ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

DEVELOPMENT OF DROUGHT INTENSITY-DURATION-FREQUENCY CURVES BASED ON STANDARDIZED CLIMATIC INDICES USING PHYSICAL VARIABLES, DEFICIT IN PRECIPITATION AND DEFICIT IN STREAMFLOW

Ph.D. THESIS

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ISTANBUL TEKNİK ÜNİVERSİTESİ ★ LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

YAĞIŞ AÇIĞI VE AKIM AÇIĞI FİZİKSEL DEĞİŞKENLERİNİ KULLANAN STANDARTLAŞTIRILMIŞ İKLİM İNDEKSLERİ TABANLI KURAKLIK ŞİDDET-SÜRE-FREKANS EĞRİLERİNİN GELİŞTİRİLMESİ

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FOREWORD

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ABBREVIATIONS

CLD	: Causal Loop Diagram
DPI	: Discrepancy Precipitation Index
DI	: Drought Index
DSI	: State Hydraulic Works
DWD	: German Weather Service
ERDI	: Effective Reconnaissance Drought Index
FDC	: Flow Duration Curves
G2	: 2-paramater Gamma Probability Distribution Function
G3	: 3-paramater Gamma Probability Distribution Function
GEV	: Generalized Extreme Value Probability Distribution Function
LN2	: 2-paramater Log-normal Probability Distribution Function
LN3	: 3-paramater Log-normal Probability Distribution Function
LP3	: Log-Pearson Type 3 Probability Distribution Function
LUBW	: Environment Agency of Baden-Württemberg
MGM	: State Meteorological Service
NDVI	: Normalized Difference Vegetation Index
PTH	: Precipitation Threshold
PTH	: Partially Dry Year
S/IDF	: Severity/Intensity-Duration-Frequency
SPI	: Standardized Precipitation Index
SPEI	: Standardized Precipitation Evapotranspiration Index
SRB	: Seyhan River Basin
SSDWI	: Standardized Supply and Demand Water Index
SSI	: Standardized Streamflow Index
STH	: Streamflow Threshold
TD	: Totally Dry Year
TW	: Totally Wet Year
W2	: 2-paramater Weibull Probability Distribution Function
W3	: 3-paramater Weibull Probability Distribution Function

SYMBOLS

D	**:** Drought duration
$\mathbf{D_n}$	**:** The major dry period
$\mathbf{DI_0}$	**:** Drought index/indicator threshold
$\mathbf{DI_c}$	**:** The critical precipitation or critical streamflow value
$\mathbf{DI_d}$	**:** The deficit in the drought indicator
L	**:** The dry period length
$\mathbf{L_n}$	**:** The lengths of major dry periods
$\mathbf{R_n}$	**:** The lengths of each reference
i	**:** The number of critical droughts in dry period
j	**:** The number of critical droughts in each year
n	**:** The number of drougths/dry periods

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SUMMARY

Drought is a natural disaster that causes water scarcity and affects the population seriously in many ways such as economic, social and environmental impacts. These effects have been further aggravated by rising demands for agricultural, municipal and industrial water, etc. due to the growing population coupled with rising life standards and increasing industrialization in the world. Compared to other natural hazards, drought is among the most damaging disasters as it develops slowly over a considerable period of time that may linger for several years even after the drought has terminated.

How important the drought is in the sustainability of water resources requires an extra effort to understand and explain. Domestic use, agriculture, industry, energy, tourism and many more sectors are exposed to drought, which has a direct impact on ecology, economy and society. As one of the least understood hydrological phenomena, drought stands as both a technical and social problem. This is a great motivation to explore drought concepts and methodologies in this thesis by extending them from their quantitative technical context to qualitative social context. Case studies were performed in two river basins with different climatic characteristics. One is Seyhan River Basin in the south of Turkey with a Mediterranean climate, and another is the Kocher catchment in the southwestern corner of Germany with a humid subtropical climate.

In the literature, the drought is commonly analyzed by the use of available hydroclimatic or hydrologic data with little in-depth consideration of specific major dry periods experienced over a region. Also, it is not a common practice to assess the probability of drought categories with a rolling time series and hence the changing knowledge for operational drought monitoring. A combination of such quantitative analysis with a comprehensive qualitative assessment of drought as a human-water relation aimed to fill this gap by performing a case study in the Seyhan River Basin, Turkey. Therefore, the first part of this thesis focuses on non-stationary rolling time series analysis together with the stationary full-record time series analysis and the individual major dry period analysis. Six major dry periods were identified from the precipitation time series of 19 meteorological stations. Dry periods extended over 1970-1974, 2002-2008, and 2013-2015, known also as droughts of 1974, 2008, and 2014, respectively, should particularly be noted among all as they affected several sectors in the river basin with the long-lasting deficit in water. Major dry periods were analyzed by rolling time series and full time series, and they were also analyzed individually. The results show that significantly higher probabilities were calculated for extreme droughts with the use of individual major dry periods. An important outcome of the study is that drought is underestimated in practice with the sole use of

the whole data record. Also, a major dry period could be important in terms of its duration while another in terms of its severity or intensity. Each major dry period has its own impact on human-water relations that can be influential on drought mitigation, management and governance.

The second part of the thesis investigates the statistical properties of drought characteristics for a better understanding of drought to mitigate its negative impacts and improve drought management strategies. Differently from the common approach based on the run theory, the hypothesis is that drought is different from the dry period and dry periods identify droughts of different durations. Up to now, no attention has been paid in this sense to the statistical properties of dry periods versus those of more severe and impactful droughts as separate phenomena. The study shows how different the statistical properties of dry periods and droughts are by quantifying them with the Standardized Precipitation Index (SPI) together with the total probability theorem-coupled frequency analysis. The study tests four concepts in this context: (1) Dry period, (2) Critical drought for a dry period, (3) Critical drought for a year. The results uncover the high number of droughts, which are not addressed in the run theory, and reveal more intense droughts that are masked within the dry periods. Specifically, the drought impact is more often related to drought intensity than severity and duration. In addition, the dry period is less intense than other concepts. Among the droughts newly proposed, critical droughts are the most intense concepts. This demonstrates that drought characteristics calculated for the drought concepts are different from the common approach of the dry period. The difference among the concepts is large enough to carry potential implications for local or regional scale drought management planning.

In the third study, drought intensity-duration-frequency (IDF) curves were developed by using the critical drought identified in the second study. The drought IDF curves are based on precipitation and streamflow deficits because drought estimates in terms of physically measurable variables are key knowledge for effective water management. However, how these deficits vary with the drought event severity indicated by commonly used standardized indices is often unclear. Drought characteristics assigned the same value in the index are not necessarily the same in different regions, and in different months of the same region. The study investigates drought to remove this disadvantage of the index-based drought IDF curves and develop intensity-duration-frequency (IDF) curves in terms of the associated deficit. In order to study the variation of deficits, the link between precipitation and streamflow was used, and the associated indices, standardized precipitation index (SPI) and standardized streamflow index (SSI). More specifically, the analysis relies on frequency analysis combined with the total probability theorem applied to the critical drought severity. The critical drought has varying durations and it is extracted from dry periods. IDF curves in terms of precipitation and streamflow deficits for the most severe drought of each drought duration in each year are then subject to the comparison of statistical characteristics of droughts for different return periods. Precipitation and streamflow data from two catchments, the Seyhan River (Turkey) and the Kocher River (Germany) provide examples of two climatically and hydrologically different cases. A comparison of the two cases allows to test a similar method in different hydrological conditions. The results show that precipitation and streamflow deficits vary systematically reflecting seasonality and the magnitude of precipitation and streamflow characteristics of the catchments. Deficits change from one month to another at a given station. Higher precipitation deficits were observed in winter months compared to summer months. Additionally, major droughts experienced in both catchments on the IDF curves show that the major droughts have return periods at the order of years at short durations. This coincides with the observation in the catchments and shows the applicability of the IDF curves. The IDF curves can be considered a tool for the use in a range of specific activities of agriculture, ecology, industry, energy, water supply, etc. This is particularly important to end-users and decision-makers to act against the drought quickly and precisely in a more physically understandable manner.

Other than quantitative methodologies, drought was also analyzed by a qualitative approach. Using the causal loop diagram, the drought event of 2008 observed in the Seyhan River Basin was taken as an example to focus on the identification of bidirectional feedback between humans and water under drought conditions. This particular drought is short but severe as it coincided with the least amount of precipitation ever recorded in the river basin. It is an important example because it gave an impetus to the governmental water authorities to initiate basin-scale drought management plans. The quantitative and qualitative data collected for this drought were used in the causal loop analysis. The causal loop diagram shows that short-term measures under economic, structural and conservation frameworks can only provide temporary solutions which may aggravate drought impact. A sustainable water availability under drought conditions can only be achieved by long-term reactions such as drought management plans.

In summary, the thesis contributes to drought analysis research by proposing new methodologies and drought concepts. The outcomes of the study underline the need for such drought analyses. The analysis of the conceptualization reveals strong differences among the statistical properties of the drought characteristics. Moreover, the thesis emphasizes the region-specific characteristics of drought that need to be considered for drought management strategies.

YAĞIŞ AÇIĞI VE AKIM AÇIĞI FİZİKSEL DEĞİŞKENLERİNİ KULLANAN STANDARTLAŞTIRILMIŞ İKLİM İNDEKSLERİ TABANLI KURAKLIK ŞİDDET-SÜRE-FREKANS EĞRİLERİNİN GELİŞTİRİLMESİ

ÖZET

Kuraklık, su kıtlığına neden olan ve nüfusu ekonomik, sosyal ve çevresel bakımdan ciddi şekilde etkileyen bir doğal afettir. Kuraklığın etkisi, artan nüfus, yükselen yaşam standartları, gelişen sanayi ile artan tarımsal, evsel ve endüstriyel su talepleriyle daha da ağırlaşmıştır. Diğer doğal afetlerle karşılaştırıldığında, kuraklık uzun bir süre boyunca yavaşça geliştiği ve sona erdikten sonra bile etkisi uzun dönem devam ettiği için kalıcı zarar veren afetler arasındadır.

Su kaynaklarının sürdürülebilirliği açısından kuraklığı tüm yönleri ile anlamak tartışmasız önemlidir. Henüz tam olarak anlaşılmadığından kuraklık sadece bir hidrolojik olay olarak değil aynı zamanda hem teknik hem de sosyal bir sorun olarak karşımıza çıkmaktadır. Bu durum, tezdeki kuraklık kavramlarını ve metodolojilerini nicel teknik bağlamından nitel sosyal bağlamlarına genişleterek incelemek için büyük bir motivasyon kaynağı oluşturmuştur. Tezin uygulama alanı olarak biri Türkiye'nin güneyinde Akdeniz iklimine sahip Seyhan Nehri Havzası, diğeri Almanya'nın güneybatısında nemli iklime sahip Kocher havzası olarak seçilmiş, farklı iklim özelliklerine sahip bu nehir havlarına ait yağış ve akış verileri kullanılmıştır.

Literatürde, kuraklık yaygın olarak, bir bölgede yaşanan belli başlı kurak dönemlerderinlemesine ele alınmadan mevcut iklim veya hidrolojik veriler kullanılarak analiz edilir. Ayrıca, şiddet bakımından her bir kuraklık sınıfına ait görülme olasılığının kayan (rolling) zaman serisi ile değerlendirmek yaygın bir uygulama değildir. Durağan olmayan bu nicel analizin insan-su ilişkisini içeren nitel analiz ile birleştirilmesiyle Türkiye'de Seyhan Nehri Havzası'nda yapılan çalışma ile bu boşluğun doldurulması amaçlanmıştır. Bu nedenle, tezdeki birinci çalışma, tüm zaman serisini esas alan durağan analizin yanında her bir kuru döneme ve durağan olmayan kayan (rolling) zaman serisi analizine odaklanmaktadır. Havzadan seçilen 19 meteoroloji istasyonunun yağış zaman serisinden altı büyük kuru dönem belirlenmiştir. Bunlardan 1970-1974, 2002-2008 ve 2013-2015 yıllarını kapsayan ve sırasıyla 1974, 2008 ve 2014 kuraklıkları olarak da bilinen kurak dönemler, nehir havzasındaki birçok sektörü uzun süreli etkilediklerinden özellikle not edilmelidir. Her bir kuru dönem bahsedilen yöntemlerle analiz edilmiştir. Sonuçlar, her bir kuru dönemin kullanılmasıyla şiddetli kuraklık için önemli ölçüde daha yüksek olasılıkların hesaplandığını göstermektedir. Buna göre, çalışmadan elde edilen önemli bir sonuç, pratikte tüm veri kaydı bir bütün olarak kullanılarak kuraklığın şiddet bakımından hafife alınmaktadır. Ayrıca, bir kuru dönem uzunluğu bakımından önemliyken, bir diğeri şiddeti veya büyüklüğü bakımından önemli olabilir. Her kuru dönemin insan-su ilişkileri üzerinde etkisi vardır. Bunun önceden bilinmesi kuraklığın etkisinin azaltılması ve kuraklık yönetimi için stratejilerin geliştirilmesi bakımından önemlidir.

Tezin ikinci çalışması, kuraklığın negatif etkilerini azaltmak, kuraklık yönetim stratejilerini geliştirmek ve kuraklığın daha iyi anlaşılması için kuraklığın istatistik

özelliklerini araştırmaktadır. Gidiş (run) teorisine dayanan yaygın yaklaşımdan farklı olarak, bu çalışmadaki hipotez, kuraklığı bir kuru dönemden farklı tanımlamakta, her bir kuru dönemin farklı süreli kuraklıklardan oluştuğunu kabul etmektedir. Bu farkındalık bugüne kadar yapılan çalışmalara yansımamıştır. Tezin bu konuyu ele alan kısmı, kuru dönemlerin ve kuraklıkların istatistiksel özelliklerinin ne kadar farklı olduğunu, Standartlaştırılmış Yağış İndeksi (SPI) ile hesaplanan kuraklık şiddetinin toplam olasılık teoremi kullanılarak yapılan frekans analizi sonuçlarına göre ortaya koymaktadır. Bu kapsamda üç farklı kavram test edilmektedir: (1) Kuru dönem, (2) Kuru dönem kritik kuraklığı, (3) Yıllık kritik kuraklık. Sonuçlar, gidiş (run) teorisi kullanıldığında ele alınamayan çok sayıda kuraklığı ortaya çıkarmakta ve kuru dönemlerde maskelenen daha şiddetli kuraklıkları ortaya çıkarmakatdır. Kuraklığın büyüklük ve süresinin yanında özellikle şiddeti önemlidir. Kuru dönemler kritik kuraklıklara göre daha az şiddetlidir. Şiddet bakımından kuru dönem ve kritik kuraklık arasındaki fark, havza veya bölgesel ölçekte kuraklık yönetim planlarını etkileyebilecek kadar büyüktür. Bu durum, kuraklık çalışmalarında kuru dönemlerin içinde kalan kritik kuraklıkların ortaya çıkarılmasının ve uygulamada kullanılmasının uygun ve gerekli olduğunu göstermektedir.

Üçüncü çalışmada, ikinci çalışmada tanımlanan kritik kuraklık kavramı kullanılarak kuraklık şiddet-süre-frekans (IDF) eğrileri geliştirilmiştir. Kuraklık IDF eğrileri, yağış ve akım açığına dayanmaktadır. Çünkü fiziksel olarak ölçülebilir değişkenler cinsinden kuraklık tahminleri yapmak etkili bir su yönetimi için önemlidir. Yağış ve akım açığının, yaygın olarak kullanılan standartlaştırılmış indeksler ile belirlenen kuraklık şiddetine göre nasıl değiştiği genellikle belirsizdir. Kuraklık indeksinin aynı bir değeri farklı bölgelerde ve hatta aynı bölgenin farklı aylarında farklı yağış ve akım açıklarına karşı gelmektedir. Tezdeki bu çalışma, indeks tabanlı kuraklık IDF eğrilerinin bu dezavantajını ortadan kaldırmak için kuraklığı SPI ve standart akım indeksi (SSI) cinsinden incelemekte ancak kuraklık IDF eğrilerini yağış veya akım açığına bağlı olarak geliştirmektedir. Bu açıkların değişimini incelemek için, yağış ile SPI ve akım SSI arasındaki ilişki kullanılmıştır. Kullanılan yöntem spesifik olarak her bir yıl için belirlenen farklı süreli her bir kritik kuraklık kümesine ait şiddet değerlerine uygulanan toplam olasılık teoremi ile birleştirilmiş frekans analizini kullanmaktadır. Uygulama amacıyla seçilen Seyhan Nehri (Türkiye) ve Kocher Nehri (Almanya) yağış ve akım verileri iklimsel ve hidrolojik bakımdan farklı iki duruma örnek teşkil etmektedir. Nehirler arasındaki farklılık yöntemin farklı hidrolojik koşullarda uygulabilirliğini ortaya koymaktadır. Sonuçlar, yağış ve akım açığının, havzaların mevsimselliğini, yağış miktarını ve akım özelliklerini yansıtmakta ve yıl içinde sistematik olarak değiştiğini göstermektedir. Bir istasyondaki yağış ve akım açığı bir aydan diğerine değişmetedir. Kış aylarında yaz aylarına göre daha yüksek yağış açıkları gözlenmiştir. Geliştirilen kuraklık IDF eğrileri, her iki havzada da geçmişte yaşanan kuru dönemlerden alınan kısa süreli kuraklıkların uzun dönüş aralıklarına ve dolayısıyla yüksek şiddete sahip olduğunu, göstermektedir. Bu durum havzalardaki gözlemle örtüşmekte ve IDF eğrilerinin uygulanabilirliğini göstermektedir. Geliştirilen kuraklık IDF eğrileri mevcut halleriyle, tarım, ekoloji, endüstri, enerji, su temini vb. bir dizi spesifik faaliyette kullanmak için fiziksel anlamı olan bir araç olarak kabul edilebilir.

Tezin dördüncü çalışmasında, nicel yöntemler dışında kuraklık nitel bir yaklaşımla analiz edilmiştir. Nedensellik döngü diyagramı kullanılarak, kuraklık koşullarında insan ve su arasındaki çift yönlü geri bildirimlerin belirlenmesine odaklanmak için 2008 yılında Seyhan Havzasında gözlenen kuraklık olayı örnek alınmıştır. Bu kuraklık, akarsu havzasında şimdiye kadar kaydedilen en az yağış miktarıyla çakıştığı için kısa ama şiddetlidir. Bu önemli bir örnektir, çünkü Türkiye'deki su ile ilgili kamu kurumlarına havza ölçeğinde kuraklık yönetim planlarını başlatması için itici güç olmuştur. Bu kuraklık için toplanan nicelik ve nitelik veriler, nedensel döngü analizinde kullanılmıştır. Bu analiz, ekonomik destek sağlama, su yapısı yapma ve suyu koruma gibi kısa vadeli önlemlerin kuraklığa karşı geçici çözümler sağlayabileceğini ancak bunların aslında belki de kuraklığın etkisini artırabileceğini göstermiştir. Kuraklık koşullarında sürdürülebilir bir su varlığı ancak kuraklık yönetim planları gibi uzun vadeli çözümler ile sağlanabilir.

Özetle tez, yeni metodoloji ve kuraklık kavramları önererek kuraklık araştırmalarına katkıda bulunmaktadır. Tez çalışmasının sonuçları, böyle bir kuraklık analizine duyulan ihtiyacın altını çizmektedir. Yeni önerilen kavramlar kullanıldığında elde edilen kuraklık şiddetinin literatürde mevcut yöntemler kullanıldığında elde edilen kuraklık şiddetinden farklı olduğunu ve bu farkın pratikte alınması gerekecek kadar büyük olduğunu ortaya koymaktadır. Ayrıca tez, kuraklık yönetim stratejileri için dikkate alınması gereken kuraklığın bölgeye özgü özelliklerine vurgu yapmaktadır.

ENTWICKLUNG VON DÜRREINTENSITÄTS-DAUER- HÄUFIGKEITS-KURVEN AUF DER BASIS VON STANDARDISIERTEN KLIMAINDIZES UNTER VERWENDUNG PHYSIKALISCHER VARIABLEN, DEFIZIT BEIM NIEDERSCHLAG UND DEFIZIT BEIM STROMFLUSS

ZUSAMMENFASSUNG

Dürre ist eine Naturkatastrophe, die zu Wasserknappheit führt und die Bevölkerung in vielerlei Hinsicht ernsthaft beeinträchtigt, beispielsweise in wirtschaftlicher, sozialer und ökologischer Hinsicht. Diese Auswirkungen wurden durch den steigenden Bedarf an landwirtschaftlichem, kommunalem und industriellem Wasser usw. aufgrund der wachsenden Bevölkerung in Verbindung mit steigendem Lebensstandards und zunehmender Industrialisierung in der Welt noch verschärft. Im Vergleich zu anderen Naturgefahren gehört die Dürre zu den schlimmsten Katastrophen, da sie sich langsam über einen längeren Zeitraum entwickelt und auch nach dem Ende der Dürre noch mehrere Jahre andauern kann.

Wie wichtig die Dürre für die Nachhaltigkeit der Wasserressourcen ist, erfordert zusätzliche Anstrengungen, um zu verstehen und zu erklären. Privathaushalte, Landwirtschaft, Industrie, Energie, Tourismus und viele weitere Sektoren sind Dürreperioden ausgesetzt, die direkte Auswirkungen auf Ökologie, Wirtschaft und Gesellschaft haben. Als eines der am wenigsten verstandenen hydrologischen Phänomene ist Dürre sowohl ein technisches als auch ein soziales Problem. Dies ist eine große Motivation, in dieser Arbeit Dürrekonzepte und -methoden zu untersuchen, indem sie von ihrem quantitativen technischen Kontext auf den qualitativen sozialen Kontext ausgeweitet werden. Fallstudien wurden in zwei Flusseinzugsgebieten mit unterschiedlichen klimatischen Eigenschaften durchgeführt. Eine davon ist das Seyhan-Flussbecken im Süden der Türkei mit mediterranem Klima und eine andere das Kocher-Einzugsgebiet im Südwesten Deutschlands mit feuchtem subtropischem Klima.

In der Literatur wird die Dürre üblicherweise anhand verfügbarer hydroklimatischer oder hydrologischer Daten analysiert, ohne dass spezifische größere Trockenperioden in einer Region eingehend berücksichtigt werden. Außerdem ist es keine gängige Praxis, die Wahrscheinlichkeit von Dürrekategorien mit einer fortlaufenden Zeitreihe abzuschätzen, und daher ändern sich die Erkenntnisse für die betriebliche Dürreüberwachung. Eine Kombination einer solchen quantitativen Analyse mit einer umfassenden qualitativen Bewertung der Dürre als Mensch-Wasser-Beziehung zielte darauf ab, diese Lücke durch die Durchführung einer Fallstudie im Seyhan-Flussbecken in der Türkei zu schließen. Daher konzentriert sich der erste Teil dieser Arbeit auf die Analyse instationärer rollierender Zeitreihen zusammen mit der Analyse stationärer Gesamtzeitreihen und der Analyse einzelner großer Trockenperioden. Aus den Niederschlagszeitreihen von 19 Wetterstationen wurden sechs große Trockenperioden identifiziert. Besonders hervorzuheben sind die Trockenperioden, die sich über die Jahre 1970–1974, 2002–2008 und 2013–2015 erstreckten und auch als Dürren von 1974, 2008 bzw. 2014 bekannt sind, da sie mehrere Sektoren im

Flusseinzugsgebiet mit der langandauernden Trockenheit betrafen. anhaltender Wassermangel. Große Trockenperioden wurden anhand rollierender Zeitreihen und vollständiger Zeitreihen analysiert, außerdem wurden sie einzeln analysiert. Die Ergebnisse zeigen, dass durch die Nutzung einzelner großer Trockenperioden deutlich höhere Wahrscheinlichkeiten für extreme Dürren berechnet wurden. Ein wichtiges Ergebnis der Studie ist, dass Dürren in der Praxis bei alleiniger Nutzung des gesamtenDatensatzes unterschätzt werden. Außerdem könnte eine große Trockenperiode hinsichtlich ihrer Dauer wichtig sein, während eine andere hinsichtlich ihrer Schwere oder Intensität wichtig ist. Jede größere Trockenperiode hat ihre eigenen Auswirkungen auf die Mensch-Wasser-Beziehungen, die Einfluss auf die Eindämmung, Bewältigung und Steuerung von Dürren haben können.

Der zweite Teil der Arbeit untersucht die statistischen Eigenschaften von Dürremerkmalen, um Dürre besser zu verstehen, ihre negativen Auswirkungen zu mildern und Dürremanagementstrategien zu verbessern. Anders als beim gängigen Ansatz auf Basis der Lauftheorie wird die Hypothese aufgestellt, dass sich Dürre von der Trockenperiode unterscheidet und Trockenperioden Dürren unterschiedlicher Dauer kennzeichnen. Bisher wurde in diesem Sinne den statistischen Eigenschaften von Trockenperioden im Vergleich zu denen schwererer und schwerwiegenderer Dürren als separate Phänomene keine Beachtung geschenkt. Die Studie zeigt, wie unterschiedlich die statistischen Eigenschaften von Trockenperioden und Dürren sind, indem sie sie mit dem Standardisierten Niederschlagsindex (SPI) zusammen mit der mit dem Gesamtwahrscheinlichkeitssatz gekoppelten Häufigkeitsanalyse quantifiziert. Die Studie testet in diesem Zusammenhang vier Konzepte: (1) Trockenperiode, (2) Kritische Dürre für eine Trockenperiode, (3) Kritische Dürre für ein Jahr. Die Ergebnisse zeigen die hohe Anzahl an Dürren, die in der Run-Theorie nicht berücksichtigt werden, und offenbaren intensivere Dürren, die innerhalb der Trockenperioden maskiert werden. Insbesondere hängen die Auswirkungen der Dürre häufiger mit der Intensität der Dürre als mit ihrer Schwere und Dauer zusammen. Zudem ist die Trockenzeit weniger intensiv als bei anderen Konzepten. Unter den neu vorgeschlagenen Dürren sind kritische Dürren die intensivsten. Dies zeigt, dass sich die für die Dürrekonzepte berechneten Dürrecharakteristika vom üblichen Ansatz der Trockenperiode unterscheiden. Der Unterschied zwischen den Konzepten ist groß genug, um potenzielle Auswirkungen auf die Planung des Dürremanagements auf lokaler oder regionaler Ebene zu haben.

In der dritten Studie wurden Dürreintensitäts-Dauer-Häufigkeits kurven (IDF) unter Verwendung der in der zweiten Studie identifizierten kritischen Dürre entwickelt. Die Dürre-IDF-Kurven basieren auf Niederschlags- und Abflussdefiziten, da Dürreschätzungen anhand physikalisch messbarer Variablen Schlüsselwissen für ein effektives Wassermanagement sind. Allerdings ist oft unklar, wie diese Defizite mit der Schwere des Dürreereignisses variieren, die durch häufig verwendete standardisierte Indizes angegeben wird. Dürremerkmale, denen im Index derselbe Wert zugewiesen wird, sind in verschiedenen Regionen und in verschiedenen Monaten derselben Region nicht unbedingt gleich. Die Studie untersucht Dürren, um diesen Nachteil der indexbasierten Dürre-IDF-Kurven zu beseitigen und Intensitäts-Dauer-Häufigkeits Kurven (IDF) im Hinblick auf das damit verbundene Defizit zu entwickeln. Um die Variation der Defizite zu untersuchen, wurde der Zusammenhang zwischen Niederschlag und Abfluss sowie die zugehörigen Indizes, der standardisierte Niederschlagsindex (SPI) und der standardisierte Abflussindex (SSI), verwendet. Genauer gesagt basiert die Analyse auf der Häufigkeitsanalyse in Kombination mit dem Gesamtwahrscheinlichkeitssatz, der auf den Schweregrad der kritischen Dürre angewendet wird. Die kritische Dürreperiode dauert unterschiedlich lange und geht aus Trockenperioden hervor. IDF-Kurven in Bezug auf Niederschlags- und Abflussdefizite für die schwerste Dürre jeder Dürredauer in jedem Jahr werden dann dem Vergleich statistischer Merkmale von Dürren für verschiedene Wiederkehrperioden unterzogen. Niederschlags- und Abflussdaten aus zwei Einzugsgebieten, dem Seyhan-Fluss (Türkei) und dem Kocher-Fluss (Deutschland), liefern Beispiele für zwei klimatisch und hydrologisch unterschiedliche Fälle. Ein Vergleich der beiden Fälle ermöglicht es, eine ähnliche Methode unter unterschiedlichen hydrologischen Bedingungen zu testen. Die Ergebnisse zeigen, dass Niederschlags- und Abflussdefizite systematisch variieren, was die Saisonalität sowie die Niederschlagsmenge und Abflusseigenschaften der Einzugsgebiete widerspiegelt. Die Defizite ändern sich von Monat zu Monat an einer bestimmten Station. In den Wintermonaten wurden im Vergleich zu den Sommermonaten höhere Niederschlagsdefizite beobachtet. Darüber hinaus zeigen schwere Dürren in beiden Einzugsgebieten auf den IDF-Kurven, dass die großen Dürren kurze Zeiträume in der Größenordnung von Jahren aufweisen. Dies deckt sich mit der Beobachtung in den Einzugsgebieten und zeigt die Anwendbarkeit der IDF-Kurven. Die IDF-Kurven können als Werkzeug für den Einsatz in einer Reihe spezifischer Aktivitäten in den Bereichen Landwirtschaft, Ökologie, Industrie, Energie, Wasserversorgung usw. betrachtet werden. Dies ist besonders wichtig für Endverbraucher und Entscheidungsträger, um schnell und effizient gegen die Dürre vorgehen zu können und zwar auf eine physikalisch verständlichere Art und Weise.

