ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

CRITICAL DROUGHT SEVERITY-DURATION-FREQUENCY CURVES BASED ON PRECIPITATION DEFICIT

M.Sc. THESIS

Yonca ÇAVUŞ

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ISTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

YAĞIŞ AÇIĞI CİNSİNDEN KRİTİK KURAKLIK ŞİDDET-SÜRE-FREKANS EĞRİLERİ

YÜKSEK LİSANS TEZİ

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İnşaat Mühendisliği Anabilim Dalı

Hidrolik ve Su Kaynakları Mühendisliği Programı

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HAZİRAN 2019

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Date of Submission : 3 May 2019
Date of Defense : 11 June 2019

To my mother,

FOREWORD

This thesis was written during my Master of Science study at Istanbul Technical University. While I was studying on the thesis, I received help from a precious person who has deep traces on my life and whom I will never forget. I am in a place where words are insufficient, deficient and meaningless to express this sense. On account of this, I deeply thank to my advisor Prof. Dr. Hafzullah Aksoy for receiving me into his academic family and for guiding me. I took a role in a research project supported by Turkish National Union of Geodesy and Geophysics (TUJJB) at the start point of my academic life. I have been involved in a research project and received financial support from The Scientific and Technological Research Council of Turkey (TUBITAK) at the turning point in my academic life. This thesis was supported by Research Fund of Istanbul Technical University (ITU BAP), Project number 42141. I am thankful to all Organizations for the opportunities they provided. I am thankful to all members of my family but I should particularly mention that this thesis would not come out without the encouragement and love of my mother whom I am deeply thankful. Last but not least, I want to express my thanks to my cousin Şeyda Tan who loved me unconditionally.

May 2019

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ABBREVIATIONS

AI : Aridity Index
AMO : Atlantic Multidecadal Oscillation
AMS : Annual Maximum Series
CGCMa2 : Canadian Centre for Climate Modeling Analysis General Circulation Model
CMI : Crop Moisture Index
CZI : China Z Index
DAI : Drought Area Index
DI : Decile Index
DR : Deficit Rate
DrinC : Drought Indices Calculator
DSI : The General Directorate of State Hydraulic Works
DWS : Drought Water Scarcity
EDI : Effective Drought Index
EDO : European Drought Observatory
ENSO : El Nino-Southern Oscillation
ET_0 : Evapotranspiration
ETDI : Evapotranspiration Deficit Index
G2, G3 : Gamma2, Gamma3
GCMs : Global Climate Models
GEV : General Extreme Value
GWP : Global Water Partnership
IAHS : International Association of Hydrological Sciences
IC : Volume Criterion
IDF : Intensity-Duration-Frequency
IPO : Inter-decadal Pacific Oscillation
IPPC : Intergovernmental Panel on Climate Change
JDI : Joint Deficit Index
LN2, LN3 : Log-normal 2, Log-normal 3
LP3 : Log-Pearson Type 3

MA : Moving Average
MAM : Marmara Resarch Center
MDF : Magnitude-Duration-Frequency
MGM : State Meteorological Service of Turkey
NAO : North Atlantic Oscillation
NDMC : National Drought Mitigation Center
NDVI : Normalized Difference Vegetation Index
PD : Precipitation Deciles
PDO : Pacific Decadal Oscillation
PDS : Partial Duration Series
PDSI : Palmer Drought Severity Index
PET : Potential Evapotranspiration
PHDI : Palmer Hydrological Drought Severity Index
PNPI : Percentage of Normal Precipitation Index
RCP : Representative Concentration Pathway
RDI : Reconnaissance Drought Index
SDF : Severity-Duration-Frequency
SDI : Streamflow Drought Index
SGI : Standardised Groundwater Index
SMA : Soil Moisture Anomaly
SMDI : Soil Moisture Deficit Index
SOI : Southern Oscillation Index
SPA : Sequent Peak Algorithm
SPEI : Standardized Precipitation Evapotranspiration Index
SPERI : Standardized Precipitation Evapotranspiration Runoff Index
SRES : Special Report on Emissions Scenarios
SRI : Standardized Runoff Index
SPI : Standardized Precipitation Index
SPTI : Standardized Precipitation Temperature Index
SRSI : Standardized Reservoir Supply Index
SSFI : Standardized Streamflow Index
SST : Sea Surface Temperature
SWS : Soil Water Storage
SWSI : Surface Water Supply Index
TUBITAK : The Scientific and Technological research council of Turkey

UK : United Kingdom
UN : United Station
VCI : Vegetation Condition Index
W2, W3 : Weibull 2, Weibull 3
WASP : Weighted Anomaly Standardized Precipitation
WMO : World Meteorological Organization

SYMBOLS

AD : Anderson-Darling

AD_c : Critical Value

C_s : Coefficient of skewness

C_v : Coefficient of variation

D : Duration

D_{max} : The duration of drought with the largest length

I : Intensity

n : The time duration of a drought

k : Time scale

P_C : Critical precipitation

P_D : Precipitation deficit

P_{TH} : Threshold value

S : Severity

S_n : The water deficiency in a drought

SPI_k : SPI in k- time scale

r_1 : Lag-one autocorrelation coefficient

$x_{i, j}$: The precipitation (in mm) in the jth month (j = 1, 2, 3, ……, 12)

μ_j : The mean precipitation (in mm) in the jth month

σ_j : The standard deviation of precipitation in the jth month

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CRITICAL DROUGHT SEVERITY-DURATION-FREQUENCY CURVES BASED ON PRECIPITATION DEFICIT

SUMMARY

Drought is one of the most disastrous natural phenomena that causes scarcity and lack of water in hydrological basins such as the Seyhan River Basin in Turkey. The precipitation is the merely source of the natural water resources in the country which has a semi-arid climate with a dry and hot summer. It changes also depending on seasonality within the year. Because of the decrease in precipitation and increase in evapotranspiration, water resources have dropped remarkably and it is certain that the precipitation deficit is a more difficult problem to overcome. Accordingly, it is of significance to determine how much the precipitation deficit is in terms of water supply in this region.

The main purpose of this study is to define as the drought severity/intensity-duration-frequency curves based on precipitation deficit. In the study, drought analysis was performed by using the Standardized Precipitation Index (SPI) for 19 meteorological stations in the Seyhan River basin. In order to find SPI values of each station, the monthly precipitation data were used. An executable file developed by the National Drought Mitigation Center, University of Nebraska–Lincoln, USA was used to calculate the SPI_k (k = 1, 3, 6, 9, 12, 24 months) values. After the SPI_k values were obtained, dry and wet periods were determined from the SPI_k time series for each time scale.

Drought characteristics are determined from the SPI time series. Droughts are characterized by severity, duration and frequency. Also, time scale is important when SPI is used for the drought. Severity can be replaced by intensity, the average severity over the length of the dry period. Drought duration from D = 1 month (at minimum) up to the longest duration (48 months at maximum when exists) were considered. Severity values of SPI_k series were determined in dry periods.

For each year, one or higher number of droughts are likely to be observed. Drought with the highest severity in each year is defined as the critical drought of the year. When more than one drought is observed within a year, no matter how long the drought period in a year is, it is assigned as the critical drought of this particular year. When no drought is observed in a year, the critical drought severity is not calculated and a zero value is assigned to the critical drought severity of this particular year.

Frequency analysis was applied on the critical severity time series to determine the best-fit probability distribution function among followings commonly used in the literature: General Extreme Value (GEV), Log-normal 2 (LN2), Log-normal 3 (LN3), Gamma 2 (G2), Gamma 3 (G3), Log-Pearson type III (LP3), Weibull 2 (W2), Weibull 3 (W3). Since the critical severity values include zeros, the total probability theorem was applied after the frequency analysis. The best-fit probability distribution functions were determined and their parameters were calculated for each D-month drought of the SPI_k series. For the frequency analysis, critical severity series with at least 10 years

at length were considered; i.e., no frequency analysis was applied on a critical severity time series shorter than 10 years. The General Extreme Value (GEV) distribution was found as the best-fit distribution to the critical severities almost for all drought durations in the meteorological stations in Seyhan River basin considering SPI_k for time scales k = 1, 3, 6, 9, 12, 24 and 48 months. The goodness-of-fit of the probability distribution function was checked with the Anderson Darling statistical test. The critical drought severities corresponding to different return periods were calculated with the frequency analysis. As the drought duration increases, the critical drought severity increases for each of the k-time scales. Accordingly, the severity-duration-frequency curve was obtained. Also, the intensity values were calculated as the ratio of the drought severity to its duration.

On the other hand, the relationship between the precipitation and corresponding SPI values was examined with regression analysis. A logistic function was found suitable to use in the regression. The severity of the critical drought is the cumulative SPI over the k months. The severity of the D month-duration and T year-return period drought at k time scale was inserted as the independent variable into the logistic type regression equation to calculate the corresponding precipitation to be considered as the critical precipitation under which the D-month duration and T-year return period drought at k time scale is observed. SPI is taken zero (no drought) for the threshold level; i.e., if SPI is below zero, it is a dry period; if SPI is above zero, it is a wet period. The difference between the threshold level and the critical precipitation is defined as the precipitation deficit of D month-duration and T year-return period at k-time scale. Precipitation deficit was calculated for each month of the year in the case of SPI_1, SPI_3, SPI_6 and SPI_9 due to seasonality in the precipitation but it was calculated at annual scale for SPI_{12} and SPI_{24}. The precipitation deficits were calculated for each k time scale (SPI_1, SPI_3, SPI_6, SPI_9, SPI_{12} and SPI_{24}), D drought duration (from D = 1 month to the longest duration or up to 48 months at maximum) and T return period (2, 5, 10, 25, 50 and 100 years) and thus, the critical drought severity-duration-frequency (SDF) curves were obtained.

In addition, the curves of the average severity (intensity) of each month were obtained as the intensity-duration-frequency curves. It is seen that average precipitation deficit over drought periods decreases as the drought duration and the return periods increase. Furthermore, boundary values representing drought classes were inserted into the regression equation for each k time scale, D drought duration and T return period to determine the classes of drought (mild, moderate, severe or extreme).

At the end of the study, it is concluded that as the drought duration and return period increase, so does the precipitation deficit. This allows to calculate precipitation deficit for longer drought duration. The precipitation deficit values can be changed depending on seasonality and climate. At the 2-year return period, the SDF traces a curve well below and separated clearly from the curves at higher return periods from 5 to 100 years; it has, however the same character with the curves of other return periods. Also, almost no difference is seen between precipitation deficits of droughts with 25 year- or longer return periods. Besides, the intensity-duration-frequency curves based on the precipitation deficit are obtained and drought classes are identified. As k time scale increases average precipitation (intensity) deficit decreases. Another conclusion is that longer duration drought with high return periods (i.e., 50, 100 year-return periods) are generally expected not to belong extreme drought class. While in shorter drought durations and longer return periods are seen extreme droughts, in longer drought durations are observed mild drought at all the return periods. Drought intensity decreases in time approaches to mild drought. Also, together with the precipitation deficit and such newly introduced concepts as the critical drought severity, singular drought, the within-period drought, boundary precipitation and the methodology proposed to determine the precipitation deficit gains a novelty. With this approach, meteorological, agricultural and hydrological droughts can be foreseen before being faced with their destructive and irreversible effects. The methodology is simple and physically self-explanatory, it is therefore expected to be easily understood by end-users, water resources managers, and decision-makers. Thus, it provides the end-users information needed for taking medium- and long-term actions in the drought risk management, irrigation planning and water resources development strategies.

YAĞIŞ AÇIĞI CİNSİNDEN KRİTİK KURAKLIK ŞİDDET-SÜRE-FREKANS EĞRİLERİ

ÖZET

Kuraklık, hidrolojik havzalarda yağış eksikliği veya su kıtlığına sebep olan en büyük doğal afetlerden biridir. Yağış, kurak bir iklime sahip olan bir bölgede mevcut bulunan suyun tek kaynağıdır. Yağış ayrıca yıl içerisinde mevsimselliğe bağlı olarak değişebilir. Yağıştaki azalma buna karşın buharlaşmadaki artış mevcut su kaynaklarında önemli ölçüde azalmalara sebep olmakta ve yağış eksikliklerini üstesinden gelinmesi zor bir duruma getirmektedir. Kuraklık sırasında nüfusun içme ve kullanma suyu ihtiyacı ile tarım, hayvancılık, sanayi ve turizm faaliyetlerinin ve ekosistemin devamlılığı için gerekli olan yağış açığının bilinmesi, böylece ortaya çıkan yağış açığının kapatılarak bu faaliyetlerin devamlılığının sağlanması bakımından önemlidir.

Bu çalışmanın amacı kritik kuraklık şiddet-süre-frekans eğrilerinin yağış açığı cinsinden belirlenmesidir. Kuraklık analizi Standart Yağış İndeksi (SYİ) kullanılarak uygulanmıştır. Uygulama alanı olarak Seyhan havzası seçilmiş, havzada bulunan 19 meteorolojik yağış gözlem istasyonunun aylık yağış verileri kullanılmıştır. SYİ değerleri 1, 3, 6, 9, 12 ve 24 aylık zaman ölçeklerinde hesaplanmıştır. SYİ serileri elde edildikten sonra bu serilerden kurak ve ıslak periyotlar her bir zaman ölçeği için belirlenmiştir. 1- ve 3-aylık SYİ'ler meteorolojik kuraklığı, 6- ve 9- aylık SYİ'ler tarımsal kuraklığı, 12- ve 24-aylık SYİ'ler hidrolojik kuraklığı temsil etmek üzere değerlendirilmiştir.

Ancak karmaşıklığı nedeniyle sadece kurak ve ıslak periyodları belirlemek, kuraklığı tanımlamada tek başına yeterli değildir. Bu yüzden kuraklığın başka parametreler ile karakterize edilmesi büyük önem taşımaktadır. Bu parametreler kuraklığın şiddeti, süresi, frekansı ve büyüklüğüdür. Kuraklık yaşanan belli bir dönemde, kuraklığın ne sıklıkta görüldüğü (frekansı), ne kadar uzun devam ettiği (süresi) ve devam ettiği süre boyunca toplamda ve ortalama olarak ne kadar büyük olduğu (büyüklüğü ve şiddeti) gibi soruların yanıtlanması kuraklığın karakterizasyonu için gereklidir.

Her bir yıl içinde bir veya daha çok kurak dönem gözlenebilir. Herhangi bir yılda birden fazla kurak dönem gözlenmesi halinde gözlenen en büyük şiddetteki kuraklık kritik kuraklık olarak tanımlanmıştır. Bir yıl içerisinde sadece bir kurak dönem gözlenmesi halinde süresi ve şiddeti ne olursa olsun bu dönem o yılın kritik kuraklığı olarak alınır. Herhangi bir yılda hiç kurak dönem gözlenmemesi halinde ise kritik kuraklık değeri hesaplanmaz ve kuraklık şiddeti bu yıl için sıfır alınır. Çalışmada kuraklık süre ve şiddeti hesaplanırken aşağıda örnekle açıklanan yöntem izlenmiştir: Herhangi bir yılda yaşanan 5 ay süreli kurak bir dönemde, 5 adet 1 ay süreli kuraklık; 4 adet 2 ay süreli kuraklık; 3 adet 3 ay süreli kuraklık; 2 adet 4 ay süreli kuraklık ve 1 adet 5 ay süreli kuraklık olduğu düşünülmüştür. Bu yıla ait kritik kuraklık değerleri olarak, her bir süre için aralarında şiddet olarak en büyük olan kuraklık alınmıştır. Yani, 1 ay süreli kritik kuraklık olarak 5 adet 1-aylık; 2-aylık kritik kuraklık için 4 adet

2-aylık; 3-aylık kritik kuraklık için 3 adet 3-aylık ve 4-aylık kritik kuraklık için 2 adet 4-aylık kuraklık arasından en şiddetli olanı alınmıştır. Gözlenen 5 aylık kuraklık ise doğrudan bu yıla ait 5 aylık kritik kuraklık olarak değerlendirilmiştir. Bu örnek yılda daha uzun süreli bir kuraklık gözlenmemiştir.

Kritik kuraklık şiddeti değerlerine literatürde yaygınca kullanılan olasılık dağılım fonksiyonları seçilerek frekans analizi uygulanmış ve en uygun olasılık dağılım fonksiyonları belirlenmiştir. Bu amaçla kullanılan olasılık dağılımları şunlardır: Genel Ekstrem Değer (GEV), Log-normal 2 (LN2), Log-normal 3 (LN3), Gama 2 (G2), Gama 3 (G3), Log-Pearson Tip III (LP3), Weibull 2 (W2), Weibull 3 (W3). Kritik kuraklık şiddeti sıfır değerler de içerdiğinden frekans analizi sıfır olan ve sıfır olmayan değerler dikkate alınarak uygulanmıştır. Bunun için toplam olasılık yasası kullanılmış; sıfır olan değerleri de hesaba katacak şekilde frekans analizi yapılmıştır. Her bir k ölçeğinde D ay süreli kuraklıklar için en uygun olasılık dağılımları belirlenmiş ve parametreleri hesaplanmıştır. Frekans analizinin uygulanması için sıfır değerler hariç kritik kuraklık şiddetinin en az 10 değerden oluşması gereklidir. Yani en az 10 yıl için D-ay süreli bir kurak periyodun gözlenmiş olması koşulu aranmış, 10 yıldan daha az sayıda kritik kuraklık şiddet değerlerine frekans analizi uygulanmamıştır.

Uygulama alanı olarak Seyhan havzası seçilmiştir. Havza içinde Meteoroloji Genel Müdürlüğü (MGM) ve Devlet Su İşleri (DSİ) tarafından işletilen 19 yağış gözlem istasyonuna ait aylık toplam yağış verileri elde edilmiştir. Bu veriler üzerinde yapılan uygulama sonucunda k = 1, 3, 6, 9, 12 ve 24 ay zaman ölçeklerinde tüm D ay süreli kurak dönemlere ait kuraklık şiddetleri için en uygun olasılık dağılımı olarak genellikle GEV belirlenmiştir. Alternatif olarak LP3, LN3 ve G2 dağılımlarının da uygun olduğu söylenebilir. Belirlenen en uygun olasılık dağılım fonksiyonlarının performansı Anderson-Darling istatistik testi ile kontrol edilmiştir. Frekans analizi ile 2, 5, 10, 25, 50 ve 100 yıl dönüş aralıklarına karşılık gelen kritik kuraklık şiddet değerleri hesaplanmıştır.

Herbir k zaman ölçeği için kuraklık süresi arttıkça kritik kuraklık şiddetinin de arttığı görülmüştür. Kuraklık şiddet-süre-frekans değerleri kuraklık sürecinin bu fiziksel gerçeğini ortaya koyacak şekilde elde edilmiştir. Ayrıca, kuraklığın toplam şiddetinin süresine oranı kuraklığın ortalama şiddetini temsil etmektedir. Bunun sonucunda ortalama şiddet-süre-frekans değerleri hesaplanmıştır.

Öte yandan, SYİ değerleri ve bu değerlere karşılık gelen yağış değerleri arasında bir ilişki olduğu düşünülerek regresyon analizi kullanılmış, bu iki değişken arasındaki ilişki bir eğri uydurularak belirlenmiştir. SYİ ile karşı gelen yağış değerleri arasındaki grafik çizildiğinde, $SYİ_1$, $SYİ_3$, $SYİ_6$ ve $SYİ_9$ için her aya ait ayrı bir ilişkinin mevcut olduğu, buna karşın $SYİ_{12}$ ve $SYİ_{24}$ ölçeklerinde eğrinin kümelendiği ve tek bir doğru şeklini aldığı görülmüştür. Bunun sonucunda k = 1, 3, 6 ve 9 aylık zaman ölçekleri her ay için ayrı ayrı olmak üzere yağış açığı hesaplanırken 12 ve 24 aylık zaman ölçeklerinde yıllık ve tek değer olarak hesaplanmıştır. Uydurulan tüm eğriler içerisinden en uygun denklem Logistic regresyon denklemi ile elde edilmiştir. Kuraklık süresi arttıkça ve dönüş aralığı büyüdükçe yağış açığının giderek artması beklenmektedir. Bu fiziksel olguyu sağlayamayan 2. ve 3. mertebeden polinom denklemleri bu nedenle regresyon analizinde dikkate alınmamıştır. Ayrıca Temmuz veya Ağustos gibi yağışın hiç olmadığı (sıfır değer aldığı) yaz aylarındaki zaman serilerine eğri uydurulamadığından bazı regresyon denklemleri seçenekler arasından çıkarılmıştır. Sonuç olarak en uygun bulunan Logistic regresyon denklemi tüm zaman ölçeklerinde yağış açıklarını belirlemek için uygulanmıştır. Frekans analizi ile her bir k aylık zaman ölçeginde, D aylık kuraklık süresinde ve T yıllık dönüş aralığında belirlenen kritik kuraklık şiddet değerleri ilgili regresyon denkleminde bağımsız değişken olarak yerleştirilmiş, böylece k aylık zaman ölçeginde, D ay kuraklık süresinde ve T yıl dönüş aralığında olan kritik kuraklık şiddetine karşı gelen kritik yağış değeri hesaplanmıştır. Bu sınır yağış değeri, kritik kuraklıklarda görülen yağış değerleridir. Bu arada SYİ = 0 durumundaki yağış kuraklığın eşik değeri olarak kabul edilmiştir. SYİ > 0 ıslak dönem, SYİ < 0 kurak dönemi temsil etmektedir. Bu eşik değer ile sınır yağış değeri arasındaki fark yağış açığı olarak tanımlanmıştır. Yağış eksiklikleri her bir k = 1, 3, 6, 9, 12 ve 24 aylık ölçek, D = 1, 2, …, 48 aya kadar kuraklık süresi ve T = 2, 5, 10, 25, 50 ve 100 yıllık dönüş aralıkları için hesaplanmıştır. Sonuç olarak yağış açığı cinsinden kritik kuraklık şiddet-süre-frekans eğrileri elde edilmiştir.

Bunun yanısıra, yağış açığı cinsinden ortalama şiddet-süre-frekans eğrileri elde edilmiştir. Kuraklık süresi ve dönüş aralığı arttıkça, kuraklığın ortalama şiddetinin azaldığı görülmüştür. Öte yandan, kuraklığın sınıflandırılmasında kullanılan SYİ sınır değerleri (-0.5, -1, -1.5 ve -2) logistic regresyon denkleminde yerine yazılarak hafif, orta, şiddetli ve çok şiddetli kuraklığın sınırları yağış açığı cinsinden belirlenmiştir. Böylece, hesaplanan yağış açıklarının hangi kuraklık sınıfında olduğu kolaylıkla belirlenebilmektedir.

Bu çalışmanın sonucu olarak, kuraklık süresi ve dönüş aralığı arttıkça yağış açığının arttığı gözlenmiştir. Zaman ölçeği büyüdükçe daha uzun süreli kuraklıklar ortaya çıkmıştır. Başka bir deyişle, uzun süreli kuraklıklarda kalıcılık fazladır; başlayan kuraklığın uzun süre devam edeceği anlaşılmaktadır. Öte yandan, 2-yıllık yani belli bir dönüş aralığında şiddet-süre-frekans eğrilerinin açık bir şekilde daha uzun süreli dönüş aralıklarındaki eğrilerden ayrıldığı ancak aynı karaktere sahip olduğu görülmüştür. Ayrıca, 25 yıl ve daha uzun süreli dönüş aralıklarındaki yağış eksikliği değerleri arasında neredeyse hiç fark bulunmamıştır. Başka bir çıkarım, ortalama şiddet-süre-frekans eğrilerinde kuraklık süresi arttıkça, yani daha uzun süreli kuraklıklarda çok şiddetli kuraklıklar beklenmemektedir. Uzun süreli kuraklıklarda kuraklık sınıfı hafif kuraklığa doğru yönelmektedir. Buna karşın, kısa süreli kuraklıklarda dönüş aralığı büyüdükçe çok şiddetli kuraklıkların görülme olasılığı artmaktadır.

Bu çalışmada elde edilen kuraklık şiddet-süre-frekans eğrileri ile herhangi bir ayda gözlenen yağış miktarı kullanılarak yağış açığının belirlenmesi mümkündür. Yağış açığının bilinmesi ile içinde bulunulan ayda hangi ölçekte, hangi süreli ve hangi dönüş aralığındaki bir kuraklığın gözlendiği belirlenebilmekte; buna karşı gelen yağış açığı ve kuraklık sınıfı da ortaya konmaktadır. Bu bir yeni yaklaşımdır ve kuraklığın yıkıcı ve geri dönülmez etkileri gerçekleşmeden meteorolojik, tarımsal ve hidrolojik kuraklıkların öngörülmesini sağlamaktadır. Yağış açığının belirlenmesi, bölge bitki desenindeki tarımsal rekolteye zarar vermeden gerekli olan su miktarının belirlenerek sağlanması bakımından önem arz etmektedir. Bu yeni yaklaşım kolay anlaşılabilir ve bundan dolayı son kullanıcılar, karar vericiler ve su kaynakları planlamacıları tarafından kolaylıkla uygulanabilir niteliktedir. Yaklaşımın ayrıca, su kaynaklarını geliştirme stratejileri, sulama, kuraklık risk yönetimi, orta ya da uzun süreli kuraklık eylem planları için önemli bilgi sağlayacağı düşünülmektedir.

1. INTRODUCTION

1.1 Subject of The Study

Water is the source of life and the most precious natural resource that is vital to several sectors. It is important to know any water deficit in advance, when it is likely to occur, in the domestic use, agriculture, farming, industry, energy and tourism as well as ecosystem under drought conditions for the sustainability of these sectors. For the effective use and sustainability of water resources, it is important to meet the needs of living beings and the environment. Furthermore, the sustainability makes water resources always available in long dry periods for the needs of fast-growing population. Thus, in order to make water sustainable, the drought analysis should be performed and needs for water should be determined well in advance.

The subject of this study is to determine critical drought severity-duration-frequency curves based on precipitation deficit with the frequency analysis of drought severity calculated by the use of the Standardized Precipitation Index (SPI). The concept of the critical drought was first defined after which its parameters were determined. Frequency analysis was applied on the critical drought severities to develop the critical drought severity-duration-frequency curves. Drought classification was adopted based on the boundaries proposed in the SPI.

1.2 Purpose of The Study

Owing to the climate change, the frequency of drought events has increased. Therefore, it is required to study droughts to detect the severity, frequency, duration, and intensity of drought events. In any case a drought is foreseen, measures are taken in the form of applicable precautions. In order to analyse the drought condition, a drought index is needed and thus the Standardized Precipitation Index (SPI) was used. The purposes of the study are:

(i) to obtain SPI values by using monthly precipitation data from the Seyhan River basin in Southern Turkey

(ii) to determine critical drought severity and drought duration

(iii) to detect return periods of critical severity values by using frequency analysis

(iv) to create regression equation between precipitation and corresponding SPI

(v) to obtain critical drought severity-duration-frequency curves based on precipitation deficit

(vi) to determine drought class based on its intensity

1.3 Method of The Study

In this study, drought analysis was performed by using monthly precipitation data of meteorological stations operated by State Meteorological Service of Turkey (MGM with its Turkish acronym) and from the General Directorate of State Hydraulic Works (DSI with its acronym) in Seyhan River basin, Turkey. The standardized precipitation index (SPI) was chosen for the drought analysis. Dry and wet periods were first determined. Critical severities in dry periods were calculated and corresponding drought durations were counted. Frequency analysis was applied to the critical severity values. Furthermore, the relationship between SPI and the corresponding precipitation was determined by a regression equation which is established based on a logistic function to calculate precipitation in the critical drought. Precipitation at SPI = 0 (no drought) is considered as the precipitation threshold. Difference between the critical precipitation and the threshold value at SPI = 0 is referred to the precipitation deficit. Hereby, the critical drought severity-duration-frequency curves were obtained and the intensity values were then calculated.

1.4 Scheme of The Study

The rest of this study is organized as follows: Chapter 2 gives definitions and basic concepts of drought, drought classification, indicator and indices, hydrological, agricultural and meteorological drought indices, literature review to cover a wide range of studies and related issues, drought studies in Turkey and outcomes of the literature review. Chapter 3 describes the methodology which is basically composed of a general look at the method, the standardized precipitation index (SPI), definitions and basic concepts, frequency analysis, total probability theorem, the Anderson-Darling statistical test and the precipitation deficit. Chapter 4 introduces the study area, relevant studies and data, the monthly precipitation, recorded in meteorological stations in the Seyhan River basin. Chapter 5 explains all details how the methodology is applied on the data; provides results in tables and figures and makes a deep discussion under the sub-sections (i) steps of application, (ii) calculation of SPI_k and determination of wet and dry periods, (iii) identification of critical drought from SPI_k time series, (iv) frequency analysis of critical drought, (v) determination of drought severity/intensity-duration-frequency, (vi) regression between precipitation and SPI, (vii) precipitation threshold, (viii) calculation of precipitation deficit, (ix) critical drought severity-duration-frequency (SDF) curves based on precipitation deficit, (x) intensity-duration-frequency curves (IDF) and drought classes (xi) further case study. Chapter 6 provides conclusions and recommaditions drawn from the results. The study accommodates two appendices (Appendix A and Appendix B) to present results of the application of the methodology on 19 meteorological stations at the end.

2. DROUGHT ANALYSIS

2.1 Definitions and Basic Concepts

Drought is defined as the naturally occurring phenomenon that exists when precipitation has been significantly below normal recorded levels, causing serious hydrological imbalances that adversely affect land resource production (UN, 1994). Other than this general definition, drought can also be defined based on indicator used (precipitation, streamflow, soil moisture, groundwater, reservoir storage, etc.), threshold selected, time interval and areal coverage. The drought does not mean the same as the aridity which is the dry characteristics of the climate in a region. In a dry region, even at normal periods, there is always deficit of available water resources. As for the drought, it is an extreme process during which the amount of precipitation falls below the recorded normal level and it is independent of the climate in a region (Bayazıt and Önöz, 2008). In semi-arid regions, the impact of drought may be more important. As the avaliable water is already limited, drought becomes economically more harmful in such regions.

Precipitation on a region and streamflow in a river are random variables which take different values in time. In some years, precipitation is above its average value whereas it might remain below in some other years. The same situation is valid also for seasonal or monthly precipitation. This affects the humidity in the river basin as well as the amount of water which can be obtained from the river. Therefore, the analysis of drought periods in the precipitation and streamflow time series is important in terms of hydrological practice. Precipitation and streamflow show similar trends since the source of the streamflow in the river is the precipitation itself falling on the river basin. However, evapotranspiration and accumulation in the groundwater might cause differences in the harmony between the precipitation and streamflow depending on how wet and dry the period is.

2.2 Drought Classification

Drought is classified by its type as follows: meteorological, agricultural, and hydrological; all with socioeconomic and environmental impacts (Wilhite, 2000). Figure 2.1 explains the relationship between these various types of drought and the propagation of the drought (Appurv et al., 2017) from meteorological drought to hydrological drought.

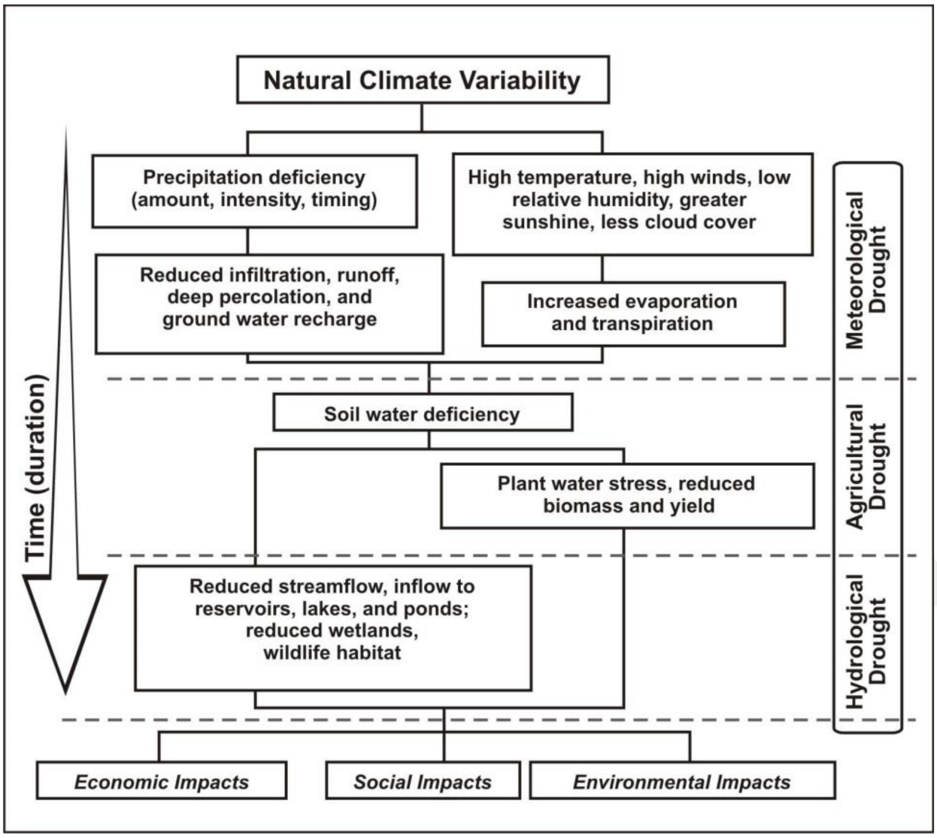

Figure 2.1: Drought classification and its propagation over time (Wilhite, 2000).

The definition of drought can be made according to the purpose of the analysis. Yevjevich (1967) describes the drought as follows:

1) The meteorologists view the drought depending on the amount of water vapor in the atmosphere.
2) Agricultural engineers define the drought according to the water need of the plants; i.e., it defines the moisture content of the soil. Thus, drought depends on the season, plant species and soil moisture.
3) The engineers view drought as a set of variables affecting rainfall, runoff and water storage in its many forms. When the available water is less than the amount of water needed, drought is observed.

4) The hydrogeologists define the drought according to the decrease in the groundwater level and flow.
5) Economists describe drought based on its effect on society.

Meteorological drought is defined in terms of the magnitude and duration of precipitation deficit (often in comparison to some normal or average value). Therefore, magnitude and duration are the key characteristics of all types of droughts, which must be considered as region-specific since the atmospheric conditions that cause deficiencies in precipitation depend on the climate regime. For example, some definitions determine meteorological drought on the basis of days with precipitation less than some specified threshold rather than the magnitude of the deficiency over some period of time (Wilhite, 2000). Meteorological drought starts when precipitation falls below normal level and may lead to hydrological drought which affects environmental functions in a region such as ecological, climatological, hydrological, socioeconomic and cultural aspects (Van Loon and Laaha, 2015; Heudorfer and Stahl, 2016; Crausbay et al., 2017; Ahmadi, 2019).

Agricultural drought can be defined as the lack of soil moisture to grow and develop in the root zone of the plant. It occurs when the water needed by a specific plant is not enough in the soil moisture during the growing period. Agricultural drought is typically emerging before the hydrological drought but after the meteorological drought. Agricultural drought reduces the fertility of crops significantly, even if the soil is saturated. High temperature, low relative humidity and desiccant winds cause folding of the impacts of precipitation deficit (MGM, 2019).

Hydrological drought is expressed as the decrease and deficiency in the surface water and groundwater emerging from eventually the precipitation deficit lasting for long term. This event can be followed via river flow, lake, reservoir, groundwater level measurement. Hydrometeorological measurements alone do not indicate drought because of time lag between precipitation deficit and water deficit in river, lake, reservoir, etc. Hydrological drought might exist even after the end of the meteorological drought (MGM, 2019). Also, the frequency and severity of hydrological drought are often defined at the river basin scale (Wilhite, 2000).

Socioeconomic drought is associated with the supply and demand of some economic good or service with elements of meteorological, hydrological, and agricultural drought. Some scientists suggest that the time and space processes of supply and demand are the two basic processes that should be included in an objective definition of drought (Yevjevich, 1967).

Drought generally takes three or more months to develop. The length of drought development period can vary considerably as it depends on the length of time period with deficit in precipitation. For example, a significant dry period during the winter season may have few, if any, impacts for many locations. Nevertheless, if this deficiency continues into the growing season, the impacts may magnify quickly since low precipitation during the autumn and winter season results in low soil moisture recharge rates, leading to deficient soil moisture at spring planting (Wilhite, 2000). As another example, in the period which plants need water, water deficit causes the drought in terms of agriculture. However, the same period of time may not be considered a dry period in terms of hydrology if a reservoir supplying city water is full. On account of this difference between the types of droughts, it is difficult to determine the beginning and end of drought periods.

2.3 Indicators and Indices

In order to determine drought, certain indices have been developed. They are calculated from hydrometeorological or climatological variables (e.g. indicators) such as precipitation, temperature, groundwater and surface water levels, soil moisture, vegetation, snow moisture, etc. After determining the indicator (such as streamflow) to describe the drought, the areal extend, threshold value of the indicator and time interval (month, season, year) are decided. Dry periods may differ depending on the indicator selected. Indicators can be also defined as variables to represent the deficit depending on the type of drought; meteorological, hydrological, agricultural and socio-economical drought. An index on the other hand is a *plus precious* information derivation method by comparing current conditions with the past information based on statistical calculations (Gürler, 2017).

2.4 Literature Review

Drought is a stochastic natural event which emerges from remarkable deficiency in precipitation. It has an impact on large number of sectors since water is the source of life. The fact that lack of water affects different sectors, makes it harder to point one certain definition. Owing to the increase in water demand, drought hydrology has been receiving much attention. As a result, extensive research studies were performed on drought and numerous review paper were published (Heim, 2002; Mishra and Singh, 2010; 2011; Zargar et al., 2011; Eslamian et al., 2017). A review paper on drought characterization from a multivariate perspective and the development of different methods for multivariate drought indices were also published (Hao and Singh, 2015).

2.4.1 Literature on drought definition

The description of drought itself is complicated and a certain definition does not exist because of differences in hydrometeorological variables, the stochastic nature of water demands in different regions around the world (Mishra and Singh, 2010) and the specific climate of the region. Gumbel (1963) defined the drought as the minimum value of the daily mean discharge of a river in a year; therefore, every year there exists one drought. Palmer (1965) described a strictly meteorological phenomenon depending on anomalies characterized by a prolonged and abnormal moisture deficiency. According to Yevjevich (1967), definition of the drought could be different due to the wide diversity in the drought studies. The UN Convention to Combat Drought and Desertification (UN, 1994) states that *drought means the naturally occurring phenomen that exists when precipitation has been significantly below normal recorded levels, causing serious hydrological imbalances that adversely affect land resource production systems*. The World Meteorological Organization (WMO, 2006) defines the drought as *an insidious natural hazard characterized by lower than expected or lower than normal precipitation that, when extended over a season or longer period of time, is insufficient to meet the demands of human activities and the environment*. Wilhite and Glantz (1987) pays a particular attention to distinguish between the conceptual and operational definitions for the drought. The conceptual definition refers to definitions formulated in general terms to identify the boundaries of the drought concept while operational definitions attempt to identify the onset, severity, and termination of drought episodes. Operational definitions are also related to drought frequency, severity, and duration for a given historical period (Wilhite and Glantz, 1987). Tsakiris and Vangelis (2004) refers to a severe decrease of water amount or substantial precipitation deficit (Zargar et al., 2011) within an important period of time and over a large region. Of course, the interpretation to be given to each of the defining terms such as 'severe reduction', 'significant period', and 'large region', introduces a strong subjectivity in the definition of drought (Rossi et al., 1992). On the other hand, drought occurs when a significant water deficit that spreads both in time and space takes place (Correia et al., 1994). The water deficit can be changed from case to case and from region to region. Perhaps the most general description is that in the specific period and region, drought is a reduction of water availablity (Beran and Rodier, 1985).

2.4.2 Literature on drought identification and drought analysis

One of the common methods for the drought analysis is the run theory, which was first proposed by Yevjevich (1967). The application of the run theory on a hydrological time series is the main tool for the point-scale (station-based) drought analysis (Sen, 1976; Dracup et al., 1980; Bayazit and Oguz, 1984; Loaiciga and Leipnik, 1996). Once a threshold value (x_0 in Figure 2.2) is chosen as a given percentage of the mean value or a quantile of given probability, surplus runs and deficit runs can be defined and their statistical properties such as duration, severity and intensity can be determined. The number of consecutive time intervals where the hydrological variable has lower values than x_0 is the length of deficit run and it indicates the drought duration (n in Fig. 2.2). The sum of deviations between the x_0 and the variable values along the deficit run represents the deficit (S_n in Fig. 2.2). If the deficit is divided by the duration, the deficit intensity of drought is obtained. The analysis of the runs determined from the precipitation time series allows one to evaluate the probability distribution of duration, deficit sum and deficit intensity (Guerrero-Salazar and Yevjevich, 1975). In order to characterize the drought, various statistical parameters associated with drought duration, magnitude, severity and intensity at different threshold levels are very useful. A drought occurrence has the following major components (Dracup et al., 1980):

(a) Duration: It is expressed that the drought parameter is continuously below the critical level or the time period between the inception and end of a drought.
(b) Magnitude: The cumulative precipitation deficit.
(c) Intensity: The rate of magnitude to its duration or the average value of a drought parameter below the threshold value.
(d) Severity: The degree of precipitation deficit; in other words, the magnitude.
(e) Frequency (return period): It is described as the mean time interval between two consecutive droughts with a given magnitude.

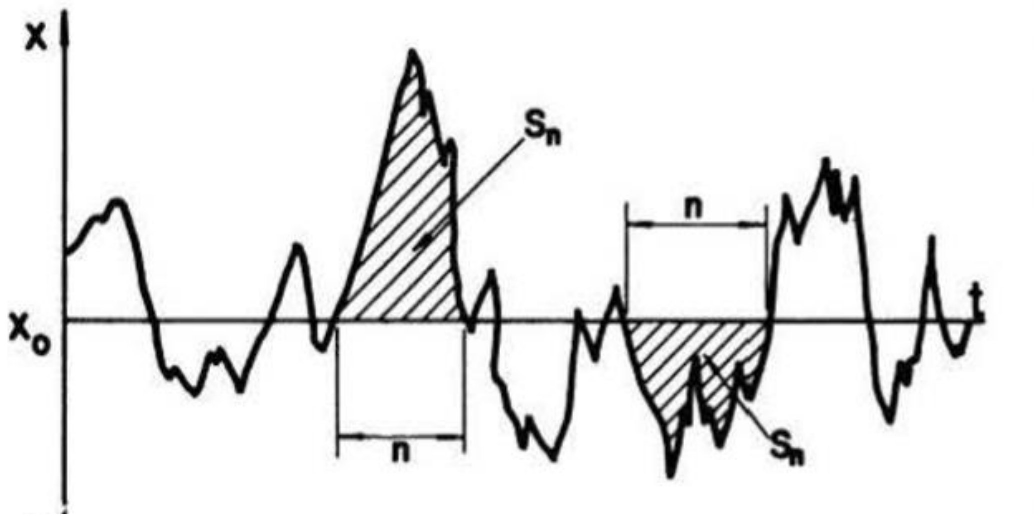

Figure 2.2: The run-length as the time duration of a drought (n), the run-sum as the water deficiency in a drought (S_n), and x_0 the threshold value (Yevjevich, 1967).

2.4.3 Literature on drought indices

Monitoring and predicting drought are real challenges since droughts are becoming more common and severe due to the impacts of climate change and variability (Alexander et al., 2009; Easterling et al., 2000). Therefore, a complicated natural drought is best characterized by using meteorological and hydrological variables. Such variables or indicators are used to derive a drought index (or indices). A great number of drought indices have been developed in recent decades. A drought indice comes to mind, first, to evaluate the impact of drought and drought parameters which include severity, duration, intensity and magnitude (Mishra and Singh, 2010).

The drought indices, among many, include (Tables 2.1-2.3) Palmer drought severity index (PDSI; Palmer, 1965); deciles (DI; Gibbs and Maher, 1967); crop moisture index (CMI; Palmer, 1968), surface water supply index (SWSI; Shafer and Dezman, 1982), standardized precipitation index (SPI; McKee et al., 1993), normalized difference vegetation index (NDVI; Kogan, 1995), vegetation condition index (VCI; Liu and Kogan, 1996), effective drought index (EDI; Byun and Wilhite, 1999), reconnaissance drought index (RDI; Tsakiris and Vangelis, 2005), soil moisture deficit index (SMDI) and evapotranspiration deficit index (ETDI) (Narasimhan and Srinivasan, 2005), standardized runoff index (SRI; Shukla and Wood, 2008), streamflow drought index (SDI; Nalbantis and Tsakiris 2009), standardized precipitation evapotranspiration index (SPEI; Vicente-Serrano et al., 2010), standardized groundwater index (SGI; Bloomfield and Marchant, 2013). Particular examples among the drought indices in Tables 2.1-2.3 are given. The 'ease of use' classification of the indices is based on the 'traffic-light' approach in which green, yellow and red colors show that the index is easy, moderate and hard, respectively, in terms of their use. Indices usually have a straightforward use due to their simplicity; those given especially for agricultural drought are however not that simple. For example, evapotranspiration deficit index (ETDI) has a complex calculation procedure because of multiple inputs required; soil moisture deficit index (SMDI) is complicated due to weekly calculations at different soil depths; soil water storage (SWS) is a difficult index to calculate owing to variations in both soil and crop types (Table 2.2) (WMO and GWP, 2016). Therefore, the agricultural drought indices are limited owing to the large quantities of inputs required. The indices can be used for short- as well as medium- and long-term projections. When particular examples among the drought indices in Tables 2.1-2.3 are analysed, it is seen that the fundamental concept behind most of the indices is linked to the concept of SPI. For instance; Nalbantis and Tsakiris (2009) proposed the streamflow drought index (SDI) for characterizing the severity of hydrological droughts based on the analogy to the SPI. Instead of precipitation data in SPI, streamflow data are used in SDI for overlapping periods of 3, 6, 9 and 12 months within each hydrological year. Drought events are defined in the form of a non-stationary Markov chain. Khallili et al. (2011) used the SPI and RDI (Reconnaissance drought index), both being meteorological drought index and applied in different climatological zones. SPI is based on precipitation only while the RDI utilizes the ratio of precipitation (P) over potential evapotranspiration (ET_0). Drought characteristics of the 3, 6, and 12 month-SPI and RDI times series were developed to examine Markov chain in using for the drought analysis. Both indices have shown similar behaviour; both followed the first order Markov chain dependency although climatological variability might have created some minor differences. Khattak et al. (2019) investigated the characteristics of the hydrological drought by using streamflow data of major rivers of the Indus River basin, in Pakistan. The severities of drought were determined by streamflow drought index (SDI). A drought starting from 1999 to end in 2002 was observed for all stations which is considered to be the worst drought in the history of Pakistan. As a result, it was determined that all stations experienced a drought from the moderate to severe in terms of severity in the common periods starting in 1998 and terminating in 2002.

Table 2.1 Indices for meteorological drought analysis (WMO and GWP, 2016).

	Index	Ease of use	Input	Remarks
METEOROLOGICAL DROUGHT INDEX	Standardized Precipitation Index (SPI) (1-3 Month)	Green	Precipitation	Highlighted by the World Meteorological Organization as a starting point for meteorological drought monitoring
	Decile Index (DI)	Green	Precipitation	Easy to calculate
	Percentage of Normal Precipitation Index (PNPI)	Green	Precipitation	Simple calculations
	Weighted Anomaly Standardized Precipitation (WASP)	Green	Precipitation, Temperature	Uses gridded data for monitoring drought in tropical regions
	Palmer drought severity index (PDSI)	Yellow	Precipitation, Temperature, Available water content	Not green due to complexity of calculations and the need for serially complete data
	Palmer-Z index	Yellow	Precipitation, Temperature, Available water content	One of the many outputs of PDSI calculations
	Standardized Precipitation Evapotranspiration Index (SPEI)	Yellow	Precipitation, Temperature	Serially complete data required; output similar to SPI but with a temperature component
	Effective Drought Index (EDI)	Yellow	Precipitation	Program available through direct contact with originator
	Aridity Index (AI)	Yellow	Precipitation, Temperature	Can also be used in climate classifications
	China Z Index (CZI)	Yellow	Precipitation	Intended to improve upon SPI data
	Crop Moisture Index (CMI)	Yellow	Precipitation, Temperature	Weekly values are required
	Aridity Index (AI)	Yellow	Precipitation, Temperature	Can also be used in climate classifications
	Drought Area Index (DAI)	Yellow	Precipitation	Gives an indication of monsoon season performance

Table 2.2 Indices for agricultural drought analysis (WMO and GWP, 2016).

	Index	Ease of use	Input	Remarks
AGRICULTURAL DROUGHT INDEX	Standardized Precipitation Index (SPI) (6-9 Month)	Green	Precipitation	Highlighted by the World Meteorological Organization as a starting point for agricultural
	Soil Moisture Anomaly (SMA)	Yellow	Precipitation, Temperature, Available water content	Intended to improve upon the water balance of PDSI
	Evapotranspiration Deficit Index (ETDI)	Red	Modelled	Complex calculations with multiple inputs required
	Soil Moisture Deficit Index (SMDI)	Red	Modelled	Weekly calculations at different soil depths; complicated to calculate
	Soil Water Storage (SWS)	Red	Available water content, Reservoir, Soil type, Soil water deficit	Owing to variations in both soil and crop types, interpolation over large areas is challenging Hydrology

Wambua et al. (2018) detected the spatial, temporal and trend of meteorological drought using standardized precipitation index (SPI) and effective drought index (EDI) in the Upper Tana river basin, Kenya. The change in drought occurrences was determined using the Mann-Kendall trend test which is a non-parametric test and results show that the trend in the drought increases in the south-eastern parts of the basin. Also, drought severities were calculated and mapped using the Kriging method for some selected years. Sanginabadi et al. (2019) proposed a new index, drought water scarcity (DWS) index, in such a way that couples the existing groundwater drought and water scarcity indices (namely; SGI, the standardized groundwater index and DR, the deficit rate). Moreover, the MODFLOW groundwater simulation tool and an artificial neural network model were used to detect the time series of the naturalized groundwater level between the period 1966-2016 in Central Iran. It is seen that a severe negative trend exists in the groundwater level in comparison with natural causes. Moreover, DrinC (Drought Indices Calculator) is a software package which was developed by Tigkas et al. (2015) for the calculation of drought indices which are the Reconnaissance Drought Index (RDI), the Streamflow Drought Index (SDI), the Standardized Precipitation Index (SPI), and the Precipitation Deciles (PD).

Table 2.3 Indices for hydrological drought analysis (WMO and GWP, 2016).

	Index	Ease of use	Input	Remarks
HYDROLOGICAL DROUGHT INDEX	Standardized Precipitation Index (SPI) (12-24 Month)	Green	Precipitation	Highlighted by the World Meteorological Organization as a starting point for hydrological
	Palmer Hydrological Drought Severity Index (PHDI)	Yellow	Available water content, Reservoir, Soil type, Soil water deficit	Serially complete data required
	Effective Drought Index (EDI)	Yellow	Precipitation	Program available through direct contact with originator
	Standardized Reservoir Supply Index (SRSI)	Yellow	Reservoir	Similar calculations to SPI using reservoir data
	Standardized Streamflow Index (SSFI)	Yellow	Streamflow	Uses the SPI program along with streamflow data
	Standardized Water-level Index (SWI)	Yellow	Groundwater	Similar calculations to SPI, but using groundwater or well-level data instead of precipitation
	Streamflow Drought Index (SDI)	Yellow	Streamflow	Similar calculations to SPI, but using streamflow data instead of precipitation
	Surface Water Supply Index (SWSI)	Yellow	Precipitation, Reservoir, Streamflow, Snowpack	Many methodologies and derivative products are available, but comparisons between basins are subject to the method chosen

The software includes a module for the prediction of potential evapotranspiration (PET). The software can also be used in a variety of applications such as drought monitoring, investigation of climatological and drought events and assessment of the distribution of drought. Wang et al. (2019) proposed a drought index, the standardized precipitation evapotranspiration runoff index (SPERI) for which methods such as Penman-Monteith and copula were used. It is applied to Yunnan Province of China with the SPI and SPEI. As a result, the SPERI was found correlated with the SPI and SPEI and it can reflect all drought conditions. Moreire et al. (2006) used a loglinear modelling approach to investigate differences in drought class transitions. Thus, a total period of 67 years of SPI data sets were divided into three periods for which the drought class transitions were calculated in the form of a 3-dimensional contingency table. The loglinear modelling of these data was compared for the three periods in order to detect a possible trend which could be related to climate change. Results show that while the first and last periods are similar in terms of the drought behavior, the second was found different from others. In addition, it was concluded that this hypothesis should be tested using longer time series to determine more meaningful results. Moreire et al. (2008) was again used the loglinear modelling for 3-dimensional contingency tables to fit to drought class transitions based on the SPI time series calculated at 12month-time scale. Ratios and confidence intervals were calculated to understand the drought evolution and to predict the drought class transition probabilities. As a result, the loglinear prediction of drought class transitions is found a useful tool in short term drought warning. Mallya et al. (2015) proposed a new method on probabilistic drought classification adapted from the SPI methodology of drought classification by employing a gamma mixture model. The method was applied over India by using rainfall data. Results show that the SPI has significant differences when assumptions on the data distribution are violated. Gocic and Trajkovic (2014) evaluated spatiotemporal characteristics of drought based on monthly precipitation data in Serbia to illustrate the driest years by the percent of normal precipitation, and to capture the drought patterns by the SPI and the S-mode principal component analysis. It is concluded that 70% of the frequency of drought belongs approximately to the near normal drought category. In literature, several techniques such as the loglinear models, odds ratios and multiple confidence intervals were employed to estimate the time at which any changes in drought patterns occur. Duggins et al. (2010) suggested an alternative method for the detection of a change point in SPI data, especially in the transition matrix from one drought class to another. Results validated the method through simulation. Mirabbasi et al. (2013) evaluated drought conditions in northwest of Iran by means of Joint Deficit Index (JDI) which is based on monthly precipitation data. The JDI provided a comprehensive assessment of drought. Furthermore, the method demonstrated a good performance to determine the exceedance probability of precipitation required to reach normal conditions in future months. The method indicated also a good skill in predicting the evolution of drought conditions.

2.4.4 Comparison of drought indices

In order to find the most appropriate indices in certain drought occurences, several attempts have been made to compare them among each other. There has been a lot of comparison studies for the indices. As an example; based on case studies from Pakistan, Adnan et al. (2017) compared 15 drought indices including standardized precipitation index (SPI), standardized precipitation temperature index (SPTI), standardized precipitation evapotranspiration index (SPEI), China Z-Index, deciles index, modified CZI, Z-Score, rainfall variability index, standardized soil moisture anomaly index, weighted anomaly standardized precipitation index, percent of normal precipitation index, self-calibrated Palmer drought severity index, composite index, percentage area weighted departure and reconnaissance drought index (RDI). Different statistical tests were applied on the data of 58 meteorological stations for the period 1951-2014. As a result, SPI, SPEI and RDI were determined as the most appropriate indices to monitor drought.

In comparison to the PDSI, the SPI is relatively simple and versatile, flexible for observing different time scales and does not have many of the limitations associated with the PDSI (Hayes et al., 1996). The SPI demonstrates that it is a quite useful tool for detecting and monitoring the drought in the southern plains and southwestern United States in 1996. Hayes et al. (1996) demonstrated that the SPI detected the onset and severity of the drought at least 1 month in advance of the PDSI. Also, Hayes et al. (2000) shows a clear quantitative assessment of the three main drought parameters; intensity, duration and spatial extent. Furthermore, Guttman (1998) compares drought indices in USA which include data for 1035 sites. Similarly, SPI was recommended because of its simplicity, spatially consistency, and decision analysis.

Khanmohammadi et al. (2018) determined the spatial-temporal variation of dry and wet periods by comparing standardized precipitation index (SPI) and reconnaissance drought index (RDI) based on the most appropriate probability distribution function in Iran. The meteorological data of 30 synoptic stations for the period of 1960-2014 were used. The trend was analyzed using the modified Mann–Kendall test. Results demonstrated that the behavior of the two indices was roughly the same and the difference between them was not significant. Also, the results of the trend analysis showed that the variation of dry and wet periods decreased for both indices. Using 14 well-known meteorological, hydrological and agricultural drought indices, Keyantash and Dracup (2002) showed that SPI and Deciles were the two most valuable estimators of drought severity while PDSI ranked the least (Table 2.4) based on six-evaluation criteria which are tractability (to represent the practical aspects of the drought index), transparency (to consider the clarity of the objective and rationale behind the drought index), sophistication, extendabilitiy, dimensionality, robustness (to imply usefulness over a wide range of physical conditions). Pros and cons of the most drought indices are extensively given in a number of review studies by Heim (2002), Mishra and Singh (2010; 2011), Zargar et al. (2011), Eslamian et al. (2017).

2.4.5 Probabilistic characterization of droughts

Drought shows typically probabilistic characteristics (Dracup et al., 1980; Rossi et al., 1992; Loaiciga and Leipnik, 1996; Mishra and Singh, 2011). Basic parameters are the severity, duration, intensity, frequency and interarrival time, calculated using the run theory (Mishra and Singh, 2011). Frequency analysis is one of the most common and earliest applications of the statistical science in hydrology; therefore, the frequency analysis of droughts is significant especially in drought-prone regions. However, the sole frequency of the events become insufficient for drought studies unless it is numerically related to other factors such as the severity, duration and intensity (Rahmat et al., 2015). An important tool in drought studies is the severity-duration-frequency (SDF) curve that accommodates the interrelation between the severity, duration and frequency of drought occurrence from which drought with a certain severity and return period can be determined (Dalezios et al., 2001; Rahmat et al., 2015). Several studies discussed that the severity and frequency of droughts increased in many parts of the world as a consequence of the changes in precipitation and streamflow depending on climate change (Karamouz et al., 2012; Ahmadalipour et al., 2017a, b; Ahmadi et al., 2019). Dalezios (2001) developed the severity-duration-frequency (SDF) curves by using the Palmer Drought Severity Index (PDSI), and applied it to prepare the drought iso-severity maps of various return periods over Greece. In addition to the drought severity-duration-frequency (SDF) curves, alternatively, the magnitude-duration-frequency (MDF) curves are of significant importance in drought analysis.

