

ASSESSMENT OF THE HYDROLOGICAL ALTERATIONS AND
ENVIRONMENTAL FLOWS IN SAKARYA WATERSHED, TURKEY

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ABSTRACT

ASSESSMENT OF THE HYDROLOGICAL ALTERATIONS AND ENVIRONMENTAL FLOWS IN SAKARYA WATERSHED, TURKEY

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In this study, a holistic environmental flow assessment (EFA) adopted from the ELOHA framework is performed for the Sakarya Watershed. The most significant environmental flow events were quantified using natural streamflow data estimated at the selected target streamflow gages. Also, hydrologic alterations due to several human pressures were assessed. The U.S. Geological Survey approach was adopted as the streamflow naturalization methodology. 18 FDC exceedance probability percentile flows (i.e., $Q_{0.1}$ - $Q_{99.9}$) were naturalized combining three approaches. Multiple linear regression models were developed using SPSS software to calculate Q_1 - Q_{85} ; Drainage Area Ratio (DAR) method was used to calculate $<Q_1$; and regressions against the flow values was performed to calculate $>Q_{85}$. The QPPQ method was implemented to interpolate these 18 estimated percentile flows to generate daily natural streamflows. The model performance was evaluated by R^2 , NSE and PBIAS calculated from the FDC percentile flows. The predictive performance of the entire naturalization methodology (i.e., regional regression modeling + QPPQ method) was evaluated by NSE between the estimated and measured daily natural streamflows. The NSE values indicated the source gauge selection procedure is critical because the difference between gauge characteristics

and the prediction performance are inversely correlated. The hydrologic alteration assessment was performed by the Indicators of Hydrologic Alteration (IHA) – Range of Variability Approach (RVA). The 32 IHA/RVA indicators demonstrated that all anthropogenic pressures have significantly changed the natural streamflow dynamics. With this regard, the environmental flow requirements of the Sakarya River were proposed using 34 Environmental Flow Components (EFCs) parameters.

Keywords: Hydrologic Alteration Assessment, Environmental Flows (EFs), Streamflow Naturalization, ELOHA, Regression Modeling, QPPQ Method



ÖZ

SAKARYA HAVZASINDA HİDROLOJİK MÜDAHALELERİN VE ÇEVRESEL AKIŞLARIN DEĞERLENDİRİLMESİ

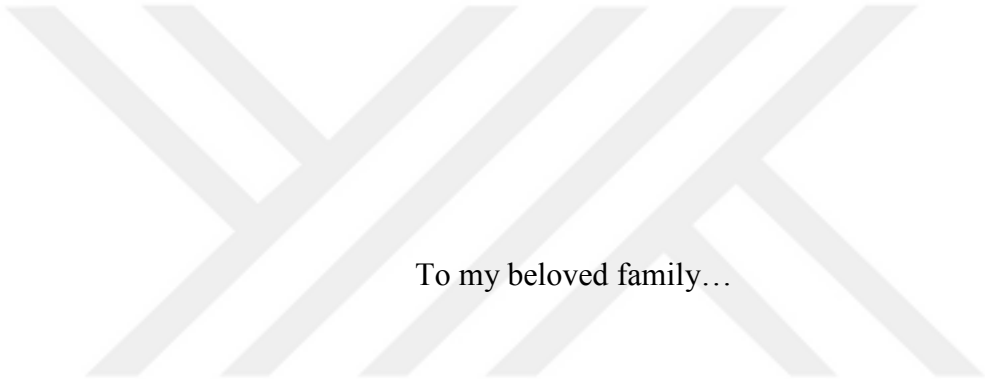
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Bu çalışmada, ELOHA yöntemi seçilerek Sakarya havzası için holistik bir çevresel akış değerlendirmesi yapılmıştır. Havza içerisinde seçilmiş olan hedef akım gözlem istasyonları (AGİ) noktalarında, günlük doğal akım verisi kullanılarak en önemli çevresel akış bileşenleri hesaplanmıştır. Ayrıca, havza içerisindeki insan baskıları dolayısıyla meydana gelen hidrolojik müdahaleler de değerlendirilmiştir. Birleşik Devletler Jeolojik Araştırma Kurumu (USGS) yaklaşımı ile akım doğallaştırması yapılmıştır. Akım Süreklilik Eğrisi (FDC) üzerindeki 18 doğal akım değeri ($Q_{0.1}$ - $Q_{99.9}$) üç yöntemin kombinasyonu kullanılarak hesaplanmıştır. Q_1 - Q_{85} değerleri SPSS yazılımı ile “Çoklu Doğrusal Regresyon Modelleri” koşularak; Q_1 ’den küçük değerler Drenaj Alanı Oranı (DAR) yöntemi uygulanarak; ve Q_{85} ’ten büyük değerler ise artarda akım değerleri arasında regresyon yapılarak hesaplanmıştır. QPPQ yöntemi ile, hesaplanan 18 akım değeri arasında interpolasyon yapılmış, günlük doğal akımlar elde edilmiştir. Model performansı Akım Süreklilik Eğrisi (FDC) akım değerleri ile R^2 , NSE ve PBIAS parametreleri hesaplanarak değerlendirilmiştir. Uygulanan doğallaştırma yönteminin (bölgesel regresyon modellemesi ve QPPQ yöntemi) tahmin performansı ise, NSE parametresi ile değerlendirilmiştir. NSE

değerleri, Akım Gözlem İstasyonu (AGİ) karakteristikleri arasındaki fark ile tahmin performansının ters orantılı olmasından dolayı seçilen kaynak AGİ'lerin kritik olduğunu göstermiştir. Hidrolojik müdahale değerlendirmesi IHA/RVA kullanılarak yapılmıştır. 32 IHA/RVA indikatörü, tüm insan müdahaleleri nedeniyle doğal akım rejiminde önemli değişikliklerin meydana geldiğini göstermiştir. Bu kapsamda, Sakarya Nehri'nin çevresel akış gereksinimi 34 Çevresel Akış Bileşeni (EFC) parametresi ile önerilmiştir.

Anahtar Kelimeler: Hidrolojik Müdahale Değerlendirmesi, Çevresel Akışlar, Doğallaştırma, ELOHA, Regresyon modellemesi, QPPQ Yöntemi



To my beloved family...

