3). The median duration of hydrological droughts (Q.DURA) shows the strongest positive correlation ($r = 0.56$) with the percentage of urban land cover (URBA%) of the catchment characteristics, meaning the median duration was longer in more urbanized catchments. It is also significantly correlated with the percentage of forest land cover (FORE%), probably due to the strong negative correlation between URBA% and FORE%. The effect of urban land covers on streamflow is widely known (e.g., Choi et al. 2016, Nardi, Annis, and Biscarini 2018, Astuti et al. 2019), and they appear to have negative effects on hydrological droughts. Van Loon and Laaha (2015) found durations of hydrological droughts significantly correlated with baseflow index, which is similar to recharge in this study. But Q.DURA had only an insignificant negative correlation with recharge (RECHA) ($p > 0.4$) and did not have a significant correlation with annual streamflow (RUNOFF) either ($p > 0.17$).

Table 3. Pearson's correlation coefficients between drought characteristics from the variable threshold approach and the other variables. Boldfaced numbers indicate $p < 0.05$, and boldfaced and underlined indicate $p < 0.01$. The entire correlation matrix is available as online supplements.

	Q.DURA	Q.DEFI	P.DURA	P.DEFI	Q.FREQ
RECHA	–0.179	–0.208	0.217	0.059	–0.365
AREA	–0.346	–0.273	–0.011	–0.155	–0.13
SLOPE	0.134	–0.094	0.137	0.159	**–0.513**
AS_150	0.151	0.07	0.254	**0.453**	0.207
DRAIN	–0.156	0.086	–0.249	–0.226	**0.715**
FORE%	**–0.408**	–0.301	–0.204	–0.337	–0.249
AGRI%	–0.016	–0.225	0.117	0.285	–0.243
URBA%	**0.560**	0.575	0.144	0.165	0.382
WELLS	–0.214	**–0.195**	0.038	–0.047	0.117
RUNOFF	0.283	0.383	0.091	0.033	–0.104
Q.DURA	1	0.934	–0.108	0.088	**–0.433**
Q.DEFI	0.934	1	–0.207	–0.039	–0.254
P.DURA	–0.108	–0.207	1	0.844	0.023
P.DEFI	0.088	–0.039	0.844	1	–0.043
PRECI	0.125	0.010	**0.724**	**0.815**	0.049
Q.FREQ	**–0.433**	–0.254	0.023	–0.043	1

The median deficit of hydrological droughts (Q.DEFI) had a significant correlation only with URBA% and no other catchment characteristic. It had a positive correlation with RUNOFF ($p < 0.065$), suggesting deficits tend to increase with streamflow. The number of hydrological drought events (Q.FREQ) was significantly correlated with mean slope (SLOPE) ($p < 0.011$) and drain class (DRAIN) ($p < 0.0001$), and it had a marginally significant correlation with RECHA ($p < 0.08$). More frequent droughts tend to be associated with smaller recharge, which makes sense because streamflow is more stable with higher recharge. RECHA was significantly correlated with DRAIN which was significantly correlated with SLOPE. This is probably why Q.FREQ showed significant correlations with DRAIN and SLOPE.

We note that hydrological drought characteristics had no significant correlations with meteorological drought characteristics (P.DURA and P.DEFI) or annual precipitation (PRECI). PRECI was significantly correlated only with P.DURA and P.DEFI. Even though hydrological droughts occur following the onset of meteorological droughts, catchments with higher annual precipitation do not necessarily have hydrological droughts with longer durations or larger deficits.

Drought propagation during 2012

There were significant meteorological drought events in 2012 and to a less extent in 2011 and 2013 (Figure 7). In the figure, the red areas indicate drought conditions of all durations before pooling. There were many occasions in 2012 when precipitation was extremely low for weeks. The year 2011 also saw a few intense drought events in the middle of the year when the threshold was high, but not as frequently as 2012. The meteorological drought in 2013 is mostly concentrated in late summer and early autumn. This picture of meteorological drought is very similar across the catchments.