Table 2.4: Comparison of drought indices (Keyantash and Dracup, 2002).

Index	Weighted total	Raw scores (I-5)					
		Robust-ness	Tracta-bility	Transpa-rency	Sophisti-cation	Expenda-bility	Dimensi-onality
Meteorological drought							
Rainfall deciles	116	5	3	4	3	5	4
SPI	115	5	2	3	5	5	4
Cumulative Precipitation anomaly	97	3	4	4	2	3	5
RAI	94	3	4	4	2	4	2
DAI	70	2	3	2	3	3	1
PDSI	61	2	1	1	4	4	1
Hydrological drought							
Total water deficit	102	3	4	5	2	3	5
Cumulative streamflow anomaly	89	2	4	4	2	3	5
SWSI	75	4	1	2	3	2	3
PHDI	58	2	1	1	4	3	1
Agricultural drought							
Computed soil moisture	102	4	1	5	4	3	5
Soil moisture anomaly index	83	4	2	3	3	3	4
Z index	77	3	2	2	4	3	1
CMI	55	3	1	1	4	2	1

Therefore, the severity, magnitude and duration of drought periods at monthly or longer time intervals were determined using the dimensionless Z-score and the run theory. Severity-duration-frequency (SDF) curves were obtained by Saghafian et al. (2003) who examined droughts in Iran by using the run theory and derived the SDF curves and iso-severity maps of the region. The station-based SDF curves were plotted and regional drought maps were derived for a range of drought duration and frequency. Also, drought periods in the region were studied by Markov chain analysis combined with the run theory. Finally, it was concluded that the most-severe drought duration decreased from south to north, in the historical Zabol area in Iran.

In the literature, there have been limitless studies on the drought characterization (Dalezios et al., 2001; Tsakiris and Vangelis, 2005; Nalbantis and Tsakiris, 2009; Eriş and Aksoy, 2008; Vicente-Serrano et al., 2010; Santos et al., 2011; Tigkas et al., 2015; Yan et al., 2018). Aksoy et al. (2018a, b) and Çetin et al. (2018) derived precipitation deficits from drought SDF curves for the drought characterization in different hydrological basins in Turkey by using frequency analysis. Van Loon and Laaha (2015) explained hydrological drought severity by climate and catchment characteristics. Drought analysis was applied with the variable threshold level method and various statistical tools such as bivariate correlation analysis, heatmaps, linear models based on multiple regression, varying slope models and automatic stepwise regression. It is concluded that the drought duration and deficit are governed by a combination of climate and catchment control, but not in a similar way.

Hydrological drought severity is highly dependent on terrestrial hydrological processes (Van Loon and Laaha, 2015). Kwak et al. (2014) examined hydrological drought by using the joint drought probability distribution derived from the copula theory and analyzed the drought return periods at the upstream of Namhan River in the upper Han River basin, Korea where the most severe drought of 110 year-return period was observed in 1981-1982. Caloire et al. (2018) analyzed drought to calculate different return period-droughts by using the standardized precipitation index (SPI) in the northern hemisphere to include the European continent, Ireland, UK and Mediterranean basins. Tallaksen et al. (1997) used the threshold level approach to define drought duration and deficit volume from time series of daily streamflow. The extreme values of drought duration and deficit volume were analysed by both a partial duration series (PDS) and an annual maximum series (AMS) approach. Also, a comparison is made by three different performance criteria; inter-event time and volume criterion (IC), moving average (MA), the sequent peak algorithm (SPA). The case study was performed on two Danish catchments with very different flow regimes. The results found the PDS model superior despite minor errors due to its simplicity.

2.4.6 Drought under climate change scenarios

The change in the global surface temperature for the end of the 21st century is likely to exceed 1.5°C relative to the period from 1850 to 1900 for all RCP (Representative Concentration Pathway) scenarios. Warming will continue to exhibit interannual-to-decadal variability and will not be regionally uniform (IPCC, 2013). Also, global surface temperature will continue to rise unless greenhouse gas emissions are drastically reduced (IPCC, 2007). In order to determine the effects of the climate change, numerous climate indices have been developed such as the El Nino-Southern

Oscillation (ENSO), which is numerically defined by the Southern Oscillation Index (SOI), Sea Surface Temperature (SST), North Atlantic Oscillation (NAO), Pacific Decadal Oscillation (PDO), Inter-decadal Pacific Oscillation (IPO) and Atlantic Multidecadal Oscillation (AMO).

With the global climate change, drought has recently become more frequent and intense, causing global and local water problems in the world (IPCC, 2007; Ryan 2011; Çankal, 2016). The climate change affects differently for each region in terms of the intensity and duration of drought as well as its areal extent. Climate change has been affecting the hydrology of a region through changes in precipitation, evaporation, soil moisture as well as the drought characteristics. Few studies on climate change impacts of drought have used meteorological drought indices, which require considerably fewer input data when compared to weather, soil and land use information needed by agricultural or hydrological drought indices (Kothavala, 1999; Loukas et al., 2007; Blenkinsop and Fowler, 2007; Mavromatis, 2007). In order to understand the impact of climate change, Global Climate Models (GCMs) are used generally. Loukas et al. (2007) investigated the possible effects of climate change on droughts in Thessaly, Greece. The standardized precipitation index (SPI) was used for the identification of drought occurrence for the period from 1960 to 1990. The Canadian Centre for Climate Modeling Analysis General Circulation Model (CGCMa2) was used to estimate change in the precipitation for the periods 2020-2050 and 2070-2100. The impacts of various climate change scenarios on drought were evaluated and drought characteristics for the past and future periods were compared indicating that the drought intensity, duration and severity increase for the three examined climate change scenarios. Kothavala (1999) applied the Palmer drought severity index (PDSI) to determine the duration and severity of drought over a 30-year period. The PDSI was applied on monthly mean temperature and total monthly precipitation. The combined effects of precipitation and temperature simulated by a coupled ocean-atmosphere General Circulation Model were examined for its effects on drought over eastern Australia. Finally, it is worthwhile to mention that Burke et al. (2006) evaluated meteorological drought in the Hadley Centre global climate model by using the PDSI. As a result, the Special Report on Emissions Scenarios (SRES) showed a net global drying trend resulting in an increase in the area of an extreme drought from 1% to 30% by the end of 21st century. Zarch et al. (2014) investigated the changes in drought characteristics on different arid regions with and without consideration of potential evapotranspiration (PET) by using two drought indices including the standardized precipitation index (SPI) which is solely based on precipitation; and the reconnaissance drought index (RDI) which takes precipitation and PET into account. The results indicate that the agreement between SPI and RDI is reduced in hyper-arid zones and the indices exhibit different trends; RDI has more decreasing trends compared to SPI when a region becomes drier. Also, results suggest that RDI will be consistently different from SPI because of the global warming effect. This hypothesis is further tested in climate change scenarios for historical and future climate projections. All these lead to the conclusion that PET is an important component in hydrological cycle and it should not be ignored in drought modeling in case the climate change is faced. Park et al. (2015) predicted the drought under RCP 8.5 climate change scenarios in Korea over the period 2014-2100. In the study utilized, the daily effective drought index (EDI) was calculated from precipitation data. Moreover, characterization of drought within the clustered regions was represented as a spatial map. Finally, a spatial-temporal drought map was created for all clusters and time periods under consideration. In a similar way, Dabanli et al. (2017) presented the long-term spatio-temporal variability of drought in Turkey.

In this regard, efforts within the hydrological community that look at the future by keeping in mind that the past is no longer fully representative should be mentioned. The *Panta Rhei* (Change in Hydrology) initiative of International Association of Hydrological Sciences (IAHS) is such an effort. Understanding the past by keeping at the same time that hydrology is under change gives a good direction to the scientists, practicing engineers, decision-makers, and even end-users when a decision is made for the near- or far-future (Montanari et al., 2013; McMillan et al., 2016; Ceola et al., 2016).

2.5 Spatial Drought Analysis

A particular meteorological station is used when the point-scale temporal analysis of drought is concerned. On the other hand, spatial analysis of drought is as important as its temporal analysis. Because, it could be common for one point in an area to suffer dry conditions, whilst surrounding points in the same area experience normal or even humid conditions. Thus, information related to not only one particular station but also to neighbouring stations are needed in making decision for drought mitigation or preparedness at basin scale. Spatial analysis is performed using data from all available meteorological stations in the basin. This provides spatial drought characterization that utilizes the severity, intensity, duration and return period. It can be presented in the form of spatial patterns of drought intensity contours for a given drought duration and return period. Spatial variability of drought events in the literature have been approached from different perspectives (Turkes, 1996; Komuscu, 2001; Bonaccorso et al., 2003; Sonmez et al., 2005; Loukas and Vasiliades, 2009). Bin et al. (2011) investigated drought hazard and spatial characteristic analysis in China using a GIS-based drought hazard assessment model.

2.6 Drought Studies in Turkey

Turkey is situated in the East Mediterranean. Annual average precipitation in Turkey is 630 mm 67% of which falling during the winter and spring months with the influence of Mediterranean depression (Turkes, 1996; Komuscu, 2001; Sonmez et al., 2005). Climate models predict that, by the end of the 21st century, Europe will face droughts extending over larger areas in the Mediterranean region with increasing intensity and duration (Jones et al., 1996; Vicente-Serrano and Begueria, 2006). Therefore, monitoring of drought and management plans are vital to determine the impact of drought on the Mediterranean. Drought action plans should be more efficient such that the use of economic resources is optimized. As examples; Vicente-Serrano and Begueria (2007) evaluated the impact of drought using remote sensing in the semi-arid Mediterranean region in Spain. Caloiero et al. (2018) analysed drought to calculate different return period-droughts by using the SPI in the northern hemisphere including the European continent, Ireland, UK and the Mediterranean basins. Vicente-Serrano et al. (2004) studied drought patterns in the eastern Spain of the Mediterranean region and found the frequency, duration and intensity of drought for each region considered.

Akbaş (2014) studied the Palmer drought severity index (PDSI) by using the temperature and precipitation data from 96 meteorological stations in Turkey. With the PDSI, drought is divided into seven classes each with an occurence probability spatially distributed over of climatological regions in the country. Results were found such that distribution of extreme droughts and probabilities of wet periods have similar patterns with the droughts observed in the past. The so-called normal class was found having the highest frequency or the likelihood occurrence. Kayam et al. (2017) compared some drought indices such as percentage of normal, deciles, Keetch-Byram drought index, standardized precipitation index and reconnaissance drought index representing agricultural drought in the climatological analyzes in the Lower Gediz Basin in the Aegean region of Turkey. With the analyses, it was found that the region will possibly be under the effect of severe droughts gradually. Despite the general harmony among the indices, there has been a remarkable difference between the drought reconnaissance index and the standardized precipitation index because of the high increase in atmospheric evaporation. Bacanlı and Kargı (2019) performed long- and short-term period drought analysis on a case study for Bursa province by using the standardized precipitation index. In addition, precipitation data were evaluated using the run analysis, and no significant trend was found in the annual and monthly rainfall data. Aksoy et al. (2018c) investigated the drought in Gediz Basin and determined drought occurence probabilities by using SPI which is a reliable index that requires only precipitation data. SPI has widely been used in many research studies on drought analysis in Turkey (Türkeş and Tatlı, 2009; Yıldız, 2014; Dinc et al., 206; Bacanli, 2017; Baran et al., 2017; Aksoy et al., 2018c).

Using precipitation and temperature data, Simsek et al. (2014) evaluated the drought for 2013-2014 agricultural year based on standardized precipitation index, percent of normal precipitation index, Palmer drought severity index. As a result, it was observed that drought decreased production for some types of crops importantly in the agricultural year mentioned. Streamflow drought index (SDI) was used in determining the drought analysis, and dry and wet periods were identified (Gumus, 2017; Ozfidaner et al., 2018). According to SDI at 3, 6, 9,12 month-time scales, the drought severity values were calculated by using monthly streamflow data.

2.7 Outcomes of The Literature Review

From the literature review above, it is seen that

1) A quite high number of drought indices have been developed among which the SPI is the simplest one. Although SPI is quite simple, it is convincing in the drought analysis. It has also a wide range of applications from the meteorological drought to agricultural and hydrological droughts as it is usable at different time scales.

2) Many among the drought indices are mostly based on the SPI concept. However, they use not only precipitation as it is the case in SPI but also different indicators such as streamflow, evaporation, groundwater, reservoir etc.

3) The drought indices have different ease-of-use depending on the indicators involved, the formulation, the availability of the data or the time scale considered. Simple indices for the drought analysis have been useful so far.

4) As they are usually correlated, the drought indices provide mostly similar results even if not the same.

5) Even if the literature is full of large number of case studies, up-to-date methodologies will always be needed with the change in hydrology

6) The severity-duration-frequency or intensity-duration-frequency curves have less been touched in the drought literature. This is the case also for Turkey. Therefore, a methodology to develop these curves is beneficial.

7) The use of drought indices is rather a technical issue. The technical information they provide should be converted into practical knowledge. Therefore, it is important to develop the severity-duration-frequency or intensity-duration-frequency curves in terms of a physical variable such as the precipitation deficit which has been taken as the subject of this study.

3. METHOD

3.1. A General Look at the Method

Method proposed in this study uses monthly precipitation data of a single meteorological station as the input and plots the precipitation deficit-based SDF and IDF curves of critical droughts as the final outputs (Figure 3.1). The SPI is the start point of the methodology which is considered for time scales k = 1, 3, 6, 9, 12 and 24 months. The SPI series is composed of positive or negative runs; a positive run shows a wet period while a negative run shows a dry period. Dry periods are identified from the SPI time series, droughts of different durations are counted from the dry periods. At the same time, using regression analysis an equation is established between the SPI and precipitation time series. Among the droughts identified, the most severe drought, the critical drought, was determined for each year. Frequency analysis is then applied to the severity of the critical droughts of different durations. Critical drought severities of different return periods are obtained with the back-transformation of the probability distribution function fitted, and the corresponding precipitation from the regression equation. Precipitation corresponding to SPI = 0, that is precipitation threshold, is calculated from the regression equation. The difference between the precipitation threshold and the critical precipitation, the precipitation deficit, and its ratio to the drought duration, the intensity deficit, are finally calculated. Severity-Duration-Frequency (SDF) or Intensity-Duration-Frequency (IDF) curves of the critical droughts are plotted after the procedure is repeated for all return periods, duration durations and time scales. The curves use the severity and intensity values converted into precipitation deficit.

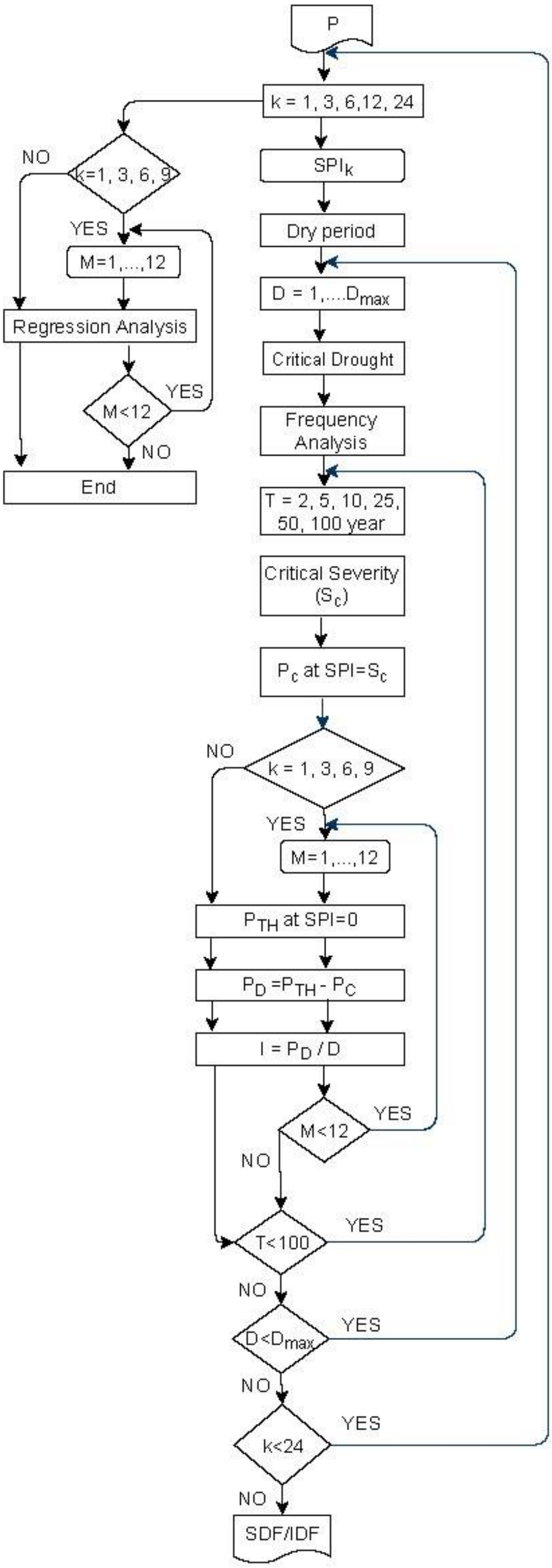

Figure 3.1: Flowchart of the methodology proposed

3.2. Standardized Precipitation Index (SPI)

SPI was developed by McKee et al. (1993) to define and observe the drought. With the help of SPI calculated by using only monthly precipitation data, dry periods can be monitored as well as wet periods. SPI can be calculated for various time scales. For each month of the time period considered a value of $SPI_{i,j,k}$ (i = 1, …., n; j = 1, …., 12 and k = 1, 3, 6, 9, 12, 24, 48 months) is calculated where i indicates the year (with n is the total number of years in the observation), j indicates month of the year (from 1 to 12) and k is the time scale taken usually as 1, 3, 6, 9, 12, 24 and 48 months. Since the monthly precipitation data are used, the length of the SPI_k series is N = n x 12 – (k – 1) for an n-number of annual uninterrupted monthly precipitation time series. The sum of consecutive k-month precipitation is considered in calculating the standardized precipitation index of the k-month time scale (SPI_k). More precisely, SPI_k at month j is calculated by adding the total precipitation of the k - 1 previous months to the monthly precipitation of month j. When this process is repeated N - k + 1 times, an (N - k + 1)-month long precipitation series is obtained for a k-month time period (Aksoy et al., 2018a).

Precipitation is typically not a normal distribution process for the accumulation periods shorter than 12 months particularly but this can be overcome by applying a transformation to the distribution (McKee et al., 1993). Each of the data sets is fitted to the gamma function (Aksoy, 2000) to determine the relationship of probability to precipitation.

The 2-parameter gamma probability distribution function (pdf) is defined as

$$g(x) = \frac{x^{\alpha-1}e^{-x/\beta}}{\Gamma(\alpha)\beta^{\alpha}} \tag{3.1}$$

where α is shape parameter and β is scale parameter which can be estimated using the method of maximum likelihood; x is the precipitation value, the independent variable; and $\Gamma(\alpha)$ is the gamma function at α. The estimated parameters can be used to find the probability distribution function of the observed precipitation events for the given month and time scale.

The cumulative probability distribution function, $G(x)$ is obtained by integrating Equation (3.1) as

$$G(x) = \int_0^x g(x)dx = \int_0^x \frac{x^{\alpha-1}e^{-x/\beta}}{\Gamma(\alpha)\beta^{\alpha}}dx \qquad (3.2)$$

where

$$\alpha = \frac{1}{4A}\left(1 + \sqrt{1 + \frac{4A}{3}}\right) \qquad (3.3)$$

$$\beta = \frac{x}{\alpha} \qquad (3.4)$$

$$A = ln\,(\bar{x}\,) - \frac{\sum ln(x)}{n} \qquad (3.5)$$

and n is the number of observations in the precipitation series (number of years at annual time scale), and $\bar{x}$ refers to the mean of the available precipitation data.

As a further step in calculating the SPI values, the gamma probability distribution function is transformed into the standard normal distribution with zero mean and unit variance (Figure 3.2). The SPI is obtained simply by taking first the difference between the precipitation and its mean value and dividing the difference by the standard deviation as

$$SPI_{i,j} = \frac{x_{i,j} - \mu_j}{\sigma_j} \qquad (3.6)$$

where $x_{i,j}$ is the precipitation (in mm) in the jth month (j = 1, 2, 3, ……, 12) of the ith year (i = 1, 2, ……n); μ_j, the mean precipitation (in mm) in the jth month; and σ_j, the standard deviation of precipitation in the jth month. The SPI values are calculated similarly for different time scales such as k = 1, 3, 6, 9, 12, 24, 48 months. These arbitrarily selected time scales are used to represent the three types of drought; meteorological, agricultural, and hydrological (McKee et al., 1993).

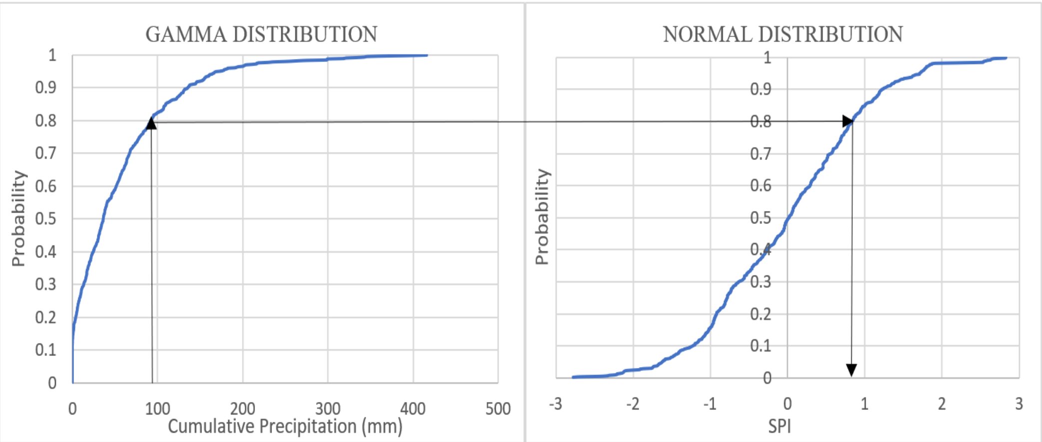

Figure 3.2: Transformation from gamma distribution to standard normal distribution.

A flowchart showing step-by-step calculation of the SPI is given in Figure 3.3. The presumably gamma distributed monthly precipitation data were first transformed into the standard normal distribution. Starting with the first month in the observation (i = 1 year and j = 1 month), SPI is calculated as the ratio of the difference between the normalized precipitation and its mean value (in the respective month) to its standard deviation. After calculating the SPI of all months (j = 1, …, 12) in the year i, it is calculated for the months in the next year. This process is repeated for N - k + 1 times where k represents the time scale (i.e., 1, 3, 6, 9, 12 and 24 months) (Figure 3.3).

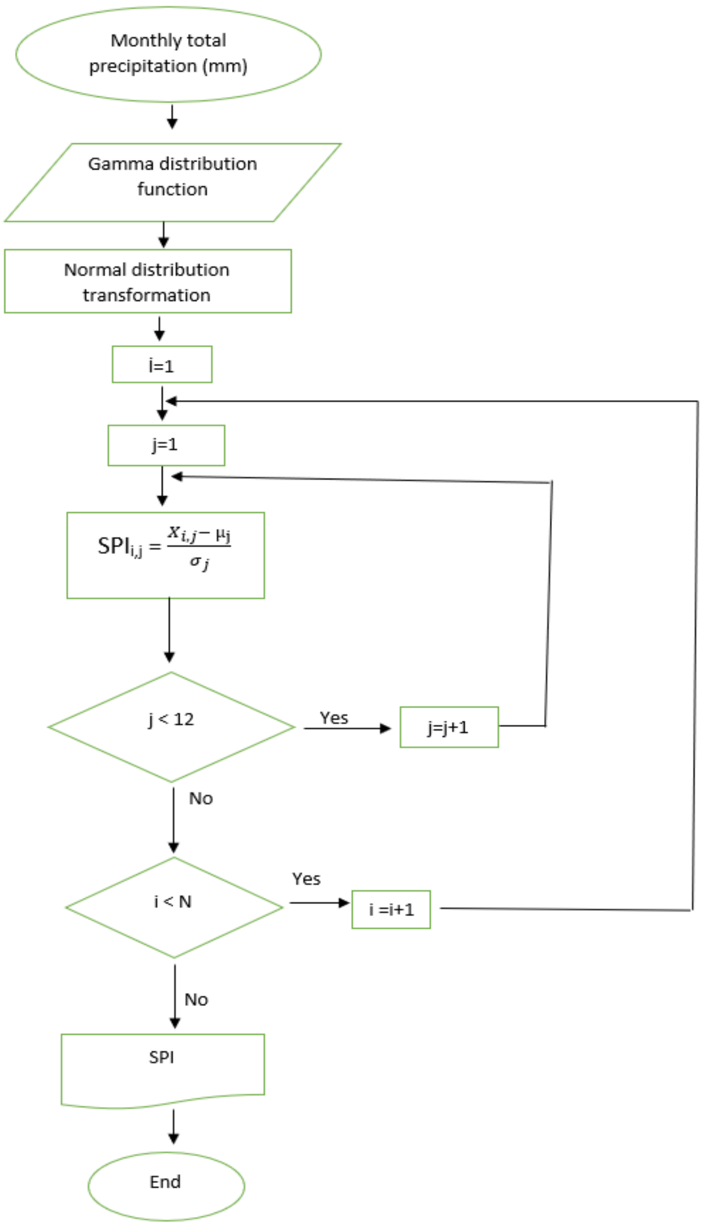

Figure 3.3: Step-by-step calculation of SPI

SPI calculated over short periods of time (up to 3 months) is appropriate for measuring short-term effect on soil moisture, streamflow of rivers. SPI associated medium-term accumulated values (3-12 months) is appropriate for measuring the effect on reservoir storage; and SPI for long accumulation periods (12-24) is best for evaluating long-term process such as groundwater recharge and reservoirs (McKee et al., 1993; Aksoy et al., 2018a). On the other hand, SPI values of 12, 24, 48 month-time scales are considered as drought in groundwater. Using the methodology of SPI, drought indices can be calculated for other hydrological variables such as streamflow, groundwater, reservoir and snowpack (Nalbantis and Tsakiris, 2009; Bloomfield and Marchant, 2013).

3.3 Definitions and Basic Concepts

The drought period begins when the SPI falls first time below zero. Its severity depends on the value of SPI. Drought is categorised depending on the values of the SPI as given in Table 3.1. Probability of each drought category demonstrates the probability of occurrence calculated from the normal probability distribution function as shown in Table 3.1.

Table 3.1: Drought categorization based on the SPI values (McKee et al, 1993).

SPI values	Drought Category	Probability of Occurrence (%)
0 to -0.99	Mild	33
-1 to -1.49	Moderate	10
-1.5 to -1.99	Severe	5
≤ -2	Extreme	2.5

In addition to calculating the SPI values, it is important to determine the drought duration formed by consecutive months with negative values in the dry periods. Therefore, the determination and analysis of following parameters of dry periods has formed the essence of drought studies (Figure 3.4). A dry period begins immediately when the SPI falls below zero. Droughts are determined from the dry periods, and drought characteristics such as the duration, severity, intensity, and return period are calculated. The concepts used in this study are defined as follows:

a) Dry period length (L): The cluster which consists of consecutive negative values of SPI refers to as the dry period (Figure 1). It begins in a month with a negative SPI and continue until a positive SPI value is obtained in the time series. A dry period is shown as

$$A = \{SPI | SPI < 0\} \tag{3.7}$$

where $s(A)$ is the number of elements of set Athat shows the length of the dry period as

$$L = s(A) \tag{3.8}$$

b) Drought duration (D): Duration of droughts in a dry period with length L is $0 < D \leq L$ (Figure 3.4).

c) Drought severity (S): The accumulation of negative SPI values preceded and followed by positive SPI values is called *severity*. The severity of a drought D month-long is calculated by

$$S = \sum_{i=1}^{D} SPI\, i,\ SPIi \in A \tag{3.9}$$

In other words, it is the largest absolute value of the cumulative drought index (SPI in this study) in the dry period considered.

$$S = \sum_{i=1}^{D} |SPI_i| \tag{3.10}$$

d) Drought intensity (I): The intensity is obtained by dividing the severity to the drought duration:

$$I = S / D \tag{3.11}$$

e) Frequency (return period): The frequency or return period of a drought is defined as the avarege time between two consecutive drought events.

In this study, following definitions are made considering the drought:

f) Critical drought severity: When more than one drought is recorded for any year, drought with maximum severity is taken as the critical drought. No critical drought is assigned to a year in which drought is not observed.

g) Within-period drought: Any drought with a duration shorter than the length of dry period is called *within-period drought*. For example, in a dry period of 3 month-long, there are three 1 month-droughts and two 2 month-droughts. Similarly, there are two 1 month-droughts in a dry period of 2 month-long.

h) Singular drought: Drought that extends over the dry period is called a *singular drought*. For example, there exists a 1 month-singular drought in a dry period of 1 month-long; a 2 month-singular drought in a dry period of 2 month-long; a 3 month-singular drought in a dry period of 3 month-long and so on. The length of dry period becomes the same as the drought duration for singular droughts while the former is larger than the latter for within-period droughts.

i) No drought year: Any year with no negative run of SPI is considered a year with no drought. Thus, the critical drought severity is not calculated for such a year, a zero value is assigned to the critical drought severity.

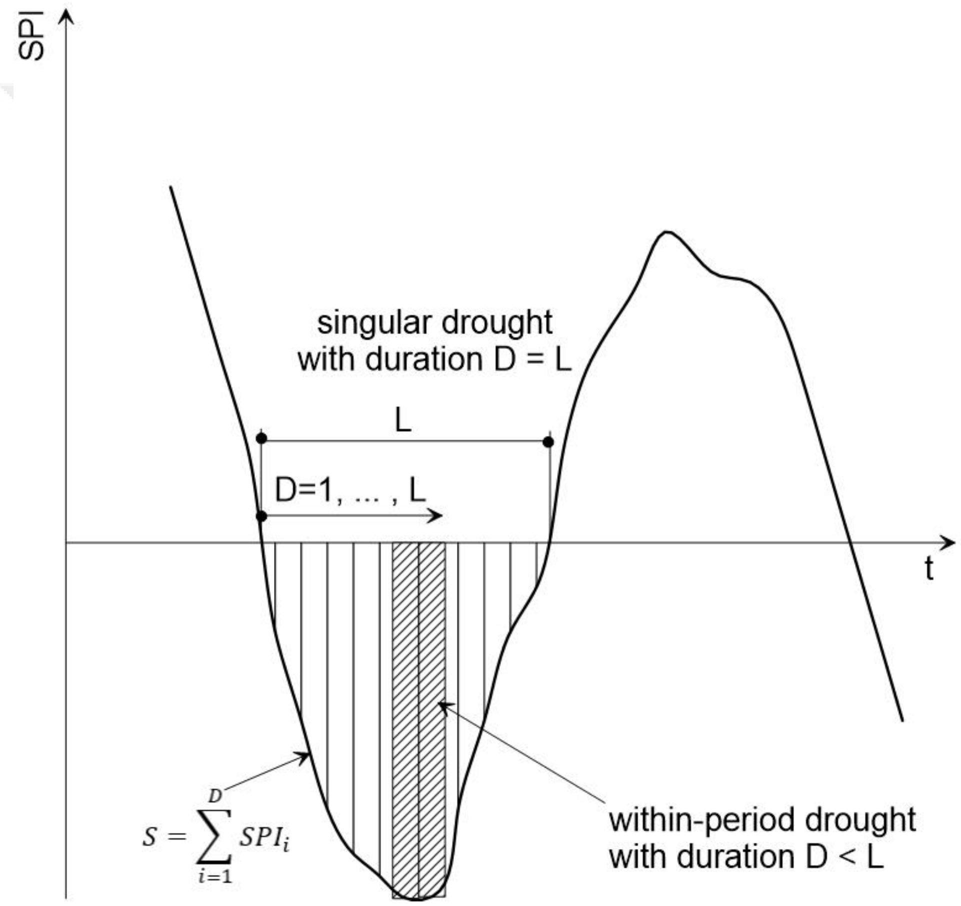

Figure 3.4: Dry period length (L), drought duration (D), and drought severity (S). The dry period length (L) is determined as a fixed value for each dry period; drought duration (D) changes from 1 month to L. Drought with duration L is called a singular drought while droughts with duration shorter than the dry period length are called within-period drought.

3.4 Frequency Analysis

Frequency analysis is performed to characterize the drought and to determine the probability distribution function. In the frequency analysis of drought, the 2- and 3-parameter Gamma (G2, G3), the General 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 are often used in literature. The probability distribution functions are listed in Table 3.2 together with their cumulative distribution function as well as their parameters. For the sake of consistency with the literature, the above probability distribution functions were considered for the frequency analysis of drought in this study.

For months, when no precipitation is observed in some particular years, the frequency analysis is applied on the non-zero values only to distinguish the zero values from the non-zero values; because, the frequency analysis would otherwise not be meaningful. The combination of zero and non-zero values is called a censored or intermittent process. The total probability theorem is available to use for the intermittency to examine the process in two parts; zero and non-zero parts.

3.4.1. Total probability theorem

According to the total probability theorem (Haan, 1997; p.168)

$$P(X \geq x) = P(X \geq x|X = 0)P(X = 0) + P(X \geq x|X \neq 0)P(X \neq 0) \qquad (3.12)$$

is used. Here,

$$P(X \geq x|X = 0) = 0 \qquad (3.13)$$

Therefore;

$$P\,(X \geq x) = P\,(X \geq x \mid X \neq 0)\,P\,(X \neq 0) \qquad (3.14)$$

is obtained.

Table 3.2: Probability distribution functions used in the frequency analysis of drought characteristics.

Distribution	Probability Distribution Function (f(x)) Cumulative Distribution Function (F(x))	Parameter
2- parameter Gamma (G2)	$f(x) = \frac{x^{\alpha-1}}{\beta^{\alpha}\,\Gamma(\alpha)} exp(-x/\beta)$ $F(x) = \frac{\Gamma_{\frac{x}{\beta}}(\alpha)}{\Gamma(\alpha)}$	β, scale parameter (α>0) α, shape parameter (β>0) γ, location par. (γ ≤ x ≤ + ∞) Γ, Gamma function
3- parameter Gamma (G3)	$f(x) = \frac{(x-y)^{\alpha-1}}{\beta^{\alpha}\Gamma(\alpha)} exp\left(-\frac{x-\gamma}{\beta}\right)$ $F(x) = \frac{\Gamma_{\frac{(x-\gamma)}{\beta}}(\alpha)}{\Gamma(\alpha)}$	
General Extreme Value	$f(x) = \begin{cases} \frac{1}{\sigma} exp(-(1+kz)^{-\frac{1}{k}})(1+kz)^{-1-\frac{1}{k}} & k \neq 0 \\ 1/\sigma\, exp(-z - exp(-z)) & k = 0 \end{cases}$ $F(x) = \begin{cases} exp(-(1+kz)^{-\frac{1}{k}}) & k \neq 0 \\ (exp(-z - exp(-z)) & k = 0 \end{cases}$	k, shape parameter 1+ k$\frac{x-\mu}{\sigma}$ > 0 $k \neq 0$ -∞ <x <+ ∞ $k = 0$ α, scale parameter μ, location parameter $z = \frac{x-\mu}{\sigma}$
2- parameter log-normal (LN2)	$f(x) = \frac{exp(-\frac{1}{2}\left(\frac{ln(x)-\mu}{\sigma}\right)^{2}}{x\sigma\sqrt{2\pi}}$ $F(x) = \Phi\,(\frac{ln\,x-\mu}{\sigma})$	σ, shape par. μ, scale par. γ, location par. (γ<x<+∞) Φ, Laplace integration
3- parameter log-normal (LN3)	$f(x) = \frac{exp(-\frac{1}{2}\left(\frac{ln(x-\gamma)-\mu}{\sigma}\right)^{2}}{(x-\gamma)\sigma\sqrt{2\pi}};$ $F(x) = \Phi\,(\frac{ln(x-\gamma)-\mu}{\sigma})$	
Log-Pearson III (LP3)	$f(x) = \frac{1}{\frac{x}{\beta}/\Gamma(\alpha)} (\frac{ln(x)-\gamma}{\beta})^{\alpha-1} exp\,(-\frac{ln(x)-\gamma}{\beta}$ $F(x) = \frac{\Gamma_{\frac{(ln(x)-\gamma)}{\beta}}(\alpha)}{\Gamma(\alpha)}$	α, shape par. (α>0) β, scale par. (β≠0) 0<x≤ e^{γ} β<0 e^{γ}≤x<+∞ β>0 γ, location par.
2- parameter Weibull (W2)	$f(x) = \frac{\alpha}{\beta}(\frac{x}{\beta})\alpha - 1\, exp\,(-(\frac{x}{\beta})\alpha)$ $F(x) = 1 - exp(-(\frac{x}{\beta})\alpha)$	α, shape par. (α>0) β, scale par. (β>0) γ, location par. (γ≤x<+∞)
3- parameter	$f(x) = \frac{\alpha}{\beta}(\frac{x-\gamma}{\beta})\alpha - 1\, exp\,(-(\frac{x-\gamma}{\beta})\alpha)$	

P (X ≠ 0) is the rate of years with non-zero values in the SPI_k (k = 1, 3, 6, 9, 12, 24 months) time series. Equation (3.13) can also be written in terms of the cumulative probability distribution as;

$$1 - F(x) = (1 - p)[1 - F^*(x)] \quad (3.15)$$

In Equation (3.14), p is the probability of the zero values (Figure 3.5). F(x) is the cumulative probability distribution function of all X including zeros and F*(x) is the cumulative probability distribution function of the non-zero values of X, which are expressed as [P (X ≤ x | X ≥ 0)] and [P (X ≤ x | X ≠ 0)], respectively.

The rate of the non-zero values, 1 - p in Equation (3.14), can be expressed in terms of the probability as

$$1 - p = P(X \neq 0) \quad (3.16)$$

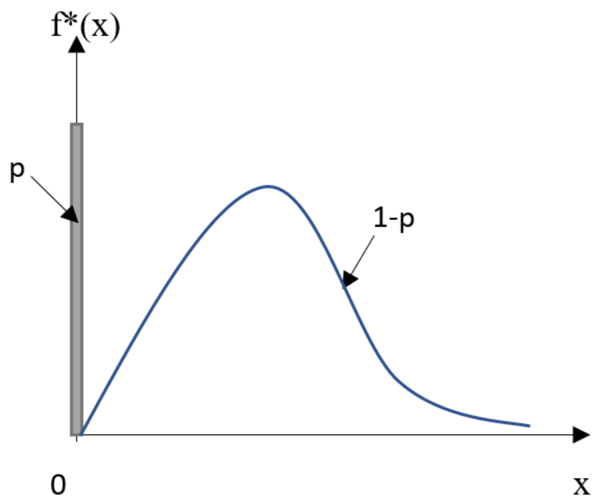

Figure 3.5: The mass density of zero values and probability distribution of non-zero values.

Equation (3.14) can be used to predict the magnitude of an event with return period T by solving for F*(x) and then using the inverse transformation of F*(x) to get the value of X. From Equation (3.14)

$$\frac{1-F(x)}{1-p} = 1 - F^*(x) \tag{3.17}$$

and

$$F^*(x) = \frac{F(x)-p}{1-p} \tag{3.18}$$

can be written. Considering that return period of a given severity for a particular drought duration can be predicted by

$$F(x) = 1 - \frac{1}{T} \tag{3.19}$$

Equation (3.13) turns into

$$F^*(x) = \frac{1-\frac{1}{T}-p}{1-p} \tag{3.20}$$

As the probability changes, by its definition, between 0 and 1 (that is a non-negative value), the application of the total probability theorem to the drought analysis depends on the relation

$$p \geq \frac{T-1}{T} \tag{3.21}$$

between T and p. Equation (3.19) becomes void unless (Equation 3.20) is satisfied. This condition also means that for the given return period T and fraction p, the probability of observing a given severity is zero when $F^*(x) < 0$. The commonly used return periods, and the corresponding rates of non-zero values, p are given in Table 3.3.

Table 3.3: The p values depending on the return period.

T(year)	2	5	10	25	50	100
p ≥	0.5	0.8	0.9	0.96	0.98	0.99

3.4.2 Anderson-Darling (*AD*) test

The performance of the probability distribution function and the goodness of fit were examined using the Anderson-Darling (*AD*) test, which is a transformation of the Kolmogorov-Smirnov (K-S) test (Anderson and Darling, 1952; 1954; Scholz and Stephens, 1987). The *AD* test statistics can be calculated using:

$$AD = (\sum_{i=1}^{N} \frac{2i-1}{N} [lnF (Y_i) + ln(1 - F(Y_N + 1 - i)]) - N \qquad (3.22)$$

where F is the cumulative probability distribution function; i is the position of the variable in an ascending order; N is the number of the data, Y_i is the position in the form of an average recurrence interval of years. The critical value (AD_c) at the 0.05 confidence level, is given by

$$ADC = \frac{0.752}{1+\frac{0.75}{N}+\frac{2.25}{N^2}} \qquad (3.23)$$

If the calculated *AD* test statistics is found higher than the critical value $AD_{C,}$ then it is said that the tested probability distribution function is not appropriate at the selected confidence level.

3.5 Precipitation Deficit

A drought is defined as a period in which the SPI is continuously negative (McKee et al, 1993; Paulo and Pereira, 2006; Rahmat et al., 2015). In other words, it begins when the SPI first falls below zero and ends with a positive value of SPI (McKee et al., 1993). Thus, the retrospective analysis of drought events by using runs of SPI values may be useful to derive tangible information for the amount of precipitation required (Çetin et al., 2018).

Instead of the direct use of drought indices to develop severity-duration-frequency (SDF) curves as in previous studies (Dalezios et al., 2001; Kim et al., 2014), the precipitation deficit will be calculated in this study. This approach helps to better understand as the accumulated precipitation is used to define a drought event so that it can be easily identified by end-users such as farmers and decision-makers.

The relationship between the precipitation and SPI is detected by regression analysis. In the drought analysis, when the drought duration (*D* month) and return period (2, 5, 10, 25, 50 and 100 years) increase, precipitation is expected to decrease, and therefore, the precipitation deficit is expected to increase. Any function to be used between precipitation and the corresponding SPI should satisfy this expectation. Because of this physical reality, some types of functions such as the second and the third order polynomials were omitted as they might produce negative precipitation deficit values. On the other hand, some functions such as Gompertz were discarded; because, it was discovered after trials that they could not fit properly to SPI_k time series of months with high number of zero values (such as SPI_1 in August-July). As a result, it was seen that the logistic function could be appropriate to choose among the functions tested due to the above expectation of the physical realization. The logistic regression equation was fitted to the relation between precipitation and the corresponding SPI values and therefore logistic regression equation was used to analyze data clusters. It describes a family of sigmoidal curves. The simple logistic function has the form of

$$f(x) = \frac{a}{1+be^{-cx}} \tag{3.24}$$

in which *a*, *b* and *c* are parameters estimated through the use of data scatter. A general display of the logistic function on the interval (−6, 6) is shown in Figure 3.6.

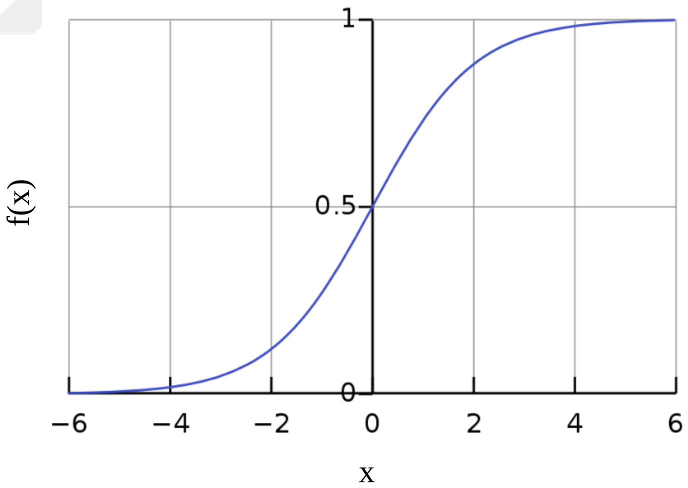

Figure 3.6: Display of the logistic function.

The regression equation can be used to calculate the precipitation threshold value. Referring to Figures 3.7, the precipitation threshold (P_{TH}) were taken as precipitation at SPI = 0 for all time scales. Precipitation values at the boundary of drought classes ($P_{B,\ Extreme}$, $P_{B,\ Severe}$, $P_{B,\ Modarete}$, $P_{B,\ Mild}$) are shown in Figure 3.7. Also shown is the critical precipitation (*Pc*) which is expected to occur in a critical drought severity and the precipitation threshold value (P_{TH}). The difference between the precipitaion threshold and the critical precipitation is defined as the precipitation deficit a calculated by

$$P_D = P_{TH} - Pc \tag{3.25}$$

for each drought of a given duration and return period. Flowchart of the steps that will be implemented for calculating precipitation deficit is given in Figure 3.8. For time scales 1, 3, 6 and 9 months, relation between precipitation and SPI changes from month to month. That is, for each month of the year a particular function should be used. However, for time scales of 12 and 24 months, one curve exist.

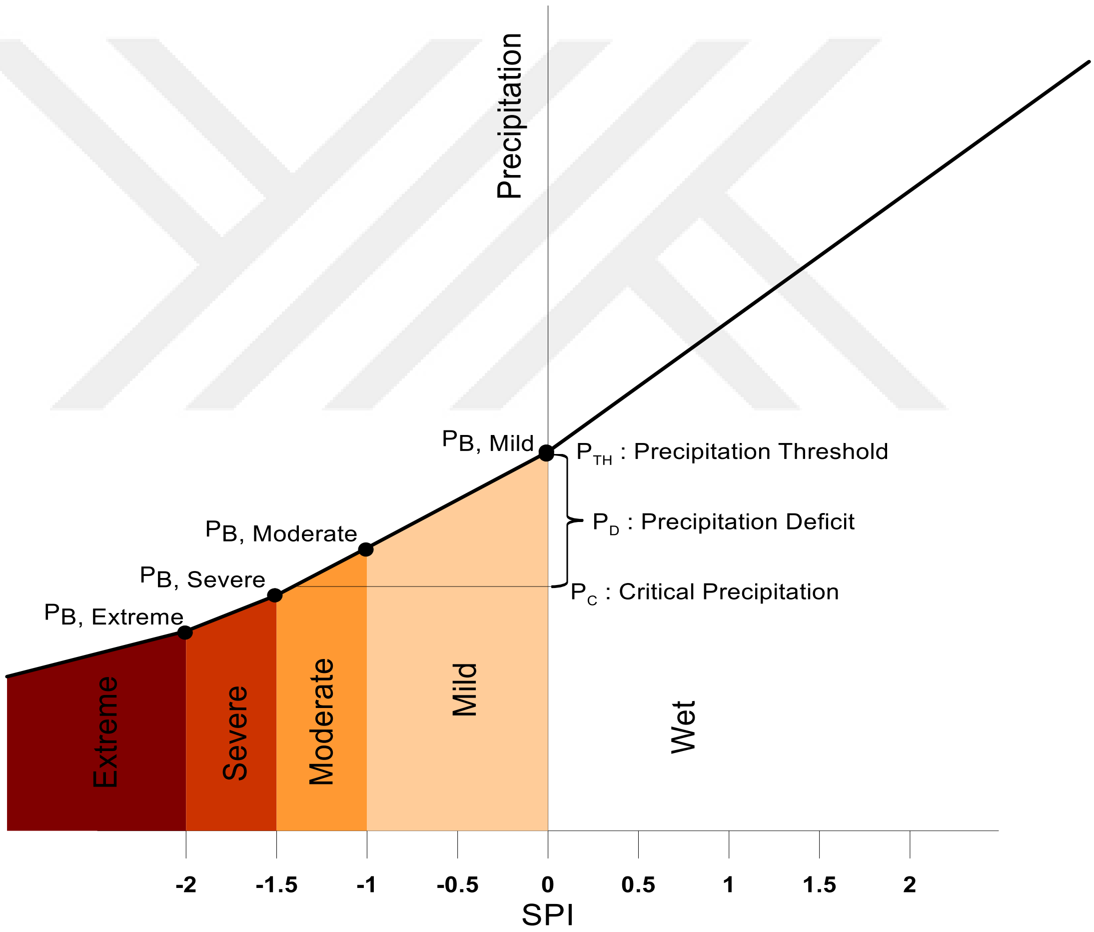

Figure 3.7: Definition of precipitation threshold, boundary precpitation and critical precipitation.

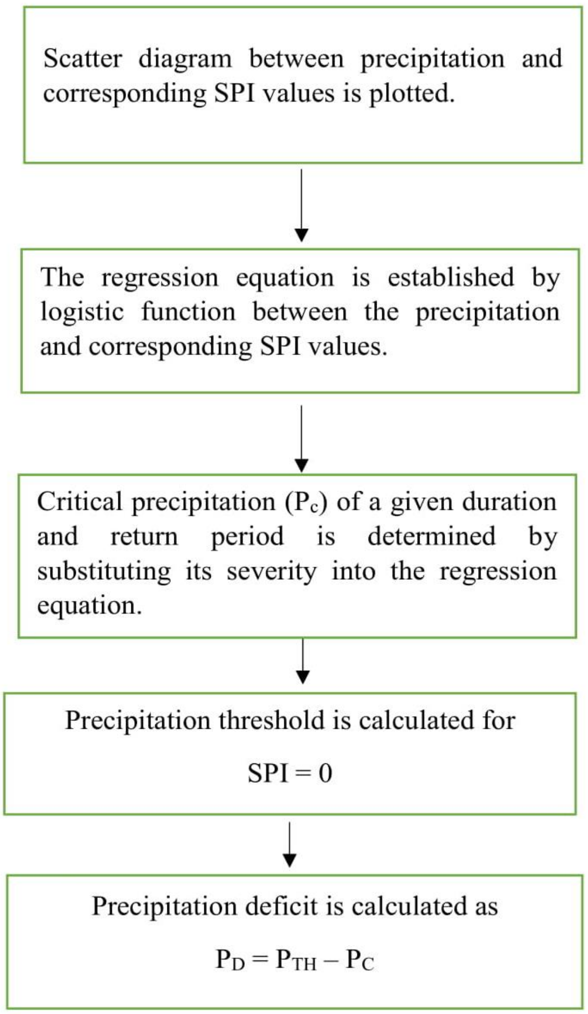

Figure 3.8: Steps for the calculation of precipitation deficit.

4. STUDY AREA AND DATA

4.1 Seyhan River Basin

The Seyhan River Basin is located in the southern part of Turkey, between the latitudes 36^0 33’ N - 39^0 24’ N and the longitudes 34^0 24’ E - 36^0 56’ E (Figure 4.1). It is bordered by Kızılırmak, Konya, Eastern Mediterranean basins to the west and by Ceyhan and Euphrates River basins to the east. The drainage area of the basin is 20731 km^2 which is composed of 2.82% of surface area of Turkey. The average annual total precipitation is 624 mm in the coastal area in the basin; it increases to approximately 1000 mm in higher elevations in the north. The annual mean flow at the outlet of the basin to the Mediterranean Sea is 211.07 m^3/s. The most important river is Seyhan River, which gives its name to the basin and has a length of 560 km as one of the largest rivers in Turkey flowing into the Mediterranean Sea. Seyhan River is formed by the confluence of two main rivers; Zamantı River (306 km-long) and Göksu River (199 km-long).

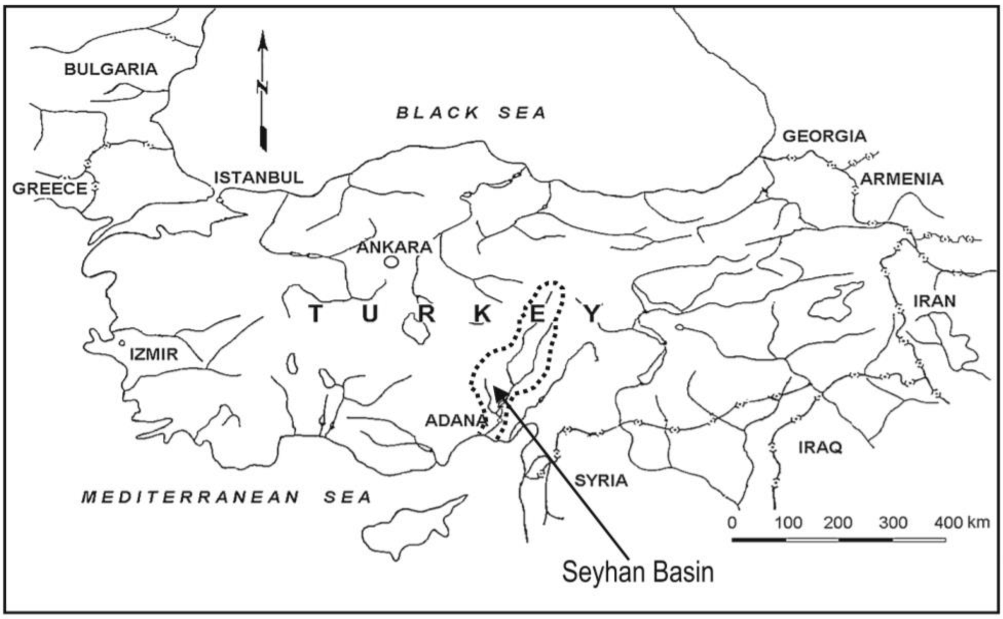

Figure 4.1: Location of the Seyhan River Basin (Selek and Tuncok, 2014).

4.1.1 Rivers

Two important branches of the Seyhan River are Tomarza which passes through Develi and Yahyalı districts, and Zamantı which passes Pınarbaşı, Tomarza, Develi, Yahyalı districts of Kayseri and is born from Uzunyayla at elevation 1500 m above mean sea level. Yedigöze, Çatalan and Seyhan hydroelectric power plants were established on the Seyhan River. Important streams within the basin except for the Seyhan River are Çakıt, Eğlence, Körkün and Üçürge.

4.1.2 Climate characteristics

The climate in the Seyhan River basin is strongly influenced by topography. The northern part of the basin is characterized by a mountainous steep, harsh topography while lowlands prevail in the southern part of the basin (Figure 4.2). The basin extends from the coast to the Central Anatolia and shows three different characteristics in terms of climate. The northern part of the basin exhibits the characteristics of the Central Anatolian climate; thus, it is probably colder than the southern part of the basin; the highest precipitation is observed at highlands in this part of the basin. In the coastal areas of Çukurova and surrounding areas, the summer season is hot and dry while the winter is warm and rainy. That part of the basin between the coastal zone and the Tarsus mountains has a semi-arid Mediterranean climate with dry and hot summers and rainy and warm winters.

4.2 Relevant Studies

The Seyhan River basin has been studied widely due to its importance for irrigation, energy and also flood control. Many studies have been carried out on water resources management and water use in the Seyhan River basin. For example, the Impact of Climate Change on Water Resources Project, the Seyhan Basin Pollution Prevention Action Plan and the Seyhan Basin Sectoral Water Allocation Plan are among the studies completed respectively (SYGM, 2016; CYGM, 2016; SYGM, 2017) and the Water Management and Preparation of Basin Protection Action Plans completed by The Scientific and Technological Research Council of Turkey (TUBITAK) Marmara Resarch Center (MAM) (TUBITAK, 2010). Further examples to be mentioned are performed by Dikici et al. (2018) who studied drought analysis with Palmer drought index, Selek and Tuncok (2014) who examined the effect of climate change on surface water management and Topaloğlu (2002) who determined the best-fit probability distribution functions for flow and precipitation in the basin. It should be emphasized that these are only a very short list of the studies conducted in the Seyhan River basin.

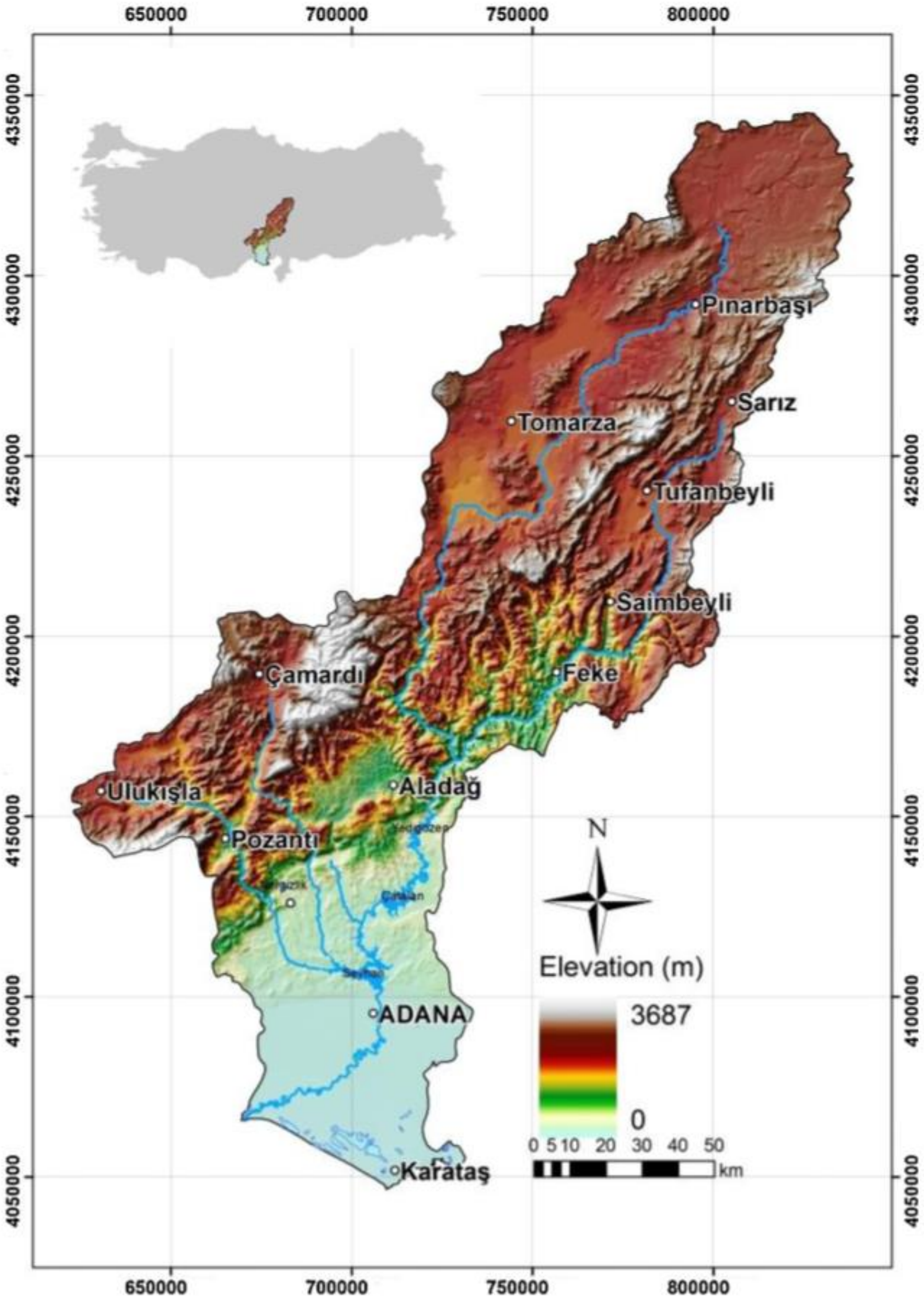

Figure 4.2: Topography of the Seyhan River basin (Gölge et al, 2013).