Neben quantitativen Methoden wurde die Dürre auch mit einem qualitativen Ansatz analysiert. Mithilfe des Kausalschleifendiagramms wurde das im Seyhan-Flussbecken beobachtete Dürreereignis von 2008 als Beispiel herangezogen, um sich auf die Identifizierung bidirektionaler Rückkopplungen zwischen Mensch und Wasser unter Dürrebedingungen zu konzentrieren. Diese besondere Dürre ist kurz, aber schwerwiegend, da sie mit der geringsten Niederschlagsmenge zusammenfiel, die jemals im Flusseinzugsgebiet registriert wurde. Dies ist ein wichtiges Beispiel, da es den staatlichen Wasserbehörden den Anstoß gab, in der Türkei Dürremanagementpläne auf Einzugsgebietsebene zu initiieren. Die für diese Dürre gesammelten quantitativen und qualitativen Daten wurden in der Kausalkreislaufanalyse verwendet. Das Kausalschleifendiagramm zeigt, dass kurzfristige Maßnahmen im Rahmen wirtschaftlicher, struktureller und naturschutzrechtlicher Rahmenbedingungen nur vorübergehende Lösungen bieten können, die die Auswirkungen der Dürre verstärken können. Eine nachhaltige Wasserverfügbarkeit unter Dürrebedingungen kann nur durch langfristige Reaktionen wie Dürremanagementpläne erreicht werden.

Zusammenfassend trägt die Arbeit zur Dürreanalyseforschung bei, indem sie neue Methoden und Dürrekonzepte vorschlägt. Die Ergebnisse der Studie unterstreichen die Notwendigkeit solcher Dürreanalysen. Die Analyse der Konzeptualisierung zeigt starke Unterschiede zwischen den statistischen Eigenschaften der Dürremerkmale. Darüber hinaus betont die Arbeit die regionalspezifischen Merkmale der Dürre, die bei Dürremanagementstrategien berücksichtigt werden müssen.

1. INTRODUCTION

1.1 Significance of the Thesis

Water plays a critical role in human life since all life on earth depends on it. Yet, millions of people have no access to water and they suffer from water scarcity. It is, therefore, important to know any water deficit in advance, in the domestic use, agriculture, farming, industry, energy, tourism, etc. for their sustainability. The effective use and sustainability of water resources can make more water available in long dry periods for the needs of fast-growing population.

Probably, drought is one of the least understood natural disasters because of its complex behaviour. It is a natural process that negatively affects land and water resources as a result of precipitation falling below the recorded normal levels, and causes disruption in the hydrological water balance (Hagman, 1984). These disruptions have been further aggravated by rising demands for municipial and industrial water due to the growing population coupled with rising life standard and increasing industrialization. Climate change and contamination also cause water scarcity as, in recent years, floods and droughts have been experienced with higher peaks and severity levels, respectively (Mishra and Singh, 2010). Predictions on climate change scenarios clearly show that drought conditions are becoming worse especially in regions with arid and semi-arid climate (Carrillo et. al., 2023). Both preparing for drought and mitigating its negative effects are of high importance in terms of scientific development and policy making. The significance of drought studies comes also from its impacts becoming increasingly widespread and severe on society with its consequences. It is thus necesarry to monitor and anticipate drought before it occurs, but this is becoming increasingly difficult due to the inevitable continuous change in hydrology and climate (Easterling et al., 2000; Alexander et al., 2009). This study is such an attempt to understand the drought through data-based analysis by also proposing new concepts and developing new quantitative tools for better practice of water resources management under drought conditions.

1.2 Purpose and Scope of Thesis

In order to better understand the drought, it is important to determine dry periods and to know drought-related fundamental concepts such as severity, duration, intensity and frequency. One of the common methods for the drought analysis is the run theory proposed by Yevjevich (1967). The run theory assumes that a physically measurable indicator, e.g., precipitation, streamflow, displays a time series composed of subsequent positive and negative periods relative to a given threshold level. Once a threshold value is chosen as a given percentage of the mean value or a quantile of a given probability, surplus runs and deficit runs can be identified and their statistical properties such as the severity, duration, and intensity can be determined. In the so-far research and practice, drought has been analyzed according to definitions based on the run theory, which indicates that a drought is experienced when the drought indicator or drought index falls below the selected threshold level. This thesis hypothesizes that period of time during which the indicator is lower than the threshold level is a "dry period" but not a "drought". A dry period, therefore, consists of droughts not longer than the dry period itself. With this reconceptualization, a large number of droughts, which is not addressed in the run theory is revealed. Droughts are called "within-period drought" and "singular drought". In the conceptualization within the scope of this thesis, also, I define "critical drought" of a given duration for a dry period and a year separately. Thus, three different cases have emerged in total, which are (I) Dry period, (II) Critical drought for a dry period, (III) Critical drought for a year. These novel concepts and their comparative analysis improved the existing understanding about the drought through the hypothesis.

Within the scope of this thesis, I performed several analyses by using methodologies applied to hydrometeorological data recorded at stations, i.e., point-scale data. In the first study, I introduce a non-stationary rolling time series analysis which is more complex than the common practice of the stationary time series analysis. Second, I hypothesize that drought is different from the dry period through the reconceptualization for which three cases listed above were tested. Frequency analysis of drought characteristics; namely, duration, severity, and intensity, was performed to choose the best among the pre-selected probability distribution functions for the cases. The difference between the run theory-based classical and the novel concepts improved the reliability in drought prediction. In the third study, based on the knowledge of the reconceptualization, the aim is to analyze meteorological and streamflow data and to derive station-based drought Intensity-Duration-Frequency (IDF) curves to quantify the return intervals of droughts. One detail that should be mentioned here is that the IDF curves were derived in terms of precipitation and water deficits not the standardized drought indices. This is a new methodology established together with novel drought-related definitions and concepts. Case studies considered in this thesis may elucidate and reveal temporal change in drought characteristics at a station. Besides this technical context, at the end, I discuss the results through the relation of humans to water as emerged from the amplified potential for sociopolitical and economic disruption of drought.

1.3 Posing Some of the Open Questions in Drought

The battle of drought analysis against methods and its impacts resulted into a substantial body of literature. Substantial efforts were also deployed to understand drought characteristics and to mitigate its impacts, using different sources of information, such as multiple observations or drought indices. What seems to have received much less attention, even today, are the basic questions about the prediction of drought, which were investigated through the combination of four interrelated studies in this thesis (Figure 1.1). What knowledge do we not have before each drought event? Could we have estimated the risk correctly with the data available before the drought event? Does the risk change after drough events? What do we learn from the past drought events and do they really estimate the drought event correctly? An important question remaining to be explored is “what actually do we get about a drought if we use the time series of drought indicator for the analysis?” and “how much exactly?”. This remains unanswered or depends on many more factors to be taken into account. Based on this knowledge and research gaps, Study 1 in Chapter 2 of the thesis focuses to respond following research questions:

a) Which additional insight can be gained from revisiting major dry periods?

b) How can a time series analysis be made more useful for not underestimating the drought?

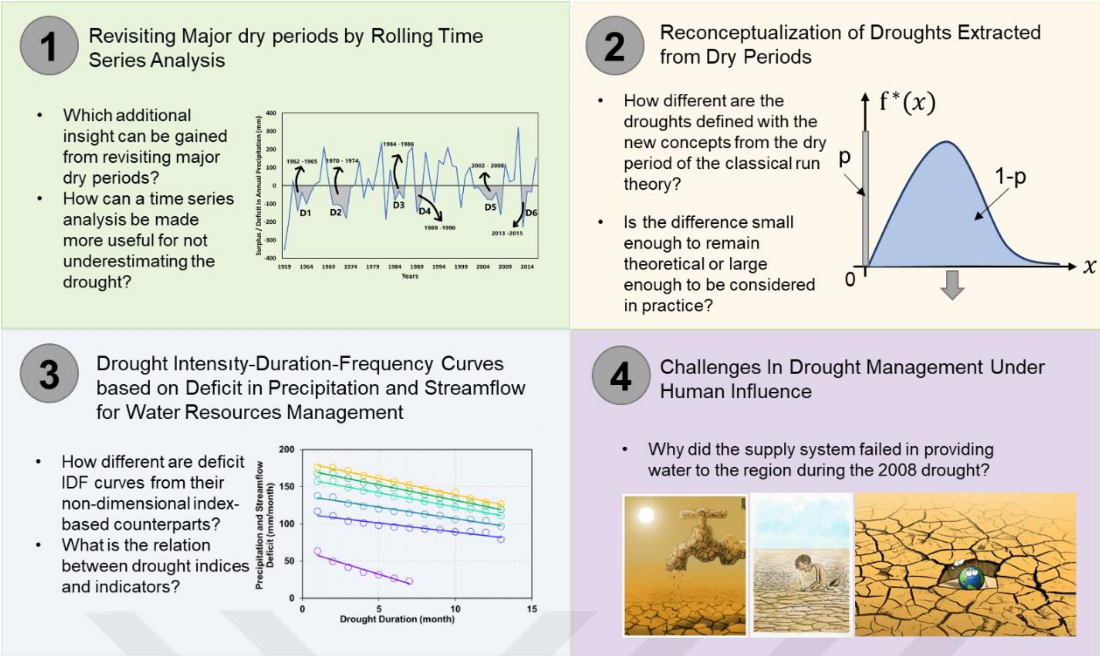

Figure 1.1 : Studies performed within the framework of the thesis and research questions (photos in the lower right box (Number 4) are from https://cartoonmovement.com/).

Another missing aspect of knowledge on drought definition is how to formulate the available quantitative and qualitative information in drought management. In the hydrological community, there is no doubt that the lack of drought definition might cause indecision and inaction in drought management. The quantitative definitions other than the known drought concepts are important to determine the degree of drought impact. In doing that, I basically hypothesize that a dry period is not the same as a drought, but is made of multiple droughts with durations shorter than the dry period lengths. Yet, the effect of this distinction on the duration, severity and intensity of the droughts and dry periods is not clear. Study 2, to fill this knowledge gap, essentially tests the hypothesis and justifies the need for the distinction between drought and dry period for basic understanding and its practical implication by addressing following research questions:

a) How different are the droughts defined with the new concepts from the dry period of the classical run theory?

b) Is the difference small enough to remain theoretical or large enough to be considered in practice?

c) Do the results change from one location to another?

Although studies have been trying to cover this aspect of drought, the aforementioned question remains open to debate. The hypothesis can be put into a neat method and then can be tested against observed data or physical characteristics such as deficit amount at the catchment scale. If the established hypothesis manages the methods designed for its eligibility, then this hypothesis is more likely to be the explanation of the underlying processes or the method functionality.

Another open question is that non-dimensionality of drought studies comes at the expense of physical non-interpretability, i.e. most drought indices cannot be read quantitatively as actual precipitation and streamflow deficits. It is not well understood to which degree of deficit or detail a method can be given by the available data. In fact there is no approach that can justify a certain level information. The research gap itself is also not well understood and debated in hydrology. However, in scientific approaches there are many assumptions which are not fully justified, and the only reason for accepting them is to enable to reduce problems to a manageable scale. For this, Study 3 focuses on the physical indicators such as precipitation and streamflow deficits for drought studies. Specifically, it aims to assess deficits at different climatic catchments based on the IDF curves and finally explore how deficit IDF curves can be developed and be used for different purposes in water resources management practice. The study addresses the following research questions:

a) How different are deficit IDF curves from their non-dimensional index-based counterparts?

b) What is the relation between drought indices and indicators? How do deficits in precipitation and streamflow change with the associated standardized drought index in time and space?

c) For what purposes might deficit-IDF curves be used in water management practice?

The qualitative approach in Study 4 is a focus in a specific drought to identify bidirectional human-water feedbacks and to better understand challenges under drought conditions. The technical understanding and the tool development accompanied with qualitative assessment methodologies become more usfeul for water authorities, stake holders and end users to answer questions such as:

a) Why do the water supply systems fail in providing water during the drought?

b) How can water shortage be balanced by short-term and long-term preventive measures?

1.4 Outline of the Thesis

In this thesis, I address the open questions about drought analysis and concepts posed earlier. Although these open questions are not fully answered, it tries to pave a path toward a framework or strategy which can lead to a better understanding of the conceptualization and methods; better understanding of what we know and what we improve on the drought studies; better interaction of knowledge, the use of methodologies in practice (Figure 1.1). The study in Chapter 2 focuses on the assessment of the probability of drought categories with a rolling time series and hence the changing knowledge for operational drought monitoring with a comprehensive qualitative assessment of drought as a human-water relation. Chapter 3 is an elaboration of drought concepts for a better understanding of drought and their practical implication. Chapter 4 is an effort of building intensity-duration-frequency (IDF) curves based on deficit in precipitation and streamflow for water resources management after the most severe drought was defined as 'critical drought' in Chapter 3. Additionally, the IDF curves were implemented on major dry periods idenfied for the river basin in Chapter 2 to show how applicable the deficit IDF curves are in determining return periods of drought. Chapter 5 takes the qualitative approach for the identification of bidirectional feedbacks between humans and water under drought conditions. Chapter 6 is finally devoted to my synthesis about the whole study to share conclusions and provide gaps left for future studies.

2. REVISITING MAJOR DRY PERIODS BY ROLLING TIME SERIES ANALYSIS FOR HUMAN-WATER RELEVANCE IN DROUGHT

2.1 Introduction

Drought can broadly be defined as a prolonged deficit in hydrological/meteorological drivers without being confused with water shortage, where water demand is greater than water supply (van Loon et al. 2016). It is a natural hazard (Tsakiris et al. 2013; Khanmohammadi et al. 2022) unless it is caused or intensified by human activities, which may then be called anthropogenic drought. It is a threat to water and food security, and consequently to all water-dependent sectors. It can make even wealthy societies vulnerable by causing conflicts between water users, affecting the human-water relationship, disturbing the environment, and reducing the resilience of the ecosystem conditions.

A drought impact is an observable loss or change that occurred at a specific place and time. It has a widespread impact on various elements of hydrological cycle; a prolonged drought reduces soil moisture (Williams et al. 2009; Singh et al. 2019), and with excessive withdrawal it might cause groundwater level to deplete which may then permit salt water intrusion into the freshwater aquifer in a coastal river basin (Basack et al. 2013; 2022). There is little consensus on which type of drought analysis is most meaningful for the measurement of drought impacts on society and environment (Bachmair et al. 2016). Society needs information about when and where drought conditions transform into impacts. Such information can help people to prepare and react proactively by developing management and response strategies to mitigate drought impacts. Despite numerous drought studies in the literature, what knowledge is missing is an integration that bridges the gap between scientific developments and current operational practices including drought impacts.

In drought analysis, physically measurable indicators such as precipitation, streamflow and groundwater are conventionally used (Bonaccorso et al. 2012) together with indices; Standardized Precipitation Index (SPI; McKee et al. 1993), Normalized

Difference Vegetation Index (NDVI; Kogan 1995), Streamflow Drought Index (SDI; Nalbantis 2008), Standardized Precipitation Evapotranspiration Index (SPEI; Vicente-Serrano et al. 2010), Effective Reconnaissance Drought Index (ERDI; Tigkas 2017), Discrepancy Precipitation Index (DPI; Tayfur 2021) and Standardized Supply and Demand Water Index (SSDWI; Zhou et al. 2022) among many others. There exists a comprehensive body of literature using drought indices (Yacoup and Tayfur 2017; Roushangar et al. 2022). They are useful in the determination of the onset, development, recovery, termination of drought (Nemati et al. 2019), and in the quantification of its severity, intensity and frequency (van Loon 2015; Sattar et al. 2019; Aksoy et al. 2021; Kim et al. 2022). The collection of these characteristics provides a good basis to monitor drought effectively, to take proper measures against drought, and to keep drought exposure at an affordable level (Heim 2002).

In this study, we focus on the Seyhan River Basin in the Eastern Mediterranean. It is the breadbasket of the country because of the richness of the agriculture and advantageous climate. The river basin experienced extended periods of below-normal precipitation and major dry periods. Recent droughts in 2008 and 2014 raised concerns to preparing the Drought Management Plan at the governmental level (GDWM, 2019). It could be considered representative for other regions with a similar climate in this wider area. Due to its geographical proximity, a comprehensive drought analysis will be particularly helpful in getting knowledge applicable to the Eastern Mediterranean region and Middle East because of some general problems such as poor data, inadequate models or misspecification of variables controlling drought and also the political instability (Barlow et al. 2016; Ide 2018).

Previous studies only considered the full records of meteorological data in the drought analysis. In this study, we revisited the drought by focusing on major dry periods that the river basin exposed to in the past. As a new approach, we introduced a non-stationary rolling time series analysis, which is composed of data recorded until each dry period first to which the length of the dry period itself is added. The non-stationary analysis proposed in this study is more complex than the common practice of the stationary time series analysis. Besides this technical context, we discuss the results through the relation of humans to water as emerged from the amplified potential for sociopolitical and economic disruption of drought in the Eastern Mediterranean (Cook et al. 2016; Mahthbout et al. 2021). The aim of this study therefore focuses at identifying individual major dry periods from the precipitation records of the river basin to respond following research questions:

a) Which additional insight can be gained from revisiting major dry periods?
b) How can a time series analysis be made more useful for not underestimating the drought?
c) How can the quantitative outcomes be converted into qualitative knowledge through human-water relation?
Our research questions are addressed using two complementary approaches; firstly, through revisiting each major dry period and implementing the rolling time series analysis of SPI, and secondly, through a qualitative analysis of drought as the relation of humans to water. We close the analysis with a quantitative and qualitative discussion of the results regarding the major dry periods and their use in practice, to identify the knowledge gaps, conclusions and ways forward.

2.2 Material and Methods

2.2.1 Study area and dataset

Turkey is divided into 25 hydrological basins among which Seyhan River Basin is in the southern part of the country (Fig. 1). The river basin's headwaters rise to 3700 m a.s.l. in the mountainous north. It has a dense drainage network of tributaries joining the Seyhan River before it discharges into the Mediterranean Sea. Precipitation is the highest in the central part of the river basin. Average annual total precipitation in the river basin is 641 mm, 67% of which falls during the winter and spring months under the influence of the Mediterranean low-pressure systems (Cavus and Aksoy 2019; 2020). The river basin drainage area is 22.042 km^2, and it accommodates approximately 2 million of population within the basin. About 900.000 ha of lands which cover approximately 41% in the basin are used for agriculture. Dry farming is practiced in 78% of the agricultural land and the rest is irrigated. With 2.546 industrial facilities, Adana has 98% of the industrial facilities in the basin and is the most concentrated province in terms of industry (GDWM, 2019). Monthly precipitation data of 19 meteorological stations operated by the State Meteorological Service (MGM) and the General Directorate of State Hydraulic Works (DSI) were obtained for the study. The stations are almost evenly distributed over the river basin (Figure 2.1), and their record length varies between 10 and 57 years.

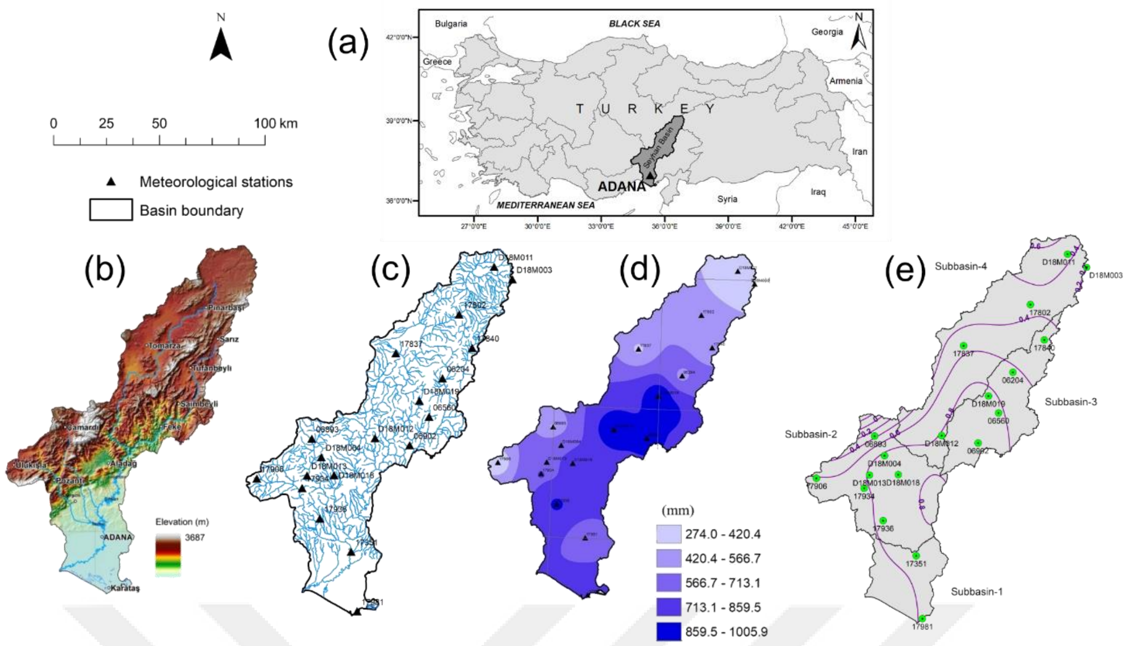

Figure 2.1 : (a) River basins of Turkey and location of Seyhan River Basin over the country, (b) Topography, (c) Drainage network of surface water courses and meteorological stations, (d) Areal precipitation distribution, (e) Sub-basins of river basin, and spatial distribution of cross-correlation calculated for annual precipitation of each station with respect to the basin-average.

2.2.2 Major dry periods

A single time series was obtained from the average of the annual precipitation records of 19 meteorological stations for the period 1959-2016. The average of annual precipitation was calculated for each year t as

$$\bar{P}_t = \frac{1}{n_t}\sum_{i=1}^{n_t} P_i \quad t = 1, \dots, N \tag{2.1}$$

where P_i annual precipitation at station i and n_t is the number of stations for which data exist at year t. The number of stations is changing for each year as we used the whole record period of each station not a common period of all. This was repeated for the length of the time series N. The overall average through the length of the time series was then taken by

$$\bar{P} = \frac{1}{N}\sum_{t=1}^{N} \bar{P}_t \tag{2.2}$$

The difference between the average in each year and the overall average of the time series was obtained as

$$P_t = \bar{P}_t - \bar{P} \quad t = 1, \ldots, N \tag{2.2}$$

which was called either surplus or deficit depending on whether it takes a positive or a negative value, respectively.

The surpluses and deficits in the time series indicate that the river basin experienced major dry periods (Figure 2.2). We identified six major dry periods in 1962-1965, 1970-1974, 1984-1986, 1989-1990, 2002-2008 and 2013-2015. A deficit that lasted 2-year long at minimum was defined as a *major dry period* in this study. This is in accordance with previous studies which found that a 2-year long dry period could impact on the region with important negative consequences; e.g., the 1989-1990 dry period (Altin et al. 2020).

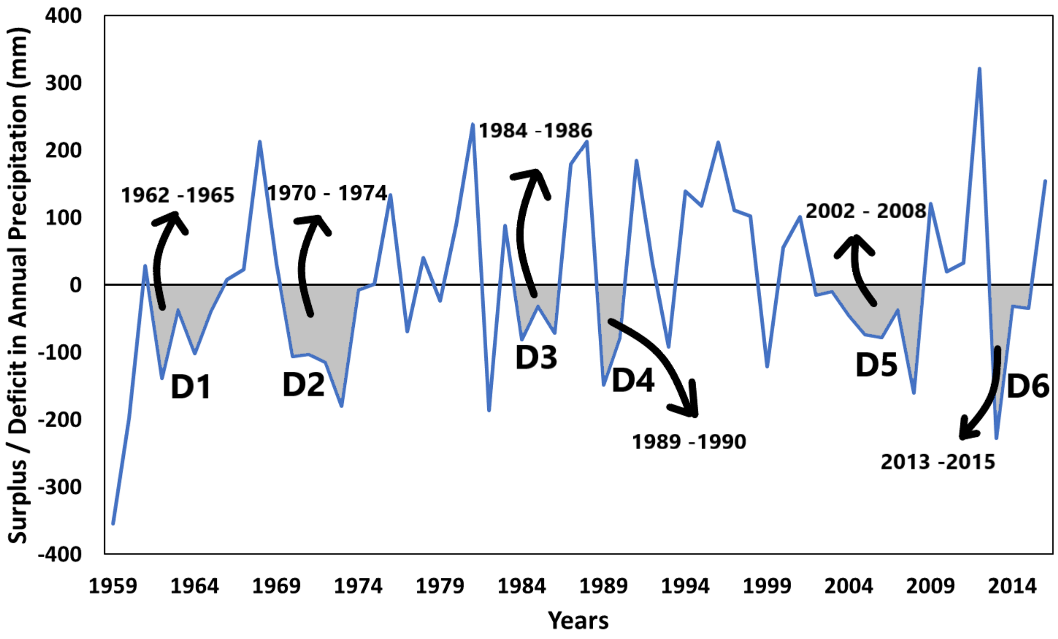

Figure 2.2 : Major dry periods identified from annual precipitation surplus and deficit time series in the Seyhan River Basin.

2.2.3 Temporal analysis of major dry periods

In this study, drought was investigated based on SPI, which is one of the most commonly used drought indices due to its availability for diverse time scales and limited data needs. Precipitation is assumed to fit by Gamma distribution which can be alternated by other probability distribution functions (Stagge et al. 2015). Depending on the value of SPI, drought is categorized as mild (-1.0 < SPI < 0), moderate (-1.5 < SPI ≤ -1.0), severe (-2.0 < SPI ≤ -1.5), and extreme (SPI ≤ -2.0).

Temporal analysis of major droughts was performed through drought probability graphs. Drought probability is the likelihood of a drought event which is quantified as the frequency calculated from the SPI time series by counting number of months falling into a given drought category (Eris et al. 2020).

The Seyhan River Basin consists of four sub-basins (GDWM 2019) each represented by a station. In selecting representative stations, we focused on two criteria; (i) cross-correlation of the annual precipitation of stations with the basin average, (ii) time series length of their record to cover as many of the major dry periods as possible. The correlation of the meteorological stations with the basin average was calculated. It changes from one station to another within the range of 0.192 to 0.901. It increases in the central part of the basin where most of the stations are located and decreases northerly (Fig. 1e). The representative stations are 17351 for sub-basin 1, 17936 for sub-basin 2, 17837 for sub-basin 3, 6902 for sub-basin 4. It should be mentioned that representative stations of sub-basins 2 and 3 have the second highest correlation. They were preferred as they have longer periods of record to cover larger number of dry periods (4 dry periods each) than the stations with the highest correlation.