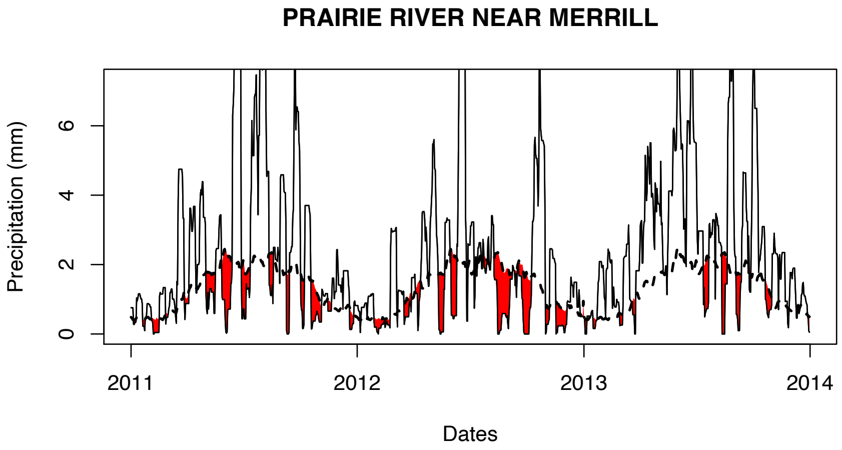

Figure 7. Meteorological drought for the station Prairie River near Merrill during 2011–2013. The dashed line is the variable threshold and the solid line is daily precipitation, thus the red areas indicate drought events of all sizes before pooling.

Hydrological droughts in 2012 are very different from those in 2011 and 2013 and between catchments (Figure 8). We identified three types of hydrological droughts during that time and each of them is represented in the figure. The Prairie River catchment (Figure 8A) represents most of the catchments. There were some minor drought events throughout 2011 and a noticeable event in June 2011, and through much of 2012, the catchment was in a drought condition. The streamflow was extremely low in much of summer and autumn of 2012 in response to intense meteorological drought events, but because it is a low-flow season anyway, the deficit is much smaller than in spring droughts. After pooling dependent events and removing minor ones, we found three major events in 2012. The first one occurred from late March to early May, the second one mid-May to mid-June, and the third one late June through the end of the year. During these times, meteorological drought occurred partially overlapping the hydrological drought but with more frequent and longer intermissions. The intermission was particularly long in the autumn, from early October to mid-November. The late summer of 2013 had very little precipitation, but it did not translate into a hydrological drought.

The Kinnickinnic River catchment (Figure 8B) is a unique case. It was in a drought condition in much of the period, and the streamflow is extremely variable during not only this period but also the entire data period. Major droughts occurred over the entire year of 2012 except for about two weeks from late January to early February. It is as if hydrological drought occurred regardless of meteorological drought. The catchment also shows remarkably different drought occurrences between fixed and variable threshold levels. Hydrological drought events with a deficit of 50–100 mm (approximately middle of the range) occurred almost evenly according to the variable threshold (Figure 6). However, because low flows were clearly lower in the second half of the data period, droughts were much more frequent in the second half based on the fixed threshold (Figure 5).

The Platt River catchment (Figure 8C), along with Kickapoo River, Grant River, and Badfish Creek (not shown) had no drought in 2011 through the spring of 2012. There was only one major hydrological drought event, and it started in June after the onset of the third major meteorological drought event of the year. All of the catchments are found in the southwestern part of Wisconsin where there are no glacial deposits and show similar deficit-duration trends over time (Figure 6). In terms of deficit, both the meteorological and hydrological drought events that started in 1988 were the most significant in the catchments. The catchments also lie over confined aquifers (Borchardt 2019), and recharge is high relative to streamflow. The number of wells is relatively few. Therefore, we speculate that there is not a high level of human activity negatively affecting hydrological drought in these catchments.

