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DOI
10.1002/hyp.15229

Publication date
2024

Document Version
Final published version

Published in
Hydrological Processes

Received: 7 November 2023 | Revised: 20 June 2024 | Accepted: 24 June 2024
DOI: 10.1002/hyp.15229

RESEARCH ARTICLE

WILEY

Formative drought rate to quantify propagation from meteorological to hydrological drought

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Funding information
Scientific and Technological Research Council of Turkey (TUBITAK); Department of Water Management

Abstract
In this study, we propose a probabilistic metric, the formative drought rate (FDR), to quantify drought propagation. It is the probability that a meteorological drought in precipitation forms a hydrological drought in streamflow. Drought events were identified based on the standardized precipitation index and streamflow drought index, respectively, at 1-, 3-, 6- and 12-month timescales. The method was tested in three river basins in Turkey (Kucuk Menderes, Gediz and Ergene). In each river basin, meteorological stations were coupled with streamflow gauging stations to form pairs of stations depending on their distance from each other and the length of their common record periods. The FDR was calculated across all timescales for each pair of stations. It was found capable to describe the river basin-specific spatial and temporal variability of drought propagation. As the FDR is defined in the form of probability, it is expected to be a useful metric for quantifying propagation from meteorological to hydrological drought. Thus, it carries a potential for scientific research and practice in water resources management.

KEYWORDS
drought propagation, formative drought rate, hydrological drought, meteorological drought, standardized precipitation index, streamflow drought index

1 | INTRODUCTION

Understanding droughts is of significant importance for water resources planning and management as they have a profound impact on water availability. For a full understanding, it is important to investigate different types of droughts and how they evolve from one type to another; that is, *drought propagation* (Changnon, 1987; Eltahir & Yeh, 1999; Van Loon, 2015). Drought typically starts as meteorological drought with a deficit in precipitation, which then can further propagate into agricultural and hydrological droughts if the precipitation deficit leads to deficits in soil moisture and eventually in streamflow. Drought propagation is not straightforward, the underlying processes behind it and their interactions are manifold and not yet completely understood nor quantitatively described. According to Wang et al. (2016), most of the descriptions of drought propagation remain qualitative, while more quantitative descriptions are required for more reliable predictions of drought propagation. In other words, to improve the preparedness for droughts, the underlying mechanisms of how precipitation deficits evolve into soil moisture and streamflow deficits need to be explored quantitatively. One possible starting point is to compare the occurrence frequencies of precipitation deficits of specific magnitudes to the frequencies of soil moisture and/or streamflow deficits. This may allow estimating the probability of meteorological droughts leading to deficits in soil moisture and/or streamflow. Robust descriptions of this relation between the hydro-climatic variability and the soil moisture or streamflow drought occurrence can then serve as a basis for drought early warning systems. However, an early warning system with a lead time of several weeks or even months has the potential to mitigate the effects of soil moisture and hydrological drought. It facilitates time to implement interventions, such as temporal adjustments in reservoir management or irrigation water allocation to minimize the impacts of the drought.

The number of studies on droughts has been increasing over the past years, and those on drought propagation accommodate a considerable fraction thereof. For example, Heudorfer and Stahl (2017) compared different threshold-level methods in drought propagation and found a substantial increase in short droughts, a moderate decrease in intermediate droughts and a minor increase in long droughts when a variable versus a constant threshold was used. The conclusion was the potential of diverging inference from the same data, depending on the chosen methodology. By using copulas, Wong et al. (2013) showed the probabilistic information contained in meteorological drought which will likely propagate into hydrological drought. Apurv et al. (2017) used numerical experiments in order to understand the roles of climate characteristics by identifying three different drought propagation mechanisms; seasonality, aridity and timing, among which the timing of precipitation was found to have the largest impact. Intermittency in streamflow, that is, the ratio of time with no flow to the total length of observation, was also found to be a driving indicator of the drought propagation (Yildirim & Aksoy, 2022). In a slightly different approach, Roodari et al. (2021) studied human interventions to show how they contribute to moderating or amplifying drought propagation in the downstream and upstream parts of a river basin over time.

Over the last decade, propagation from meteorological drought to hydrological drought has received increased attention. Many studies investigated the specific relation between these two types of droughts using standardized climate indices. For example, Lorenzo-Lacruz et al. (2013) studied drought propagation in the form of streamflow response to meteorological drought in the Iberian Peninsula by using the standardized precipitation index (SPI) for meteorological drought and the standardized streamflow index (SSI) for hydrological drought. By performing a regional analysis of Austrian catchments, Haslinger et al. (2014) found meteorological drought significantly linked with streamflow drought unless groundwater storage and snow are important in the catchment. Barker et al. (2016) found a strong correlation between long accumulation scales of SPI and 1-month SSI for catchments with aquifers large in volume. In catchments with small aquifers, average annual precipitation seemed to have a strong correlation with hydrological drought and propagation characteristics. Shin et al. (2018) performed a comparative analysis between the SPI and the Palmer Hydrological Drought Index (PHDI) for the propagation of meteorological drought, and found that the majority of meteorological droughts propagated into hydrological droughts. Huang et al. (2017) investigated the time of propagation from meteorological drought to hydrological drought, represented by SPI and SSI, respectively, and found that the propagation was a seasonal process; that is, the seasonality was effective on the propagation. Hulsman, Hrachowitz, et al. (2021), Hulsman, Savenije, et al. (2021) analysed spatially averaged and local drought duration, intensity and severity using precipitation, total water storage and reservoir water level data in different drought years from a basin in the Zambezi River at the border of Zambia and Zimbabwe, and found that alternative data sources improved runoff predictions in poorly gauged basins and lead to enhanced understanding of hydrological processes under dry conditions. Um et al. (2022) used standardized precipitation-evaporation index (SPEI), standardized runoff index (SRI) and standardized soil moisture index (SSMI) for meteorological, hydrological and agricultural droughts, respectively, in the Yangtze River basin, China, and found that the 12-month indices are clearer indicators of drought propagation than the 6-month indices as they are based on longer accumulation periods of precipitation deficit, and they become more prone to propagate into deficit in streamflow or soil moisture as their time scale increases.

Considerable number of studies not limited with those above are available within a large range of specific approaches to explain the relation between different types of droughts, that is, propagation from one type to another. These studies are basically devoted to understanding the drought propagation process. The main tool they used are varieties of standardized drought indices such as SPI, SPEI, SSI, streamflow drought index (SDI), SSMI, PHDI, and so forth. The need that emerges from the existing understanding and the state-of-knowledge of drought propagation is a metric to describe drought propagation from meteorological drought to hydrological drought quantitatively. Not many studies exist devoted to the development of such a quantitative metric. One of the two examples is Sattar et al. (2019) who proposed drought propagation rate (DPR). By definition, it is the ratio of number of hydrological droughts to number of meteorological droughts, it is thus not a probability. The non-probabilistic conceptualization of the DPR makes it hard to quantify drought propagation. Liu et al. (2023) made a progress on the DPR by taking the ratio of the number of hydrological droughts propagated from meteorological droughts to the total number of meteorological drought. This is a similar thinking to our approach in this study as a part of a long-lasting research extended over several years (Yildirim, 2023). Our approach differs from that of Liu et al. (2023) who focused on the probability of the propagation between the most correlated timescales among all combinations. In this study, we consider the propagation of meteorological drought to hydrological drought for all combinations of the selected timescales. Thus, we obtain a probability matrix instead of a single probability. This difference with the approach of Liu et al. (2023) is the new point and added value of this study. We aim to address the following research questions based on the knowledge gained from the hydrometeorological data sets of three river basins in Turkey:

1. How can we develop a probability-based simple metric to quantify the propagation from meteorological drought to hydrological drought?
2. How effective will this metric be in passing the drought propagation information to stakeholders and decision-makers for better drought mitigation?

3. Which insights can a data-driven analysis provide regarding the attributes of drought propagation, and in particular the lag time between meteorological drought and hydrological drought?

Next in the paper, we introduced river basins in the study area and the data inventory. The method was then explained step-by-step as detailed as needed from the identification of drought events based on the SPI and SDI time series to the enhanced presentation of results. Discussion of results is followed next to express the pros and cons of the proposed metric together with its potential use by providing also concluding remarks and probable near-future research topics at the end.

2 | STUDY AREA AND DATA

2.1 | River basins

Hydrometeorological data from three river basins in western Turkey, Kucuk Menderes, Gediz and Ergene were used (Figure 1). The characteristics of the river basins are presented in Table 1. Located in the Aegean Region, the Kucuk Menderes River Basin is influenced by the Mediterranean climate with hot dry summers and mild wet winters. Plains cover the downstream part of the river basin. The hilly and mountainous upstream part receives a considerable amount of snow which causes occasional floods in winter. Lands in the river basin are