On the other hand, The European Drought Observatory (EDO) observes and maps the formation of drought by using precipitation, soil moisture and plant indicators. It found that the most severe drought and precipitation deficit in the Seyhan River basin were observed in 1990 (Figure 4.3).

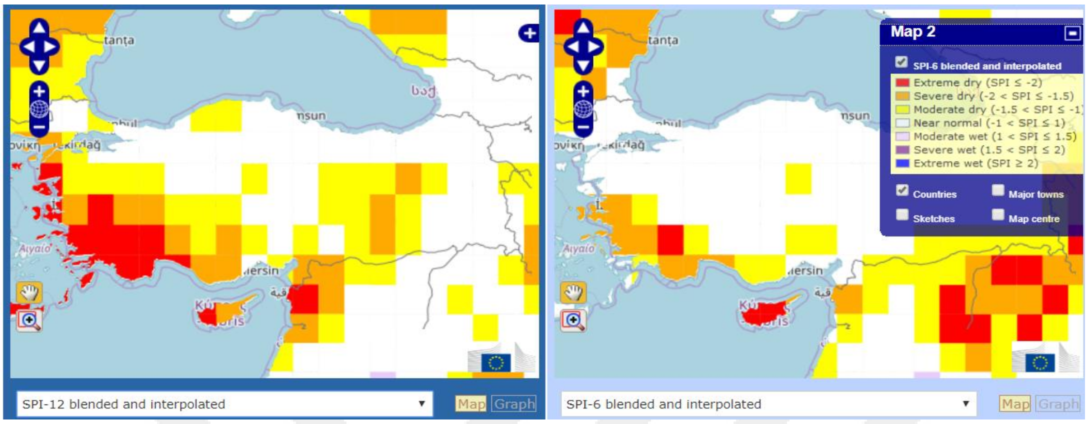

Figure 4.3: SPI6 and SPI12 drought maps in 1990 the European Drought Observatory.

4.3 Data

Monthly precipitation data were obtained from 19 meteorological stations operated by the State Meteorological Service (MGM with its Turkish acronym) and from the General Directorate of State Hydraulic Works (DSI with its acronym). The meteorological stations are listed in Table 4.1. The first 12 of the 19 stations belong to MGM and the remaning 7 to DSI. The number and name of the stations are given in Table 4.1 together with the observation period of the stations and the total number of missing data filled (in months). Any meteorological station with 10 years of observation at minimum is taken before any gap in the observation period was filled. For any month with missing data, the long-term monthly mean was taken to assign for the missing value. For example; a meteorological station which has 30 years of data might have a month that is missing in a year. Such a missing month is filled with the average of the remaining 29 months. When completing the missing data, only gaps not exceeding 12 subsequent months were taken into account; any gap longer than 12 subsequent months was not filled. From the data before or after such a gap, the longer one with 10 years of observation at minimum was considered. In other words, any gap longer than 12 subsequent months was not filled. The precipitation time series of 19 meteorological stations from the Seyhan River basin satisfied the above criteria of the

10 year-minimum length with missing data gap, if any, of the 12 month- uninterrupted length at maximum.

Layout of the stations in the Seyhan River basin is shown in Figure 4.4 from which it is seen that the stations scattered to the whole basin almost homogeneously. Statistical characteristics calculated from the monthly precipitation time series of each meteorological station are given in Table 4.2. They are the minimum, maximum, mean, standard deviation, the coefficient of variation (C_v), the coefficient of skewness (C_s), and lag-one autocorrelation coefficient (r_1). The characteristics of stations were also calculated from the observed precipitation data and provided in Table 4.2. It is seen that station 17981 (Karataş) among all has the highest percentage of no-rainy months (15.31%) and also the lowest altitude (22 m above mean sea level) compared to other stations. The altitude of the meteorological stations varies greatly within the basin owing to the topography.

Table 4.1: Meteorological stations in Seyhan River basin.

	Station	Station name	Observation period	Missing data (month)
1	6204	Tufanbeyli	1998-2012	3
2	6560	Saimbeyli	1986-1995	4
3	6893	Çamardı	1969-1982	1
4	6902	Feke	1970-1993	1
5	17351	Adana Bölge	1960-2016	0
6	17802	Kayseri Pınarbaşı	1963-2009	5
7	17837	Tomarza	1965-2010	8
8	17840	Sarız	1968-2011	0
9	17906	Ulukışla	1962-2011	11
10	17934	Pozantı	1963-1992	24
11	17936	Karaisalı	1965-2011	0
12	17981	Karataş	1963-2011	5
13	D18M003	Uzunpınar	1959-2005	11
14	D18M004	Seyhan Baraj	1974-2015	4
15	D18M011	Kazancık	1965-2003	8
16	D18M012	Hasan Çavuşlar	1990-2005	0
17	D18M013	Kamışlı	1963-2002	2
18	D18M018	Gıcak	1988-2006	0
19	D18M019	Çeralan	1991-2005	4

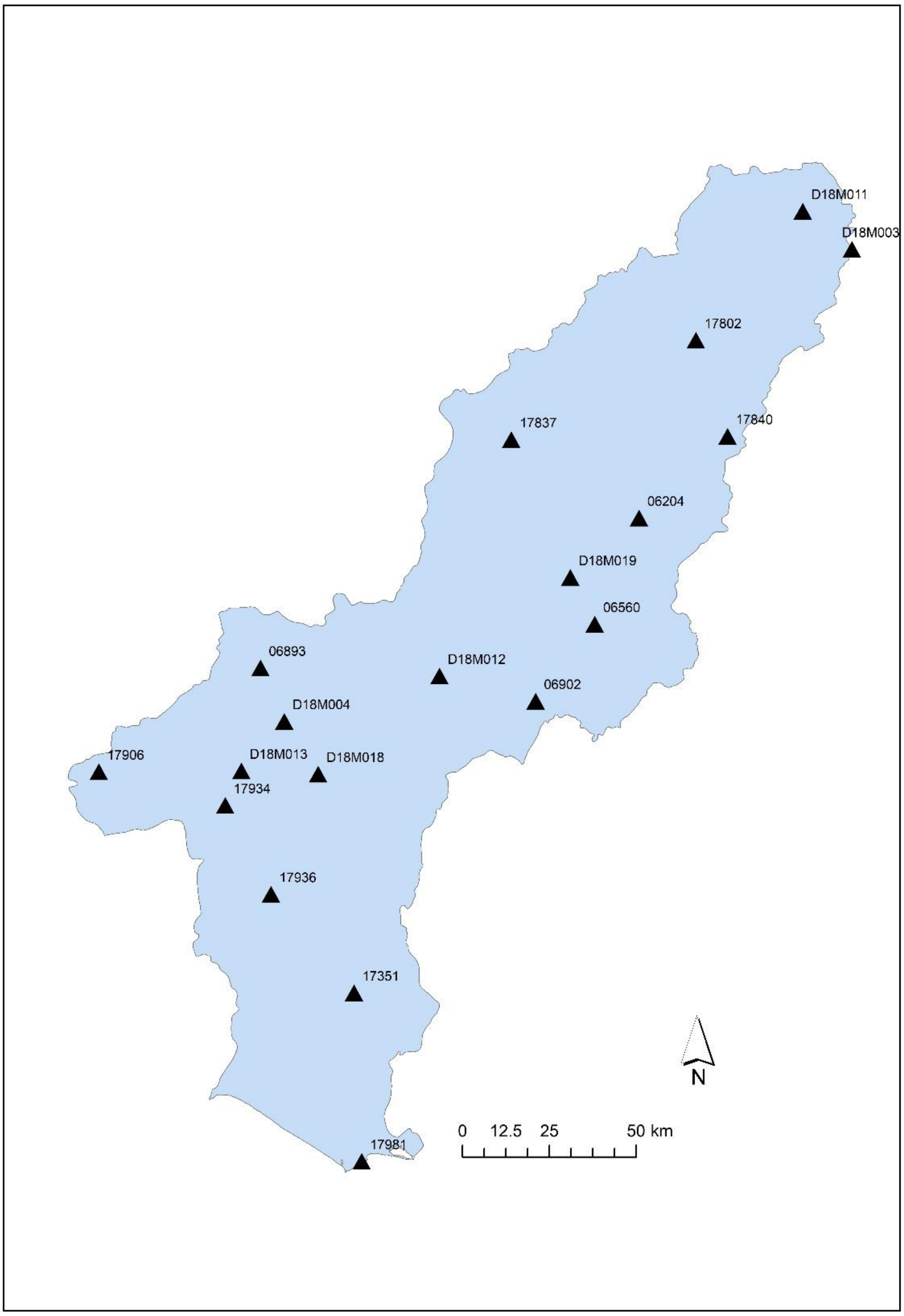

Figure 4.4: Layout of the meteorological stations in the Seyhan River basin.

Table 4.2: Meteorological stations in the Seyhan River basin and statistical characteristics of the annual precipitation data.

Code	Station name	Latitude	Longitude	Altitude (m)	Company Instıtutıon	Observation period	Observation lenght (years)	No-rainy months (%)	Mean (mm)	Min (mm)	Max (mm)	St. dev. (mm)	C_v	C_s	K	r_1
6204	Tufanbeyli	38.26	36.2195	1415	MGM	1998-2012	15	6.67	545	312	706	99.2	0.18	-0.46	1.015	-0.1
6560	Saimbeyli	37.9811	36.0853	1050	MGM	1986-1995	10	4.17	923	625	1233	232.3	0.25	0.219	-1.6	0.25
6893	Çamardı	37.8358	34.9975	1603	MGM	1969-1982	14	7.74	412	316	546	74.1	0.18	0.531	-0.62	-0.1
6902	Feke	37.7764	35.9	583	MGM	1970-1993	24	4.86	910	598	1352	236.3	0.26	0.471	-1.21	0.18
17351	Adana Bölge	37.0041	35.3443	23	MGM	1960-2016	57	11.40	663	317	1265	203.0	0.31	0.828	0.831	-0
17802	Kayseri Pınarbaşı	38.7251	36.3904	1542	MGM	1963-2009	47	4.08	423	267	597	77.8	0.18	0.007	-0.25	0.28
17837	Tomarza	38.4522	35.7912	1402	MGM	1965-2010	46	4.53	408	269	585	74.2	0.18	0.309	-0.19	-0.1
17840	Sarız	38.4781	36.5035	1599	MGM	1968-2011	44	5.30	524	354	748	88.8	0.17	0.24	-0.16	0.09
17906	Ulukışla	37.548	34.4867	1453	MGM	1962-2011	50	6.33	322	182	428	63.8	0.2	-0.39	-0.56	-0
17934	Pozantı	37.4758	34.9022	1080	MGM	1963-1992	30	6.11	719	380	1299	205.6	0.29	0.774	1.276	-0.2
17936	Karaisalı	37.2505	35.0628	240	MGM	1965-2011	47	4.61	881	437	1451	230.9	0.26	0.334	-0.28	0.18
17981	Karataş	36.5683	35.3894	22	MGM	1963-2011	49	15.31	777	366	1365	228.8	0.29	0.508	0.033	0.02
D18M003	Uzunpınar	38.971	36.899	1740	DSİ	1959-2005	47	7.45	303	161	493	82.4	0.27	0.392	-0.53	0.38
D18M004	Seyhan Baraj	37.7	35.083	55	DSİ	1974-2015	42	14.48	657	314	1117	195.5	0.3	0.968	0.373	-0.2
D18M011	Kazancık	39.067	36.733	1585	DSİ	1965-2003	39	7.69	274	176	433	53.5	0.2	0.519	0.801	0.04
D18M012	Hasan Çavuşlar	37.833	35.583	1400	DSİ	1990-2005	16	3.65	1006	713	1539	209.5	0.21	1.014	1.471	0.19
D18M013	Kamışlı	37.567	34.95	1225	DSİ	1963-2002	40	9.17	628	328	1123	189.4	0.3	0.478	-0.21	-0.1
D18M018	Gıcak	37.567	35.2	975	DSİ	1988-2006	19	10.53	843	520	1173	218.5	0.26	-0.08	-1.31	0.23
D18M019	Çeralan	38.1	36	1600	DSİ	1991-2005	15	6.67	970	622	1342	214.2	0.22	0.166	-0.53	0.31

5. APPLICATION, RESULTS AND DISCUSSION

5.1 Steps of Application

The application of the methodology explained in Chapter 3 on the data set given in Chapter 4 is detailed in this chapter. The flowchart showing the step-by-step application is as in Figure 5.1. The data set is first made ready for the application, in terms of formatting for computer codes and softwares used. The primary point is the missing data, when exists, in the monthly precipitation time series of the meteorological station. Gaps due to missing data were completed by taking the observed mean value of the monthly total precipitation to replace for the missing value of precipitation in a month. The 1, 3, 6, 9, 12 and 24 month-SPI values were calculated by using the filled-in precipitation time series. This is performed for the 19 meteorological stations in the Seyhan River basin.

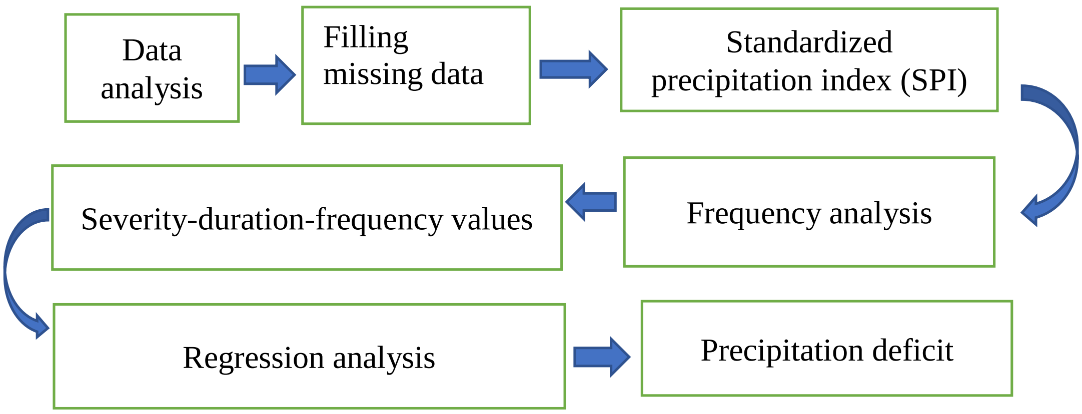

Figure 5.1: Step-by-step application of the methodology.

5.2 Calculation of SPI$_k$ and Determination of Dry and Wet Periods

In order to obtain the SPI$_k$ (k = 1, 3, 6, 9, 12, 24 months), the executable file developed by the National Drought Mitigation Center (NDMC), University of Nebraska-Lincoln, USA was used. The precipitation time series must have integer values owing to the format of the file. Thus, the time series were multiplied by 10 to adjust. The input screen of the software for the time series is shown in Figure 5.2. The input and output files are named as given in Figure 5.3 which indicates the number of time scales used in the SPI calculation. The cumulative SPI_k values in each month (the k month-summation) are calculated from the k month-moving total precipitation which is the summation of the previous k - 1 months added on the last month, the k^{th} month. The SPI_k values were assigned -99 in the first k - 1 months owing to the format of the computer code meaning that no SPI_k values are calculated for these months. The outputs are obtained in the format as shown in Figure 5.4 in which SPI_k (k = 1, 3, 6, 9, 12, 24 months) are produced in a tabular form for each month of the year in the observation period of the meteorological station.

	Years	month	precipitation
2	1966	1	2251
3	1966	2	301
4	1966	3	935
5	1966	4	599
6	1966	5	200
7	1966	6	36
8	1966	7	0
9	1966	8	165
10	1966	9	236
11	1966	10	11
12	1966	11	712
13	1966	12	1535
14	1967	1	1044
15	1967	2	199
16	1967	3	203
17	1967	4	582
18	1967	5	376
19	1967	6	0
20	1967	7	87
21	1967	8	0
22	1967	9	210
23	1967	10	113
24	1967	11	165
25	1967	12	1802
26	1968	1	2138
27	1968	2	915
28	1968	3	495
29	1968	4	33
30	1968	5	114
31	1968	6	60
32	1968	7	0
33	1968	8	48
34	1968	9	794
35	1968	10	368
36	1968	11	718
37	1968	12	1175
38	1969	1	1483
39	1969	2	983

The precipitation time series must have integer values owing to the format of the execute file. Thus, the time series is multiplied by 10 to adjust.

Figure 5.2: Input file for the SPI calculation.

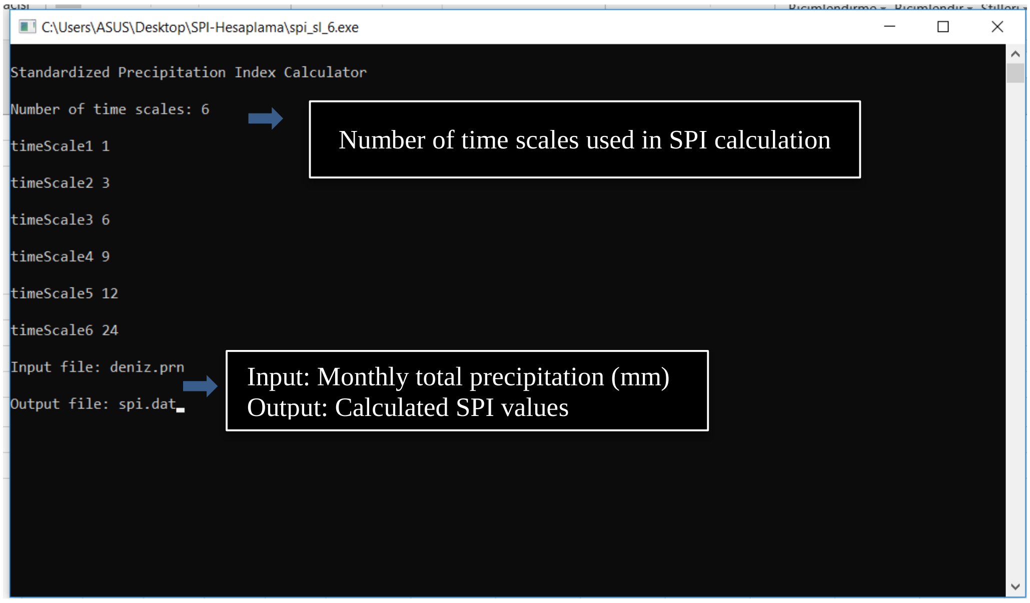

Figure 5.3: Input screen for the SPI calculation.

Year	Mon.	SPI_1	SPI_3	SPI_6	SPI_9	SPI_{12}	SPI_{24}
1965	1	-0.93	-99.00	-99.00	-99.00	-99.00	-99.00
1965	2	1.98	-99.00	-99.00	-99.00	-99.00	-99.00
1965	3	-0.67	0.74	-99.00	-99.00	-99.00	-99.00
1965	4	-0.24	1.26	-99.00	-99.00	-99.00	-99.00
1965	5	2.28	0.65	-99.00	-99.00	-99.00	-99.00
1965	6	0.00	1.39	1.13	-99.00	-99.00	-99.00
1965	7	0.43	2.16	1.82	-99.00	-99.00	-99.00
1965	8	0.81	-0.21	0.54	-99.00	-99.00	-99.00
1965	9	-0.10	-0.32	1.12	1.00	-99.00	-99.00
1965	10	-0.31	-0.58	0.83	1.32	-99.00	-99.00
1965	11	0.24	-0.37	-0.51	0.04	-99.00	-99.00
1965	12	1.12	0.96	0.80	1.26	1.30	-99.00
1966	1	1.00	1.40	1.15	1.58	2.11	-99.00
1966	2	-1.50	1.00	0.68	0.61	0.91	-99.00
1966	3	1.26	0.68	1.19	1.06	1.50	-99.00
1966	4	-0.41	-0.24	1.12	0.85	1.28	-99.00
1966	5	-0.83	0.49	1.06	0.76	0.69	-99.00
1966	6	1.14	-0.61	0.35	0.88	0.78	-99.00
1966	7	0.43	-0.22	-0.37	1.06	0.79	-99.00
1966	8	2.55	1.49	0.80	1.19	0.89	-99.00
1966	9	2.40	2.50	1.59	1.17	1.50	-99.00
1966	10	-0.97	1.38	1.09	0.41	1.35	-99.00
1966	11	-0.66	0.59	0.85	0.84	1.22	-99.00
1966	12	1.29	0.75	1.65	1.34	1.32	1.94
1967	1	0.44	0.97	1.47	1.33	1.02	2.17
1967	2	-1.30	0.82	0.96	1.12	1.36	1.45
1967	3	-0.78	-0.92	-0.14	0.74	0.50	1.40
1967	4	0.04	-1.47	0.10	0.63	0.53	1.39
1967	5	0.15	-0.76	0.36	0.53	0.66	0.99
1967	6	0.00	-0.25	-0.96	-0.22	0.57	1.00
1967	7	0.43	-0.22	-1.56	0.04	0.57	1.00
1967	8	0.81	-0.21	-0.98	0.29	0.47	1.01

Figure 5.4: Output file for the SPI calculation.

Results of the application of the methodology are presented by using monthly precipitation data of one meteorological station taken as an example. The Adana meteorological station (Station number 17351) was selected for this purpose. The station is located in the Adana province in the Seyhan River basin, and it has a record of monthly total precipitation in hand for the period 1960-2016 (57 years). Also, at each meteorological station, SPI time series calculated from the monthly precipitation were analysed to determine the drought periods observed for time scales k = 1, 3, 6, 9, 12, 24 months; i.e., SPI_1, SPI_3, SPI_6, SPI_9, SPI_{12}, SPI_{24} were used. Such drought parameters as the severity, duration and intensity were also calculated of each SPI_k time series by using monthly precipitation data of each meteorological station in the Seyhan River basin. In this context, dry and wet periods were determined for each station at each time scale taken into consideration. The critical drought severity (S) of each year were obtained from the SPI_k time series for the drought duration from D = 1 month up to 48 months at maximum (when exists). Annual drought severity series were obtained from the SPI_k time series for each drought duration. Table 5.1 shows the events for each class of drought and the occurrence percentage of each in the time series of the k time-scales. Accordingly, for the Adana meteorological station, SPI_{24} is the most likely to experience (total percentage 50.3%) among all time scales. The class with the highest occurrence frequency is the mild drought with probabilities changing in the range 32-35% (Table 5.1).

SPI_k values and dry-wet periods of the selected station (17351) are given in Figure 5.5-5.10 for the period from 1960 to 1991 at time scales k = 1, 3, 6, 9, 12 and 24 months. The remaining portion of the observation period between 1992 and 2016 of the station is given in Appendix A.1-A.6. Wet periods were taken at once without being classified while dry periods were indicated as mild, moderate, severe and extreme droughts based on the classification of Mc Kee et al. (1993). As seen in Figure 5.5, for the time scale k = 1 month, the maximum duration of dry period is 6 months. The maximum drought duration continued uninterrupted from December 1988 to May 1989 with the most severe month in February 1989. For the time scale k = 3 months, the maximum drought duration is 12 months which lasted from July 1971 to June 1972; the most severe drought of this period is in February 1973.

	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975
JANUARY	-0.58	-0.89	-0.12	0.89	-1.89	-0.36	1.84	0.07	1.38	1.17	-0.38	-1.53	-1.42	-1.21	0.12	0
FEBRUARY	-1.38	2.1	1.09	1.29	0.98	1.14	-1.54	-0.65	-0.21	-0.38	0.38	0.29	0.21	-1.51	-1.14	0.43
MARCH	1.96	-0.13	-0.55	0.2	0.75	1.05	0.47	1.84	-0.21	1.29	0.33	-0.64	-0.9	-0.58	-0.01	-0.17
APRIL	-0.31	-0.51	0.47	0.94	-0.01	0.56	-1.07	2.36	-1.66	-0.71	-1.68	1.54	-0.3	0.88	-0.22	1.91
MAY	0.66	-0.09	-0.07	2.52	0.12	-0.48	-1.08	0.83	0.63	-0.17	-0.87	-1.37	0.01	-0.23	-1.76	-0.34
JUNE	0	-1.16	-1.16	0.73	1.6	0.65	-0.97	0.51	0.87	0.81	-0.73	0.22	0.61	0.82	-1.16	-0.36
JULY	0.34	-0.15	-0.15	0.79	-0.15	-0.15	0.6	0.2	0.8	-0.15	0.61	0.06	0.69	-0.15	-0.15	-0.15
AUGUST	0.15	0.15	0.15	0.15	0.15	0.72	0.15	0.15	0.24	0.15	0.15	0.72	0.15	0.15	1.98	0.15
SEPTEMBER	-0.61	0.51	-1.08	-0.3	-0.72	-1.08	0.17	-0.73	1.49	0.25	-0.24	0.09	-0.06	0	1.46	-0.65
OCTOBER	-1.15	0.66	-0.01	-0.78	-1.81	-0.43	-0.83	0.09	0.65	0.85	0.24	-1.61	0.21	-0.44	-0.06	-1.61
NOVEMBER	-0.02	-0.98	-1.85	-0.74	0.51	-0.86	0.19	1.02	2.49	-0.51	0.55	0.06	-0.6	0.14	-0.41	0.32
DECEMBER	-0.72	1.79	1.3	-1.1	-0.95	0.67	0.85	0.04	1.7	0.05	-0.51	-0.52	-1.81	-0.32	1.64	-0.28

	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991
JANUARY	0.81	0.76	0.85	-0.21	1.01	2.38	-0.39	0.04	0.68	0.97	0.26	0.77	-0.67	-0.31	-1.52	-0.91
FEBRUARY	-0.4	-0.33	1.3	-1.21	0.58	1.2	-1.39	1.1	0.17	0	-0.17	-0.86	0.9	-3.53	0.95	0.33
MARCH	-0.16	-0.15	0.26	-1.29	1.26	-0.34	-0.25	0.36	-0.18	-0.12	-2.78	2.25	1.82	-0.03	0	-1.32
APRIL	1.55	0.77	0.11	-0.35	1.04	0.43	-0.32	0.93	1.03	-0.49	-1.59	-1.13	-0.27	-2.11	-0.51	0.7
MAY	1.91	-0.03	-1.55	-0.19	0.64	0.33	-0.87	1.32	-2.17	0.64	0.36	0.06	0.63	-3.37	0.12	-0.46
JUNE	-0.88	-0.73	0.3	1.11	-0.84	2.37	1.04	0.73	-1.06	-0.18	0.14	-0.48	1.4	0.32	1.46	-0.59
JULY	1.98	0.92	-0.15	-0.15	-0.15	-0.15	1.42	-0.15	-0.07	-0.15	-0.15	2.07	-0.15	-0.15	-0.15	-0.07
AUGUST	0.56	0.15	0.15	0.15	0.15	0.15	0.74	0.24	1.3	0.15	0.15	2.11	0.15	0.15	0.24	0.56
SEPTEMBER	0.73	-0.01	0.35	-0.29	-0.72	-0.38	0.28	1.05	-1.08	0.02	-0.5	-1.08	-0.94	0.79	0.31	0.03
OCTOBER	1.33	0.47	1.39	0.05	-0.2	0.8	1.08	-0.98	-1.05	1.63	0.73	1.03	1.5	1.5	0.15	0.24
NOVEMBER	1.19	-1.73	-0.98	1.01	0.59	0.05	-0.98	0.88	0.27	0.18	0.01	0.23	0.79	0.51	-1.01	0.45
DECEMBER	0.51	0.38	0.64	0.31	-0.42	0.93	-0.45	0.04	-0.65	-0.92	-0.25	0.83	-0.17	0.26	-0.54	2.04

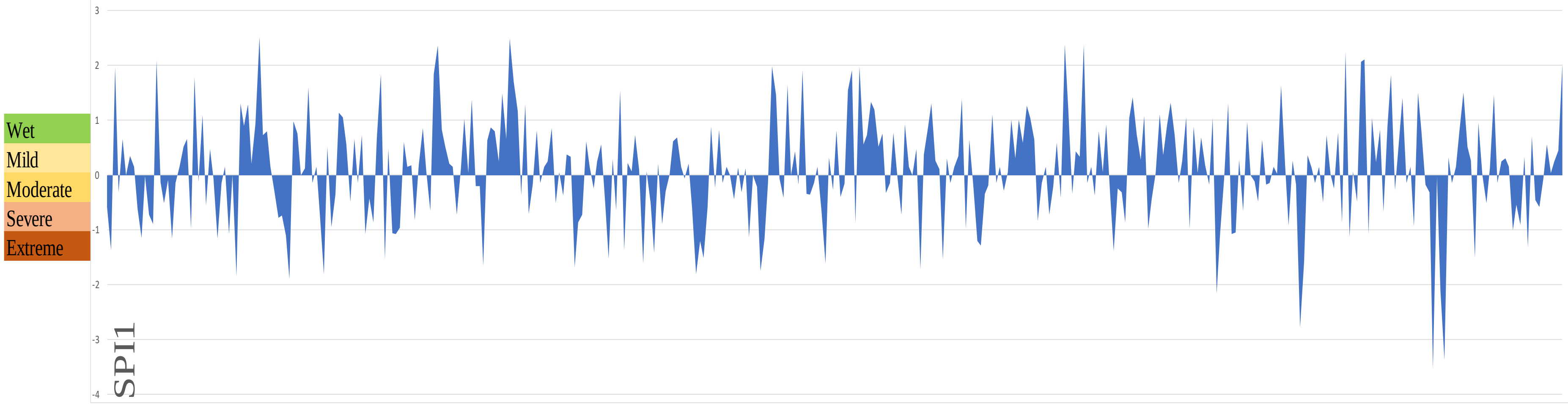

Figure 5.5: Dry and wet periods calculated from SPI_1 series for Adana meteorological station.

	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975
JANUARY		-1.07	0.92	0.86	-2.09	-0.64	1.1	0.46	1	2.48	-0.55	-0.77	-1.07	-2.3	-0.29	0.91
FEBRUARY		0.14	1.61	1.69	-1.07	-0.41	1.2	0.27	0.66	1.71	-0.26	-1.12	-1.15	-3.08	-0.8	1.29
MARCH	0.06	0.68	0.14	1.18	-0.04	0.65	1.22	0.52	0.83	1.12	-0.14	-1.11	-1.22	-2.03	-0.61	-0.07
APRIL	0.45	1.27	0.58	1.25	0.86	1.37	-1.19	2.01	-1.09	0.12	-0.29	0.64	-0.63	-0.71	-1.01	1.15
MAY	1.35	-0.69	-0.32	2.18	0.28	0.56	-0.86	2.69	-0.6	0.29	-1.11	0.15	-0.94	-0.1	-0.98	0.9
JUNE	-0.01	-0.95	-0.21	2.37	0.65	0.12	-2.04	2.02	-0.09	-0.39	-2.28	0.55	-0.21	0.54	-1.5	0.99
JULY	0.31	-0.72	-0.7	2.27	0.82	-0.27	-1.33	0.63	0.78	0.04	-1.12	-1.07	0.17	0.01	-2.49	-0.79
AUGUST	-0.57	-1.62	-1.62	0.51	1.28	0.27	-1.04	-0.04	0.69	0.29	-0.93	-0.18	0.32	0.3	0.57	-1.18
SEPTEMBER	-0.84	0.03	-1.81	-0.19	-1.31	-0.86	-0.02	-1.1	1.17	-0.23	-0.32	-0.1	-0.12	-0.49	1.67	-1.22
OCTOBER	-1.56	0.51	-0.54	-1.03	-2.5	-0.76	-0.76	-0.39	1.01	0.57	-0.12	-0.96	-0.09	-0.6	1.18	-2.06
NOVEMBER	-0.92	-0.37	-1.76	-1.49	-0.39	-1.56	-0.41	0.63	2.77	-0.08	0.26	-0.74	-0.7	-0.39	-0.01	-0.59
DECEMBER	-1.07	1.32	0.58	-1.77	-0.86	-0.03	0.43	0.42	2.62	-0.11	-0.2	-0.91	-1.77	-0.53	1.12	-0.54

	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991
JANUARY	0.21	0.97	0.18	-0.11	0.91	1.36	0.31	-0.78	0.54	0.15	-0.46	0.08	0.21	-0.07	-0.28	-1.39
FEBRUARY	-0.03	0.48	1.03	-0.18	0.8	1.76	0	0	0.25	0.04	-0.72	-0.18	0.5	-1.28	-0.15	-0.93
MARCH	0.22	0.2	1.18	-1.41	1.32	2.36	-1.23	0.54	0.32	0.54	-0.69	1.18	0.79	-1.39	-0.35	-1.03
APRIL	0.45	-0.07	0.91	-1.84	1.36	0.72	-1.34	1.17	0.38	-0.52	-1.97	0.65	1.38	-2.51	0.28	-0.1
MAY	1.87	0.11	-0.53	-1.28	1.42	-0.02	-1.02	1.27	-0.17	-0.17	-1.83	1.13	1.24	-1.98	-0.47	-0.63
JUNE	1.93	0.09	-0.71	-0.02	0.68	1.54	-0.34	1.4	-0.25	-0.16	-0.72	-1.06	0.69	-2.51	0.33	-0.16
JULY	1.84	-0.27	-1.08	0.26	0.05	1.55	0.41	1.11	-2.85	0.19	0.04	0.62	0.97	-1.28	0.71	-0.99
AUGUST	0.91	-0.52	-0.37	0.67	-1.56	2.26	1.4	0.18	-0.31	-0.97	-0.58	1.98	1.04	-0.34	1.12	-1.12
SEPTEMBER	1.43	0.1	-0.13	-0.81	-1.31	-0.9	0.82	0.56	-0.07	-0.47	-1.04	1.77	-1.61	0.3	-0.16	-0.28
OCTOBER	1.17	0.16	1.06	-0.31	-0.67	0.35	0.85	-0.1	-0.68	1.19	0.26	1.17	0.95	1.3	0.02	0.04
NOVEMBER	1.59	-0.96	0.18	0.65	0.06	0.11	-0.11	0.6	-0.6	0.86	0.02	0.35	1.12	1.17	-0.85	0.21
DECEMBER	1.18	-0.21	0.5	0.58	-0.24	0.79	-0.5	0.14	-0.79	0.01	-0.17	0.84	0.62	0.73	-1.05	1.81

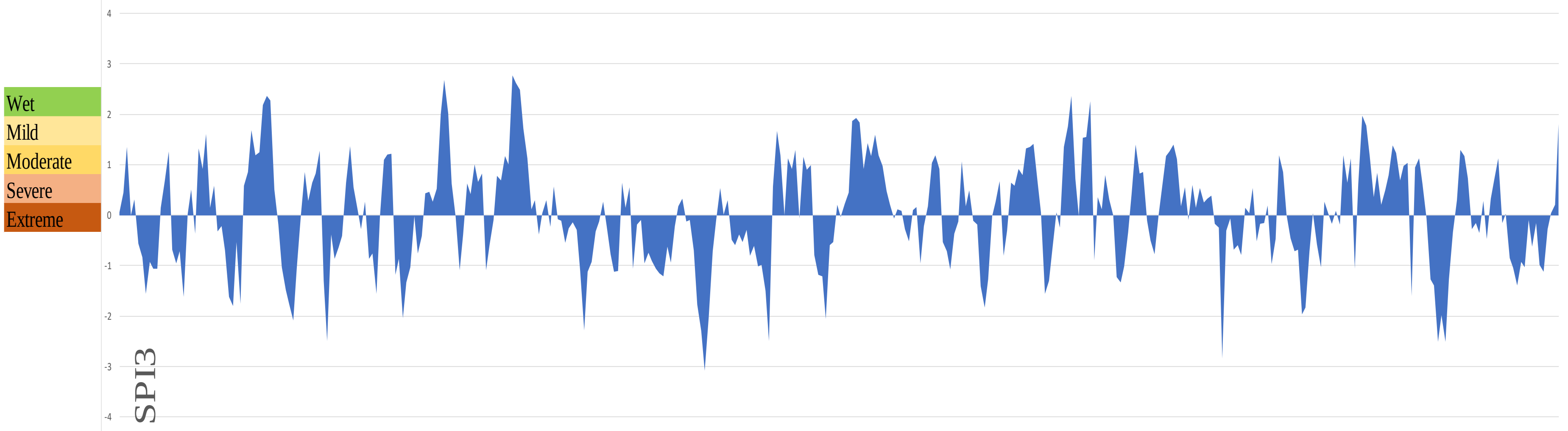

Figure 5.6: Dry and wet periods calculated from SPI_3 series for Adana meteorological station.

	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975
JANUARY		-1.64	0.98	0.68	-2.6	-1.2	0.92	0.2	0.86	2.77	-0.46	-0.96	-1.52	-2.3	-0.6	1.2
FEBRUARY		-0.35	1.29	1.07	-1.75	-0.67	0.58	-0.04	0.78	2.84	-0.39	-0.9	-1.5	-2.91	-1.02	1.09
MARCH		-0.3	1.09	1.1	-1.24	-0.22	0.7	0.54	0.74	2.79	-0.3	-0.96	-1.62	-2.8	-0.93	0.79
APRIL		-0.22	1.02	1.24	-1	0.12	0.6	1.28	0.52	2.51	-0.73	-0.41	-1.34	-2.19	-0.82	1.25
MAY		-0.21	1.3	2.31	-0.76	-0.12	0.74	1.53	0.3	1.58	-0.73	-0.86	-1.44	-2.13	-1.16	1.43
JUNE	-0.04	0.15	-0.07	2.17	0.22	0.53	0.43	1.47	0.6	0.75	-1	-0.62	-1.19	-1.19	-1.27	0.4
JULY	0.41	0.73	0.09	2.31	1.03	0.96	-1.73	1.89	-0.42	0	-0.83	0.05	-0.53	-0.69	-1.79	0.6
AUGUST	1.06	-1.13	-0.76	2.08	0.68	0.51	-1.18	2.45	-0.33	0.27	-1.4	0	-0.79	-0.07	-0.69	0.53
SEPTEMBER	-0.45	-1.1	-0.78	2.27	0.23	-0.31	-2.08	1.78	0.41	-0.68	-2.51	0.34	-0.45	0.22	-0.07	0.61
OCTOBER	-0.66	-0.25	-1.15	1.57	-0.2	-0.92	-1.76	0.09	1.13	0.26	-1.05	-1.73	-0.14	-0.58	0.03	-1.97
NOVEMBER	-1.07	-0.78	-2.21	-1.01	0.14	-1.19	-0.71	0.49	2.65	-0.05	-0.05	-0.78	-0.55	-0.3	0.11	-0.92
DECEMBER	-1.34	1.27	0.36	-1.88	-1.17	-0.25	0.34	0.21	2.79	-0.25	-0.36	-1.03	-1.85	-0.73	1.46	-0.83

	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991
JANUARY	-0.2	1.26	0.1	0.17	0.78	1.23	0.31	-0.53	0.42	-0.13	-0.08	0.04	0.51	0.15	0.14	-1.48
FEBRUARY	-0.41	1.16	0.53	-0.19	0.91	1.58	-0.07	-0.17	0.41	-0.34	-0.21	-0.27	0.49	-0.4	0.41	-1.35
MARCH	-0.36	0.99	0.56	-0.45	1.19	1.48	-0.08	-0.09	0.2	-0.27	-0.54	0.59	1.04	-0.31	0.29	-1.6
APRIL	0.29	0.82	0.48	-0.93	1.34	1.51	-0.31	-0.1	0.56	-0.19	-1.35	0.27	0.75	-1.08	-0.22	-1.27
MAY	0.85	0.4	0.67	-0.71	1.24	1.53	-0.46	0.54	0.09	-0.1	-1.4	0.34	0.91	-1.98	-0.39	-1.11
JUNE	1.21	0.12	0.7	-1.21	1.36	2.66	-1.27	1.1	0.07	0.3	-1.03	0.6	0.92	-2.33	-0.2	-1.02
JULY	1.44	-0.31	0.3	-1.33	1.07	1.41	-0.88	1.45	-0.43	-0.44	-1.6	0.75	1.54	-2.89	0.51	-0.62
AUGUST	1.91	-0.12	-0.69	-0.87	1.01	1.01	-0.23	1.14	-0.34	-0.5	-1.95	1.71	1.39	-1.97	0	-0.97
SEPTEMBER	2.39	-0.06	-0.96	-0.46	0.26	1.26	-0.05	1.47	-0.47	-0.52	-1.28	0.27	0.25	-2.08	0.1	-0.47
OCTOBER	2.07	-0.29	0.17	-0.2	-0.59	1.33	0.74	0.69	-2.25	0.88	0.01	1.14	1.22	0.37	0.39	-0.83
NOVEMBER	1.6	-1.09	-0.01	0.71	-0.33	1	0.4	0.52	-0.7	0.54	-0.21	1.01	1.23	0.93	-0.25	-0.12
DECEMBER	1.44	-0.29	0.39	0.4	-0.51	0.61	-0.33	0.18	-0.91	-0.16	-0.42	1.23	0.41	0.7	-1.19	1.74

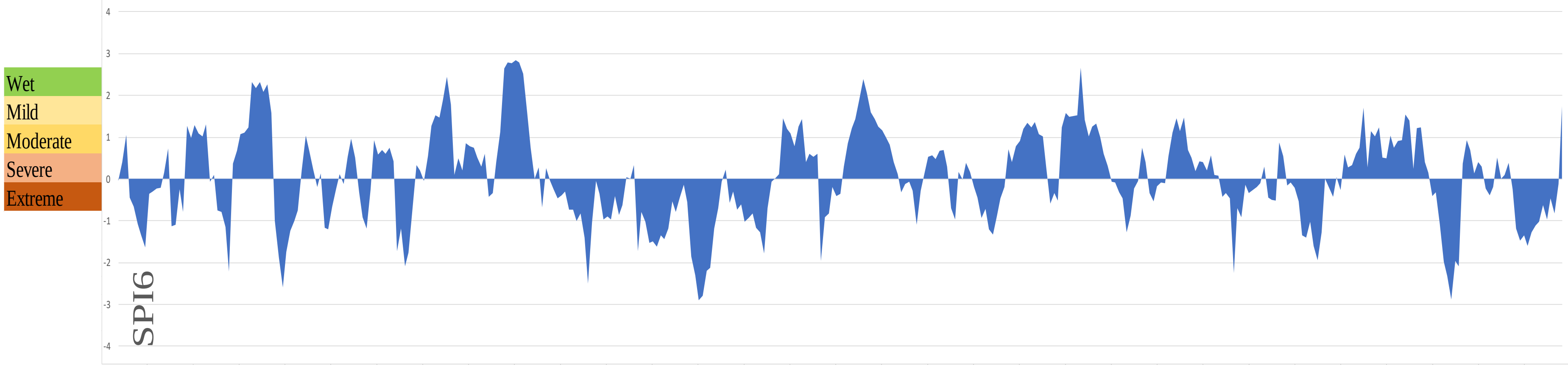

Figure 5.7: Dry and wet periods calculated from SPI_6 series for Adana meteorological station.

	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
JANUARY	0.86	1.28	0.4	1.8	0.46	-1	0.24	0.24	-1.48	-0.71	1.47	-1.23	0.34	-1.27	-0.72	-0.28	-0.75	-0.65	0.26	-0.43	1.03	1.12	-1.58	0.7	-0.23
FEBRUARY	0.81	0.93	0.03	1.66	0.54	-0.97	-0.11	0.39	-0.92	-1.02	1.04	-0.91	0.67	-1.2	-0.42	0.1	-0.93	-0.21	0.23	-0.5	0.94	0.83	-2.3	0.94	-0.42
MARCH	0.65	0.76	-0.1	1.58	0.71	-1.19	0.11	0.34	-1.09	-0.92	0.95	-0.53	0.39	-0.97	-0.48	0.24	-1.17	0.29	0.05	-0.09	0.7	0.74	-2.05	0.89	-0.28
APRIL	0.5	0.31	-0.26	1.62	0.53	-0.78	0.14	0.54	-0.82	-1.2	1.14	-0.48	0.25	-0.94	-0.79	0.37	-1.4	0.21	0.15	0.06	0.56	0.69	-2.24	0.74	-0.36
MAY	0.66	0.6	-0.08	1.5	0.38	-0.88	0.06	0.34	-0.61	-0.55	0.86	-0.82	0.13	-0.91	-1.04	0.3	-1.47	0.08	0.22	0.39	0.72	0.75	-2.31	0.81	-0.13
JUNE	0.79	0.65	-0.07	1.65	0.44	-0.86	-0.03	0.22	-1	-0.83	0.7	-0.82	0.06	-0.84	-1.24	0.22	-1.47	-0.03	0.03	0.61	0.77	0.75	-1.85	0.37	-0.65
JULY	1	0.76	0.18	1.73	0.46	-1.07	-0.26	0.32	-0.78	-1.5	0.8	-0.6	0.17	-0.58	-0.93	-0.42	-1.3	0.12	0.15	0.62	0.94	0.6	-1.81	0.27	-0.6
AUGUST	1.03	0.04	0.51	0.78	-0.02	-0.77	-0.54	0.12	-0.44	-1.16	0.96	-0.39	0.47	-1.01	-1.04	-0.63	-1.55	0.27	-0.2	1.04	1.17	0.47	-1.54	0.38	-0.25
SEPTEMBER	-0.97	-0.65	1.05	0.68	0.52	-1.06	-0.98	0.07	0.31	-0.55	-0.26	-0.19	0.17	-0.35	-0.62	0.07	-2.18	0.91	-0.45	0.8	1.19	-0.64	-0.29	1.33	0.75
OCTOBER	-0.54	-1.05	-0.48	0.04	0.5	-0.08	-0.88	-0.04	1.26	0	-0.79	-0.3	-1.92	0.05	0.95	0.51	-1.9	0.56	-0.82	0.92	0.35	-0.21	0.43	1.55	0.28
NOVEMBER	1.06	-0.91	1.58	0.99	-0.26	0.4	0.34	-0.92	0.59	0.24	-1.07	-1.05	-1.31	0.07	0.68	0.22	-1.74	0.63	-1.42	0.59	0.49	-0.56	0.75	0.72	-0.27
DECEMBER	1.43	-1.42	1.58	0.3	-0.67	0.94	0.41	-1.28	0.11	1.47	-1.01	-0.66	-1.36	-0.36	-0.18	0.11	-1.59	0.08	-0.07	0.41	1.45	-1.25	0.6	-0.86	0.42

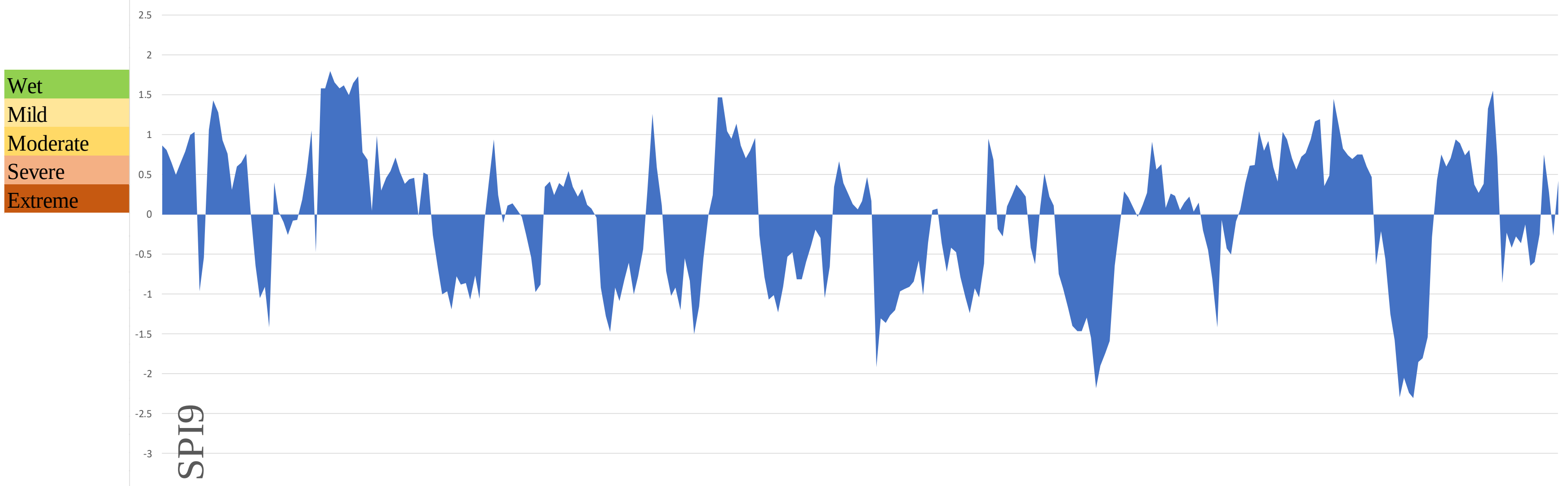

Figure 5.8: Dry and wet periods calculated from SPI_9 series for Adana meteorological station.

Similarly, for the time scale k = 6 months, the longest drought duration is 23 months that lasted from October 1971 to August 1973 with the most severe drought observed in February 1974. The longest drought for the time scale k = 9 and 12 months is longer than that for time scale k = 48 months; they last from December 1969 to November 1974 (for k = 9 months) and from January 1970 to November 1974 (for k = 12 months) with extreme droughts spanning over the year 1973. For the time scale k = 24 months, the longest drought duration is extended from December 1970 to March 1975. It is seen at the same time that the most severe drought which is an extreme drought is observed in this particular dry period to extend over 24 months from December 1972 to November 1974.

As mentioned in Chapter 4, the European Drought Observatory (EDO) observes and maps droughts over a region by using precipitation, soil moisture and plant indicators. Based on the observation of EDO, the most severe drought in the Seyhan River basin was observed in 1990-1991 (Figure 4.3). Results for SPI_6 and SPI_{12} in Figure 5.5 support the observation of EDO. The wettest period was observed mostly in 1969 for all k time scales. Furthermore, droughts with longer durations become more significant as the k time scale increases.

Table 5.1: Percentage of drought occurrences in Adana meteorological station.

Drought class	SPI Class	Drought percentage (%)					
		k = 1	k = 3	k = 6	k = 9	k = 12	k = 24
Mild	[-0.99, 0]	32.2	32.3	33.6	31.8	33.4	35.4
Moderate	[-1.49, -1]	7.3	9.8	8.8	10.9	9.4	7.6
Severe	[-1.99, -1.5]	3.8	4.1	3.5	3.6	4.0	2.6
Extreme	≤ -2.00	1.3	2.8	3.4	2.4	2.4	3.8
Wet	≥ 0	55.4	51.0	50.7	51.3	50.8	50.7
Total		100	100	100	100	100	100

	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974
JANUARY		-1.06	1.18	0.57	0.03	-0.35	1.24	-0.7	1.71	2.54	-0.48	-1.39	-1.25	-2.14	-1
FEBRUARY		0.17	0.77	0.65	-0.1	-0.29	0.67	-0.56	1.8	2.54	-0.27	-1.46	-1.3	-2.78	-0.96
MARCH		-0.51	0.71	0.79	0.05	-0.18	0.52	-0.05	1.34	2.83	-0.58	-1.73	-1.35	-2.7	-0.83
APRIL		-0.53	0.86	0.89	-0.18	-0.04	0.25	0.83	0.46	2.82	-0.67	-0.85	-2.01	-2.17	-1.11
MAY		-0.71	0.86	1.63	-1.22	-0.14	0.19	1.1	0.41	2.68	-0.76	-0.88	-1.75	-2.21	-1.27
JUNE		-0.78	0.85	1.73	-0.94	-0.38	0.04	1.19	0.46	2.64	-0.96	-0.78	-1.65	-2.12	-1.49
JULY		-0.8	0.85	1.78	-1.02	-0.38	0.08	1.18	0.51	2.63	-0.93	-0.83	-1.61	-2.21	-1.51
AUGUST		-0.81	0.86	1.8	-1.03	-0.36	0.05	1.19	0.51	2.65	-0.94	-0.81	-1.67	-2.24	-1.23
SEPTEMBER		-0.73	0.78	1.87	-1.1	-0.39	0.11	1.16	0.78	2.59	-1.04	-0.81	-1.75	-2.31	-0.97
OCTOBER		-0.4	0.64	1.76	-1.15	-0.27	0.07	1.24	0.88	2.57	-1.2	-1.03	-1.43	-2.43	-0.87
NOVEMBER		-0.64	0.58	1.87	-0.71	-0.7	0.33	1.55	1.77	1.39	-0.79	-1.27	-1.69	-2.13	-1.07
DECEMBER	-0.92	0.96	0.12	0.79	-0.62	0.12	0.44	1.1	2.53	0.29	-1.02	-1.2	-2.09	-1.41	0.4

	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991
JANUARY	0.37	0.08	1.79	-0.17	0.21	0.06	1.58	0.97	-1.04	1.09	-0.44	-0.4	-0.82	0.77	0.93	-1.15	-0.89
FEBRUARY	0.7	-0.16	1.82	0.36	-0.53	0.46	1.77	0.36	-0.32	0.82	-0.51	-0.46	-1.02	1.18	0.31	-0.34	-1.18
MARCH	0.68	-0.15	1.84	0.46	-0.82	0.97	1.46	0.39	-0.17	0.72	-0.49	-0.76	0.15	1.03	-0.26	-0.33	-1.45
APRIL	1.19	-0.29	1.61	0.3	-0.9	1.22	1.3	0.24	0.13	0.74	-0.87	-0.88	0.19	1.11	-0.46	-0.14	-1.09
MAY	1.27	0.37	1.11	0.15	-0.73	1.35	1.22	0.06	0.58	0.23	-0.48	-0.95	0.13	1.2	-0.83	0.07	-1.2
JUNE	1.28	0.34	1.1	0.22	-0.56	1.14	1.71	-0.39	0.51	0.07	-0.43	-0.91	0.07	1.42	-1.1	0.3	-1.62
JULY	1.29	0.59	0.94	0.16	-0.56	1.15	1.72	-0.24	0.38	0.07	-0.44	-0.92	0.36	1.2	-1.11	0.3	-1.63
AUGUST	1.12	0.61	0.94	0.16	-0.57	1.16	1.74	-0.21	0.35	0.17	-0.56	-0.93	0.59	1	-1.13	0.3	-1.63
SEPTEMBER	0.9	0.74	0.88	0.19	-0.67	1.17	1.8	-0.17	0.47	-0.04	-0.52	-1.02	0.59	1.02	-0.98	0.23	-1.74
OCTOBER	0.76	1.16	0.64	0.45	-1.08	1.12	1.91	-0.07	0.1	-0.04	0.11	-1.37	0.66	1.14	-0.95	-0.15	-1.67
NOVEMBER	0.96	1.5	-0.13	0.52	-0.34	0.95	1.78	-0.31	0.64	-0.32	0.08	-1.46	0.73	1.35	-1.11	-0.59	-1.16
DECEMBER	-0.3	1.75	-0.2	0.65	-0.53	0.62	2.23	-1.17	0.81	-0.6	0.01	-1.08	1.21	0.82	-0.79	-0.96	0.79

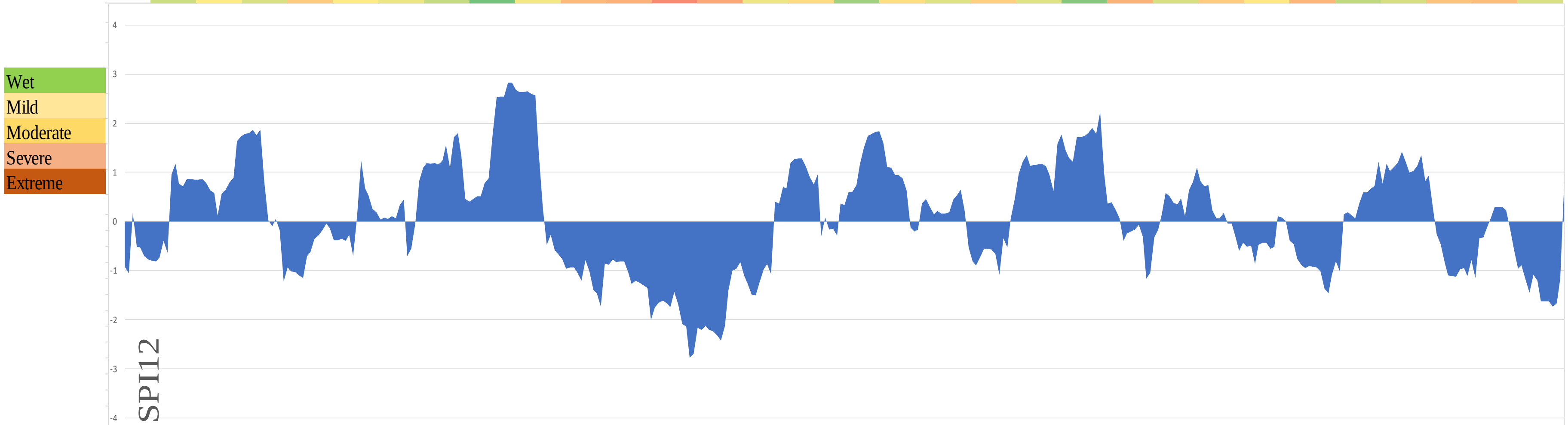

Figure 5.9: Dry and wet periods calculated from SPI_{12} series for Adana meteorological station.