2.2.4 Temporal analysis with rolling time series

The key assumption of time series analysis that precipitation is stationary changes considerably due to climate change or variability. Rolling analysis is often used to assess the nonstationary of a time series (Zivot and Wang 2006). It is commonly used to back test a statistical model established on historical data to evaluate its stability and accuracy in prediction. The back testing works in the following way in this study:

The time series was divided into a reference period and a redefining event (Figure 2.3). The portion before the major dry period (e.g., R1 in Figure 2.3) was defined as the reference period, and the major dry period itself was called the redefining event. The analysis was made first using the time series until the major dry period starts (R1) to define the drought characteristics; it was then extended to the end of major dry period (the redefining event, R1 + L1). The time series was rolled to the next reference period (R2) and the redefining event (R2 + L2). This was repeated until the end of the last major dry period was reached. Occurrence probabilities of each drought categories were calculated for the collection of major dry periods and their reference periods to compare with the full-record of the time series.

Using SPI time series, major dry periods were analyzed (or revisited). The SPI time series were calculated for each reference period and the redefining event at different time scales. Comparison was made between SPIs calculated from the reference periods including major dry periods (Rn + Ln). With the use of the rolling time series in revisiting major dry periods, it has been possible to extract the change in the drought occurrence probability over time. This makes the concept of the 'revisiting' of this study clear/important for water managers before a dry period starts. The new aspect of this study might be significant considering a 'rolling' drought probability estimate that each drought event management would have had from the past until then.

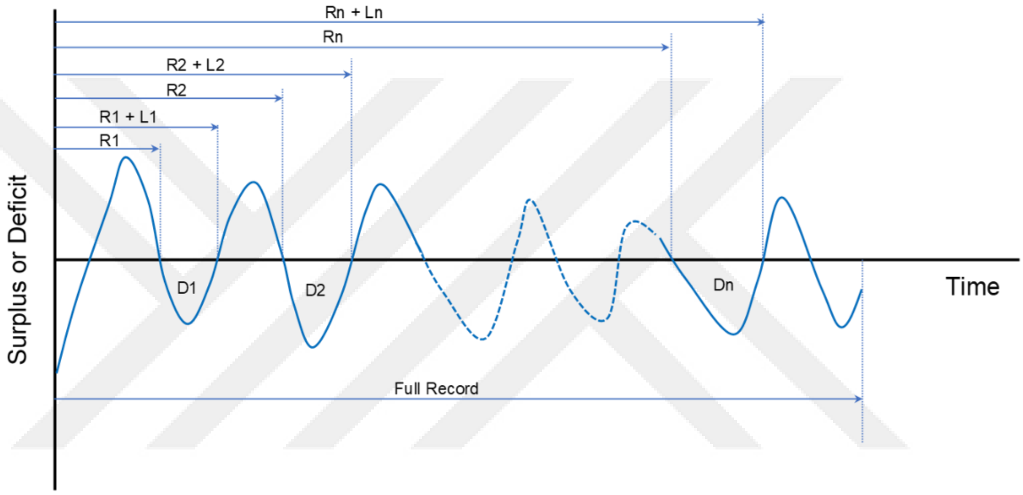

Figure 2.3 : Rolling time series analysis. D denotes the major dry period (redefining event), R and L show the lengths of each reference and major dry periods, respectively.

2.3 Results

2.3.1 Characteristics of identified events

The SPI time series show temporal variation of major dry periods (Figure 2.4), which illustrates similar patterns for each time scale with varying drought characteristics such as the duration, severity and intensity. In terms of the time scale, the frequency of SPI decreases with moving from one-month time scale to longer scales. Wet and dry periods are frequent in shorter time scales. Wet periods are dominant between 1962-1963 in D1, 1971-1972 in D2, 1988-1989 in D4 and 2013-2014 in D6. In some of the major dry periods, these wet periods last up to one year at the longer time scales. For example, in D1, the year 1963 is mostly wet and the next year (1964) is dry.

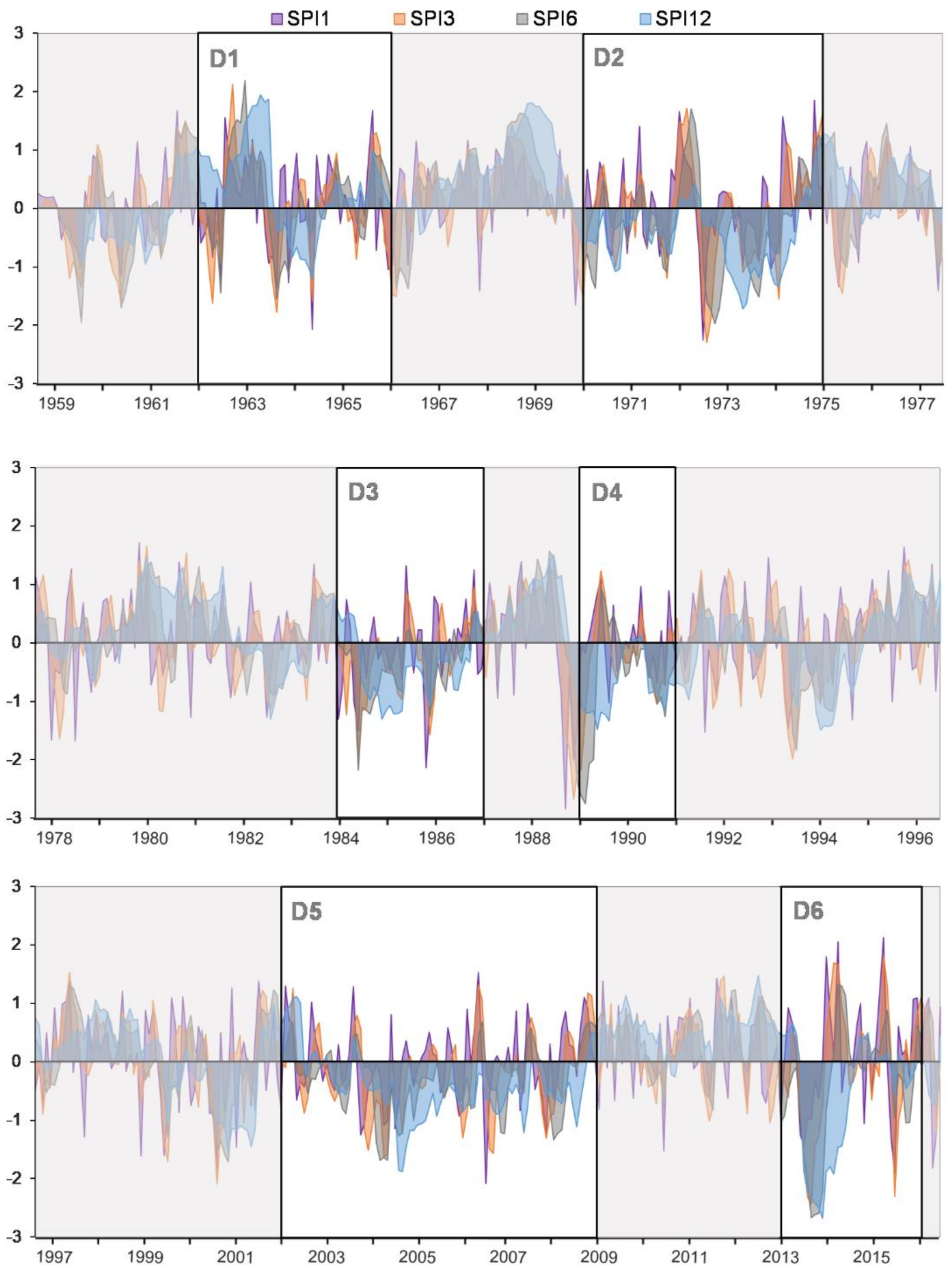

Figure 2.4 : SPI time series of major dry periods at 1, 3, 6 and 12-month time scales.

2.3.2 Temporal analysis

Major dry periods: Figure 2.5 shows how each drought category changes among major dry periods and in the full record period. Mild drought has the highest percentage for all major dry periods at each time scale. Its probability is the highest (60%) for station 17837 in D3 at SPI6. At the same station and at the same time scale, extreme drought reached the highest probability (25%) in D4. For station 17351 at SPI3, mild drought exceeds 50% in D2 while it is exactly 50% in D3; which means dry periods D2 and D3 have mild droughts at least for the half of their record lengths. Similarly, at least in half of the record lengths, dry periods D2 (50%) and D3 (52.8%) have been mild in SPI6. The number of mild droughts in half of the record length at minimum has increased to three (D3, 58.3%; D4, 50%; D5, 56%) in SPI12. This shows how the frequency of the mild drought category increases with increasing time scale. This is the case about the mild drought in one hand; on the other hand, the extreme drought has not been observed in some of the major dry periods. For example; D1, D2 and D6 have not experienced extreme drought in SPI1, and D1, D3 and D4 in SPI12 at the same station. D2 and D5 are two dry periods that have the highest probability of extreme and severe droughts in SPI12. With increasing time scale, more strengthened droughts change to less strengthened droughts although results do not show a systematic change in the probability of drought categories. However, in general, the probabilities of the drought categories show a similar character for all stations (Figure 2.5).

Rolling time series: Figure 2.6 shows how the probability of each drought category changes among the reference periods, redefining events and in the full record period. The first reference period and redefining event (R1 and R1+L1) were skipped, because the number of meteorological stations with long precipitation time series is not sufficient. Mild drought has the highest percentage for all reference periods and redefining events, and it is the most frequent drought category at all-time scales. However, the percentage of mild droughts is lower when the reference period andredefining events are considered instead of taking major dry periods individually. For example, the probability of mild drought approached 40% for station 17351 in the second redefining event (R2+L2 in Figure 2.7) at SPI6. At the same station and at the same time scale, the percentage of extreme drought reached (4%) in R5. For station 17936 at SPI12, mild droughts approached 40% in R2+D2, R3 and R3+D3 while no extreme drought was observed in these periods; which means mild droughts dominate. This situation can be observed in other meteorological stations; i.e., extreme droughts observed in short time scales changed to mild droughts as the time scale increases. At meteorological station 6902, mild and extreme droughts observed in short time scales changed to moderate and severe droughts in SPI12. This is the case about the mild and extreme droughts in one hand; on the other hand, the extreme drought has been consistently observed at all stations with a certain probability.

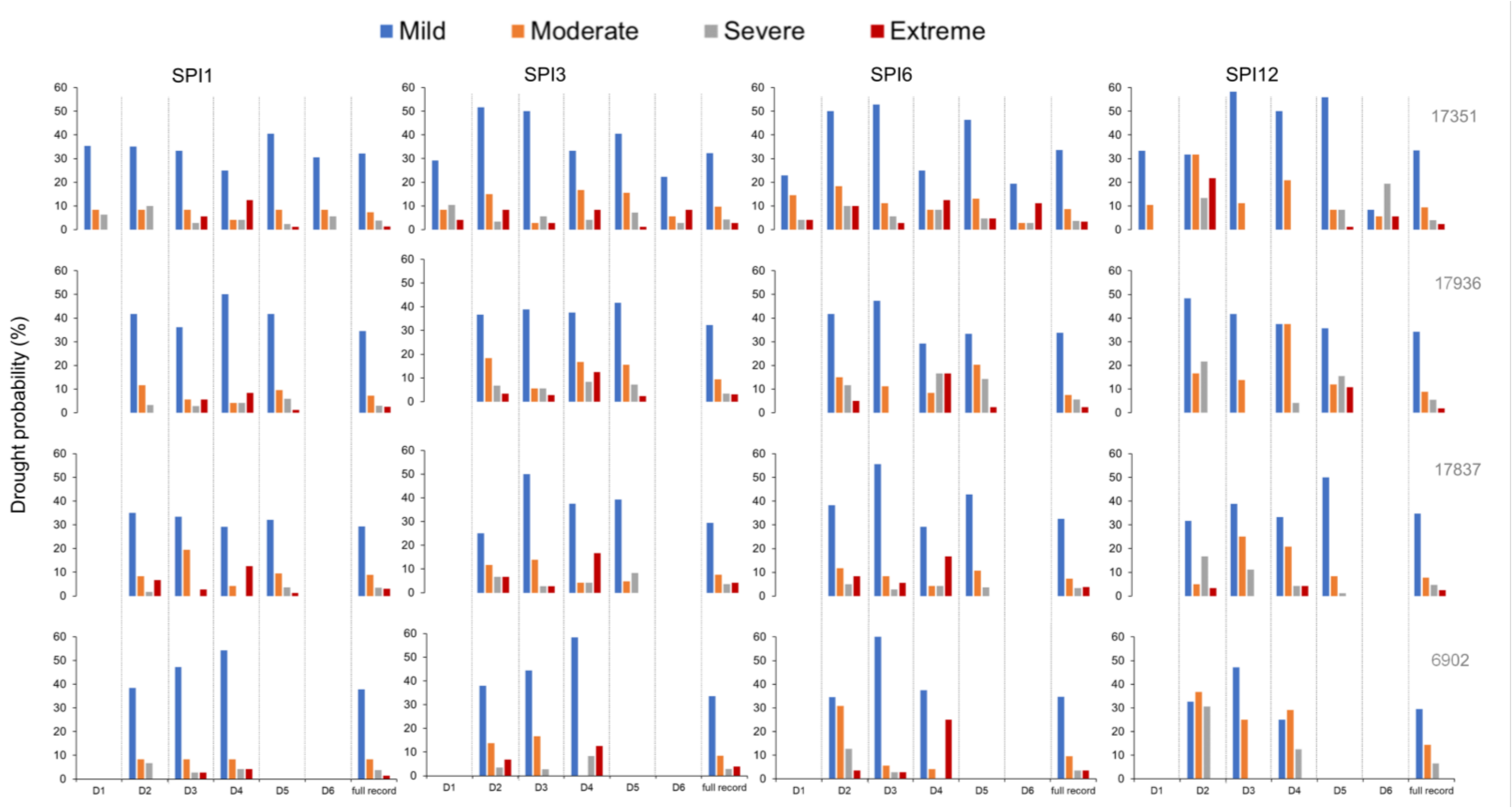

Figure 2.5 : Probability of drought categories for major dry periods and the full record (SPI1, SPI3, SPI6, SPI12).

For example; at stations 17351 and 17837, extreme droughts have almost been experienced at all-time scales; and at stations 17936 and 6902, extreme droughts are seen in SPI1, SPI3 and SPI6. There is no great increase or decrease in the probability of mild, moderate, severe and extreme droughts when the full record is considered

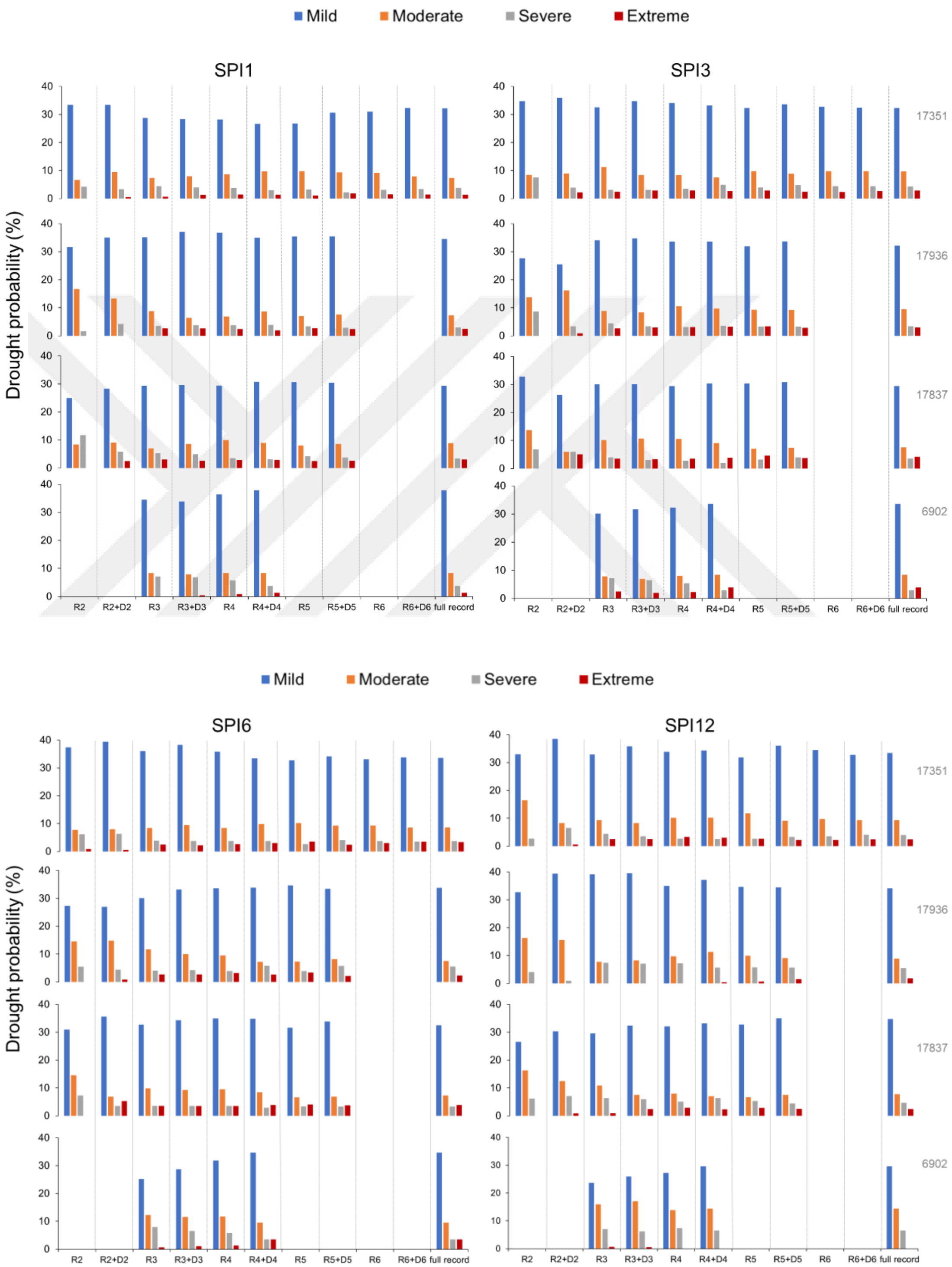

Figure 2.6 : Probability of drought categories based on the rolling time series analysis and the full record (SPI1, SPI3, SPI6, SPI12).

2.4 Discussion

2.4.1 Temporal analysis

The above results provide new insights into the temporal patterns of drought in the Seyhan River Basin. Although numerous studies on the drought analysis have been performed for the basin, none has focused on observed major dry periods. Examining major dry periods over the basin is a challenging task due to the lack of a common period of meteorological data and their limited availability. To overcome this limitation, we selected a representative station for each sub-basin to enable us to cover as many of the major dry periods as possible. The length of the data set is limited such that only one representative station covered the six major dry periods.

Over the last half century, Turkey experienced strengthened and widespread droughts in 1971-1974, 1983-1984, 1989-1990, 2007-2008 and 2013-2014 coinciding mostly with what we identified from the precipitation surplus and deficit time series although they are not exactly the same. Major dry periods identified in this study are in line with previous studies (Simsek and Cakmak 2010; Altin et al. 2020).

In the temporal analysis part of this study, significant differences were observed in the drought probabilities (e.g. between the mild and extreme droughts, and extreme droughts compared with moderate droughts). D4 was found to have the most strengthened droughts and D5 to have the longest drought duration. This finding disagrees with the previous studies performed on the river basin, which ignore the D4 major dry period although it was identified (Simsek and Cakmak 2010; Altin et al. 2020). Instead, previous studies emphasized D2, D5 and D6 due to their impacts on the society, economy and agriculture. Turkes (2012) explained that D5 was triggered in 1990s with a decrease in the frosty and snowy days and an increase in the temperature in the Eastern Mediterranean. Sonmez et al. (2005) indicated a similar climatological reasoning stating that a warming trend began to dominate the annual mean temperature in early 1990s.

A quantitative comparison shows the new insight this study brings. Sonmez et al. (2005) and Turkes and Tatli (2009) calculated SPI values at the country-scale, and Gumus and Algin (2017) analyzed the Seyhan and Ceyhan River Basin, the eastern neighbor. Results agree with previous studies in terms of timing of major dry periods. This study provides two insights: (i) A major dry period ignored because of its short duration could be as important as a long-lasting major dry period, (ii) A drought masked by the analysis of the whole SPI time series at the country or basin-scale can be prominent if a detailed analysis is made at the sub-basin scale. In addition, comparison of Figs. 5 and 6 shows that the probability of mild droughts has a notable decrease for all stations in the rolling time series analyses compared to the drought probability calculated from individual major dry periods. This is applicable at all-time scales. The probability of extreme droughts increases significantly with the use of individual major dry periods. The rolling time series analysis underestimates the drought probability compared to individual use of major dry periods. This is an important outcome to consider for practical purposes such as the drought management. Because severe and extreme droughts have higher occurrence probabilities when the dry period is taken in calculating the drought probabilities. This prevents underestimation of severe and extreme droughts and allows managers to take precautions against the drought in advance.

By using data from representative meteorological stations at the sub-basin scale, higher probabilities reaching 25% were calculated for moderate, severe and extreme droughts in major dry periods. This is a notable outcome that short extreme droughts masked by large-scale temporal analysis are indeed not ignorable in the river basin. This statement is supported with the results of Cook et al. (2016).

2.4.2 Significance and importance for practice

The study has potential to be used for regional drought management plans. It also sheds light on the need for such analyses for regional drought adaptation and mitigation. This is an important issue to be resolved in the basin where agriculture represents an important livelihood for the population. Given the limitations that emerged on the determination of the representative stations, it would be advisable to consider additional data (e.g., remote sensing) in future studies to gain further insights into the temporal and spatial characteristics of drought. Although the river basin is prone to droughts and suffers from their effects, it does not have any tool to monitor and predict the drought in advance to take proper measures. Thus, we expect that the outputs of this study can significantly be used in the river basin-specific sectoral water allocation plan, drought management plan and drought early warning studies, and be improved for a possible extension to river basins with similar climatological characteristics.

2.4.3 Human-water relevance in drought management

All major dry periods identified in the basin are equally important, none being less important than any other no matter how long or severe they are. For example, D2 and D5 are important for their duration, D4 and D6 for their severity, and D1, D3 and D4 for their higher probability of severe and extreme drought categories. D2 was newsworthy emphasizing that agricultural activities stopped due to insufficient rainfall in the region (Hurriyet 2007). The low precipitation of D6 in 2013 affected also the year 2014. It has been indicated in the newspapers that it caused to reduce water level in the Seyhan River with more than 40% (IHA 2014). The local population in the river basin was affected by water shortages in cities, economic impacts, negative consequences on agriculture during both events (D2 and D6). It could be important to mention that drought in D2 has mostly affected the agricultural activities and energy sector while drought in D6 affected not only the agriculture and industry but also it heavily caused shortages in urban water supply system.

A few more droughts were observed in this region, but none has been as severe as D4 and D5 which had some consequences to accelerate the public institutions to take actions. Drought in 2008 is particularly important as it has been a milestone to initiate structural and non-structural solutions through the governance and gave an impetus to many institutional and legislative developments within the water policy agenda of Turkey. State authorities took some actions against the drought primarily by increasing supply, i.e., by exploiting groundwater, building dams and infrastructure for water storage to provide water mainly for population and agricultural irrigation. Even the farmers tried to take some drought mitigation actions individually. Whenever a drought is observed, reduction in agricultural products, pastures and forest productions; depletion in water levels in the rivers, lakes and reservoirs become unavoidable. Also, increase in fires, losses in livestock and wild animals come out. These are all direct consequences of drought which cause, for example, a decrease in agricultural products that, in turn, results in a decrease in farmers' income; an increase in the food price (economical effects). Besides, the rate of unemployment increases, tax revenues of the state decrease and finally migration starts (social effects). These cascading impacts or 'knock-on effects' show how widely the drought phenomena have affected the region. In order to avoid or minimize all these consequences, the Ministry of Food, Agriculture and Livestock subsidized farmer families by granting cash support. Monetary compensation by the government can only be considered a temporary solution mitigating these negative effects. Also, in order to take some precautions to drought, State Hydraulic Works (DSI) of Turkey restricted irrigation, encouraged night watering, and prevented a second crop cycle per year in the region. These precautions are adaptation strategies which were developed to increase resilience to external drivers such as climate change, variability, natural and social events (Selek et al. 2016).

Each of these major dry periods was a kind of a 'redefining event' for water resources management such as the allocation and prioritizations, because people and managers took some actions after being failed in water supply during these drought events. An interesting management question would then be: What knowledge did the water managers not have before each drought? Could they have estimated the risk correctly with the data available before the drought event? What is the new estimated risk after these events?

These dry periods are important to reveal the importance of the time series analysis used in this study. Its importance come from the output obtained by the individual use of dry periods, which gives higher probability for more strengthened droughts compared to the nonstationary rolling time series and the stationary full record period. The above questions were tried to be answered with the use of rolling time series and the individual use of major dry periods. The final outcomes are (i) the rolling time series analysis is superior to the full record analysis to show the nonstationary evolution of drought occurrence probability, and (ii) the individual use of dry periods should be preferred not to underestimate the drought.

2.5 Conclusion

The aim of this study was to revisit major dry periods with different time series analyses by linking them with human-water relations. Major dry periods over the Seyhan River Basin were investigated with a methodology adapted specifically for the river basin where local meteorological data are limited. The results illustrate that:

1. The probability of mild drought dominates at each time scale and their frequencies increase with increasing time scale.

2. A significant change in the probabilities of drought categories was not found, instead, we observed no systematic change.
3. In the rolling time series analysis, the probability of mild droughts decreased in all stations compared to drought probability calculated from major dry periods.
4. The probability of the strengthened drought categories (severe and extreme droughts) is found higher when the dry periods are taken into account.
5. Major dry period in 1989-1990 is the most severe compared to the others. This makes it considerably important to take into account and to conclude that a short-duration drought can be as important as a long-duration drought. This outcome has provided a better understanding of droughts.
6. The non-stationary rolling time series or the stationary full-record time series analysis underestimate strengthened droughts. This is the current practice which should be replaced by the individual major dry period analysis with which higher probabilities are found for severe and extreme droughts.

3. RECONCEPTUALIZATION OF DROUGHTS EXTRACTED FROM DRY PERIODS

3.1 Introduction

Droughts most commonly develop slowly over substantially long periods of time, and their consequences may persist for several years even after the drought has terminated. Less common, but highly relevant are also so-called 'flash droughts', which develop much faster out of a non-drought period or quickly exacerbate from only moderate dry conditions (Pendergrass et al. 2020). Drought analysis is implemented in practice for the planning and management of all water-related activities, and its characterization plays a major role in risk management, which includes mitigation efforts of stakeholders and decision makers in taking precautionary measures to prepare for drought (Dantas et al. 2020, Kreibich et al. 2022). However, drought characteristics such as duration, severity, intensity and inter-arrival time have not yet been fully understood to better design future drought management plans and strategies, making it an emerging unsolved problem of hydrology in change (Blöschl et al. 2019). Therefore, there is a great demand on developing new methods and proposing new concepts or definitions for drought characterization in the scientific community (Mishra and Singh 2010), and it has also been the inspiration of this study.

Frequency analysis is one of the most common tools used in drought hydrology. It allows estimating the probability of quantitative variables such as duration, severity and intensity. Frequent short-duration droughts affect agriculture most, and droughts with high severity and short duration affect run-off-the river hydropower production and cooling water bans for thermal hydropower (Mishra and Singh 2009). A specific time span within a given dry period can be particularly important for a specific activity of a given sector when it is more severe. For instance, a particular crop needs more water during a particular month or season in the year when water is indispensable for it to grow. As for the engineering practice such as water allocation schemes higher needs of water emerge in summer, peaking in a month or shorter time intervals; e.g., a week or even a day.