The drought in 2012 occurred in much of the Great Plains region without an early warning (Hoerling et al. 2014), and our results demonstrate its sudden nature for streamflow. It is considered a flash drought due to its sudden onset and rapid development (Haile et al. 2020, Pendergrass et al. 2020). The sudden onset is manifested in Figure 8C which shows no drought from 2011 through the middle of 2012. The spring streamflow was lower in 2012 than 2011 and 2013, but it was well above the threshold. Streamflow remained below the threshold for most of the second half of 2012. In the Prairie River catchment (Figure 8A), there were major drought events in spring 2012, and the summer-autumn drought was much smaller in terms of deficit. Because spring is a high-flow season, the variable threshold level is higher than in summer and autumn. Therefore, even though hydrological droughts with large deficits and long durations occurred in spring 2012, they probably did not receive much attention. According to the fixed threshold, there were only a few events with short durations and small deficits (not shown). The drought continued through the summer with a growing deficit, meaning a lack of streamflow in a low-flow season. Therefore, the absolute flow level was extremely low. Summer is a humid season in the region, but precipitation was very low in much of 2012. Combined with high evaporation and low soil moisture, the hydrological drought was extraordinary.

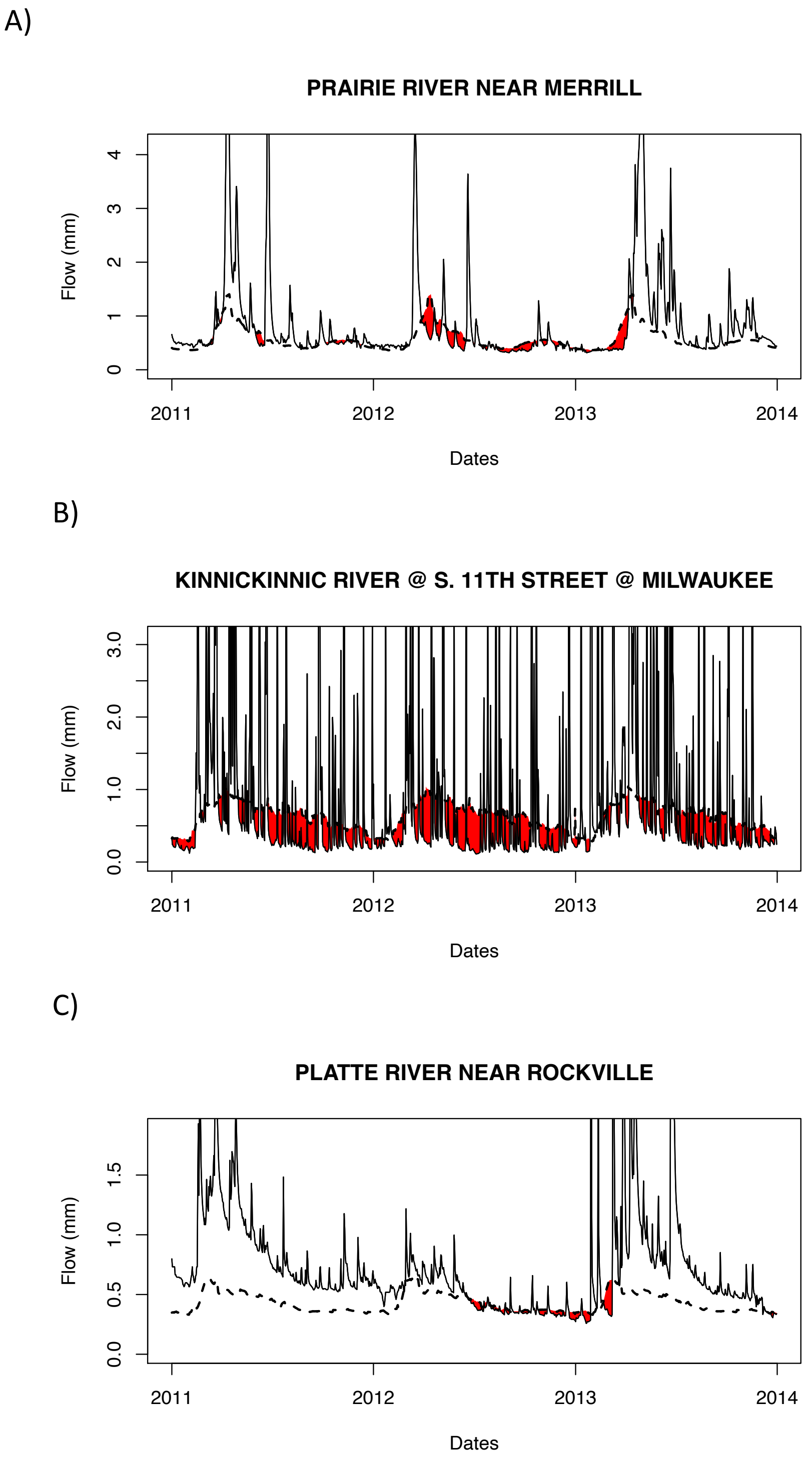

Figure 8. Hydrological drought for three representative stations during 2011-2013. The dashed line is the variable threshold, and the solid line is daily streamflow, thus the red areas indicate drought events of all sizes before pooling.

Our results reveal drought conditions in the mid-summer of 2012 that the USDM did not show. Approximately the southern half of Wisconsin had drought at the beginning of July 2012 according to the USDM (Tinker 2012a), and a nationwide map (Tinker 2012b) shows that the drought was expanding from the south. Our data showed that all but seven catchments were already experiencing hydrological drought at the time. Six of them are in the north, consistent with the USDM. However, several catchments in the northern half of the state had hydrological drought missing in USDM data. The spring hydrological droughts were better captured in the USDM. By the 1st of May, approximately the northern half of Wisconsin had drought according to the USDM (not shown), which is consistent with Figure 8A. In May and June, most of the state was drought-free according to the USDM, but our data showed hydrological droughts in several catchments. Therefore, the USDM is plausibly more cautious than our approach in identifying droughts in part because it considers not only streamflow percentiles but also precipitation- and soil-moisture-based indices.

Human impacts on drought characteristics