	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975
JANUARY			0.17	1.14	0.35	-0.28	0.61	0.41	0.8	2.85	1.59	-1.32	-1.87	-2.36	-2.17	-0.44
FEBRUARY			0.57	0.88	0.32	-0.31	0.22	0.06	0.92	2.82	1.65	-1.14	-1.87	-2.66	-2.39	-0.14
MARCH			0.11	0.92	0.51	-0.14	0.17	0.25	0.83	2.71	1.71	-1.53	-2.07	-2.63	-2.23	-0.09
APRIL			0.22	1.11	0.44	-0.22	0.07	0.67	0.81	2.29	1.72	-1.09	-1.94	-2.88	-2.23	0.15
MAY			0.1	1.65	0.47	-0.97	-0.04	0.84	0.98	2.19	1.59	-1.2	-1.85	-2.78	-2.42	0.14
JUNE			0.06	1.71	0.69	-0.97	-0.3	0.81	1.07	2.18	1.46	-1.26	-1.71	-2.64	-2.53	0.04
JULY			0.05	1.74	0.69	-1.01	-0.27	0.81	1.08	2.18	1.45	-1.26	-1.7	-2.64	-2.57	0.04
AUGUST			0.05	1.76	0.7	-1	-0.28	0.8	1.09	2.2	1.47	-1.26	-1.72	-2.71	-2.38	0.03
SEPTEMBER			0.03	1.74	0.71	-1.06	-0.25	0.81	1.24	2.27	1.33	-1.31	-1.76	-2.79	-2.21	-0.01
OCTOBER			0.12	1.55	0.59	-0.98	-0.2	0.84	1.34	2.28	1.24	-1.54	-1.69	-2.59	-2.16	-0.06
NOVEMBER			-0.06	1.56	0.87	-0.98	-0.27	1.19	2.08	1.98	0.46	-1.39	-1.97	-2.52	-2.09	-0.01
DECEMBER		0.08	0.71	0.58	0.11	-0.41	0.32	1.02	2.55	2.07	-0.54	-1.65	-2.37	-2.53	-0.67	0.01

	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991
JANUARY	0.23	1.29	1.15	-0.04	0.11	1.11	1.68	0.01	0.11	0.44	-0.65	-0.9	-0.03	1.09	-0.08	-1.47
FEBRUARY	0.32	1.15	1.44	-0.14	-0.07	1.46	1.41	-0.01	0.31	0.2	-0.69	-1.02	0.2	0.95	-0.06	-1.03
MARCH	0.3	1.15	1.49	-0.25	0.13	1.53	1.18	0.09	0.32	0.13	-0.88	-0.43	0.73	0.49	-0.44	-1.18
APRIL	0.6	0.93	1.27	-0.42	0.29	1.63	1	0.18	0.52	-0.07	-1.25	-0.49	0.83	0.44	-0.47	-0.87
MAY	1.08	0.96	0.82	-0.45	0.48	1.69	0.84	0.37	0.48	-0.23	-1.05	-0.6	0.87	0.31	-0.57	-0.79
JUNE	1.06	0.93	0.86	-0.28	0.42	1.88	0.96	0.04	0.33	-0.31	-0.98	-0.61	1	0.35	-0.55	-0.84
JULY	1.22	0.97	0.69	-0.33	0.42	1.88	1.05	0.04	0.24	-0.31	-0.98	-0.39	1	0.16	-0.55	-0.84
AUGUST	1.11	0.98	0.69	-0.33	0.42	1.91	1.08	0.03	0.28	-0.32	-1.08	-0.22	1.01	-0.01	-0.56	-0.84
SEPTEMBER	1.03	1.02	0.66	-0.37	0.37	1.93	1.13	0.14	0.22	-0.44	-1.09	-0.28	1.01	0.08	-0.52	-0.95
OCTOBER	1.21	1.13	0.65	-0.41	0.11	1.95	1.26	-0.05	-0.03	-0.02	-0.83	-0.41	1.13	0.19	-0.77	-1.19
NOVEMBER	1.54	0.9	0.2	0.07	0.38	1.72	1.01	0.18	0.17	-0.22	-0.88	-0.39	1.29	0.26	-1.16	-1.19
DECEMBER	1.08	1.14	0.27	0.06	0.03	2.02	1.05	-0.2	0.14	-0.48	-0.79	0.2	1.36	0.03	-1.32	-0.09

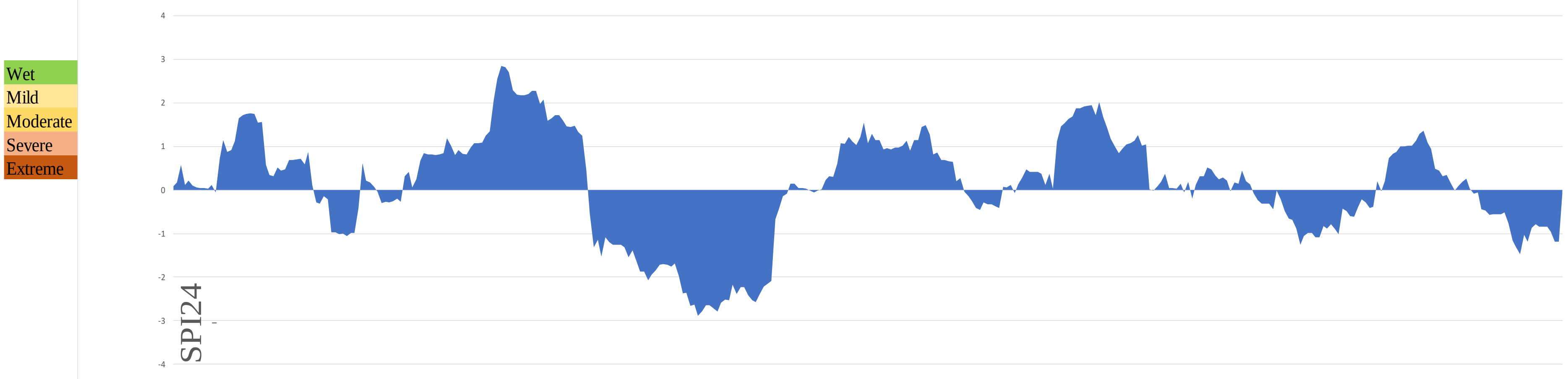

Figure 5.10: Dry and wet periods calculated from SPI_{24} series for Adana meteorological station.

5.3 Identification of Critical Drought from SPI_k Time Series

Once the SPI_k time series have been calculated, dry and wet periods were determined; duration of drought is counted and its severity is calculated. Any droughts that lasts longer than one month was assigned as the drought of the month in which it ends. For example; a 3 month-drought period from June to August (both inclusive) was assigned to August. This is applied also to over-year drought periods; i.e., a drought period starting in October and ending in April next year is considered as a 7month-drought of April in the next year. The critical drought severity of each year was obtained from the SPI_k time series for the drought duration from D = 1 month up to 48 months at maximum. For each year, drought with the highest severity is defined as the critical drought when multiple droughts are observed in the same year. When there is only one drought period (no matter how long it is) within a year, it is assigned as the critical drought of this particular year. The most severe drought observed in any month of the year is taken as the critical drought severity in the year independent from the month it was observed. For droughts lasting longer than one month, the within-period droughts with durations shorter than the duration of the dry period are also considered. For example, in a dry period of 3-months, there are three 1 month-droughts, two 2 month-droughts and one 3 month-drought. As a more comprehensive but similar example, there exist one 5 month-drought in the dry period of 5 months; two 4 month-droughts; three 3 month- droughts; four 2 month- droughts; and finally, the dry period is composed of five 1 month-droughts. When more than one drought is observed within a year, either within-period or singular, drought with the highest severity is taken as the critical drought for each drought duration. Another option is that, no drought might be observed in some years for which then no critical drought exists. Based on the explained conceptualization, critical droughts are determined at k time scales for each D month-duration for each meteorological station.

The critical drought severity was determined based on the most severe drought of each dry period in the year. The cumulative precipitation over k consecutive months shows the k time-scale precipitation (k = 3, 6, 9, 12, 24-month). Likewise, the maximum of absolute sum of the consecutive SPIs gives the critical drought severity of each year for the desired drought duration. Thus, the most severe drought was identified for each drought duration and time scale. As the drought duration decreases, the drought severity reflected by the precipitation deficit decreases; in other words, the drought duration increases with increasing drought severity. Besides, when the drought duration increases, that is a longer drought, the likelihood of drought is reduced. However, there exist some years through which no negative SPI is obtained for longer drought, thus severity of critical drought in such a year is taken zero.

Frequency analysis was applied on the critical drought severity series for each drought duration (D = 1, 2, … months up to the longest duration or to 48 months at maximum) to find the best-fit probability distribution function. Years with no drought are subject to removal from the SPI_k time series used in the frequency analysis. In other words, when detecting the probability distribution function, zero values were ignored. The non-zero critical drought severity time series 10 years long at minimum were used in the frequency analysis. Because, for the critical drought severity time series shorter than 10 years, frequency analysis was found unsuccessful in determining the probability distribution function. In order to apply the frequency analysis, the absolute value of the critical drought severity was taken. The critical drought severities for k = 1, 3, 6, 9, 12 and 24 month-time scales and the drought durations are given in Table 5.2 for the period of 1960-1980 for Adana meteorological station. The rest of the observation period, from 1992 to 2016, is given in Table A.1 (Appendix A.1). Therefore, Table 5.2 and Table A.1 should be considered together when a discussion is made. It is seen from Tables 5.2 and A.1 that the number of the one month-drought in SPI_1 is 57. In other, the one month-drought was observed every year in the observation period from 1960 to 2016. No drought duration longer than 5 months is expected for SPI_1. Similarly, no drought lasting longer than 6 months is expected for SPI_6. It is seen that when the drought duration and the time scale increase, the critical drought severity increases. As a matter of fact, no drought was observed in longer drought durations, as it is clear in Tables 5.2 and A.1 at time scales k = 1, 3, 6, 9, 12 and 24 months.

Table 5.2: Critical severity values for SPI_1, SPI_3, SPI_6, SPI_9, SPI_{12} and SPI_{24} in Adana meteorological station.

Drought duration (month)	SPI_1					SPI_3						
	D=1	D=2	D=3	D=4	D=5	D=1	D=2	D=3	D=4	D=5	D=6	D=7
Number of years	57	50	33	18	12	57	50	46	33	28	23	17
1960	1.38	1.96	1.89	2.5	0	1.56	2.48	3.55	4.39	4.96	0	0
1961	1.16	1.61	1.76	2.78	3.39	1.62	2.34	3.29	4.62	5.46	6.0	0
1962	1.85	1.86	2.94	0	0	1.81	3.43	4.13	5.73	6.43	6.6	6.96
1963	1.1	1.84	2.62	2.92	0	1.77	3.26	4.29	4.48	0	0	0
1964	1.89	2.99	3.73	4.51	4.81	2.5	3.86	5.35	6.42	7.45	7.6	7.7
1965	1.08	1.51	2.37	0	0	1.56	2.32	3.18	4.39	5.7	6.1	0
1966	1.54	2.15	3.12	0	0	2.04	3.37	4.41	5.42	6.46	6.5	7.2
1967	0.73	0	0	0	0	1.1	1.49	1.53	0	0	0	0
1968	1.66	1.87	2.08	0	0	1.09	1.69	1.78	0	0	0	0
1969	0.71	0.88	0	0	0	0.39	0.19	0	0	0	0	0
1970	1.68	2.55	3.28	0	0	2.28	3.4	4.51	5.44	5.76	6.1	6.2
1971	1.61	2.04	0	0	0	1.12	2.23	3	3.2	3.05	3.96	0
1972	1.81	2.41	0	0	0	1.77	2.47	3.44	4.35	5.09	6.1	6.7
1973	1.51	3.02	4.53	5.13	5.71	3.08	5.38	7.41	9.18	9.89	10.6	10.7
1974	1.76	2.92	3.14	3.29	4.29	2.49	3.99	4.97	5.98	6.59	7.39	7.7
1975	1.61	2.26	0.85	0	0	2.06	3.28	4.46	5.25	5.84	6.38	0
1976	0.88	0.56	0	0	0	0.03	0	0	0	0	0	0
1977	1.73	0.76	0	0	0	0.96	1.17	0	0	0	0	0
1978	1.55	0	0	0	0	1.08	1.79	2.32	2.69	2.82	0	0
1979	1.29	2.5	2.85	3.06	3.25	1.84	3.25	4.53	4.71	4.82	4.84	0
1980	0.84	0.99	0	0	0	1.56	2.87	3.54	0	0	0	0
1981	0.38	0	0	0	0	0.9	0	0	0	0	0	0
1982	1.39	1.78	2.03	2.83	0	1.34	2.57	3.59	3.93	0	0	0
1983	0.98	0	0	0	3.22	0.78	1.28	1.39	0	0	0	0
1984	2.17	3.23	3.3	0	0	2.85	3.16	3.41	3.91	4.51	5.3	5.55
1985	0.92	0.61	0	0	0	0.97	1.44	0.85	0	0	0	0
1986	2.78	4.37	4.54	0	0	1.97	3.8	4.52	5.21	5.93	6.39	0
1987	1.13	0	0	0	0	1.06	0	0	0	0	0	0
1988	0.94	0	0	0	0	1.61	0	0	0	0	0	0
1989	3.53	5.48	5.67	9.04	9.35	2.51	4.49	7	8.39	9.67	10.9	11.3
1990	1.52	1.55	0	0	0	1.05	1.9	0.78	0	0	0	0
1991	1.32	1.45	2.46	0	0	1.39	2.44	3.37	4.4	5.25	5.35	5.98

Table 5.2 (Continued)**:** Critical severity values for SPI_1, SPI_3, SPI_6, SPI_9, SPI_{12} and SPI_{24} in Adana meteorological station.

Drought Duration (months)	SPI_6										
	D=1	D=2	D=3	D=4	D=5	D=6	D=7	D=8	D=9	D=10	D=11
Number of Years	54	50	45	36	30	27	23	21	16	12	10
1960	1.34	2.41	3.07	3.52	0	0	0	0	0	0	0
1961	1.64	2.98	4.05	4.71	5.16	5.51	5.81	6.03	6.24	0	0
1962	2.21	3.36	4.14	4.9	0	0	0	0	0	0	0
1963	1.88	2.89	0	0	0	0	0	0	0	0	0
1964	2.6	4.48	6.23	7.47	8.48	9.48	10.24	0	0	0	0
1965	1.2	2.37	3.04	3.26	0	0	0	0	0	0	0
1966	2.08	3.84	5.02	6.75	7.46	0	0	0	0	0	0
1967	0.04	0	0	0	0	0	0	0	0	0	0
1968	0.42	0.75	0	0	0	0	0	0	0	0	0
1969	0.68	0.3	0	0	0	0	0	0	0	0	0
1970	2.51	3.91	4.96	5.79	6.79	7.52	8.25	8.55	8.94	9.4	9.65
1971	1.73	2.51	3.54	3.23	4.93	6.33	7.23	8.19	9.06	10.02	10.75
1972	1.85	3.12	4.64	5.98	7.42	8.61	9.64	10.96	12.15	12.68	13.47
1973	2.91	5.71	8.01	10.2	12.33	14.18	15.37	16.06	16.61	16.75	17.3
1974	1.79	3.06	4.22	5.04	5.97	6.99	7.68	8.32	9.01	9.31	9.89
1975	1.97	2.89	3.72	0	0	0	0	0	0	0	0
1976	0.41	1.03	1.95	3.92	4.33	4.69	0	0	0	0	0
1977	1.09	1.38	1.67	1.73	1.87	2.16	0	0	0	0	0
1978	0.96	1.65	0	0	0	0	0	0	0	0	0
1979	1.33	2.54	3.41	4.18	5.05	5.51	5.96	6.16	6.35	0	0
1980	0.59	0.92	1.43	0	0	0	0	0	0	0	0
1981	0	0	0	0	0	0	0	0	0	0	0
1982	1.27	2.15	2.61	2.92	3.15	3.23	3.3	3.35	0	0	0
1983	0.53	0.86	1.03	1.12	1.22	0	0	0	0	0	0
1984	2.25	2.95	3.86	4.33	4.67	5.1	0	0	0	0	0
1985	0.52	1.04	1.74	3.99	4.46	4.8	5.23	5.57	5.84	6.03	6.13
1986	1.95	3.55	4.83	5.98	7.33	8.61	9.15	9.36	9.44	9.6	0
1987	0.27	0	0	0	0	0	0	0	0	0	0
1988	0	0	0	0	0	0	0	0	0	0	0
1989	2.89	5.22	7.2	9.27	11.25	12.33	12.64	13.04	0	0	0
1990	1.19	1.44	0.81	0	0	0	0	0	0	0	0
1991	1.6	2.95	4.43	5.7	6.89	8	9.02	9.64	10.61	11.08	11.91

Drought Duration (months)	SPI_9												
	D=1	D=2	D=3	D=4	D=5	D=6	D=7	D=8	D=9	D=10	D=11	D=12	D=13
Number of Years	51	48	43	38	33	29	28	28	27	22	20	17	13
1960	1.31	0.41	0	0	0	0	0	0	0	0	0	0	0
1961	1.45	2.76	3.24	3.69	4.29	4.9	5.55	6	6.42	0	0	0	0
1962	1.75	2.02	2.35	0	0	0	0	0	0	0	0	0	0
1963	0	0	0	0	0	0	0	0	0	0	0	0	0
1964	1.6	2.91	4.3	5.61	6.5	7.21	7.83	8.32	8.33	0	0	0	0
1965	0.83	1.58	1.97	2.36	2.62	2.98	3.21	3.23	3.36	0	0	0	0
1966	2.23	3.52	3.93	0	0	0	0	0	0	0	0	0	0
1967	0.21	0.57	1.86	4.09	4.3	0	0	0	0	0	0	0	0
1968	0	0	0	0	0	0	0	0	0	0	0	0	0
1969	0.55	0	0	0	0	0	0	0	0	0	0	0	0
1970	1.27	2.23	3.16	4.35	5.25	6.28	7.18	7.96	8.61	8.99	9.37	9.88	10.43
1971	1.33	2.6	3.67	4.73	5.68	6.75	7.81	8.71	9.74	10.64	11.42	12.07	12.72
1972	1.9	3.45	5.12	6.86	8.57	10.2	11.47	12.87	14.21	14.93	16.13	17.96	18.68
1973	2.8	5.51	7.87	10.17	12.29	14.39	16.45	18.5	20.33	21.74	22.94	24.05	25
1974	1.42	2.72	3.97	5.08	6.15	7.2	8.27	10.39	12.69	15.05	17.85	20.56	22.61
1975	0.27	0.34	0	0	0	0	0	0	0	0	0	0	0
1976	0.59	1.12	1.61	1.88	1.95	2	0	0	0	0	0	0	0
1977	0.82	1.2	1.55	0	0	0	0	0	0	0	0	0	0
1978	0.49	0.5	1.23	1.61	0	0	0	0	0	0	0	0	0
1979	1.62	3.1	3.72	4.59	5.09	5.74	6.36	6.88	7.17	7.36	7.52	7.83	8.02
1980	0.22	0	0	0	0	0	0	0	0	0	0	0	0
1981	0	0	0	0	0	0	0	0	0	0	0	0	0
1982	1.09	1.54	1.92	2.52	2.7	2.95	3.21	3.67	3.99	4.22	0	0	0
1983	0.45	1.05	1.43	1.88	2.97	3.15	3.4	3.66	4.12	4.44	4.67	0	0
1984	1.09	1.88	2.74	2.77	2.78	0	0	0	0	0	0	0	0
1985	0.62	1.71	2.5	3.36	3.78	4.12	4.58	4.99	5.37	5.57	5.83	5.86	5.87
1986	1.54	2.89	4.37	5.75	7.09	7.95	8.77	9.65	10.51	11.16	11.53	11.63	11.99
1987	0.39	0.9	2.28	3.79	5.11	6.65	7.99	8.81	9.62	10.55	11.2	11.59	11.96
1988	0	0	0	0	0	0	0	0	0	0	0	0	0
1989	2.31	4.38	5.82	7.23	8.18	9.21	10.02	10.51	10.72	10.93	10.98	0	0
1990	0.97	1.62	0.58	1.92	4.23	6.3	7.71	8.66	9.69	10.5	10.99	11.2	0
1991	1.66	3.14	4.59	6.1	7.65	8.96	10.15	11.2	12.31	13.28	14.02	14.67	15.3

Table 5.2 (Continued)**:** Critical severity values for SPI_1, SPI_3, SPI_6, SPI_9, SPI_{12} and SPI_{24} in Adana meteorological station.

Drought Duration (months)	SPI12													
	D=1	D=2	D=3	D=4	D=5	D=6	D=7	D=8	D=9	D=10	D=11	D=12	D=13	D=14
Number of Years	46	40	38	35	32	29	28	27	27	25	22	19	16	12
1960	0.92	0	0	0	0	0	0	0	0	0	0	0	0	0
1961	1.06	1.98	2.39	3.12	3.83	4.36	4.87	5.4	5.91	0	0	0	0	0
1962	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1963	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1964	1.22	2.25	3.28	4.3	5.31	6.46	7.17	7.79	7.97	0	0	0	0	0
1965	0.7	0.97	1.68	2.83	3.93	4.96	5.98	6.92	8.14	8.43	8.61	8.79	8.83	9.17
1966	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1967	0.7	1.26	1.31	0	0	0	0	0	0	0	0	0	0	0
1968	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1969	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1970	1.2	2.24	3.18	4.11	5.07	5.92	6.88	7.64	8.31	8.89	9.16	9.64	0	0
1971	1.73	3.19	4.58	5.6	6.45	7.59	8.63	9.57	10.5	11.46	12.31	13.19	14.06	14.85
1972	2.09	3.78	5.41	7.02	8.69	10.44	11.89	13.64	15.65	17	18.3	19.55	20.75	22.02
1973	2.78	5.48	7.65	9.86	12	14.19	16.43	18.74	21.17	23.31	25.44	27.53	29.22	30.65
1974	1.51	3	4.54	6.97	9.28	11.52	13.73	15.85	18.06	20.23	22.93	25.71	27.85	29.94
1975	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0
1976	0.29	0.44	0.6	0	0	0	0	0	0	0	0	0	0	0
1977	0.2	0.33	0	0	0	0	0	0	0	0	0	0	0	0
1978	0.17	0.37	0.5	0	0	0	0	0	0	0	0	0	0	0
1979	1.08	1.75	2.45	3.01	3.57	4.17	5.07	5.89	6.42	6.76	7.29	0	0	0
1980	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1981	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1982	1.17	1.48	1.55	1.72	1.93	2.17	2.56	0	0	0	0	0	0	0
1983	1.04	2.21	2.53	2.84	3.01	3.08	3.29	3.6	3.92	4.09	0	0	0	0
1984	0.6	0.92	0.96	1	0	0	0	0	0	0	0	0	0	0
1985	0.87	1.36	1.87	2.35	2.91	3.39	3.82	4.3	4.82	5.34	5.66	5.7	5.74	0
1986	1.46	2.83	3.91	4.93	5.86	6.78	7.69	8.64	9.52	10.28	10.74	11.14	0	0
1987	1.02	1.9	3.36	4.73	5.75	6.77	7.7	8.62	9.53	10.48	11.36	12.12	12.58	12.98
1988	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1989	1.13	2.24	3.34	4.32	5.28	6.38	7.21	8	8.46	8.72	0	0	0	0
1990	1.15	1.94	3.05	4	4.98	6.11	7.22	8.32	9.15	9.61	9.95	10.28	10.54	10.68
1991	1.74	3.41	5.04	6.67	8.29	9.49	10.65	12.03	13.21	14.37	15.26	16.22	16.81	16.96

Table 5.2 (Continued)**:** Critical severity values for SPI_1, SPI_3, SPI_6, SPI_9, SPI_{12} and SPI_{24} in Adana meteorological station.

Drought Duration (months)	SPI_{24}													
	D=1	D=2	D=3	D=4	D=5	D=6	D=7	...	D=27	D=28	D=29	D=30	D=31	D=32
Number of Years	40	31	31	29	29	28	28	....	11	11	11	10	10	10
1960	0	0	0	0	0	0	0	....	0	0	0	0	0	0
1961	0	0	0	0	0	0	0	....	0	0	0	0	0	0
1962	0.06	0	0	0	0	0	0	....	0	0	0	0	0	0
1963	0	0	0	0	0	0	0	....	0	0	0	0	0	0
1964	0	0	0	0	0	0	0	....	0	0	0	0	0	0
1965	1.06	2.06	3.07	4.05	5.03	6	6.97	....	0	0	0	0	0	0
1966	0.3	0.57	0.85	1.1	1.3	1.57	1.61	....	0	0	0	0	0	0
1967	0	0	0	0	0	0	0	....	0	0	0	0	0	0
1968	0	0	0	0	0	0	0	....	0	0	0	0	0	0
1969	0	0	0	0	0	0	0	....	0	0	0	0	0	0
1970	0.54	0	0	0	0	0	0	....	0	0	0	0	0	0
1971	1.65	3.04	4.58	5.89	7.15	8.41	9.67	....	0	0	0	0	0	0
1972	2.37	4.34	6.03	7.79	9.6	11.31	13.01	....	0	0	0	0	0	0
1973	2.88	5.66	8.3	10.95	13.65	16.44	19.07	....	58.83	60.14	61.4	62.66	63.92	65.12
1974	2.57	5.1	7.52	9.9	12.6	15.31	17.95	....	64.9	66.62	68.32	70.03	71.88	73.82
1975	0.44	1.11	3.2	5.36	7.57	9.95	12.52	....	62.56	64.25	66.01	67.73	69.43	71.14
1976	0	0	0	0	0	0	0	....	0	0	0	0	0	0
1977	0	0	0	0	0	0	0	....	0	0	0	0	0	0
1978	0	0	0	0	0	0	0	....	0	0	0	0	0	0
1979	0.45	0.87	1.15	1.48	1.81	2.18	2.59	....	0	0	0	0	0	0
1980	0.07	0	0	0	0	0	0	....	0	0	0	0	0	0
1981	0	0	0	0	0	0	0	....	0	0	0	0	0	0
1982	0	0	0	0	0	0	0	....	0	0	0	0	0	0
1983	0	0	0	0	0	0	0	....	0	0	0	0	0	0
1984	0	0	0	0	0	0	0	....	0	0	0	0	0	0
1985	0	0	0	0	0	0	2.1	....	0	0	0	0	0	0
1986	0	0	0	0	0	0	7.31	....	0	0	0	0	0	0
1987	18.05	18.37	18.68	18.99	19.22	19.29	6.59	....	18.05	18.37	18.68	18.99	19.22	19.29
1988	0	0	0	0	0	0	0	....	0	0	0	0	0	0
1989	0	0	0	0	0	0	0	....	0	0	0	0	0	0
1990	0	0	0	0	0	0	5.43	....	0	0	0	0	0	0
1991	0	0	0	0	0	0	7.82	....	0	0	0	0	0	0

5.4 Frequency Analysis of Critical Drought

Frequency analysis of the D month-duration critical drought severity calculated at k = 1, 3, 6, 9, 12 and 24 month-time scales were performed to determine the best-fit probability distribution function. As explained in Chapter 3 (Section 3.2), following probability distribution functions which are used often in the literature were considered as the candidates for the best-fit probability distribution function of each SPI_k series (k = 1, 3, 6, 9, 12, 24 month): 2- and 3-parameter Gamma (G2, G3), Generalized Extreme Value (GEV), 2- and 3- parameter Log-Normal (LN2, LN3), Log-Pearson Type 3 (LP3), and 2- and 3- parameter Weibull (W2, W3) distributions. Probability distribution functions and their parameters are given in Table 3.2 as detailed in Chapter 3 (Section 3.2). The best-fit probability distribution functions were determined and their parameters were calculated for each D month-drought of the SPI_k series by the frequency analysis. Critical severity series with at least 10 years of length were considered for the frequency analysis; i.e., no frequency analysis was applied on critical severity series shorter than 10 years.

Frequency analysis of intermittent time series with zero values are explained in Chapter 3. The frequency analysis takes the zero values separately into account and assigns a probability mass to the zero values, and what remains left from the unity is the probability of the non-zero values. This is called the total probability theorem.

The output screen of the software used for the implementation of the frequency analysis to determine the best-fit probability distribution function and its parameters is shown in Figure 5.11. Frequency analysis was applied on the D month-duration critical drought severity time series at each k month-time scale for 19 meteorological stations in the Seyhan River basin. In majority of the cases, the Generalized Extreme Value (GEV) distribution was found the best in fitting to the critical severities in the meteorological stations for all selected durations at 1, 3, 6, 9, 12 and 24 month-time scales. In some cases, also the LN3, G2 and LP3 distributions were found applicable as the best-fit distribution. By determining the parameter of these distributions, the severity values corresponding to return periods of 2, 5, 10, 25, 50 and 100 years were calculated.

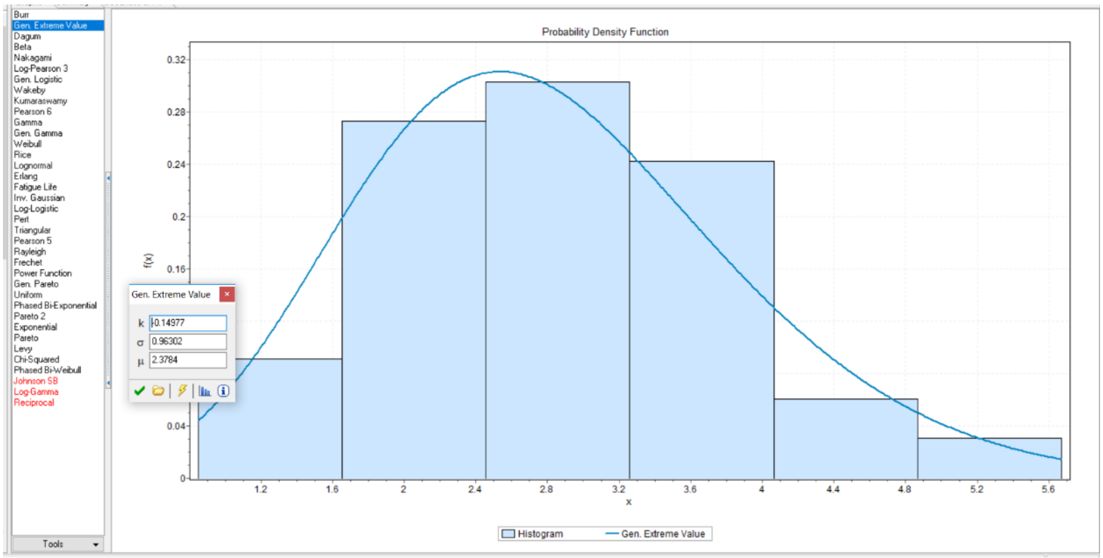

Figure 5.11: Determination of the best-fit probability distribution function.

Results of the frequency analysis corresponding to 2, 5, 10, 25, 50 and 100 year-return periods through the use of the best-fit probability distribution functions in Adana meteorological station are given in Tables 5.3. The full observation period of the station is given in Tables A.3 (Appendix A.3). For example, a one month-drought was observed every year; therefore, there is no zero-year in terms of 1 month-drought at k = 1 and 3 month-time scales. For this particular station, GEV was determined as the best-fit probability distribution function in majority of cases.

5.5 Determination of Drought Severity/Intensity-Duration-Frequency Values

For the frequency analysis of drought, the commonly used 2, 5, 10, 25, 50 and 100 year-return periods were taken into account for the D-month drought duration. The critical severity of a D month-duration drought corresponding to the given return periods were determined by the best-fit probability distribution function. The drought severity-duration-frequency curves for different time scales were obtained through the use of frequency analysis. The intensity-duration-frequency curves were alternatively derived in terms of intensity instead of severity. Critical drought severity and intensity values corresponding to 2, 5, 10, 25, 50 and 100 year-return periods and different drought durations are given in Tables 5.4 for Adana meteorological station.

Table 5.3: The best-fit probability distribution functions and parameters for SPI_1, SPI_3, SPI_6 SPI_9, SPI_{12} and SPI_{24} in Adana meteorological station.

	SPI_1				SPI_3				SPI_6			
Drought duration (month)	1	2	…	5	1	2	…	7	1	2	…	11
No drought years	0	7		45	0	7		40	3	7		47
Number of years	57	50	…	12	57	50	…	17	54	50	…	10
Probabilty of zero severity (p)	0	0.123	…	0.7895	0	0.1223	…	0.702	0.053	0.123	…	0.825
T (Year)	F*(x)				F*(x)				F*(x)			
2	0.5	0.43	…		0.5	0.43	…		0.472	0.43	…	
5	0.8	0.772	…	0.05	0.8	0.77	…	0.33	0.789	0.772	…	
10	0.9	0.886	…	0.525	0.9	0.89	…	0.66	0.894	0.886	…	0.43
25	0.96	0.954	…	0.81	0.96	0.95	…	0.87	0.958	0.954	…	0.772
50	0.98	0.977	…	0.905	0.98	0.98	…	0.93	0.979	0.977	…	0.886
100	0.99	0.989	…	0.9525	0.99	0.99	…	0.97	0.989	0.989	…	0.943
Probability distribut. func.	GEV	GEV	…	LP3	GEV	GEV	…	GEV	GEV	GEV	…	GEV
α			…	4.802			…				…	
β			…	0.146			…				…	
γ			…	0.788			…				…	
μ	1.196	1.726	…		1.321	2.353	…	6.214	1.095	1.931	…	10.20
σ	0.455	0.855	…		0.637	1.056	…	2.293	0.712	1.192	…	3.411
k	-0.016	-0.126	…		-0.275	-0.305	…	-0.197	-0.197	-0.148	…	-0.28

Table 5.3: The best-fit probability distribution functions and parameters for SPI_1, SPI_3, SPI_6 SPI_9, SPI_{12} and SPI_{24} in meteorological Adana station (Continued).

	SPI_9				SPI_{12}				SPI_{24}			
Drought duration (month)	1	2	…	13	1	2	…	14	1	2	…	32
No drought years	6	9		44	11	17		45	17	26		47
Number of years	51	48	…	13	46	40	…	12	40	31	…	10
Probabilty of zero severity (p)	0.105	0.158	…	0.772	0.193	0.298	…	0.789	0.298	0.456	…	0.825
T (Year)	F*(x)				F*(x)				F*(x)			
2	0.441	0.406	…		0.380	0.288	…		0.288	0.081	…	
5	0.776	0.763	…	0.123	0.752	0.715	…	0.05	0.715	0.632	…	
10	0.888	0.881	…	0.562	0.876	0.858	…	0.525	0.858	0.816	…	0.43
25	0.955	0.953	…	0.825	0.950	0.943	…	0.81	0.943	0.926	…	0.772
50	0.978	0.976	…	0.912	0.975	0.971	…	0.905	0.972	0.963	…	0.886
100	0.989	0.988	…	0.956	0.988	0.986	…	0.952	0.986	0.982	…	0.943
Probability distribut. func.	GEV	GEV	…	LP3	GEV	GEV	…	LP3	GEV	GEV	…	LP3
α			…	29.515			…	52.752			…	5.224
β			…	-0.078			…	0.0562			…	0.225
γ			…	4.897			…	-0.205			…	2.345
μ	0.923	1.664	…		0.809	1.541	…		0.560	1.442	…	
σ	0.545	1.023	…		0.554	0.989	…		0.534	0.875	…	
k	-0.130	-0.118	…		-0.139	-0.055	…		0.039	0.114	…	

The ratio of drought severity to the drought duration is called drought intensity, which is shown in Tables 5.4. It is seen that drought severity and intensity increase with increase in return period; however, the former increases with increasing drought duration while the latter decreases. When the return period and the drought duration increase, the drought severity is expected to increase owing to the physics of the drought process. However, in some cases, but not many in number, this is not satisfied because of different best-fit probability distribution functions used for different D month-duration droughts. A minor modification was therefore applied to satisfy the physics of the drought process. To explain on the example in Table 5.4 and Appendix A.3, the severity value is 10.963 for D = 12 month-drought duration whereas it is 8.163 for D = 13 month-drought duration in T = 5 year-return period and k = 9 month-time scale in Adana meteorological station. The severities should have increased with the drought duration. Therefore, the severity of D = 13 months was increased from 8.163 to 10.964 manually by increasing the severity of D = 12 month-drought duration by 0.001. The calculations were continued in this way. In addition, the drought severity in short return periods such as 2 and 5 years were not calculated for longer drought duration. Because, long-duration droughts are observed less frequently compared to short-duration droughts. If an example is given from Table 5.4, the drought severity of k = 1 month-time scale and D = 5 month-duration has a return period longer than 2 years. Similarly, the drought severity of k = 6 month-time scale and D = 11 month-duration has a return period longer than 5 years. It is deduced that the longer the drought duration, the higher the return period.

Table 5.4: Critical drought severity and intensity values corresponding to 2, 5, 10, 25, 50 and 100 year-return periods for SPI_1, SPI_3, SPI_6 SPI_9, SPI_{12} and SPI_{24} in Adana meteorological station.

Severity	SPI_1				SPI_3				SPI_6			
					D (month)							
T (Year)	D=1	D=2	…	D=5	D=1	D=2	…	D=7	D=1	D=2	..	D=11
2	1.363	1.869	…		1.543	2.528	…		1.294	2.131	..	
5	1.871	2.789	…	2.88	2.104	3.524	…	5.971	1.987	3.392	..	
10	2.202	3.312	…	4.31	2.391	3.998	…	8.097	2.363	4.094	..	10.767
25	2.616	3.900	…	5.754	2.677	4.457	…	9.91	2.765	4.870	..	14.050
50	2.919	4.293	…	6.9	2.847	4.720	…	10.974	3.018	5.378	..	15.660
100	3.216	4.649	…	8.148	2.986	4.931	…	11.877	3.235	5.832	..	16.909
Intensity												
2	1.363	0.935	…		1.543	1.264	…		1.294	1.065	..	
5	1.871	1.394	…	0.576	2.104	1.762	…	0.853	1.987	1.696	..	
10	2.202	1.656	…	0.862	2.391	1.999	…	1.157	2.363	2.047	..	0.979
25	2.616	1.950	…	1.151	2.677	2.229	…	1.416	2.765	2.435	..	1.277
50	2.919	2.146	…	1.38	2.847	2.360	…	1.568	3.018	2.689	..	1.424
100	3.216	2.324	…	1.63	2.986	2.465	…	1.697	3.235	2.916	..	1.537

Table 5.4(Continued)**:** Critical drought severity and intensity values corresponding to 2, 5, 10, 25, 50 and 100 year-return periods for SPI_1, SPI_3, SPI_6 SPI_9, SPI_{12} and SPI_{24} in Adana meteorological station.

Severity	SPI_9				SPI_{12}				SPI_{24}			
	D (month)											
T (Year)	D=1	D=2	…	D=13	D=1	D=2		D=14	D=1	D=2		D=32
2	1.031	1.770	⋯		0.828	1.322	⋯		0.443	0.675	⋯	
5	1.609	2.902	⋯	8.163	1.448	2.589	⋯	8.334	1.156	2.156	⋯	
10	1.938	3.542	⋯	14.691	1.786	3.301	⋯	15.879	1.598	2.971	⋯	28.812
25	2.308	4.265	⋯	19.944	2.160	4.139	⋯	22.441	2.162	4.058	⋯	47.321
50	2.552	4.751	⋯	23.244	2.406	4.727	⋯	27.244	2.590	4.927	⋯	63.749
100	2.774	5.190	⋯	26.247	2.627	5.290	⋯	32.178	3.028	5.873	⋯	83.419
Intensity												
2	1.031	0.885	⋯		0.828	0.661	⋯		0.443	0.337	⋯	
5	1.609	1.451	⋯	0.628	1.448	1.295	⋯	0.595	1.156	1.078	⋯	
10	1.938	1.771	⋯	1.130	1.786	1.651	⋯	1.134	1.598	1.486	⋯	0.900
25	2.308	2.133	⋯	1.534	2.160	2.069	⋯	1.603	2.162	2.029	⋯	1.479
50	2.552	2.376	⋯	1.788	2.406	2.363	⋯	1.946	2.590	2.464	⋯	1.992
100	2.774	2.595	⋯	2.019	2.627	2.645	⋯	2.298	3.028	2.937	⋯	2.607

5.6 Regression Between Precipitation and SPI

Regression analysis is a statistical technique for investigating relationship between two or more cross-correlated variables. Precipitation total over k months and corresponding SPI_k values in this study are correlated variables. Therefore, it is thought that regression analysis can be applied to find the relation between the two variables. The relationship between the precipitation time series and the corresponding SPI is detected by regression analysis. The best-fit regression equation was detected as detailed in Chapter 3 (Section 3.5).

Due to the periodicity in the monthly precipitation process, the best regression equations were fitted for each month of the year; i.e., 12 regression equations were determined for SPI_k times series of k = 1, 3, 6 and 9 months. When k = 12 or 24 months are concerned, a unique regression equation was established between the precipitation total over the k month-period and corresponding SPI_k.

The plot between the precipitation total over k months and the corresponding SPI_k values scatters as in Figure 5.12. Regression equations were developed between the precipitation and SPI_k values for each of the time scales. Owing to periodicity (seasonality) of precipitation, the relation between precipitation and SPI_k changes from month to month for time scales shorter than a year (k = 1, 3, 6, 9-months). As far as the 12- and 24-month time scales are concerned, one regression equation is obtained for each. Figure 5.12 clearly shows that 12 curves exist on the scatter diagrams between precipitation and SPI_k for k = 1, 3, 6, 9 months. Nonetheless, it is only one for k = 12 and 24 month-time scales. As a result of this fact, monthly regression equations in the form of logistic functions as in Equation (3.24) are used in calculating precipitation deficit for SPI_1, SPI_3, SPI_6 and SPI_9. Precipitation deficit changes depending on the seasonality of the precipitation as it is clear that precipitation deficit is minimum in summer while it is higher in spring and autumn. Although precipitation deficit increases in magnitude with increasing k, the scattering becomes less variable. In other words, monthly regression curves getting closer with increasing k and finally they overlap when the time scale is a year or its multiple.

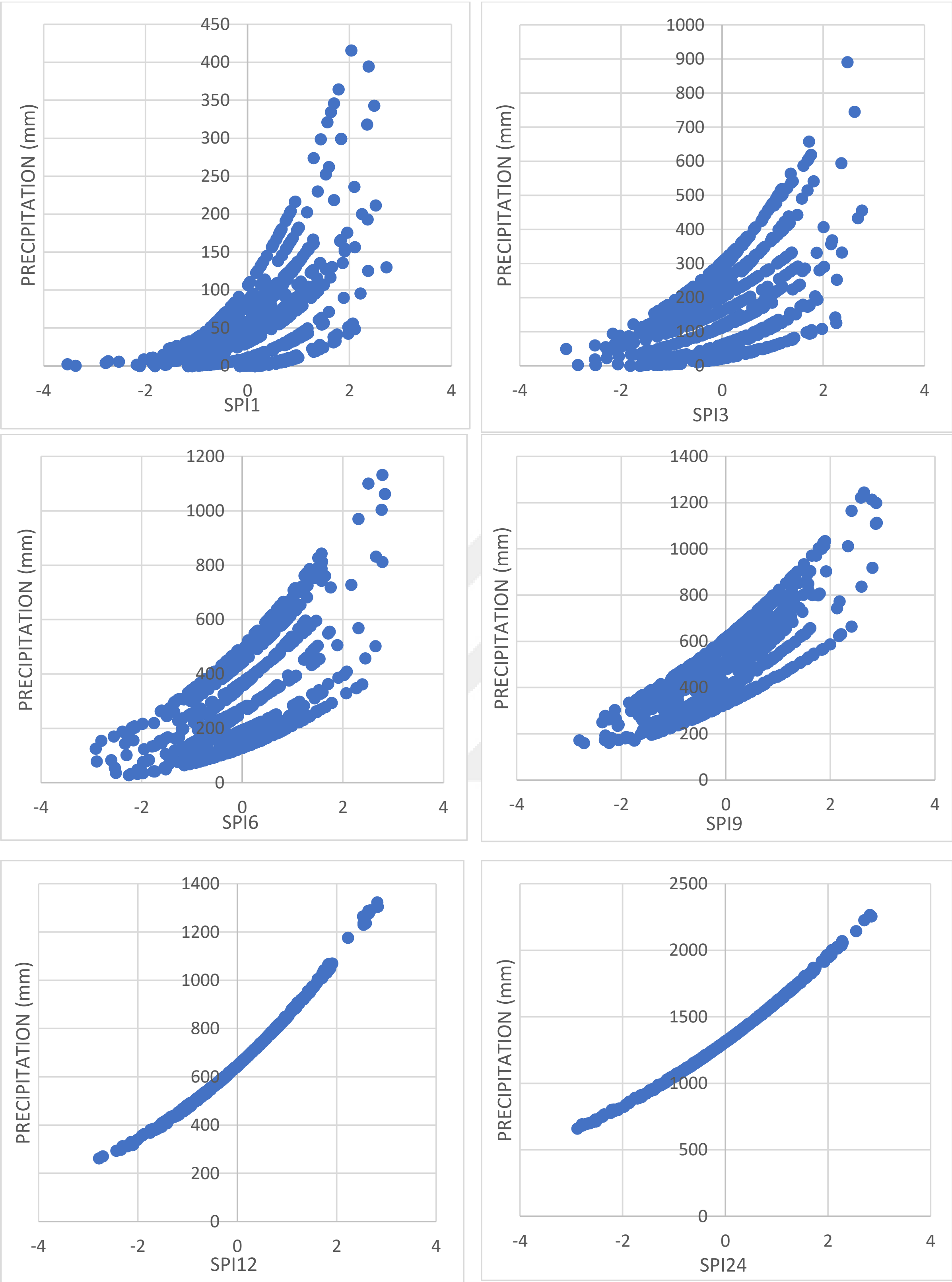

Figure 5.12: Scattering between precipitation and corresponding SPI values

5.7 Precipitation Threshold

The value of precipitation threshold (P_{TH}) for all time scales were taken as the precipitation at SPI = 0, because drought starts when the SPI value falls below zero. In other words, a drought begins when it reaches the precipitation threshold which corresponds to SPI = 0. The precipitation threshold values are calculated by using the regression equations developed for each month in the SPI_1, SPI_3, SPI_6 and SPI_9 cases. Nevertheless, for the SPI_{12} and SPI_{24}, a single value is calculated for each of the regression equations valid at annual time scale and its multiple. The relationship between the observed precipitation and the corresponding SPI may demonstrate rather different characters depending on the climate of the region and seasonality in precipitation. The precipitation threshold calculated from the regression analysis is shown in Figure 5.13 for Adana meteorological station in the SPI_1, SPI_3, SPI_6 and SPI_9 time scale. According to this, at k = 1 month, drought begins when precipitation falls below 84 mm in January. Similarly, 75 mm in February, 58 mm in March, 45 mm in April etc. are threshold values. In any case precipitation is lower the monthly threshold, it is said that a drought has started at the k time scale considered. The precipitation threshold is obviously lower in summer than winter because of the seasonal character of precipitation due to the climate of the Seyhan River basin. The threshold values of the SPI_{12} and SPI_{24} are 644 mm and 1309 mm, respectively. Since these two thresholds represent hydrological drought reflected by reservoirs and groundwater storage, the precipitation threshold values are higher than SPI_k values for k = 1, 3, 6, 9 months which are considerable for meteorological and agricultural droughts. The precipitation threshold values for the SPI_1 are the lowest in the summer season. The lowest values of SPI_k shift from summer to autumn for k = 3, 6, 9 months due to the accumulation of the low precipitation-summer over the autumn season when calculating the SPI_k. Besides, the precipitation threshold values change from station to station or location and depend on climatological characterization.

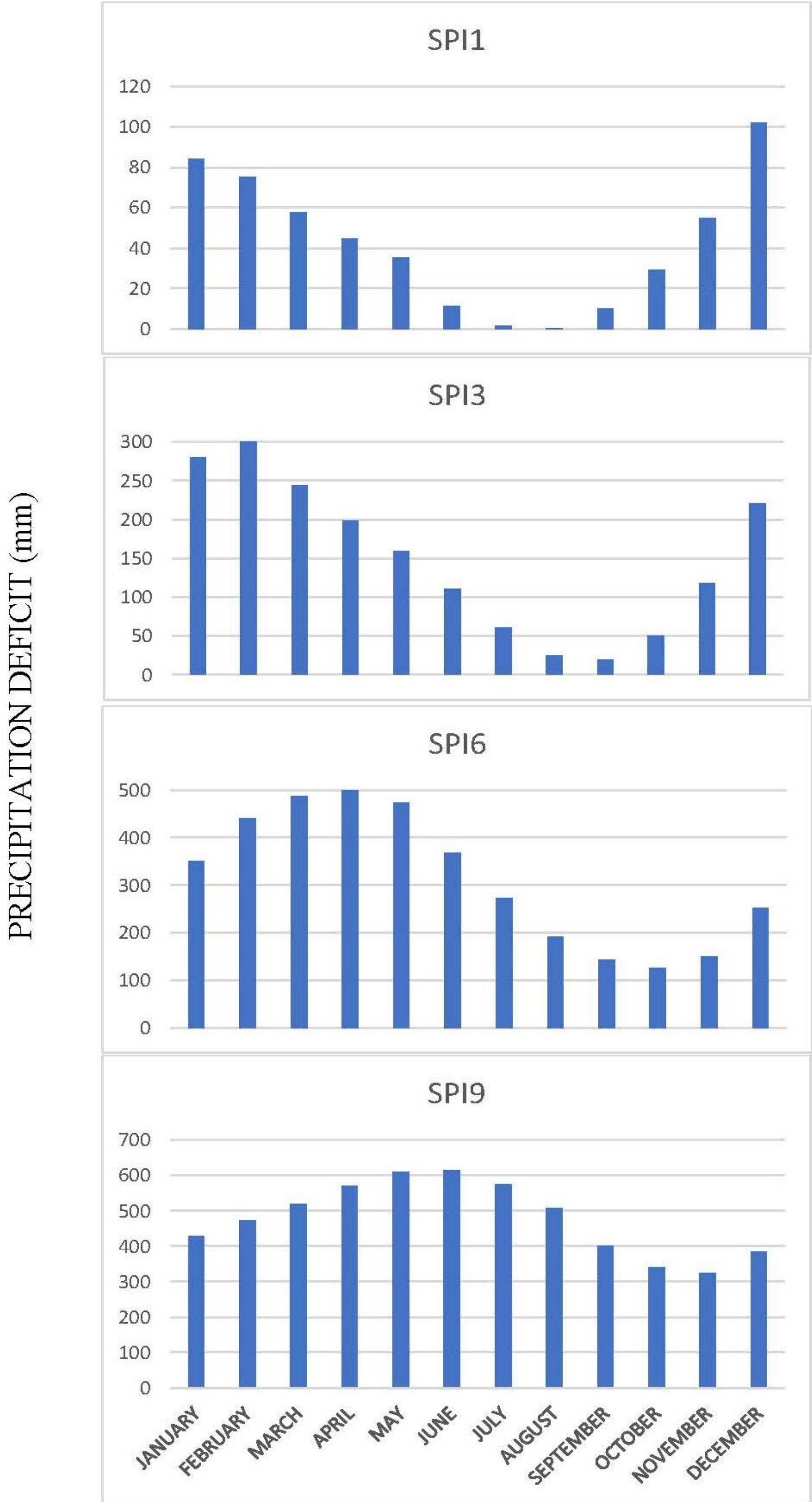

Figure 5.13 Seasonality in the precipitation threshold at time scales k = 1, 3, 6 and 9 months for Adana meteorological station.

5.8 Calculation of Precipitation Deficit

The critical drought severity values (the sum of SPIs) of D month-duration and T year-return period for each of the k time scales were inserted into the regression equation to find the corresponding precipitation. Precipitation values calculated in this way are taken as the precipitation in the critical drought (critical precipitation). When precipitation total over k month-time scale in a particular month is lower than the calculated critical precipitation, it is said that the D month-duration and T year-return period drought is reached. On the other hand, the precipitation threshold is calculated when SPI = 0 is inserted into the regression equation. Any precipitation above this value corresponds to a wet period while, in the opposite case, it is a dry period over the k month-time scale. The difference between the precipitation threshold (at SPI = 0, no drought) and the critical precipitation is defined as the precipitation deficit and calculated by Equation 3.25. It was calculated at all time scales (k = 1, 3, 6, 9, 12 and 24 months) for return periods (T = 2, 5, 10, 25, 50 and 100 years) for drought durations (D = 1, 2, … months). Finally, by using the precipitation deficit, the drought severity-duration-frequency curves were plotted at each k time scale at each of the meteorological stations separately**.** The severity-duration-frequency curves were then converted into the intensity-duration-frequency curves by simply dividing the drought severity with drought duration as in Equation 3.11. The intensity-duration-frequency curves give the average severity per a month, the intensity, of the drought period.

5.9 Critical Drought Severity-Duration-Frequency (SDF) Curves Based on Precipitation Deficit

The novel part of this study is to develop the critical drought severity-duration-frequency curves for the Seyhan River basin in terms of precipitation deficit calculated from the regression equation between the observed precipitation and corresponding SPI. In the regression equation, the critical precipitation of the k month-time scale, D month-duration and T year-return period was calculated by substituting the critical drought severity value into the regression equation as the independent variable. Similarly, precipitation threshold at SPI = 0 above which no drought exists is calculated. As calculated by Equation (3.25), the difference between the T year-return period D month-duration critical precipitation calculated at k month-time scale and the threshold precipitation is called the precipitation deficit. When the duration and return period of drought increase, the precipitation deficit increases as well. The precipitation deficit curves were presented at monthly scale for SPI_1, SPI_3, SPI_6, SPI_9 in Figures 5.14-5.17 for Adana meteorological station. There presented also is the annual precipitation deficit for k = 12 and 24 months in the same station (Figures 5.18-5.19). In drought management practice, it is of great importance to determine and supply the amount of water required to overcome or minimize any damage and destructive effect that might be caused by the drought. When making a decision on the drought management, on the other hand, it is technically difficult to interpret the drought occurrences based on the SPI values which can provide an indirect information about precipitation. However, by using the precipitation deficit as in this study, a direct interpretation is possible to do. Because, the precipitation deficit is a physically better understandable and more tangible information for end-users such as farmers and decision-makers. Therefore, the characterization of severity-duration-frequency of drought events is of great importance. Example plots of the severity-duration-frequency are given for k = 1, 3, 6 and 9 months in Figures 5.14-5.17, respectively.

SPI_1 and SPI_3 are generally assumed to represent meteorological drought while SPI_6 and SPI_9 are considerable for agricultural drought, and longer time scales such as SPI_{12} and SPI_{24} are proposed for hydrological drought in this study. Therefore, results of SPI_k (k = 1, 3, 6, 9, 12, 24 months) are discussed in pairs of SPI_1 and SPI_3, SPI_6 and SPI_9, and SPI_{12} and SPI_{24}. First, SPI_1 and SPI_3 are discussed based on the precipitation deficit-duration-frequency curves given in Figure 5.14-5.15. At first glance, it is seen that the 2 year-return period precipitation deficit traces a curve far from the curves of 5, 10, 25, 50 and 100 year-return periods. It is also seen that the longest drought duration is 5 months for 5, 10, 25, 50 and 100 year-return periods whereas it is only 3 months for the 2-year return period drought for the 1 month-time scale. The longest drought duration is 7 months at k = 3 month-time scale for return periods other than T = 2 years which has a drought duration of 4 months at maximum. This shows that the drought duration increases with increasing time scale. In other words, a meteorological drought is shorter than an agricultural drought or a hydrological drought. From the comparison of precipitation deficit at k = 1 and 3 months, an increase is observed in the precipitation deficit as k the time scale increases.

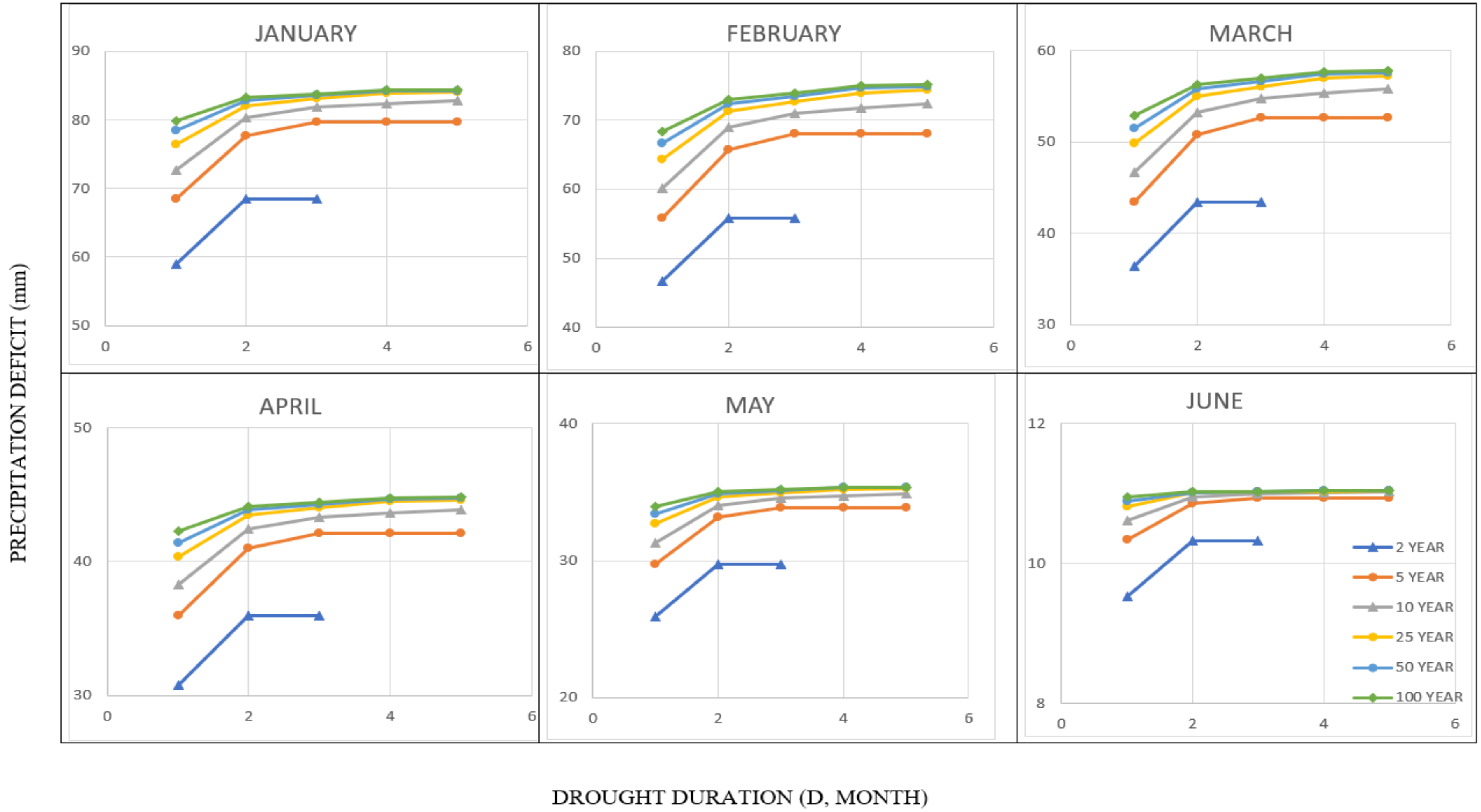

Figure 5.14: Precipitation deficit for SPI_1 in Adana meteorological station.