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LIST OF ABBREVIATIONS

ABBREVIATIONS

CORINE	Coordination of Information on the Environment
DSİ	Devlet Su İşleri (State Hydraulic Works of Turkey)
EC	European Commission
EFA	Environmental Flow Assessment
EFC	Environmental Flow Components
ELOHA	Ecological Limits of Hydrologic Alterations
FDC	Flow Duration Curves
IHA/RVA	Indicators of Hydrologic Alteration
IWRM	Integrated Water Resources Management
MGM	Meteoroloji Genel Müdürlüğü (Turkish State Meteorological Service)
NSE	Nash-Sutcliffe Efficiency
PBIAS	Percent Bias
QPPQ	Methodology developed to transfer flow and FDC exceedance percentile information of a streamflow gauge to its couple gauge by assuming the two gauges have the same exceedance percentile value at the same day
TNC	The Nature Conservancy
TUBITAK	Türkiye Bilimsel ve Teknolojik Araştırma Kurumu (The Scientific and Technological Research Council of Turkey)
USGS	United States Geological Survey
WFD	Water Framework Directive



CHAPTER 1

INTRODUCTION

Streamflow is the central component on both native biodiversity and biotic integrity of the river ecosystems. Most of the aquatic and terrestrial organisms and their habitats depend largely on the hydrological regime. As population increases, water resources are drastically exploited for different purposes such as industrial productions, food (agriculture) and energy security, drinking water supply, fisheries, and flood prevention. Due to these human activities, the five critical components, i.e., magnitude, frequency, duration, timing, and rate of change, of a streamflow regime have significantly changed (Acreman et al., 2014; Poff, 2014; Whiting, 2002). In addition, the resulting anthropogenic (i.e., originating from human activities) emissions of greenhouse gases due to the population and economic growth resulted in global warming, which adversely changed the climate system of the Earth (Core Writing Team et al., 2014). Since the world's rivers are being threatened by these various natural and anthropogenic pressures, sustainable water resources management has increasingly gained global attention in the last two decades to prevent further degradation and maintain rivers' health (Pahl-Wostl et al., 2013).

Meanwhile, all countries have set global sustainable development goals (SDGs) to call for action by 2030. The **SDG 6** (*Ensure availability and sustainable management of water and sanitation for all*), **SDG13** (*Strengthen resilience and adaptive capacity to climate-related hazards and natural disasters in all countries*), **SDG 14** (*Conserve and sustainably use the oceans, seas and marine resources for sustainable development*) and **SDG 15** (*Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss*) are directly addressed by the sustainable water management practices. In this aspect, scientists have been

developing several sustainable water management practices ranging from Integrated Water Resources Management (IWRM) to the state-of-the-art Water-Food-Energy-Ecosystems Nexus approach. They are valuable tools for addressing hydrological and ecological alteration issues to achieve the aforementioned 5 SDGs ultimately. Also, they are in line with the management perspective of good ecological status/potential definitions in the Water Framework Directive (WFD) (United Nations, n.d.).

Integrated Water Resources Management (IWRM), as a tool for addressing the ecological changes worldwide, has become the main concern for scientists and the public. As it is discussed by Galvez & Rojas (2019), pillars of the IWRM point out that fresh water resources are finite and essential to sustain life, development, and the environment. Also, the authors expressed that water management should be participatory in this context, and water should be recognized as an economic good.

As research on the IWRM has evolved, new terminologies and concepts have been introduced to the literature. Water for the ecosystem services is the core of this management perspective (for example, water-food-energy-ecosystem (WFEE) nexus). This ecologic point of view has been adopted by several countries/regions with different tools. The Water Framework Directive (WFD) published by the European Commission is one of them.

In the WFD, there are two ecological status definitions introduced as the overall quality of surface waters in terms of targeted structure and function of aquatic ecosystems:

- I. Good ecological status for the water bodies not heavily modified or artificial (i.e. natural or semi-natural), and
- II. Good ecological potential for the water bodies heavily modified or artificial

According to the directive, all member states must achieve a good water status/potential for their water bodies ((EC), 2000; Ramos et al., 2018). The ecological status of a water body is expressed by the biological, physicochemical

and hydromorphological quality elements supporting the integrity of the ecosystem.

The hydromorphological quality elements are classified as follows:

- Hydrological regime (quantity and dynamics of water flow and connection to groundwater bodies),
- River continuity, and
- Morphological conditions (river depth and width variation, structure and substrate of the river bed, and structure of the riparian zone).

Since it is necessary to implement an integrated approach to improve these interconnected quality elements. Environmental flow management methodologies are one of the best tools to support integrated water management.

Even though the environmental flow assessments (EFAs) are not explicitly referred in the WFD, it is considered as a tool to address a wide range of issues related to the restoration of river ecosystems. Environmental flows have been defined as 'ecological flows' in the guidance document prepared by the European Commission ((EC), 2015), referring to the context and environmental objectives of the WFD. River basin management plans and programs of measures are prepared at the relevant management cycles to achieve these objectives. Member states and countries adopting this directive as their reference water management legislative body are looking to integrate ecological (i.e. environmental) flows into these river basin management plans since environmental flows are thought to be an essential tool to address water management challenges. As indicated, the directive does not explicitly refer environmental flow assessment; however the mid-term assessment of the WFD implementation revealed that quantitative water management needs to be built on a solid foundation where ecological flows have been identified (Ramos et al., 2018).

Godinho et al. (2014) state that environmental flow assessment is a tool presently focused on in river restoration projects to decrease the effects of streamflow modification and improve degraded fluvial ecosystems' conditions. Also, environmental flows are provided to achieve the environmental objectives of the WFD and reach the ecological status desired. It is essential to use the best available

scientific information and methodologies for determining the environmental water requirements of a river because potential trade-offs between different water sectors would change the dynamics of socio-economic development, energy production, agricultural activities and so on. Thus, complete quantitative water management can be achieved by implementing relevant environmental flow assessment methodology and/or framework.

This thesis study aims to determine the environmental flow requirements of the Sakarya River with the help of a comprehensive hydrologic conditions assessment in the region. In addition, streamflow naturalization has been performed that provides an important hydrological source of information. A hydrologic foundation which is composed of daily natural (minimally modified) and altered (highly modified) streamflow data is the output of the naturalization methodology. Hence, this study aims to fill a gap in the literature for sustainable water management of Turkey by implementing a holistic environmental flow assessment. Water allocation for the dominant sectors such as energy, agriculture, and drinking water is generally the country's primary focus. There are individual attempts to quantify environmental flows, especially for the water management at the hydropower plants, by using the most common minimum environmental flow determination methods. For example, Tennant method is generally used to calculate the minimum environmental flows for the rivers in Turkey (Atak et al., 2014; Karakoyun et al., 2016). However, it is well known that a single environmental flow value does not offer a sustainable way of environmental water management. Thus, holistic approaches are included in the integrated water resources management decisions.