In the Eau Claire River catchment (number 9 in Figure 1), human impacts generally led to more frequent hydrological droughts with longer durations and larger deficits (Table 4). Frequency increased by 21 percent, and median duration increased by 115 percent. The increase in deficit is astounding. Maximum deficit almost tripled, and median deficit increased fivefold. The catchment has much lower streamflow than the benchmark catchment despite having very similar temperature and precipitation. Therefore, the drought threshold derived from the benchmark catchment is much higher than that from the human-impact catchment. When such a high threshold was applied to the human-impact catchment, drought occurred on more days, and the streamflow fell further below the threshold. Withdrawal from the unconfined aquifer led to reduced streamflow and aggravated drought in the Eau Claire River catchment.

Table 4. Changes in drought characteristics due to human activities in the Eau Claire River (human-impact) catchment compared to the Prairie River (benchmark) catchment

	Human-impact	Benchmark	Changes due to human activities
Frequency	92	76	21%
Maximum duration (days)	505	305	66%
Maximum deficit (mm)	115.69	38.99	197%
Median duration (days)	87	40.5	115%
Median deficit (mm)	14.48	2.87	404%

Discussion

Spatial and temporal trends of drought characteristics

There is geographical consistency in hydrological drought for the conterminous United States (Ahmadi, Ahmadalipour, and Moradkhani 2019), and we have provided a more detailed picture for Wisconsin. In particular, we examined drought in southeastern Wisconsin that was missing in previous national-scale studies (Poshtiri, Towler, and Pal 2018, Ahmadi, Ahmadalipour, and Moradkhani 2019) and identified roughly three distinctive regions of hydrological drought in Wisconsin.

In general, southwestern Wisconsin belongs to the Driftless Area and has distinctive characteristics of hydrological drought from the rest of the state. The three catchments with the steepest slopes (Appendix 2) are located here. They show significantly increasing trends in annual 7-day minimum flow between the 1930-40s and 1991 (Gebert and Krug 1996) and in baseflow since the 1980s (Borchardt 2019). The increasing low-flow trend is largely due to land management (Gebert and Krug 1996). Such trends align with the decreasing trends in the number of drought days with the fixed threshold (Figure 5) and highlight the effect of catchment conditions on hydrological drought. In southeastern Wisconsin, the heavily-urbanized Kinnickinnic River basin is unique and strongly contrasts with the nearby Milwaukee River basin (number 14 in Figure 1) which is about half-agricultural. The Kinnickinnic River basin clearly shows an increasing trend in the number of drought days, whereas the Milwaukee River basin or others in the area do not. Even though the Kinnickinnic River basin shows an increasing trend in mean annual runoff during the period 1983-2008 (Choi et al. 2016), its hydrological drought did not abate. Therefore, catchment management should focus not only on flood management but also on drought management.