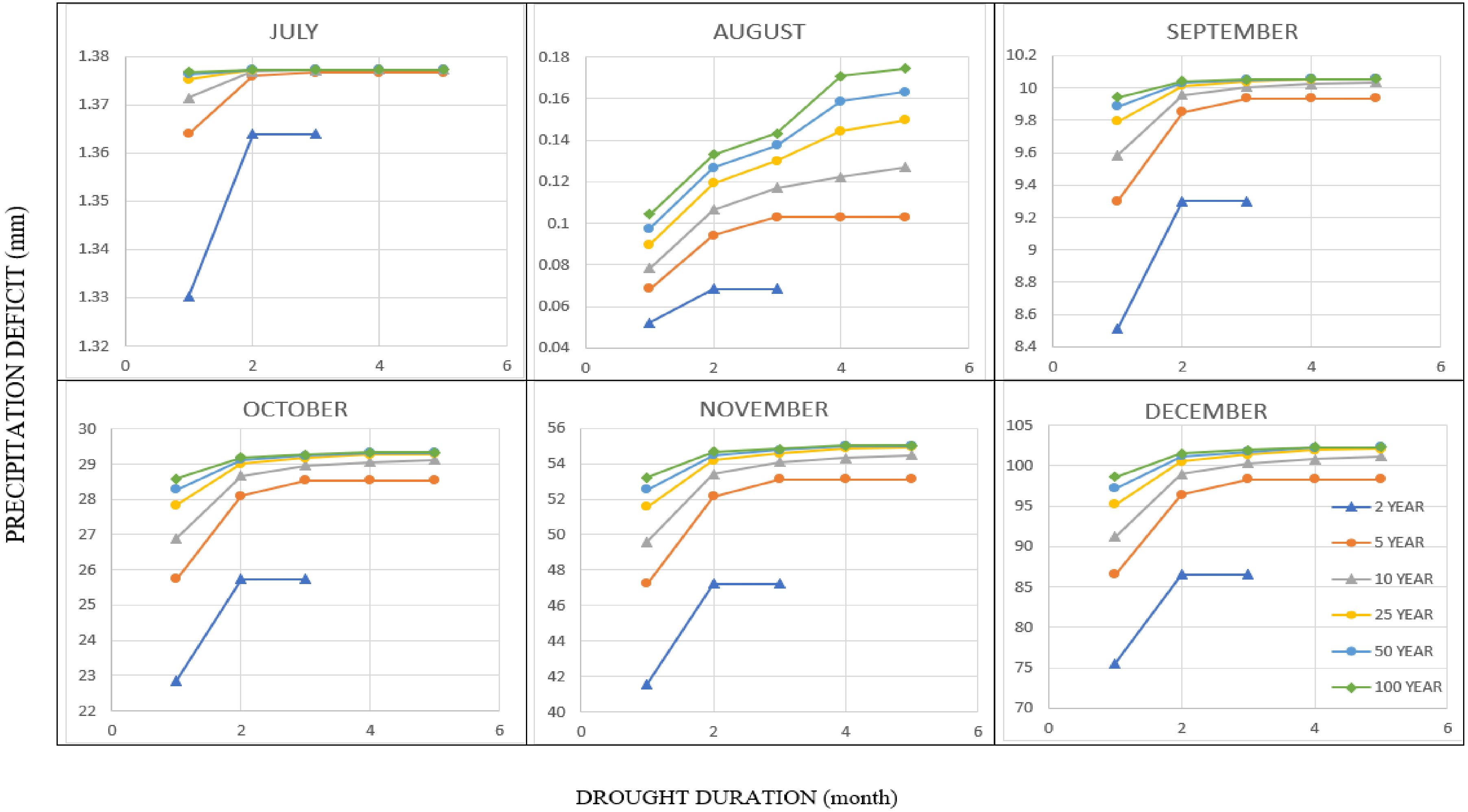

Figure 5.14 (Continued)**:** Precipitation deficit for SPI_1 in Adana meteorological station.

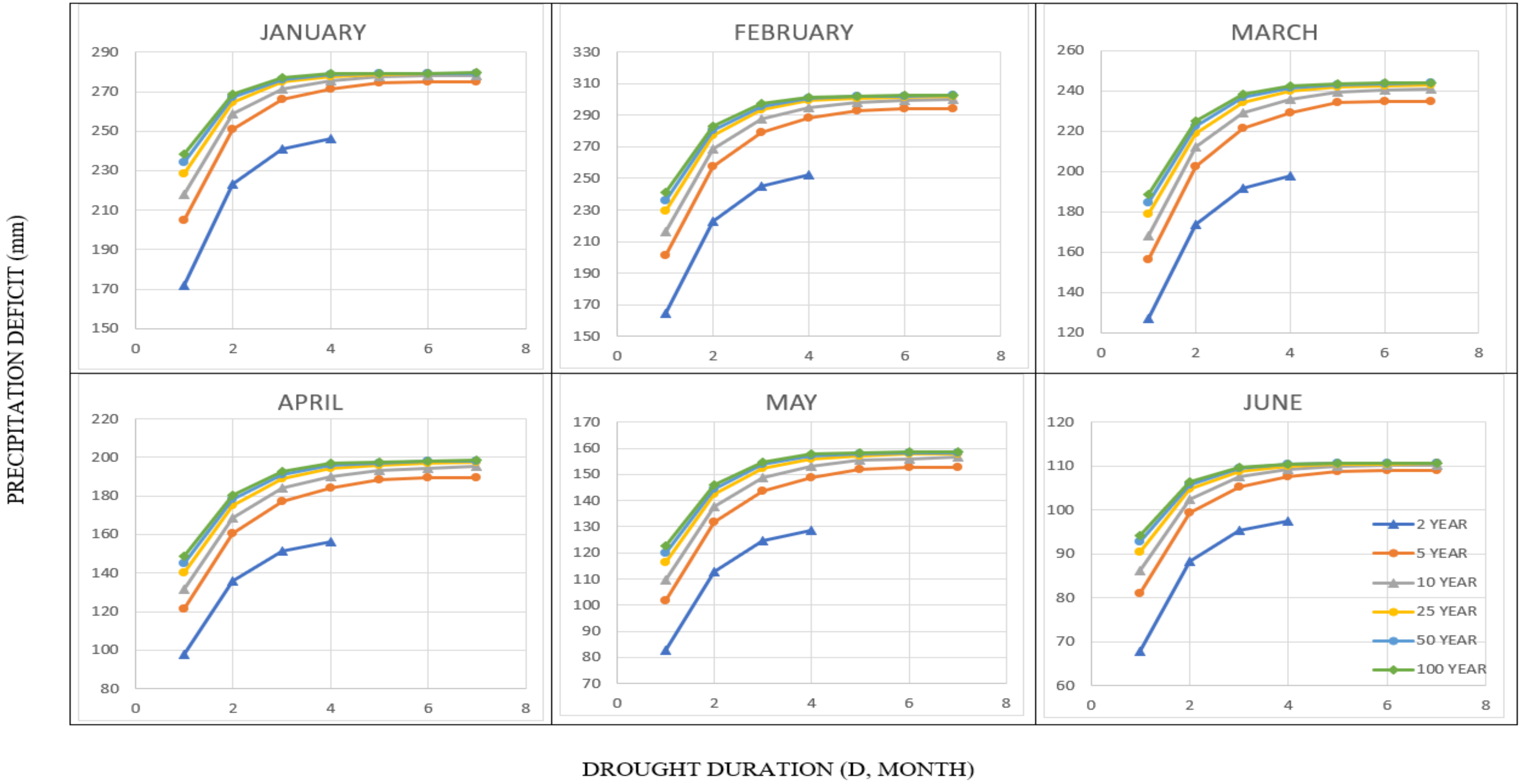

Figure 5.15: Precipitation deficit for SPI_3 in Adana meteorological station.

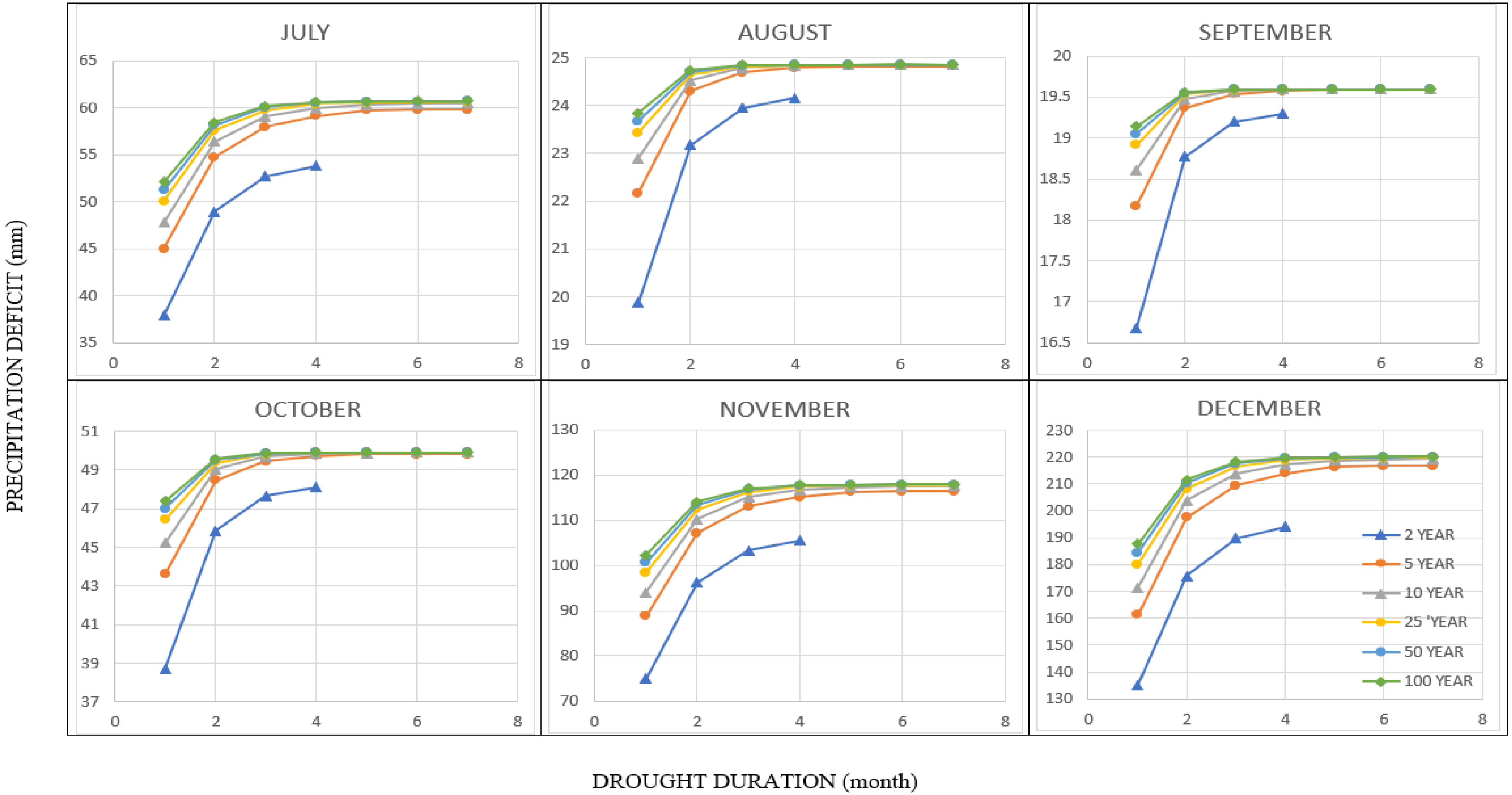

Figure 5.15 (Continued)**:** Precipitation deficit for SPI_3 in Adana meteorological station.

Another outcome of Figures 5.14 and 5.15 is that precipitation deficit increases with drought duration as well as return period. However, the precipitation deficit rate decreases with increasing drought duration. Also, the difference among precipitation deficit becomes gradually negligible with increase in the drought duration, and the precipitation deficit curves approach each other. This is a general result which is valid for all months in the year and more obvious in k = 3 month-time scale (Figure 5.15). At seasonal scale, precipitation deficit decreases in summer months while it increases in winter due to the natural seasonality in the precipitation. Finally, it should be emphasized that almost no difference exists among precipitation deficits for 25 year- or longer return periods. Critical precipitation deficits for k = 1 and 3 months in Figures 5.14 and Figure 5.15, respectively, are calculated for each month again owing to the seasonality in the precipitation. As explained in Chapter 3 (Section 3.3), the largest total severity over the drought duration D in each year is assigned as the D month-duration critical drought of the relevant year. Regardless of the month in which the critical drought observed within the year, the largest precipitation deficit calculated from the critical drought was assigned to each of the 12 months of the year as if the critical drought could be seen in any months. In other words, the precipitation deficits were calculated based on the most severe drought severity that could be observed for each year.

When a detailed monthly look at Figures 5.14 and 5.15 is a made, it is seen for k = 1 month-time scale and D = 1 month-drought duration that the precipitation deficits are calculated as 59, 47, 36.5, 30.8, 26, 9.5, 1.33, 0.052, 8.5, 22.86, 41.6, 75.52 mm from January to December, respectively in the T = 2 year-return period; and 68.5, 56, 43, 36, 29.7, 10.3, 1.37, 0, 9.3, 26, 47, 87 mm in the T = 5 year-return period. Similary, 73, 60, 47, 38, 31, 11, 1.4, 0.07, 9.6, 27, 49, 91 mm are obtained in the T=10 year-return period and 77, 64, 50, 40, 33, 11, 1.375, 0.09, 9.8, 28, 52, 95 mm in the T = 25 year-return period. For the T = 50 year-return period the monthly precititation deficit are 79, 67, 52, 41, 33, 11, 1.378, 0.1, 9.8, 28.5, 53, 97 mm, and finally, they are 80, 68, 53, 42, 34, 11, 1.379, 0.11, 10, 28.9, 53, 99 in the T = 100 year-return period. It can be said that the largest precipitation deficit is in winter and the lowest in summer. Also, it is possible to extract that the precipitation deficit increases for D = 1 month-drought duration as the return period increases. For the k = 3 month-time scale and the D = 1 month-drought duration, the precipitation deficits are 171, 165, 127, 98, 83, 68, 38, 19, 16.7, 38.5, 75, 135 mm from January to December, respectively in the T = 2 year-return period; 205, 201, 156, 122, 102, 81, 45, 23, 18.5, 44, 89, 161 mm in the T=5 year-return period etc.

It is a general tendency to represent the agricultural drought by SPI_6 and SPI_9 which are discussed as follows based on the precipitation deficit-duration-frequency curves given in Figure 5.16-5.17. As in the case of SPI_6 and SPI_9, at first glance, it is seen again that the 2 year-return period precipitation deficit traces a curve far from the curves of 5, 10, 25, 50 and 100 year-return periods. The longest drought duration at k = 6 months is 11 months for 10, 25, 50 and 100 year-return periods whereas it is 10 months for the 5 year-return period and only 5 months for the 2 year-return period droughts. The longest drought duration is 13 months at k = 9 month-time scale for return periods other than T = 2 years, and 6 months for return period T = 2 years. This shows that the agricultural drought duration increases with increasing time scale as it was in the meteorological drought case represented by SPI_6 and SPI_9. This shows also that the drought duration increases with increasing time scale. In other words, an agricultural drought tends to persist longer than a meteorological drought but shorter than a hydrological drought. From the comparison of precipitation deficit at k = 6 and 9 months, an increase is observed in the precipitation deficit as the time scale increases. Another outcome of Figures 5.16 and 5.17 is that precipitation deficit increases with drought duration as well as return period. However, the precipitation deficit rate decreases with increasing drought duration. Also, the difference among precipitation deficits becomes gradually negligible with increase in the drought duration and the precipitation deficit curves approach each other. This is a general result which is valid for all months in the year and obvious in k = 6 and k = 9 month-time scales. At seasonal scale, precipitation deficit decreases in autumn (the lowest value shifted to October at k = 6 months and to November at k = 9 months) while it increases in winter (the highest value shifted to April at k = 6 months and to June at k = 9 months) due to the natural seasonality in the precipitation. Finally, it should be emphasized that the difference among the precipitation deficits of 25-year or higher return periods becomes more negligible when the duration of drought becomes longer.

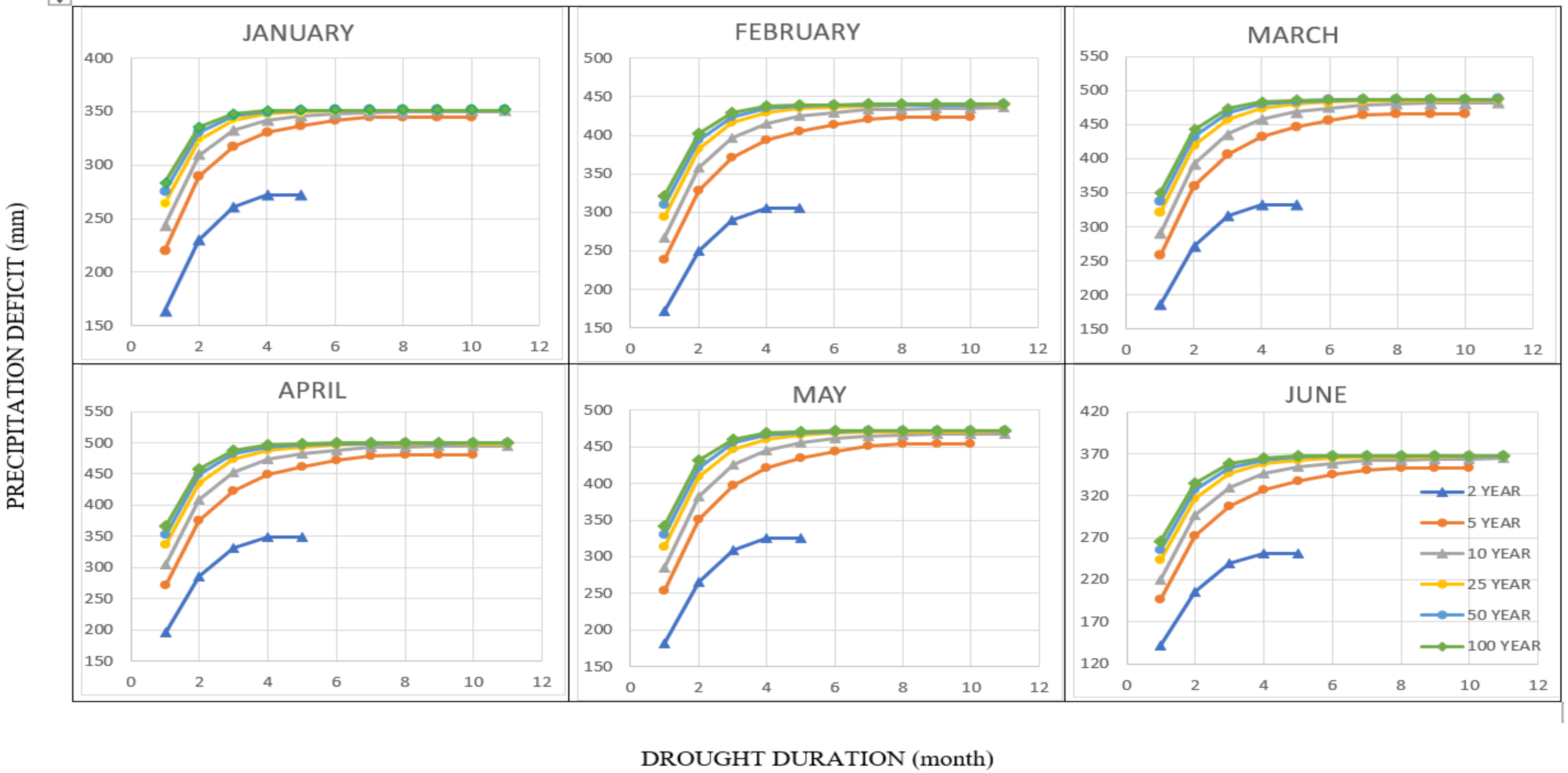

Figure 5.16: Precipitation deficit for SPI_6 in Adana meteorological station.

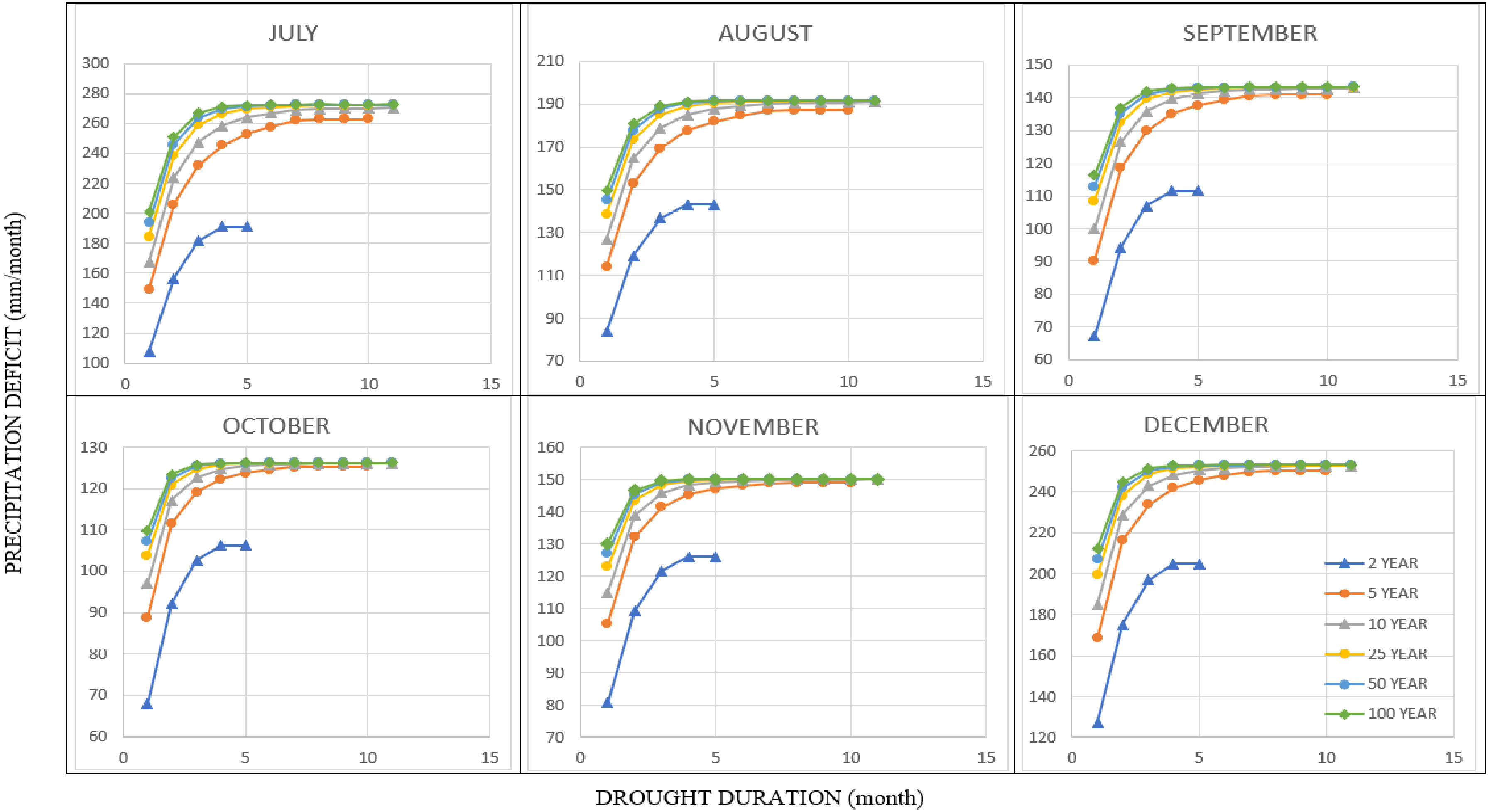

Figure 5.16 (Continued**):** Precipitation deficit for SPI_6 in Adana meteorological station.

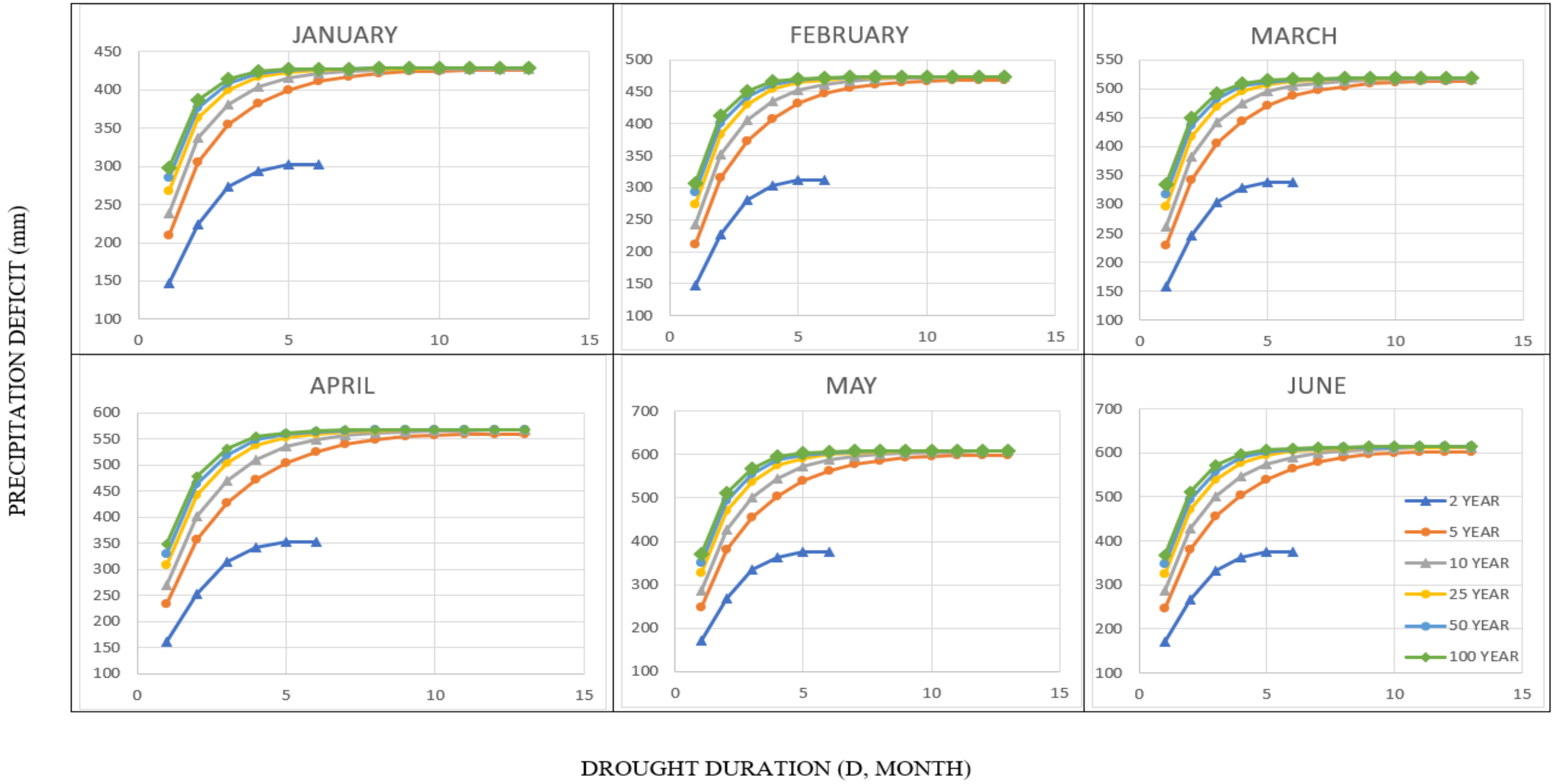

Figure 5.17: Precipitation deficit for SPI_9 in Adana meteorological station.

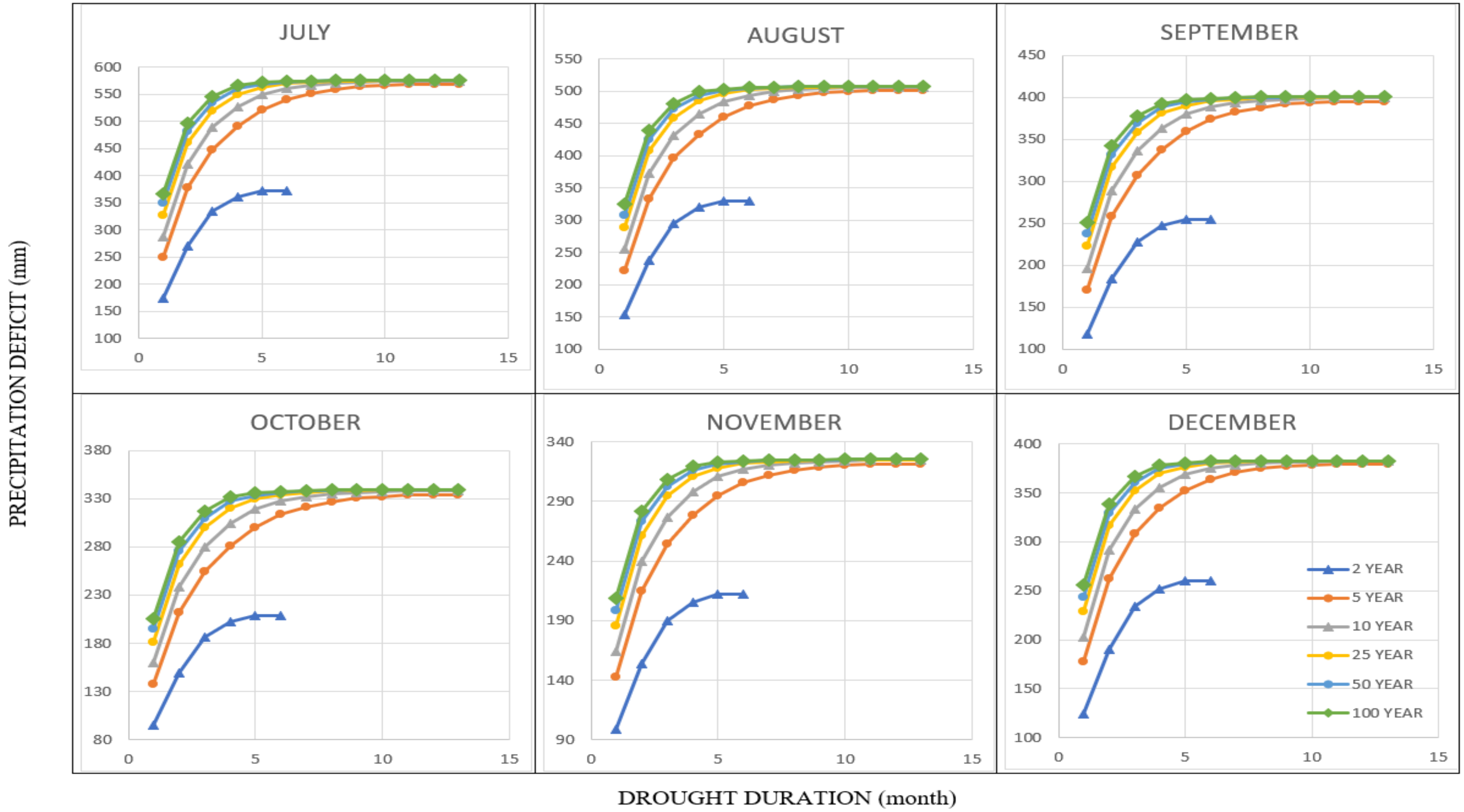

Figure 5.17 (Continued)**:** Precipitation deficit for SPI_9 in Adana meteorological station.

When a detailed monthly look at Figures 5.16 and 5.17 is a made, it is seen for k = 6 month-time scale and D = 1 month-drought duration that the precipitation deficits are calculated as 164, 172, 186, 197, 182, 141, 108, 84, 67, 68, 80.7, 127 mm from January to December, respectively in the T = 2 year-return period; and 220, 238, 258, 272, 253, 196, 149, 114, 90, 90, 105, 168 mm in the T = 5 year-return period. Similary, 244, 267, 290, 305, 285, 220, 168, 127, 100, 97, 115, 185 mm are obtained in the T = 10 year-return period and 264, 294, 320, 336, 314, 243, 184, 139, 108, 104, 123, 199 mm in the T = 25 year-return period. For the T = 50 year-return period the monthly precititation deficit are 275, 309, 337, 353, 329, 255, 194, 145, 113, 197, 127, 207 mm, and finally they are 284, 321, 350, 366, 342, 265, 201, 150, 116, 110, 130, 212 in the T = 100 year-return period. It can be said that the largest precipitation deficit is in winter and the lowest in summer. Also, it is possible to extract that the precipitation deficit increases for D = 1 month-drought duration as the return period increases. For the k = 9 month-time scale and the D = 1 month-drought duration, the precipitation deficits are 148, 147, 159, 161, 171, 170, 173, 153, 118, 94, 99, 124 mm from January to December, respectively in the T = 2 year-return period; 210, 211, 228, 234, 249, 247, 250, 221, 170, 138, 143, 177 mm in the T = 5 year-return period etc.

SPI_{12} and SPI_{24} represent generally the hydrological drought. The longest drought duration of SPI_{12} at return periods T = 5, 10, 25, 50 and 100 years is 14 months (Figures 5.18-5.19). It is 32 months for SPI_{24} at the same return periods. At the 2 year-return period, the longest drought lasted for 6 months at k = 12 month-time interval and 5 months at k = 24 months. The precipitation deficits are 142, 231, 274, 316, 342, 364 mm corresponding to 2, 5, 10, 25, 50 and 100 year-return periods, respectively at k = 12 month-time scale and the D = 1 month-drought duration. For the same drought duration, they are 121, 298, 397, 512, 590, 665 corresponding to 2, 5, 10, 25, 50 and 100 year-return periods, respectively at k = 24 month-time scale.

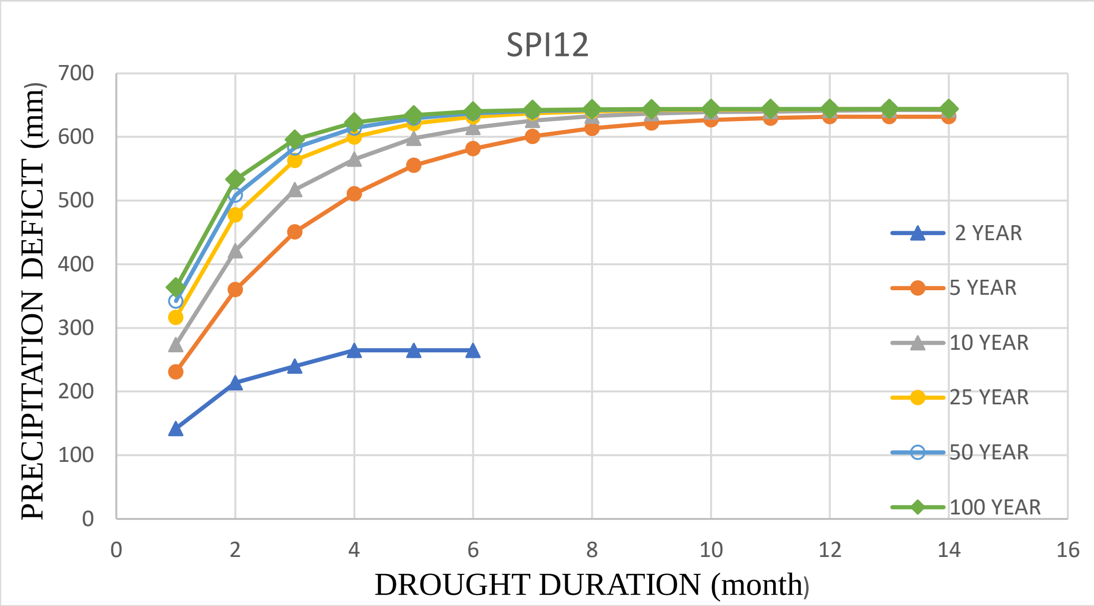

Figure 5.18: Precipitation deficit for SPI_{12} in Adana meteorological station.

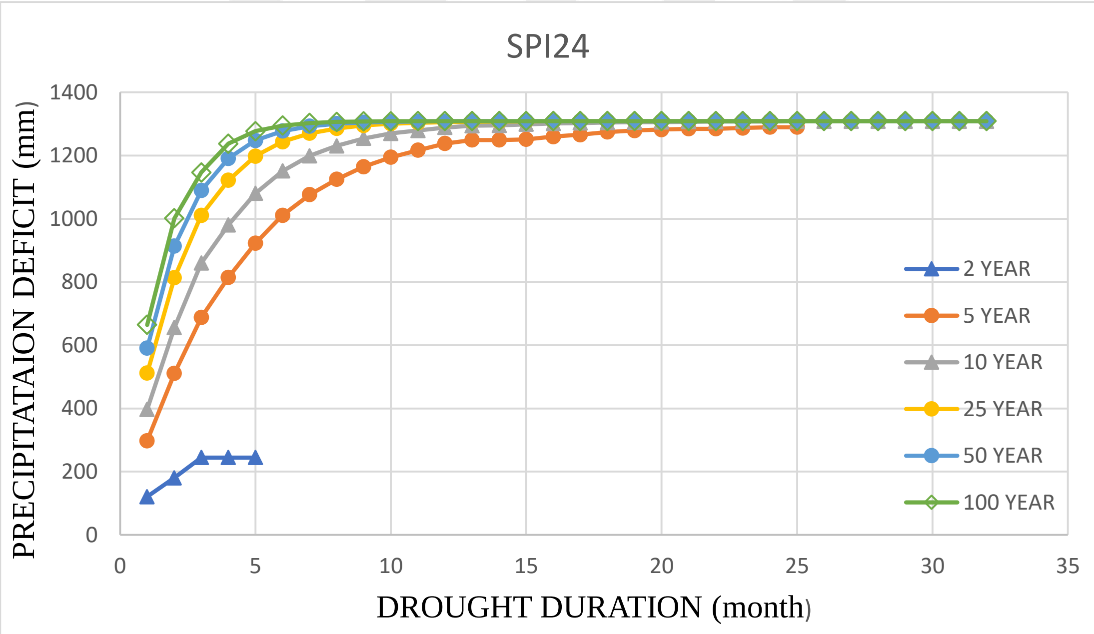

Figure 5.19: Precipitation deficit for SPI_{24} in Adana meteorological station.

5.10 Intensity-Duration-Frequency (IDF) Curves and The Drought Classes

Based on Equation (3.11), the average drought severity (intensity) is obtained by dividing the total severity over the drought duration for different return periods. The drought severity is determined from the best-fit probability distribution functions found after the frequency analysis. As an example, for Adana meteorological station, the intensity-duration-frequency curves based on the precipitation deficit corresponding to 2, 5, 10, 25, 50 and 100 year-return periods are shown Figures 5.20-5.25 for k = 1, 3, 6, 9, 12 and 24 months.

With the use of this method, it is expected that the destructive and irreversible effects of meteorological, agricultural and hydrological droughts can be realized more physically. While using the SPI, information on the drought phenomenon is hidden. It requires a technical and analytical mechanism to extract the final information in terms of physical variables such as precipitation as in the case of this study. In the proposed methodology, however, by the use of precipitation, a direct and physically meaningful information is provided to the end-users such as farmers, water resources managers and decision-makers who are familiar with monthly, seasonal or annual precipitation after their experience in the field. The direct information on the precipitation deficit to be provided will allow making advance planning and taking measures against droughts. Thus, the intensity-duration-frequency curves based on the precipitation deficit are important tools to develop for using in actions against drought.

The intensity-duration-frequency curves (based on the average precipitation deficit) for the SPI_1 and SPI_3 were given in Figures 5.20-5.21. At first glance, it is seen that the 2 year-return period intensity traces a curve lower than the curves of 5, 10, 25, 50 and 100 year-return periods. With increase in drought duration and return period, the average precipitation deficit (intensity) decreases. This means also that the likelihood of very severe droughts decreases. When the 2 year-return period is excluded, almost no difference exists among the average precipitation deficit for all the return periods. From the comparison of the precipitation deficit intensity at k = 1 and 3 months, an increase is observed in the average precipitation deficit as the k time scale increases.

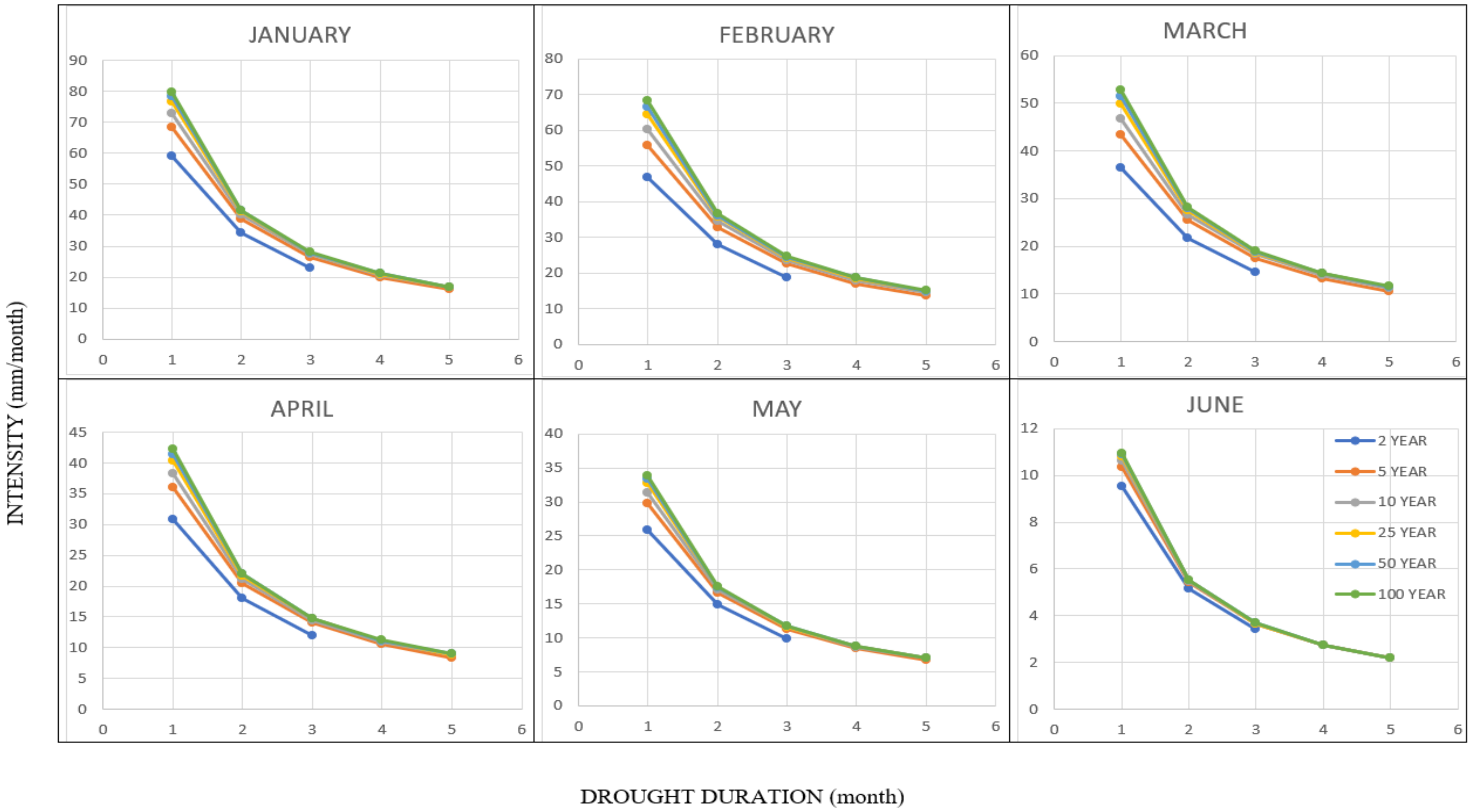

Figure 5.20: Average precipitation deficit (intensity) for SPI_1 in Adana meteorological station.

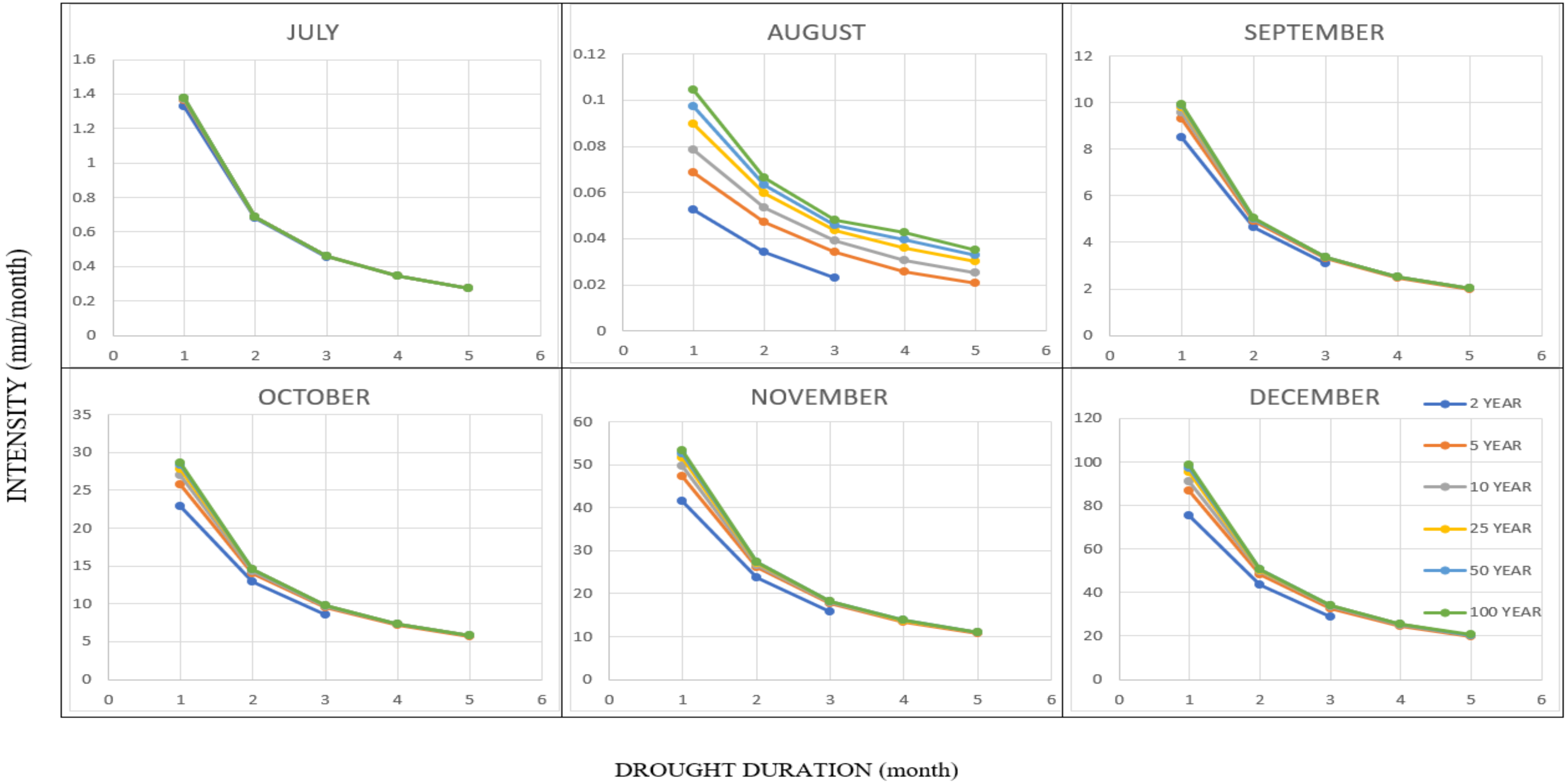

Figure 5.20 (Continued)**:** Average precipitation deficit (intensity) for SPI_1 in Adana meteorological station.

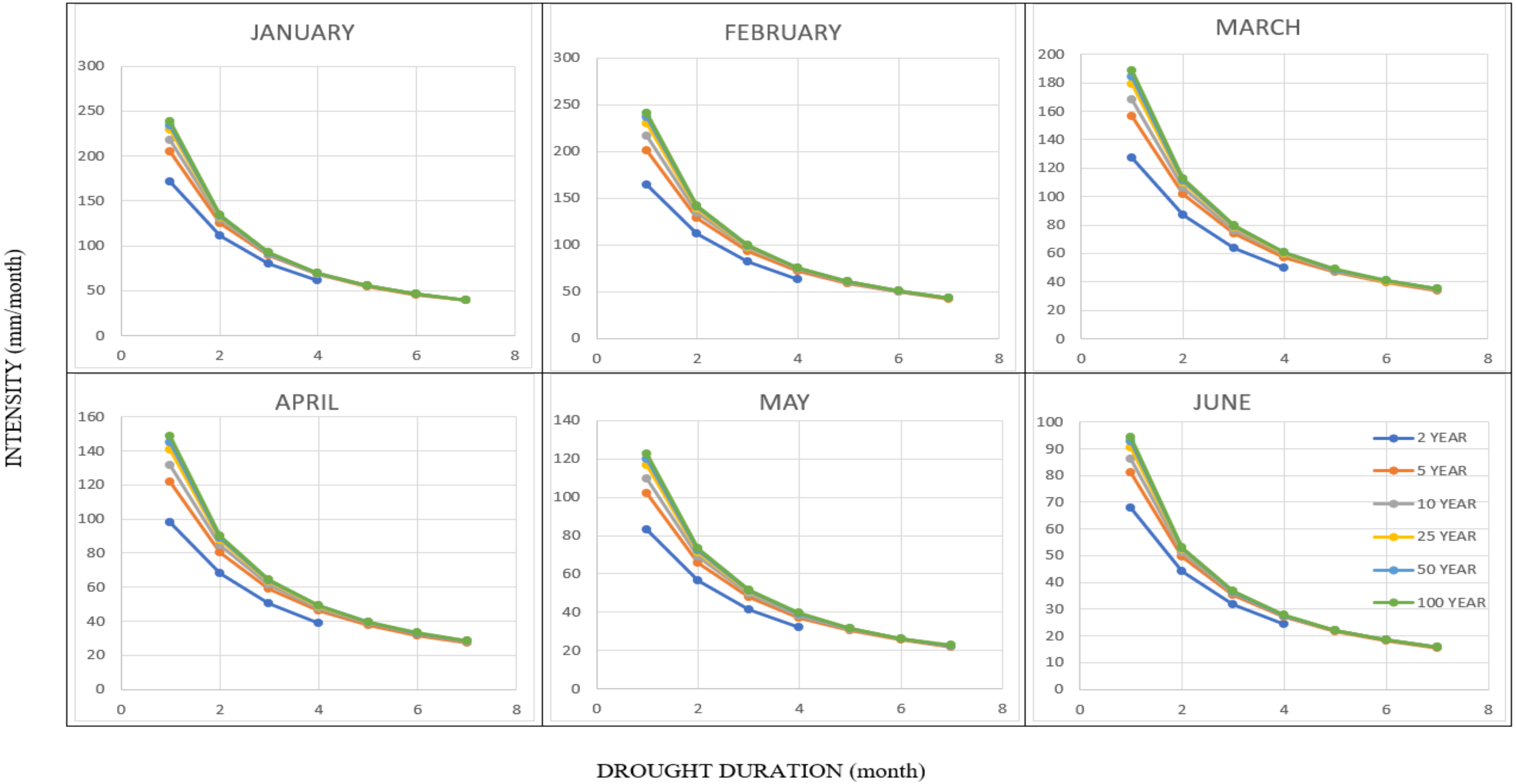

Figure 5.21: Average precipitation deficit (intensity) for SPI_3 in Adana meteorological station.

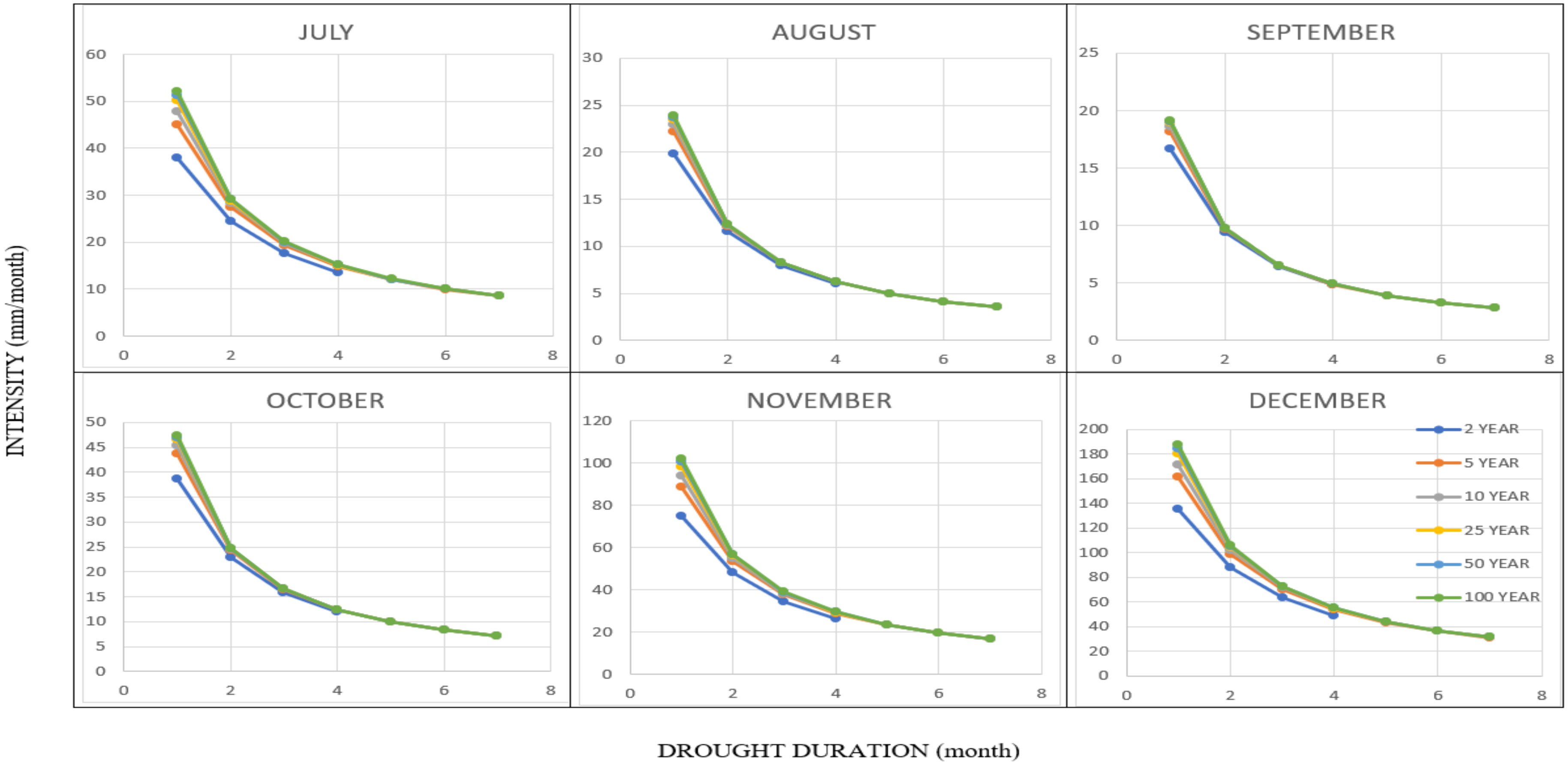

Figure 5.21 (Continued)**:** Average precipitation deficit (intensity) for SPI_3 in Adana meteorological station.

Another outcome of Figures 5.20 and 5.21 is that the intensity decreases with drought duration; it increases however slightly with increasing return period although it converges to a curve for other return periods in drought durations longer than one month. Because, the difference between the intensity becomes quickly negligible with increase in the drought duration. This is a general result which is valid for all months in the year and more obvious in long drought durations. At seasonal scale, intensity in the precipitation deficit decreases in summer while it increases in winter due to the natural seasonality in the precipitation.