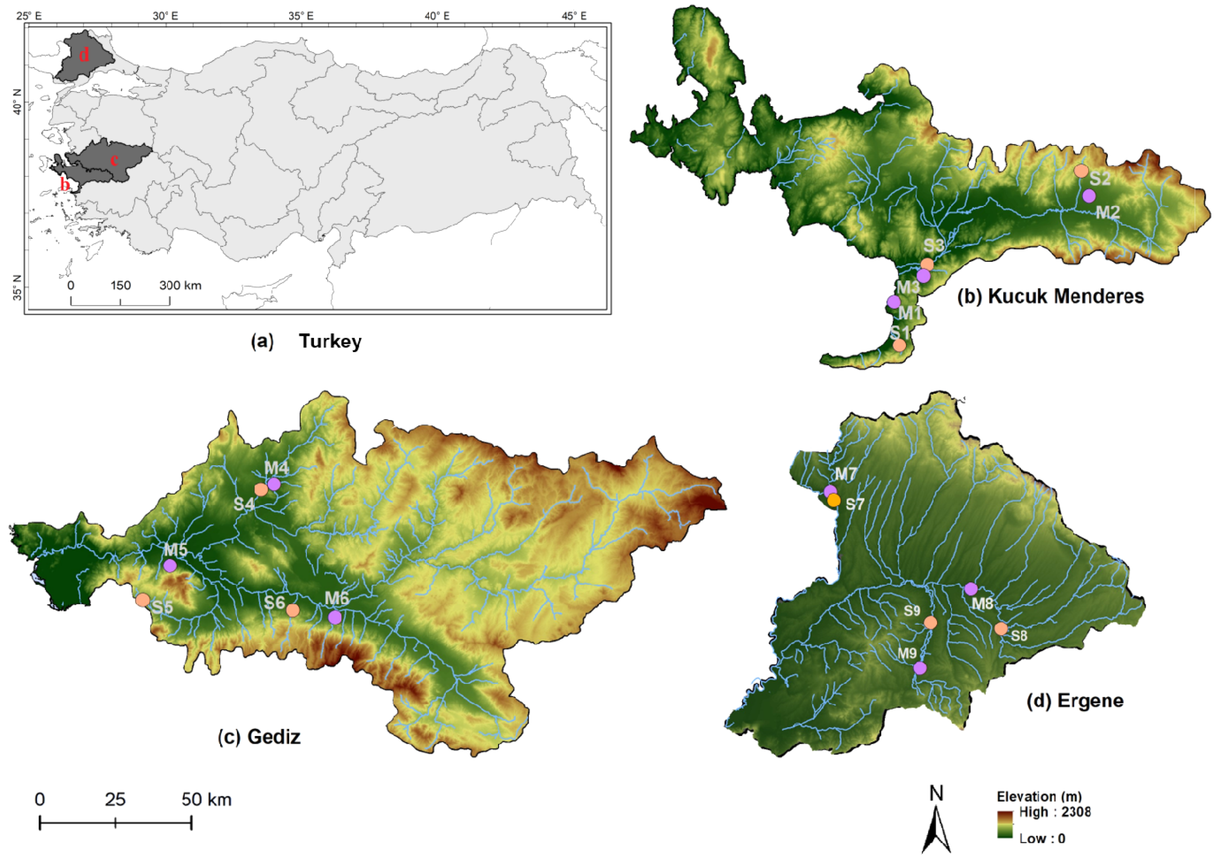

FIGURE 1 (a) Location of studied river basins in Turkey, (b–d) Location of meteorological stations and streamflow gauging stations over Kucuk Menderes, Gediz and Ergene river basins. Letters M and S indicate meteorological and streamflow gauging stations, respectively, and dots numbered together with letters M and S show location of stations in river basins. Scale on the lower left is applied to the maps of the river basins.

TABLE 1 Characteristics of river basins (Aksoy, 2020).

River Basin	Drainage area (km^2)	Mean elevation (m)	Peak elevation (m)	Mean annual temperature (°C)	Mean annual precipitation (mm year^{-1})	Runoff coefficient (–)	Mean annual runoff (mm year^{-1})
Kucuk Menderes	7060	357	2155	17.9	611	0.12	75
Gediz	17 034	576	2305	16.9	578	0.16	90.7
Ergene	14 444	154	1000	13.7	591	0.22	127.5

Note: Mean annual temperature was taken from Izmir and Manisa, two provinces with the largest area in Kucuk Menderes and Gediz river basins, respectively; and it was calculated as the average of three provinces (Edirne, Kirklareli and Tekirdag) in Ergene river basin.

occupied by important agricultural activities with irrigation facilities (Aksoy, 2020; SYGM, 2016). The Gediz River Basin is climatologically similar to the neighbouring Kucuk Menderes. The basin is mountainous in the upstream and it has a large plain in the downstream mostly used for agriculture (Aksoy, 2020; SYGM, 2016, 2019). The Ergene River Basin is one of the main tributaries of Meric River. It is located in the north-western part of Turkey and drains into the Aegean Sea. The river basin has a dendritic river network composed of small rivers and creeks which are mostly intermittent. It is characterized by Mediterranean climate with warm, humid and moderately dry summers, and cold, wet and sometimes snowy winters. The basin has a large plain with a hilly upstream part. Water is mostly consumed by agriculture and industry in the basin (Aksoy, 2020; DSI, 2018; SYGM, 2016).

2.2 | Precipitation and streamflow data

Precipitation data were acquired from meteorological stations (MSs) of the Turkish State Meteorological Service (MGM), and streamflow data from gauging stations (SGSs) of the State Hydraulic Works (DSI) of Turkey. Characteristics of MSs and SGSs are presented in Tables 2 and 3, respectively. The river is considered dry when the streamflow discharge is less than 1 L/s, the smallest value recorded, or the river channel gets totally dry at the SGS cross-section. We coupled MSs and SGSs in pairs depending on their distance from each other and the length of their common record periods. The selected MS-SGS pairs are given in Table 4. The layout of MSs and SGSs can be seen in Figure 1 for the three river basins. The geographical proximity of station pairs in our analysis was driven by practical considerations related to data availability.

3 | METHOD

The method in this study is based on an experiment executed in several steps (Figure 2): (1) Standardization of precipitation and streamflow, (2) Identification of drought events, (3) Determination of propagated drought events, (4) Definition of drought propagation metric, (5) Implementation of the metric, (6) Assessment of findings.

3.1 | Standardization of precipitation and streamflow

In Step 1 of the experiment, monthly precipitation data were transformed into standardized drought indices, which are probabilistic transformation of physical variables with a known distribution to the standard normal distribution (Aksoy & Cavus, 2022; Erhardt & Czado, 2018). As drought indices are widely known in the literature (Cavus et al., 2023; Hong et al., 2015; Tabari et al., 2013), we provide no detail about their formulation but explain how we treated them in this study. Among the standardized drought indices, we used SPI of McKee et al. (1993) and SDI of Nalbantis and Tsakiris (2009), to identify periods of precipitation and streamflow deficits, respectively. The rationale for using SPI is its basic definition applicable to various timescales using precipitation only and the fact that it is a well-established, commonly used index that is used to detect meteorological droughts reliably (Cavus & Aksoy, 2019; Moccia et al., 2022). Similarly, the reason for using SDI is its effectiveness in various timescales and the fact that it has been commonly used to detect hydrological droughts (Malik et al., 2021).

Before the drought indices are calculated, we checked first if the Gamma and Lognormal probability distribution functions fit the

TABLE 2 Meteorological stations and characteristics of annual total precipitation.

River Basin	Station code	Station name (number)	Observation period (mm. yyyy–mm.yyyy)	Observation length (years)	Mean (mm year^{-1})	Max (mm year^{-1})	Min (mm year^{-1})	St dev (mm year^{-1})
Küçük Menderes	M1	Kuşadası (17232)	10.1990–12.2016	26	625.1	798.2	355.0	131.6
	M2	Ödemiş (17822)	10.1979–09.2014	35	565.7	874.2	371.5	111.5
	M3	Selçuk (17854)	01.1970–09.2012	43	669.0	1060.1	342.2	154.4
Gediz	M4	Akhisar (17184)	01.1970–09.2012	43	561.2	866.6	312.5	127.3
	M5	Yunusemre (17186)	01.1970–03.2012	42	691.2	1053.5	294.1	177.0
	M6	Salihli (17792)	10.1997–09.2014	17	493.7	648.4	284.6	101.1
Ergene	M7	Edirne Merkez (17050)	01.1980–12.2014	35	592.0	958.6	387.0	132.8
	M8	Lüleburgaz (17631)	01.1980–03.2011	31	575.1	871.3	388.9	129.4
	M9	Kurtdere (01M010)	01.1970–12.2014	45	582.3	882.0	324.1	125.5

TABLE 3 Streamflow gauging stations and characteristics of annual mean streamflow.

River basin	Station code	Station name (number)	Observation period (mm.yyyy–mm.yyyy)	Observation length (years)	Drainage area (km^2)	Elevation (m)	Mean (mm $year^{-1}$)	Max (mm $year^{-1}$)	Min (mm $year^{-1}$)	St dev (mm $year^{-1}$)
Küçük Menderes	S1	Davutlar (D06A018)	10.1990–12.2016	26	11.3	63	352.3	922.1	56.3	248.8
	S2	Bebekler (D06A011)	10.1979–09.2014	35	37	220	324.5	964.5	51.4	200.1
	S3	Selçuk (E06A001)	01.1970–09.2012	43	3255	4	69.0	321.4	1.7	62.9
Gediz	S4	Kayalıoğlu (E05A009)	01.1970–09.2012	43	902	77	86.3	237.5	12.5	48.0
	S5	Çiçekli (D05A018)	01.1970–03.2012	42	39.5	276	177.8	477.8	31.0	102.1
	S6	Dereköy (D05A039)	10.1997–09.2014	17	95	125	235.8	373.7	69.7	91.6
Ergene	S7	Kirişhane (D01A003)	01.1980–12.2014	35	34 990	30	144.2	267.1	42.6	61.7
	S8	İnanlı (D01A020)	01.1980–03.2011	31	1415	58	95.0	269.5	12.2	60.5
	S9	Hayrabolu (E01A006)	01.1970–12.2014	45	1381	45	130.8	475.1	12.6	100.9

TABLE 4 Selected pairs of meteorological stations (MSs) and streamflow gauging stations (SGSs) and their common data periods.