As a real case, we might consider the Seyhan River basin in Türkiye which was exposed to droughts several times. Cavus et al (2022) identified six major droughts in the region. One of the dry periods was 59 month-long starting in January 1970 and ending in November 1974 (Aksoy et al. 2021). Droughts in this dry period were classified as extreme drought with -2.78 in terms of SPI12 (Kreibich et al, 2022a, ID26). It was an extreme drought extending over 1973 for 11 months, from January to November. A second dry period was 13-month long which lasted from December 2013 to December 2014 (Aksoy et al 2021). The most severe drought in this dry period with a large negative impact in the region was observed in May 2014 (Aksoy et al. 2021). Droughts in 2014 were classified as extreme drought with -2.34 in terms of SPI12 (Kreibich et al, 2022a, ID26). These two real cases show that 11 months of the dry period in 1970-1974 and 1 month of the second dry period in 2013-2014 have been particularly important for drought management and mitigation. The 1973 drought affected especially agricultural activities and the energy sector due to its effect lasting for 11 months (Kreibich et al, 2022a, ID26). The 2014 drought caused severe shortages in the water supply to the cities and rural areas due to its timing at the beginning of summer season (Kreibich et al, 2022a, ID26). Both short droughts were much more impactful in the region compared to the entire dry period length. The impact of a drought with given severity also depends on the number of past months with precipitation deficits, which affect the availability of water resources to face the drought. These examples illustrate a clear need of such practical implications to identify shorter, more severe/intense time spans within dry periods and study their specific statistical properties. This practical consideration is the motivation of this study to extract dry periods into shorter time spans.

Besides, systematic quantitative drought definition is still the missing piece in drought hydrology (Lloyd-Hughes, 2014; Vorobevskii et al., 2022). Generally, drought indices to identify a drought are divided into qualitative drought concepts which provides descriptive and linguistic definitions of degree of severity and/or quantitative drought concepts which is obtained with statistical analysis (Vorobevskii et al., 2022). As Vorobevskii et al. (2022) and Veettil and Mishra (2023) mentioned, quantifying the evolution of a drought event is often challenging and a holistic drought identification and classification should include: type, intensity and their impacts on ecosystem and society. This is an important issue as lack of drought definition might cause indecision and inaction in drought management (Wilhite and Glantz 1985). Therefore, we suggest that quantitative definitions other than the known drought concepts are important to determine the degree of drought impact. In doing that, our understanding is different from the classical run theory (Yevjevich 1967). In our conceptualization, a dry period has a length, and a drought is a subset of this dry period. The dry period may thus contain multiple droughts with durations changing from 1 month up to the entire length of the dry period. Therefore, the concept we present extracts droughts of various durations from a dry period of a given length and defines the most intense drought of each duration as the critical drought. The characteristics of proposed critical droughts should be explored for drought, because average values do not provide a firm basis for reliable engineering decisions in water resources management (Sen 1980). Yet, the effect of this distinction on the intensity of the droughts and dry periods needs further investigation. Here, we extend drought definitions and concepts of previous studies (Cavus and Aksoy 2019, 2020) to assess the difference in this characteristic. This study essentially tests how different the drought characteristics of proposed cases are from each other by addressing following research questions:

a) How different are the droughts defined with the new concepts from the dry period of the classical run theory?

b) Is the difference large enough to be considered in practice?

c) Do the results change from one location to another?

We perform an analysis on monthly precipitation data to answer these questions. For this, we apply frequency analysis on intensities for each drought duration of selected return periods. We provide drought characteristics in the form of intensity-return-period charts, which are expected to be highly useful for the drought management practice.

3.2 Proposed Concepts and Definitions

A consecutive negative values of a typical standardized drought index, here the exemplary the SPI, is a dry period in our conceptualization. Droughts of different durations are extracted from such a dry period. Drought is a sub-period of time in a dry period, which is similar to trials in the statistical terminology. For example, trials are drawn from a negative run, where the run corresponds to the dry period, and the trials to the droughts (Schwager 1983). We consider a hypothetical 9-month dry period to exemplify our concepts (Figure 3.1). Each month in the dry period constitutes a 1-month drought individually, and there are 9 droughts. Every two consecutive months form a 2-month drought. For instance, Months 1 and 2 are the first 2-month drought, Months 2 and 3 are the second 2-month drought, Months 3 and 4 are the third 2-month drought, and so on. For 3-month durations, Months 1, 2 and 3 form the first 3-month drought, Months 2, 3 and 4 identify the second 3-month drought, and so on. Droughts with 4-, 5-, 6-, 7- and 8-month durations are identified in similar way. This is a moving windows approach. In this dry period (Figure 3.1), we have two 8-month droughts; from Month 1 to Month 8 is for the first drought, from Month 2 to Month 9 is for the second. Finally, there is one 9-month drought extending over from Month 1 to Month 9, the entire length of the dry period.

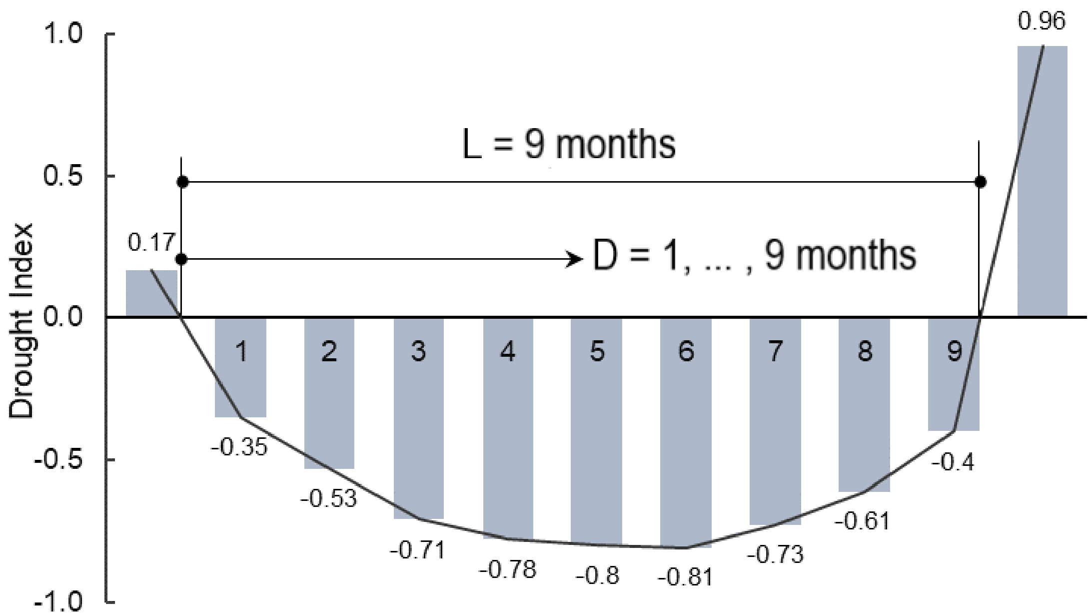

Figure 3.1 : A hypothetical example of a 9-month dry period.

Based on these definitions, we propose new cases in this study which are (1) Dry period, (2) Critical drought for each dry period, (3) Critical drought for each year. Case 1 is the dry period itself. A dry period has a length and a drought has durations. Droughts are shorter than the dry period. Their duration becomes equal to the dry period length once. Depending on drought duration, a drought is either called (a) within-period drought or (b) singular drought. When the drought duration is shorter than the dry period length ($D < L$), this is within-period drought. The within-period drought has durations starting from 1 month at minimum to the dry period length ($L - 1$) at maximum. When drought duration extends over the entire dry period, this is singular drought. The singular drought duration is equal the dry period length ($D = L$). We also defined the most severe (critical) drought of each duration for each dry period which is called Case 2. In each dry period, the critical droughts are identified only one time for each drought duration separately. Critical droughts of each drought duration are identified in the same way also for each year in Case 3. Here, some years are totally wet, and thus no critical drought is assigned. In totally wet years, critical drought severity and intensity are zero.

For Case 3 (critical drought for a year), we developed further definitions on the concepts as follows: Time series of a drought index (DI) show the sequence of wet and dry periods (Figure 3.2). Any period of time with $DI \geq DI_0$ is a wet period; $DI < DI_0$ is a dry period where DI_0 is the threshold. DP1 and DP2 are two dry periods and WP1 is a wet period. DP1 extends over Year 1 through Year 3, it is therefore an "over-year dry period". Years 1 and 3 are partially dry (PD) while Year 2 is totally within DP1 and it is a totally dry (TD) year. WP1 starts in Year 3 to end in Year 5 which is an "over-year wet period" making Year 4 totally wet (TW). DP2 is within Year 5, and it is a "within-year dry period", and Year 5 itself is a partially dry (PD) year. L_1 and L_2 are dry period lengths of DP1 and DP2, respectively. Based on these concepts and definitions, we present Table 3.1 to show how one can obtain the drought characteristics of proposed concepts. In Table 3.1 and in Figure 3.2, $j = 1, \dots, N$ indicates the year and $i = 1, \dots, n$ indicates the dry periods. $D_j \leq L_i$ is satisfied for an over-year dry period and $D_j = L_i$ for a within-year dry period or a year in which the dry period is terminated. Table 3.1 shows that the characteristics of droughts change in each of the proposed cases (Cases 2, and 3).

Table 3.1 : Characteristics of Cases 1, 2 and 3. (*i*: dry period, *j*: year, *D*: duration, *n*: number of dry periods, *N*: number of years).

Case	Definition	Number of droughts / dry periods	Dry period length / Drought duration	Severity	Intensity	Remarks
1	Dry period	n	L_i $i = 1, \ldots, n$	$S_i = \sum_{k=1}^{L_i} DI_k$ $i = 1, \ldots, n$	$I_i = \frac{S_i}{L_i}$ $i = 1, \ldots, n$	Classical approach taking a dry period as a drought
2	Critical drought of each dry period	$\sum_{i=1}^{n} L_i$	$1 \leq D \leq L_i$ $i = 1, \ldots, n$	$S_{i,D} = max\left(\sum_{l=k}^{k+D-1} DI_l, k = 1, \ldots, L_i - D + 1\right)$ $D = 1, \ldots, L_i$ $i = 1, \ldots, n$	$I_{i,D} = \frac{S_{i,D}}{D}$ $D = 1, \ldots, L_i$ $i = 1, \ldots, n$	New definition taking drought of a given duration with a maximum severity in each dry period
3	Critical drought of each year	$\sum_{j=1}^{N} D_j$ ($D_j = 0$ for TW years)	$1 \leq D \leq D_j$ $j = 1, \ldots, N$ (Skip TW years)	$S_{j,D} = max\left(\sum_{l=D_{j-1}+k}^{D_{j-1}+k+D-1} DI_l, k = 1, \ldots, D_j - D + 1\right)$ $D = 1, \ldots, D_j$ $j = 1, \ldots, N$ (Skip TW years)	$I_{j,D} = \frac{S_{j,D}}{D}$ $D = 1, \ldots, D_j$ $j = 1, \ldots, N$ (Skip TW years)	New definition taking drought of a given duration with a maximum severity in each year (No critical drought is assigned to TW years.)

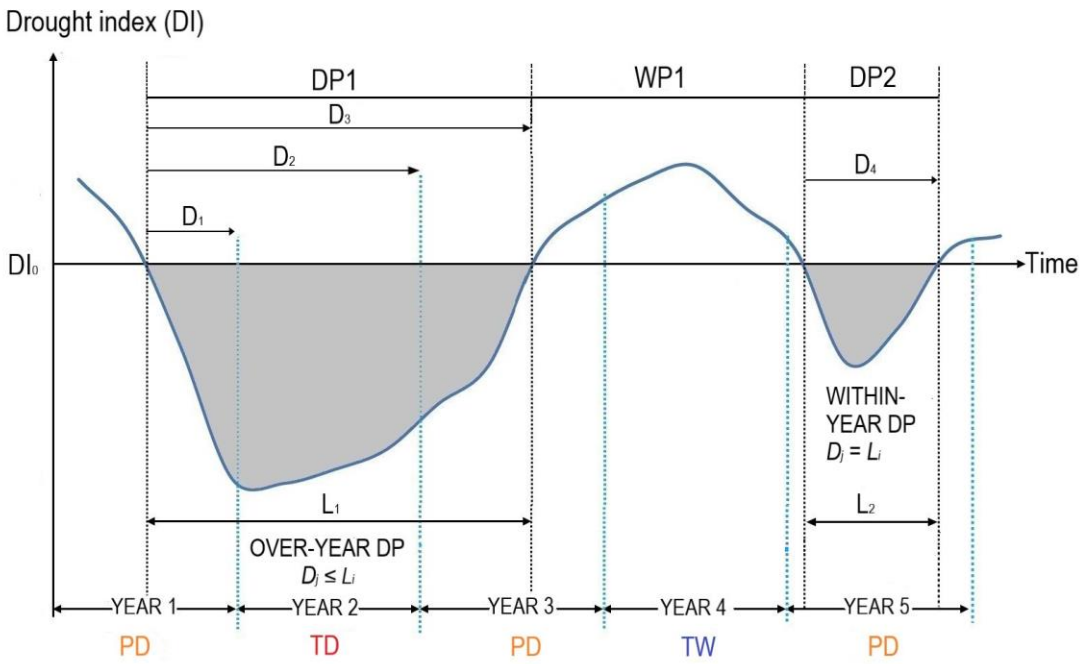

Figure 3.2 : Descriptive characteristics of the proposed concepts based on change in drought index with time (DP: Dry period, WP: Wet period, PD: Partially dry year, TD: Totally dry year, TW: Totally wet year).

3.3 Data

For the implementation of the methodology, we selected meteorological stations from Seyhan River Basin in the Mediterranean region, the southern part of Türkiye (36^{o}33'N-39^{o}24'N latitude and 34^{o}24'E-36^{o}56'E longitude) (Figure 3.3). The size of the river basin is 22241.6 km^2 (Aksoy, 2020). The river basin extends from the Mediterranean coast to the north with spatially varying topography and climate characteristics. The southern part of the basin exhibits the characteristics of the Mediterranean climate; thus, it is warmer in the south than its northern part. In the coastal areas and the surrounding areas in the south, the summer season is hot and dry while the winter is warm and rainy. It has a temporal variability in precipitation from year to year and spatial variability from location to location which causes widespread drought over regions at various intensities (Cavus and Aksoy 2019). The southern part of the river basin has experienced particularly long periods of below-normal precipitation and major dry periods (Cavus et al. 2022).

We selected two meteorological stations of the Turkish State Meteorological Service (Ulukisla and Karatas, station codes 17906 and 17981) with uninterrupted records of monthly precipitation data for the period 1962-2022 and 1963-2022, respectively (Table 3.2). The distance between the two stations is 116 km. These stations provide different precipitation characteristics in the basin where they are located.

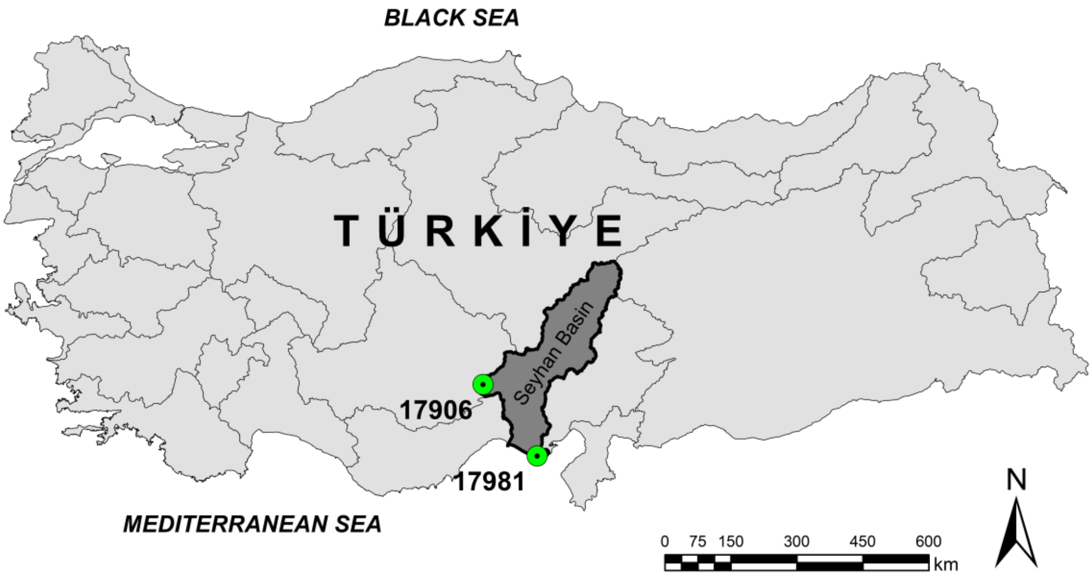

Figure 3.3 : Location of meteorological stations within the Seyhan River basin in the southern part of Türkiye.

Table 3.2 : Meteorological stations and statistical characteristics of their annual precipitation (Pmean: average precipitation, Pmin: minimum precipitation; Pmax: maximum precipitation; St.Dev.: standard deviation of precipitation. *Cv*: coefficient of variation

Stations	Latitude	Longitude	Elevation (mm)	No precipitation month (%)	Pmean (mm)	Pmin (mm)	Pmax (mm)	St. Dev (mm)	Cv
17906	37.548	34.4867	1453	6.55	325	182	428	62.77	0.193
17981	36.5683	35.3894	22	15.27	767	366	1365	228	0.297

3.4 Methodology

This study follows several methodological steps (Figure 3.4): (1) Calculation of standardized drought index, (2) Identification of dry periods, (3) Identification of droughts from dry periods, (4) and (5) Determination of the most severe/intense (critical) droughts of each drought duration for each dry period and year, (6) Calculation of drought intensity (7) Application of frequency analysis with the total probability theorem on critical drought intensity to estimate at different return periods.

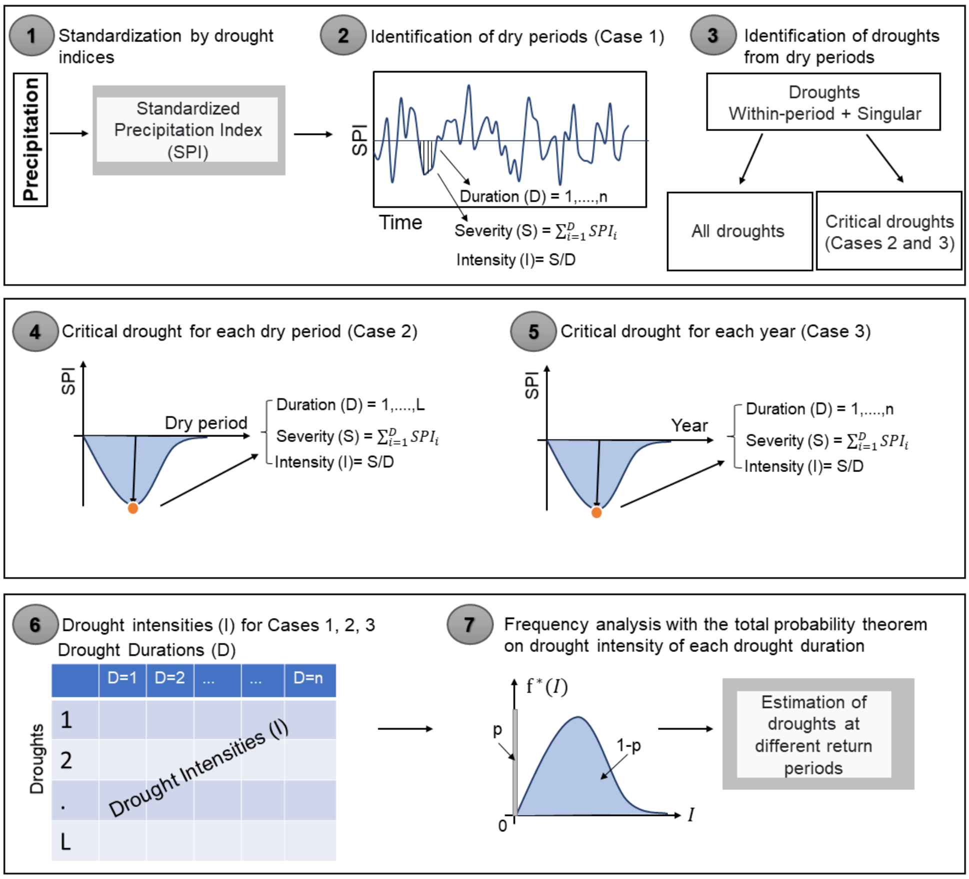

Figure 3.4 : Illustration of the methodology.

In Step 1, among the drought indices, we selected the standardized precipitation index (SPI; McKee et al. 1993) due to its simplicity, limited need in the data, and reliability in detecting drought events. SPI time series at the 12-month time scale were calculated from the monthly precipitation data of the two meteorological stations. SPI12 is normalized values of cumulative monthly precipitation. In addition, each value of SPI has a constant value of precipitation as a percent of average. This study considers only normalized SPI12 values to see dry periods clearly because in the short timescales of SPI, fluctuations are high and dry periods are quite short and changable. Dry periods were identified (Case 1 in the Step 2) first, droughts were then identified from the dry periods for durations from $D = 1$ month up to $D = D_{max}$, and their severity and intensity were calculated (Step 3). Maximum drought severity and its corresponding intensity of each drought duration were calculated to assign the critical drought for each dry period (Case 2 in the Step 4). In Case 3, one critical drought of each drought duration was assigned for each year, and severity and intensity of critical droughts of any given duration were calculated for each year (Step 5). For wet years, a value of zero was assigned to critical drought in Case 3. In this way, dry periods of Case 1 and droughts of Cases 2 and 3 were identified together with their characteristics (Step 6). In Step 7, frequency analysis was applied on critical drought intensity time series 10 years long at minimum of Cases 1, 2, and 3 to determine the best-fit probability distribution functions of drought intensity.

Among the probability distribution functions; this study considers the 2- and 3-parameter Gamma (G2, G3), the 2- and 3- parameter Log-normal (LN2, LN3), the 2- and 3- parameter Weibull (W2, W3), Log-Pearson Type 3 (LP3) and the Generalized Extreme Value (GEV) which are widely used in literature. The Anderson-Darling (A-D) statistical test at the 5% significance level was considered for the fitting of the probability distribution functions to the drought characteristics (Anderson and Darling 1952). The A-D is a general test to compare the fit of an observed cumulative distribution function to an expected cumulative distribution function. This test gives more weight to the tails than the Kolmogorov-Smirnov test. The A-D test makes use of the specific distribution in calculating critical values. This has the advantage of allowing a more sensitive test, because it has critical values for each distribution separately. The hypothesis regarding the distributional form is rejected at the chosen significance level (α) if the test statistic is greater than the critical value. The fixed values of (0.01, 0.05 etc.) are generally used to evaluate the null hypothesis (H_0) at various significance levels. A value of 0.05 was used in this study. Drought characteristics corresponding to 2, 5, 10, 25, 50, 100-year return periods were then calculated after the best-fit probability distribution functions were determined by the A-D test.

Cases 1, and 2 do not include zero values on which a typical frequency analysis was applied to identify the best-fit probability distribution function. The approach of Cavus and Aksoy (2019, 2020) was followed for Case 3 because no drought is observed in some years. For those years, a value of zero is assigned to the critical drought intensity. Frequency analysis was then applied on non-zero values only. Zero values in the critical drought intensity series have a probability mass while the non-zero values can be described by a probability distribution function. This makes the drought intensity an intermittent process for which the total probability theorem is available to examine the process in two parts; the zero and non-zero parts (Haan 1977). Probability distribution function selected for drought intensity (*I*) can be given by

$$f = f(I; \vec{a}\,) \tag{3.1}$$

where $\vec{\boldsymbol{a}}$ is the parameter set of the distribution. The cumulative probability distribution is given in the form of

$$F = F(I; \vec{a}) \tag{3.2}$$

The inverse of the probability distribution function is used to establish a relation between the drought intensity and its return period. The return period of the drought intensity is calculated by

$$T = \frac{1}{1 - F(I)} \tag{3.3}$$

and the inverse of the probability distribution is used to calculate any value corresponding to a given theoretical return period (*T*) explicity as

$$I = F^{-1}(I) \tag{3.4}$$

If there exist zero values as in Case 3, the probability distribution function of the non-zero values, $F^*(I)$, is considered as

$$I = F^{*^{-1}}(I) \tag{3.5}$$

The applicability of Equation (5) depends on obtaining positive values for the cumulative probability $F^*(I)$. It is valid for return periods that satisfies

$$p \leq \frac{T - 1}{T} \tag{3.6}$$

Any negative value obtained for $\boldsymbol{F}^*(\boldsymbol{I})$ means that, for the given return period *T* and the fraction *p* of zero-values, the probability of observing non-zero drought intensity is zero. Regression curves were finally fitted to establish a relationship between the drought intensity and their return period to calculate drought intensity values at different return periods. The regression curves were established by considering critical drought intensities calculated by the best fit probability distribution function of each drought duration.

3.5 Results

3.5.1 Drought intensities

Change of the drought intensities with drought durations show similar character in both stations for the proposed cases (Figure 3.5). Change in the intensity with the duration shows also how different Case 2 and 3 are from Case 1 when the critical droughts of each drought duration are considered individually. For instance, Case 1 shows lower intensity values and clearly distinguishes from Cases 2 and 3 which have higher intensities at both stations (Figure 3.5). The intensity values from 1-month to 10-month drought duration show the highest value in Cases 2 and 3 compared to Case 1 (the intensity value exceeds 2 in Case 2 and 3 while it is less than 1 in Case 1). In Case 1, less intense droughts cluster in short drought durations and relatively more intense droughts are observed in the intensities of longer drought durations. Case 1 has the smallest number of events and its intensity is the average value of the whole dry period; therefore, the variation of the intensity is limited. However, Cases 2 and 3 include critical droughts of all durations, and the variation of intensity with drought duration is clear. Cases 2 and 3 indicate two characters in the variability of drought intensity. First, higher intensity values decrease with increasing drought duration. This means strong high-intensity droughts in short drought durations become less intense in longer drought duration. On the contrary, low-intense droughts become more intense droughts with increasing drought durations. The results of the study emphasize that Cases 2 and 3 show more intense droughts than Case 1.

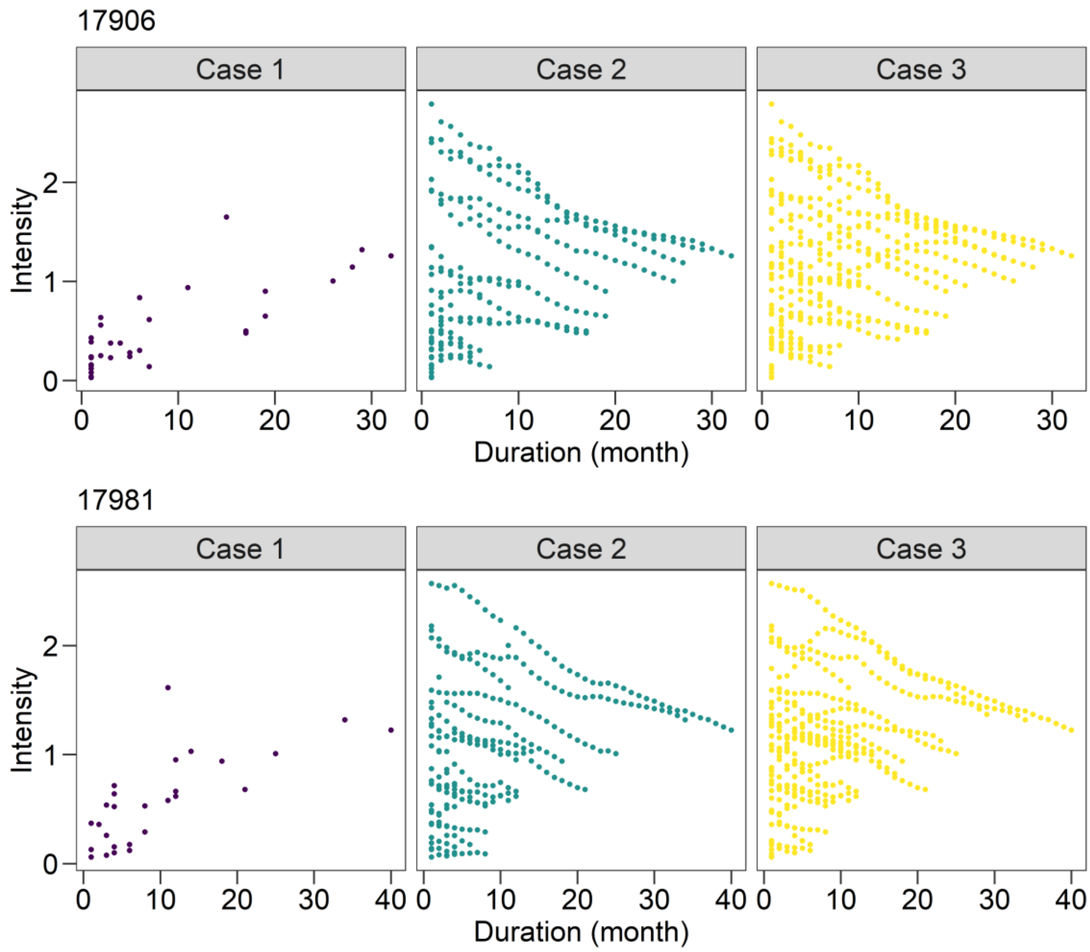

Figure 3.5 : Change of drought intensity with duration for all individual cases.