Moreover, this is the first study in which both streamflow naturalization and hydrologic alteration assessment were performed in a region of Turkey. It is important to generate a high-resolution natural streamflow data for future research studies and current water management decisions. Also, a number of assessment studies (e.g. risk assessments, hydromorphological assessments, etc.) can be performed using this high resolution data.

As mentioned, it is currently preferred to use holistic methodologies or frameworks for determining environmental flow requirements of rivers. The river ecosystems deal with an integrated approach covering all abiotic and biotic components instead of only specific organisms or physical habitats. Also, since changes in the hydrological regime support the environmental flow determination process, quantification of this change is important within a holistic framework. Therefore, to estimate the hydrologic alteration and environmental flow needs of Sakarya watershed, the first and third steps of the (Ecological Limits of Hydrologic Alteration) ELOHA framework were selected. The ELOHA framework (Figure 1.1) was developed by a group of international scientists for regional environmental flow assessment for many streams and rivers. It mainly addresses the relationship between streamflow alteration and ecological responses to determine environmental flow needs. The framework is one of the recent holistic approaches proposed for environmental flow assessment (EFA) literature. Underlying logic of this framework is to set regional environmental flow standards using existing scientific information by taking opinions of different stakeholders (e.g., scientists, water-resource managers, policy makers, etc.) into account while meeting ecologically feasible conditions in the river ecosystems (Poff et al., 2010). There are two processes within the scope of this framework: scientific and social processes.

Scientific process of this framework consists of four steps, given in the following (Arthington et al., 2012; Buchanan et al., 2013; Kendy et al., 2012; Mackay et al., 2014; Poff et al., 2010; The Nature Conservancy, n.d.):

1. Building a hydrologic foundation
2. Classification of natural river types
3. Description of flow-ecology relationships associated with each river type
4. Implementation of operational flow standards

In the social process, on the other hand, administrative, legislative, or legal processes are used to determine standards for environmental flows. Stakeholders participate in

at this stage and acceptable ecological conditions are determined. With the flow alteration-ecological response relationships for each river type, environmental flow standards are obtained through the scientific process. After linking societally driven ecological conditions with scientifically generated environmental flow standards, expert judgement and management goals set the final regional environmental flow standards to be implemented.

Because of limited data availability in the Sakarya watershed, the framework could not be fully implemented in this study. Nevertheless, it provided possible tools, methodologies and approaches for a comprehensive environmental flow assessment. Also, this framework enables future integration of the biological data for developing hydrologic alteration-biological response hypotheses.

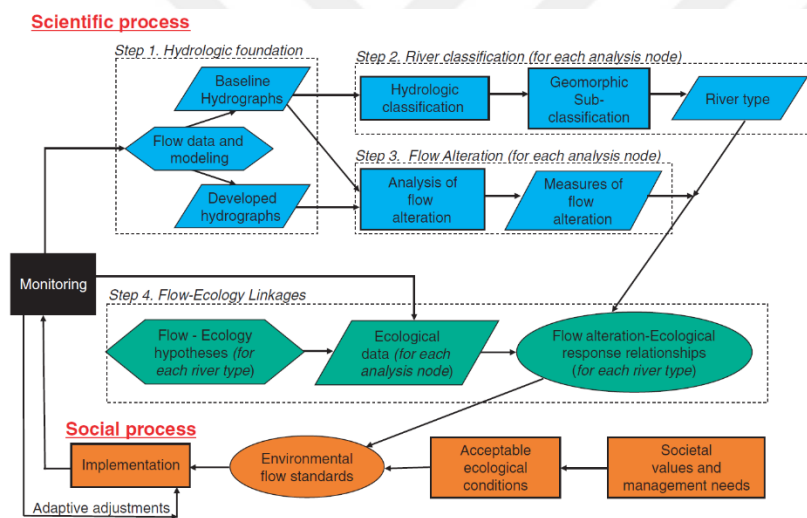


Figure 1.1. The ELOHA framework (Poff et al., 2010)

The research questions of this study are ‘At what degree have streamflow regime in the Sakarya watershed changed?’, ‘What are the hydrologic pressures and alterations on Sakarya River and its tributaries?’, and ‘What are the environmental water requirements of Sakarya River?’ Specifically, the objectives are:

- I. Obtaining natural streamflow characterization in the watershed
- II. Assessing cumulative hydrologic alteration caused by anthropogenic activities

III. Determining the environmental flows

Figure 1.2 shows the research methodology of this study. The green box named ‘Target’ corresponds to the ultimate target of this study. The ecological integrity of river ecosystems is maintained by a proper streamflow regime, water quality, energy sources, biotic interactions, and physical habitats. The ‘Guidance’ box, on the other hand, is the legal basis of this study. Also, the ‘Methodology/Tool’ boxes are the methods and tools used in this study to perform the targeted hydrological regime assessment. As seen in the figure, each chapter is part of the overall environmental flow assessment under the ELOHA framework in this study.

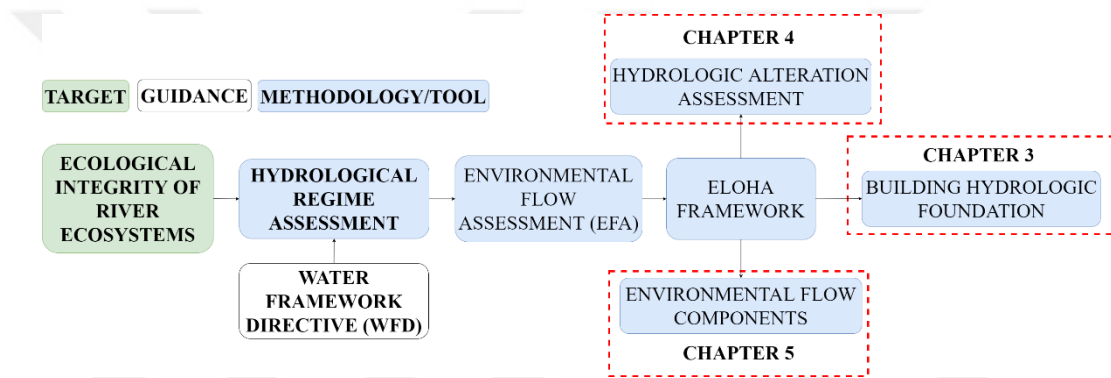


Figure 1.2. The research framework of this thesis study

The chapter organization is as follows:

5. Chapter 2: The details of the climatic, geospatial, and land-use characteristics of the study region
6. Chapter 3: Estimation of the Sakarya River daily natural (i.e., little or no modification) streamflow magnitudes
7. Chapter 4: Determination of the hydrologic alteration degrees at the selected representative (target) locations in the Sakarya watershed
8. Chapter 5: calculation of the environmental flow requirements at the target locations of the Sakarya watershed

Chapter 3 is the basis for Chapter 4 and 5 because the daily natural streamflow data generated by streamflow naturalization implemented in Chapter 3 were used to calculate hydrologic alterations in Chapter 4 and environmental flows in Chapter 5.



CHAPTER 2

STUDY AREA

Sakarya watershed, the study area, is located northwest of Turkey with a drainage area of 62,083 km². It constitutes 1/10 of Turkey's area (Figure 2.1). Sakarya River and its tributaries have a total length of 720 km. The total population and the population density of the watershed are 7,588,968 and 130 cap/km², respectively. The watershed has an annual average precipitation of 479 mm and it is among the four river basins in Turkey having annual precipitation less than 500 mm. Also, the elevation ranges from the sea level to 2491 meters across the watershed. Sakarya Watershed is a semi-arid area where integrated and sustainable water resources management is of the utmost importance (TUBITAK MAM, 2013).

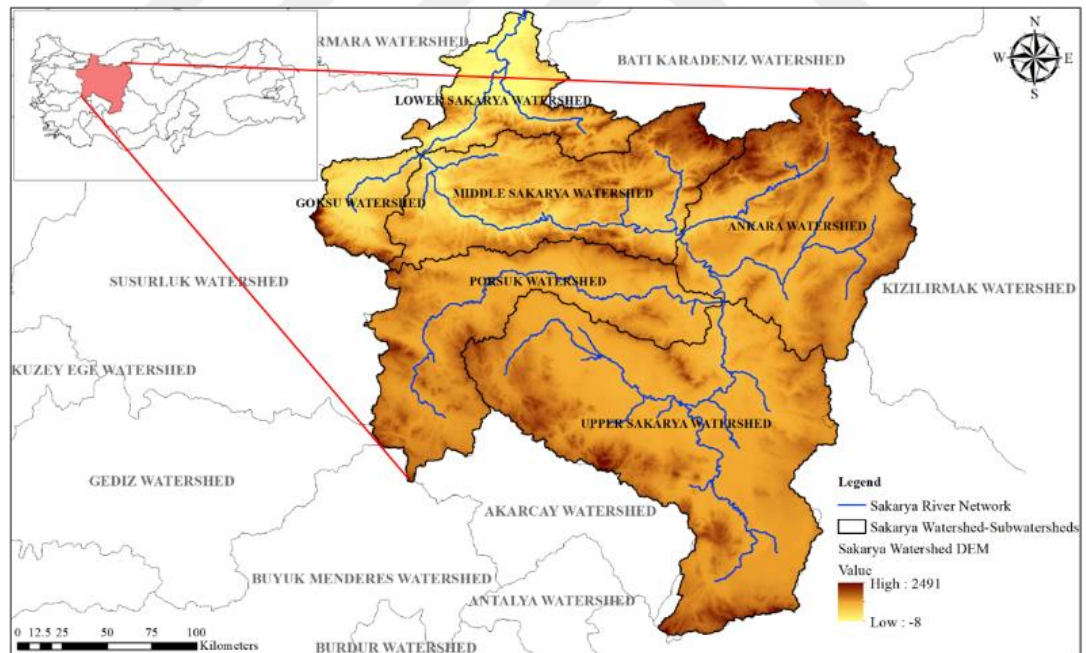


Figure 2.1. Sakarya Watershed Boundaries and Sakarya River Network, Turkey

In the watershed, there are 6 sub-watersheds, Upper Sakarya, Ankara Creek, Porsuk Creek, Goksu Creek, Middle Sakarya, and Lower Sakarya sub-watersheds (Figure

2.1). There are 347 streamflow gauges (Figure 2.2) and 308 meteorological stations (Figure 2.3) located within and around the watershed.