River Basin	Pair of MS and SGSs	Common data period (mm.yyyy–mm.yyyy)
Küçük Menderes	M1-S1	10.1990–12.2016
	M2-S2	10.1979–09.2014
	M3-S3	01.1970–09.2012
Gediz	M4-S4	01.1970–09.2012
	M5-S5	01.1970–03.2012
	M6-S6	10.1997–09.2014
Ergene	M7-S7	01.1980–12.2014
	M8-S8	01.1980–03.2011
	M9-S9	01.1970–12.2014

Note: The MS-SGS pairs were formed by selecting among the stations of each river basin depending on their distance from each other and the length of their common record periods.

precipitation and streamflow time series, respectively, by using the Kolmogorov–Smirnov test. Both probability distribution functions passed the test, they were taken as the best-fit probability distribution functions. Monthly precipitation accumulated over 1-, 3-, 6- and 12-month timescales were used for calculating SPI and monthly streamflow volume accumulated over the same timescales for SDI. The drought indices were calculated for each month at each time scale. Thus, monthly sequences of SPI_1, SPI_3, SPI_6, SPI_{12}, and SDI_1, SDI_3, SDI_6, SDI_{12} were obtained. We used R4.0 (R Core Team, 2022) and the SPEI package of Beguería and Vicente-Serrano (2017) to calculate SPI and the DrinC software (Tigkas et al., 2015) to calculate SDI. Months with no flow in the rivers were adjusted as follows to avoid gaps in the SDI calculation: zero values of the streamflow records were changed to 0.1 L/s, which is a value one order of magnitude lower than the smallest value of the recorded discharge (1 L/s).

3.2 | Identification of drought events

In Step 2, we identified drought events from the calculated SPI and SDI sequences. A drought event is a period of time over which the drought index has a value lower than the threshold. As proposed by McKee et al. (1993) and applied frequently (e.g., Aksoy et al., 2021; Cavus & Aksoy, 2020; Moccia et al., 2022), we used zero ($SPI = 0$, $SDI = 0$) as the threshold for both indices. Fleig et al. (2006) refers to subsequent drought events interrupted by short (in time) and weak (in magnitude) wet periods as dependent droughts. In this study, we called such wet periods the intervening wet periods (IWPs). Sequences of multiple short droughts interrupted by IWPs may lead to misinterpretations of propagation from precipitation drought to streamflow drought. To avoid this, we pooled such droughts if the following criteria are met (Figure 3):

1. Duration of the IWP (w) is shorter than the duration of the previous and next droughts (e.g., $w_1 < \min(d_1, d_2)$). Here, the duration is the time over which the drought extends.
2. Duration of the IWP is shorter than the timescale (k) of the drought index ($w_1 < k$).
3. Maximum value of the drought index in the IWP (W) is smaller than its minimum absolute value in the previous and next droughts (D) ($W_1 < \min(D_1, D_2)$).
4. Severity of the IWP (S^+) is lower than the severity of the previous and next droughts (S^-) ($S_1^+ < \min(S_1^-, S_2^-)$). Here, the severity is the sum of the drought index over the drought duration, and the intensity is the ratio of severity to the drought duration.
5. Maximum value of the drought index in the IWP does not exceed 0.5 ($W_1 < 0.5$).

By implementing these criteria, Figure 3 shows that the first wet period can be considered an IWP and be omitted as it is shorter and weaker than the neighbouring droughts. However, the second wet period is not omitted because it is longer than the third drought event and/or the timescale ($w_2 > \min(d_2, d_3)$ and/or $w_2 > k$); it is stronger than the neighbouring droughts ($W_2 > \min(D_2, D_3)$ and/or $S_2^+ > \min(S_2^-, S_3^-)$), and/or the index value exceeds 0.5 ($W_2 > 0.5$). Having identified the drought events, their descriptive characteristics, for example, duration, severity, intensity, were obtained for the selected meteorological and streamflow gauging stations.

3.3 | Determination of drought propagation

In Step 3, we assumed that a drought in precipitation (meteorological drought) propagated to a drought in streamflow (hydrological drought) if the latter started before the former ended. These overlapping droughts were called Propagating Meteorological Drought (PMD) and Propagated Hydrological Drought (PHD). The number of months from the beginning of a PMD to the first month of the associated PHD was taken as the lag time between the PMD and PHD. In case multiple PMDs overlap the same PHD, the one that started the earliest was considered in calculating the lag time. The lag time was calculated between the SPI_k and SDI_m time series ($k = 1, 3, 6, 9$ months and $m = 1, 3, 6, 9$ months) for meteorological droughts propagated into hydrological droughts. Thus, a 4×4 matrix of lag times is obtained for each station pair.

3.4 | Definition of drought propagation metric

Step 4 of the experiment is devoted to the development of the quantitative drought propagation metric. For the quantification of drought propagation, Sattar et al. (2019) defined the drought propagation rate (DPR) as:

$$DPR = \frac{n_p}{m}, \quad (1)$$

where n_p is the number of hydrological droughts propagated from meteorological droughts, and m is the total number of meteorological droughts in the entire period of observation. Higher drought

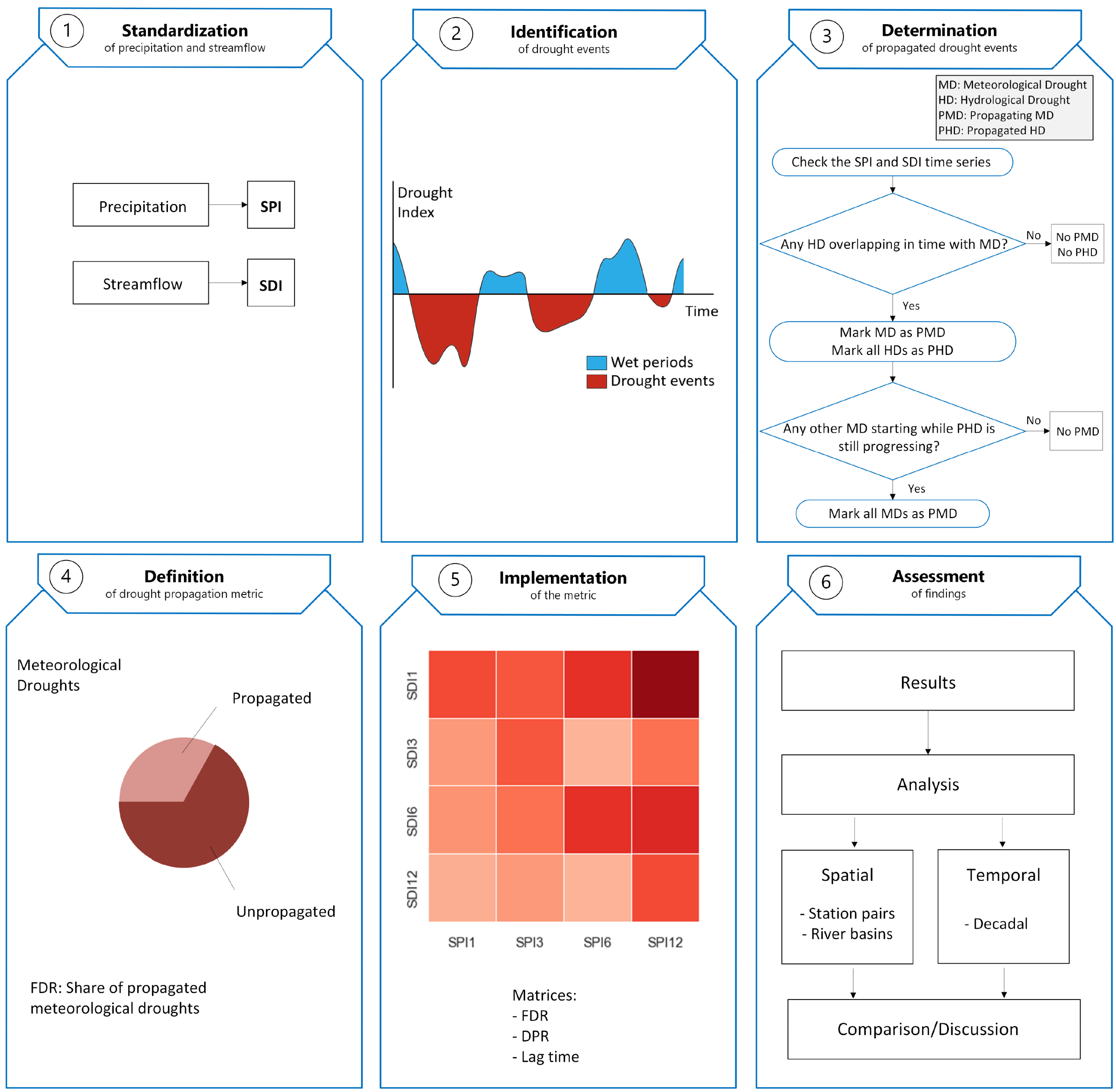

FIGURE 2 Flow chart of the experiment.

propagation rates indicate higher fractions of hydrological droughts generated from meteorological droughts. Thus, rather than a probability, which has a range from zero to one, the DPR is a response rate, that is, a ratio, which can take values larger than one. As such it provides information on how many droughts occurred in the hydrological drought index time series for each drought event in the meteorological drought index time series. As it is a ratio but not a probability, the DPR cannot quantify the drought propagation in a probabilistic manner.