3.5.2 Theoretical characteristics of proposed cases

Frequency analysis of the critical drought intensity shows that GEV is the best-fit probability distribution function for the majority of drought durations when all drought durations are considered (Table 3.3). The LP3 and W2 are the second best-fit distributions for a few cases. At short drought durations, the best-fit probability distribution function tends to be LP3 for Case 3 and W2 for Case 2 as an alternative probability distribution function. Shape and scale parameters show higher values in short drought durations in Case 2 while they decrease with increasing drought durations. These parameters increase with increasing drought duration in Case 3 in general. The value of drought intensity of Case 3 (10 years at minimum) is higher than that of Case 2 because in over-year droughts longer drought durations take place in the next year.

Table 3.3 : The best fit probability distribution functions of drought intensities.

Drought Duration (month)	17906					17981				
	Case 1	Case 2		Case3		Case 1	Case 2		Case3	
1		LP3	α:6.86 β:-0.55 γ:2.86	GEV	μ:0.72 σ:0.67 k:-0.06		LP3	α:4.31 β:-0.77 γ:2.36	GEV	μ:0.69 σ:0.63 k:-0.09
2		LP3	α:5.51 β:-0.29 γ:2.29	LP3	α:6.01 β:-0.28 γ:1.69		W2	α:1.16 β:1.05	GEV	μ:0.79 σ:0.59 k:-0.09
3		W2	α:1.34 β:1.24	W2	α:1.68 β:1.31		W2	α:1.20 β:1.04	GEV	μ:0.85 σ:0.57 k:-0.14
4		W2	α:1.39 β:1.25	W2	α:1.69 β:1.32		GEV	μ:0.72 σ:0.63 k:-0.06	GEV	μ:0.88 σ:0.57 k:-0.15
5		W2	α:1.37 β:1.28	W2	α:1.69 β:1.32		GEV	μ:0.93 σ:0.69 k:-0.22	GEV	μ:0.98 σ:0.57 k:-0.18
6		LP3	α:3.87 β:-0.34 γ:1.43	LP3	α:6.25 β:-0.25 γ:1.59		LP3	α:2.45 β:-0.53 γ:1.22	LP3	α:5.33 β:-0.23 γ:1.31
7		GEV	μ:1.02 σ:0.71 k:-0.25	GEV	μ:0.94 σ:0.59 k:-0.18		LP3	α:2.47 β:-0.54 γ:1.22	LP3	α:5.49 β:-0.23 γ:1.34
8		GEV	μ:1.05 σ:0.73 k:-0.33	LP3	α:2.48 β:-0.39 γ:1.03		GEV	μ:0.95 σ:0.64 k:-0.25	LP3	α:5.00 β:-0.25 γ:1.30
9		GEV	μ:1.19 σ:0.57 k:-0.24	GEV	μ:1.11 σ:0.49 k:-0.19		GEV	μ:1.09 σ:0.59 k:-0.27	LP3	α:5.00 β:-0.25 γ:1.30
10	LP3 α:6.53 β:-0.50 γ:2.08	GEV	μ:1.17 σ:0.55 k:-0.20	GEV	μ:1.18 σ:0.47 k:-0.26	LP3 α:4.99 β:-0.64 γ:1.86	GEV	μ:1.07 σ:0.57 k:-0.25	LP3	α:21.05 β:-0.09 γ:2.11
11		GEV	μ:1.13 σ:0.53 k:-0.19	GEV	μ:1.11 σ:0.46 k:-0.20		GEV	μ:1.05 σ:0.55 k:-0.23	LP3	α:42.17 β:-0.06 γ:2.82
12		GEV	μ:1.09 σ:0.51 k:-0.21	GEV	μ:1.09 σ:0.47 k:-0.26		GEV	μ:1.06 σ:0.53 k:-0.22	LP3	α:33.65 β:-0.07 γ:2.44
13		GEV	μ:1.19 σ:0.55 k:-0.46	GEV	μ:1.15 σ:0.48 k:-0.41				W2	α:3.37 β:1.56
14		GEV	μ:1.16 σ:0.54 k:-0.49	GEV	μ:1.18 σ:0.52 k:-0.58				GEV	μ:1.22 σ:0.39 k:-0.18
15		GEV	μ:1.10 σ:0.52 k:-0.47	GEV	μ:1.16 σ:0.54 k:-0.65					
16		GEV	μ:0.96 σ:0.47 k:-0.25	GEV	μ:1.09 σ:0.54 k:-0.57					
17		GEV	μ:0.90 σ:0.45 k:-0.19	GEV	μ:1.07 σ:0.53 k:-0.57					
18				GEV	μ:1.13 σ:0.52 k:-0.7					
19				GEV	μ:1.16 σ:0.53 k:-0.83					
20				GEV	μ:1.33 σ:0.39 k:-0.23					

We selected D = 1, 3, 6, and 12-month drought duration to present how the cumulative probability distributions of the intensity are changing in the proposed cases. The cumulative probability distribution functions of Case 1 and of the critical drought intensities of each drought duration (Case 2 and 3) show similar result in both stations (Figure 3.6). The cumulative probability distribution values change from 0 to 1 in Cases 1 and 2 while it changes from a certain probability to 1 in Case 3 as the time series has a fraction of zero values with probability p. In both stations, Case 1 shows lower drought intensity values while Case 2 and 3 show higher drought intensity values (Figure 3.6). The cumulative probability increases faster which shows less intense droughts have higher probability in Case 1 than Cases 2 and 3. The likelihood of less intense droughts in Cases 2 and 3 is higher for shorter drought durations than longer drought durations. The likelihood of drought years decreases with increasing drought duration in Case 3. In longer drought durations of Case 3, zero years have higher probability. When all the cumulative probability distributions are considered at once, faster increase rates are seen at low intensity values than high intensity values (Figure 3.6). This means that in low values of the drought intensity, the non-exceedance probability has a higher rate of increase.

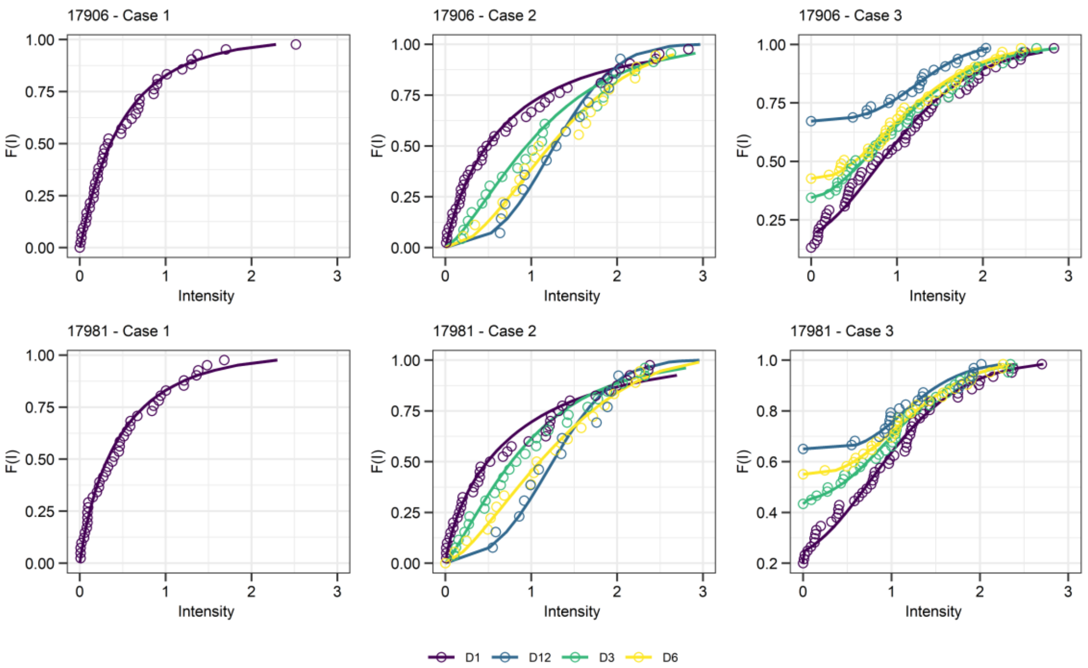

Figure 3.6 : Cumulative probability distribution functions of drought intensity for stations 17906 and 17981. D1, D3, D6 and D12 show 1-, 3-, 6- and 12-month drought duration respectively for Case 2 and 3. Dots show observed drought intensity values and curves show fitted cumulative distribution function.

The drought intensity corresponding to any return period was obtained from the cumulative probability distribution functions. Drought intensities of Cases 2 and 3 at different return periods are presented for 1-, 3-, 6-, and 12-month durations separately while the drought intensties of Case 1 are presented in one single graph (Figure 3.7). Drought intensities of proposed cases show similarities in general at the different return periods. In all curves, drought intensity increases linearly as the return period increases. Drought intensities of Case 1 shows the less intense drought at all return periods compared to drought intensities of Cases 2 and 3 up to the 6-month drought duration. At the 12-month drought duration, more intense drought can be expected from Case 1 for longer return periods compared to Cases 2 and 3. Case 3 relatively indicates more intense droughts at 1-month drought duration and short return periods compared to Case 1 and 2 while Case 2 indicates the most intense droughts for all other drought durations and return periods. Cases 2 and 3 are therefore separated from each other. Drought intensity of Case 2 shows a relatively steeper increase than Case 3. Compared to Case 1, drought intesities in Cases 2 and 3 show more intense droughts. Drought intensity of Case 1 is particularly higher at 50- and 100-year return period but it still shows less intense conditions compared to Case 2 and 3 at all return periods. Separation among the cases is clearer in drought intensity (Figure 3.7). In addition, the results show that, in Case 3, droughts with long durations, such as 12-month for 17906, 6- and 12-month for 17981, are not expected every 2 years on average, they can be expected at higher return periods.

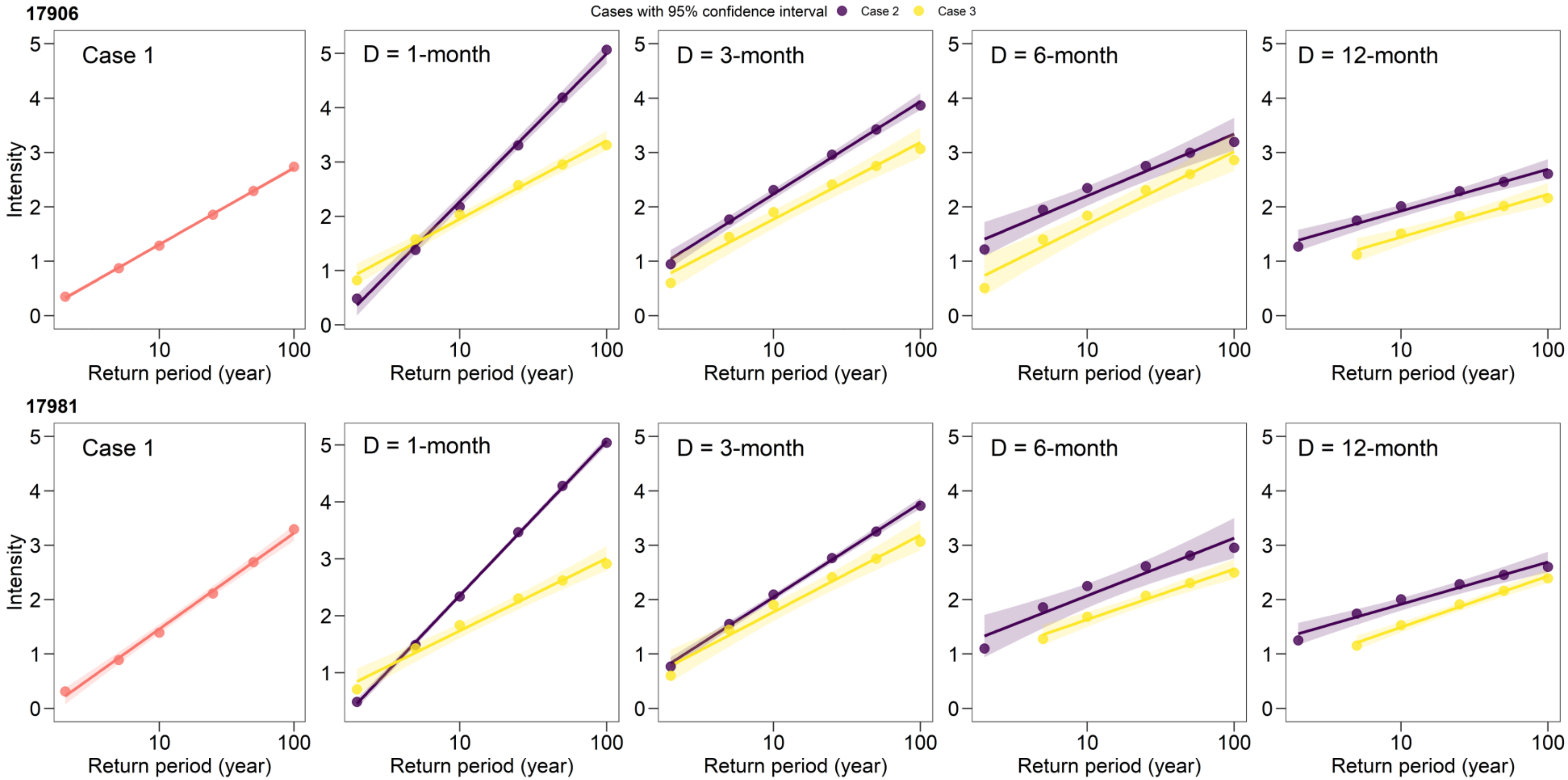

Figure 3.7 : Intensities of Case 1 and Cases 2 and 3 of 1, 3, 6 and 12-month drought durations at 2, 5, 10, 25, 50 and 100-year return periods for stations 17906 and 17981. Dots show calculated intensity values and lines show linear fits with 95% confidence interval.

3.6 Discussion

Comparison of the proposed cases provide a comprehensive overview about how different the intensity of the dry periods is from those of the droughts. The intensity of dry periods in Case 1 is less compared to those in Case 2 and 3 (Figure 3.7). Cases 2 and Case 3 show the most intense droughts of each drought duration which are needed to reconsider in drought studies because they show the most critical drought conditions.

We demonstrated the difference in intensities of the proposed cases. Intense droughts, even if they have short drought duration, are important for agricultural, energy generation and water supply activities in seasons with higher demand. For agricultural drought, precipitation accumulated over longer time scales, e.g., annual precipitation or precipitation accumulated over the dry period length, is also important, but a more important aspect is precipitation during the crop growing season or crop yield (Panu and Sharma 2002). To establish a relationship between the crop yield and soil moisture deficit for a specific time is of the utmost importance in agriculture (Panu and Sharma 2002). Focusing on a short duration drought within the dry period could be important in terms of intensity for water resources managers to supply water demand. Wilhite and Glantz (1987) also stated that the lack of a certain definition of drought for a specific sector has been an obstacle for water resources managers and policy makers to understand the drought and mitigate its effects. Certainly, nobody can provide a universal definition for the drought under specific conditions (Wilhite and Glantz 1987). A further increase has been noticed on the high diversity of drought definitions over the past years (Stahl et al. 2020).

The main challenge in drought analysis is to estimate a certain drought intensity for a given drought duration at certain return periods for practical use. Hao et al. (2016) developed a theoretical method using a multivariate drought index that enables the classification of drought intensity into drought categories. In addition, in the literature, numerous statistical techniques have been already developed for drought duration, but a considerable improvement is still needed for drought intensity (Panu and Sharma 2002). Our study is an attempt to explore the drought in terms of intensity. No doubt, the drought duration is important in frequency analysis of drought characteristics, but the crucial parameter is the intensity for designing the size of storage reservoirs to prepare for droughts (Sharma 2000, Panu and Sharma 2002). Our results show that the drought intensity is underestimated when the whole dry period is considered as a single drought without being partitioned into shorter droughts (Figure 3.7). This is an implication that has not been considered in the literature and suggesting the use of drought as different concept from dry period.

As the drought is an extreme event, its critical values should be explored rather than its average, which does not provide a firm basis to make reliable engineering decision for water resources systems (Sen 1980). The drought cases investigated in this study show that the most intense cases are the critical droughts for all return periods. This supports the suggestion to extract droughts of shorter durations from dry periods and that the most intense droughts of a given duration should be used for hydrological design purposes such as drought management plans or water infrastructure developments. This study shows that critical droughts in a dry period should be considered in practice to avoid underestimating the risk of extreme droughts and, drought intensity would be the most suitable for defining a critical drought. This study also considers critical drought for each calendar (meteorological) year. This might be considered for the water (hydrological) year in case discharge/streamflow data is used. Critical drought intensity at a year is useful to take into account for annual water resources planning and management. For example, a drought begins in one year and ends in the following years which is multi year droughts (Tallaksen et al., 1997). Critical drought of each year is important in the consideration of water resource management because water managers perform all analyses at the annual scale and standard engineering practice in water supply has relied heavily on the use of critical values which defined as the period of time in which the hydrologic record would have been most critical with respect to the demands of the system (Askew et al., 1971; Zappa et. al., 2014). Cavus et al. (2023) considered critical drought intensity for a year to obtain drought intensity-duration-frequency curves based on precipitation and streamflow deficit; and categorized critical droughts at different time scales how they are useful for the purpose of water resources management. For example, critical drought intensity at long timescales (e.g. SPI12) are important drought tolerant crops, annual and perennial grasses, trees for water supply plan and water resourses management under drought conditions. For drip irrigation allocations, to plan seasonal and critical stage irrigation at short time scales of critical droughts provide important information. For further explanation and how to consider this critical droughts of a calender year see Cavus et al (2023).

Our results consider only SPI = 0 as the threshold level which is the limitation of this study. However, some researchers studied the effect of different threshold level on drought (Horn, 1989; Frick et al., 1990). Assessments of the threshold level can be found in Tallaksen et al. (1997) and Hisdal and Tallaksen (2000) with recommendations about which procedure is appropriate for a given purpose. It is possible to choose a threshold level lower than SPI = 0 to exclude mild droughts which are also denoted as normal in many cases (Barker et al. 2016, Quesada-Montano et al. 2018). When a lower threshold level is applied, the drought occurrence probability will reduce, and the drought duration will become shorter. Also, the number of droughts would considerably decrease in case a lower threshold level is used. Thus, we decided to consider all drought classes of McKee et al. (1993) (extreme, severe, moderate, and mild drought) based on the SPI = 0 in our methodology.

Our methodology is based on the sole use of precipitation data and results are restricted by the number of meteorological stations used. However, regarding the importance of the intensity in identifying the drought, we gained considerable knowledge from the results to finally answer the three research questions as follows: (1) Dry periods are different from droughts (concepts proposed in this study) in terms of drought intensity. (2) The difference between the dry period and the drought is sufficiently large to consider in practice. (3) Results of the two meteorological stations agree in providing an opportunity to generalize the findings.

3.7 Conclusions

Drought and dry period are often used synonymously. These concepts may even overlap and create misunderstanding. This is an important reason for the reconceptualization presented here and critical drought intensity of different drought durations are introduced for drought studies. Comparison of drought intensities shows the differences of dry periods and droughts. Differences among the cases emerge from drought intensity which is a crucial drought characteristic for drought management. Dry periods show the lowest drought intensity compared to proposed cases. Our analysis makes it clear that critical drought intensity for different drought durations in a dry period should be considered individually for a precise drought analysis and drought studies should consider drought intensity as the main drought characteristics. The difference between the dry period and the proposed drought concepts is large enough in intensity, which is an important drought characteristic to be considered in practice. Implementation of the methodology in two different locations shows that results do not change greatly, and they are in agreement in both locations. This study justifies the need for the distinction between drought and dry period for basic understanding of the process and its practical implication. The conceptual distinction and drought is expected to support reliable engineering decisions in water resources practice by increasing the confidence level in drought prediction, thus improving risk management and mitigating negative effects of drought. As the future perspective of this study, these concepts can be employed to explain drought by using physical variables such as precipitation deficit and water deficit instead of using standardized drought indices.

4. DROUGHT INTENSITY-DURATION-FREQUENCY CURVES BASED ON DEFICIT IN PRECIPITATION AND STREAMFLOW FOR WATER RESOURCES MANAGEMENT

4.1 Introduction

The risk of climate extremes has increased with global change and presents great challenges to the management of unprecedented droughts (Kreibich et al., 2022). Therefore, reliable drought analyses and estimations are needed to protect people's water demand in a sustainable way by mitigating the effect of water scarcity. Drought has been commonly assessed by using different types of standardized drought indices. These drought indices are derived from different variables each representing different types of droughts such as precipitation for meteorological drought, soil moisture for agricultural drought and streamflow for hydrological drought. Standardized drought indices are used by national meteorological and hydrological services around the world due to their advantage of being non-dimensional variables, and they are useful for comparison of drought in different climate regions in terms of their characteristics such as duration, intensity, severity and return period. The separate use of the duration, severity/intensity and return period is not sufficient for a comprehensive drought characterization unless they are related in the form of severity/intensity-duration-frequency (S/IDF) curves. IDF curves reflect the statistical characteristics of variables and the relation among intensity and frequency for different durations at a station, providing rich hydrological information in a single graph. Similar to precipitation IDF curves which are traditionally used in hydrological design, this study concentrates on drought IDF curves which can be proposed as useful tools in water management against low extremes.

Studies on the drought S/IDF curves are limited in the drought literature. In the existing literature, drought S/IDF curves have been developed mainly by using drought indices. As an early study, Dalezios et al. (2000) developed drought SDF curves based on the Palmer drought severity index in the form of tables and isolines illustrating more severe droughts for longer return periods. Drought severity and duration were combined by a probabilistic model and copulas were applied on standardized precipitation index (SPI) to construct the joint distribution function and to establish the drought SDF curve in the form of return period isolines (Shiau and Modarres, 2009). In addition, performances of different copulas using various statistical methods were tested for the derivation of drought SDF curves based on SPI (Reddy and Ganguli, 2012). Todisco et al. (2013) developed index-based SDF curves and integrated them with a methodology to account for the economic impact of drought. Halwatura et al. (2015) derived SDF curves at different timescales by using bivariate functions of duration and severity calculated from several drought indices. Most recently, Aksoy et al. (2021) focused on IDF curves of critical droughts based on SPI by using an empirical relationship between the drought intensity and its return period.

The drought curves described above are non-dimensional IDF or SDF curves based on standardized drought indices to assess drought characteristics as in a few more studies (Gupta et al., 2020; Sahana et al., 2020; Pandya and Gontia, 2023). To date, only a few studies investigated drought S/IDF curves and their relation with physical drought indicators such as soil moisture, runoff, precipitation deficit and streamflow deficit, limiting the experience to a few specific regions. For example, Sung and Chung (2014) developed dimensional-drought SDF curves based on streamflow deficit using various threshold levels for water use in Korea. These drought S/IDF curves presented an insight into the use of deficits for a humid continental climate. Cavus and Aksoy (2020) presented station-based S/IDF curves to quantify the recurrence intervals of critical droughts based on precipitation deficit for the Mediterranean climate.

We know that the same value of a drought index corresponds to different deficits in different regions. Meteorological and hydrological droughts correspond to temporal anomalies changing also spatially from one catchment to another and they are characterized based on long-term conditions, which are related to climatic and environmental factors (Vicente-Serrano et al., 2013; van Loon, 2015). Therefore, the same value of a drought index corresponds to different deficits in different regions. The non-dimensionality of drought indices comes at the expense of physical non-interpretability, i.e. most drought indices cannot be read quantitatively as actual precipitation and streamflow deficits. In climates with high seasonal variation (i.e., Mediterranean climate), the difference between deficits varies greatly in each month while this difference may be lower in regions with low seasonality (i.e., humid climate). Determination of precipitation and streamflow deficits is a challenge when the common drought indices are used. Thus, any non-dimensional drought severity or intensity derived from index series might insufficiently represent the actual water availability for water management under drought conditions. In practice, deficits under drought conditions in different climates and catchments need to be quantified and be linked with the duration, deficit volume and return periods. With SDF or IDF curves we can construct this relation to quantify drought characteristics and obtain knowledge about past drought events for practical consideration, which is the motivation of this study to derive deficit IDF curves.

The overarching objective is to develop drought IDF curves based on precipitation and streamflow deficits at different timescales and appraise their usefulness in different climates. For this, drought index-derived characteristics are converted into precipitation and streamflow deficits for different cases. For comparison, two catchments are considered in different climatic regions. Hence, the comparison between the regions and among the variables provides the framework of analysis. Specifically, we aim to assess how the deficits vary in the considered study regions and finally explore how deficit IDF curves might be used for different purposes. The study addresses the following research questions:

a) How different are deficit IDF curves from their non-dimensional index-based counterparts?

b) What is the relation between drought indices and indicators? How do deficits in precipitation and streamflow change with the associated standardized drought index in time and space?

c) For what purposes might deficit-IDF curves be used in water management practice?

4.2 Case Study Catchments and Data

Precipitation and streamflow data from meteorological and streamflow gauging stations of two regions, one in Turkey and another in Germany, were used. We selected Seyhan River Basin in southern Turkey and Kocher catchment in southwestern Germany. Seyhan River is important for the production of hydroelectric energy and the basin itself for irrigated agricultural activities, which increases water demand under low water availability (GDWM, 2019). The Kocher River is important for agricultural activity and hydropower production from run-of-the-river power plants (Zeitler et al., 2017).

The selected gauging stations from the headwaters of these basins are a subset of the benchmark catchments with good hydrometric performance and nearly natural flow conditions. The selected stations have long-record length dataset which is crucial for correctly characterizing the drought and estimating the long return period-droughts (Table 4.1). The data of the selected catchments come from various sources. For Turkey monthly precipitation data of station-based observation come from the State Meteorological Service (MGM). Daily streamflow data were downloaded from the State Hydraulic Works (DSI) website. For Germany, daily precipitation data were downloaded from the climate data center of the German Weather Service (DWD) website. Streamflow data of this catchment were acquired from the Environment Agency of Baden-Württemberg (LUBW).

The seasonality in precipitation and streamflow of Seyhan follows a typical Mediterranean climate with a wet winter and a dry summer. It produces seasonal precipitation and streamflow variation with peaks in December and April, respectively, and a low precipitation and flow period extending over the summer (Figure 4.1). The seasonality of precipitation in the Kocher catchment varies over the year with higher precipitation in winter and summer, less precipitation in spring and autumn. Streamflow varies within the year with high flows in winter and low flows in summer. Flow duration curves (FDC) show the Kocher can sustain flow longer and then decreases sharply at the lower end, while the Seyhan gradually approaches the minimum. This is a distinct difference in the important lower part of the FDC's. In the long-term average daily streamflow in Seyhan, maximum values concentrated in winter. In Kocher, high flows are likely to be observed throughout the year except for a period from July to September. However, in this period, maximum values are still higher than the long-term average of the daily streamflow.

Table 4.1 : Characteristics of selected meteorological and streamflow gauging stations in Seyhan (Turkey) and Kocher (Germany).