When a detailed monthly look at Figures 5.20 and 5.21 is a made, it is seen that the average precipitation deficit (intensity) is 59, 69, 73, 77, 78 and 80 mm/month in the 2, 5, 10, 25, 50 and 100 year-return periods, respectively for k = 1 month-time scale and D = 1 month-drought duration. When the drought classes are concerned, the boundary values in terms of intensity are 0, 49, 62, and 70 mm (in January as an example) and average precipitation deficit among these boundary values is mild, moderate, severe and extreme drought class, respectively (Table 5.5). In other words, when the precipitation deficit averaged over the drought duration is 59 mm, the moderate drought is observed. The average precipitation deficits were similarly calculated for each month of the year for 2, 5, 10, 25, 50 and 100 year-return periods. By making comparison of intensity of the D month-duration and T year-return period drought with the boundary intensities, the D month-duration and T year-return period droughts are classified. This allows one to determine which drought class will any D month-duration and T year-return period drought be. This is performed for Adana meteorological station as an example in Table 5.5. Similar simple analysis can be made for different D month-duration droughts. The final outcome of this analysis is that the average precipitation deficits decrease when the drought duration increases, and the likelihood of the most severe of drought decreases at the same time. In other words, the likelihood of severe droughts ascends as the drought duration declines; i.e., extreme droughts were observed for 10, 25, 50 and 100 year-return periods in D = 1 month-duration and k = 1 month-time scale in Adana meteorological station. As the drought durations also ascend, the severity of drought approached to become mild.

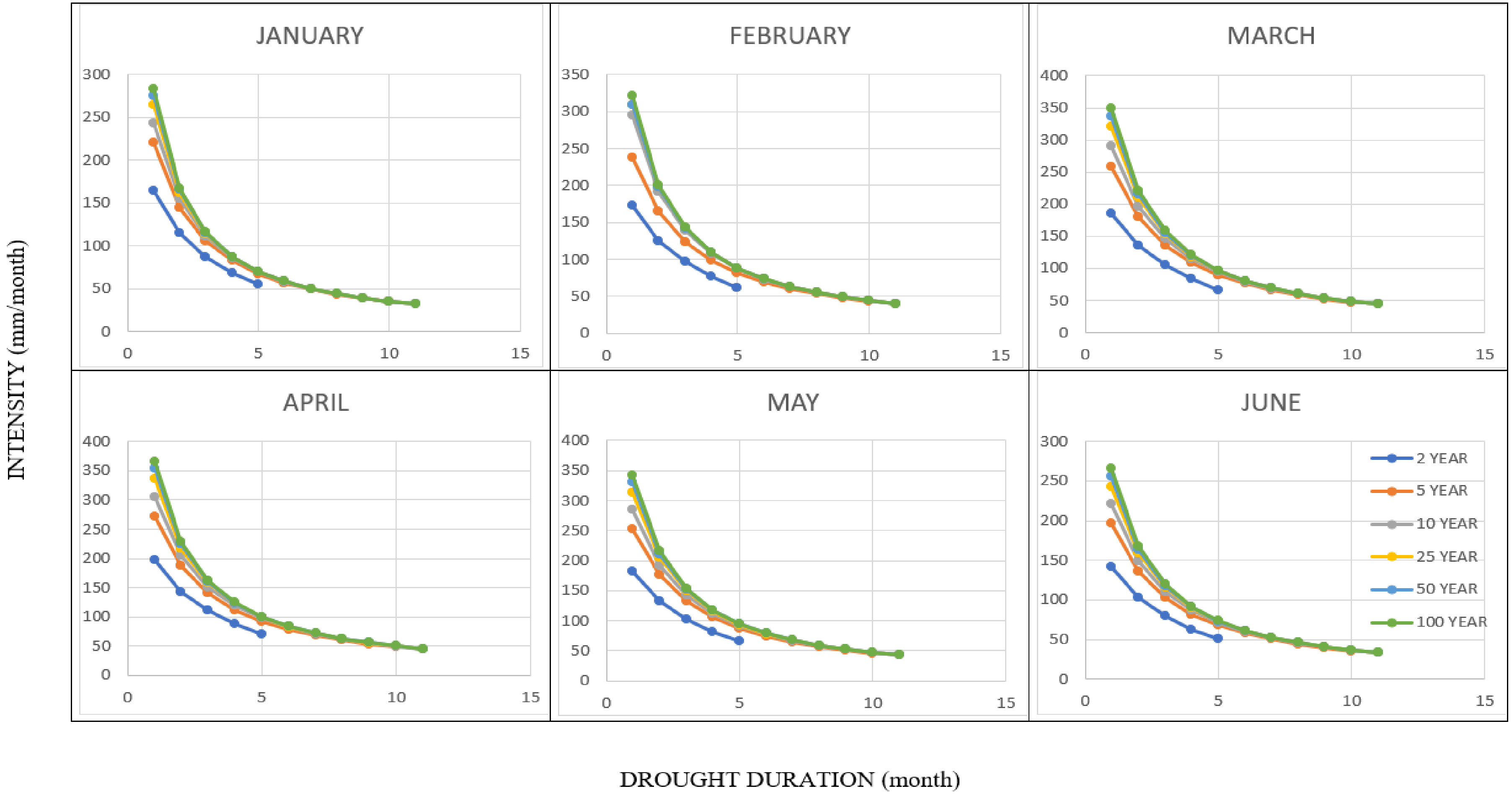

Figure 5.22: Average precipitation deficit (intensity) for SPI_6 in Adana meteorological station.

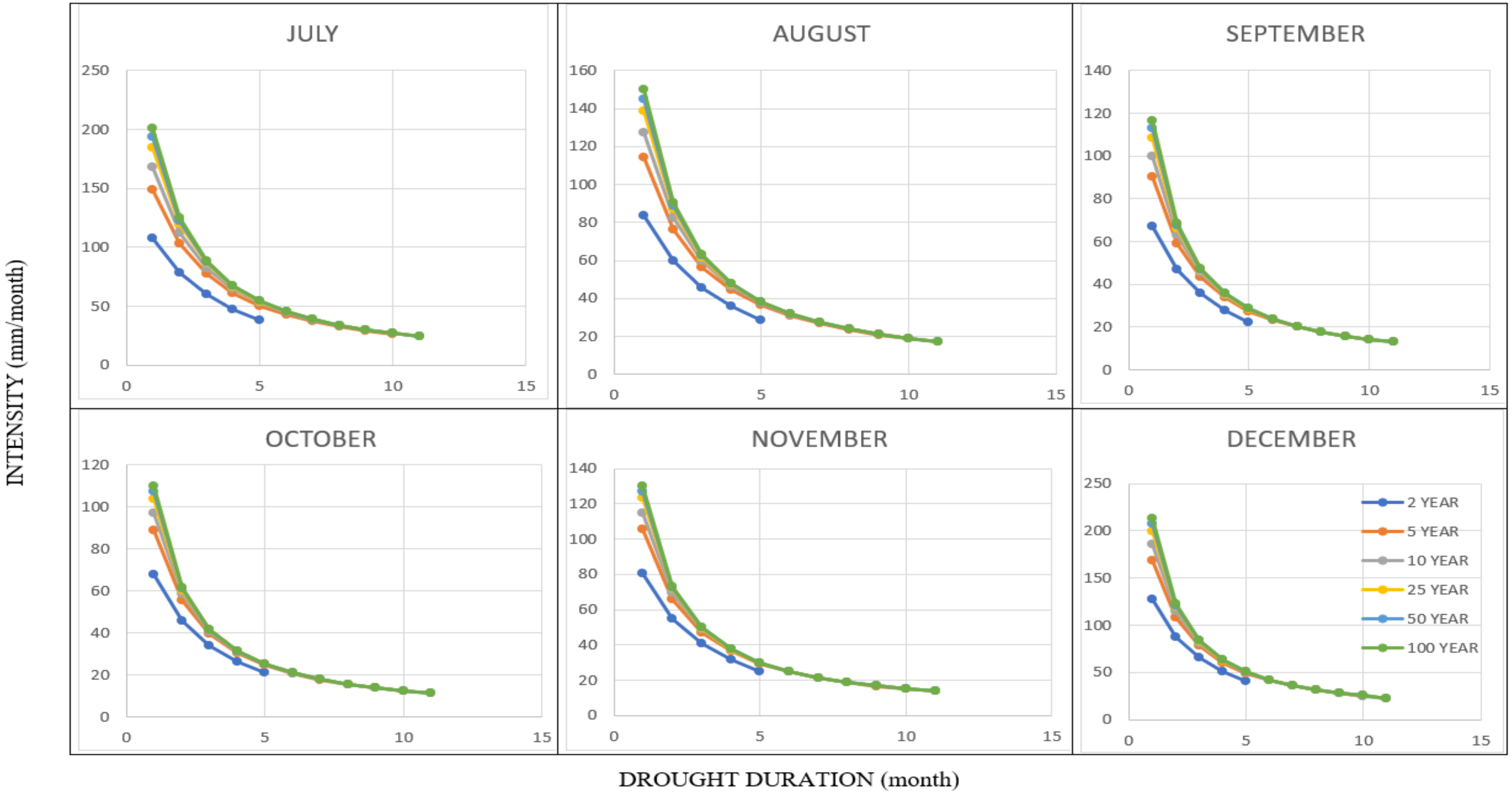

Figure 5.22 (Continued)**:** Average precipitation deficit (intensity) for SPI_6 in Adana meteorological station.

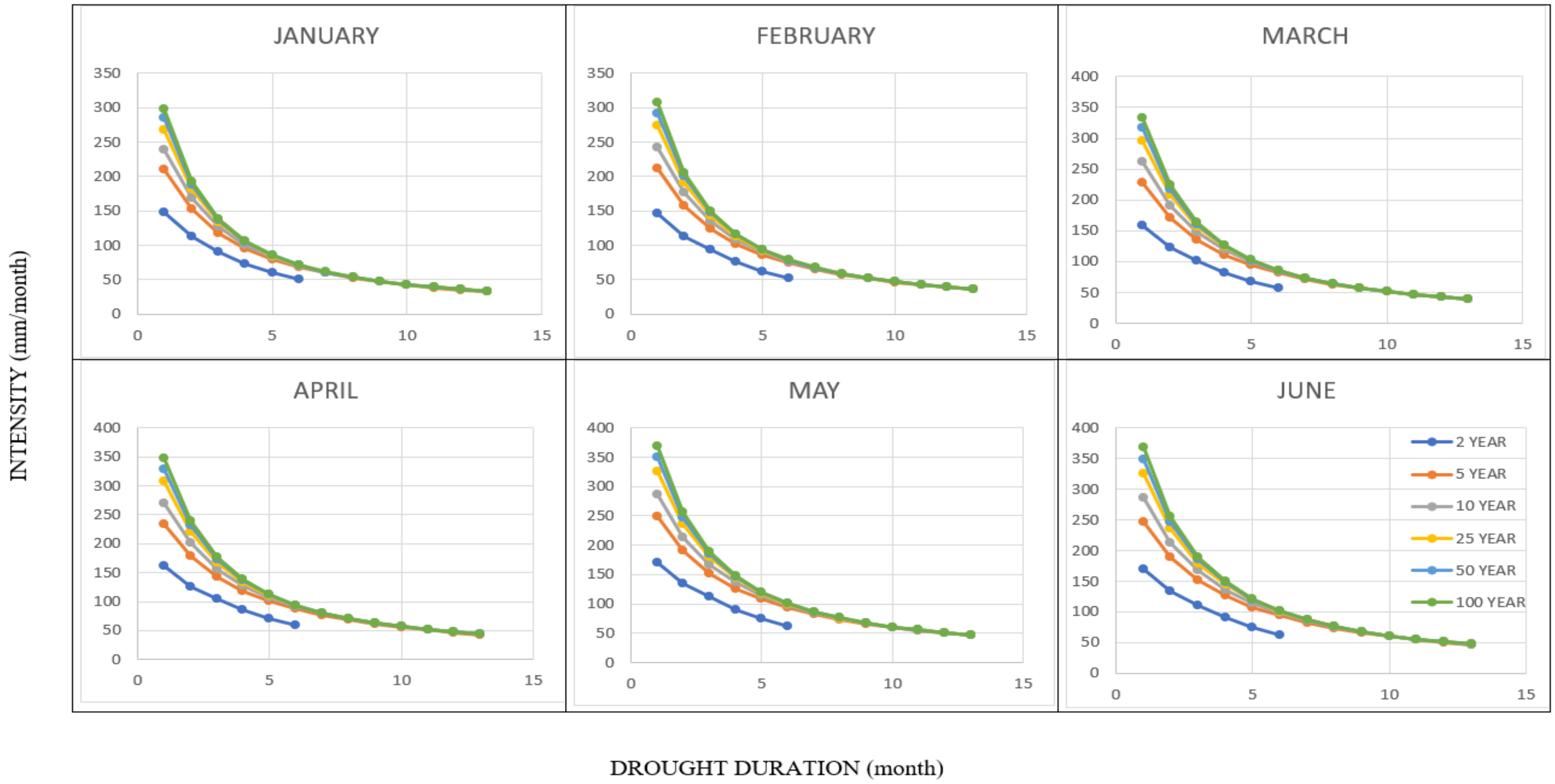

Figure 5.23 Average precipitation deficit (intensity) for SPI_9 in Adana meteorological station.

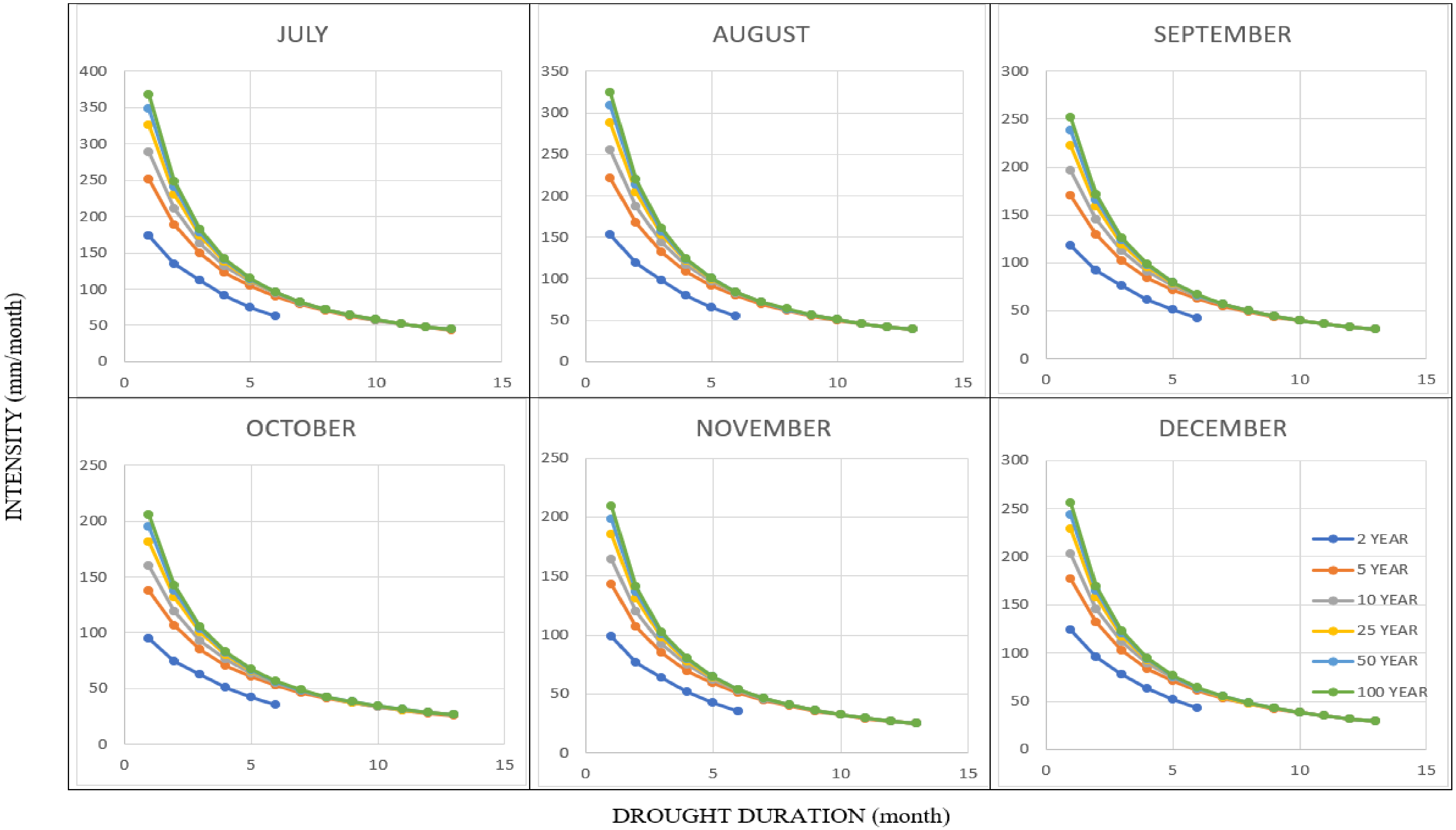

Figure 5.23 (Continued)**:** Average precipitation deficit (intensity) for SPI_9 in Adana meteorological station.

Average precipitation deficit (intensity)-duration-frequency curves of the SPI_6 and SPI_9 are given in Figure 5.22-5.23. General behaviours, caught at first glance, of the intensity-duration-frequency curves of SPI_1 and SPI_3 are valid for SPI_6 and SPI_9. That is, it is seen that the 2 year-return period intensity traces a curve lower than the curves of 5, 10, 25, 50 and 100 year-return periods. With increase in drought duration and return period, the average precipitation deficit (intensity) decreases. This means also that the likelihood of very severe droughts decreases in longer drought duration. When the 2 year-return period is excluded, almost no difference exists among the average precipitation deficit for all return periods, particularly when the drought duration increases. From the comparison of the intensity precipitation deficit at k = 6 and 9 months, an increase is observed in the average precipitation deficit as the time scale increases. Another outcome of Figures 5.22 and 5.23 is that the intensity decreases with drought duration; it increases however slightly with increasing return period although it converges to a curve for other return periods in drought durations longer than a month. Because, the difference between the intensity becomes quickly negligible with increase in the drought duration. This is a general result which is valid for all months in the year and more obvious in long drought durations. At seasonal scale, the lowest intensity shifted towards the end of autumn because of summation of summer months over autumn season with inceasing time scale.

When a detailed monthly look at Figures 5.22 and 5.23 is a made, it is seen that the average precipitation deficit is 164, 220, 244, 264, 275 and 284 mm/month for 2, 5, 10, 25, 50 and 100 year-return periods, respectively for k = 6 month-time scale and D = 1 month-drought duration. When the drought classes are concerned, the boundary values in terms of intensity are 0, 134, 182, and 221 mm/month (in January as an example) and average precipitation deficit among these boundary values is mild, moderate, severe and extreme drought, respectively (Table 5.5). In other words, when the precipitation deficit averaged over the drought duration is 164 mm/month, a moderate drought is observed. The average precipitation deficits were similarly calculated for each month of the year for 2, 5, 10, 25, 50 and 100 year-return periods. This is performed for Adana meterological station as an example in Table 5.5. Similar simple analysis can be made for different D month-duration droughts. The final outcome of this analysis is that the average precipitation deficits decrease when the drought duration increase, and the likelihood of the most severe of drought decreases at the same time. In other words, the likelihood of severe droughts ascends as the drought duration declines; i.e., extreme droughts were observed for 10, 25, 50 and 100 year-return periods in D = 1 month-duration and k = 6 month-time scale in Adana meteorological station. As the drought durations ascend, the intensity of drought approachs to the class of mild drought. Differences of the average precipitation deficits give rise to the seasonality.

As far as SPI_{12} and SPI_{24} are concerned, the average precipitation deficit, the intensity, converges to a minimum value asymptotically as the drought duration increases, for all return periods other than the 2 year-return period curve which is interrupted at drought durations of 6 months at k = 12 months and 5 months at k = 24 months (Figures 5.24-5.25). The average precipitation deficit is calculated, also the drought class is determined. The SPI_{12} and SPI_{24} is calculated at annual time scale as a single value as the time scale is a year or its multiple.

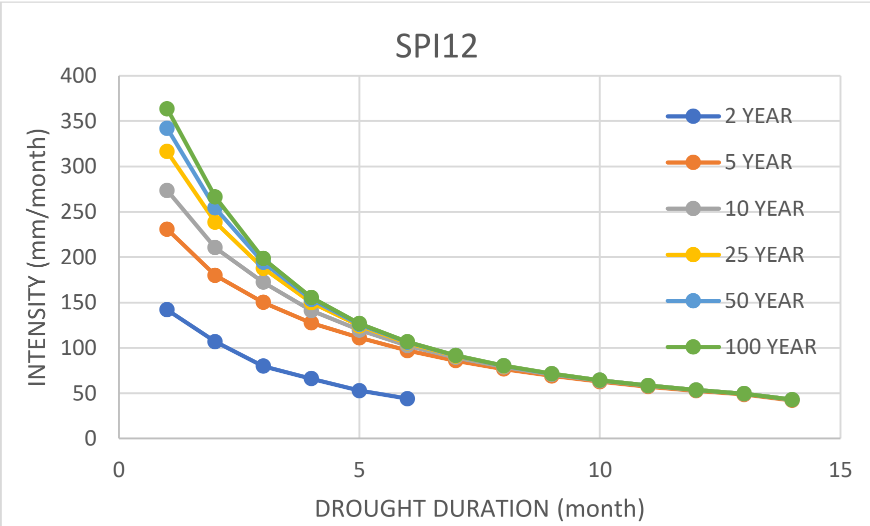

Figure 5.24 Average precipitation deficit (intensity) for SPI_{12} in Adana meteorological station.

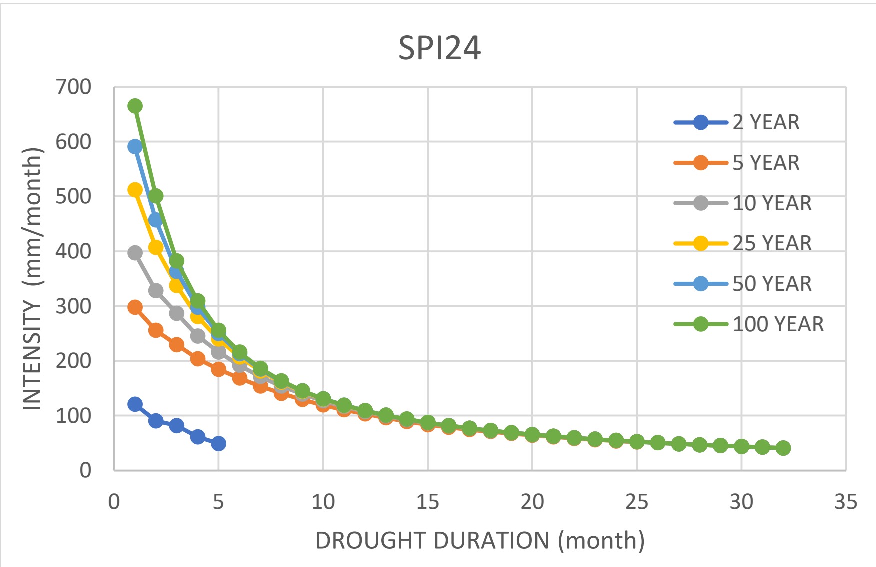

Figure 5.25 Average precipitation deficit (intensity) for SPI_{24} in Adana meteorological station.

Table 5.5: Boundary values of drought classes for SPI_1, SPI_3, SPI_6, and SPI_9 in Adana meteorological station.

	January	February	March	April	May	June	July	August	September	October	November	December
SPI_1	0.00 49.069 62.007 70.319	0.00 37.951 49.524 57.659	0.00 29.674 38.572 44.768	0.00 25.506 32.416 36.919	0.00 21.828 27.140 30.398	0.00 8.455 9.810 10.457	0.00 1.261 1.344 1.368	0.00 0.040 0.057 0.072	0.00 7.496 8.784 9.427	0.00 19.528 23.805 26.241	0.00 35.272 43.427 48.260	0.00 63.458 79.085 88.576
SPI_3	0.00 126.94 168.64 199.56	0.00 118.36 161.34 195.24	0.00 90.97 124.46 151.27	0.00 69.54 96.00 117.63	0.00 59.45 81.21 98.58	0.00 50.03 66.59 78.89	0.00 28.21 37.26 43.90	0.00 15.92 19.64 21.84	0.00 13.81 16.52 17.97	0.00 30.62 38.23 42.90	0.00 55.94 73.68 86.55	0.00 100.01 132.81 157.12
SPI_6	0.00 133.95 182.46 220.94	0.00 139.05 193.46 239.06	0.00 150.15 209.45 259.47	0.00 158.76 221.02 273.19	0.00 147.02 205.18 254.18	0.00 114.00 158.96 196.83	0.00 87.08 121.27 149.90	0.00 68.14 93.75 114.56	0.00 54.92 74.85 90.64	0.00 56.14 75.00 89.11	0.00 66.90 89.10 105.69	0.00 104.83 141.12 169.06
SPI_9	0.00 143.91 198.89 244.21	0.00 143.06 199.84 247.92	0.00 154.51 216.13 268.47	0.00 157.16 221.32 276.73	0.00 166.61 234.94 294.12	0.00 165.41 233.51 292.65	0.00 168.86 236.82 294.85	0.00 149.38 209.43 260.64	0.00 114.76 161.17 200.96	0.00 92.17 130.24 163.32	0.00 96.37 134.97 167.83	0.00 120.81 168.07 207.66

Mild	Moderate	Severe	Extreme

The boundaries of drought classes are determined by inserting SPI values in Table 3.1 into Equation (3.24) obtained after regression analysis. For a given month, intensity calculated from the observed precipitation is compared with the upper and lower boundaries of drought classes in Table 5.5. For example, a moderate is observed in January at k = 1 month-time scale if the intensity falls between 49.069 and 62.007 mm/month; a severe drought is observed in June at k = 3 month-time scale if the intensity falls between 66.59 and 78.89 mm/month; an extreme drought is observed in November at k = 6 month-time scale if the intensity is higher than 105.69 mm/month. It is important to know what precipitation deficit corresponds to which drought class such that proper actions can be taken against the drought to remove, overcome or minimize any negative effect of drought on different sectors as well as ecology and society. In Table 5.6, boundaries of drought classes are given together with the precipitation deficit assigned for k = 12 month-time scale.

Table 5.6: Drought classes of precipitation deficits for k = 12 month in Adana meteorological station.

DEFICIT	1	2	3	4	5	6	7	8	9	10	11	12	13	14
T (Yıl)	D=1	D=2	D=3	D=4	D=5	D=6	D=7	D=8	D=9	D=10	D=11	D=12	D=13	D=14
2	142.00	213.97	239.73	264.65	264.66	264.68								
5	230.95	360.16	450.54	510.56	555.27	581.59	600.78	613.54	621.67	626.66	629.60	631.72	631.73	631.73
10	273.66	421.16	517.09	564.86	597.77	614.63	625.89	632.52	636.47	638.97	639.95	641.38	642.20	642.20
25	316.42	477.39	563.18	599.73	620.91	631.67	637.38	640.41	642.01	642.83	643.18	643.51	643.68	643.68
50	342.13	508.59	582.86	613.88	629.22	637.26	640.73	642.43	643.23	643.55	643.71	643.80	643.83	643.85
100	363.67	533.17	595.71	622.79	634.04	640.19	642.31	643.28	643.66	643.78	643.85	643.86	643.87	643.88
INTENSITY														
T (Yıl)	D=1	D=2	D=3	D=4	D=5	D=6	D=7	D=8	D=9	D=10	D=11	D=12	D=13	D=14
2	142.00	106.99	79.91	66.16	52.93	44.11								
5	230.95	180.08	150.18	127.64	111.05	96.93	85.83	76.69	69.07	62.67	57.24	52.64	48.59	42.12
10	273.66	210.58	172.36	141.22	119.55	102.44	89.41	79.06	70.72	63.90	58.18	53.45	49.40	42.81
25	316.42	238.70	187.73	149.93	124.18	105.28	91.05	80.05	71.33	64.28	58.47	53.63	49.51	42.91
50	342.13	254.29	194.29	153.47	125.84	106.21	91.53	80.30	71.47	64.36	58.52	53.65	49.53	42.92
100	363.67	266.58	198.57	155.70	126.81	106.70	91.76	80.41	71.52	64.38	58.53	53.66	49.53	42.93

Drought classes	
0.00	Mild
168.09	Moderate
237.82	Severe
298.72	Extreme

The final outcome of this analysis is that the average precipitation deficits decrease when the drought duration increases, and the likelihood of the most severe of drought decreases at the same time. In other words, the likelihood of severe droughts ascends as the drought duration declines; i.e., extreme droughts were observed for 10, 25, 50 and 100 year-return periods in D = 1 month-duration and k = 1 month-time scale in Adana meteorological station. As the drought durations also ascend, the severity of drought approached to become mild.

5.11 Further Case Studies

Monthly precipitation data of 19 meteorological stations were used in implementing the methodology proposed in this study. With the help of such a diverse data set, it is possible to propose and extend the applicability of the intensity-duration-frequency curves based on precipitation deficit. It is seen from the results readily available as soft files and provided partly in Appendix B (Figures B.1-B.19) the severity-duration-frequency or intensity-duration-frequency curves could be proposed for practical use in the drought-related studies. In Appendix B, to keep the thesis at an acceptable volume, the presented results are limited to the severity-duration-frequency curves in terms of precipitation deficit at k = 12 month-time scale only.

5.12 Spatial Mapping

In this study, the Seyhan River basin in the Mediterranean region of Turkey was investigated for its drought characteristics based on the precipitation deficit by considering 19 meteorological stations. SPI was applied to monthly precipitation data at the stations at k = 12-month time scale. Critical drought severity was calculated from the SPI time series which were first implemented by frequency analysis after which critical drought severities were calculated for return periods of 2, 5, 10, 25, 50 and 100 years. From the critical drought severity, the precipitation deficit of 1-, 3-, 6- and 12-month drought durations and 2-, 5-, 10-, 25-, 50- and 100-year return periods were determined at k = 12-month time scale. The drought intensity values were also obtained as the ratio of the drought severity to its duration. Examples to describe the above analysis are given in Table 5.7 from which it is clearly seen that no drought exists in a few meteorological stations for longer drought duration and return periods as the likelihood of any drought decreases as its duration and return period increase. Also, it is seen from Table 5.7 that no drought was determined in station 6560 at k = 12-month time scale although the station has experienced drought at lower time scales. This is due to the short length of the precipitation time series that do not allow one to make a proper frequency analysis and to quantify the drought.

Spatial mapping becomes useful in obtaining information for stations with smaller size observation that prevents making a proper frequency analysis or no observation at all. The resulting precipitation deficit corresponding to D-month drought duration and T-year return period at k = 12-month time scale was mapped using the inverse distance weighted (IDW) interpolation technique (Figure 5.26). Only the precipitation deficit calculated from the SPI was considered in the interpolation process to derive the spatial mapping of the drought over the basin.

Figure 5.26 presents boundary values of precipitation deficit changes for each D-month drought. As given in Table 5.7, the D = 1-month drought has its own boundary value that changes between 42.6 mm (the 2-year return period drought in meteorological station 17802) and 567.9 mm (the 100-year return period drought in meteorological station D18M019). Similarly, for the drought of D = 3 month-duration, boundary values are between 31.2 mm (the 2-year return period drought in meteorological station D18M011) and 305.6 mm (the 100-year return period drought in meteorological station D18M012). This is also applied to D = 6 and 12-month drought durations for which the precipitation deficit intervals are 16.7 mm–231.2 mm and 22.1 mm–74.9 mm, respectively (Table 5.7). Therefore, it is important to emphasize that the maps in Figure 5.26 are only comparable for each of the drought durations, because the iso-contours of the precipitation deficit have been fixed for each of the drought durations separately. Darker colors in the maps of the same drought duration imply more severe drought. For example, it is seen that droughts become more severe with moving from shorter return periods to longer return periods for D = 1-month drought. This statement is correct for D = 3-, 6- and 12-month drought as well. However, when droughts with different durations are compared, it should be emphasized also that a darker color in a longer drought duration map does not necessarily mean that the drought is more severe than a drought with a lighter color in the shorter drought duration. Similarly, a lighter color does not necessarily mean the opposite; i.e., the drought is milder. Therefore, the discussion of results should be made through the joint use of Table 5.7 with Figure 5.26 to arrive at a conclusive discussion about the severity of the drought. It is clearly seen from Table 5.7 and Figure 5.26 that the drought severity becomes milder with the increasing longer return periods. This is an expected result of the fact that drought severity is absorbed along longer drought durations. This is a phenomenon quite similar to or even the same as the less intense precipitation of longer durations in the hydrological practice of precipitation intensity–duration–frequency curves.

The spatial distribution of D = 1-month drought duration indicates that more severe precipitation deficits tend to occur in the coastal parts of the basin for all return periods while the north-eastern part of the basin is prone to a lower precipitation deficit at the same return periods. In other words, the majority of the precipitation deficit that occurred in the coastal part was severe in D = 1-month drought duration. As the return period increases from 2 years to 100 years, the drought intensity increases and more severe intensities move towards the northern part of the basin. However, it is always lower in the north compared to the south. The intensity of precipitation deficit exhibits a more variable behavior over the basin when the return period increases.

At the D = 3-month drought duration, again more severe droughts are typically observed at the coastal part of the basin. Especially, the northern part of the Seyhan River basin exhibits a lower precipitation deficit. Nevertheless, as the return period increases, more severe droughts shift from south towards the north, as was the case for D = 1-month drought. It should be noted from Table 5.7 that for three meteorological stations (6204, 6560 and D18M019), no drought intensity is calculated. This is because the number of critical drought severities is less than 10 and the frequency analysis was therefore not applied on these particular meteorological stations. The number of such meteorological stations increases to 5 and 6 for D = 6 and 12 months, respectively. These stations are not indicated in the corresponding maps in Figure 5.26.

Another issue to discuss is the D = 12-month duration drought with 2-year return period (See blank column of T = 2-year return period in D = 12-month drought in Table 5.7 that corresponds to the blank lower-left cell of Figure 5.26). The mildest drought of D = 12-month has a return period longer than 2 years. In other words, once a 12-month drought is observed, it is as severe as a drought with a return period longer than 2 years. This is the case for 19 meteorological stations used in this study. Therefore, no map was created for D = 12-month drought at T = 2-year return period. Also, it is noticeable from Table 5.7 that this has been the case for five meteorological stations (6902, 17802, 17840, 17934, and 17936). Maps in Figure 5.26 have been created by using meteorological stations for which the precipitation deficit is calculated for a given drought duration and return period.

Except for the northern part, the majority of the basin has more severe droughts for all return periods. A conclusive result is that the coastal part of the basin with higher precipitation (Figure

5.27) experiences more severe drought at all return periods while the northern part of the basin with lower precipitation is characterized by a milder drought. This can be explained by the fact that higher temperature in the southern coastal lowlands increases evapotranspiration that reduces the available precipitation substantially and gives an increase in the precipitation deficit to end up with more severe droughts. In the northern part of the basin with higher altitudes and lower temperature, droughts are milder compared to the southern part due to the net precipitation being reduced by the lower evapotranspiration. It shows also that the coastal parts of the basin are more likely to be affected from hydrological drought with a consequent loss in water resources.

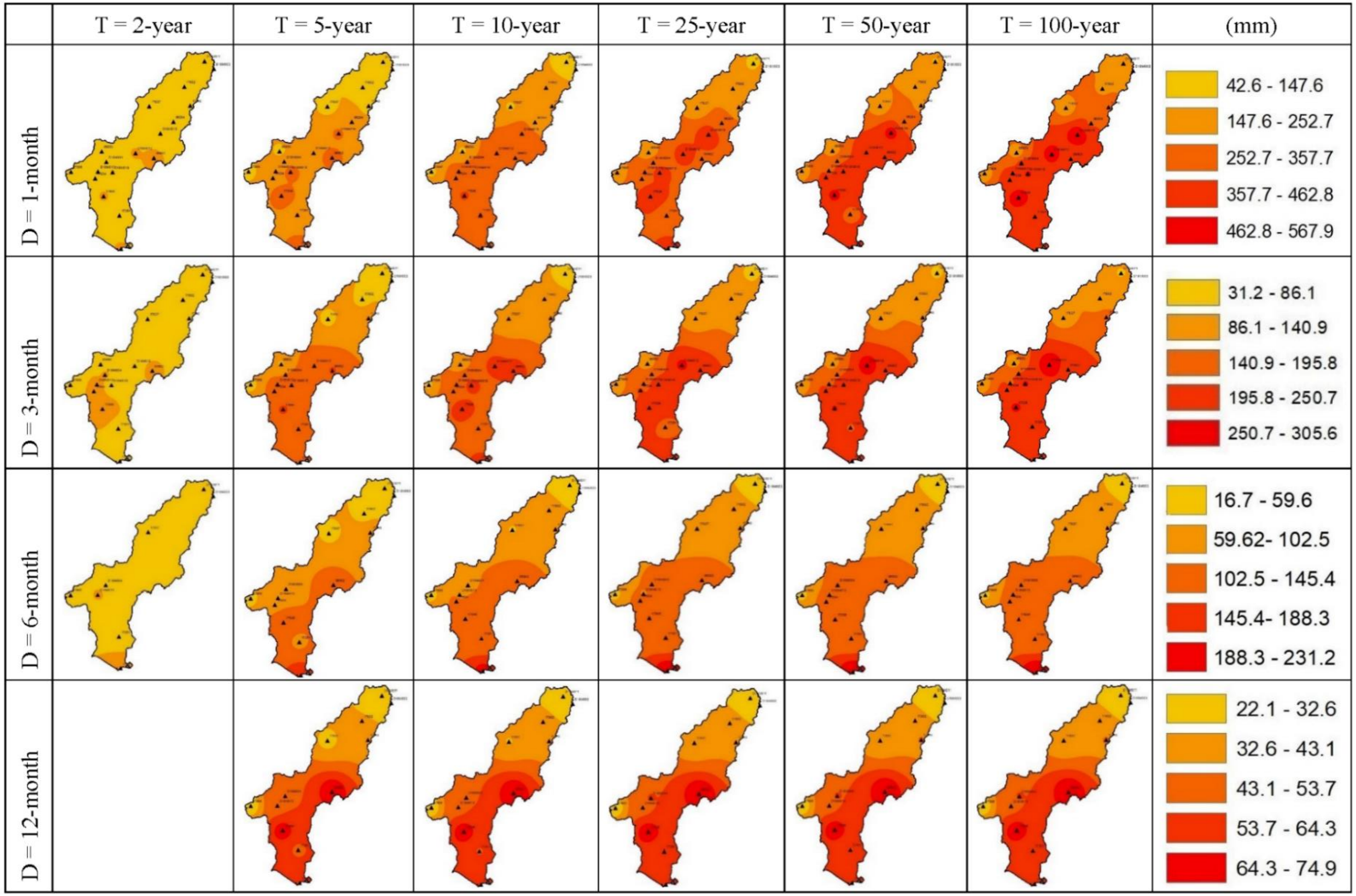

Figure 5.26: Intensity maps for droughts of 1, 3, 6 and 12 month-durations and T = 2, 5, 10, 25, 50 and 100 year-return periods over the Seyhan River basin in the Eastern Mediterranean region of Turkey.

Table 5.7 Drought intensity based on precipitation deficit corresponding to 2, 5, 10, 25, 50 and 100-year return periods at k = 12-month time scale

	D = 1 month						D = 3 months						D = 6 months						D = 12 months					
Return period / Station no	**2**	**5**	**10**	**25**	**50**	**100**	**2**	**5**	**10**	**25**	**50**	**100**	**2**	**5**	**10**	**25**	**50**	**100**	**2**	**5**	**10**	**25**	**50**	**100**
6204	50.4	152.7	214.8	281.1	321.0	353.5																		
6560																								
6893	81.3	108.7	123.0	138.6	148.7	158.1	65.3	79.3	86.1	93.3	97.8	101.8												
6902	174.3	280.5	320.4	354.2	371.5	384.3	96.4	199.7	218.4	230.4	235.4	238.6		131.3	137.6	141.1	142.5	143.4		73.4	74.4	74.7	74.8	74.9
17351	142.0	230.9	273.7	316.4	342.1	363.7	79.9	150.2	172.4	187.7	194.3	198.6	44.1	96.9	102.4	105.3	106.2	106.7		52.6	53.4	53.6	53.6	53.7
17802	42.6	113.4	156.4	199.8	224.6	243.7	31.4	81.4	99.4	114.8	122.5	127.9		56.2	63.8	67.8	69.0	69.5		32.7	34.4	34.8	34.9	34.9
17837	66.6	113.9	136.9	158.7	170.8	180.4	48.1	76.9	90.7	103.8	111.0	116.5	34.0	52.5	58.8	63.3	65.1	66.1		29.9	32.3	33.2	33.4	33.5
17840	69.7	136.4	170.9	207.8	231.4	252.2	38.6	94.3	113.4	130.4	139.6	146.7		66.6	75.4	81.3	83.7	85.2		40.2	42.3	43.2	43.5	43.6
17906	42.7	96.5	125.2	151.9	165.9	176.4	32.0	66.1	78.4	88.1	92.7	95.9	22.1	45.9	49.7	51.5	52.1	52.4		25.6	26.3	26.4	26.5	26.5
17934	146.1	242.9	294.1	348.3	382.5	412.4	98.4	154.5	178.1	199.0	209.8	217.5		98.9	107.6	113.7	115.7	116.6						
17936	150.8	296.0	374.1	452.4	498.3	535.5	105.8	204.3	228.8	246.5	254.7	260.4		129.6	136.4	140.0	141.2	141.9		70.5	71.3	71.5	71.5	71.6
17981	149.7	270.4	325.1	377.9	408.8	434.0	80.4	179.0	201.9	218.4	226.0	231.2	80.4	179.0	201.9	218.4	226.0	231.2		62.3	62.9	63.1	63.1	63.1
D18M003	57.9	109.1	134.8	159.3	173.0	183.9	45.7	72.1	80.9	87.7	90.8	93.0	31.0	45.3	47.6	48.6	48.9	49.1		24.3	24.5	24.6	24.6	24.6
D18M004	129.2	208.8	254.0	305.7	340.6	372.8	89.4	141.5	161.9	180.1	189.7	196.8	58.9	95.0	100.8	104.3	105.7	106.5		52.2	53.4	53.8	53.9	54.0
D18M011	43.0	85.6	108.3	130.9	143.9	154.3	31.2	60.7	69.8	76.9	80.3	82.8	16.7	39.6	42.8	44.4	44.8	45.0		22.1	22.5	22.6	22.6	22.6
D18M012	152.6	247.5	312.4	396.4	459.6	521.3	70.3	165.4	216.2	264.3	288.9	305.6												
D18M013	146.7	234.8	276.7	317.9	342.2	362.1	96.9	150.2	166.8	179.4	185.3	189.5	61.2	94.0	98.8	101.1	101.8	102.2		50.3	51.1	51.3	51.3	51.3
D18M018	149.2	286.5	350.0	411.9	448.4	478.1	72.7	189.1	220.0	242.3	252.3	259.1												
D18M019	109.9	270.7	356.5	451.3	512.8	567.9																		

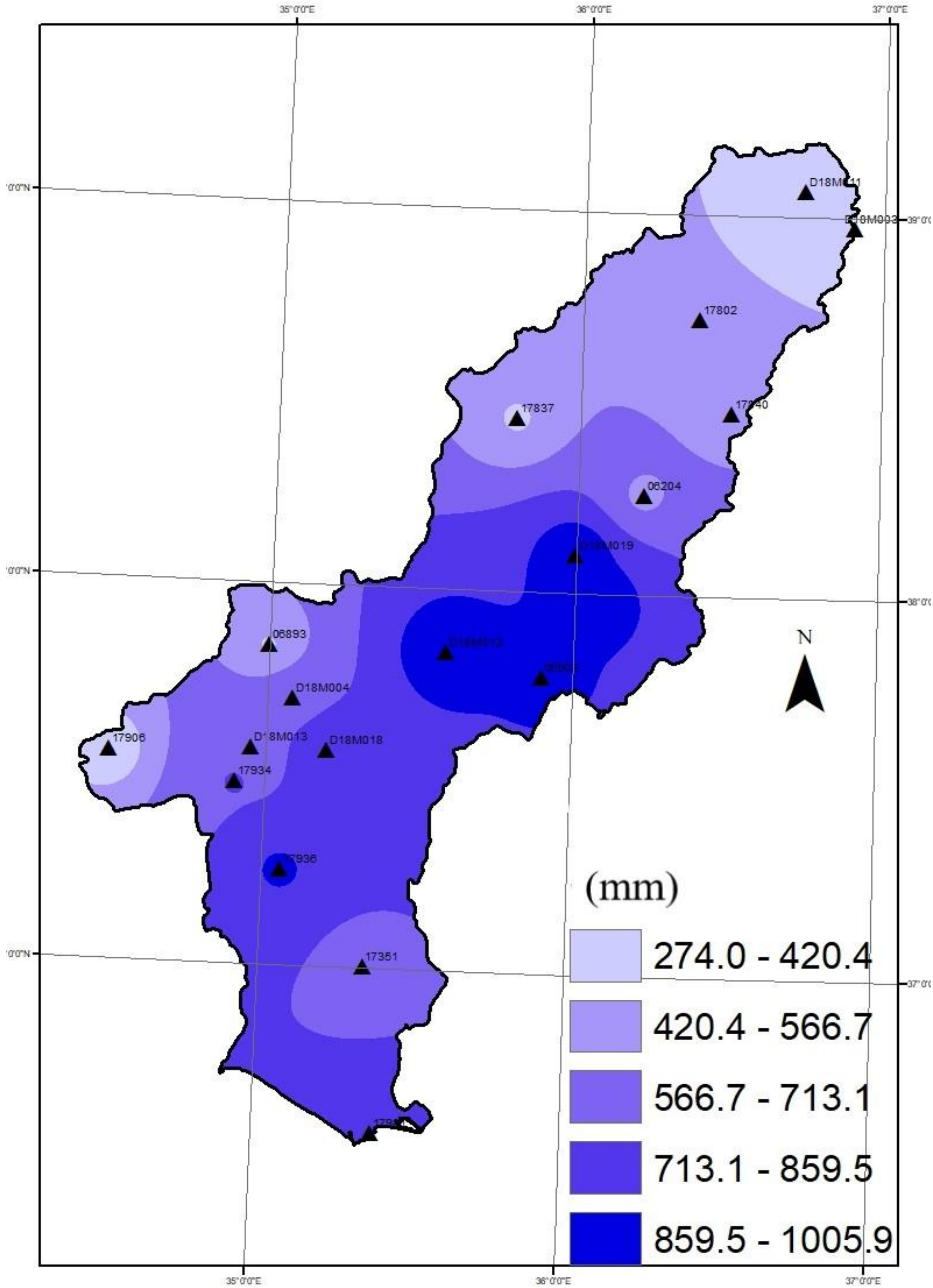

Figure 5.27. Spatial change in the annual precipitation over the Seyhan River basin.

6. CONCLUSIONS AND RECOMMENDATIONS

Drought affects seriously the majority of the population in many ways such as economical, social and environmental. Therefore, understanding, analysis and forecasting drought play a significant role in risk management. One of the many ways to be prepared against drought is to implement the drought risk evaluation by using drought parameters; e.g. frequency, severity, duration and intensity. The purpose of this study is to develop the severity-duration-frequency curves based on precipitation deficit and is to provide a comprehensive characterisation of the droughts for 19 selected stations in the Seyhan River basin, Turkey. The precipitation deficit was computed based on the Standardized Precipitation Index (SPI). Instead of the direct use of SPI, the severity was calculated to characterise the drought. On the other hand, SPI is a technical tool and it is thus difficult to be understood at the first glance by end-users and decision-makers. Precipitation deficit in different duration and return periods is more useful and physically meaningful to the users. The direct information provided by the precipitation deficit allows making in-advance planning and taking measures against drought. In this study, a concept named as the within-period drought is introduced. It is such a drought which has a duration shorter than the duration of the dry period within which the drought is observed. Together with the precipitation deficit and the within-period drought concept, the methodology gains a novelty. With the use of the methodology, it is expected that the destructive and irreversible effects of meteorological, agricultural and hydrological droughts can be realized in a more physical sense. Following conclusions are derived based on the results of the application of the methodology proposed in this study:

1) Dry and wet periods are determined from the SPI_k series for k = 1, 3, 6, 9, 12 and 24 month-time scales. As the k month-time scale increases, the likelihood of observing longer drought duration increases. Thus, longer drought duration is observed in higher time scales. It is important to mention that when the time scale increases, the drought persistency increases; i.e., once the drought has started, it continues for a long time.

2) Severity and duration of droughts are determined for each year from the observed dry periods of the SPI_k time series. Drought with the highest severity in each year is defined as the critical drought of the year. The critical drought severity increases with increasing drought duration.

3) Frequency analysis is applied on the critical drought severity in order to determine the best-fit probability distribution function. Precipitation in dry periods include a significant number of zero values. Therefore, zero values are excluded from the frequency analysis by using the total probability theorem which assigns a probability mass function to zero values and a probability distribution function to the non-zero positive values.

4) Probability distribution functions with wide application in statistical hydrology are checked by the Anderson-Darling statistical test. The Generalized Extreme Value (GEV) probability distribution function is found the best-fit distribution to the critical severities almost for all drought durations in the meteorological stations in the Seyhan River basin considering SPI_k for all time scales. The Log-Normal 2 (LN2) and Log-Pearson Type III (LP3) probability distribution functions are also found applicable alternatively. As, if the probability distribution function is not chosen properly, probability distribution might cause errors while determining frequency of the critical drought severity, a quite high importance should be paid for the frequency analysis of drought.

5) The critical drought severity is calculated for T = 2, 5, 10, 25, 50 and 100 year-return periods from the inverse transformation of the best-fit probability distribution function. It is seen that as the duration and return period of drought increase, its severity increases but the intensity decreases.

6) Relationship between the precipitation and the corresponding SPI values is examined by the regression analysis. Twelve curves are observed for each k = 1, 3, 6 and 9-month time scales, one curve for each k = 12 and 24 month-time scales. Thus, the precipitation deficit is calculated monthly for the within-year time scales (k = 1, 3, 6, 9 months) and annualy for the over-year time scales (k = 12 and 24 months).

7) In order to categorize drought severity, it is important to determine a precipitation threshold value. The selection of the threshold is also crucial to

better understand drought parameters; severity, duration and intensity. Precipitation threshold is accepted as precipitation at SPI = 0 (no drought) since drought starts when precipitation falls below this particular value. The precipitation threshold has the within-year seasonality. It is therefore calculated for each month of the year for k = 1, 3, 6 and 9 month-time scales while only one threshold exists for k = 12 and 24 month-time scales.

8) For the SPI1, the lowest threshold within the year is observed in summer months. The lowest value of SPIk shifts from summer to autumn for k = 3, 6, 9 months due to the accumulation of the low precipitation-summer over the autumn season when calculating the SPIk.

9) It is significant to analyze past droughts before planning any new project or reviewing existing water resources management plans. However, with the change in hydrology, precautions must be taken into consideration such as the nonstationarity when the past is the input of the solution.

10) The precipitation deficit is calculated based on the critical drought severity after frequency analysis is applied. It is defined as the difference between the precipitation threshold at SPI = 0 and the critical precipitation. The precipitation deficit changes depending on the seasonality in the climate within the year. The precipitation deficit is therefore calculated at monthly scale for SPI1, SPI3, SPI6, SPI9 while it is given at annual scale for SPI12 and SPI24.

11) The novel methodology of this study will help in supplying information related to the precipitation deficit to represent water demand in dry periods. The methodology will also be useful to develop water resources in order to compensate the difficulty likely to occur in the event of a future drought.

12) The novel definitions such as the critical drought severity, the singular drought, and the within-period drought introduced in this study are expected to be beneficial for the future studies on drought.

13) The drought duration and the return period increase, as does the precipitation deficit. Higher precipitation deficit is therefore calculated for longer drought duration. In this sense, the 2 year-return period drought intensity-duration-frequency curve is found well lower than and separated clearly from the the curves at higher return periods of from 5 to 100 years. Nevertheless, it has the

same character with the higher return period curves. Also, almost no difference is observed between the precipitation deficit of the droughts of 25 years or longer return periods.

14) The drought intensity-duration-frequency curves based on the precipitation deficit are obtained in a similar way to the drought severity-duration-frequency curves. As the drought duration and the return period increase, the precipitation deficit based on the intensity decreases.

15) Droughts with such high return periods as 50 or 100 years are generally expected not to belong to the extreme drought class while shorter duration-droughts with longer return periods could fall into the extreme drought class. In longer drought durations, mild drought is observed at all return periods. Because, drought intensity decreases with increase in its duration and approaches to the mild drought.

16) The spatial analysis indicates that the Seyhan River basin in the Mediterranean region of Turkey experiences droughts with quite different severities simultaneously. The spatial distribution would alter greatly with increasing return period and drought duration. While the coastal part of the basin is vulnerable to droughts at all return periods and drought durations, the northern part of the basin would be expected to be less affected by the drought.

17) The drought severity-duration-frequency and intensity-duration-frequency curves based on the precipitation deficit are developed for the selected 19 meteorological stations in the Seyhan River basin. The curves are station-based and are not applicable to any other station or another hydrological basin. A methodology emerges to develop a unique drought severity-duration-frequency curve, the regional drought severity-duration-frequency curve, that could be a master key for the region or hydrological basin. The regional drought severity-duration-frequency curve will particularly be useful in ungauged points with missing data.

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APPENDICES

APPENDIX A:

	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
JANUARY	-1.85	-0.06	1.84	1	0.75	-0.86	-0.67	-0.05	0.1	-2.03	0.29	-0.03	1.54
FEBRUARY	-0.58	-0.78	0.09	-0.26	0.57	-0.19	-2.73	0.47	0.75	-0.03	-0.17	0.55	0.71
MARCH	-1.04	0.09	-0.54	-0.14	1.24	-1.38	0.73	-0.52	-0.76	-0.32	-0.51	0.72	-2.52
APRIL	-0.96	-1.06	-0.77	0.52	0.14	1.19	0.25	1.11	0.88	-1.56	0.93	0.37	-0.71
MAY	0.99	1.28	0.79	0.41	-0.72	-0.55	-0.09	-1.43	0.73	1.66	-0.47	-0.8	-0.56
JUNE	0.98	0.29	-0.41	0.89	0.23	0.02	-1.06	0.48	-1.16	-1.16	-0.9	-0.26	-1.16
JULY	2.06	-0.15	0.92	1.69	-0.15	0.12	0.77	0.04	-0.15	-0.15	0.49	0.13	-0.03
AUGUST	0.15	0.15	1.42	0.15	0.42	0.77	0.15	0.29	0.15	1.69	1.73	0.15	0.66
SEPTEMBER	-0.54	-1.08	-1.08	-0.82	-0.52	0.13	1.19	1.5	1.14	0.94	-0.7	-0.06	-1.08
OCTOBER	-0.88	-1.58	0.23	0.01	0.97	1.25	-0.53	-1.02	1.87	-0.67	-1.15	-0.49	-1.05
NOVEMBER	1.7	-0.4	2.35	1.29	-1.12	0.7	0.76	-1.8	-0.54	0.47	-0.68	-0.79	1.06
DECEMBER	0.75	-0.82	0.49	-1.03	0.17	0.65	0.62	-0.98	-0.97	1.57	-0.33	0.57	-1.19

	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
JANUARY	-0.58	-0.91	-0.96	-1.02	0.68	0.34	-0.14	1.6	-0.68	-0.92	0.27	0.6
FEBRUARY	-0.01	0.91	0.85	-0.47	0.89	-0.18	0.3	0.79	-0.45	-1	0.78	0.13
MARCH	0.06	-0.33	0.39	-1.07	1.43	-1.65	0.98	-0.02	-0.11	-0.29	1.42	0.21
APRIL	0.18	-1.52	1.37	-0.99	-0.36	0.94	0.73	-0.85	0.2	-0.82	-0.85	-0.28
MAY	0.14	-0.56	-0.12	-0.59	-0.22	0.5	1.33	0.94	0.6	-0.03	0.68	1.07
JUNE	0.24	-0.43	0.55	-0.4	-1.16	-0.79	1.18	0.28	-0.88	1.89	-0.4	1.1
JULY	0.66	1.76	0.16	-0.15	1.27	0.08	-0.15	0.96	-0.15	0.39	0.02	-0.03
AUGUST	1.49	0.15	0.15	0.94	0.15	0.15	0.15	0.21	1.35	0.24	1	0.88
SEPTEMBER	0.76	1.04	-0.94	0.33	0.93	-0.73	-0.45	-1.08	0.88	2.22	2.73	1.1
OCTOBER	0.21	2.11	-0.44	0.03	-0.58	0.01	-1.17	0.79	0.27	0.62	0.05	-1.81
NOVEMBER	0.13	0.51	0.4	-0.21	0.95	-2.11	-0.24	0.93	-1.54	0.16	-1.27	-1.2
DECEMBER	-0.52	-1.81	0.2	-0.61	0.26	0.78	0.48	1.44	-1.32	0.01	-1.81	0.94

Figure A.1: Dry and wet periods calculated from SPI_1 series for Adana meteorological station.