To fill this gap, Liu et al. (2023) who realized the conceptual difficulty in the DPR, formulated the problem as the ratio of meteorological droughts, which is in turn a probability. This is the same approach we considered in this study independently from Liu et al. (2023) with a parallel understanding by using different drought indices, assumptions, thresholds and further concepts. In the same way with Liu et al. (2023), we introduced the ratio of meteorological droughts as:

$$\mathrm{FDR} = \frac{m_p}{m}, \tag{2}$$

and called it the formative drought rate (FDR) where m_p is the number of meteorological droughts propagating into hydrological drought. In Liu et al. (2023), m_p represents 'the number of meteorological drought events that triggered hydrological drought events', which is essentially the equivalent to our definition. In this way of definition, the FDR is not only a ratio but also the probability of meteorological droughts

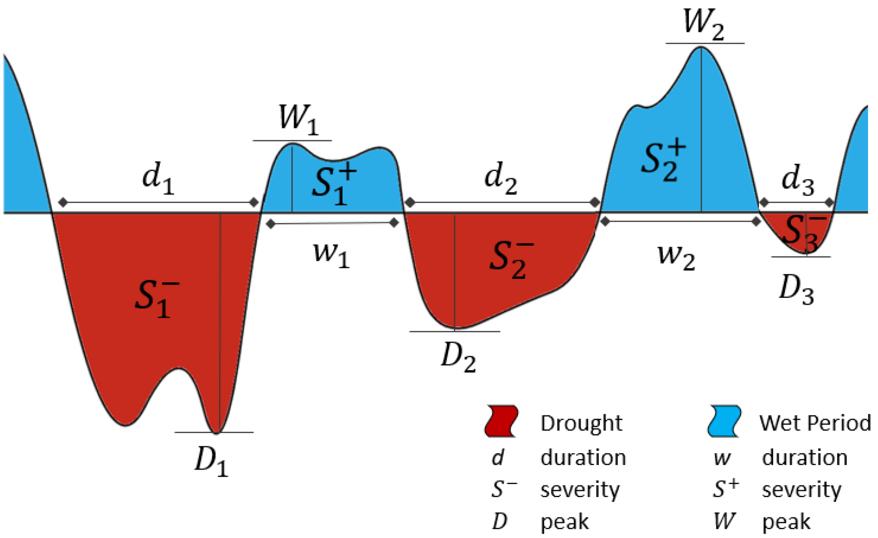

FIGURE 3 Identification of droughts by eliminating short (in time) and weak (in magnitude) intervening wet periods (IWPs). The first wet period is an IWP since it is shorter and weaker than the neighbouring droughts.

propagating into hydrological droughts. The fundamental difference between the two concepts is that the DPR uses the number of hydrological droughts propagated from meteorological droughts while the FDR is based on the number of meteorological droughts propagating into hydrological droughts. The FDR is the ratio of the number of meteorological droughts propagated into hydrological droughts to the total number of meteorological droughts in the entire observation period. As an improved version of the DPR, it is a simple drought propagation metric quantifying the lumped estimate of meteorological droughts propagating into hydrological drought, no matter what the drought characteristics (duration, severity, intensity) are.

Considering a paired MS and SGS Liu et al. (2023) used meteorological droughts and hydrological droughts with highest correlation and calculated probability of propagation for the selected droughts skipping all others. Differently from Liu et al. (2023), in this study, we considered MSs and SGSs in pairs to calculate the FDR for each pair of stations from the SPI and SDI time series of all timescales. The FDR is a quantitative metric, which is the probability that a meteorological drought in SPI_k of an MS propagates into a hydrological drought in SDI_m of the paired SGS, where k and m denote timescales ($k = 1, 3, 6, 12$ months; $m = 1, 3, 6, 12$ months). Consequently, it is a probability matrix of four rows and four columns not a single value of probability. Furthermore, instead of SRI used by Liu et al. (2023), we used the SDI for hydrological drought events by assuming also different pooling criteria and thresholds.

3.5 | Implementation of the metric

In Step 5, the newly developed FDR and the DPR were calculated for each of the station pairs for to understand the difference between the two metrics and the performance of FDR in quantifying the drought propagation. The lag time was also calculated for the propagation from meteorological drought of a given timescale to a hydrological drought of any other given timescale.

3.6 | Assessment of findings

Finally, in Step 6, a decade-by-decade temporal analysis of the FDR was studied to understand how it evolves over time. Drought characteristics were analysed for meteorological and streamflow gauging stations at river basin scale. Besides this spatial analysis, one of the station pairs with long data record was taken for the temporal analysis. Station pair M9-S9 in the Ergene River Basin, which has the longest common observation period (45 years) was chosen for the demonstration of the decade-by-decade temporal analysis performed for four decades from 1970 to 2009 to understand how the FDR changes over time. To test whether or not the FDR can be used as a quantitative metric for drought propagation, we divided the 45-year data record of the M9-S9 station pair into two periods. For each of the SPI_k-SDI_n, we calculated the FDR first by using the precipitation and streamflow data of the first 20 years after which we counted the total number of meteorological droughts in the precipitation time series for the remaining 25 years (from 1990 to 2014). The counted numbers of the meteorological droughts were multiplied by the FDR to calculate the number of meteorological droughts expected to propagate into hydrological droughts. The expected number of droughts calculated from the metric was compared with the number of propagated meteorological droughts counted from the observed precipitation and streamflow data. The absolute and relative errors between the number of expected and counted droughts were calculated for comparison.

4 | RESULTS

4.1 | Characteristics of meteorological and hydrological droughts

From the SPI of monthly precipitation and the SDI of monthly streamflow, we identified drought events for each MS and SGS at each of

Meteorological Station	SPI1	SPI3	SPI6	SPI12
M1	73	34	22	13
M2	103	54	44	14
M3	117	59	39	16
M4	125	64	44	23
M5	126	58	31	22
M6	46	23	17	7
M7	104	41	27	18
M8	91	41	27	20
M9	129	60	40	29

Streamflow Gauging Station	SDI1	SDI3	SDI6	SDI12
S1	28	16	9	5
S2	56	27	23	13
S3	49	30	22	8
S4	66	41	27	14
S5	69	42	32	18
S6	27	16	11	6
S7	48	22	12	7
S8	51	24	14	9
S9	75	37	20	13

FIGURE 4 Number of meteorological droughts identified from standardized precipitation index (SPI) of the meteorological stations and hydrological droughts from streamflow drought index (SDI) of the streamflow gauging stations at 1-, 3-, 6- and 12-month timescales.

the time scales (1-, 3-, 6- and 12-month). Number of drought events decreased as the timescale increased (Figure 4). At each MS or SGS, smaller number of droughts were counted as the timescale increased from 1 to 12 months. On top of a smaller variability of the indices, drought events over longer timescales had generally longer durations and therefore were fewer given that the time series length did not change. Precipitation oscillated around its normal, long-term average, with higher variability compared to the streamflow. This led to higher number of droughts in precipitation than streamflow (Changnon, 1987). A relatively smaller number of droughts in some of the MSs or SGSs (e.g., M6 among MSs and S6 among SGSs) was due to the short length of record periods of station pairs. The shortest record period is 17 years (Tables 2 and 3).

The average duration and the average severity of meteorological drought events increased with increasing timescale while the average intensity decreased (Figure 5). This seems as a general outcome despite minor differences from one station to another. With increasing timescale, outliers of the upper tail of the duration distribution decreased; that is, the number of outliers decreased with increasing timescale, and they tended finally to disappear at the 12-month timescale with two exceptions, three outliers in M5 and one outlier in M9. The average severity increased with increasing timescale, bringing higher variability together with outliers, which traced wider ranges as the timescale increased. The intensity decreased and became less variable with ignorable number of outliers or no outlier at all at long timescales. The Gediz River Basin (M4, M5, M6) tended to experience longer and more severe meteorological droughts compared to the Kucuk Menderes (M1, M2, M3) and Ergene (M7, M8, M9) river basins. However, the duration and severity were not that noticeably different from one river basin to another. The findings of the hydrological droughts were in parallel with the characteristics of the meteorological droughts (Figure 6). The duration and severity increased, the intensity decreased. One exemption is that the mean value of duration in S9 at the 12-month timescale was shorter than that at the 6-month timescale. The mean value was highly affected by the number of the droughts, and it was biased with the presence of outliers. The median values were ordered as expected, that is, longer the timescale higher the median value was for the duration of drought events in S9. This is applicable to all cases in general. The duration of hydrological droughts in SDI seemed to be generally shorter in the Kucuk Menderes River Basin (S1, S2, S3) compared to the other two basins. Yet, the difference from one river basin to another is not very pronounced. This can be explained by the similar climatological conditions of the three river basins as they are all located in the Mediterranean climate zone.

4.2 | Drought propagation

Figure 7 shows the FDR calculated for the MS-SGS of the three river basins. The FDR is in the form of a matrix whose cells presents the probability that a meteorological drought at a given timescale propagates into a hydrological drought of the same or another timescale. It is read, for the example of Kucuk Menderes river basin, as the probability that a 1-month meteorological drought in M1 propagates into a 1-month hydrological drought in S1 is 0.36 while the probability that a 12-month meteorological drought in M1 propagates into a 3-month hydrological drought in S1 is 0.38. Lower probabilities are concentrated on the lower left part of the FDR matrix while higher probabilities are mostly in the upper right. This corresponds to an increase in the probability as the timescale of SPI increases and the timescale of SDI decreases. It is in accordance with the fact that a short-term meteorological drought does not likely cause a hydrological drought while it is more probable that a long-term meteorological drought causes a hydrological drought because of the accumulated effect of the long-lasting precipitation deficit on the streamflow. This is a general pattern that can be applied to the three river basins.

Individual analysis of the FDR matrices shows that meteorological droughts in M1 propagates into hydrological droughts in S1 of the Kucuk Menderes river basin with the lowest probability among all pairs of stations. Ten out of 16 cells have the lowest probability in this particular pair of stations. The number of lowest probabilities is two in