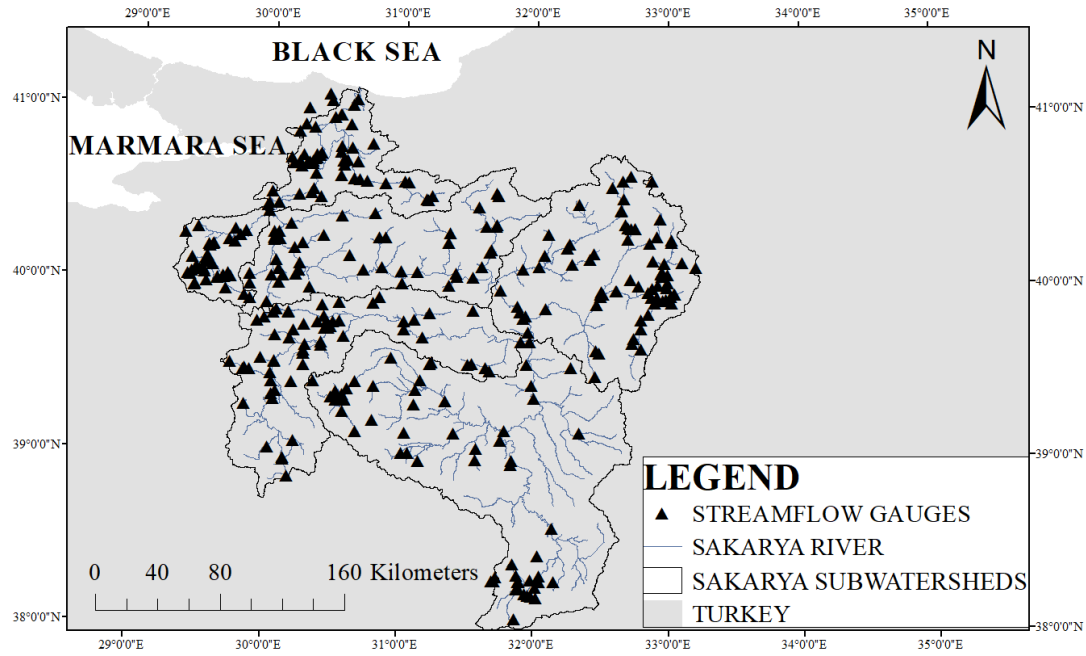


Figure 2.2. Locations of the Sakarya watershed streamflow gauges

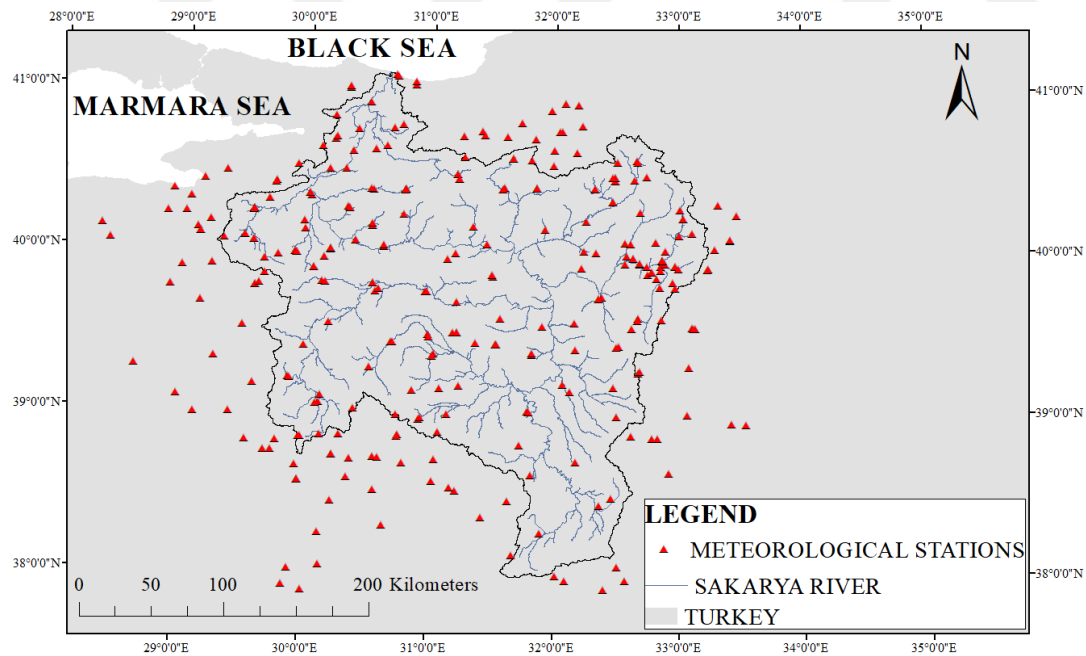


Figure 2.3. Locations of the Sakarya watershed meteorological stations

With its socio-economic development and water potential, various sectors demand water and make a cumulative pressure on the water resources in the area. Agriculture, drinking and utility water, industry and energy are the main sectors in the watershed. Hence, it is expected that hydrological pressures (e.g. flow seasonality changes, hydropeaking, reduced flow, continuum-both lateral and longitudinal-disruption, etc.) in the region can affect the integrity of the ecosystem. Dominant sectors in the subwatershed affecting the ecosystem in Sakarya River and its tributaries are given in Table 2.1.

Table 2.1 The dominant sectors in each subwatershed of the Sakarya watershed

Subwatershed	A (I)	D	E	I/M
Upper Sakarya	✓			
Ankara		✓		
Porsuk	✓	✓		✓
Middle Sakarya			✓	
Göksu	✓			
Lower Sakarya				✓

* A (I): Agriculture (Irrigation), D: Drinking water, E: Energy production, I&M: Industry and Mining

The climate of the region is represented by the 8 Köppen-Geiger climate classes and dominated by ‘Arid, steppe, cold’ and ‘Cold, dry summer, warm summer’ types (Figure 2.4).

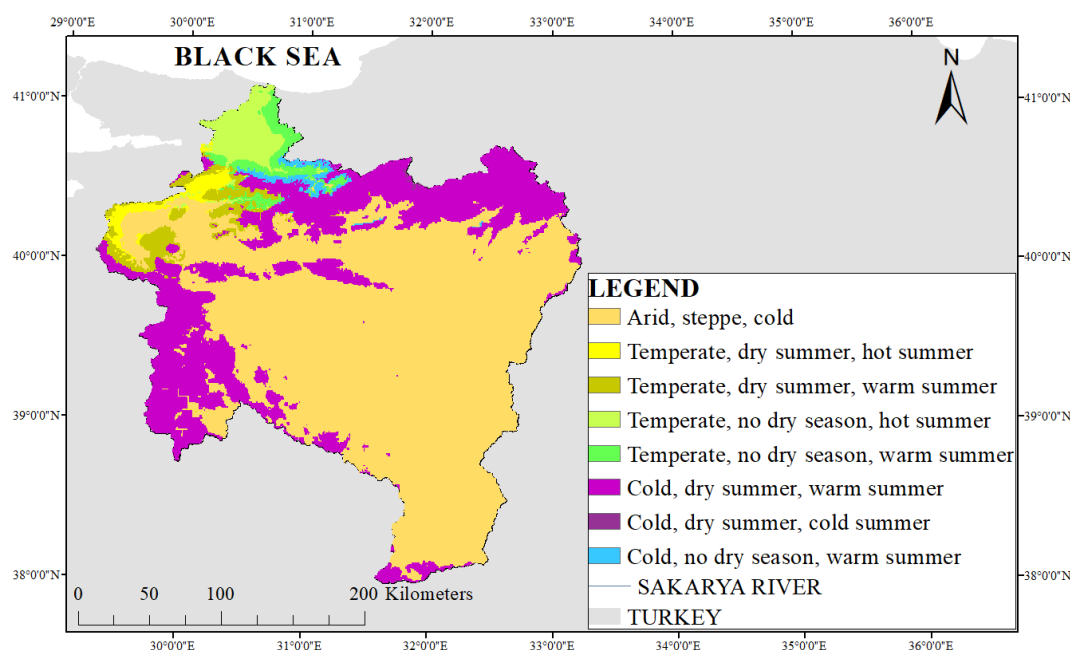


Figure 2.4. Sakarya watershed climate classes created by the data downloaded from <http://www.gloh2o.org/koppen/> (Beck et al. (2018))

In addition to the climate, land use of the region is given by the maps showing subwatershed level land use classification. The land uses are presented in between Figure 2.5 and Figure 2.10. Also, Table 2.2 shows the percentage shares of each land use within the watershed.