	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
JANUARY	1.16	1.07	0.55	1.72	0.41	-0.79	0.28	0.49	-1.18	-1.89	1.18	-0.67	0.84
FEBRUARY	1.07	0.09	0.78	0.65	-0.06	-0.6	-0.58	0.38	-0.41	-1.75	1.18	-0.25	1.37
MARCH	-2.02	-0.59	1.34	0.46	1.1	-1.4	-1.1	-0.2	0.01	-1.32	-0.27	0.34	1.04
APRIL	-1.63	-1.12	-0.78	-0.19	0.93	-0.11	-0.6	0.49	0.47	-0.99	-0.03	0.7	-0.71
MAY	-0.48	0.29	-0.39	0.19	0.41	-0.23	0.3	-0.21	0.37	0.35	-0.13	0.12	-2.2
JUNE	0.45	0.36	-0.21	0.65	-0.49	0.36	-0.39	0.25	0.61	0.41	0	-0.51	-1.43
JULY	1.6	0.92	0.48	1.02	-0.74	-0.74	-0.44	-0.84	0.12	1.06	-0.9	-1.09	-1.2
AUGUST	1.77	-0.39	0.48	1.36	-0.39	-0.33	-0.83	-0.1	-1.62	0.19	0.44	-0.99	-1.24
SEPTEMBER	1.02	-1.81	0.47	0.59	-0.9	-0.03	0.9	1	0.64	1.15	0.59	-0.48	-0.92
OCTOBER	-1.26	-2.5	0.19	-0.49	0.51	0.96	0.18	0.28	1.73	0.52	-0.24	-0.67	-1.33
NOVEMBER	1.2	-1.57	2.16	0.89	-0.44	1	0.63	-0.86	0.98	0.21	-1.72	-1.28	0.36
DECEMBER	1.23	-1.48	1.69	0.07	-0.11	0.99	0.56	-2.16	-0.15	1.24	-1.11	-0.13	-0.4

	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
JANUARY	-0.43	-0.87	-1.26	-0.28	-0.22	0.52	-0.08	0.94	0.99	-2.12	-0.02	-1.02
FEBRUARY	-1.34	-0.57	-1.26	-0.74	0.21	0.07	0.4	1.4	0.63	-2.16	0.22	-0.65
MARCH	-0.59	-0.31	-0.09	-1.58	1.29	-0.5	0.27	1.49	-0.97	-1.47	0.96	0.38
APRIL	-0.12	-0.16	1.26	-1.56	1.09	-0.36	0.87	0.03	-0.47	-1.42	0.88	-0.16
MAY	-0.07	-1.51	0.8	-1.82	0.51	0.01	1.5	-0.01	0.14	-0.89	0.79	0.42
JUNE	-0.02	-1.8	0.83	-1.49	-0.94	0.52	1.5	0.11	0.07	0.51	-0.34	0.81
JULY	0.06	0.07	-0.08	-1.03	-0.23	-0.07	1.35	0.81	0.01	1.03	0.17	1.1
AUGUST	0.72	0.66	0	-0.55	-0.14	-1.48	0.76	0.2	-0.23	1.73	-0.45	0.88
SEPTEMBER	1.05	1.38	-1.33	0.22	0.97	-1.21	-0.99	-0.27	0.88	1.7	2.24	0.8
OCTOBER	0.7	1.89	-0.97	0.15	-0.05	-0.47	-1.46	0.25	0.72	1.46	1.69	-0.07
NOVEMBER	0.14	1.64	-0.26	-0.39	0.7	-1.76	-1.15	0.83	-0.65	1.07	0.63	-1.2
DECEMBER	-0.48	0.19	0.03	-0.81	0.39	0.02	-0.13	1.58	-1.74	0.04	-2.26	0.04

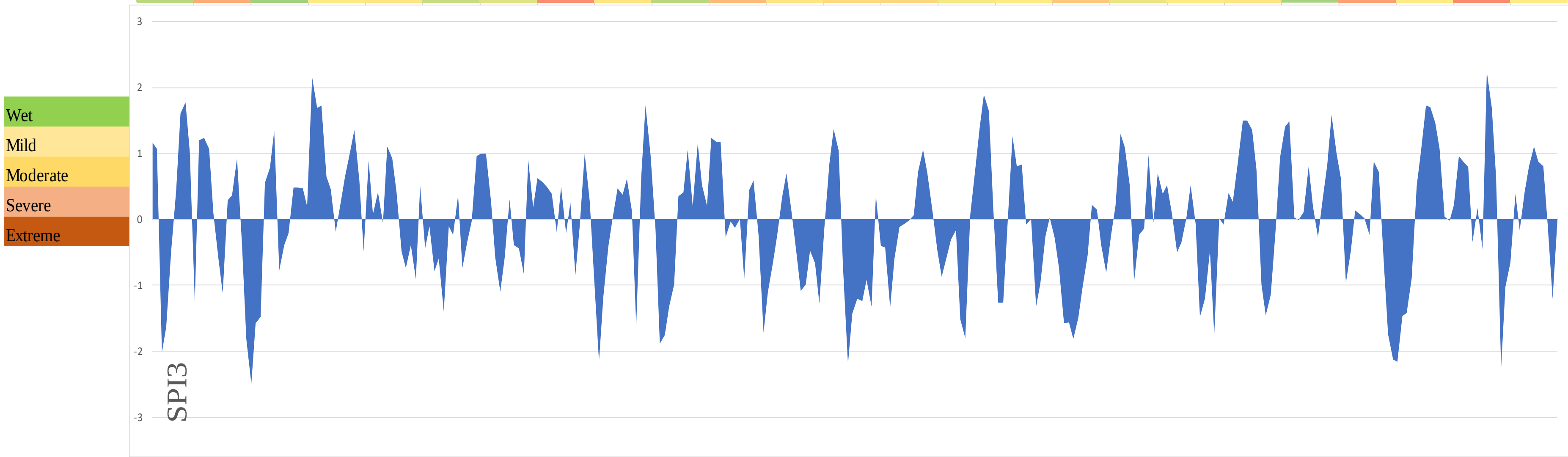


Figure A.2: Dry and wet periods calculated from SPI_3 series for Adana meteorological station.

	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
JANUARY	1.12	0.83	0.17	1.76	0.19	-0.71	0.5	0.44	-1.17	-0.7	1.26	-0.9
FEBRUARY	0.96	0.61	0.13	1.65	0.31	-0.87	-0.01	0.53	-0.87	-0.78	1.06	-0.98
MARCH	0.75	0.64	0.07	1.59	0.69	-1.03	0.18	0.22	-1.34	-1.03	0.8	-0.6
APRIL	0.56	0.58	0.12	1.58	0.69	-0.84	-0.08	0.57	-0.78	-2.14	1.05	-0.3
MAY	0.73	0.14	0.48	0.58	0.08	-0.67	-0.39	0.18	-0.22	-1.15	0.94	-0.22
JUNE	-1.25	-0.37	1.02	0.62	0.7	-0.94	-1.2	-0.13	0.24	-0.86	-0.32	-0.02
JULY	0.01	-0.33	-0.44	0.38	0.4	-0.54	-0.85	-0.03	0.33	-0.13	-0.52	0.1
AUGUST	0.38	0.07	-0.25	0.65	0.19	-0.4	-0.01	-0.31	-0.07	0.29	-0.04	-0.22
SEPTEMBER	0.78	-0.12	-0.15	0.72	-0.99	0.17	-0.03	0.58	0.71	0.82	0.1	-0.9
OCTOBER	0.81	-0.09	0.3	0.43	-0.25	0.19	-0.39	-0.53	1.35	0.99	-1.04	-1.52
NOVEMBER	1.56	-1.54	2.03	1.16	-0.59	0.78	0.33	-0.85	0.59	0.17	-1.19	-1.53
DECEMBER	1.36	-1.86	1.71	0.11	-0.34	0.91	0.68	-1.52	-0.08	1.41	-0.97	-0.31

	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
JANUARY	0.64	-0.88	-0.68	-0.22	-0.65	-0.31	0.41	-0.33	0.67	0.98	-1.61	0.45	-0.2
FEBRUARY	0.82	-1	-0.53	0.03	-0.9	-0.09	0.3	-0.3	0.87	0.85	-2.27	0.64	-0.31
MARCH	0.51	-0.82	-0.69	-0.03	-0.99	0.32	-0.1	0.07	0.85	0.84	-2.38	0.56	-1.05
APRIL	0.46	-0.55	-0.93	-0.33	-1.01	0.26	0.25	0.25	0.82	0.69	-2.55	0.31	-1.04
MAY	0.63	-1.14	-1.15	-0.58	-1.41	0.34	0	0.97	1.19	0.54	-2.17	0.48	-0.38
JUNE	0.37	-0.59	-1.07	0.29	-2.16	0.74	-0.2	0.96	1.28	-0.82	-0.88	0.62	0.64
JULY	-1.25	-0.19	-0.21	0.93	-1.95	0.72	-0.46	1.38	0.39	-0.51	-0.41	0.71	0.45
AUGUST	-2.53	0.13	-1.05	0.65	-1.92	0.34	-0.4	1.53	-0.03	-0.03	0.07	0.54	0.62
SEPTEMBER	-2.02	0.38	-0.53	0.43	-1.45	-0.41	0.09	1.2	-0.18	0.35	1.29	1.16	0.99
OCTOBER	-2.08	0.38	1.48	-0.86	-0.75	-0.42	-0.58	0.5	0.61	0.37	1.66	1.34	0.7
NOVEMBER	0.01	0.3	1.59	-0.3	-0.58	0.53	-2.14	-0.65	0.73	-0.72	1.44	0.4	-0.61
DECEMBER	-0.65	-0.23	0.5	-0.22	-0.84	0.54	-0.22	-0.37	1.5	-1.33	0.5	-0.61	0.15

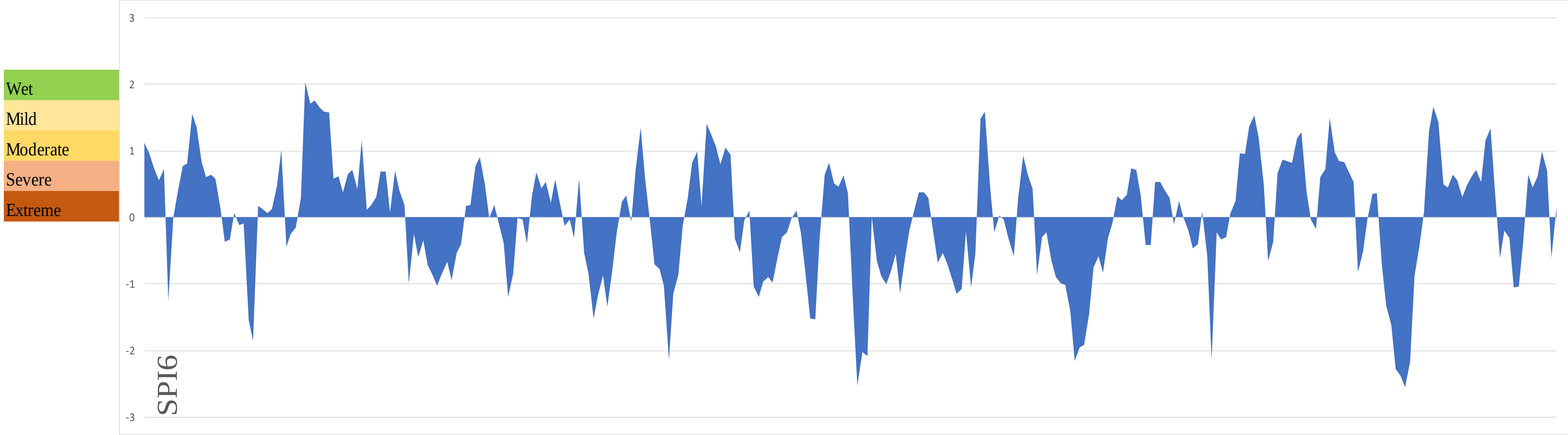


Figure A.3: Dry and wet periods calculated from SPI_6 series for Adana meteorological station.

	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
JANUARY	0.86	1.28	0.4	1.8	0.46	-1	0.24	0.24	-1.48	-0.71	1.47	-1.23	0.34	-1.27	-0.72	-0.28	-0.75	-0.65	0.26	-0.43	1.03	1.12	-1.58	0.7	-0.23
FEBRUARY	0.81	0.93	0.03	1.66	0.54	-0.97	-0.11	0.39	-0.92	-1.02	1.04	-0.91	0.67	-1.2	-0.42	0.1	-0.93	-0.21	0.23	-0.5	0.94	0.83	-2.3	0.94	-0.42
MARCH	0.65	0.76	-0.1	1.58	0.71	-1.19	0.11	0.34	-1.09	-0.92	0.95	-0.53	0.39	-0.97	-0.48	0.24	-1.17	0.29	0.05	-0.09	0.7	0.74	-2.05	0.89	-0.28
APRIL	0.5	0.31	-0.26	1.62	0.53	-0.78	0.14	0.54	-0.82	-1.2	1.14	-0.48	0.25	-0.94	-0.79	0.37	-1.4	0.21	0.15	0.06	0.56	0.69	-2.24	0.74	-0.36
MAY	0.66	0.6	-0.08	1.5	0.38	-0.88	0.06	0.34	-0.61	-0.55	0.86	-0.82	0.13	-0.91	-1.04	0.3	-1.47	0.08	0.22	0.39	0.72	0.75	-2.31	0.81	-0.13
JUNE	0.79	0.65	-0.07	1.65	0.44	-0.86	-0.03	0.22	-1	-0.83	0.7	-0.82	0.06	-0.84	-1.24	0.22	-1.47	-0.03	0.03	0.61	0.77	0.75	-1.85	0.37	-0.65
JULY	1	0.76	0.18	1.73	0.46	-1.07	-0.26	0.32	-0.78	-1.5	0.8	-0.6	0.17	-0.58	-0.93	-0.42	-1.3	0.12	0.15	0.62	0.94	0.6	-1.81	0.27	-0.6
AUGUST	1.03	0.04	0.51	0.78	-0.02	-0.77	-0.54	0.12	-0.44	-1.16	0.96	-0.39	0.47	-1.01	-1.04	-0.63	-1.55	0.27	-0.2	1.04	1.17	0.47	-1.54	0.38	-0.25
SEPTEMBER	-0.97	-0.65	1.05	0.68	0.52	-1.06	-0.98	0.07	0.31	-0.55	-0.26	-0.19	0.17	-0.35	-0.62	0.07	-2.18	0.91	-0.45	0.8	1.19	-0.64	-0.29	1.33	0.75
OCTOBER	-0.54	-1.05	-0.48	0.04	0.5	-0.08	-0.88	-0.04	1.26	0	-0.79	-0.3	-1.92	0.05	0.95	0.51	-1.9	0.56	-0.82	0.92	0.35	-0.21	0.43	1.55	0.28
NOVEMBER	1.06	-0.91	1.58	0.99	-0.26	0.4	0.34	-0.92	0.59	0.24	-1.07	-1.05	-1.31	0.07	0.68	0.22	-1.74	0.63	-1.42	0.59	0.49	-0.56	0.75	0.72	-0.27
DECEMBER	1.43	-1.42	1.58	0.3	-0.67	0.94	0.41	-1.28	0.11	1.47	-1.01	-0.66	-1.36	-0.36	-0.18	0.11	-1.59	0.08	-0.07	0.41	1.45	-1.25	0.6	-0.86	0.42

Wet
Mild
Moderate
Severe
Extreme

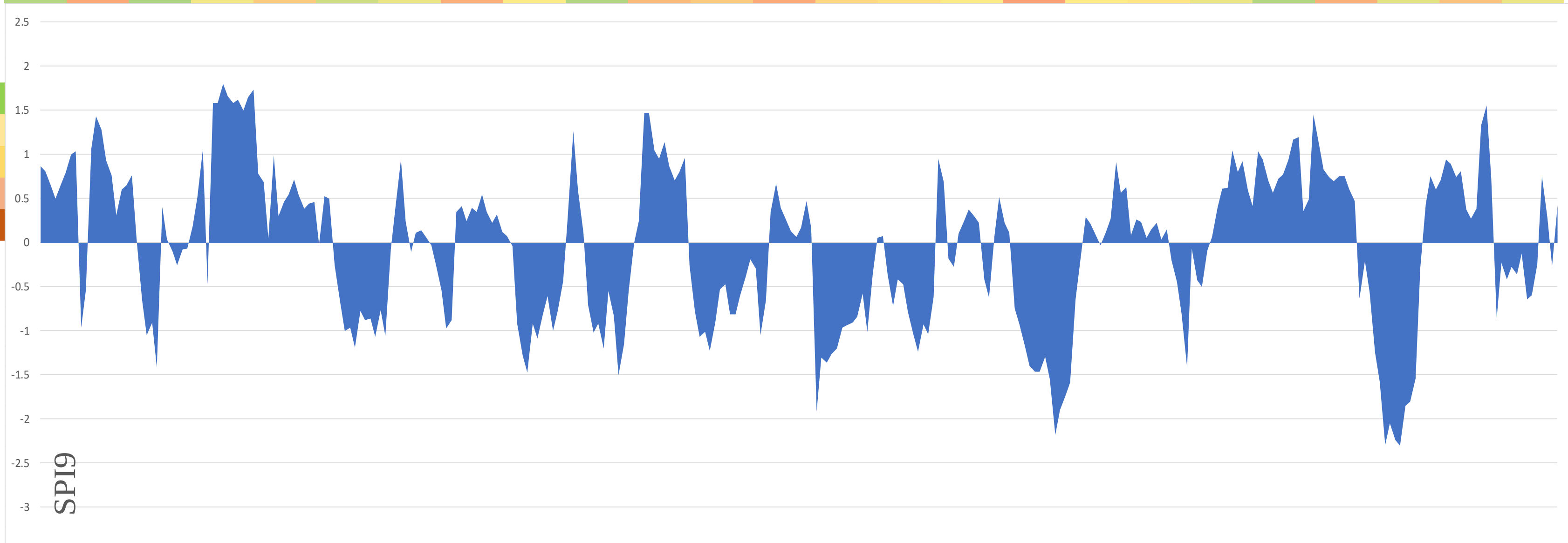


Figure A.4: Dry and wet periods calculated from SPI$_9$ series for Adana meteorological station.

	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
JANUARY	0.69	0.68	-0.12	1.44	0.28	-0.44	0.1	-0.1	-1.06	-0.47	1.04	-1.16	0.54
FEBRUARY	0.48	0.64	0.08	1.38	0.5	-0.71	-0.25	0.4	-0.96	-0.77	1.01	-0.92	0.59
MARCH	0.52	0.83	-0.04	1.45	0.85	-1.4	0.17	0.14	-1	-0.68	1	-0.58	0.16
APRIL	0.23	0.8	0	1.61	0.76	-1	-0.09	0.36	-1.06	-1.15	1.33	-0.73	-0.03
MAY	0.52	0.88	-0.16	1.51	0.58	-0.96	-0.02	0.22	-0.65	-0.74	0.84	-0.77	0
JUNE	0.69	0.76	-0.23	1.62	0.47	-0.98	-0.08	0.33	-0.78	-0.73	0.83	-0.72	-0.04
JULY	0.95	0.51	-0.16	1.73	0.29	-0.99	-0.03	0.28	-0.8	-0.74	0.86	-0.76	-0.05
AUGUST	0.94	0.51	-0.05	1.66	0.3	-0.97	-0.07	0.29	-0.81	-0.56	0.88	-0.98	-0.03
SEPTEMBER	0.93	0.5	-0.06	1.71	0.31	-0.95	0.09	0.36	-0.95	-0.63	0.74	-0.97	-0.09
OCTOBER	0.78	0.46	0.14	1.65	0.52	-0.82	-0.32	0.31	-0.15	-1.42	0.69	-0.87	-0.13
NOVEMBER	1.38	-0.53	1.47	1.01	-0.29	-0.26	-0.28	-0.28	0	-1.03	0.4	-0.9	0.49
DECEMBER	0.32	-1.41	1.84	0.42	0.2	0.06	-0.28	-1.07	0.02	0.56	-0.94	-0.32	-0.23

	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
JANUARY	-1.55	-0.79	-0.41	-0.05	-1.32	0.66	-0.64	1.25	1	-1.68	0.11	0.14
FEBRUARY	-1.91	-0.46	-0.45	-0.48	-0.84	0.35	-0.5	1.39	0.69	-1.87	0.54	-0.07
MARCH	-1.48	-0.54	-0.27	-0.78	-0.17	-0.3	0.03	1.19	0.69	-1.92	0.97	-0.46
APRIL	-1.24	-0.79	0.31	-1.41	-0.07	0.02	-0.02	0.91	0.83	-2.13	0.95	-0.35
MAY	-1.07	-0.92	0.36	-1.48	-0.02	0.16	0.23	0.78	0.73	-2.34	1.07	-0.23
JUNE	-0.96	-0.98	0.46	-1.61	-0.05	0.17	0.46	0.63	0.65	-1.59	0.68	-0.01
JULY	-0.92	-0.78	0.26	-1.64	0.07	0.05	0.46	0.7	0.59	-1.59	0.67	-0.01
AUGUST	-0.81	-0.95	0.26	-1.59	0.02	0.05	0.46	0.7	0.69	-1.76	0.73	-0.03
SEPTEMBER	-0.67	-0.93	0.06	-1.52	0.1	-0.13	0.48	0.7	0.85	-1.34	0.91	-0.56
OCTOBER	-0.46	-0.19	-0.73	-1.39	0.02	-0.04	0.35	0.95	0.73	-1.2	0.78	-0.74
NOVEMBER	-0.94	-0.04	-0.78	-1.68	0.46	-0.81	0.58	1.34	0.13	-0.8	0.52	-0.74
DECEMBER	-0.66	-0.37	-0.03	-2.11	0.79	-0.39	0.38	1.83	-1.52	-0.26	-0.01	0.45

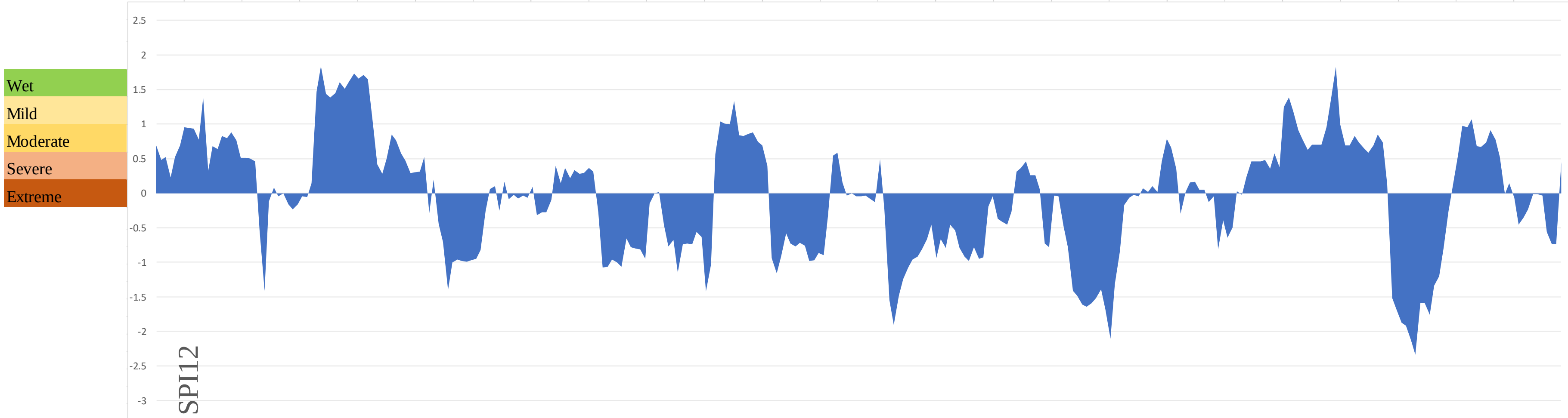


Figure A.5: Dry and wet periods calculated from SPI_{12} series for Adana meteorological station.

	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
JANUARY	-0.13	0.86	0.33	0.91	1.14	-0.16	-0.3	-0.07	-0.83	-1.11	0.39	0
FEBRUARY	-0.43	0.69	0.43	0.96	1.21	-0.14	-0.67	0.06	-0.36	-1.19	0.21	0.12
MARCH	-0.54	0.82	0.48	0.92	1.45	-0.26	-0.79	0.14	-0.58	-1.15	0.23	0.28
APRIL	-0.59	0.63	0.49	1.09	1.54	-0.13	-0.77	0.12	-0.47	-1.56	0.24	0.46
MAY	-0.43	0.89	0.45	0.94	1.39	-0.26	-0.72	0.07	-0.34	-1.03	0.08	0.06
JUNE	-0.52	0.92	0.32	0.98	1.4	-0.35	-0.77	0.1	-0.34	-1.11	0.08	0.08
JULY	-0.31	0.92	0.18	1.1	1.36	-0.49	-0.73	0.1	-0.38	-1.11	0.1	0.09
AUGUST	-0.32	0.92	0.26	1.11	1.31	-0.47	-0.75	0.08	-0.38	-1	0.21	-0.03
SEPTEMBER	-0.39	0.89	0.24	1.13	1.34	-0.45	-0.62	0.23	-0.41	-1.13	0.06	-0.13
OCTOBER	-0.46	0.75	0.33	1.18	1.4	-0.21	-0.81	-0.06	0.04	-1.06	-0.4	-0.11
NOVEMBER	0.26	0.59	0.66	1.55	0.45	-0.42	-0.42	-0.43	-0.24	-0.7	-0.41	-0.34
DECEMBER	0.72	-0.74	0.58	1.58	0.36	0.1	-0.23	-1.01	-0.78	0.34	-0.27	-0.95

	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
JANUARY	-0.4	-0.61	-1.65	-0.89	-0.39	-0.96	-0.39	0	0.45	1.47	-0.29	-1.04	0.1
FEBRUARY	-0.2	-0.71	-1.54	-0.65	-0.66	-0.91	-0.33	-0.13	0.63	1.33	-0.61	-0.73	0.26
MARCH	-0.32	-0.83	-1.35	-0.59	-0.74	-0.67	-0.36	-0.23	0.77	1.17	-0.64	-0.42	0.33
APRIL	-0.57	-0.87	-1.43	-0.36	-0.71	-1	-0.1	-0.07	0.56	1.1	-0.65	-0.54	0.38
MAY	-0.58	-0.78	-1.44	-0.4	-0.72	-1.03	0.02	0.2	0.63	0.97	-0.84	-0.54	0.56
JUNE	-0.58	-0.73	-1.4	-0.36	-0.71	-1.12	0.01	0.36	0.67	0.8	-0.54	-0.51	0.4
JULY	-0.6	-0.7	-1.22	-0.38	-0.87	-1.03	0.01	0.28	0.72	0.8	-0.58	-0.51	0.39
AUGUST	-0.72	-0.62	-1.26	-0.49	-0.85	-1.04	-0.02	0.28	0.72	0.87	-0.59	-0.56	0.42
SEPTEMBER	-0.75	-0.57	-1.14	-0.62	-0.97	-0.94	-0.09	0.17	0.72	0.97	-0.24	-0.2	0.22
OCTOBER	-0.71	-0.46	-0.5	-0.67	-1.45	-0.91	-0.08	0.14	0.8	1.04	-0.26	-0.22	0.03
NOVEMBER	-0.27	-0.29	-0.67	-0.58	-1.63	-0.7	-0.24	-0.15	1.19	0.92	-0.48	-0.19	-0.15
DECEMBER	-0.47	-0.7	-0.8	-0.36	-1.42	-0.7	0.25	-0.06	1.55	0.52	-1.28	-0.27	0.24

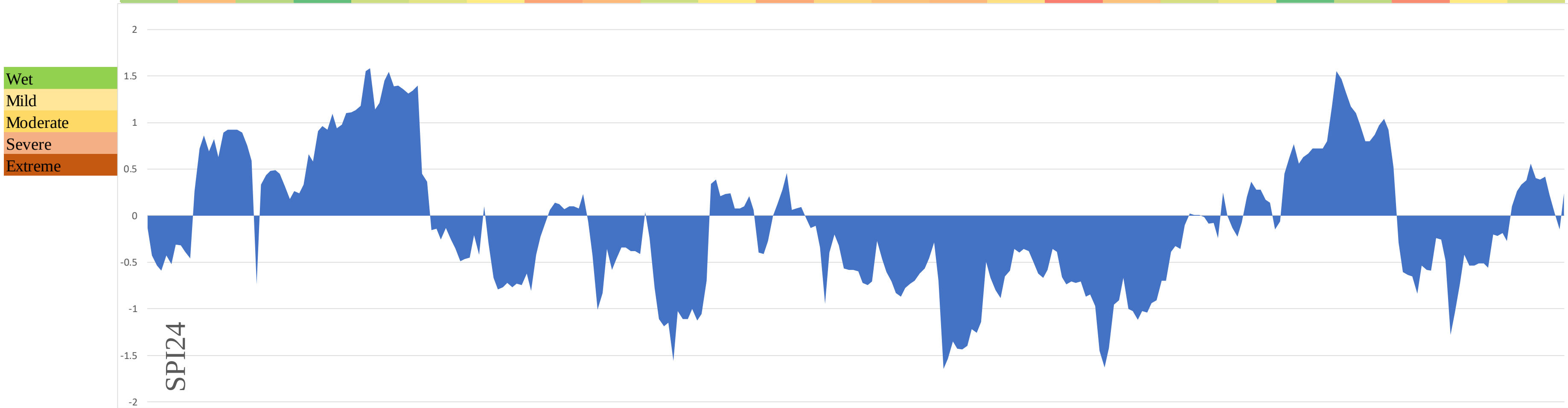


Figure A.6: Dry and wet periods calculated from SPI_{24} series for Adana meteorological station.

Table A.1: Critical severity values for SPI_1, SPI_3, SPI_6, SPI_9, SPI_{12} and SPI_{24} in Adana meteorological station.

Drought duration (month)	SPI_1					SPI_3						
	D=1	D=2	D=3	D=4	D=5	D=1	D=2	D=3	D=4	D=5	D=6	D=7
Number of years	57	50	33	18	12	57	50	46	33	28	23	17
1992	1.85	2.43	3.47	4.43	0	1.39	2.44	3.37	4.4	5.25	5.35	5.98
1993	1.58	2.66	3.06	3.88	0	2.02	3.65	4.13	0	0	0	0
1994	1.08	1.31	0	0	0	2.5	4.31	5.88	7.36	7.75	0	0
1995	1.03	0.4	0	0	0	0.78	1.17	1.38	0	0	0	0
1996	1.12	0	0	0	0	0.49	0	0	0	0	0	0
1997	1.38	1.57	2.43	0	0	0.9	1.29	2.03	2.52	0	0	0
1998	2.73	3.4	0	0	0	1.4	2	2.79	2.9	3.34	3.45	3.68
1999	1.8	2.82	3.8	0	0	1.1	1.7	2.28	0	0	0	0
2000	1.16	1.51	0	0	0	2.16	3.02	0	0	0	0	0
2001	2.03	3	3.54	3.94	4.91	1.62	3.34	4.2	4.61	0	0	0
2002	1.15	1.85	2.53	2.86	0	1.89	3.64	4.96	5.95	6.1	0	0
2003	0.8	1.28	1.34	2.19	2.89	1.72	2.83	3.07	0	0	0	0
2004	2.52	3.23	3.79	4.95	4.98	1.28	2.08	3.5	3.75	4.51	5.02	5.15
2005	0.58	1.77	1.78	0	0	2.2	3.63	4.83	6.07	6.99	8.32	9.03
2006	1.81	2.08	2.51	2.84	0	1.34	1.93	2.36	2.76	2.88	2.95	2.97
2007	0.96	2.77	0	0	0	1.8	3.31	3.47	3.78	4.35	5.22	5.7
2008	1.07	2.06	2.65	3.55	4.14	1.33	2.52	2.61	0	0	0	0
2009	1.16	1.38	1.74	0	0	1.82	3.38	4.96	6.45	7.48	8.22	8.77
2010	2.11	1.83	0	0	0	0.94	1.17	1.42	0	0	0	0
2011	1.17	1.62	1.86	0	0	1.76	2.69	3.44	4.92	4.99	0	0
2012	1.08	0.87	0	0	0	1.46	2.61	3.6	3.73	0	0	0
2013	1.54	2.86	1.24	0	0	0.27	0	0	0	0	0	0
2014	1	2.24	3.78	4.78	5.07	1.74	2.39	0	0	0	0	0
2015	1.81	3.08	0	0	0	2.16	4.28	6.02	7.49	8.91	9.8	10.5
2016	1.81	3.01	0	0	0	2.26	0	0	0	0	0	0

Table A.1 (Continued.**):** Critical severity values for SPI_1, SPI_3, SPI_6, SPI_9, SPI_{12} and SPI_{24} in Adana meteorological station.

Drought duration (month)	SPI_6										
	D=1	D=2	D=3	D=4	D=5	D=6	D=7	D=8	D=9	D=10	D=11
Number of years	54	50	45	36	30	27	23	21	16	12	10
1992	1.6	2.95	4.43	5.7	6.89	8	9.02	9.64	10.61	11.08	11.91
1993	1.25	0	0	0	0	0	0	0	0	0	0
1994	1.86	3.4	3.49	3.61	0	0	0	0	0	0	0
1995	0.44	0.69	0.84	0	0	0	0	0	0	0	0
1996	0	0	0	0	0	0	0	0	0	0	0
1997	0.99	1.24	1.83	2.17	0	0	0	0	0	0	0
1998	1.03	1.9	2.74	3.48	4.35	5.06	5.6	6	6.53	7.23	7.77
1999	1.2	2.05	2.44	2.52	2.53	2.87	2.95	0	0	0	0
2000	1.52	2.37	2.9	0	0	0	0	0	0	0	0
2001	1.34	2.69	3.56	4.9	5.75	6.53	7.06	7.28	0	0	0
2002	2.14	3.29	4.32	5.18	5.96	6.66	6.79	6.87	0	0	0
2003	1.19	2.23	3.2	0	0	0	0	0	0	0	0
2004	1.53	3.05	3.95	4.26	5.08	5.68	5.98	6.2	6.22	0	0
2005	2.53	4.55	6.63	7.88	0	0	0	0	0	0	0
2006	1.14	1.88	2.7	3.51	4.39	5.04	5.63	5.82	0	0	0
2007	1.15	2.22	3.15	3.84	4.41	5.1	5.63	6.31	6.84	7.07	0
2008	0.86	1.16	1.38	0	0	0	0	0	0	0	0
2009	2.16	4.11	6.03	7.48	8.89	9.9	10.89	11.79	12.54	13.19	13.96
2010	0.42	1.15	1.73	2.48	3.93	5.85	7.8	9.96	11.37	12.38	13.37
2011	2.14	2.72	2.94	0	0	0	0	0	0	0	0
2012	0.65	1.02	2.69	3.27	3.57	0	0	0	0	0	0
2013	0.18	0.21	0	0	0	0	0	0	0	0	0
2014	1.33	2.05	1.36	0	0	0	0	0	0	0	0
2015	2.55	4.93	7.2	9.37	10.98	12.31	13.19	13.91	14.32	0	0
2016	0.61	0	0	0	0	0	0	0	0	0	0

Table A.1(Continued.): Critical severity values for SPI_1, SPI_3, SPI_6, SPI_9, SPI_{12} and SPI_{24} in Adana meteorological station.

Drought duration (month)	SPI_9												
	D=1	D=2	D=3	D=4	D=5	D=6	D=7	D=8	D=9	D=10	D=11	D=12	D=13
Number of years	51	48	43	38	33	29	28	28	27	22	20	17	13
1992	1.66	3.14	4.59	6.1	7.65	8.96	10.2	11.2	12.31	13.28	14.02	14.67	15.3
1993	0.97	1.51	0	0	0	0	0	0	0	0	0	0	0
1994	1.42	2.33	3.38	4.03	0	0	0	0	0	0	0	0	0
1995	0.48	0.36	0.44	0.51	0	0	0	0	0	0	0	0	0
1996	0	0	0	0	0	0	0	0	0	0	0	0	0
1997	0.67	0.93	0	0	0	0	0	0	0	0	0	0	0
1998	1.19	2.16	3.16	3.94	4.82	5.75	6.75	7.58	8.58	9.25	9.51	9.59	0
1999	0.98	1.86	2.4	2.66	2.69	0	0	0	0	0	0	0	0
2000	1.28	2.2	2.24	0	0	0	0	0	0	0	0	0	0
2001	1.48	2.76	3.68	4.77	5.69	6.51	7.2	8.12	8.9	9.34	9.38	0	0
2002	1.5	2.66	3.49	4.08	5.24	6.16	7.18	7.89	8.44	0	0	0	0
2003	1.07	2.08	2.87	3.13	0	0	0	0	0	0	0	0	0
2004	1.23	2.24	3.31	4.22	5.01	5.54	6.05	6.87	7.66	8.26	8.65	8.91	9.4
2005	1.92	3.23	4.59	0	0	0	0	0	0	0	0	0	0
2006	1.27	2.63	3.94	5.86	7.06	8.03	8.97	9.88	10.72	11.3	12.31	12.66	0
2007	1.24	2.28	3.21	4.25	5.04	5.66	6.14	6.66	7.28	7.64	0	0	0
2008	0.63	1.05	0	0	0	0	0	0	0	0	0	0	0
2009	2.18	4.08	5.82	7.41	8.96	10.26	11.73	13.2	14.6	15.77	16.7	17.45	0
2010	0.65	2.24	3.98	5.88	8.06	9.61	10.91	12.38	13.85	15.25	16.42	17.35	18.1
2011	1.42	2.24	2.69	2.89	2.96	0	0	0	0	0	0	0	0
2012	0.5	0.93	1.92	2.74	3.24	3.69	3.89	3.98	0	0	0	0	0
2013	0	0	0	0	0	0	0	0	0	0	0	0	0
2014	1.25	1.81	2.02	2.66	0	0	0	0	0	0	0	0	0
2015	2.31	4.55	6.6	8.9	10.75	12.56	14.14	15.68	16.93	17.49	17.78	18.34	18.63
2016	0.86	0	0	0	0	0	0	0	0	0	0	0	0

Table A.1(Continued.**):** Critical severity values for SPI_1, SPI_3, SPI_6, SPI_9, SPI_{12} and SPI_{24} in Adana meteorological station.

	SPI_{12}													
Drought duration (month)	D=1	D=2	D=3	D=4	D=5	D=6	D=7	D=8	D=9	D=10	D=11	D=12	D=13	D=14
Number of years	46	40	38	35	32	29	28	27	27	25	22	19	16	12
1992	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1993	1.41	1.94	0	0	0	0	0	0	0	0	0	0	0	0
1994	0.23	1.53	2.06	0.6	0.66	0	0	0	0	0	0	0	0	0
1995	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1996	0.29	0	0	0	0	0	0	0	0	0	0	0	0	0
1997	1.4	2.4	3.36	4.34	5.33	6.3	7.25	8.07	8.78	9.22	9.48	0	0	0
1998	0.32	0.6	0.88	0.22	0.29	0	0	0	0	0	0	0	0	0
1999	1.07	1.35	0.66	0.98	0	0	0	0	0	0	0	0	0	0
2000	1.06	2.13	3.09	4.09	5.15	5.8	6.58	7.38	8.19	9.14	9.42	9.57	0	0
2001	1.42	2.45	3.08	3.64	4.38	5.11	5.97	7	7.68	8.45	8.92	0	0	0
2002	0.94	0	0	0	0	0	0	0	0	0	0	0	0	0
2003	1.16	2.1	3.02	3.72	4.48	5.2	5.97	6.7	7.59	8.53	9.4	10.3	10.62	0
2004	0.23	0.22	0.25	0.3	0.34	0	0	0	0	0	0	0	0	0
2005	1.91	3.46	4.94	6.18	7.25	8.21	9.13	9.94	10.61	11.07	12.01	12.67	12.9	0
2006	0.98	1.9	2.71	3.64	4.56	5.35	5.89	6.35	7.28	8.52	10	11.91	13.46	13.92
2007	0.78	1.51	1.54	1.5	1.94	2.89	3.67	4.65	5.57	6.36	6.9	7.36	8.15	8.81
2008	2.11	3.79	5.18	6.7	8.29	9.93	11.54	13.02	14.43	15.21	15.69	15.74	15.77	16.55
2009	1.32	3.43	5.11	6.5	8.02	9.61	11.25	12.86	14.34	15.75	16.59	17.37	17.85	18.02
2010	0.81	1.2	1.24	1.37	0	0	0	0	0	0	0	0	0	0
2011	0.64	1.14	1.84	2.34	2.38	2.51	0	0	0	0	0	0	0	0
2012	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2013	1.52	0	0	0	0	0	0	0	0	0	0	0	0	0
2014	2.34	4.47	6.39	8.26	9.94	11.53	13.2	14.88	16.4	17.74	18.94	19.74	20	0
2015	0.01	0	0	0	0	0	0	0	0	0	0	0	0	0
2016	0.74	1.48	2.04	2.07	2.08	2.09	2.32	2.67	3.13	3.2	0	0	0	0

Table A.1(Continued.): Critical severity values for SPI_1, SPI_3, SPI_6, SPI_9, SPI_{12} and SPI_{24} in Adana meteorological station.

Drought duration	SPI_{24}																		
(month)	D=8	D=9	D=10	D=11	D=12	D=13	D=14	D=15	D=16	D=17	D=18	D=19	D=20	D=21	D=22	D=23	D=24	D=25	D=26
Number of years	27	27	26	25	24	19	16	16	16	16	15	15	15	15	14	14	14	12	11
1960	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1961	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1962	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1963	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1964	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1965	7.38	7.6	7.74	8.05	8.33	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1966	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1967	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1968	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1969	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1970	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1971	10.87	11.96	13.49	14.63	15.95	16.49	0	0	0	0	0	0	0	0	0	0	0	0	0
1972	14.77	16.71	18.78	20.65	22.52	24.17	25.56	27.1	28.41	29.67	30.93	32.19	33.39	34.48	36.01	37.15	38.47	39.01	0
1973	21.73	24.32	26.84	29.37	31.73	34.1	36.07	37.76	39.52	41.24	42.94	44.65	46.5	48.44	50.51	52.38	54.25	55.9	57.29
1974	20.59	23.37	26.25	28.88	31.54	33.93	36.29	38.66	40.89	43.34	45.91	48.29	50.65	53.02	55.23	57.39	59.48	61.45	63.14
1975	15.05	17.47	19.7	21.93	24.32	26.49	29.02	31.54	34.13	36.92	39.63	42.27	44.91	47.69	50.57	53.2	55.86	58.22	60.59
1976	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1977	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1978	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1979	2.84	2.98	3.02	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1980	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1981	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1982	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1983	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1984	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1985	2.33	2.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1986	8.14	9.02	9.81	10.5	11.15	11.63	11.85	11.87	12.31	12.63	12.94	13.25	13.48	13.55	0	0	0	0	0
1987	7.57	8.58	9.83	10.85	11.73	12.42	13.07	13.55	13.99	14.59	15.2	15.68	16.07	16.29	16.57	16.98	17.37	17.59	17.69
1988	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1989	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1990	6	6.47	6.91	6.97	7.05	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table A.1(Continued.**):** Critical severity values for SPI_1, SPI_3, SPI_6, SPI_9, SPI_{12} and SPI_{24} in Adana meteorological station.

	SPI_{24}																		
Drought duration (month)	D=8	D=9	D=10	D=11	D=12	D=13	D=14	D=15	D=16	D=17	D=18	D=19	D=20	D=21	D=22	D=23	D=24	D=25	D=26
Number of years	27	27	26	25	24	19	16	16	16	16	15	15	15	15	14	14	14	12	11
1991	6.07	6.86	7.73	8.91	9.94	11.41	12.73	13.89	14.66	15.18	15.74	16.29	16.84	17.41	17.88	18.4	18.97	19.44	19.92
1992	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1993	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1994	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1995	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1996	2.78	3.04	3.18	3.34	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1997	5.96	6.63	7.05	7.35	7.58	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1998	4.4	5.12	5.89	6.68	7.35	7.65	0	0	0	0	0	0	0	0	0	0	0	0	0
1999	4.36	4.74	5.12	5.53	5.59	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2000	9.28	10.39	11.45	12.23	12.93	13.17	0	0	0	0	0	0	0	0	0	0	0	0	0
2001	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2002	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2003	4.83	5.25	5.67	6.38	6.72	7.12	7.46	7.57	7.7	7.73	0	0	0	0	0	0	0	0	0
2004	5.85	6.42	6.89	7.45	8.15	8.77	9.37	9.95	10.53	11.1	11.67	12.13	12.55	13.12	13.54	14	14.34	14.99	15.33
2005	11.29	12.43	13.13	13.63	14.4	15.1	15.39	15.85	16.5	17.28	18.15	18.98	19.69	20.3	20.95	21.66	22.27	22.74	23.22
2006	7.88	9.32	10.75	12.1	13.64	15.29	15.99	16.64	17.23	17.59	17.99	18.63	19.36	20.14	21.01	21.84	22.55	23.2	23.81
2007	8.62	9.33	10.07	10.73	11.12	11.48	12.06	12.73	13.35	13.84	14.22	14.58	14.98	15.34	16.6	17.95	19.49	21.14	21.84
2008	9.07	10.19	11.22	12.26	13.23	14.17	15.08	15.93	16.8	17.51	18.23	18.94	19.68	20.38	21.08	21.74	22.13	22.49	23.07
2009	6.83	7.86	8.86	9.53	10.44	11.4	12.82	14.45	15.9	16.87	17.72	18.59	19.3	20.02	20.73	21.47	22.13	22.52	22.88
2010	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2011	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2012	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2013	4.81	5.46	6.1	6.71	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2014	5.57	6.13	6.61	7.23	7.87	8.48	8.9	9.44	9.98	10.49	11	11.56	11.85	12.05	12.27	12.46	12.73	0	0
2015	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2016	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table A.1(Continued.**):** Critical severity values for SPI_1, SPI_3, SPI_6, SPI_9, SPI_{12} and SPI_{24} in Adana meteorological station.

Drought duration (month)	SPI_{24}													
	D=1	D=2	D=3	D=4	D=5	D=6	D=7	…	D=27	D=28	D=29	D=30	D=31	D=32
Number of years	27	27	26	25	24	19	16	…	16	16	15	15	15	15
1992	0.74	0	0	0	0	0	0	…	20.39	20.83	21.14	21.46	21.87	22.31
1993	0	0	0	0	0	0	0	…	0	0	0	0	0	0
1994	0	0	0	0	0	0	0	…	0	0	0	0	0	0
1995	0	0	0	0	0	0	0	…	0	0	0	0	0	0
1996	0.49	0.96	1.41	1.76	2.04	2.39	2.65	…	0	0	0	0	0	0
1997	0.81	1.56	2.28	3.05	3.78	4.53	5.2	…	0	0	0	0	0	0
1998	1.01	1.44	1.5	1.53	2.15	2.9	3.63	…	0	0	0	0	0	0
1999	0.83	1.84	2.27	2.78	3.25	3.68	4.02	…	0	0	0	0	0	0
2000	1.56	2.71	3.9	5.01	6.04	7.15	8.26	…	0	0	0	0	0	0
2001	0.41	0.81	1.08	0	0	0	0	…	0	0	0	0	0	0
2002	0.95	1.29	1.4	1.53	1.56	0	0	…	0	0	0	0	0	0
2003	0.75	1.47	2.18	2.78	3.36	3.94	4.51	…	0	0	0	0	0	0
2004	0.87	1.7	2.48	3.21	3.92	4.62	5.24	…	0	0	0	0	0	0
2005	1.65	3.19	4.54	5.97	7.41	8.81	10.03	…	15.44	15.57	15.6	0	0	0
2006	0.89	1.69	2.36	3.01	4	5.26	6.48	…	23.82	24.47	25.19	25.79	26.37	26.95
2007	1.63	3.08	4.5	5.47	6.32	7.19	7.9	…	24.4	24.87	25.36	26.08	26.73	27.33
2008	1.12	2.38	4.01	5.46	6.43	7.34	8.19	…	22.54	23.25	23.97	24.68	25.55	26.4
2009	0.39	1.09	1.79	2.7	3.64	4.68	5.71	…	23.74	24.36	24.85	25.23	25.59	25.99
2010	0.23	0.36	0.43	0	0	0	0	…	23.46	24.13	24.75	25.24	25.62	25.98
2011	0	0	0	0	0	0	0	…	0	0	0	0	0	0
2012	0	0	0	0	0	0	0	…	0	0	0	0	0	0
2013	1.28	1.76	2.13	2.74	3.28	3.86	4.45	…	0	0	0	0	0	0
2014	1.04	2.32	3.05	3.53	4.01	4.55	5.06	…	0	0	0	0	0	0
2015	0.15	0	0	0	0	0	0	…	0	0	0	0	0	0
2016	0.74	0	0	0	0	0	0	…	0	0	0	0	0	0

Table A.2: The best-fit probability distribution functions and parameters for SPI_1, SPI_3, SPI_6 SPI_9, SPI_{12} and SPI_{24} in Adana meteorological station.

	SPI_1					SPI_3						
Drought duration (month)	1	2	3	4	5	1	2	3	4	5	6	7
No drought years	0	7	24	39	45	0	7	11	24	29	34	40
Number of years	57	50	33	18	12	57	50	46	33	28	23	17
Probabilty of zero severity (p)	0	0.123	0.421	0.68	0.789	0	0.123	0.193	0.42	0.509	0.596	0.702
T (Year)	F*(x)					F*(x)						
2	0.5	0.43	0.136			0.5	0.43	0.382	0.14			
5	0.8	0.772	0.655	0.37	0.05	0.8	0.77	0.75	0.65	0.59	0.50	0.33
10	0.9	0.886	0.827	0.68	0.53	0.9	0.89	0.88	0.83	0.80	0.75	0.66
25	0.96	0.954	0.931	0.87	0.81	0.96	0.95	0.95	0.93	0.92	0.90	0.87
50	0.98	0.977	0.965	0.94	0.905	0.98	0.98	0.98	0.97	0.96	0.95	0.93
100	0.99	0.989	0.983	0.97	0.952	0.99	0.99	0.99	0.98	0.98	0.98	0.97
Probability distribution fun.	GEV	GEV	GEV	LP3	LP3	GEV	GEV	GEV	GEV	GEV	GEV	GEV
α				3.80	4.802							
β				0.18	0.146							
γ				0.63	0.788							
μ	1.196	1.726	2.38			1.3205	2.3534	3.043	4.2562	5.033	5.5586	6.2141
σ	0.455	0.855	0.96			0.6375	1.0561	1.453	1.3467	1.689	1.766	2.2931
k	-0.016	-0.126	-0.15			-0.2746	-0.3045	-0.24	-0.04	-0.124	-0.0566	-0.1965

Table A.2 (Continued.**):** The best-fit probability distribution functions and parameters for SPI_1, SPI_3, SPI_6 SPI_9, SPI_{12} and SPI_{24} in Adana meteorological station.

SPI_6											
Drought duration (month)	1	2	3	4	5	6	7	8	9	10	11
No drought years	3	7	12	21	27	30	34	36	41	45	47
Number of years	54	50	45	36	30	27	23	21	16	12	10
Probabilty of zero severity (p)	0.053	0.123	0.21	0.368	0.474	0.526	0.596	0.632	0.719	0.789	0.825
T (Year)			F*(x)					F*(x)			
2	0.472	0.43	0.367	0.208	0.05						
5	0.789	0.772	0.747	0.683	0.62	0.578	0.504	0.457	0.288	0.05	
10	0.894	0.886	0.873	0.842	0.81	0.789	0.752	0.729	0.644	0.525	0.43
25	0.958	0.9544	0.949	0.937	0.924	0.916	0.901	0.891	0.858	0.81	0.772
50	0.979	0.9772	0.975	0.968	0.962	0.958	0.950	0.946	0.929	0.905	0.886
100	0.989	0.9886	0.987	0.984	0.981	0.979	0.975	0.973	0.964	0.9525	0.943
Probability distribution func.	GEV	GEV	GEV	GEV	GEV	GEV	GEV	GEV	GAMMA	GEV	GEV
α									8.6787		
β									1.0951		
γ									0		
μ	1.095	1.9307	2.6959	3.6981	4.4738	5.3069	6.4126	6.975		9.0432	10.202
σ	0.712	1.192	1.48	1.6925	2.129	2.2409	2.4783	2.424		2.74	3.41
k	-0.1962	-0.1476	-0.0419	0.03869	0.0113	0.05443	0.0114	0.066		-0.0922	-0.276

Table A.2 (Continued.**):** The best-fit probability distribution functions and parameters for SPI_1, SPI_3, SPI_6 SPI_9, SPI_{12} and SPI_{24} in Adana meteorological station.

					SPI_9						
Drought duration (month)	1	2	3	4	5	6	7	8	9	10	11
No drought years	6	9	14	19	24	28	29	29	30	35	37
Number of years	51	48	43	38	33	29	28	28	27	22	20
Probability of zero severity (p)	0.105	0.158	0.246	0.333	0.421	0.491	0.509	0.509	0.526	0.614	0.649
T (Year)						F*(x)					
2	0.441	0.406	0.337	0.25	0.136	0.017					
5	0.776	0.763	0.735	0.7	0.655	0.607	0.593	0.593	0.578	0.482	0.430
10	0.888	0.881	0.867	0.85	0.827	0.803	0.796	0.796	0.789	0.741	0.715
25	0.955	0.953	0.947	0.94	0.931	0.921	0.919	0.919	0.916	0.896	0.886
50	0.978	0.976	0.973	0.97	0.965	0.961	0.959	0.959	0.958	0.948	0.943
100	0.989	0.988	0.987	0.985	0.983	0.980	0.980	0.980	0.979	0.974	0.972
Probability distribution fun.	GEV	GEV	GEV	GEV	GAMMA	GEV	GEV	GEV	GEV	GEV	GEV
α					4.6597						
β					1.1631						
γ											
μ	0.9235	1.6639	2.5029	3.2586		5.3663	6.2642	6.923	7.7525	9.2021	10.26
σ	0.54481	1.0234	1.3245	1.701		2.5989	2.844	3.216	3.5593	3.8958	4.061
k	-0.1303	-0.1182	-0.065	-0.017	4.66	-0.0864	-0.0747	-0.072	-0.077	-0.1068	-0.09

Table A.2 (Continued.): The best-fit probability distribution functions and parameters for SPI_1, SPI_3, SPI_6 SPI_9, SPI_{12} and SPI_{24} in Adana meteorological station.

	SPI_{12}													
Drought duration (month)	1	2	3	4	5	6	7	8	9	10	11	12	13	14
No drought years	11	17	19	22	25	28	29	30	30	32	35	38	41	45
Number of years	46	40	38	35	32	29	28	27	27	25	22	19	16	12
Probability of zero severity (p)	0.193	0.298	0.333	0.386	0.439	0.491	0.509	0.526	0.526	0.561	0.614	0.667	0.719	0.789
T (Year)	F*(x)													
2	0.380	0.288	0.25	0.186	0.109	0.017								
5	0.752	0.715	0.7	0.674	0.644	0.607	0.593	0.578	0.578	0.544	0.482	0.4	0.287	0.05
10	0.876	0.858	0.85	0.837	0.822	0.803	0.796	0.789	0.789	0.772	0.741	0.7	0.644	0.525
25	0.950	0.943	0.94	0.935	0.929	0.921	0.919	0.916	0.916	0.909	0.896	0.88	0.858	0.81
50	0.975	0.972	0.97	0.967	0.964	0.961	0.959	0.958	0.958	0.954	0.948	0.94	0.929	0.905
100	0.988	0.986	0.985	0.984	0.982	0.980	0.980	0.979	0.979	0.977	0.974	0.97	0.964	0.952
Probability distribut. fun.	GEV	GEV	LP3	GEV	GEV	GEV	GEV	GEV	GEV	GEV	GEV	GEV	LP3	LP3
α			4.266										149	52.75
β			-0.369										-0.036	0.056
γ			2.416										7.990	-0.205
μ	0.809	1.541		2.871	3.847	5.086	6.005	6.973	7.668	8.492	9.786	10.96		
σ	0.554	0.989		2.1552	2.6743	2.6287	2.934	3.106	3.3156	3.7648	3.4243	4.249		
k	-0.139	-0.055		-0.122	-0.1513	-0.0438	-0.025	0.0212	0.0641	0.0563	0.1748	0.1098		

Table A.2 (Continued.**):** The best-fit probability distribution functions and parameters for SPI_1, SPI_3, SPI_6 SPI_9, SPI_{12} and SPI_{24} in Adana meteorological station.

	SPI_{24}										
Drought duration (month)	1	2	3	4	5	6	7	8	9	10	11
No drought years	17	26	26	28	28	29	29	30	30	31	32
Number of years	40	31	31	29	29	28	28	27	27	26	25
Probability of zero severity (p)	0.298	0.456	0.456	0.491	0.491	0.509	0.509	0.526	0.526	0.544	0.561
T (Year)	F*(x)										
2	0.288	0.081	0.081	0.017	0.017						
5	0.715	0.632	0.632	0.607	0.607	0.593	0.593	0.578	0.578	0.562	0.544
10	0.858	0.816	0.816	0.803	0.803	0.796	0.796	0.789	0.789	0.781	0.772
25	0.943	0.926	0.926	0.921	0.921	0.919	0.919	0.916	0.916	0.912	0.909
50	0.972	0.963	0.963	0.961	0.961	0.959	0.959	0.958	0.958	0.956	0.954
100	0.986	0.982	0.982	0.980	0.980	0.980	0.980	0.979	0.979	0.978	0.977
Probability distribution fun.	GEV	GEV	LP3	GEV	GEV	GEV	GEV	GEV	GEV	GEV	GEV
α			22.167								
β			-0.1399								
γ			3.9946								
μ	0.56002	1.4418		2.8769	3.5246	4.3564	5.0114	5.8543	6.4803	7.375	8.3087
σ	0.5344	0.87507		1.6476	2.0535	2.4056	2.788	3.0142	3.42	3.6316	3.6914
k	0.0388	0.11405		0.12419	0.13097	0.14634	0.15322	0.1888	0.19151	0.22146	0.26414

Table A.2 (Continued.**):** The best-fit probability distribution functions and parameters for SPI_1, SPI_3, SPI_6 SPI_9, SPI_{12} and SPI_{24} in Adana meteorological station.

	SPI_{24}										
Drought duration (month)	12	13	14	15	16	17	18	19	20	21	22
No drought years	33	38	41	41	41	41	42	42	42	42	43
Number of years	12	13	14	15	16	17	18	19	20	21	22
Probability of zero severity (p)	0.579	0.667	0.719	0.719	0.719	0.719	0.737	0.737	0.737	0.737	0.754
T (Year)	F*(x)										
2											
5	0.525	0.4	0.288	0.288	0.288	0.288	0.24	0.24	0.24	0.24	0.186
10	0.7625	0.7	0.644	0.644	0.644	0.644	0.62	0.62	0.62	0.62	0.593
25	0.905	0.88	0.858	0.858	0.858	0.858	0.848	0.848	0.848	0.848	0.837
50	0.9525	0.94	0.929	0.929	0.929	0.929	0.924	0.924	0.924	0.924	0.919
100	0.97625	0.97	0.964	0.964	0.964	0.964	0.962	0.962	0.962	0.962	0.959
Probability distribution fun.	LP3	GEV	GEV	GEV	GEV	GEV	GEV	GEV	GEV	LP3	LP3
α	7.3951									5.3628	6.6081
β	0.17745									0.21288	0.19443
γ	1.1328									1.94	1.8668
μ		11.434	12.429	13.101	13.757	14.314	15.729	16.323	16.854		
σ		4.4384	5.019	5.4238	5.7955	6.1422	5.8766	6.1737	6.5341		
k		0.27441	0.28348	0.27613	0.27254	0.27534	0.32968	0.3332	0.33326		

Table A.2 (Continued.**):** The best-fit probability distribution functions and parameters for SPI_1, SPI_3, SPI_6 SPI_9, SPI_{12} and SPI_{24} in Adana meteorological station.