Meteorological Station							
Region	Code	Name	Latitude Longitude	Altitude (m.a.s.l)	Record period	No Precipitation Months (%)	Average Annual Precipitation (mm)
Seyhan	17351	Adana	37.00 N 35.34 E	23	1960-2016	11	662.74
Kocher	01674	Göggingen	48.86 N 9.89 E	490	1952-2020	0	982.83
Streamflow Gauging Station							
Region	Code	Name	Latitude Longitude	Altitude (m.a.s.l)	Record period	Drainage Area (km^2)	Average Specific Discharge ($L\ s^{-1}\ km^2$)
Seyhan	E18A001	Göksu Himmetli	36.04 N 37.86 E	665	1953-2011	2596.8	6.01
Kocher	3465	Stein	49.25 N 9.28 E	189	1979-2021	1928.73	8.45

4.3 Method

This study follows several methodological steps (Figure 4.2): (1) calculation of standardized drought indices, (2) determination of the most severe (critical) droughts for each drought duration, (3) application of frequency analysis with the total probability theorem to critical drought severity, (4) calculation of precipitation and streamflow deficits by using logistic curve fitting, (5) derivation of drought IDF curves based on precipitation/streamflow deficits, (6) comparative analysis of IDF curves.

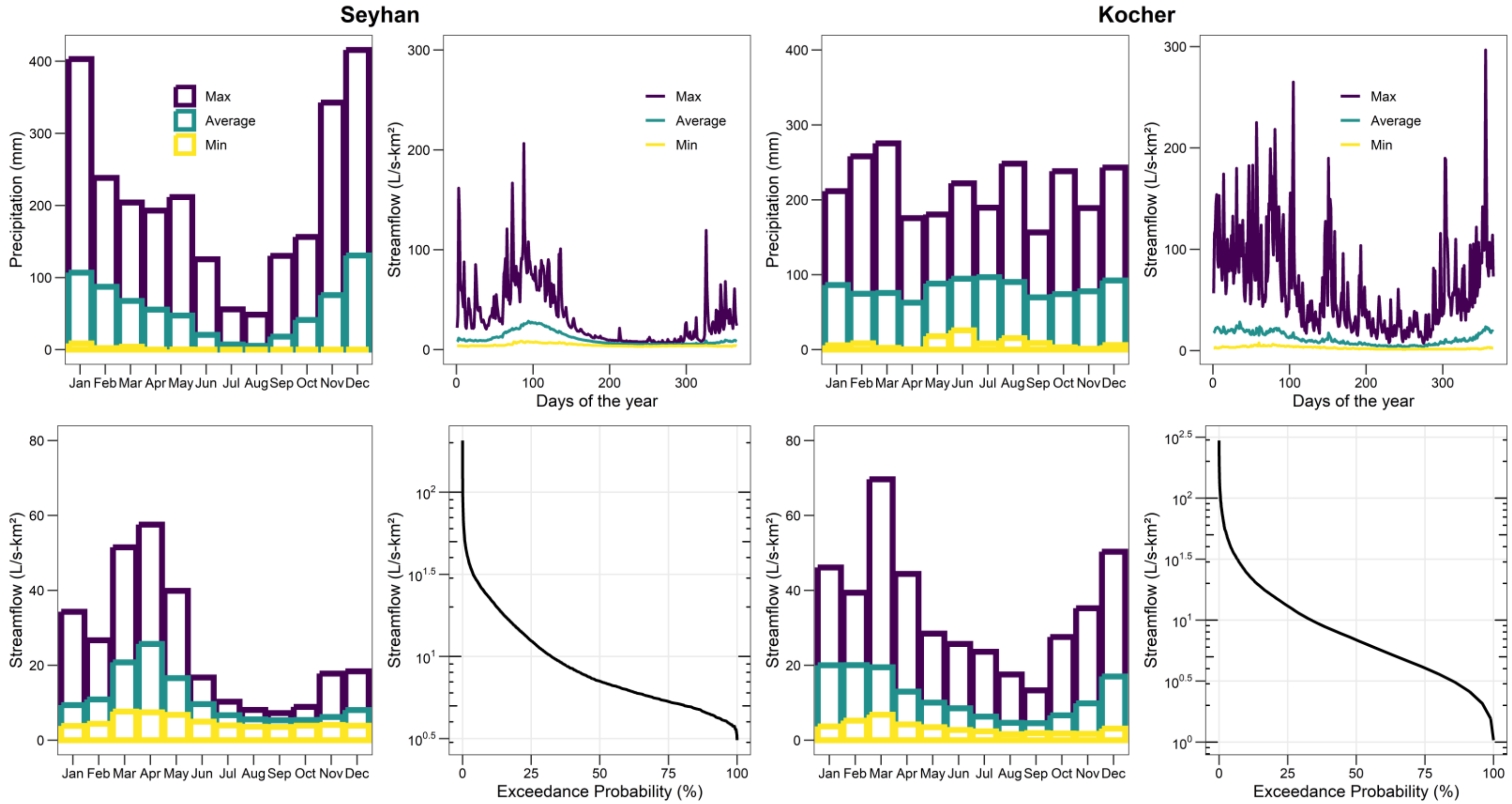

Figure 4.1 : Seasonal characteristics of the meteorology and streamflow gauging stations with their flow duration curves for Seyhan (Turkey) and Kocher (Germany).

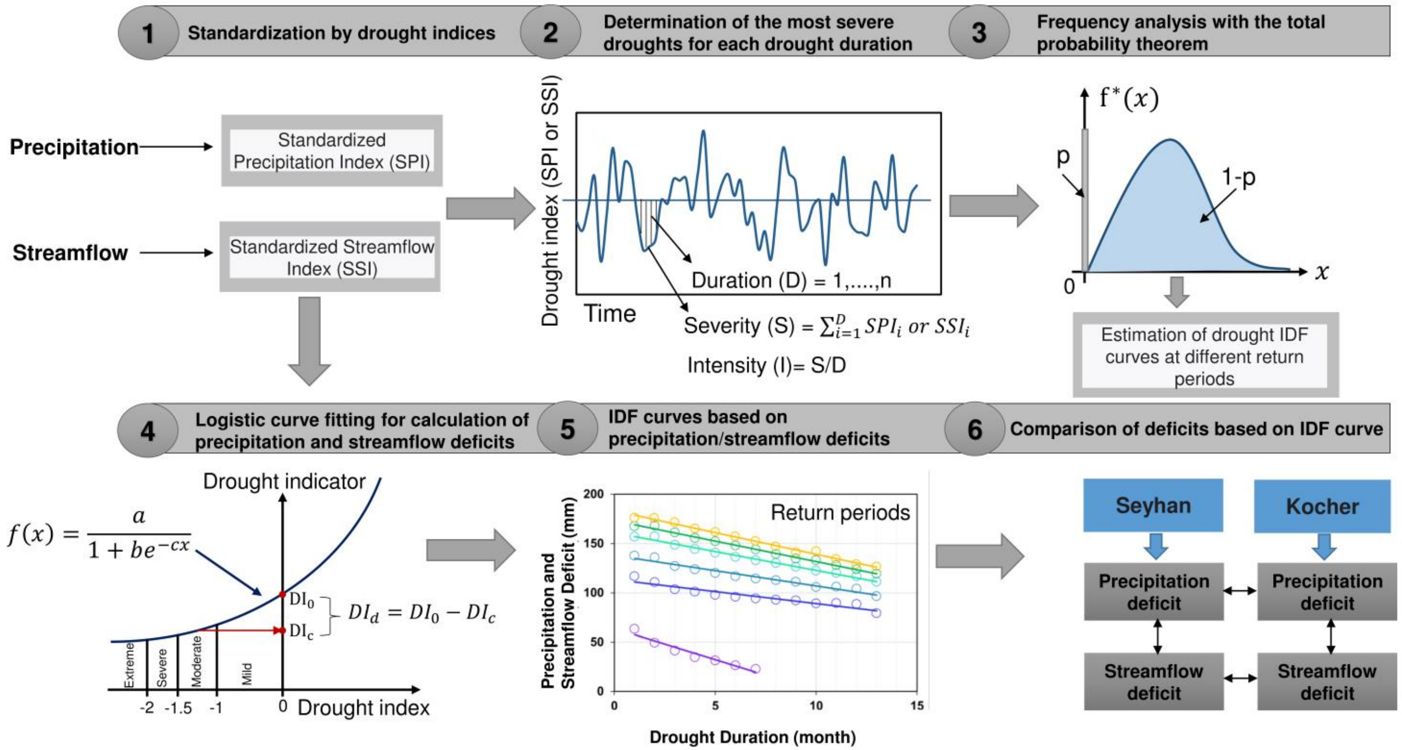

Figure 4.2 : Illustration of the methodology used to develop drought IDF curves based on precipitation deficit and streamflow deficit.

Step 1 involves standardization by drought indices. To characterize the drought, we used the Standardized Precipitation Index (SPI; McKee et al., 1993) and the Standardized Streamflow Index (SSI; Vicente-Serrano et al., 2012) (Figure 4.2). They are well-established drought indices which are widely used for the drought quantification. The SPI was calculated using monthly precipitation data accumulated at 1, 3, 6, 12-month timescales. Similarly, SSI time series of the same timescales were calculated to detect the total aggregated streamflow deficit. Precipitation was used as the monthly total precipitation for SPI while streamflow was taken as the volume of monthly average streamflow for SSI. The Gamma probability distribution function is fitted to the precipitation data and transformed to the standard normal distribution with zero mean and unit standard deviation (McKee et al., 1993). Based on the Anderson-Darling statistical test of several probability distribution functions including Gamma, Generalized Logistic, GEV, Gumbel, Logistic, Lognormal, Normal, and Weibull, we found the Generalized Extreme Value Distribution (GEV) the best, LN2 the second for Seyhan, and LN2 the best, GEV the second for Kocher for the streamflow volume accumulated over a month (Figure 4.3). The length of the streamflow record and the selected probability distribution function strongly affect the calculated SSI (Wu et al., 2005, Tijdeman et al., 2020). To allow a comparison of the streamflow deficits in the two different case study rivers in different climate regions, here we used GEV for both catchments for comparability reasons and also to be in accordance with the literature (Vicente-Serrano et al., 2012).

In Step 2, dry periods were identified from the SPI and SSI time series (Figure 4.2). Any period of time with SPI and SSI values lower than zero (SPI < 0 or SSI < 0) was considered as a dry period. Based on the concepts of Cavus and Aksoy(2020), dry periods consist of droughts; a dry period has a fixed length and a drought has a duration. Drought duration changes from 1 month to the dry period length. A drought with duration shorter than the dry period length is a within-period drought and a drought with duration that cover the whole dry period length is a singular drought. The sum of consecutive negative values of the drought index for each drought duration is the drought severity. The drought intensity is the drought severity divided by the drought duration. In any year, drought of a given duration with maximum severity was taken as the critical drought for each particular duration. When only one drought exists within one year, no matter how long and how severe it is, we assigned it as the critical drought to this particular year. A year in which drought is not observed is called the no-drought year, and for such a year, the critical drought severity is zero. For further definitions and explanations of these drought concepts see Cavus and Aksoy (2019, 2020) and Aksoy et al. (2021).

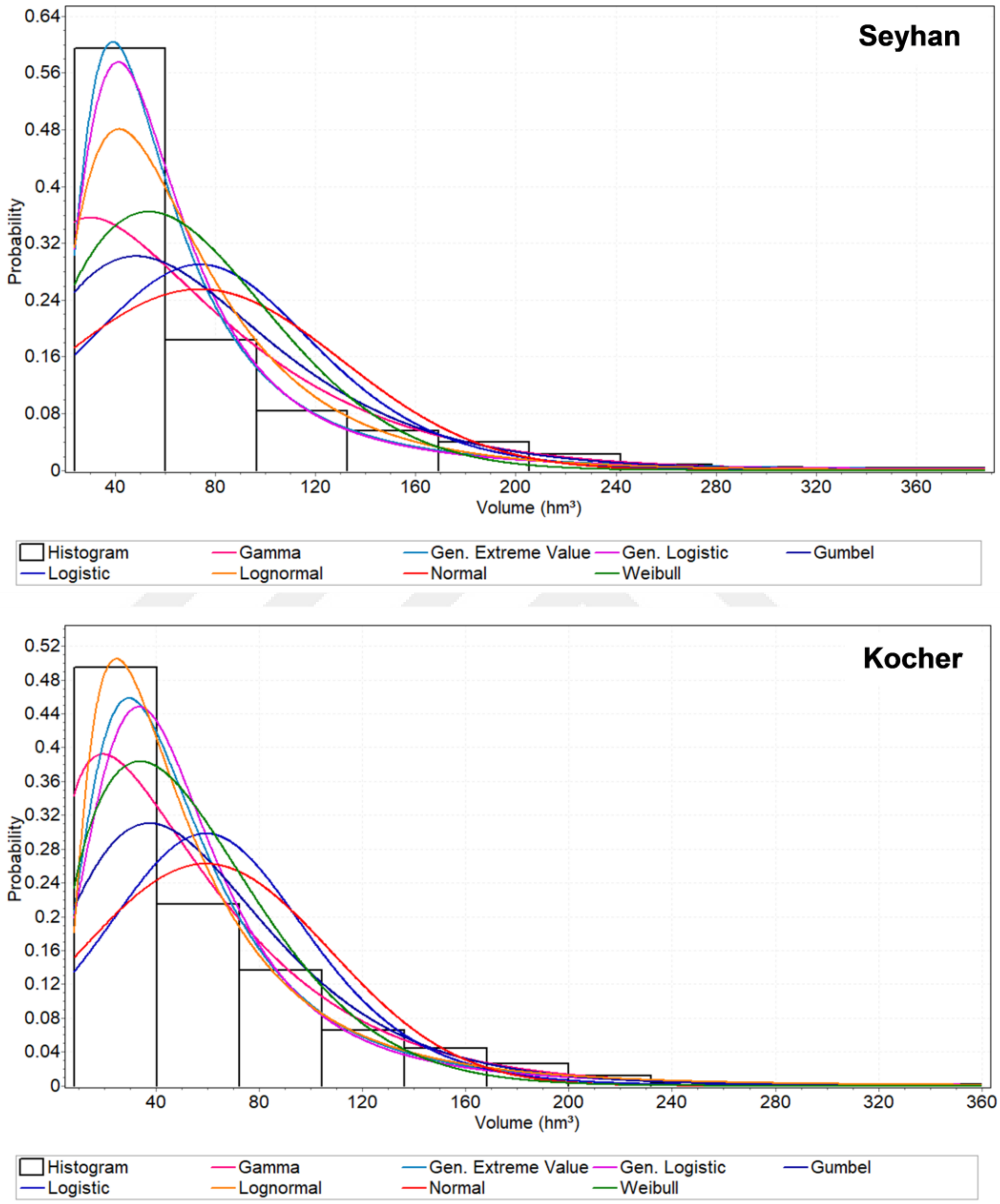

Figure 4.3 : Probability distribution functions fitted to streamflow volume for selected gauging stations in Seyhan River Basin and Kocher catchment.

In Step 3, frequency analysis was applied on the critical drought severity of each duration at each timescale (Figure 4.2). In no-drought years, the critical drought severity is zero as these years are totally covered by a wet period. Thus, the critical drought severity time series has zero and non-zero values. Frequency analysis was applied on non-zero critical drought severity time series 10-year long at minimum from which zero values were removed. Zero values in the drought severity time series have a probability of occurrence while the non-zero values have a probability distribution function. The total probability theorem described in the literature (Haan, 1977, Aksoy et al., 2021) was applied to data sets with zero and non-zero values. The best-fit probability distribution function of the non-zero critical drought severity was determined by taking into account the occurrence probability of zero values. We considered the 2- and 3- parameter Gamma (G2, G3), the Generalized Extreme Value (GEV), the 2- and 3- parameter log-normal (LN2, LN3), Log-Pearson Type 3 (LP3), and the 2- and 3- parameter Weibull (W2, W3) probability distribution functions which are widely used in literature. We used absolute values of the critical drought severity in the frequency analysis as the probability distribution functions are only expressed for positive variables. We decided on the best-fit probability distribution function after the Anderson-Darling statistical test. The critical drought severities corresponding to 2, 5, 10, 25, 50 and 100-year return periods were calculated for all drought durations by using the fitted probability distribution function of the relevant drought duration.

As SPI and SSI are calculated from precipitation and streamflow, respectively, a strong relationship can be expected between the drought indicators (precipitation and streamflow) and the associated drought indices (SPI and SSI). This relationship is determined in Step 4 by applying curve fitting in the form of nonlinear regression (Figure 4.2). To establish a functional relationship between the drought indicators and the drought indices, we tested several curves including the second and third order polynomials, exponential, Gompertz and logistic curve. The polynomials, exponential and Gompertz curves were discarded as they produced negative values of precipitation or streamflow, and they could not fit properly to SPI or SSI time series. The logistic curve was selected as the best-fit curve because it provided the highest correlation without producing negative precipitation and streamflow values (Sit and Poulin-Costello, 1994). The logistic function is given by

$$f(x) = \frac{a}{1 + be^{-cx}} \tag{4.1}$$

in which x is the drought index, and a, b and c are parameters. Each month in the time series has a drought indicator (precipitation or streamflow) accumulated at 1-, 3-, 6-, and 12-month timescales and the corresponding drought index (SPI or SSI) at the same timescales. Regression equations were developed between the drought indicators and indices by using their all values. Owing to periodicity (seasonality), the relation changes from month to month for timescales shorter than a year; 12 regression equations were obtained for 1-, 3-, 6-month timescales, and one regression equation was obtained for the 12-month timescale.

In Step 5, drought indices were converted to precipitation and streamflow deficits by using the relation between the drought indicators and indices. The critical drought severity corresponding to each drought duration and return period were inserted into the generalized logistic function (Equation 1) to find the critical precipitation or critical streamflow value (DI_c). The precipitation or streamflow value corresponding to the maximum drought severity was calculated from the logistic function. We consider SPI = 0 and SSI = 0 as the threshold value of the drought index for all timescales. Threshold values of drought indices were inserted into the logistic function to calculate the threshold drought indicator (DI_0). The difference between the threshold drought indicator and the critical drought severity is deficit in the drought indicator (DI_d), which is either precipitation deficit or streamflow deficit. For each duration and return period, it is calculated by

$$DI_d = DI_0 - DI_c \tag{4.2}$$

Based on the calculated precipitation and streamflow deficits, drought IDF curves of the meteorological and streamflow gauging stations were plotted at different timescales. These deficits provide knowledge to quantify drought IDF curves in terms of physical variables, which are the precipitation deficit and streamflow deficit.

Finally, in Step 6, drought IDF curves are compared between precipitation and streamflow deficits to determine how precipitation deficit propagates to streamflow deficit in these two catchments and how the deficits change from one catchment to another. Additionally, for the assessment of the applicability of the deficit-IDF curves we evaluated one specific drought events observed in each catchment. A severe drought hit the Eastern Mediterranean in 2008, particularly its southern part where the Seyhan River Basin is located (GDWM, 2019; Cavus et al., 2022). The Kocher catchment was affected by the drought event of 2018 in Central Europe (Brunner et al., 2019; Tijdeman et al., 2022; Rakovec et al., 2022). To show the characteristics of these major droughts on the deficit-IDF curves, we identified months with the highest severity accumulated over 12 months for droughts of different durations from D = 1 month to the longest duration in the IDF curves. We considered the 12-month timescale IDF curves for this demonstration. For each duration, the precipitation deficit was calculated by taking the difference between the 12-month precipitation accumulation and precipitation threshold of the precipitation record. The largest value of precipitation deficits calculated as the critical value of each duration was then replaced on the deficit IDF curves to derive the return period of the observed drought.

4.4 Results

4.4.1 Drought indices and indicators

The time series of SPI show a high variability with frequent fluctuations at shorter timescales. At longer timescales, the time series become smoother with less fluctuations (Figure 4.4). At the meteorological station in the Seyhan basin, dry periods become more visible with increasing timescale at the beginning of the time series. A similar observation can be made for the Kocher catchment. SPI time series at Kocher show lower negative values than those at Seyhan. Higher variability and more frequent fluctuations are also evident in the SSI time series at short timescales while they become smoother with lower variability and less frequent extreme values at longer timescales (Figure 4.4). However, the SSI time series fluctuates less frequently compared to the SPI time series. Major dry periods in Seyhan are visible in 1974, 1990, 2008 and 2014 in the SPI and SSI time series, particularly when the timescale increases. Drought events in the Kocher catchment are visible in 1990 and 2018 in the SPI and SSI time series.

The previously described seasonality in general precipitation (Section 2) is also evident in the relation between precipitation and the drought index, SPI, at 1-, 3- and 6-month timescales for which 12 curves were obtained (Figure 4.5). At the annual timescale, the relation between precipitation and SPI is represented by one a single curve as the annual precipitation has no seasonality. In comparison, the precipitation seasonality in Kocher is not as dominant as that in Seyhan and it becomes less pronounced with increase in the timescale. Therefore, at the 1-, 3-, and 6-month timescales, monthly curves between precipitation and SPI are less variable due to less seasonal precipitation in Kocher than Seyhan. Because of the climate characteristics (given by the base climatology), the derived drought characteristics differ. Similar to the case for precipitation, Figure 4.5 clearly shows that the relation between streamflow and SSI changes from month to month at timescales of 1, 3 and 6 months due to the within-year seasonality of streamflow. Therefore, separate equations of each month should be used at sub-annual timescales. One equation can be used for the 12-month timescale as the seasonality in the streamflow is removed at the annual scale. The variability in the curves that were fitted to obtain the relation between streamflow and SSI shows the seasonality in the streamflow of Kocher catchment although it is still less compared to the variability in the curves of Seyhan.

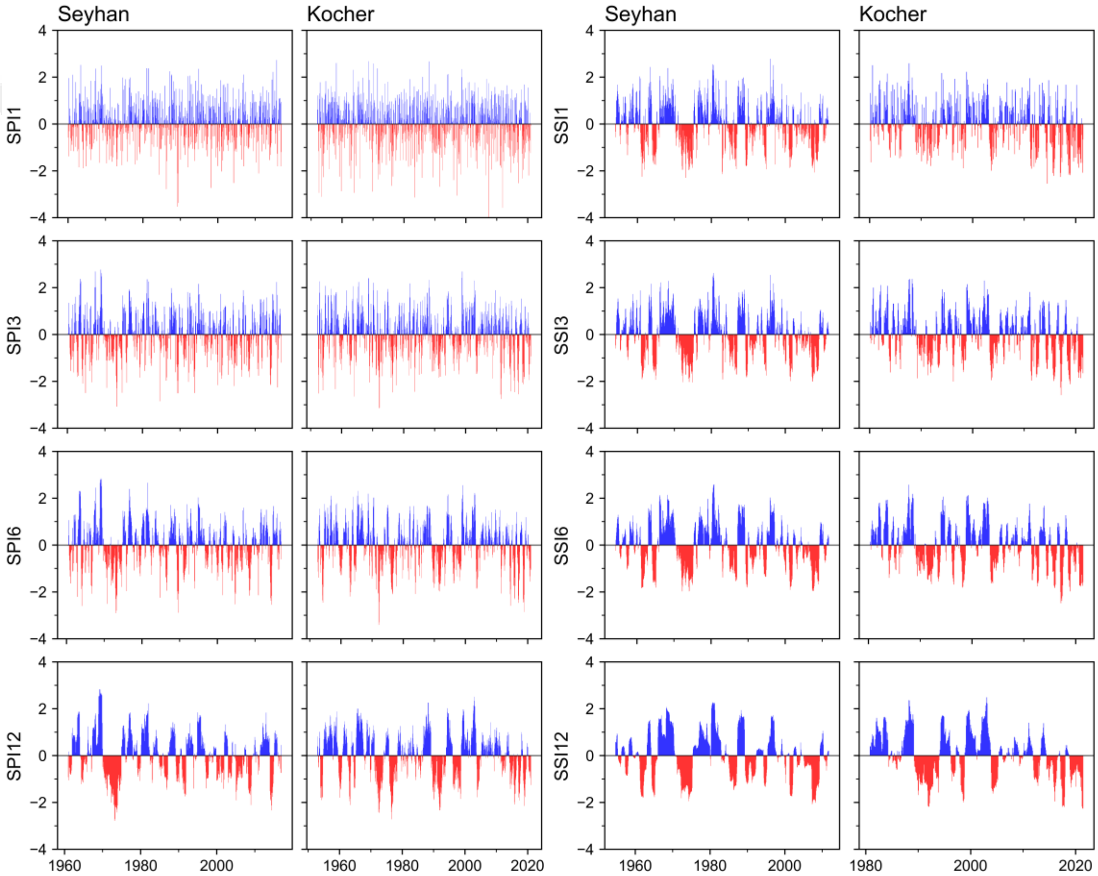

Figure 4.4 : The SPI and SSI time series at 1-, 3-, 6- and 12-month time scales for Seyhan and Kocher.

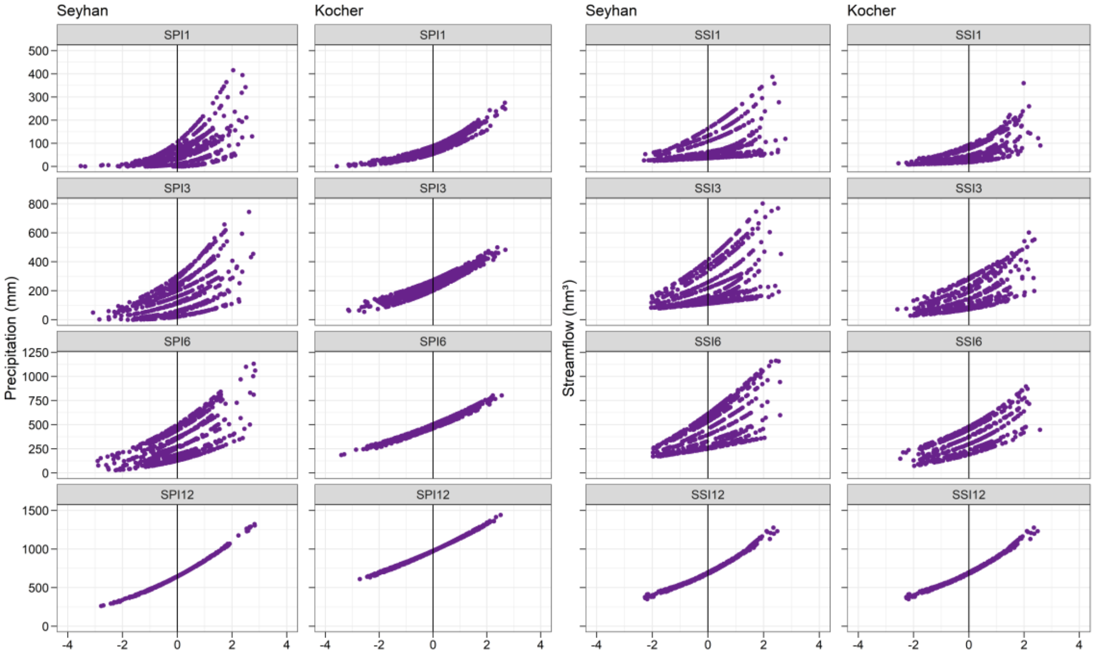

Figure 4.5 : The relation between precipitation as drought indicator and SPI, and precipitation as drought indicator and SSI at 1-, 3-, 6- and 12-month time scales for Seyhan and Kocher. Horizontal axis indicates SPI and SSI values at the top of each scatter diagram.

4.4.2 Frequency analysis of critical drought severity

Frequency analysis of the critical drought severity shows that GEV is the best-fit probability distribution function for the majority of cases when all droughts at all the timescales are considered in the meteorological and hydrological data records (Table 4.2). The LP3, W2, LN2 and G2 distributions can be considered as alternative distributions for a few cases among which LP3 is the second-best distribution for the critical drought severities calculated from SPI12 in both catchments. At this particular timescale of SPI, the best-fit probability distribution function tends to change from GEV to an alternative probability distribution function for long-drought durations.

Table 4.2 : The best-fit probability distribution functions of the critical drought intensities of different durations for the time scales used.