Table 2.2 Land use classification of the Sakarya watershed

LU class	US	A	P	MS	G	LS	Total	%
111	2.1	85.3	31.3	0.0	6.3	14.8	139.7	0.22
112	226.0	340.7	118.6	37.2	27.4	108.6	858.5	1.38
121	18.4	179.1	53.9	22.2	9.0	35.6	318.2	0.51
122	0.4	41.7	2.6	0.7	0.3	2.0	47.8	0.08
124	5.2	20.7	15.8	0.0	5.9	0.5	48.0	0.08
131	30.6	38.8	73.1	30.8	3.6	6.0	182.7	0.29
132	0.4	6.6	2.5	0.0	0.0	0.3	9.8	0.02
133	4.0	110.6	7.1	6.1	0.0	6.0	133.8	0.22
141	0.4	12.4	4.3	0.0	0.3	1.1	18.4	0.03
142	0.3	10.4	4.0	0.4	0.0	0.6	15.6	0.03
211	9923.1	3715.9	3246.8	1163.0	454.9	278.0	18781.6	30.25
212	2171.6	632.7	1115.7	223.0	233.5	516.4	4893.0	7.88
213	0.0	0.0	6.8	4.3	6.1	0.0	17.1	0.03

Table 2.2 Land use classification of the Sakarya watershed (continued)

LU class	US	A	P	MS	G	LS	Total	%
221	0.5	7.4	0.0	1.7	2.5	3.3	15.4	0.02
222	12.0	9.5	5.5	36.3	35.3	428.0	526.5	0.85
223	0.0	0.0	0.0	0.0	13.6	0.4	14.0	0.02
231	1173.3	241.5	340.3	45.0	19.7	22.7	1842.3	2.97
242	253.6	521.3	149.8	458.0	225.8	686.7	2295.0	3.70
243	714.0	1253.2	659.6	1203.1	250.4	318.4	4398.7	7.09
311	170.3	44.2	243.1	358.3	563.3	1023.8	2402.9	3.87
312	686.9	822.1	750.9	2452.7	115.8	368.8	5197.2	8.37
313	112.0	59.7	235.8	591.8	248.3	590.5	1838.1	2.96
321	2389.9	2036.0	824.1	613.9	37.6	65.1	5966.6	9.61
323	35.7	189.6	273.4	230.9	0.0		729.7	1.18
324	934.0	969.4	1634.7	2565.2	159.3	221.0	6483.6	10.44
331	0.0	5.9	0.0	0.4	0.0	0.2	6.6	0.01
332	63.8	14.8	12.0	20.9	6.2	0.2	117.9	0.19
333	1897.9	1053.0	893.5	479.6	1.9	12.7	4338.5	6.99
335	0.0	0.4	0.0	0.0	0.0		0.4	0.00
411	98.8	20.7	3.6	1.6	0.0	4.8	129.5	0.21
511	0.0	0.0	0.0	5.0	0.0	20.8	25.9	0.04
512	36.9	59.2	39.1	95.8	5.9	53.2	290.1	0.47
Total	20962.0	12502.7	10747.5	10647.7	2432.7	4790.5	62083.1	

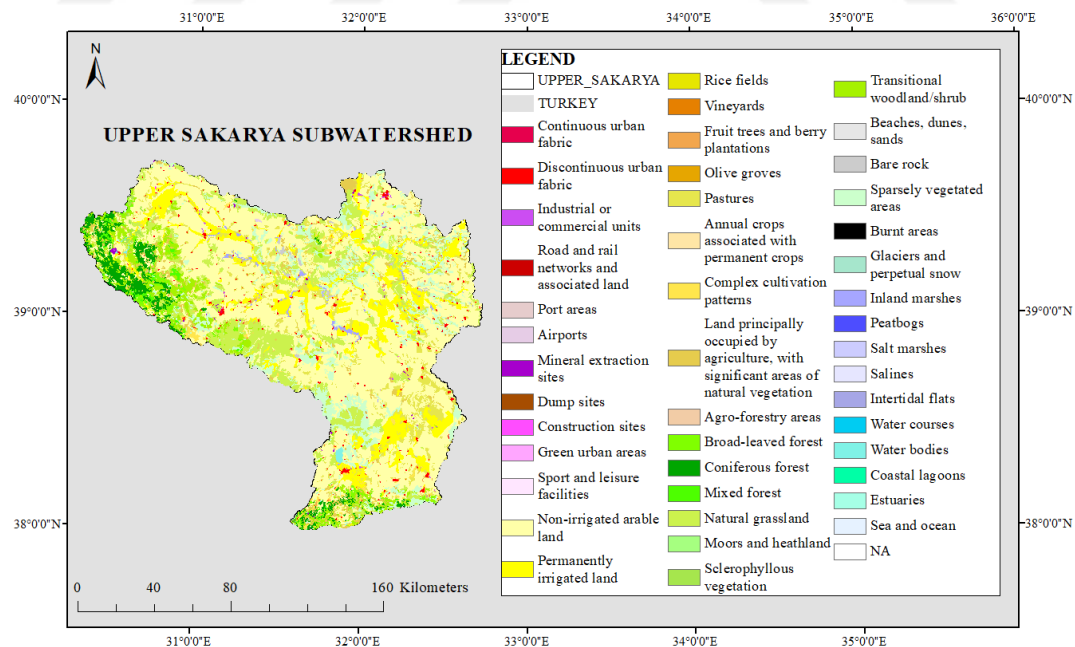


Figure 2.5. Upper Sakarya subwatershed land use classes according to the CORINE database