Even though we did not explicitly analyze temporal trends, our findings suggest that meteorological drought was generally stable, and hydrological drought increased in much of the state in terms of the deficit of the events. Previous studies found predominantly decreasing trends of drought in the 20th century in Wisconsin (Andreadis and Lettenmaier 2006) and in a river basin in Wisconsin (Choi et al. 2018). Considering that precipitation generally increased in Wisconsin during the second half of the 20th century (Kucharik et al. 2010), the decreasing drought trend is not surprising. Our study was conducted for a shorter and later period of time, so it is not in conflict with previous ones. Instead, it highlights decreasing synchrony between meteorological and hydrological droughts, which suggests human impacts on hydrological drought.

Catchment characteristics and drought characteristics

The correlation between catchment characteristics and drought characteristics was weaker than we had anticipated. Only land cover was significantly correlated with hydrological drought's duration and deficit, and there was no correlation between the characteristics of meteorological and hydrological droughts. Groundwater characteristics such as aquifer types or storage capacity are known to have substantial effects on hydrological drought (Van Lanen et al. 2013, Van Loon and Laaha 2015, Barker et al. 2016). In this study, we used soil storage and drainage and groundwater discharge variables in the correlation analysis, but none of them had significant correlations with the duration or deficit of hydrological drought. This could be in part because we did not use detailed geological variables in the analysis. The aforementioned studies were all conducted for catchments in Europe, and studies for the US hydrological drought (Mo 2008, Poshtiri, Towler, and Pal 2018) did not examine such variables. Therefore, further research is warranted in this area for the US catchments. Modeling-based approaches incorporating groundwater processes could also demonstrate the relationship.

The lack of correlation between meteorological and hydrological drought characteristics corroborates the decreasing synchrony between the two types of drought in the region. High correlations between hydrological drought deficit and climate-related variables are expected (Van Loon and Laaha 2015) because higher precipitation generally leads to higher streamflow, thus higher threshold levels. We found only a marginally significant, positive correlation between hydrological drought deficit and runoff. The variability of streamflow across the basins is much larger than that of precipitation when we measured it by the coefficient of variation (0.21 and 0.07, respectively). Because they do not covary to a great extent, the correlation is weak at best.

Human impacts on drought characteristics

We found aggravated hydrological drought due to irrigation, which was reported in previous studies (Wada et al. 2013, He et al. 2017, van Loon et al 2019). In particular, van Loon et al (2019) employed the same approach adopted here, thus their work is comparable to ours. A major difference in the results was the enormous impact on the deficits in our study. One reason is that the benchmark catchment has much larger runoff than the human-impact catchment as we mentioned before. We also think it is because the streamflows of the two catchments in our study fluctuate much more harmoniously than in van Loon et al (2019). In van Loon et al (2019), the peaks and troughs of streamflow between the two catchments were in less accordance, and the effect of groundwater abstraction was very seasonal. As a result, in our study, the occurrence of drought was relatively similar whereas the deficit was much larger in the human-impact catchment than in the benchmark catchment.

The differences in drought characteristics cannot be fully explained by human activities due to the uncertainty in the catchment pairing (Van Loon et al 2019), but human activities explain most of them for our study. There is no other major influence on drought in the catchments to the best of our knowledge, and there are no reservoirs in either catchment. Groundwater withdrawal was widespread as early as 1967 for municipal and agricultural uses in the human-impact catchment (Devaul and Green 1971). On the other hand, there is no incorporated place in the benchmark catchment, meaning it is undeveloped. These two catchments are on the edge of the major cluster of high-capacity wells in Wisconsin. The results provide a clue for the hydrological impacts of high-capacity wells in the Central Sands region, where the potential impacts of groundwater withdrawal on water resources have become a major concern (Wisconsin Department of Natural Resources 2018). Because there are not many long-term streamflow datasets for the Central Sands region, further research would require hydrological modeling.