Drought Duration (month)	Seyhan				Kocher				Seyhan				Kocher			
	SPI1	SPI3	SPI6	SPI12	SPI1	SPI3	SPI6	SPI12	SSI1	SSI3	SSI6	SSI12	SSI1	SSI3	SSI6	SSI12
1	GEV	GEV	GEV	GEV	GEV	LP3	GEV	GEV	LP3	LP3	GEV	LP3	GEV	GEV	GEV	GEV
2	GEV	GEV	GEV	GEV	GEV	W2	GEV	GEV	LP3	LP3	LP3	GEV	GEV	GEV	LP3	LP3
3	GEV	GEV	GEV	LP3	GEV	GEV	GEV	GEV	W2	W2	LP3	GEV	GEV	GEV	GEV	GEV
4	LP3	GEV	GEV	GEV	GEV	GEV	GEV	GEV	W2	W2	LP3	GEV	GEV	GEV	GEV	GEV
5	LP3	GEV	GEV	GEV	GEV	GEV	GEV	GEV	W2	W2	GEV	GEV	GEV	GEV	LP3	GEV
6		GEV	GEV	GEV		GEV	LP3	GEV	W2	W2	GEV	GEV	GEV	GEV	G2	GEV
7		GEV	GEV	GEV		GEV	LP3	GEV	W2	W2	GEV	GEV	GEV	GEV	LP3	GEV
8			GEV	GEV		GEV	GEV	GEV	GEV	GEV	GEV	GEV		GEV	GEV	GEV
9			G2	GEV		GEV	GEV	GEV	LP3	GEV	GEV	GEV		GEV	GEV	GEV
10			GEV	GEV			GEV	GEV	GEV	GEV	GEV	GEV			GEV	GEV
11			GEV	GEV			GEV	GEV	GEV	GEV	GEV	GEV			GEV	GEV
12				GEV			GEV	GEV	GEV	GEV	GEV	GEV				GEV
13				LP3			W2	LN2		GEV	GEV	GEV				GEV
14				LP3				LN2		GEV	GEV	GEV				
15								LP3		GEV	GEV	GEV				
16								LP3		GEV	GEV	GEV				
17										GEV	GEV	GEV				
18										GEV	GEV	GEV				
19										GEV	GEV	GEV				
20										GEV	GEV	GEV				
21											GEV	GEV				
22											GEV	GEV				
23											GEV	GEV				
24											GEV	LP3				
25												GEV				
26												GEV				
27												GEV				

4.4.3 Deficit-IDF curves

Precipitation and streamflow thresholds are needed to calculate deficits in precipitation and streamflow, the key elements of the deficit-IDF curves. The thresholds are not constant over the year at 1-, 3- and 6-month timescales (Figure 4.6). They change from one month to another and also the value of the thresholds changes notably from precipitation to streamflow. The annual thresholds are constant values as they accumulate the within-year seasonality. The clear seasonal variability of precipitation threshold in Seyhan is not evident in Kocher while the streamflow threshold has a notable seasonality in both catchments. These temporal and spatial variabilities in the thresholds prevent the drought IDF curves from being comparable in time and space. For the sake of comparability of the IDF curves of various timescales at two different catchments precipitation deficit and streamflow deficit were divided by the respective precipitation threshold (PTH) and streamflow threshold (STH), respectively.

Drought IDF curves of precipitation and streamflow deficits are presented for each month separately at 1-, 3-, and 6-month timescales (Figure 4.7, Figures A1-A2) while the annual deficits are presented in one single set of IDF curves (Figures A3). Drought IDF curves of precipitation and streamflow deficits show general similarities in the two different climatic regions. In all IDF curves, the precipitation and streamflow deficits decrease linearly as the drought duration increases. The IDF curves are almost parallel to each other for return periods of 5 years and higher. Deficits at the 2-year return period decrease faster, they are therefore separated from other return periods. However, the 2-year return period shows a steeper decrease rate of streamflow deficit in Kocher than in Seyhan and a relatively steeper decrease than the curves for higher return periods. Compared to the precipitation and streamflow thresholds, droughts in precipitation are more intense than in streamflow. In addition, precipitation deficits in summer are less in absolute values than in winter considering the seasonality in the precipitation threshold with higher values in winter than summer. Precipitation deficits are particularly lower during the summer months than the winter months in Seyhan because of the dominant seasonality in the Mediterranean climate while no notable difference was observed between precipitation deficits in summer and winter in Kocher because of the negligible seasonality in precipitation in the humid climate of this catchment. The linear decrease in deficits with increasing drought duration and the faster decay in the 2-year return period for the 3-, 6- and 12-month timescales (Figures A1-A3) are similar to what we obtained at the 1-month timescale (Figure 4.7).

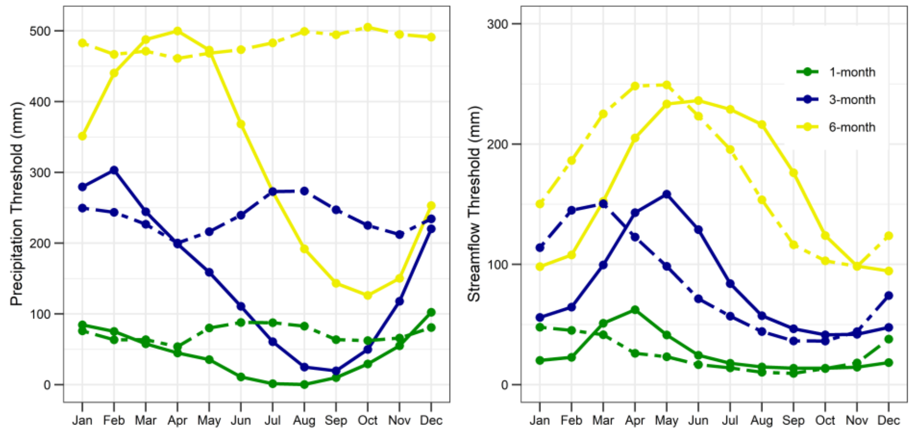

Figure 4.6 : Precipitation threshold and streamflow threshold corresponding to SPIk = 0 and SSIk = 0 (k = 1, 3, 6 months). Solid lines are for Seyhan and dashed lines for Kocher. The 12-month thresholds are constant values over the year; PTH = 643.88 mm, STH = 333.39 mm for Seyhan; and PTH = 975.57 mm, STH = 356.18 mm for Kocher.

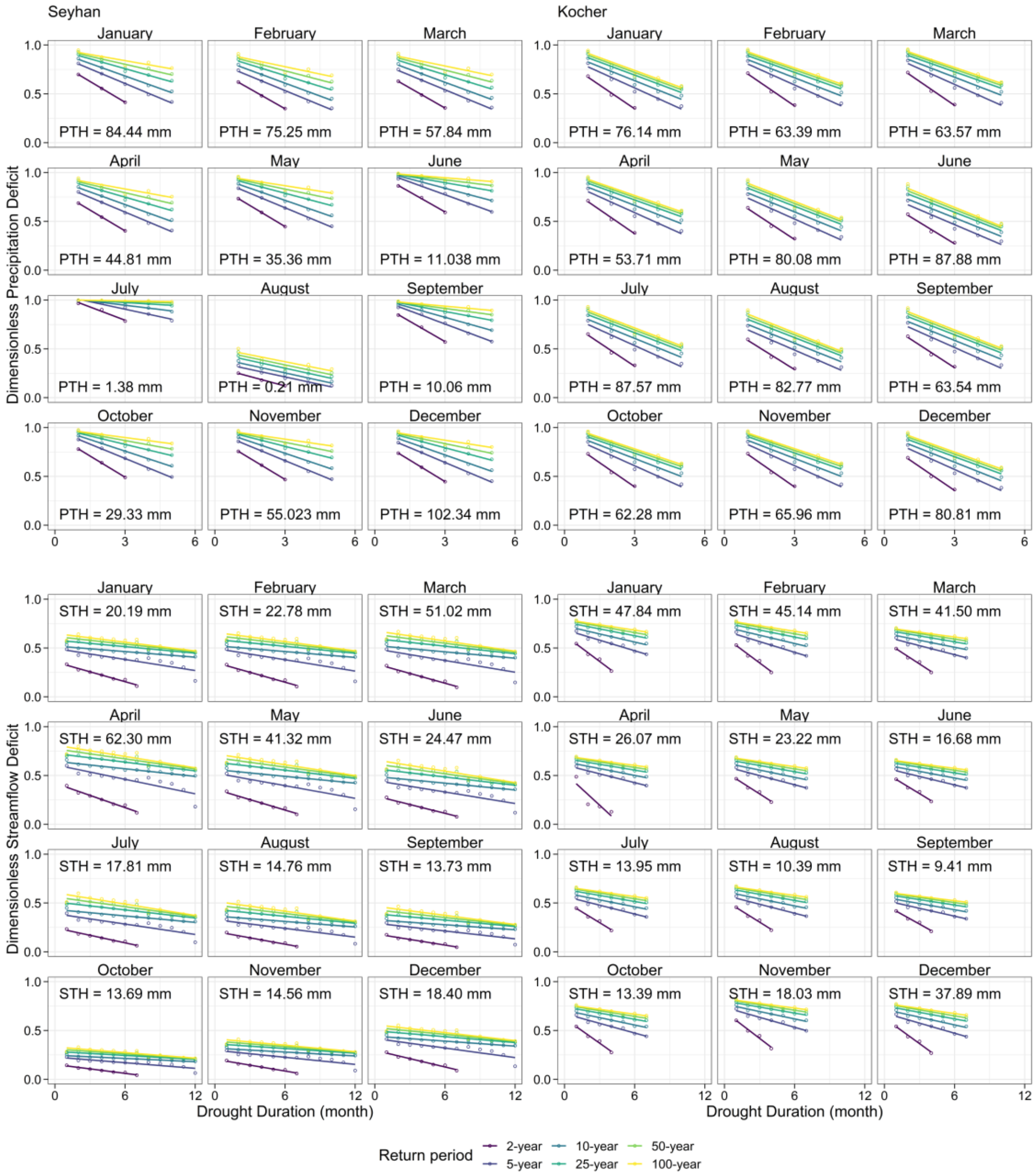

Figure 4.7 : Drought IDF curves in terms of precipitation and streamflow deficit divided by the threshold value for Seyhan and Kocher at 1-month time scale.

4.4.4 Observed major droughts in deficit IDF curves

The applicability of the drought IDF curves was tested for two specific drought events; the drought of 2008 in Seyhan River Basin and the drought of 2018 in Kocher catchment. By selecting the most critical drought of each duration, the observed drought events were plotted onto the drought IDF curves at the 12-month timescale (Figure 4.8). In the drought events, precipitation and streamflow deficits decrease as the drought duration increases. The precipitation deficit of the drought event in Seyhan corresponds to an event with about a 50-year return period at 1-month drought duration and around a 25-year return period at longer durations. The return period declines with increase in the drought duration. However, streamflow deficit exceeds the 50-year return period in the most critical month. The drought in Kocher was a 25-year event at short durations and a 10-year event at longer durations in terms of precipitation deficit. Streamflow deficit IDF curves' relations of intensity, duration and frequency are generally similar to precipitation deficit curves. The drought event of 2018-2019 in Kocher streamflow had a return period higher than the 100-year for durations shorter than 4 months and higher than the 50-year for longer durations. In both cases, the selected drought events approach the 100-year return period. In general, deficit in precipitation of a given return period is higher than streamflow deficit.

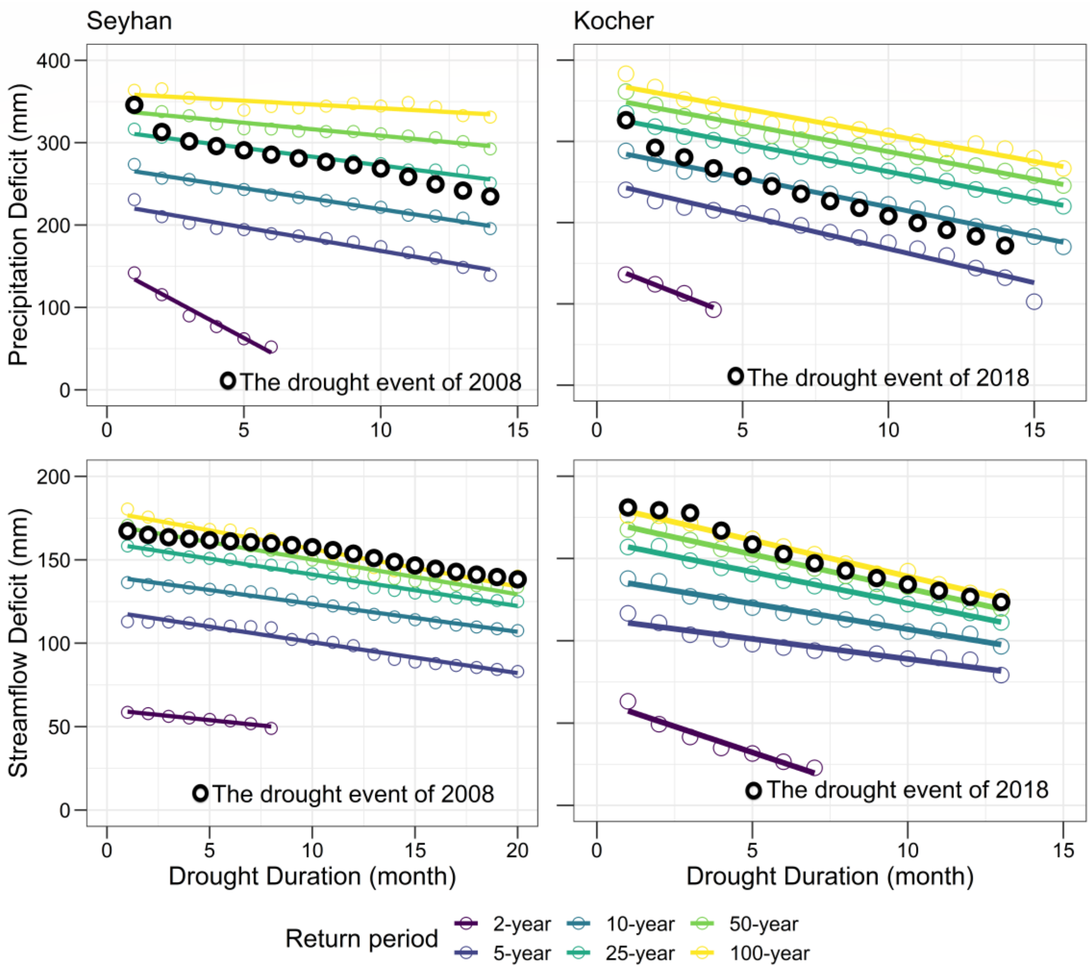

Figure 4.8 : Drought IDF curves in terms of precipitation and streamflow deficits at 12-month time scale. The drought events of 2008 in Seyhan River Basin and 2018 in Kocher catchment were used to demonstrate the applicability of IDF curves.

4.5 Discussion

4.5.1 Drought IDF curves for deficit indicators

We extended earlier studies on drought index (DI)-based IDF curves showing drought characteristics of a station in one single graph (Aksoy et al., 2021) to deficit-based monthly IDF curves. Based on those, this work first aimed to explore the question how these new curves relate to their non-dimensional index counterparts. Drought IDF curves based on precipitation and streamflow deficits for example provide the information how much precipitation and streamflow would be needed to mitigate negative impacts under the most critical drought condition. The IDF curves allow us to estimate return periods of a given deficit (or deficits of a given return period) using meteorological and hydrological drought indices. We showed how precipitation and streamflow deficits vary depending on the precipitation and streamflow characteristics of the region and the implications of this variation. IDF curves can provide similar information about the drought characteristics but physical variable IDF curves show that precipitation and streamflow deficits change in each month depending on the region's climate characteristics. Deficit values also change from one month to another at a station which means that one single IDF curve is not representative enough for the seasonal drought conditions. Drought IDF curves developed so far in literature were based on particular drought indices (Shiau and Modarres, 2009; Reddy and Ganguli 2012; Halwatura et al., 2015; Aksoy et al., 2021).

Our findings and comparisons have critical implications for drought risk assessment. DI-based IDF curves are useful for the drought prediction at sites with no meteorological station or streamflow gauge. DI values such as SPI or its modified versions are reported by national meteorological services as a monthly routine in many countries. For example, the European Drought Observatory uses SPI to indicate a 'drought watch' situation (url1, 2023); The Turkish Meteorological Service (url2, 2023) and the German Weather Service (url3, 2023) use various drought indices to indicate spatial and temporal variation of drought at national level. At a more local scale, the low flow information service in Bavaria (url4, 2023) uses three different SPI indices (90-day, 30-day, 14-day) to monitor precipitation deficit and indicate drought situations. From the reported DI values of such monitoring maps, one may read the severity class of the drought in different return periods to prepare for the next months and plan or implement drought mitigation. An important limitation of DI-based IDF curves is that they mask the local seasonality. While there is no need to generate them for each month, the disadvantage is that the information they provide is not physically generic because the same value of DI is not equal to the same value of drought indicator, i.e., precipitation deficit or streamflow deficit for each month. Further steps are therefore needed to convert the drought index into deficits for use in practice. Deficit-based IDF curves are useful tools for drought research as well as for practical implementation. The user can read the return period of the observed drought from the IDF curve by inserting the observed precipitation and streamflow deficit on the curves, which allows practitioners particularly to act quickly and respond timely to mitigate the unwanted impacts of drought.

Deficit IDF curves can be applied to quantify the frequency of drought events and characterize the droughts by their intensity and duration at different timescales. The threshold level is also important to consider in the IDF curves which is taken as the level corresponding to SPI = 0 and SSI = 0 in this study. By doing so, we considered to take all drought classes (extreme, severe, moderate, and mild drought) of McKee et al. (1993) in the methodology which is flexible to use with any other threshold. The methodology can also be adapted to other drought indices than SPI and SSI. It is possible to choose a lower threshold level to exclude mild droughts for which a new set of IDF curves will be obtained as the IDF curves are threshold-dependent.

4.5.2 IDF curves for drought mitigation planning in different climatic conditions

The work further aimed to compare how precipitation and streamflow deficits of drought indices and their associated drought event characteristics differ both between the variables within a basin and between different climatic regions. The two events shed some light on these differences. Tijdeman et al. (2022), for example, described the drought event of 2018 in southern Germany as multi-year deficit event that a short summer extreme was superimposed on. The intensities determined here confirm this notion with the event's shorter duration deficits corresponding to higher return periods on the IDF curves, i.e., more extreme conditions than the longer durations. The differences in intensity over duration are mirrored in streamflow, but less pronounced. Overall, the meteorological conditions appear to have combined into an event that corresponds to a substantially more extreme (less frequent) streamflow deficit than those of its meteorological causes. The curves therefore might help explain different drought types as well. The drought event of 2008 at Seyhan while also corresponding to higher return periods for streamflow than for precipitation, varies differently regarding the return periods over different durations. With increasing duration, the corresponding return period of this drought decreases for precipitation but increases for streamflow. Possibly, this might be due to either the increased water use having amplified the streamflow deficit or higher evapotranspiration and the missing seasonal precipitation.

DI-based drought IDF curves do not incorporate site specific precipitation and streamflow deficits of each month other than the drought indices. However, regional precipitation patterns, including intense and prolonged deficits, play a critical role in identifying frequency of drought and challenge to mitigate drought by established management plans (Kreibich et al., 2022). Short and long-term deficits can be detected from the intensity of the drought indicators combined with duration and frequency. In particular, long-term droughts with high variations and frequently occurring intense deficits can be assessed as primary characteristics for determining site sensitivity, while regular and comparatively short deficits are general characteristics of the regional climate condition (Halwatura et al., 2015). The different patterns of summer precipitation and streamflow in the two case studies, Seyhan and Kocher, illustrated how seasonality become the primary factor of deficits. We found that short timescale deficits are the most severe droughts with higher variability. The lower variability of longer timescales applied both to precipitation and streamflow. Implementation of the IDF curves on the drought events of 2008 in Seyhan and 2018 in Kocher demonstrated this reality and the impact of drought in these regions (Cavus et al., 2022; Tijdeman et al., 2022; Rakovec et al., 2022).

4.5.3 IDF curves for practice: time scale and severity

Deficit-IDF curves for the design under drought conditions have not been well established in literature and practice. There is an emerging need for guidelines worldwide to use in water resources design, planning, operation, and management under low flow or drought conditions (Vogel and Kroll, 2021). Similar to the precipitation IDF curves used in hydrological practice (Chow et al., 1988), deficit-IDF curves developed in this study can therefore be considered an improvement towards the design under drought conditions. In practical meaning, the timescale is the time lag between the initiation of water deficit and its impact on water resources, engineering activity, ecology, economy or society. An assessment about the choice of the timescales has been made by Vicente-Serrano et al. (2013) for vegetation, and Halwatura et al. (2015) for ecosystem establishment after mining. They divided the timescales into two; short and long timescales and provided a list of dominant timescales. However, the timescales can overlap and change from region to region or from season to season in the same region. For example, a short but severe drought might have the same impact as a long mild drought. For these reasons, we consider the applicability of IDF curves by timescale and severity of various activities.

Successful drought and water management require knowledge of drought characteristics at varying timescales. Seasonal or even over-year water storage and release at longer timescales are important processes in some catchments and for some water uses while in other catchments for other water needs shorter timescale variability matters as water needs to be provided regularly, e.g., for hydropower generation. Respectively, different drought threats matter as the impacts are very different and this will affect the usefulness of the IDF curves. This final section explores how IDF curves might be beneficial for management actions such as agriculture-irrigation for different crops, industrial water uses, and reservoir-storage for different purposes or run-off-the-river hydropower, as well as for nature's water needs, such as aquatic ecology. Table 4.3 categorizes these water needs and the associated drought timescales and drought severity classes that threaten them.

Irrigation methods for agricultural activities require cost-effective drought management strategies for specific sites. The IDF curves of precipitation deficit of long timescales and moderate/severe droughts can provide a useful knowledge for larger area agriculture such as the design of drainage systems and irrigational canals (Table 4.3). For drip, seasonal and critical stage irrigation for which a lower amount of water is needed compared to larger drainage systems, short timescales provide important information about the deficit. Horticulture and field crops cannot resist against long-term deficits; i.e., any design for such activities should consider short timescales. For non-irrigated agriculture, precipitation deficit IDF can be used at short and long timescales while for irrigated agriculture, streamflow deficit IDF curves can be used at different timescales depending on the region and crop type. Long timescale

IDF curves can be considered for drought-tolerant species with deep roots. Regarding crop species, some specific crop types cannot grow if the drought exceeds a certain duration or intensity. For instance, precipitation deficit-IDF curves at short timescales are important for drought intolerant crops while long timescales are important drought tolerant crops, annual and perennial grasses, trees.

Table 4.3 : Time scale and severity classes of droughts for some specific activities. SM - Short time scale and mild/moderate drought; SS - Short time scale and severe/extreme drought; LM - Long time scale and mild/moderate drought; LS - Long time scale and severe/extreme drought S: Shorter than 6 months, L: 6 months or longer.

General category	Specific activity	Drought time scale and severity
Agriculture - Irrigation	Drainage system, irrigation canals, drip irrigation Seasonal and critical stage irrigation	SM, SS, LM, LS
Agriculture-Rainfed crop species	Drought intolerant crops, horticulture, field crops	SM, SS
	Drought tolerant crops, annual and perennial grasses, trees	LS
Hydropower	Small (runoff) hydropower facilities, thermal power plants	SM, SS
	Large (reservoir) hydropower facilities	LM, LS
Reservoir storage	Water supply (depending on the reservoir size and water demand)	SS, LM, LS
	Irrigation (depending on the season and crop)	SS, LM, LS
Industry	Industrial water	SS, LM, LS
Ecology	Recreation, ecosystem habitats	SS

Diversion hydropower plants or thermal power plants as they often exist in Germany and also further downstream in the Kocher will be affected by droughts at short timescales while storage hydropower plants as they often exist in the mountains or in semi-arid climates in the Mediterranean region, will be interested in the threat from long droughts (Table 4.3). Short timescale IDF curves based on streamflow deficit can provide useful information under mild/moderate drought conditions for river water uses for industry or for recreational use. Ecosystem habitats again might mostly require consideration at short timescales but during very specific seasons (spawning, migration time, oxygen depletion), but also longer periods when it comes to overall environmental degradation. The return periods of streamflow deficits provide the probability of deficits at these durations and intensities, and the risk of drought can be interpreted correctly. This is important for water managers who can conduct a costbenefit analysis whether the cost of taking some mitigation precautions such as agriculture, reservoir, hydropower etc. are comparable with the cost of probable failure (Table 4.3). Selection of small hydropower management based on different timescales is also the key management actions for deficit-IDF curves.

Another issue could be related to the temporal variability. A less variable system can be linked with longer timescale, and a more variable system with a shorter timescale. Specifically, short timescale streamflow deficit IDF curves should be used for the run-of-the-river and pumped storage energy production plants, because they have higher fluctuation in the river. The storage systems can be tolerant for long timescale droughts if the storage is filled enough at the beginning of dry period. Therefore, long timescale streamflow deficit IDF curves work well for storage hydropower systems. For water supply systems, streamflow deficit IDF curves at short timescales can be advised. The categorization outlined in this study (Table 4.3) clarifies the usefulness of the deficit-based IDF curves to address the site-specific climatic conditions. Drought IDF curves should be a primary factor of drought mitigation strategies and eventually help to guide water recourses management planning where hydrological extremes have an impact on current operations.

4.6 Conclusion

We developed deficit-IDF curves to assess how associated deficits vary in a given catchment at different return periods although they have similar drought intensity in the drought index. We explained the advantage of using physical variables, precipitation and streamflow deficits, giving more practical and straightforward use to the deficit IDF curves than the index-based drought IDF curves. This makes the new drought IDF curves generally applicable for different climatological regions and also for a comparison of their drought risks. Deficit IDF curves can be developed for any location or catchment to convert drought index values to deficit. Precipitation and streamflow deficits distinguish the degree of drought impact and its implication for various water uses. The use of IDF curves with the observed droughts showed their applicability in identifying return periods. A given value of both deficits has higher return period at longer drought duration and lower return periods at shorter drought durations. Precipitation deficits of the observed major droughts are higher in amount but have lower return periods than their streamflow deficits. Here, we stress that deficits can be highly variable, which make it necessary to comprehensively assess the usefulness of IDF curves before establishing drought mitigation strategies. Thanks to the deficit knowledge, drought intensity in a particular system can be interpreted correctly, especially those characterized by complex hydrological systems. Deficit IDF curves can be applied to quantify the frequency of drought events and characterized by intensity and duration at different timescales. Precipitation and streamflow deficits of droughts should be used to assess drought management strategies based on return periods.

5. CHALLENGES IN DROUGHT MANAGEMENT UNDER HUMAN INFLUENCE

5.1 Motivation

Located in the Mediterranean region, the Seyhan River Basin (SRB) is the breadbasket of Turkey. With rich, fertile lands and a sub-tropical climate, the SRB also has an international importance for agricultural production as large quantities of vegetables are exported globally. The river basin was exposed to widespread drought at various intensities because of variability in precipitation from year to year. For instance, the basin was affected by an extreme drought in 2008, which received the lowest amount of precipitation on the recorded period (1960-2016). The drought negatively affected agriculture, industry, and humans, causing shortages in urban water supply throughout the region. Water level dropped lower than previous minima in reservoirs and the water supply could not fulfil domestic and agricultural water demands. This simulated the human interventions on the water resources of the basin to maximize water supply. As a temporary solution, water was pumped from the dead volumes of dam reservoirs together with substantial amounts of water discharged from regional groundwater reservoirs, which resulted in a depletion in the aquifer without fully satisfying local water demand (Selek et al., 2016). Consequently, the drought affected the population and social life depending on water supply provided by the basin for irrigation, drinking water and industry.

Before the 2008 drought, water infrastructures such as dams, river embankments etc. were built to cope with hydrological extremes in the region since historical events caused serious damages. For instance, farmlands were inundated, agricultural yields were damaged, and many settlements were destroyed with loss of lives and property. However, with the increased storage capacity, more water became readily available to agriculture which discouraged the use of efficient irrigation systems (Selek et al., 2016). Of course, the infrastructural development and human alterations of water storage were beneficial to increase water supply. This provided additional drinking water to urban areas for agricultural and economic growth but in turn, generated higher water demand during this time. Yet, it is still unclear why the supply system failed in providing water to the region during the 2008 drought. Here, we aim to identify the bidirectional feedbacks between humans and water in the SRB which contributed to the supply-demand paradox (Kallis, 2010) and amplified water shortage in the long-term.