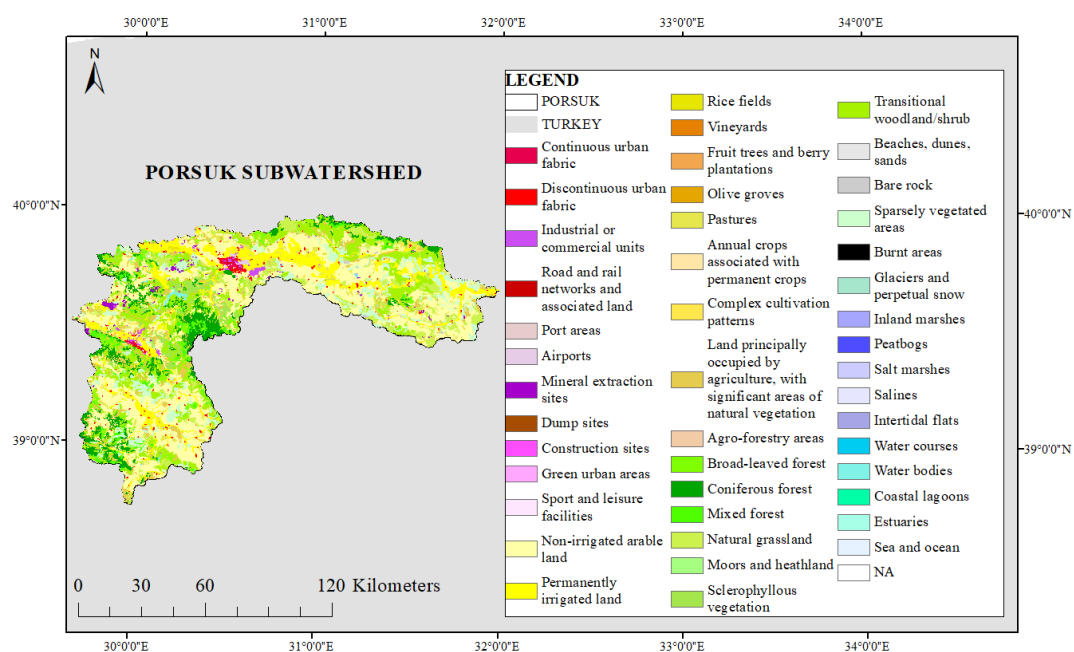


Figure 2.6. Porsuk subwatershed land use classes according to the CORINE database

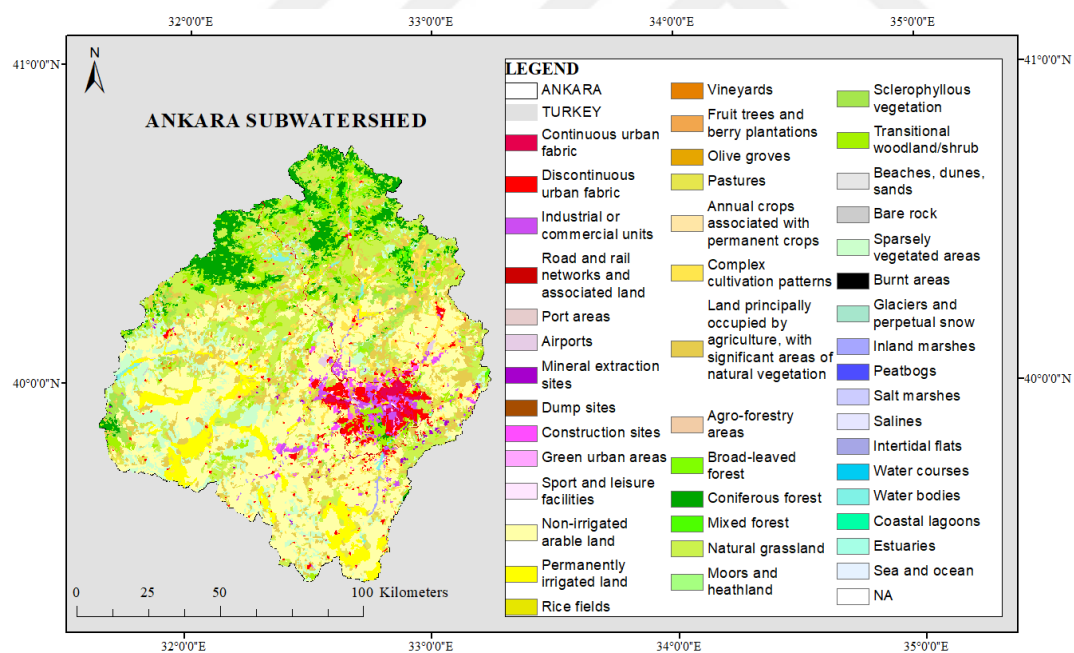


Figure 2.7. Ankara subwatershed land use classes according to the CORINE database

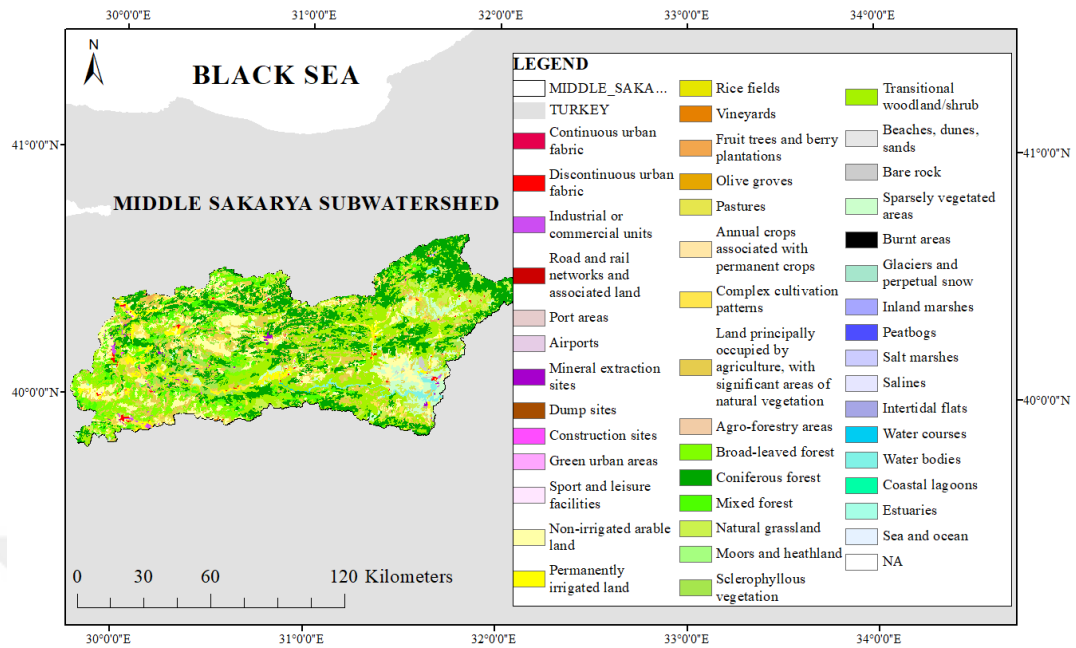


Figure 2.8. Middle Sakarya subwatershed land use classes according to the CORINE database