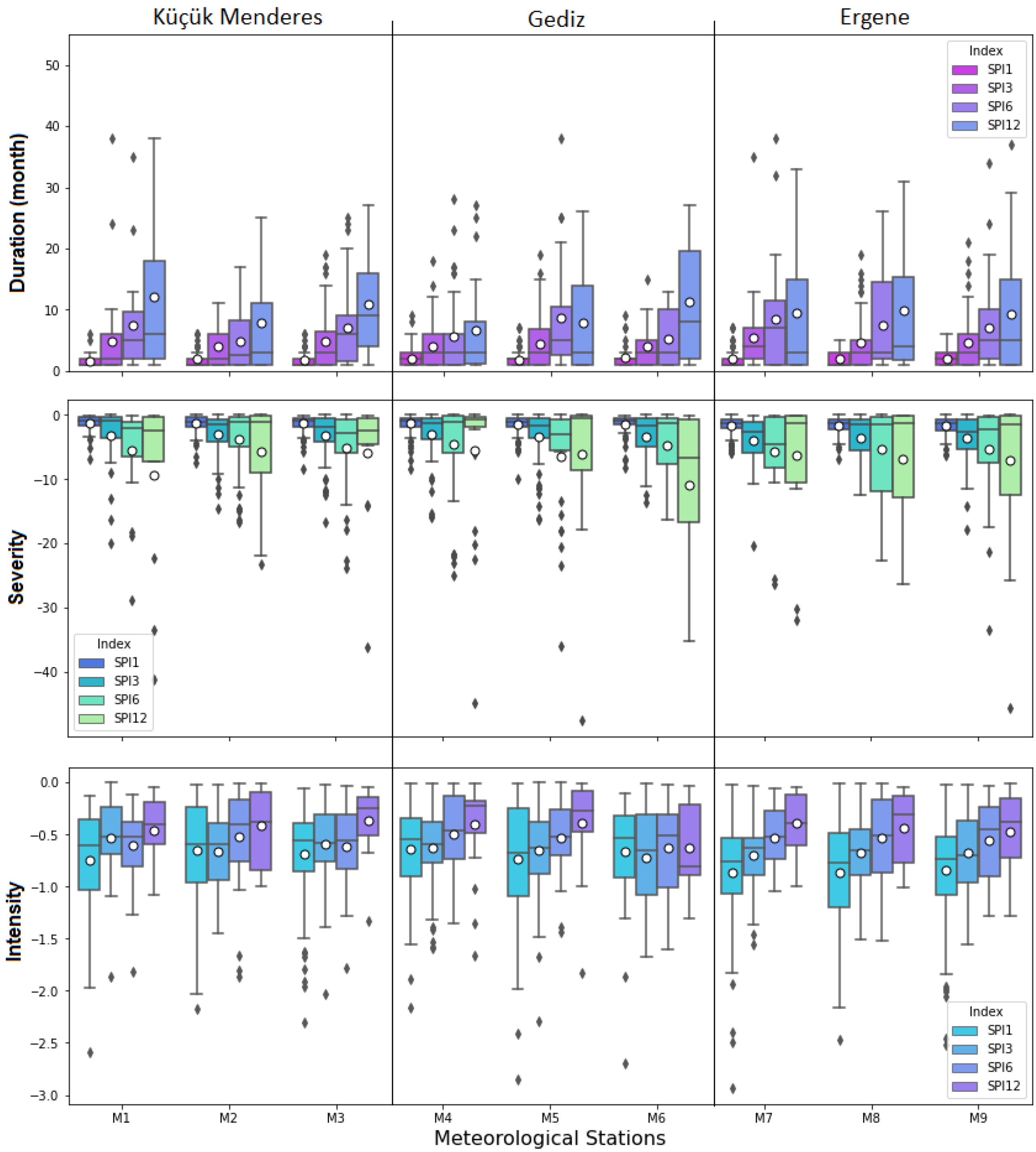

FIGURE 5 Box plots of duration, severity and intensity of meteorological droughts in SPI series. Outliers in severity smaller than −50 are not shown to keep the figure readable. The whiskers show the minimum value or the value at $Q_{25} - 1.5$ IQR, whichever closer to Q_{25}, and the maximum value or the value at $Q_{75} + 1.5$ IQR, whichever closer to Q_{75}. White dots and diamonds depict mean values and outliers, respectively. Q_{25} and Q_{75} are the first and the third quartiles, and IQR is the interquartile range, difference between the first and the third quartiles.

M2-S2 (one shared with M1-S1) and one in M3-S3. One of the probabilities in the FDR matrix of M5-S5 in Gediz has the lowest value. It is the probability that a 12-month timescale meteorological drought causes a 1-month hydrological drought; that is, transition from SPI-12 to SDI-1. The station pair M7-S7 in Ergene has three of the lowest probabilities of propagation. Other pairs of stations do not have any lowest value of probabilities. Consequently, meteorological droughts in the vicinity of meteorological station M1 propagate to hydrological droughts in the watershed of S1 with the lowest probability. This suggests a degree of resilience against drought as it is less likely that

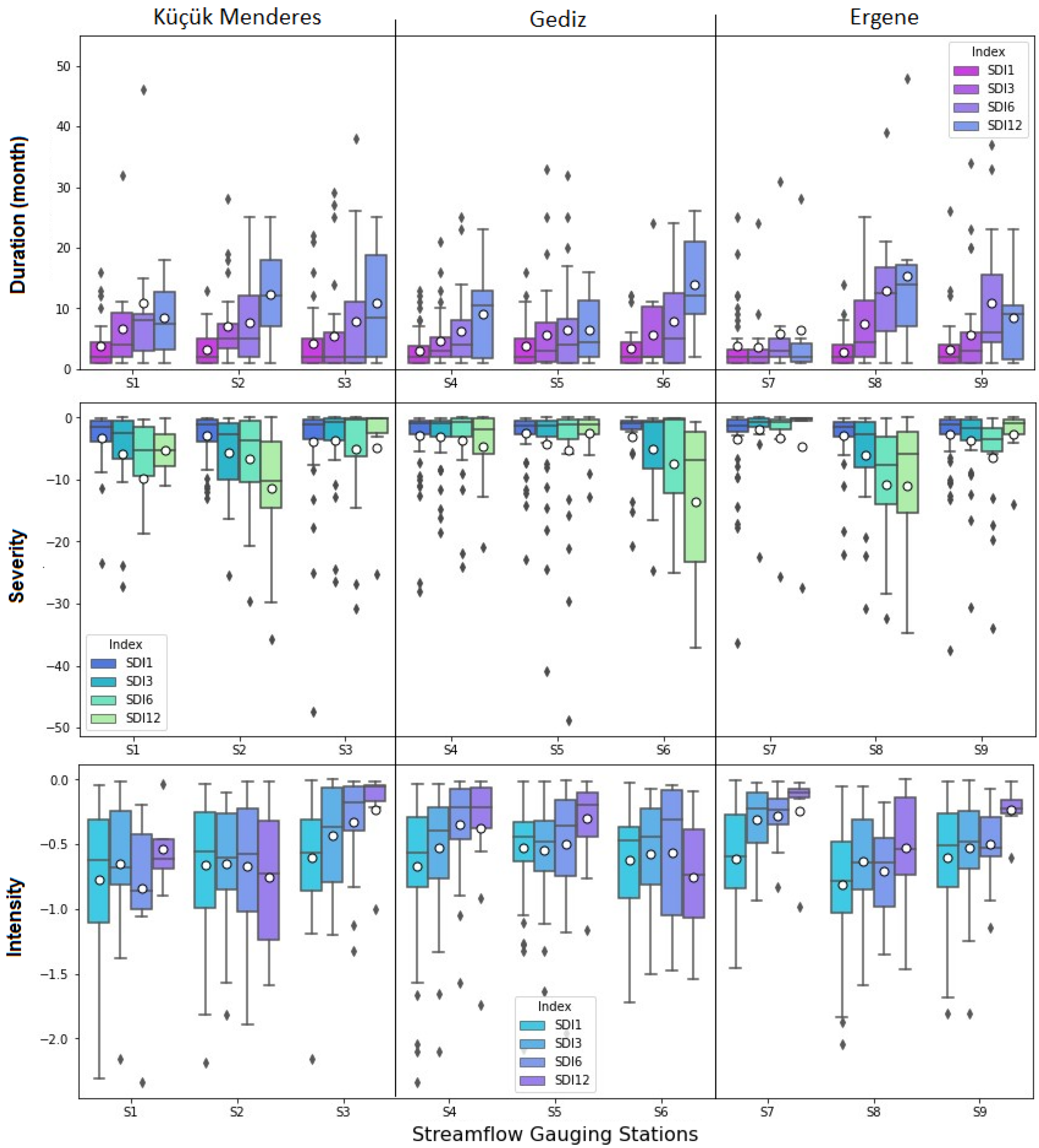

FIGURE 6 Box plots of duration, severity and intensity of hydrological droughts in SDI series. Outliers in severity smaller than −50 are not shown to keep the figure readable. The whiskers show the minimum value or the value at $Q_{25} - 1.5$ IQR, whichever closer to Q_{25}, and the maximum value or the value at $Q_{75} + 1.5$ IQR, whichever closer to Q_{75}. White dots and diamonds depict mean values and outliers, respectively. Q_{25} and Q_{75} are the first and the third quartiles, and IQR is the interquartile range, difference between the first and the third quartiles.

deficit in precipitation propagates into deficit in streamflow. When the highest probabilities are concerned, we see that they are shared among the station pairs. The highest share of the M7-S7 (in Ergene) with five highest probabilities out of 16 is noticeable. The M6-S6 in Gediz has four of the highest probabilities. Except for the M2-S2 (in Kucuk Menderes) and M4-S4 (in Gediz) all other pairs have, at least, one of the highest probabilities in the FDR matrix. In comparison to the neighbouring Kucuk Menderes, the Gediz River Basin is more susceptible to experiencing hydrological droughts, which may even be triggered by shorter timescale meteorological droughts. Based on this observation, the Ergene among the three river basins is the most prone to hydrological drought after a meteorological drought.

FIGURE 7 Formative drought rate (FDR) matrix of propagation from meteorological drought in SPI_k to hydrological drought in SDI_m for station pairs ($k = 1, 3, 6, 12$ months; $m = 1, 3, 6, 12$ months). Matrices in the upper three lines of the figure show the FDR associated with each cell calculated as the average of each station pair. Matrices in the lower line show the average of river basins. Darker shades in the cells indicate higher values of FDR.

For the comparison of the three river basins, the average FDR matrix was calculated (Figure 7). The three pairs of each river basin were taken into account in averaging the probabilities of the FDR matrix. The probability in the cell SPI_1-SDI_1 of the average FDR was calculated as an example for the Kucuk Menderes river basin by taking the average of probabilities of the respective cells in the FDR matrices of M1-S1, M2-S2 and M3-S3. All cells of the average FDR (16 in total) were calculated in this way for the Kucuk Menderes river basin and the calculation was repeated for the other two river basins. The comparison of the average FDR matrices shows that the Kucuk Menderes river basin has the majority of the lowest probabilities (13 cells out 16). This indicates that propagating from meteorological drought to hydrological drought is less likely in this particular river basin compared to the Gediz and Ergene river basins. When the highest probabilities are concerned, Ergene and Gediz river basins come front. In Ergene river basin, mid and long timescale meteorological droughts are prone to propagate not only to mid (6-month) or long (12-month) timescale hydrological droughts but also to short timescale (1- and 3-month) hydrological droughts. The probability that a short timescale meteorological drought propagates to a hydrological drought at short, mid or long timescale is higher on average in the Gediz river basin. Although it should be noticed that the average characteristics are limited with the number of station pairs (three for each river basin), they are indicative enough to demonstrate how streamflow in each river basin may respond differently to the deficit in precipitation.