Conclusions

In this study, we provide a broad picture of drought with regard to the synchrony between meteorological and hydrological droughts, the relationship between drought characteristics and catchment characteristics, and human impacts on hydrological drought for the state of Wisconsin. Both meteorological and hydrological droughts were diagnosed using the threshold-level method. The findings from the study are summarized as follows: (1) meteorological droughts do not show particular trends, but hydrological droughts tend to occur more frequently in recent years; (2) characteristics of hydrological droughts show no correlations with those of meteorological droughts or annual precipitation; (3) three drought regions have been identified in Wisconsin showing unique drought trends and propagation characteristics; and (4) groundwater withdrawal from unconfined aquifers have substantially increased the duration and deficit of hydrological droughts.

We argue that human activities have had substantial impacts on hydrological droughts which became less synchronous with meteorological droughts in recent decades in Wisconsin. The implications of the study are multifold: The reduced synchrony is likely to make drought early warning more challenging; a modeling-based approach is needed to corroborate the findings from this study for the Central Sands region where science, economy, and politics conflict; glacial deposits potentially affect hydrological droughts; drought planning and water management should consider both climate change and human activities on the ground. This study offers insights into drought propagation and human impacts and should be complemented by subsequent studies considering different types of human activities and climate regimes.

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Figure Captions

Figure 1. US Geological Survey streamflow gauges used in the study. Station IDs associated with the serial numbers are found in Appendix 1. The benchmark station and the human-impact station in Table 2 are enclosed in a circle and a triangle, respectively. The southeastern part of Wisconsin is expanded in the upper-right corner.

Figure 2. Illustrations of drought diagnosis using the (A) fixed and (B) variable threshold level methods from the same hypothetical dataset. Solid lines indicate the water level (e.g., streamflow) and the dashed lines indicate threshold levels. Red areas indicate the deficit volumes of the drought events.

Figure 3. Median deficit (A) and duration (B) of meteorological droughts from the variable threshold approach.

Figure 4. Same as Figure 3 but for hydrological droughts.

Figure 5. Number of days per year below the fixed threshold for meteorological (A) and hydrological (B) drought by catchment. The basin numbers are the same as those in Figure 1.

Figure 6. Deficits of meteorological (left) and hydrological (right) drought events from the variable threshold approach against the start dates of the events for select catchments. The size

of the circles indicates duration. The data used for the graphs are available as online supplements.

Figure 7. Meteorological drought for the station Prairie River near Merrill during 2011–2013. The dashed line is the variable threshold and the solid line is daily precipitation, thus the red areas indicate drought events of all sizes before pooling.

Figure 8. Hydrological drought for three representative stations during 2011-2013. The dashed line is the variable threshold, and the solid line is daily streamflow, thus the red areas indicate drought events of all sizes before pooling.

Appendix 1. Names and coordinates of the USGS gauging stations

Serial number	Station ID	Station name	Latitude	Longitude
1	04024430	NEMADJI RIVER NEAR SOUTH SUPERIOR, WI	46.633	-92.094
2	04025500	BOIS BRULE RIVER AT BRULE, WI	46.538	-91.595
3	04027000	BAD RIVER NEAR ODANAH, WI	46.487	-90.696
4	04063700	POPPLE RIVER NEAR FENCE, WI	45.764	-88.463
5	05393500	SPIRIT RIVER AT SPIRIT FALLS, WI	45.449	-89.979
6	05362000	JUMP RIVER AT SHELDON, WI	45.308	-90.957
7	05394500	PRAIRIE RIVER NEAR MERRILL, WI	45.236	-89.650
8	04074950	WOLF RIVER AT LANGLADE, WI	45.190	-88.733
9	05397500	EAU CLAIRE RIVER AT KELLY, WI	44.919	-89.552
10	05399500	BIG EAU PLEINE RIVER AT STRATFORD, WI	44.822	-90.080
11	05408000	KICKAPOO RIVER AT LA FARGE, WI	43.574	-90.643
12	04086600	MILWAUKEE RIVER NEAR CEDARBURG, WI	43.280	-87.943
13	04087030	MENOMONEE RIVER AT MENOMONEE FALLS, WI	43.173	-88.104
14	04087000	MILWAUKEE RIVER AT MILWAUKEE, WI	43.100	-87.909
15	04087088	UNDERWOOD CREEK AT WAUWATOSA, WI	43.055	-88.046
16	04087120	MENOMONEE RIVER AT WAUWATOSA, WI	43.046	-88.000
17	04087159	KINNICKINNIC RIVER @ S. 11TH STREET @ MILWAUKEE,WI	42.998	-87.926
18	04087204	OAK CREEK AT SOUTH MILWAUKEE, WI	42.925	-87.870
19	04087220	ROOT RIVER NEAR FRANKLIN, WI	42.874	-87.996
20	05430150	BADFISH CREEK NEAR COOKSVILLE, WI	42.833	-89.197
21	04087240	ROOT RIVER AT RACINE, WI	42.751	-87.824
22	05414000	PLATTE RIVER NEAR ROCKVILLE, WI	42.731	-90.640
23	05413500	GRANT RIVER AT BURTON, WI	42.720	-90.819
24	04087257	PIKE RIVER NEAR RACINE, WI	42.647	-87.861