	SPI_{24}									
Drought duration (month)	23	24	25	26	27	28	29	30	31	32
No drought years	43	43	45	46	46	46	46	47	47	47
Number of years	14	14	12	11	11	11	11	10	10	10
Probability of zero severity (p)	0.754	0.754	0.789	0.807	0.807	0.807	0.807	0.825	0.825	0.825
T (Year)										
2	0.186	0.186	0.05							
5	0.593	0.593	0.525	0.482	0.482	0.482	0.482	0.43	0.43	0.43
10	0.837	0.837	0.81	0.793	0.793	0.793	0.793	0.772	0.772	0.772
25	0.919	0.919	0.905	0.896	0.896	0.896	0.896	0.886	0.886	0.886
50	0.959	0.959	0.9525	0.948	0.948	0.948	0.948	0.943	0.943	0.943
100	0.186	0.186	0.05							
Probability distribution fun.	LP3	LP3	LP3	LP3	LP3	LP3	LP3	LP3	LP3	LP3
α	6.7171	6.7967	7.8289	4.6898	4.8925	5.1081	5.4018	4.9919	5.0719	5.2244
β	0.19453	0.19526	0.17819	0.23815	0.2349	0.23104	0.22635	0.2275	0.22673	0.22484
γ	1.879	1.8906	1.9349	2.2068	2.1991	2.1912	2.1696	2.3427	2.3499	2.3451
μ										
σ										
k										

Table A.3: Critical drought severity and intensity values corresponding to 2, 5, 10, 25, 50 and 100 year-return periods for SPI_1, SPI_3, SPI_6 SPI_9, SPI_{12} and SPI_{24} in Adana meteorological station.

Severity			SPI_1			SPI_3						
	D	(month)				D	(month)					
T (Year)	D=1	D=2	D=3	D=4	D=5	D=1	D=2	D=3	D=4	D=5	D=6	D=7
2	1.363	1.869	1.679			1.543	2.528	3.092	3.315			
5	1.871	2.789	3.154	3.097	2.88	2.104	3.524	4.619	5.392	6.085	6.221	5.971
10	2.202	3.312	3.796	4.056	4.31	2.391	3.998	5.372	6.421	7.316	7.700	8.097
25	2.616	3.900	4.476	5.361	5.754	2.677	4.457	6.136	7.623	8.620	9.305	9.910
50	2.919	4.293	4.915	6.470	6.9	2.847	4.720	6.599	8.473	9.470	10.399	10.974
100	3.216	4.649	5.302	7.714	8.148	2.986	4.931	6.986	9.282	10.233	11.432	11.877
Intensity												
2	1.36	0.93	0.56			1.543	1.264	1.031	0.829			
5	1.87	1.39	1.05	0.77	0.58	2.104	1.762	1.540	1.348	1.217	1.037	0.853
10	2.20	1.66	1.27	1.01	0.86	2.391	1.999	1.791	1.605	1.463	1.283	1.157
25	2.62	1.95	1.49	1.34	1.15	2.677	2.229	2.045	1.906	1.724	1.551	1.416
50	2.92	2.15	1.64	1.62	1.38	2.847	2.360	2.200	2.118	1.894	1.733	1.568
100	3.22	2.32	1.77	1.93	1.63	2.986	2.466	2.329	2.321	2.047	1.905	1.697

Table A.3 (Continued): Critical drought severity and intensity values corresponding to 2, 5, 10, 25, 50 and 100 year-return periods for SPI_1, SPI_3, SPI_6 SPI_9, SPI_{12} and SPI_{24} in Adana meteorological station.

Severity	SPI_6										
	D (month)										
T (Year)	D=1	D=2	D=3	D=4	D=5	D=6	D=7	D=8	D=9	D=10	D=11
2	1.29	2.13	2.69	2.94	2.15						
5	1.99	3.39	4.47	5.36	6.05	6.67	7.35	7.57	7.49	5.88	
10	2.36	4.09	5.54	6.78	7.82	8.66	9.55	9.87	10.35	10.22	10.77
25	2.77	4.87	6.82	8.57	9.96	11.13	12.09	12.61	12.94	13.02	14.05
50	3.02	5.38	7.73	9.92	11.53	12.99	13.92	14.68	14.58	14.74	15.66
100	3.23	5.83	8.60	11.30	13.08	14.90	15.74	16.80	16.07	16.28	16.91
Intensity											
2	1.294	1.065	0.897	0.736	0.430						
5	1.987	1.696	1.491	1.341	1.210	1.112	1.051	0.947	0.832	0.588	
10	2.363	2.047	1.846	1.694	1.564	1.444	1.364	1.234	1.150	1.022	0.979
25	2.765	2.435	2.272	2.142	1.991	1.854	1.727	1.576	1.438	1.302	1.277
50	3.018	2.689	2.577	2.479	2.305	2.165	1.989	1.835	1.620	1.474	1.424
100	3.235	2.916	2.868	2.824	2.617	2.483	2.248	2.100	1.786	1.628	1.537

Table A.3 (Continued): Critical drought severity and intensity values corresponding to 2, 5, 10, 25, 50 and 100 year-return periods for SPI_1, SPI_3, SPI_6 SPI_9, SPI_{12} and SPI_{24} in Adana meteorological station.

Severity						SPI_9							
				D	(month)								
T (Year)	D=1	D=2	D=3	D=4	D=5	D=6	D=7	D=8	D=9	D=10	D=11	D=12	D=13
2	1.0314	1.7703	2.392	2.7014	2.8413	1.4931							
5	1.6091	2.9016	4.0042	4.9969	6.055	7.1178	8.0651	8.9613	9.8412	10.407	10.944	10.963	8.1628
10	1.9378	3.542	4.9283	6.3017	7.7889	9.0661	10.249	11.437	12.601	13.605	14.478	15.163	14.691
25	2.3075	4.2651	6.0138	7.881	9.496	11.215	12.67	14.187	15.634	16.881	18.046	19.27	19.944
50	2.5521	4.7511	6.7706	9.0235	10.769	12.664	14.316	16.061	17.688	19.015	20.382	21.974	23.244
100	2.7742	5.1904	7.4825	10.14	11.969	14.002	15.847	17.807	19.601	20.953	22.519	24.502	26.247
Intensity													
2	1.031	0.885	0.797	0.675	0.568	0.249							
5	1.609	1.451	1.335	1.249	1.211	1.186	1.152	1.120	1.093	1.041	0.995	0.914	0.628
10	1.938	1.771	1.643	1.575	1.558	1.511	1.464	1.430	1.400	1.361	1.316	1.264	1.130
25	2.308	2.133	2.005	1.970	1.899	1.869	1.810	1.773	1.737	1.688	1.641	1.606	1.534
50	2.552	2.376	2.257	2.256	2.154	2.111	2.045	2.008	1.965	1.902	1.853	1.831	1.788
100	2.774	2.595	2.494	2.535	2.394	2.334	2.264	2.226	2.178	2.095	2.047	2.042	2.019

Table A.3 (Continued): Critical drought severity and intensity values corresponding to 2, 5, 10, 25, 50 and 100 year-return periods for SPI_1, SPI_3, SPI_6 SPI_9, SPI_{12} and SPI_{24} in Adana meteorological station.

Severity							SPI_{12}							
							D(month)							
T(Year)	D=1	D=2	D=3	D=4	D=5	D=6	D=7	D=8	D=9	D=10	D=11	D=12	D=13	D=14
2	0.82827	1.3215	1.5147	1.7118	1.5905	1.2851								
5	1.4477	2.5894	3.7103	4.7682	5.91	6.8835	7.8931	8.8501	9.6978	10.387	10.893	11.329	11.072	8.3344
10	1.7858	3.3011	4.9097	6.2275	7.7082	8.949	10.268	11.512	12.667	13.78	14.376	15.594	16.664	15.879
25	2.1597	4.1387	6.1691	7.8272	9.6057	11.317	13.021	14.713	16.38	17.939	19.038	20.762	22.373	22.441
50	2.4056	4.7269	6.9402	8.8803	10.822	12.972	14.973	17.07	19.216	21.085	22.911	24.784	26.312	27.244
100	2.6265	5.2898	7.5887	9.837	11.901	14.547	16.855	19.425	22.136	24.301	27.21	29.035	30.103	32.178
Intensity														
2	0.828	0.661	0.505	0.428	0.318	0.214								
5	1.448	1.295	1.237	1.192	1.182	1.147	1.128	1.106	1.078	1.039	0.990	0.944	0.852	0.595
10	1.786	1.651	1.637	1.557	1.542	1.492	1.467	1.439	1.407	1.378	1.307	1.300	1.282	1.134
25	2.160	2.069	2.056	1.957	1.921	1.886	1.860	1.839	1.820	1.794	1.731	1.730	1.721	1.603
50	2.406	2.363	2.313	2.220	2.164	2.162	2.139	2.134	2.135	2.109	2.083	2.065	2.024	1.946
100	2.627	2.645	2.530	2.459	2.380	2.425	2.408	2.428	2.460	2.430	2.474	2.420	2.316	2.298

Table A.3 (Continued): Critical drought severity and intensity values corresponding to 2, 5, 10, 25, 50 and 100 year-return periods for SPI_1, SPI_3, SPI_6 SPI_9, SPI_{12} and SPI_{24} in Adana meteorological station.

Severity	SPI_{24}										
	D (month)										
T (Year)	D=1	D=2	D=3	D=4	D=5	D=6	D=7	D=8	D=9	D=10	D=11
2	0.443	0.675	0.934	0.757	0.895						
5	1.156	2.156	3.175	4.072	5.017	5.993	6.913	7.771	8.655	9.498	10.266
10	1.598	2.971	4.440	5.632	6.976	8.331	9.643	10.839	12.142	13.319	14.306
25	2.162	4.058	5.998	7.713	9.606	11.501	13.367	15.140	17.045	18.806	20.313
50	2.590	4.927	7.127	9.391	11.739	14.101	16.439	18.792	21.216	23.599	25.732
100	3.028	5.873	8.232	11.190	14.035	16.930	19.799	22.900	25.917	29.106	32.158
Intensity											
2	0.443	0.337	0.311	0.189	0.179						
5	1.156	1.078	1.058	1.018	1.003	0.999	0.988	0.971	0.962	0.950	0.933
10	1.598	1.486	1.480	1.408	1.395	1.389	1.378	1.355	1.349	1.332	1.301
25	2.162	2.029	1.999	1.928	1.921	1.917	1.910	1.893	1.894	1.881	1.847
50	2.590	2.464	2.376	2.348	2.348	2.350	2.348	2.349	2.357	2.360	2.339
100	3.028	2.937	2.744	2.798	2.807	2.822	2.828	2.863	2.880	2.911	2.923

Table A.3 (Continued): Critical drought severity and intensity values corresponding to 2, 5, 10, 25, 50 and 100 year-return periods for SPI_1, SPI_3, SPI_6 SPI_9, SPI_{12} and SPI_{24} in Adana meteorological station.

Severity						SPI_{24}					
						D (month)					
T (Year)	D=12	D=13	D=14	D=15	D=16	D=17	D=18	D=19	D=20	D=21	D=22
2	11.203	11.827	11.357	11.941	12.518	13	13.757	14.253	14.662	15.034	14.937
5	15.687	16.723	17.063	18.093	19.083	19.965	20.64	21.489	22.321	23.647	24.654
10	22.361	23.703	24.829	26.4	27.916	29.363	30.198	31.578	32.998	35.765	37.645
25	28.307	29.969	31.782	33.791	35.75	37.717	39.056	40.957	42.924	46.707	49.181
50	35.262	37.421	40.067	42.55	45.01	47.614	49.962	52.535	55.177	59.733	62.742
100	11.203	11.827	11.357	11.941	12.518	13	13.757	14.253	14.662	15.034	14.937
Intensity											
2	0.934	0.910	0.811	0.796	0.782	0.765	0.764	0.750	0.733	0.716	0.679
5	1.307	1.286	1.219	1.206	1.193	1.174	1.147	1.131	1.116	1.126	1.121
10	1.863	1.823	1.774	1.760	1.745	1.727	1.678	1.662	1.650	1.703	1.711
25	2.359	2.305	2.270	2.253	2.234	2.219	2.170	2.156	2.146	2.224	2.236
50	2.939	2.879	2.862	2.837	2.813	2.801	2.776	2.765	2.759	2.844	2.852
100	0.934	0.910	0.811	0.796	0.782	0.765	0.764	0.750	0.733	0.716	0.679

Table A.3 (Continued): Critical drought severity and intensity values corresponding to 2, 5, 10, 25, 50 and 100 year-return periods for SPI_1, SPI_3, SPI_6 SPI_9, SPI_{12} and SPI_{24} in Adana meteorological station.

Severity	SPI_{24}							
	D(month)							
T (Year)	D=25	D=26	D=27	D=28	D=29	D=30	D=31	D=32
2								
5	13.774							
10	27.159	25.102	25.75	26.378	26.971	27.658	28.246	28.812
25	42.289	40.552	41.734	42.837	43.936	45.188	46.248	47.321
50	55.344	54.598	56.242	57.739	59.253	60.757	62.234	63.749
100	70.484	71.599	73.779	74.643	77.695	79.406	81.385	83.419
Intensity								
2								
5	0.55096							
10	1.08636	0.965462	0.953704	0.942071	0.930034	0.921933	0.911161	0.900375
25	1.69156	1.559692	1.545704	1.529893	1.515034	1.506267	1.491871	1.478781
50	2.21376	2.099923	2.083037	2.062107	2.043207	2.025233	2.007548	1.992156
100	2.81936	2.753808	2.732556	2.665821	2.679138	2.646867	2.625323	2.606844

APPENDIX B

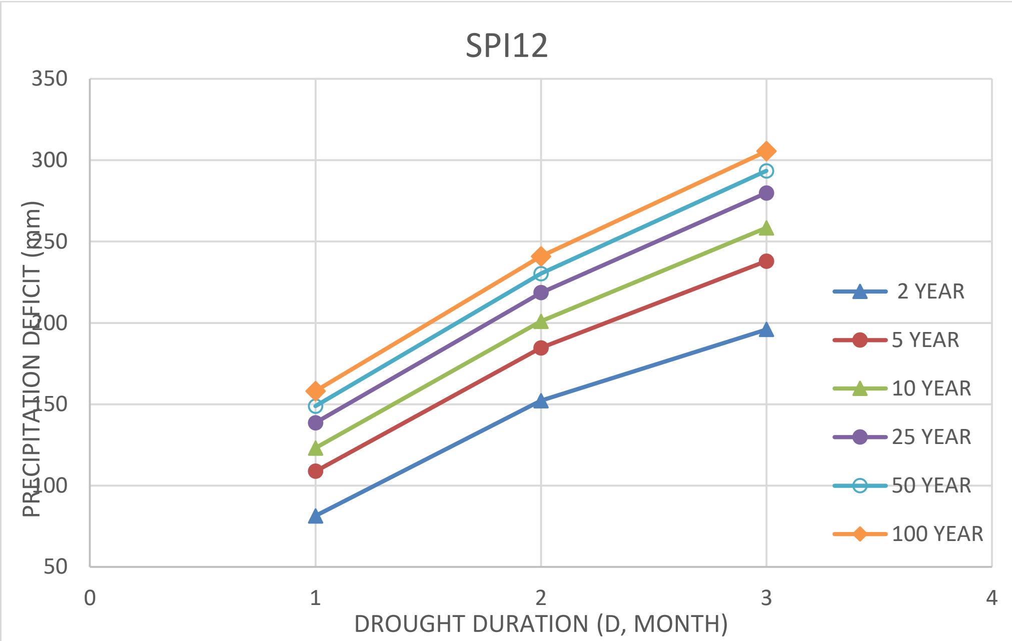


Figure B.1: Critical drought severity-duration-frequency curves based on precipitation deficit for SPI_{12} in station 06893.

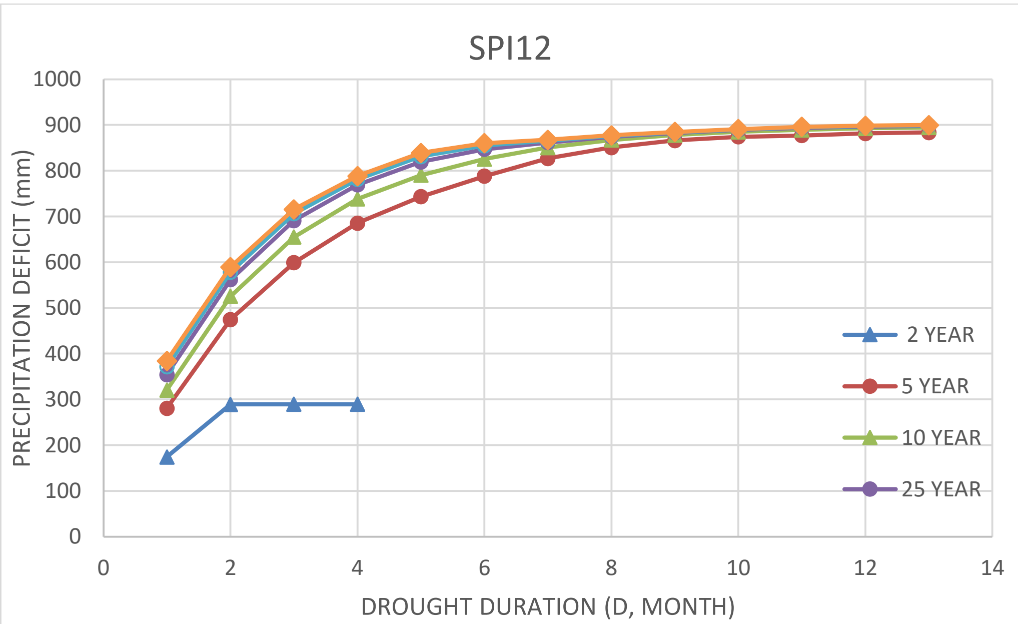


Figure B.2: Critical drought severity-duration-frequency curves based on precipitation deficit for SPI_{12} in station 06902.

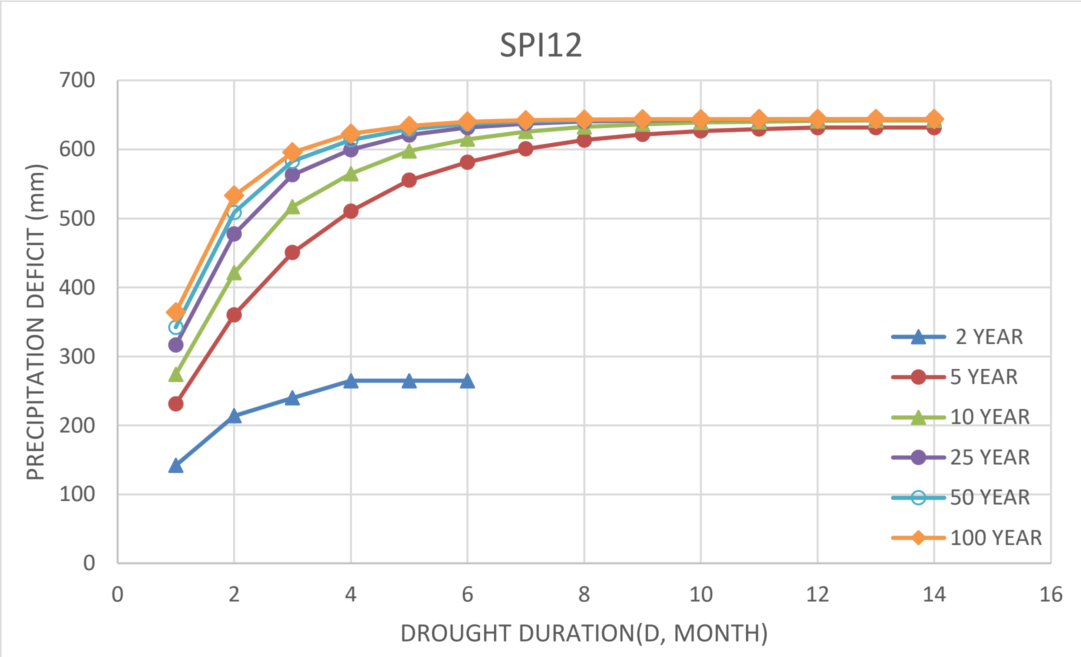


Figure B.3: Critical drought severity-duration-frequency curves based on precipitation deficit for SPI_{12} in station 17351.

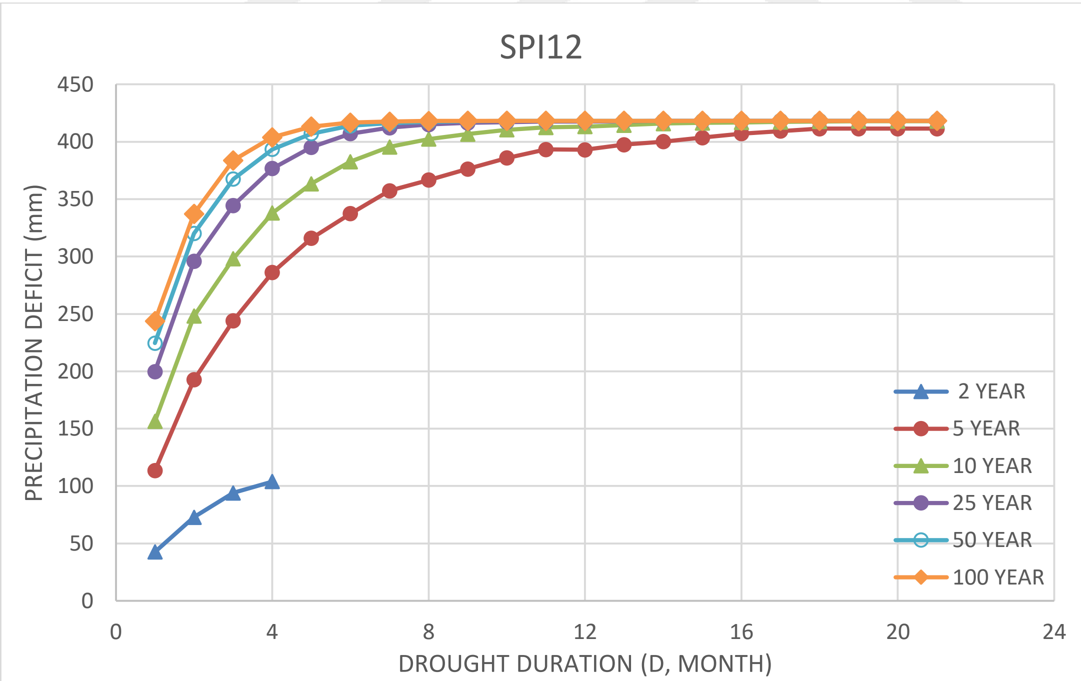


Figure B.4: Critical drought severity-duration-frequency curves based on precipitation deficit for SPI_{12} in station 17802.

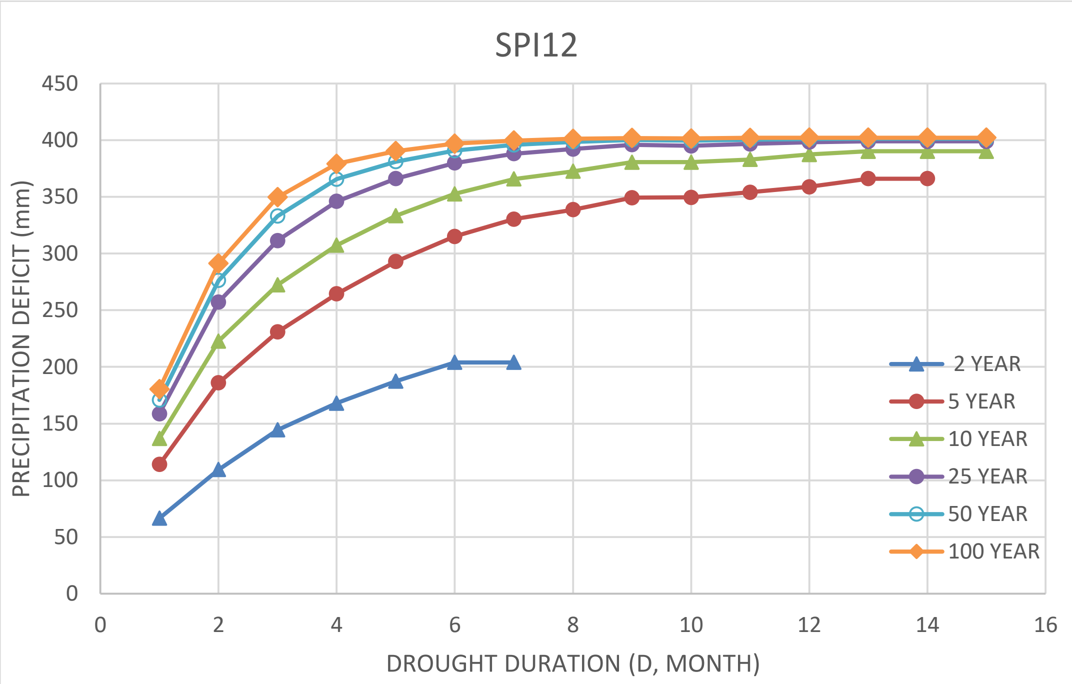


Figure B.5: Critical drought severity-duration-frequency curves based on precipitation deficit for SPI_{12} in station 17837.

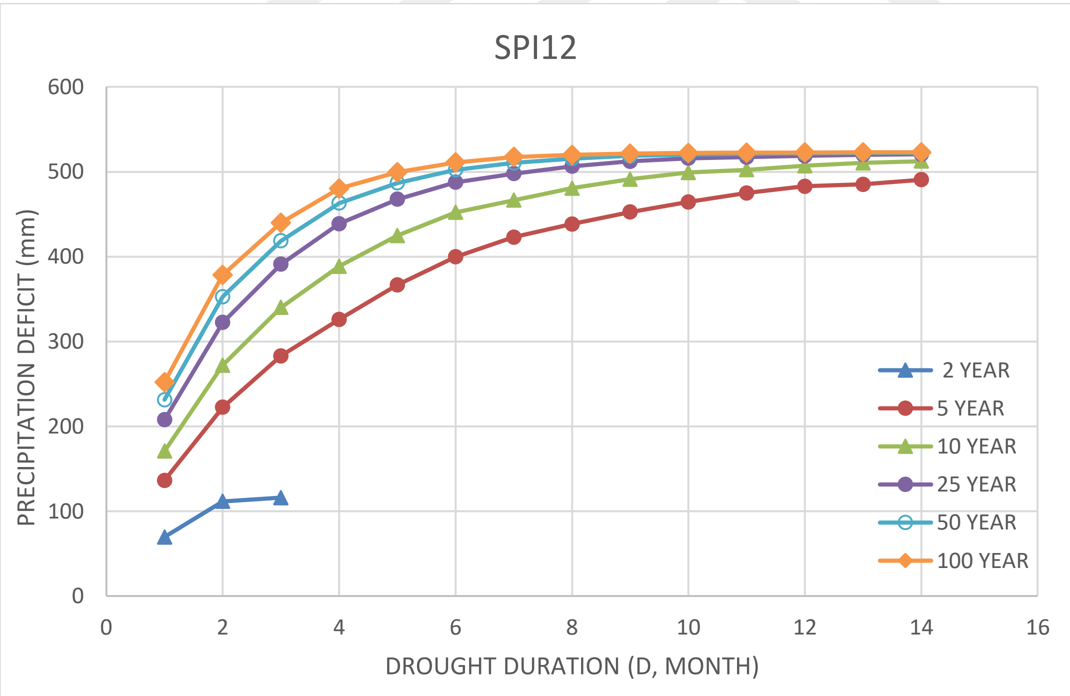


Figure B.6: Critical drought severity-duration-frequency curves based on precipitation deficit for SPI_{12} in station 17840.

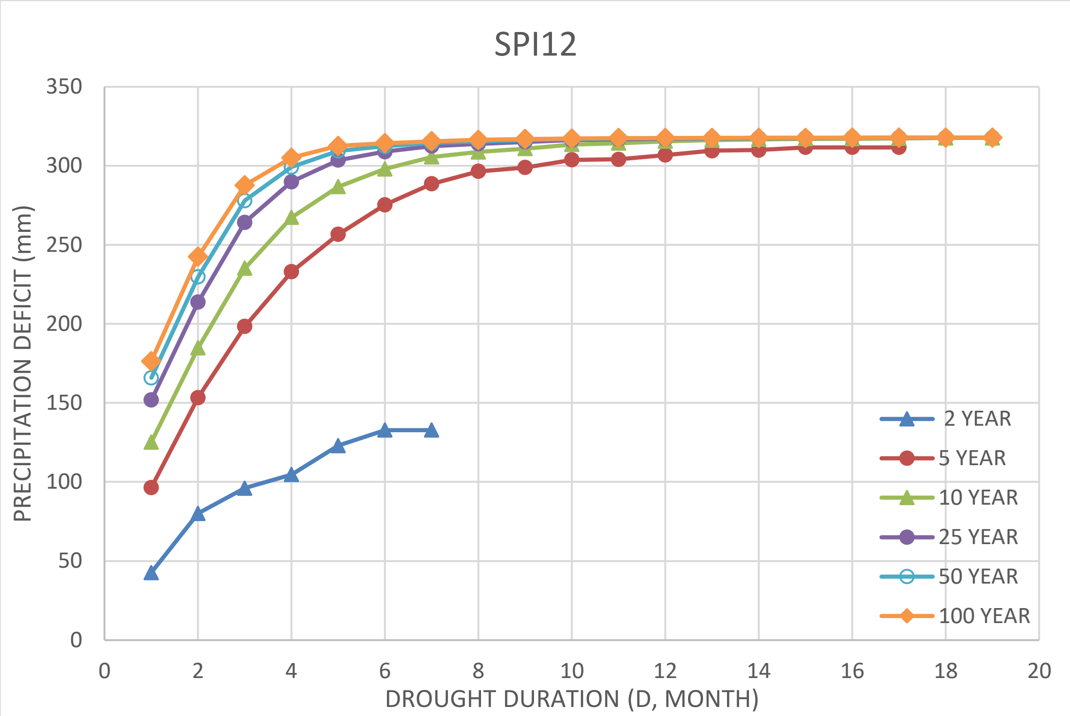


Figure B.7: Critical drought severity-duration-frequency curves based on precipitation deficit for SPI_{12} in station 17906.

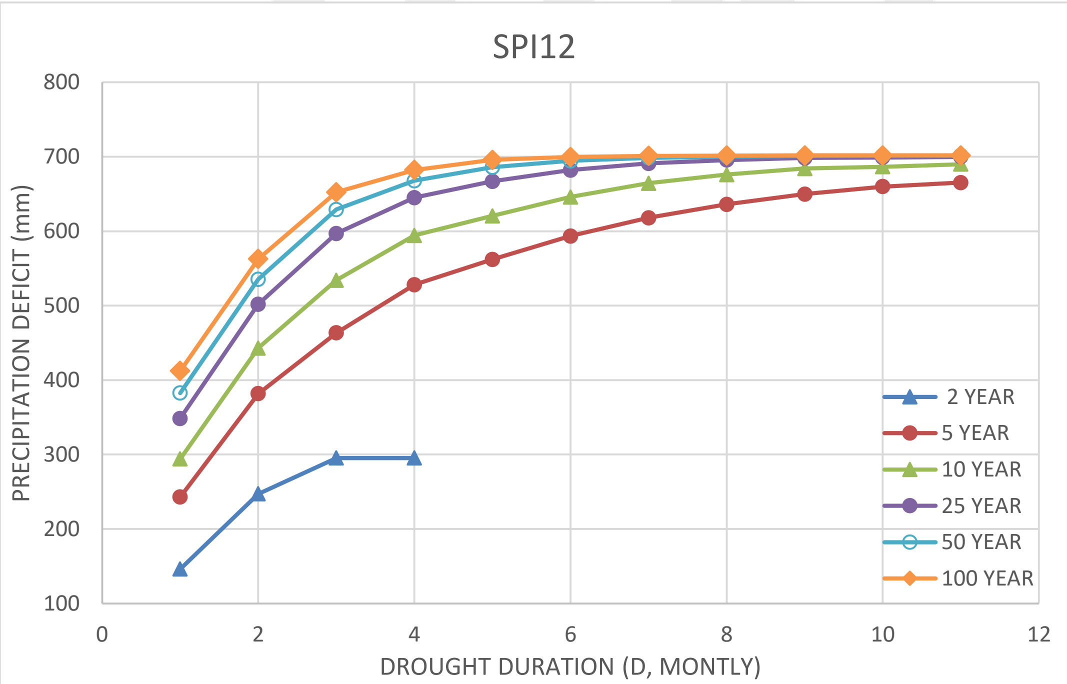


Figure B.8: Critical drought severity-duration-frequency curves based on precipitation deficit for SPI_{12} in station 17934.

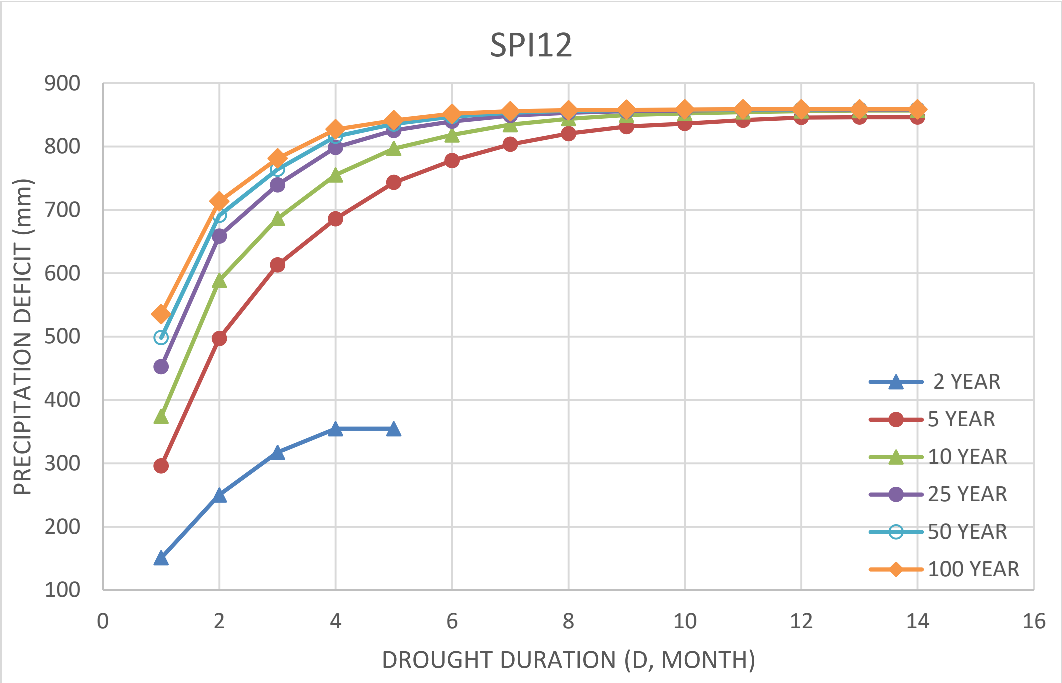


Figure B.9: Critical drought severity-duration-frequency curves based on precipitation deficit for SPI_{12} in station 17936.

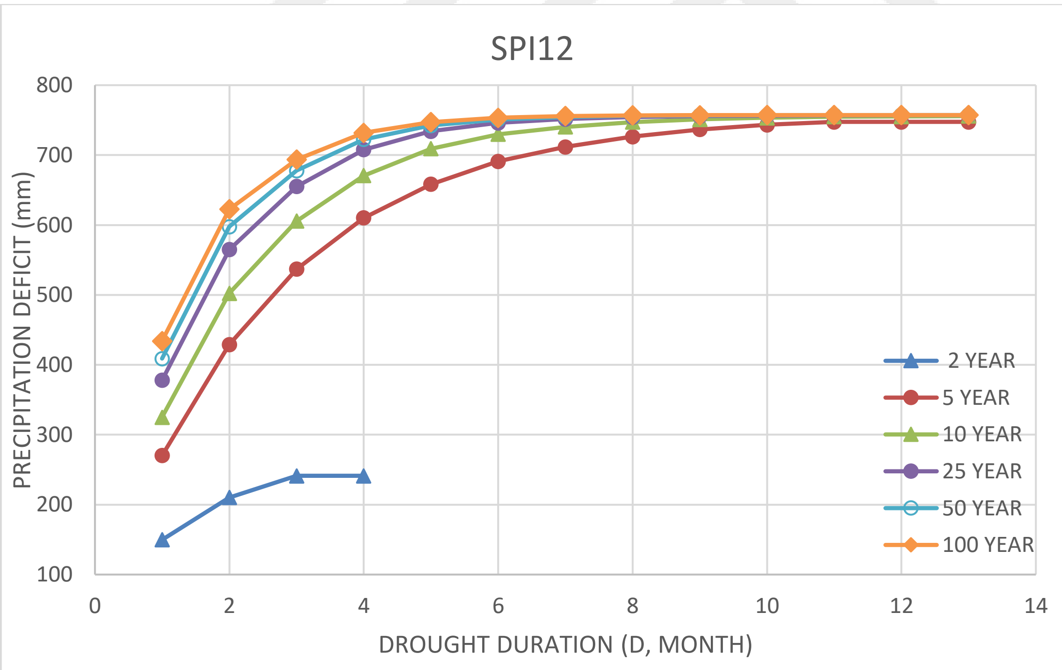
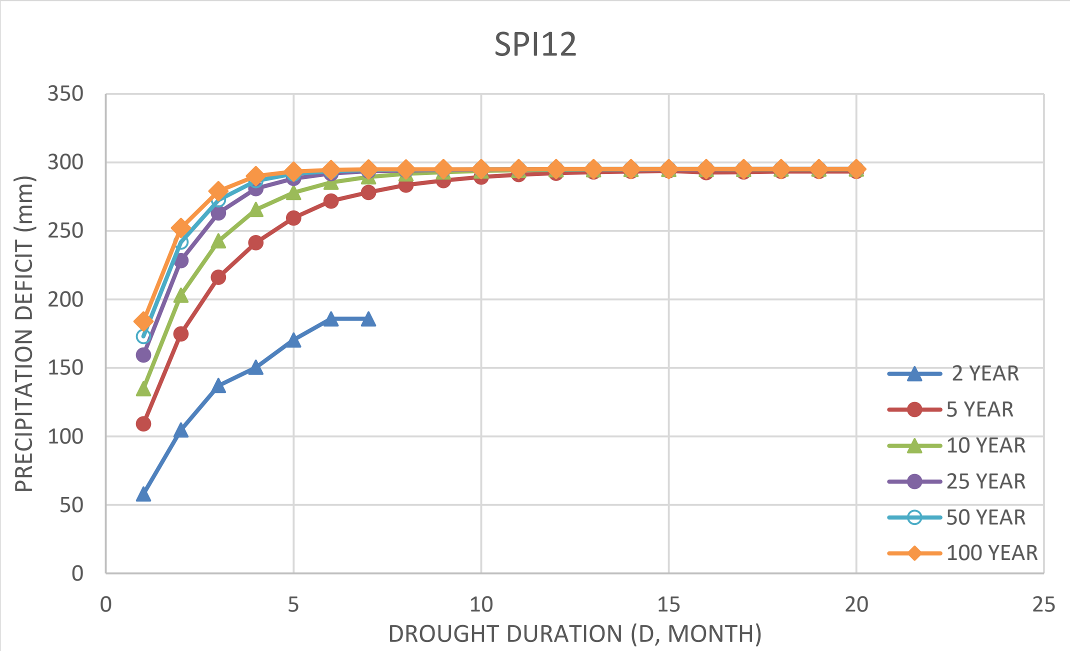


Figure B.10: Critical drought severity-duration-frequency curves based on precipitation deficit for SPI_{12} in station 17981.



FigureB.11: Critical drought severity-duration-frequency curves based on precipitation deficit for SPI_{12} in station D18M003.

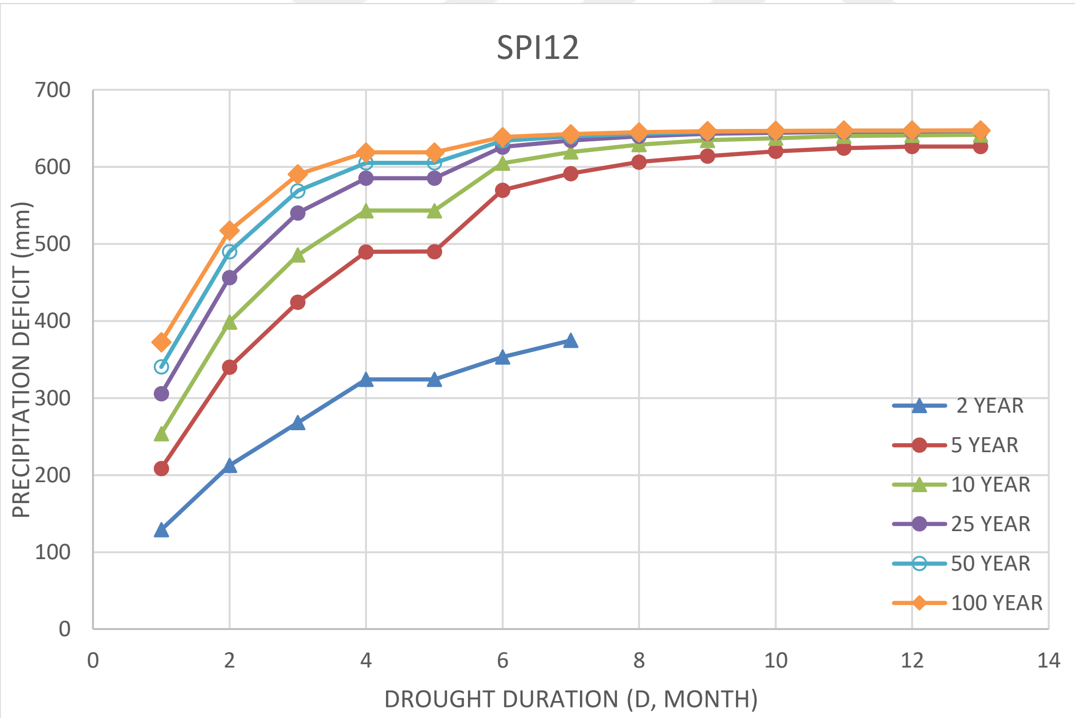


Figure B.12: Critical drought severity-duration-frequency curves based on precipitation deficit for SPI_{12} in station D18M004.

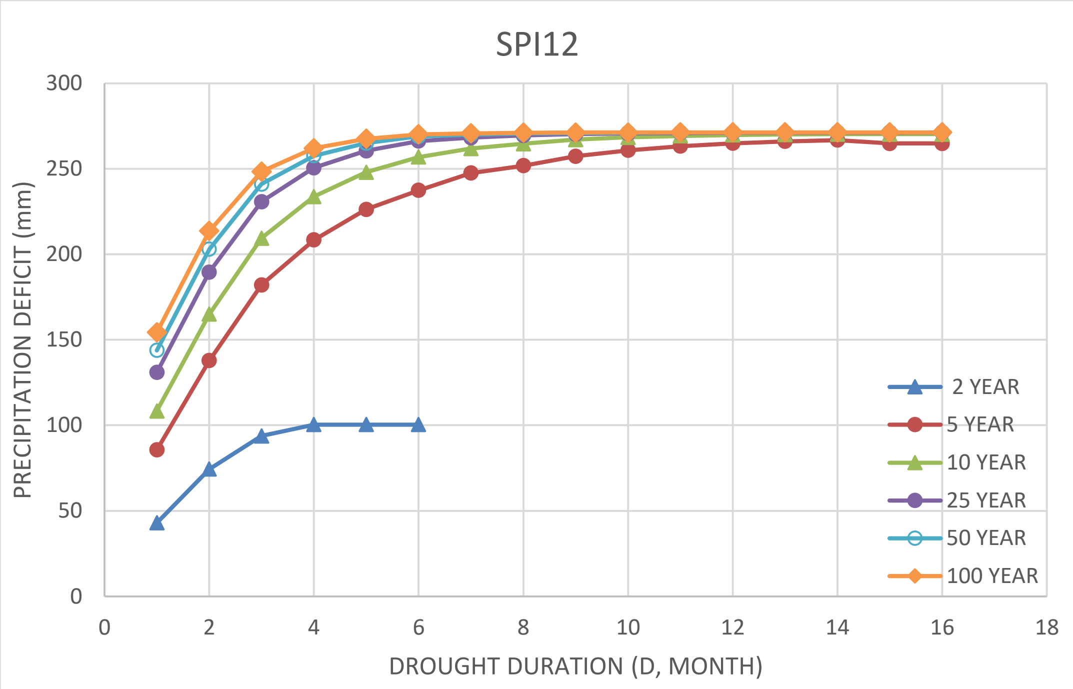


Figure B.13: Critical drought severity-duration-frequency curves based on precipitation deficit for SPI_{12} in station D18M011.

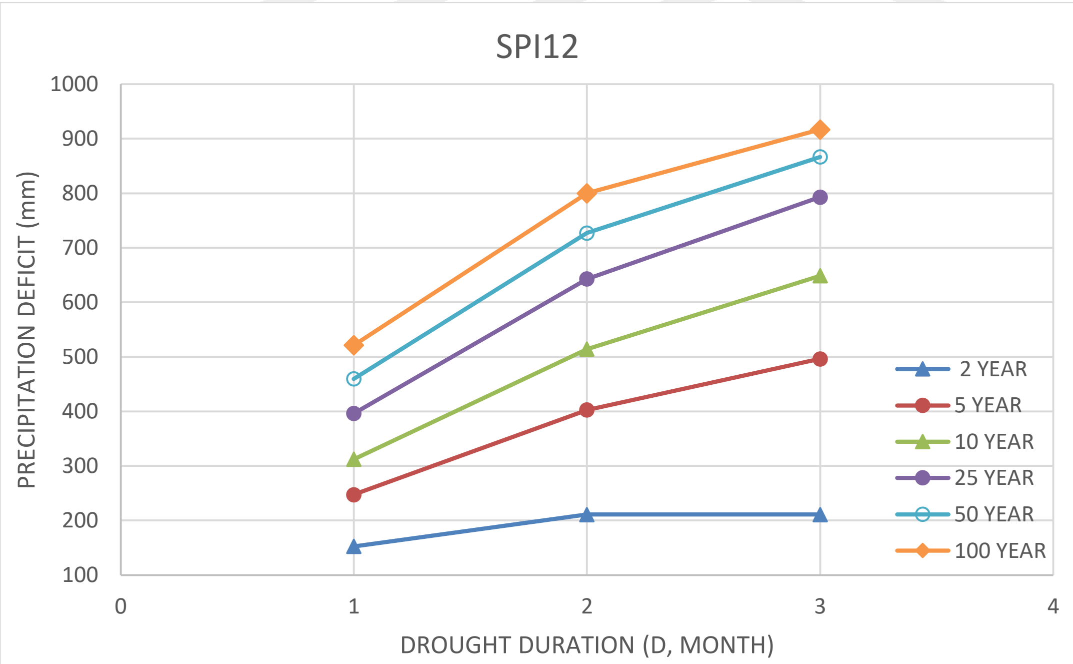


Figure B.14: Critical drought severity-duration-frequency curves based on precipitation deficit for SPI_{12} in station D18M012.

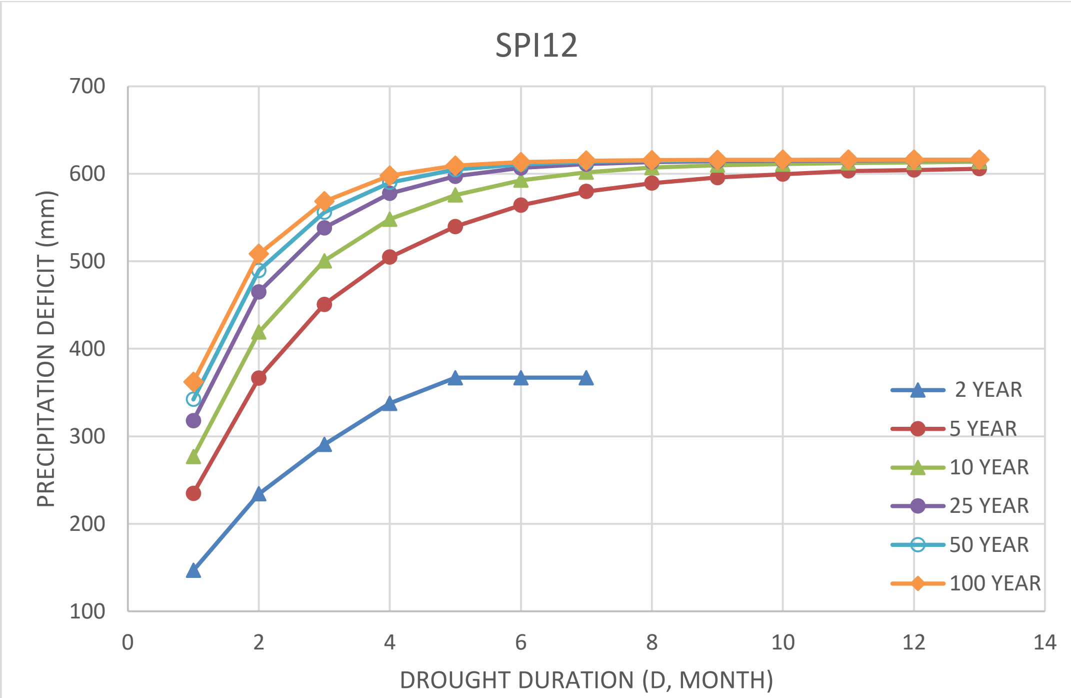


Figure B.15: Critical drought severity-duration-frequency curves based on precipitation deficit for SPI_{12} in station D18M013.

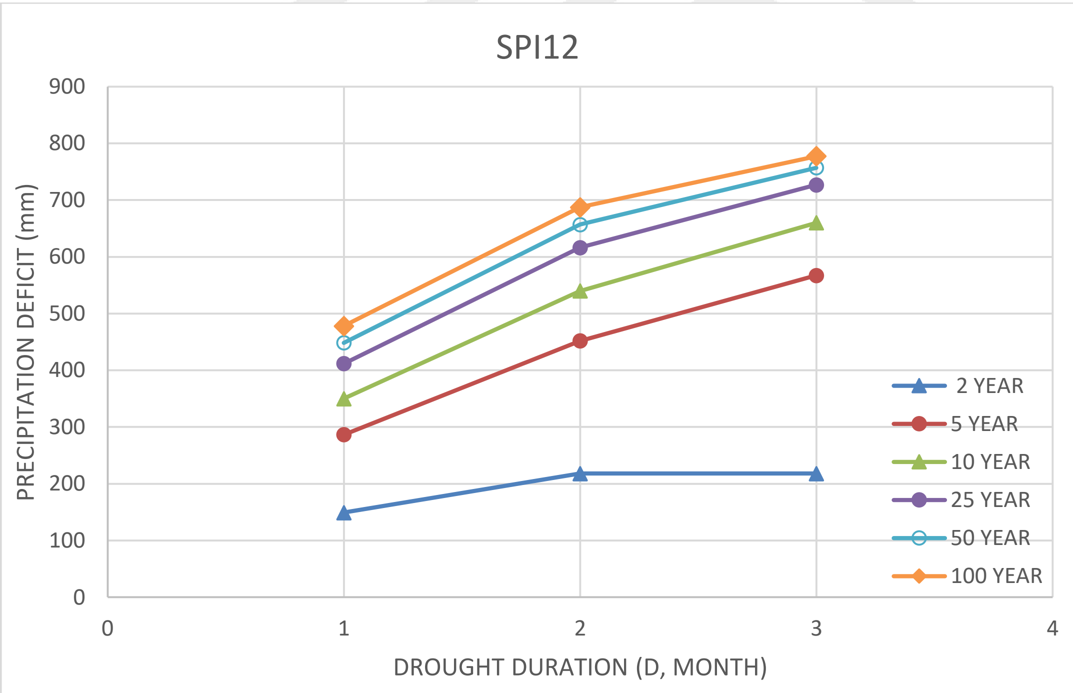


Figure B.16: Critical drought severity-duration-frequency curves based on precipitation deficit for SPI_{12} in station D18M018.

The probability distribution function could not be fitted for stations 06204, 06560, D18M019 because the length of the SPI series is less than 10 years in all drought durations.

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PUBLICATIONS, PRESENTATIONS AND PATENTS ON THE THESIS:

Articles (SCI-Expanded):

i. **Cavus, Y., Aksoy, H**. (2019) Critical drought severity/intensity-duration-frequency curves based on precipitation deficit. *Journal of Hydrology* (Under review).

ii. **Cavus, Y., Aksoy, H**. (2019) Spatial drought characterization of Seyhan River basin in the Mediterranean region of Turkey. *Water*, 11(7), 1331; doi:10.3390/w11071331.

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iii. **Cavus, Y., Orta, S., Burgan, H.I., Eris, E., Aksoy, H**. (2019). Trend analysis of low flows. *The 9th International Symposium on Atmospheric Sciences (ATMOS 2019)*, 23-26 October 2019, Istanbul Technical University, Istanbul, Turkey (accepted for oral presentation).

iv. **Cavus, Y., Demir, F.B., Önöz, B.** (2019). Low flow analysis for Gediz basin. *The 9th International Symposium on Atmospheric Sciences (ATMOS 2019), 23-26 October 2019,* Istanbul Technical University, Istanbul, Turkey (accepted for oral presentation).

v. **Cavus, Y., Aksoy, H**. (2019) *Drought severity-duration-frequency curves based on precipitation deficit*. IUGG 27th General Assembly, Symposium H24 – Modeling Hydrological Processes and Changes under a changing Environment, July 8-18, 2019, Montreal, Canada (accepted for oral presentation).

vi. **Aksoy, H., Onoz, B., Cetin, M., Yuce, M.I., Eris, E., Selek, B., Aksu, H., Burgan, H.I., Esit, M., Orta, S., Cavus, Y.** (2018). *SPI-based Drought Severity-Duration-Frequency analysis*. The 13th International Congress on Advances in Civil Engineering (ACE 2018), September 12-14, 2018, Izmir.

vii. **Cetin, M., Aksoy, H., Onoz, B., Eris, E., Yuce, M.I., Selek, B., Aksu, H., Burgan, H.I., Esit, M., Cavus, Y., Orta, S.** (2018). *Deriving accumulated precipitation deficits from Drought Severity-Duration-Frequency Curves: A case study in Adana Province, Turkey*. The 1st International Congress on Agricultural Structures and Irrigation, September 26-28 2018, Antalya.

National Conference Proceedings:

viii. **Cavus, Y., Aksoy, H**. (2019) Yağış Açığı Cinsinden Kritik Kuraklık Şiddet-Süre-Frekans Eğrileri. X. National Hydrology Congress, October 9-12, 2019, Muğla Sıtkı Koçman University, Muğla, Turkey (accepted for oral presentation).

ix. **Aksoy, H., Cetin, M., Onoz, B., Yuce, M.I., Eris, E., Selek, B., Aksu, H., Burgan, H.I., Esit, M., Cavus, Y., Orta, S.** (2019) *Frekans analizi ile kuraklık şiddet-süre-frekans eğrilerininin elde edilmesi*. X. National Hydrology Congress, October 9-12, 2019, Muğla Sıtkı Koçman University (accepted for oral presentation).

x. **Aksoy, H., Önöz, B., Çetin, M., Yüce, M.İ., Eriş, E., Selek, B., Aksu, H., Burgan, H.İ., Eşit, M., Orta, S., Çavuş, Y**. (2018). *Edirne için Kuraklık Şiddet-Süre-Frekans Eğrileri*. National Hydrogeology and Water Resources Symposium (HİDRO 2018), September 27-29, 2018, Hacettepe University, Beytepe, Ankara.

Report:

xi. **Aksoy, H., Çetin, M., Önöz, B., Yüce, M.İ., Eriş, E., Selek, B., Aksu, H., Burgan, H.İ., Eşit, M., Orta, S., Çavuş, Y**. (2018). *Hidrolojik Havzalarda Düşük Akımlar ve Kuraklık Analizi*. TUJJB-TUMEHAP-2015-01, Turkish National Union of Geodesy and Geophysics (TUJJB) Research Project, Final Report, 351 pages.

PROJECTS INVOLVED:

xii. (2019-) Critical drought severity-duration-frequency curves in terms of precipitation deficit. Scientific Research Projects Unit of Istanbul Technical University. Coordinated by Hafzullah Aksoy, Istanbul Technical University.

OTHER PROJECTS INVOLVED:

xiii. (2019-) Data-based drought analysis under hydrological change. Scientific Research Projects Unit of Istanbul Technical University. Coordinated by Hafzullah Aksoy, Istanbul Technical University (proposal in review).

xiv. (2019-) Statistical analysis of hydro-meteorological data of Küçük Menderes River basin and drought index calculation. Scientific Research Projects Unit of Istanbul Technical University. Coordinated by Hafzullah Aksoy, Istanbul Technical University (proposal in review).

xv. (2018-) Hydrological risks and water quality change for sustainable water management under climate change (IKLIM-RISK). 116Y425 *1003-Primary Subjects R&D Funding Program* funded by The Scientific and Technological Research Council of Turkey (TUBITAK). Coordinated by Ebru Eris, Ege University.

xvi. (2015-2018) Analysis of low flow and drought in hydrologic basins. TUJJB-TUMEHAP-2015-01 *Project* funded by Turkish National Union of Geodesy and Geophysics (TUJJB), Coordinated by Hafzullah Aksoy, Istanbul Technical University.