In the case studies here, the probabilities get higher values by moving from the Kucuk Menderes River Basin to Ergene, from south to north. However, the change in the latitude should not be seen as the sole reason for this difference. Apparently, the low number of station pairs causes the difference in the FDR, which can be smoothed out with availability of higher number of station pairs to use in the analysis. Despite this limitation, the findings indicate that the FDR might be affected by the basin characteristics. However, we are not confident about which physical drivers affect the difference dominantly as the river basins are geographically close to each other with similar terrains and they are not very different climatologically. Here, it is worth to mention that the intermittent flow regime of the river basins might cause the lack of resilience to hydrological drought triggered by meteorological drought for all river basins. This reminds the important role of intermittency, which likely amplifies drought propagation (Yildirim & Aksoy, 2022).

4.3 | Lag time

The lag time provides information on the drought propagation by which the delay between the meteorological drought and hydrological drought can be quantified in months. Where multiple drought-related stressors are effective, it is important to understand the lag time in order to anticipate and mitigate the effects of the drought. The drought propagation method of this study enabled us to calculate the lag time. Figure 8 shows the average lag time of drought propagation for each pair of MS-SGS and their river basin-specific average. Station pairs of each of the river basins have similar patterns. However, the pattern changes from one river basin to another. The station pair-specific matrices show that the Ergene River Basin has longer lag times than the other two river basins. On average, 10 out of 16 lag times in the matrices are the longest in the M7-S7 station pair, two in M8-S8 and another two in M9-S9 of Ergene. For each of the Kucuk Menderes and Gediz river basins, only one of the lag times was found longer (from SPI3 to SDI1 in M1-S1 of Kucuk Menderes and from SPI1 to SDI1 in M6-S6 of Gediz). Furthermore, the basin-average lag time matrices show the dominance of Ergene, where 13 out of 16 lag times are the longest. Kucuk Menderes accommodate two of the rest while Gediz have only one showing that these two basins are quicker than the Ergene river basin in experiencing hydrological drought after a meteorological drought. This can also be verified by the station pair-specific matrices where the shortest lag times concentrated in the Kucuk Menderes (eight) and Gediz river basins (seven). Lag time of 2.75 months from SPI3 to SDI1 between M8 and S8 is the only shortest one in Ergene. The basin-average matrices make this statement more concrete. The number of the shortest lag times is seven and nine in Kucuk Menderes and Gediz, respectively; and none exists in Ergene.

Lag times shorter than 1 month are concentrated in short timescales. This is because of high number of zero-lag times; that is, hydrological droughts developed in the same month as the associated meteorological droughts with no delay. However, it does not necessarily mean that there is no time delay in the transformation from precipitation to streamflow; it is thought to be linked to the monthly scale of the data, which masks lags at the scale of days in the transformation from precipitation to streamflow. Lag times in Figure 8 can be examined together with the FDR in Figure 7 showing the probability of drought propagation. As an example, for the station pair M7-S7, the probability that a drought in SPI_{12} propagates into a drought in SDI_3 is 0.76, with an average lag time of 4.88 months. Results in Figures 7 and 8 indicate that there is no clear relation between the FDR and the lag time. However, the average lag time still provides valuable information about the delay in drought propagation.

We obtained violin plots (Figure 9) from the three station pairs of each river basin in order depict the statistical characteristics, variability and probability distribution of the average lag times. Gediz has the lowest median value and the lowest variability among the three river basins. Ergene has the highest variability while the outlier in Kucuk Menderes is noticeable. The majority of lag times stays in the range 0–2 months for all river basins, and each river basin has its own lag time characteristics.

Results related to the lag time underline the complexity of the transformation from meteorological drought to hydrological drought, since there is no unique relationship at different aggregation scales of SPI and SDI. It is important to acknowledge the complexity of the drought propagation mechanism from meteorological drought to hydrological drought. Obviously, this complex structure cannot be explained fully by the simplified concept of a drought index. Factors affecting the lag time between these two types of droughts should be considered. Among the physical characteristics of the river basin,

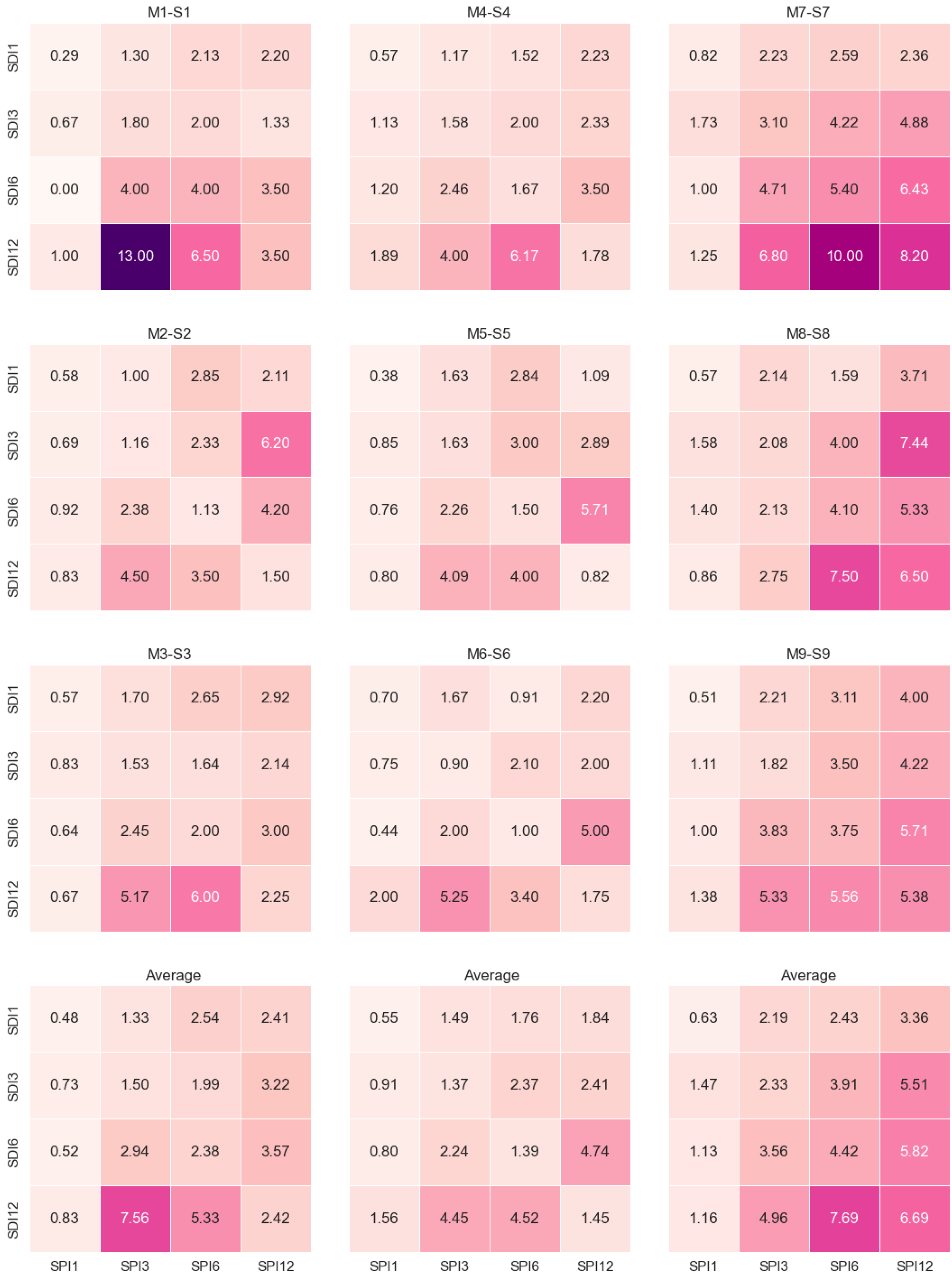

FIGURE 8 Average lag time matrix (in months) of propagation from meteorological drought in SPI_k to hydrological drought in SDI_m ($k = 1$, 3, 6, 12 months; $m = 1$, 3, 6, 12 months) for station pairs. Matrices in the upper three lines of the figure show the lag time associated with each cell calculated as the average of each station pair. Matrices in the lower line show the average of river basins. Darker shades in the cells indicate longer time delay.

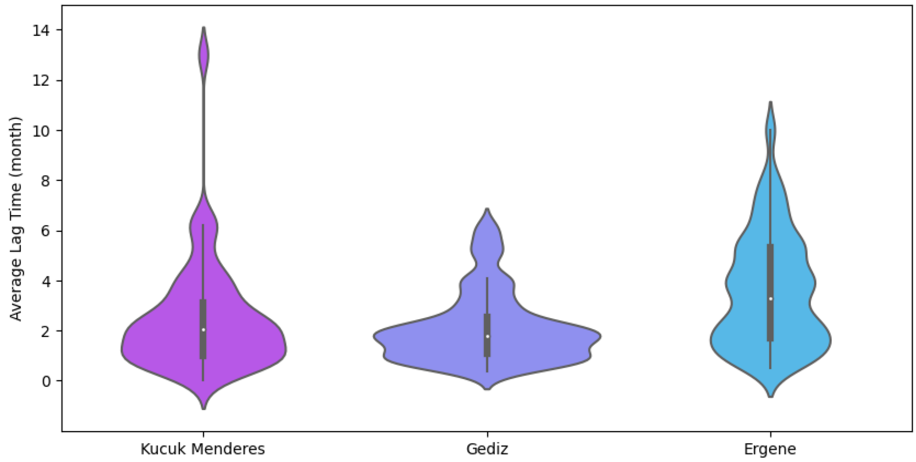

FIGURE 9 Violin plots of average lag times. White dot represents the median, the thick bar in the centre represents the interquartile range, the thin line represents the rest of the distribution except for the outliers.

groundwater storage capacity can be mentioned as one of the most pronounced factors because of its relation with baseflow generation process. A river basin with higher groundwater storage capacity might be expected to have a longer lag time between meteorological drought and hydrological drought as it can compensate precipitation deficit from its groundwater storage. Other river basin-specific factors (e.g., topography, land use and land cover characteristics, climatic seasonality, aridity, etc.) can also be considered. Consideration of such variables, however, require a physically-oriented methodology with a much broader context and data need than this study.