Appendix 2. Catchment characteristics.

Site ID	AREA	SLOPE	AS_150	DRAIN	FORE%	AGRI%	URBA%	WELLS	RUNOFF	RECHA	PRECI
04024430	1,087.8	4.757	21.62	4.143	51.2	10.5	2.5	0	322.2	232.7	915.7
04025500	305.6	4.796	17.82	3.086	65.6	1.4	3.9	5	501.5	505.2	859.4
04027000	1,546.2	5.900	20.57	4.443	67.4	5.8	2.6	10	362.4	271.4	848.3
04063700	360.0	3.226	19.02	4.552	45.8	0.6	1.9	0	264.4	220.8	773.3
05393500	211.3	3.990	19.47	4.730	59.3	4.8	2.7	0	394.0	281.8	829.8
05362000	1,491.8	2.508	25.61	5.193	48.8	9.2	2.6	11	328.1	215.2	815.6
05394500	476.6	4.627	20.50	4.347	48.9	9.0	2.8	6	322.6	271.5	827.0
04074950	1,199.2	4.625	18.08	4.002	53.8	3.2	3.3	26	309.4	293.8	799.6
05397500	971.2	2.758	20.06	4.153	37.0	30.5	5.1	239	224.8	166.1	834.9
05399500	580.2	2.396	19.71	4.800	15.5	71.1	4.9	40	280.4	140.1	807.2
05408000	688.9	18.534	21.50	3.242	50.1	43.9	4.7	35	274.3	235.1	934.5
04086600	1,572.1	4.267	22.79	3.910	13.5	53.6	11.5	208	273.9	246.3	872.3
04087030	89.9	2.646	24.64	4.423	8.9	37.9	34.9	36	332.7	249.2	869.5
04087000	1,802.6	4.080	22.91	3.914	13.0	48.8	11.8	300	279.0	250.6	850.6
04087088	46.9	3.850	24.00	4.678	2.3	1.2	90.2	29	313.1	170.0	866.5
04087120	318.6	3.049	23.50	4.467	5.7	18.6	64.8	129	341.8	226.0	1088.8
04087159	48.7	3.544	21.94	4.180	0.7	0.3	98.2	1	459.7	192.8	871.2
04087204	64.7	3.272	21.36	4.658	12.3	10.8	62.6	2	360.3	243.8	868.4
04087220	127.4	3.491	21.28	4.564	9.2	7.5	72.8	37	320.7	184.0	862.1
05430150	213.9	3.016	23.35	3.812	7.9	74.9	9.0	15	488.1	482.6	915.7
04087240	492.1	2.530	22.33	4.567	9.6	49.2	30.8	84	302.9	200.4	886.7
05414000	367.8	11.810	22.72	3.070	18.6	77.1	3.8	8	280.8	255.9	919.9
05413500	696.7	10.862	23.22	3.078	18.0	76.5	5.2	8	264.5	239.8	902.6
04087257	99.7	2.080	24.09	4.259	5.3	51.8	35.7	8	354.2	246.0	891.4