5.2 Phenomena and Processes

Drought in the SRB reduced water availability throughout the river basin, triggering a reduction in agricultural yield, increasing food prices, and adversely impacting farmers' income. This reduction in agricultural productivity led to a migration of regional farmers from rural regions toward urban centres (with limited job prospects), which negatively impacted the rate of unemployment (Figure 5.1). As a result of population growth in big cities, alterations in water consumption habits were driven by increasing socioeconomic development and growing urbanization, water-dependent sectors such as production, industry, tourism and environment as well as the traditional consumers like agricultural and domestic use (Topcu et al., 2019). Unplanned urbanization due to migration, deforestation and the use of flood plain around the river make the drought hazard worse. Excessive water consumption from aquifers leads pollution and sea water intrusion into groundwater. These 'cascading impacts' or 'knock-on effects' show how widely the drought phenomena can indirectly affect the river basin hydrology (Cavus et al., 2022).

In order to avoid or minimize drought impacts, the government gave priority to take some adaptation responses to compensate the losses and to introduce short-term measures for tackling droughts by using economic investment. Farmers' debts to government banks were postponed for one year, interest-free loans and subsidies for implementing water-saving irrigation technology were provided as well as direct payment to the farmers (Topcu et al., 2019). This subsidence balanced (or decreased) the drought impact. Monetary subsidence by the government can only be considered a temporary solution mitigating these negative effects, i.e., the safe-development paradox (Figure 5.1). State authorities responded to the drought by increasing water supply mainly for population and agricultural irrigation. Additional measures include the use of night watering, avoiding a second crop cycle per year, the use of sprinkler and drip irrigation methods, the use of treated wastewater for irrigation. These precautions are mitigation measures which were developed to increase resilience to external drivers. Even the farmers tried to take some drought mitigation actions individually to protect their own crops. The drought not only affected agriculture, industry and energy but also heavily caused shortages in water allocated to the cities and urban areas in the region. Water level was in its minimum ever recorded in reservoirs supplying with water the metropolitan area accommodating more than 2 million of population in 2008. The state authorities increased potential water holding capacity in dams. This effort mitigated drought impact together with a potential supply-demand cycle effect as easier water access triggered higher water consumption. Techniques increasing the preservation of water in the soil and the effective use of water for agriculture was ensured (Selek et al., 2016). These governance-related measures through the agricultural and urban water conservation frameworks improved performance of water supply systems, but they might lead to higher consumption of water, i.e., the rebound effect.

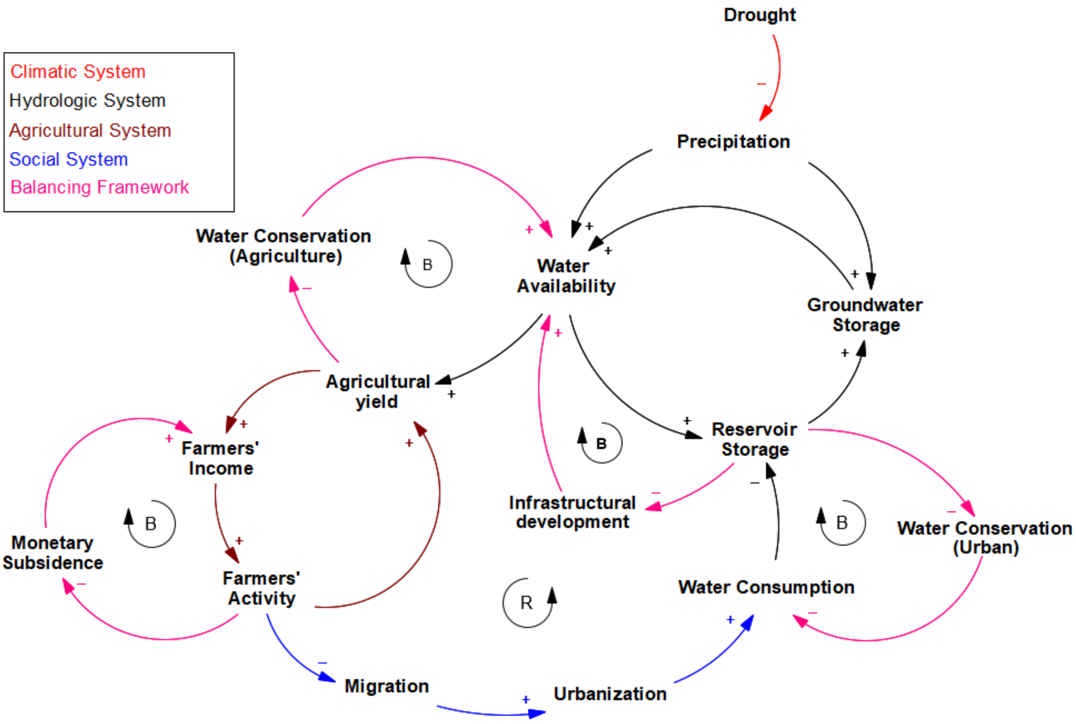

Figure 5.1 : Causal loop diagram (CLD) illustrating drought impacts reinforced by agricultural, social and hydrological activities, and balanced by economical, structural and conservation frameworks.

5.3 Implications for Change

Drought in 2008 had important impacts on the local economy and social life in the SRB. Decision-makers implemented a number of water supply techniques and adopted temporary management policies, which resulted in increasing, unsustainable water demand under drought conditions. Therefore, the region could not maintain the balance or resilience to the urban-migration patterns and population growth.

What we learned here is that the paradoxical measures in the CLD can only mitigate negative effects of drought at short term. Long-term drought mitigation measures such as drought management plans are needed, which in 2019 have been prepared for the SRB by the General Directorate of Water Management of Turkey. All feedback revealed in the causal loop should be evaluated. Towards solutions, more success story focus may be needed to create a portfolio of options that can be tested in a model before being put in practice. The balancing effects that result from drought mitigation measures need to be avoided in the absence of an effective water management plan. The effective water management plan under drought conditions is the most important component to the overall system behaviour. Any drought management is challenging as it is influenced by complex human decisions in its implementation. It requires water managers, city planners, and all related governance interpret the solutions together which make a challenge (or a complex system) overall approach.

6. SYNTHESIS AND CONCLUSIONS

6.1 Synthesis

The main objective of this thesis was to develop drought IDF curves based on standardized climatic indices using physical variables, deficit in precipitation and deficit in streamflow. First, major dry periods observed in the past were revisited (Chapter 2), new drought-related concepts were defined (Chapter 3), before the drought IDF curves were developed (Chapter 4). The human-water relevance of drought (Chapter 2) was extended on a particular example (Chapter 5). This aim was achieved by taking the following steps:

- gaining insight into the major dry periods by studying with the rolling time series analysis and developing the quantitative outcomes to be converted into qualitative knowledge.
- distinguishing between the drought and dry period by means of statistical characteristics; severity, duration, intensity, of different drought concepts
- testing the applicability of the drought IDF curves in producing deficits for catchments from different climates, and having knowledge for what purposes deficit-IDF curves are used in water resources management practice
- using a causal loop diagram to explore the influence of human response in water resources under drought conditions

All chapters in the thesis are linked each other. The final outcome of the thesis is the drought IDF curves developed as a tool based on precipitation and streamflow deficits. The overall conclusion is that, thanks to the deficit knowledge, drought intensity can be interpreted correctly and physically understandable. Precipitation and streamflow deficits of droughts should be used to assess drought management strategies. In this last chapter of the thesis, I put the outcomes of my research into a scientific context, make an overall discussion of the studies, summarise the implications and present recommendations for further research.

6.2 Overall Discussion

The outcomes of this thesis have a wider applicability that can be used for basin scale drought management plans. The thesis sheds light on the need for such drought analyses on drought adaptation and mitigation which is an important issue to be resolved in the basin for many sectors such as agriculture to mention as an example. The outputs can be used in the river basin-specific sectoral water allocation plan, drought early warning studies, and can be improved for a possible extension to river basins with similar climatological characteristics.

As stated in Chapter 2, this research aimed at enhancing the understanding of the mechanism underlying drought analysis methods. The research in Chapter 2 provides two important insights to the literature. First, a major dry period ignored because of its short duration could be as important as a long-lasting major dry period. Second, a drought masked by the analysis of the stationary analysis at the country or basin-scale can be prominent if a detailed analysis is made at the sub-basin scale. The non-stationary rolling time series analysis accumulating the length of the major dry period can be used alternatively. Also, each dry period can be taken individually. Results show that the probability of mild droughts has a notable decrease in the rolling time series analyses compared to the drought probability of individual major dry periods at all timescales. The rolling time series analysis underestimates the drought probability compared to the individual use of major dry periods. This is an important outcome to consider for practical purposes because severe and extreme droughts have higher occurrence probabilities when the dry period is taken in calculating the drought probabilities. This prevents underestimation of severe and extreme droughts and allows managers to take precautions against the drought in advance. Major dry periods are important to reveal the importance of the time series analysis. The final outcomes are (i) the rolling time series analysis is superior to the full record analysis to show the nonstationary evolution of drought occurrence probability, and (ii) the individual use of dry periods should be preferred not to underestimate the drought.

The outcomes of Chapter 3 show that distinguishing between drought and dry periods is important because, intense droughts, even if short, are important for agricultural, energy generation and water supply activities in seasons with higher demand. For agricultural drought, precipitation accumulated over longer periods of time, e.g., annual precipitation or precipitation accumulated over the dry period length, is also important, but a more important aspect is precipitation during the crop growing season or crop yield. Focusing on a short duration drought within the dry period could be important in terms of intensity for water resources managers to supply water demand. The lack of a certain definition of drought for a specific sector has been an obstacle for water resources managers and policy makers to understand the drought and mitigate its effects. In addition, the main challenge in drought analysis is to estimate a certain drought severity or intensity for a given drought duration at certain return periods for practical use and, the drought intensity is underestimated when the dry period is considered the same as the drought. Results show that the most intense cases are the critical droughts which support the suggestion to extract droughts of shorter durations from dry periods and that the most intense droughts of a given duration should be used for hydrological design purposes. The methodology has a limitation as it is based on the sole use of precipitation data and results are restricted by the number of meteorological stations used in this study. However, regarding the importance of the intensity in identifying the drought, I gained considerable knowledge from the results as follows: Dry periods are different from droughts in terms of their characteristics. The difference between the dry period and the drought is sufficiently large to consider in practice. This is an implication that has not been considered in the literature and suggesting the use of drought as a concept different from dry period and this is an untouched issue in the scientific world.

Based on the knowledge of Chapter 3, deficit IDF curves were obtained in Chapter 4 to quantify the frequency of drought events and characterize the droughts by their intensity and duration at different timescales. I proposed a methodology to convert drought indices (SPI and SSI in this study) to the amount of deficit in precipitation and streamflow, respectively. This method can also be adapted to other drought indices than SPI and SSI. It is also possible to choose a lower threshold level to exclude mild droughts for which a new set of IDF curves will be obtained as the IDF curves are threshold-dependent. The results show that short timescale deficits are the most severe droughts with higher variability. The lower variability of longer timescales is applied both to precipitation and streamflow. Implementation of the IDF curves on the major drought events (that I found in Chapter 2) demonstrated this reality and the impact of drought. Drought IDF curves have not been well established in literature for the design practice under drought conditions, and an example based on precipitation deficit or streamflow deficit does not exist. Similar to the precipitation IDF curves used in hydrological practice (Chow et al., 1988), deficit-IDF curves developed in this study can therefore be considered an improvement towards the design under drought conditions. There is an emerging need for guidelines worldwide to use in water resources design, planning, operation, and management under low flow or drought conditions (Vogel and Kroll, 2021).

Furthermore, in order to be successful, the drought and water management require knowledge of drought characteristics at varying timescales for which deficit IDF curves can work well. Seasonal or even over-year water storage and release at longer timescales are important processes in some catchments while in some other catchments, shorter timescale variability matters as water needs to be provided regularly, e.g., for the run-off-the-river hydropower generation. Therefore, I categorized IDF curves of different timescales for management actions of various sectors such as agriculture-irrigation for different crops, industrial water uses, and reservoir-storage for different purposes or run-off-the-river hydropower, as well as for nature's water needs, such as aquatic ecology. Drought IDF curves can be taken as a primary tool of drought mitigation strategies and, they eventually help to guide water recourses management planning where hydrological extremes have an impact on current operations.

6.3 Main Conclusions

Revisiting major dry periods by means of different time series analyses is the first attempt to make drought analysis in detail. Major dry periods were investigated with a methodology adapted specifically for different drought classes which are mild, moderate, severe and extreme. Results conclude that the probability of mild drought is higher at all timescales and their frequencies increase with increasing timescale. A systematic change in probabilities of drought categories was not found as well. The rolling time series analysis show that the probability of mild droughts decreased in all meteorological stations studied. The drought event of 1989-1990 in Seyhan River Basin is the most severe compared to other major droughts which makes it considerably important to consider. A short-duration drought can be as important as a long-duration drought. The non-stationary rolling time series or the stationary full-record time series analysis underestimate the most severe droughts. This is the current practice which should be replaced by the individual major dry period analysis with which higher probabilities are found for severe and extreme droughts.

Moreover, this thesis clarifies drought concepts used synonymously. Three cases proposed show clear differences from each other. Differences among the cases emerge from the number of droughts, drought duration, severity and intensity. Dry periods are the least intense of the three cases. The results conclude that the difference between the dry period and the proposed critical drought concepts is large enough particularly in intensity, which is an important drought characteristic to be considered in practice. The conceptual difference between the dry period and drought is expected to support reliable engineering decisions in water resources practice by increasing the confidence level in drought prediction, thus improving risk management and mitigating negative effects of drought.

As the next step of this study, these concepts were employed to explain drought by using precipitation deficit and water deficit instead of using standardized drought indices. Based on this knowledge, drought IDF curves were developed to assess how associated deficits vary in a given catchment at different return periods although they have similar drought intensity in the drought index. The use of physical variables giving more practical and straightforward use to the deficit IDF curves than the index-based drought IDF curves are a great advantage for interpretation of the drought severity level. Precipitation and streamflow deficits distinguish the severity of drought. The use of IDF curves with the observed droughts showed their applicability in identifying return periods. A given value of both deficits has higher return period at longer drought duration and lower return periods at shorter drought durations. Precipitation deficits of the observed major droughts are higher in amount but have lower return periods than their streamflow deficits. The deficits can be highly variable, which make it necessary to comprehensively assess the usefulness of IDF curves before establishing drought mitigation strategies.

Furthermore, I presented the challenges in drought management under human influence with focusing on the drought event of 2008. The study conclude that paradoxical measures can only mitigate negative effects of drought at short term. Long term drought mitigation measures are needed. Towards solutions, more success story focus may be needed to create a portfolio of options that can be tested in a model before being put in practice. The effective water management plan under drought conditions is the most important component for drought preparedness.

In the final conclusion, this dissertation emphasizes the importance of drought studies that need to work on it. The application here is limited to a few examples regarding indices, timescales, and thresholds etc. The non-stationary rolling time series analysis, the newly proposed drought concepts and the deficit IDF curves of this study can also be adapted to other drought indices and indicators and be studied in other regions of the world, and to threshold levels corresponding to different drought situations in terms of severity or even to impact-specific thresholds.

6.4 Further Research

On the basis of the outcomes of this PhD research, I suggest a number of steps to be taken in the drought research for the future. First of all, further work might explore the extension of station-based drought IDF curves to regional curves for a possible use at ungauged basins. How transferable the approach is to other indices, threshold levels, other climates and hydrological regimes remains to be tested in order to assess the range of applicability.

Second, there are still some intriguing issues in the hydrological processes underlying the drought analysis approaches that remain to understood, e.g.:

- **Probability distribution functions:** While this research focused on commonly well-known drought indices, i.e., SPI and SSI, it would be interesting and useful to investigate the best-fit probability distribution functions to meteorological dataset of different climate regions, such as countries in the southern hemisphere, to explore how drought characteristics are changing among different probability distribution functions.
- **The effect of regulation of basins:** This research deals with nearly natural flow conditions to determine the best-fit probability distribution functions and drought characteristics on the catchment. However, the social aspects of the coupled sociohydrometeorological system are inevitable nowadays and all regulations affect various streamflow characteristics, from low to high flows, with important implications for downstream water users. Different conditions need to be investigated in more detail.

- **Ungauged sites:** Finally, it would also be of great interest to explore how the results of this research can be applied to, for example, the prediction of the occurrence of drought in ungauged basins. As large-scale efforts at the global scale cannot be used to perform detailed local-scale analysis, a simple conceptualization of this research might provide more appropriate tools to use for ungauged sites.

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APPENDICES

APPENDIX A: Drought-IDF curves in terms of precipitation and streamflow deficit

APPENDIX A: Drought-IDF curves in terms of precipitation and streamflow deficit

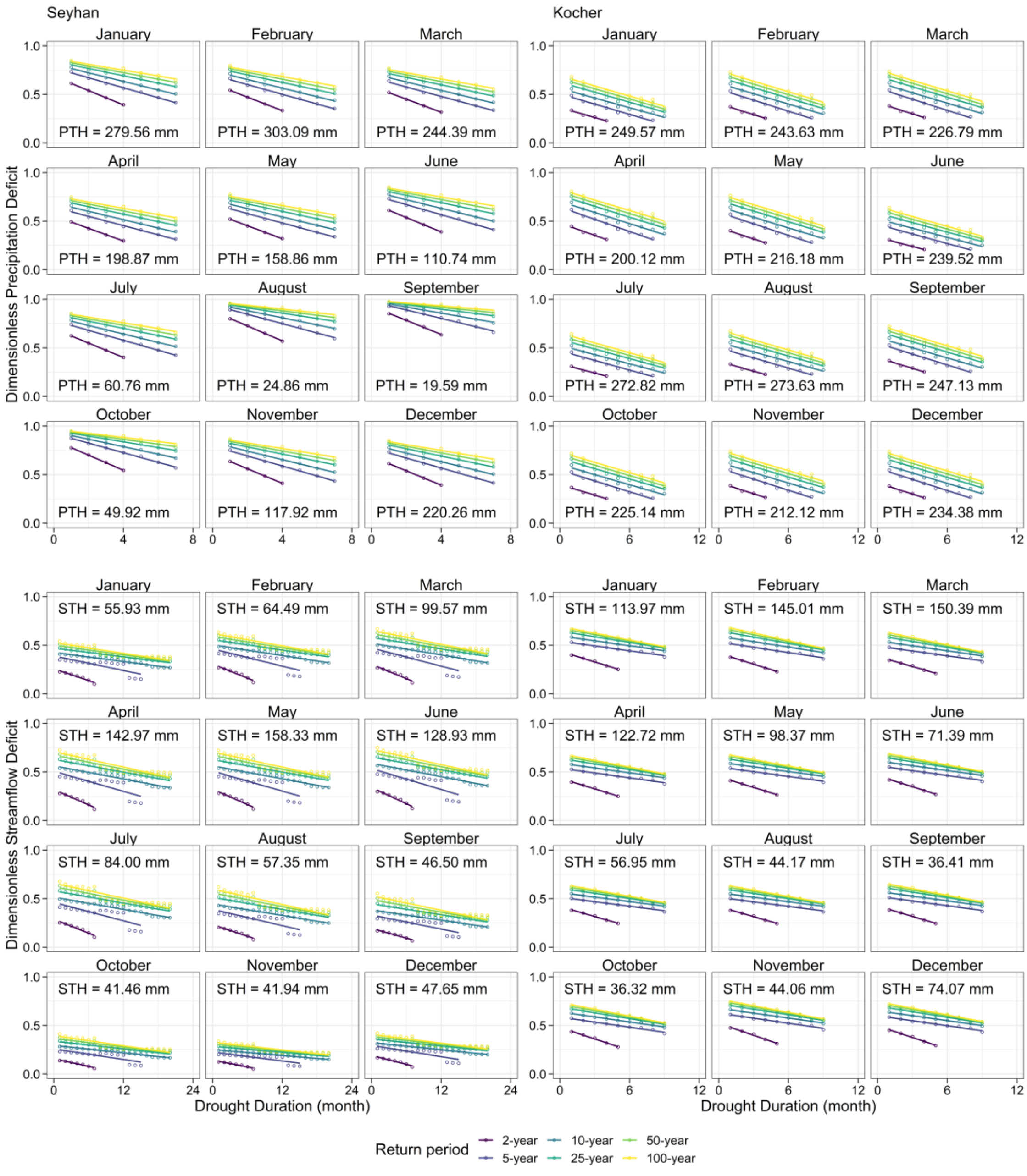

Figure A1. Drought-IDF curves in terms of precipitation and streamflow deficit divided by the threshold value for Seyhan and Kocher at 3-month time scale.

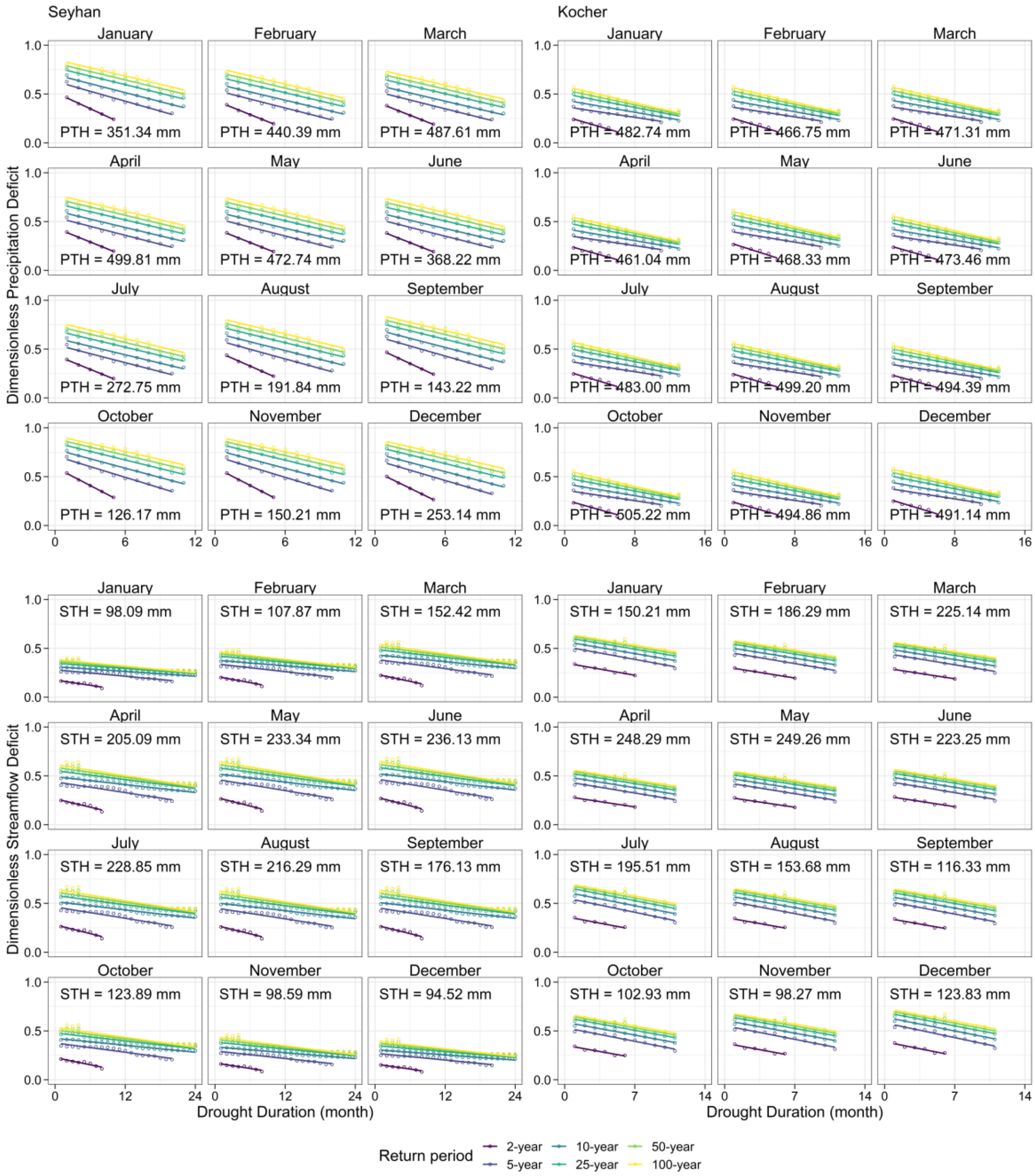

Figure A2. Drought-IDF curves in terms of precipitation and streamflow deficit divided by the threshold value for Seyhan and Kocher at 6-month time scale.

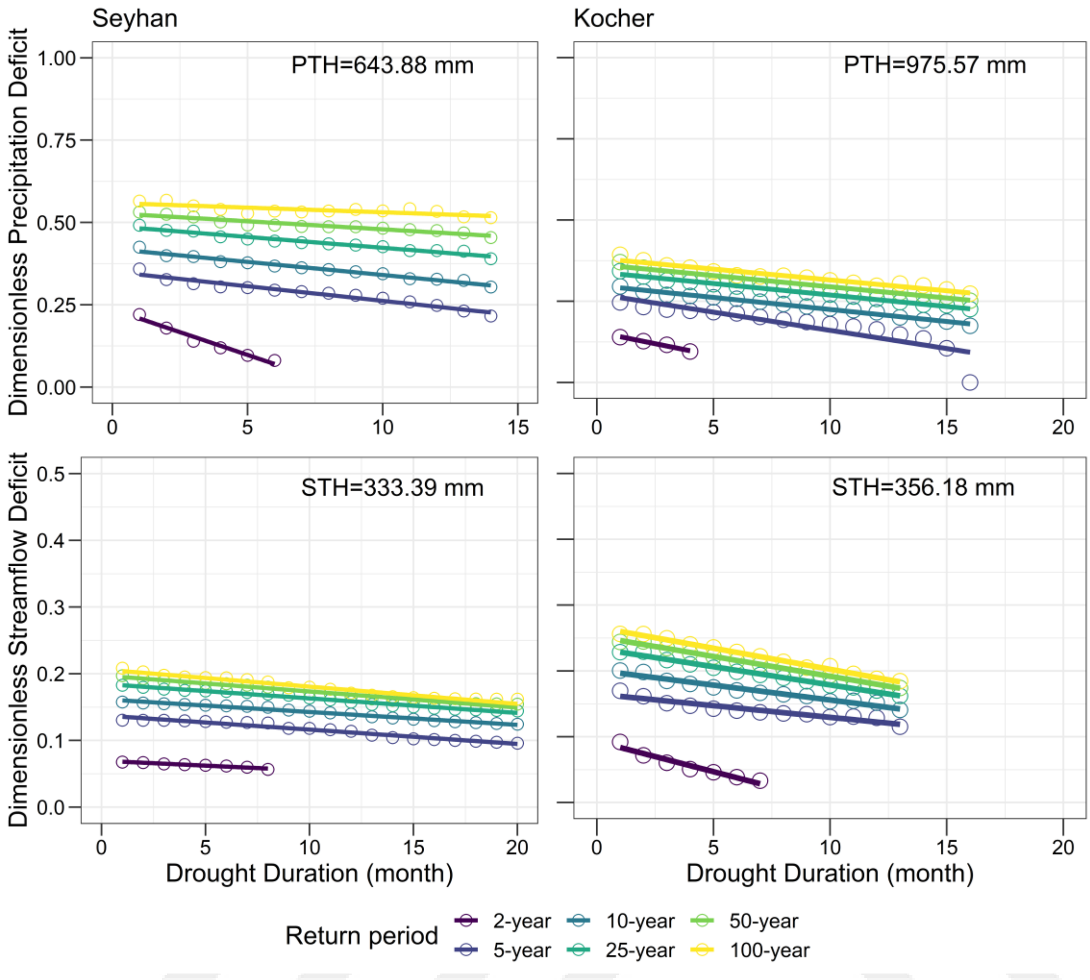

Figure A3. Drought-IDF curves in terms of precipitation and streamflow deficit divided by the threshold value for Seyhan and Kocher at 12-month time scale.

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