4.4 | Difference with DPR

Results obtained from the implementation of the DPR for each station pair are presented in Figure 10. It is seen that the highest rate of all pairs is obtained for SPI_{12}-SDI_1. Moreover, the pattern is almost identical for each station pair for all river basins without any exception. The DPR increases as we move from the bottom left corner (SPI_1-SDI_{12}) of the matrices to their top right corner (SPI_{12}-SDI_1). Although the rates are different from one river basin to another and from one station pair to another, no change is visible in the overall pattern. This can be better explained by comparing Figure 7 with Figure 10. The FDR carries the random behaviour of the drought propagation (Figure 7) while the DPR is not capable to demonstrate the randomness of the drought propagation (Figure 10).

Comparison of the emerging patterns of the FDR and DPR shows the systematic (if not deterministic) pattern of DPR increasing from the left lower corner to the right upper corner of each matrix. The reason behind this systematic change is based on the definition of the DPR, which has the number of the propagated hydrological droughts in the numerator. For the same data length, the number of hydrological drought events decreases with increasing timescale of SDI. Moreover, the DPR has the total number of meteorological droughts as the denominator which also decreases with increasing time scale of SPI. Thus, by moving from smaller timescales of SPI to larger timescales, and from larger timescales of SDI to smaller timescales, the DPR will always become larger.

4.5 | Temporal analysis and FDR as a quantitative metric

Results of the temporal analysis are presented in Figure 11. Change in the FDR from one decade to another is a result of temporal variability while still maintaining a distinctive pattern specific to the selected pair of stations. The finding of the temporal analysis is that the FDR is capable to carry the temporal variability of the drought propagation process.

Expected number of hydrological droughts propagated from meteorological droughts for the station pair M9-S9 in Ergene River basin are given in Table 5. The performance of the FDR varies. For the SPI_1, SDI at the 6-month or shorter timescales showed considerably good results with a relative error between 5% and 12%. However, the SPI_1-SDI_{12} showed higher error demonstrating poor performance in expecting the number of droughts propagated from a short timescale meteorological drought to a long timescale hydrological drought. For SPI_3, a similar pattern with a slightly larger error was found. For SPI_6, the best performance was obtained for SDI_3. Larger error of SPI_6-SDI_6 shows lower performance of FDR in estimating the average number of the 6-month timescale hydrological droughts expected from the 6-month timescale meteorological droughts. At annual scale, SPI_{12} shows a decreasing error with increasing timescales. This can be expected as longer timescales of meteorological droughts are likely to cause longer hydrological droughts. It is important to note that the number of meteorological droughts in Table 5 affects the relative error highly. Consideration of the absolute error is therefore advised to comment on the performance of the FDR. Despite its simplicity and the implementation on a data set of one single station pair with limited number of meteorological droughts, the FDR seems to have the potential to determine the expected number of meteorological droughts to be propagated. This is particularly applicable to the propagation from short timescales (1 and 3 months) to short and medium timescales (1, 3 and 6 months). Relative error is 21% at maximum for these timescales. However, we note that the findings are not yet conclusive enough to propose the FDR as a fully well-posed methodology to hydrologists for practical purposes.

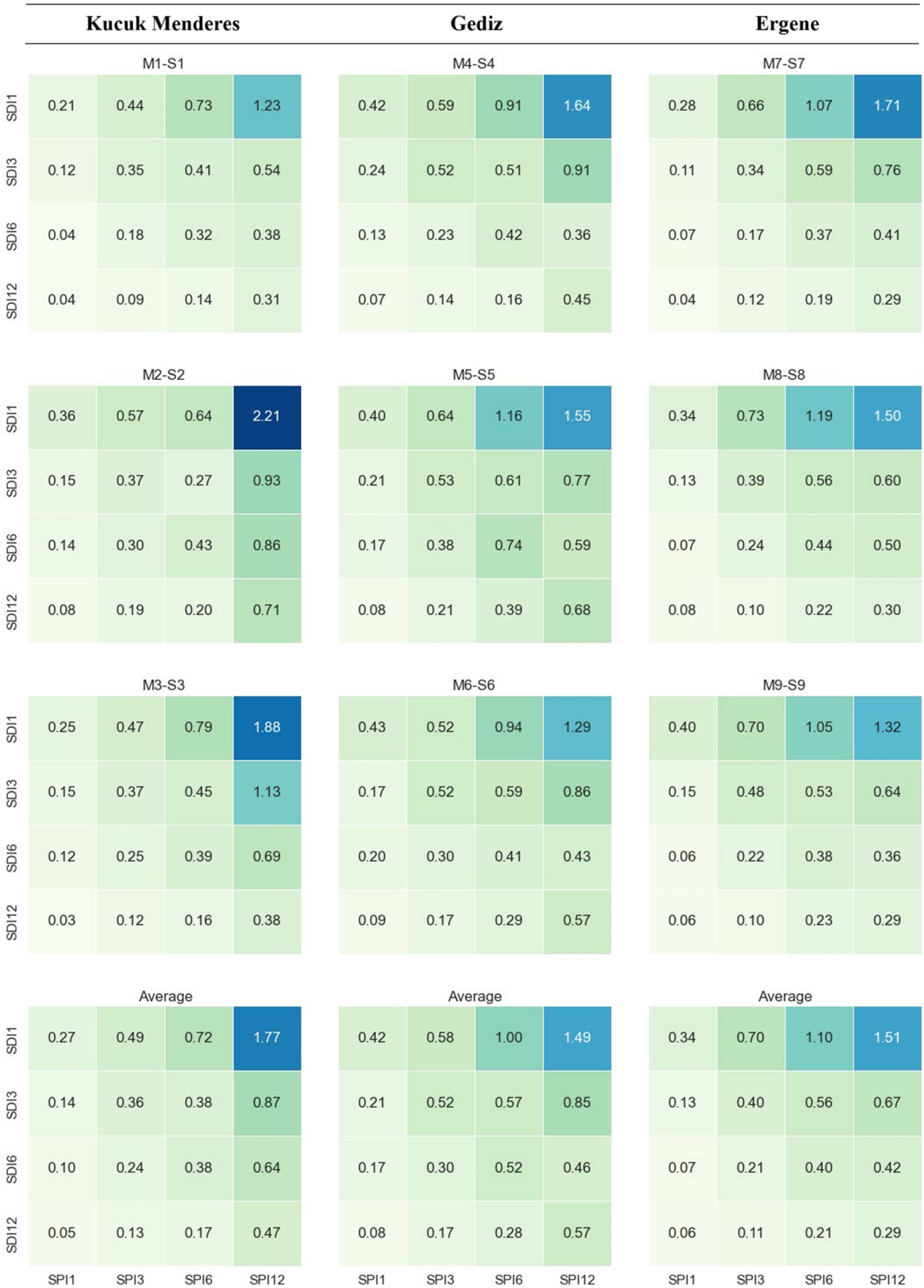

FIGURE 10 Drought propagation rate (DPR) matrix the propagation from meteorological drought in SPI_k to hydrological drought in SDI_m for station pairs ($k = 1, 3, 6, 12$ months, $m = 1, 3, 6, 12$ months). Matrices in the upper three lines of the figure show the DPR associated with each cell calculated as the average of each station pair. Matrices in the lower line show the average of river basins. Darker shades in the cells indicate higher values of DPR.

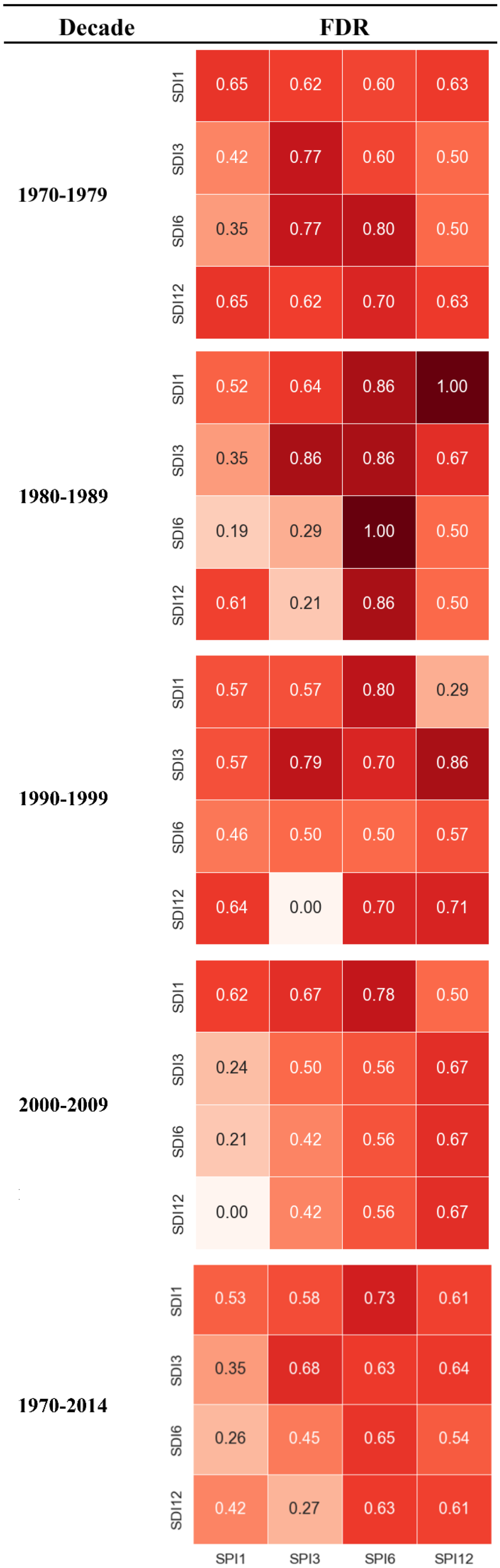

FIGURE 11 The decade-by-decade FDR and DPR of the M9-S9 station pair in Ergene River Basin. Darker shade in the cells indicates higher values of FDR and DPR.

5 | DISCUSSION

Not many research studies exist to develop a metric for the quantification of drought propagation although a vast volume-literature has been devoted to the drought propagation itself. Two studies (Liu et al., 2023; Sattar et al., 2019) have been distinguished in the literature closely linked to this study. In each of these studies, quantitative metrics were developed for drought propagation based on the ratio of number of droughts. Here, we discuss the progress of FDR of this study over the DPR of Sattar et al. (2019) and the approach of Liu et al. (2023), and explain its usefulness for practical purposes.

One point to discuss is that the FDR is conceptually different from the DPR of Sattar et al. (2019) while being similar to the other (Liu et al., 2023). The FDR is a probabilistic concept. This is not the case for the DPR that is a ratio. The probabilistic definition of FDR provides an opportunity to use it as a quantitative metric in drought propagation. It can be used as the probability that a meteorological drought caused by precipitation deficit of a given timescale propagates into a hydrological drought caused by streamflow deficit of any other given timescale. This difference between the two metrics might reduce the usefulness of the DPR in operational hydrology and show the added value that the FDR brings with, which can be considered the advantage of the FDR. Therefore, we consider the FDR is an informative and practical metric to quantify drought propagation probabilistically.

What emerges from the DPR is however that it is a largely space-invariant pattern that is inherent in its conceptualization. This rather generic, spatially stable pattern of the DPR across all timescales suggests that the DPR has no power, unlike the FDR, to describe the spatially variable basin-specific pattern of drought propagation. We can exemplify this by numerical values obtained from the case studies. The DPR in Figure 10 can get values higher than one, which shows its disability in explaining the probabilistic way of drought propagation as the values in the matrix are not probability but ratio. Each value of FDR in Figure 7 is however a probability by definition, and the collection of these probabilities is therefore called the probability matrix. Systematic change over each matrix in Figure 10 is another disadvantage of the DPR against the randomly varying FDR matrices in Figure 7. This is the strength of FDR, which comes from the fact that it quantifies drought propagation in the form of probability. With the use of FDR, we obtain probabilistic information about the propagation from meteorological drought to hydrological drought. This is an important information for stakeholders and decision makers in the drought mitigation practice.

In addition to this conceptual dissimilarity with the DPR, another point worthy to discuss is the similarity with the metric of Liu et al. (2023). By definition, it is the same metric as the so-called FDR in this study. However, it is important to state that in this study we computed the FDR within a wider range of timescales. This makes our analysis more comprehensive than Liu et al. (2023) in which the computation of the metric was limited with the probability of propagation from meteorological to hydrological droughts of timescales with the

TABLE 5 Performance of the FDR in expecting the number hydrological droughts propagated from meteorological droughts for the station pair M9-S9 in Ergene River basin.

1970–1989		1990–2014			Error	
SPI-SDI	FDR	Number of meteorological droughts	Expected number of propagated meteorological droughts	Counted number of propagated meteorological droughts	Absolute	Relative (%)
SPI_1-SDI_1	0.51	72	37	35	2	6
SPI_1-SDI_3	0.28	72	20	23	3	13
SPI_1-SDI_6	0.25	72	18	19	1	5
SPI_1-SDI_{12}	0.51	72	37	18	19	106
SPI_3-SDI_1	0.59	33	20	18	2	11
SPI_3-SDI_3	0.70	33	23	19	4	21
SPI_3-SDI_6	0.44	33	15	13	2	15
SPI_3-SDI_{12}	0.33	33	11	5	6	120
SPI_6-SDI_1	0.58	23	13	17	4	24
SPI_6-SDI_3	0.53	23	12	13	1	8
SPI_6-SDI_6	0.79	23	18	11	7	64
SPI_6-SDI_{12}	0.63	23	15	12	3	25
SPI_{12}-SDI_1	0.67	14	9	6	3	50
SPI_{12}-SDI_3	0.53	14	7	10	3	30
SPI_{12}-SDI_6	0.47	14	7	8	1	13
SPI_{12}-SDI_{12}	0.53	14	7	9	2	22

highest correlation. Instead of computing single probabilities of propagation from a given timescale to another timescale (with the highest correlation), we computed an FDR matrix (i.e., probability matrix) of propagation of meteorological drought of a given timescale into hydrological drought at any other timescale. Moreover, we used different drought indices, assumptions, thresholds and further concepts.

The practical value of the FDR matrix is shortly explained as follows: The drought type (meteorological or hydrological) and the timescale provide useful information for various practical purposes such as agriculture, water supply, navigation, energy production, water resources planning and management, drought management, etc. We selected 1-, 3-, 6- and 12-month timescales; indicating monthly, seasonal, semi-annual and annual droughts, respectively. Monthly and seasonal timescales are considered short while other timescales are considered long (Vicente-Serrano et al., 2013). In its practical meaning, the term timescale refers to the lag from the starting of a deficit in precipitation or in streamflow to the time when its consequences are identified on water resources, engineering activities, ecology, economy or society (Cavus et al., 2023). The timescale to consider differs depending on the purpose of the problem practiced. Thus, not only deficits accumulated over long timescales but also accumulation over short (monthly or seasonal) timescales might be impactful when the deficit intense particularly. For example; seasonal or over-year water storage and release are important for large hydropower systems. Deficits accumulated in short timescales matters for the runoff-the-river hydropower generation among others. Furthermore, short timescale deficits affect agriculture if drought coincides with the growing period of the particular crop. This explains how the FDR computed at various timescales might be useful as it provides probabilities of propagation from meteorological to hydrological droughts of short and long timescales and makes it a handy tool for practice.

This study is limited with the nonflexible arbitrarily selected fixed-drought thresholds, $SPI = 0$ and $SDI = 0$, threshold levels of meteorological and hydrological droughts, respectively. By taking $SPI = 0$ and $SDI = 0$, we considered the mild drought class of McKee et al. (1993) entirely. It is however possible to choose a threshold level lower than $SPI = 0$ to exclude the mild drought, which is denoted as normal in some cases (e.g., Barker et al., 2016; Quesada-Montano et al., 2018). If a threshold lower than $SPI = 0$ and $SDI = 0$ is applied, a lower probability will be obtained for the drought occurrence, the drought duration will be shorter, and the number of droughts will decrease. In our methodology, we decided to consider all drought classes of McKee et al. (1993) (extreme, severe, moderate, and mild drought) based on the $SPI = 0$ threshold for meteorological drought and $SDI = 0$ for hydrological drought. This might be concerned as a limitation of this study, and can be of interest for the follow-up research. If performed, the sensitivity of the results to the effect of different threshold level on drought can be analysed as assessed by Horn (1989), Frick et al. (1990) and Tallaksen et al. (1997).

6 | CONCLUSION

This study presents a data-based analysis of propagation from meteorological drought to hydrological drought. In order to express the probability of drought propagation, we proposed FDR, which is the ratio of number of hydrological droughts propagated from meteorological droughts to the total number of meteorological droughts. Case studies performed on precipitation and streamflow data from three river basins in Turkey showed the strength of the FDR as a quantitative drought propagation metric. It was found capable to provide probabilistic information about the drought propagation. Comparison with the drought propagation rate (DPR) from the literature consolidates the use of FDR as a simple metric for drought propagation. It is expected to become a significant quantitative metric for drought mitigation efforts of practitioners by also holding the potential to make meaningful contribution to endeavours of policy-makers. However, it should be further developed to increase its reliability through testing on larger number of data sets from river basins with different climatological characteristics, where, for instance, groundwater storage and snow processes are or not dominant. As a near future plan to serve for this, the FDR could be applied to higher number of station pairs from more river basins to understand its performance under climatological spatial variability. Longer time series, preferably with common record periods will help to dive deeper into the temporal behaviour of drought propagation. Instead of the fixed-threshold (SPI $= 0$ and SDI $= 0$) used for separating dry periods from wet periods, a variable threshold can be applied in identifying the drought events and the sensitivity of results to the selected threshold can be investigated. Assumptions and criteria followed in the determination of the drought events and in the propagation of the drought propagation can also be tested through a sensitivity analysis. Propagation from meteorological drought to hydrological drought investigated in this study can also be extended to cover propagation to drought in groundwater.

ACKNOWLEDGEMENTS

Isilsu Yildirim was supported by the Scientific and Technological Research Council of Turkey (TUBITAK) through the 2214a Doctoral Research Program for her stay at the Delft University of Technology, the Netherlands. The hospitality and support provided by the Department of Water Management during this stay are greatly appreciated.

DATA AVAILABILITY STATEMENT

Precipitation data acquired from the Turkish State Meteorological Service are purchasable from https://mevbis.mgm.gov.tr/mevbis/ui/index.html. Streamflow data provided by State Hydraulic Works (DSI) of Turkey are freely accessible at https://www.dsi.gov.tr/Sayfa/Detay/744#.

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How to cite this article: Yildirim, I., Aksoy, H., & Hrachowitz, M. (2024). Formative drought rate to quantify propagation from meteorological to hydrological drought. *Hydrological Processes*, *38*(7), e15229. https://doi.org/10.1002/hyp.15229