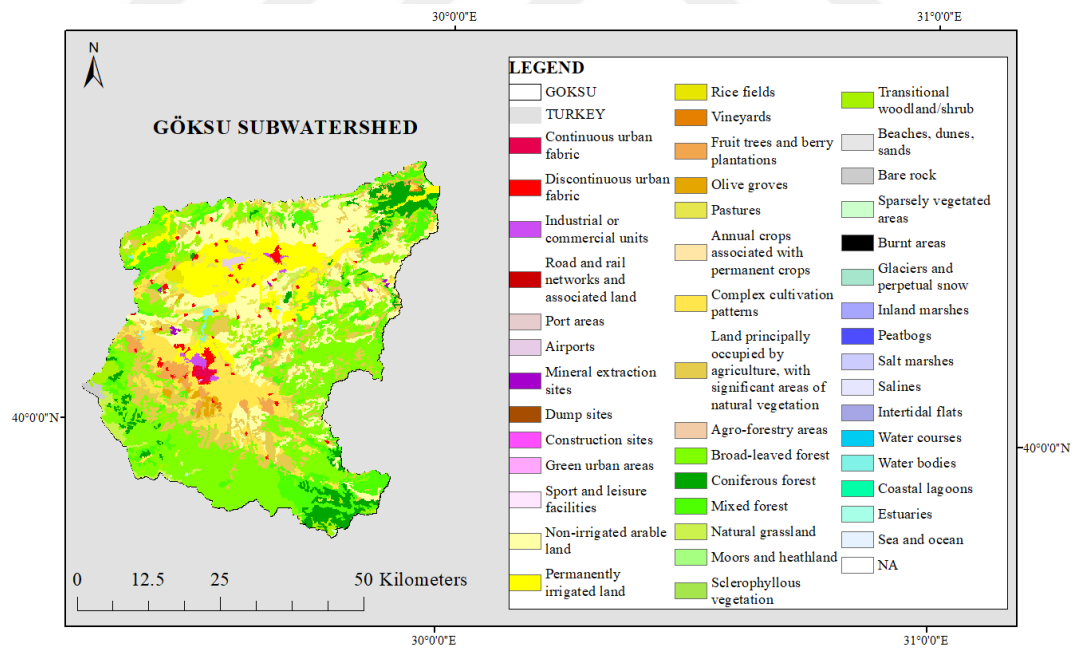


Figure 2.9. Göksu subwatershed land use classes according to the CORINE database

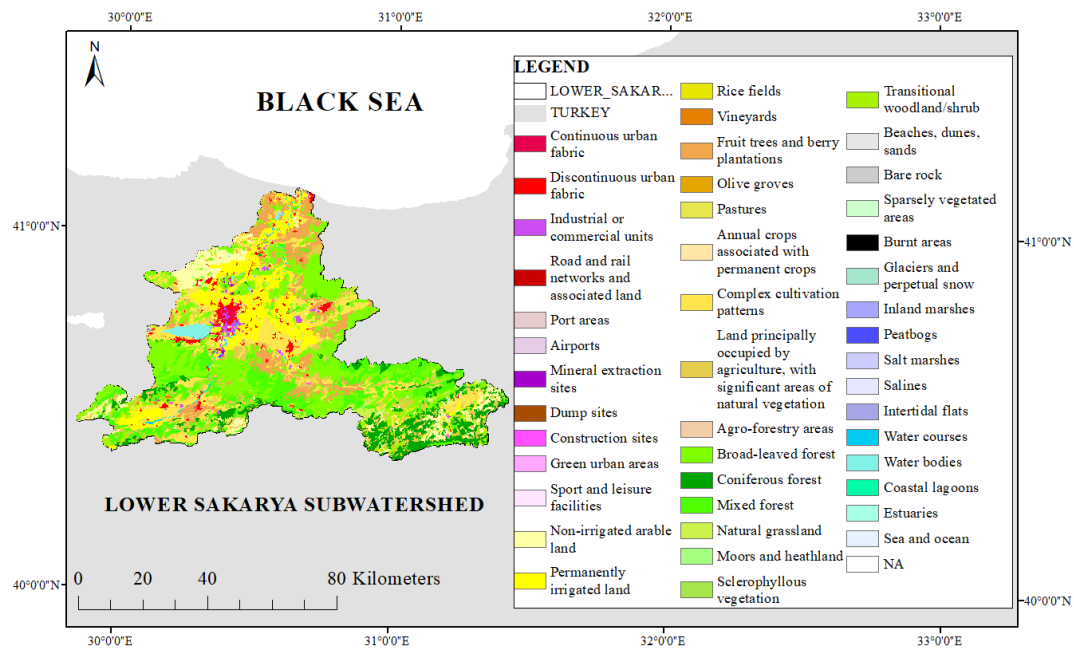


Figure 2.10. Lower Sakarya subwatershed land use classes according to the CORINE database

CHAPTER 3

BUILDING HYDROLOGIC FOUNDATION: STREAMFLOW NATURALIZATION IN THE SAKARYA WATERSHED

In this study, the ELOHA framework has been adopted as the umbrella framework for the environmental flow assessment (EFA) methodology (Figure 3.1). The first step of the ELOHA framework (i.e., building hydrologic foundation) is adopted in this chapter to be implemented for the Sakarya watershed. The chapter presents the ‘literature research’ on building a hydrologic foundation, the ‘methodology’ implemented to create a natural streamflow database in the context of building hydrologic foundation of the Sakarya watershed, and the ‘results & discussion’ sections. The literature research section is composed of a summary of the previous studies conducted on the “Building Hydrologic Foundation” step and streamflow naturalization process. Methodology section, on the other hand, involves step-by-step streamflow naturalization framework adopted. In the ‘Results & Discussion’ section, the results obtained from the streamflow naturalization procedure are discussed in a statistical point of view. Since the hydrologic alteration and environmental flow assessments need daily natural streamflow data, the results obtained from this chapter were fed into the Chapter 4 and 5.

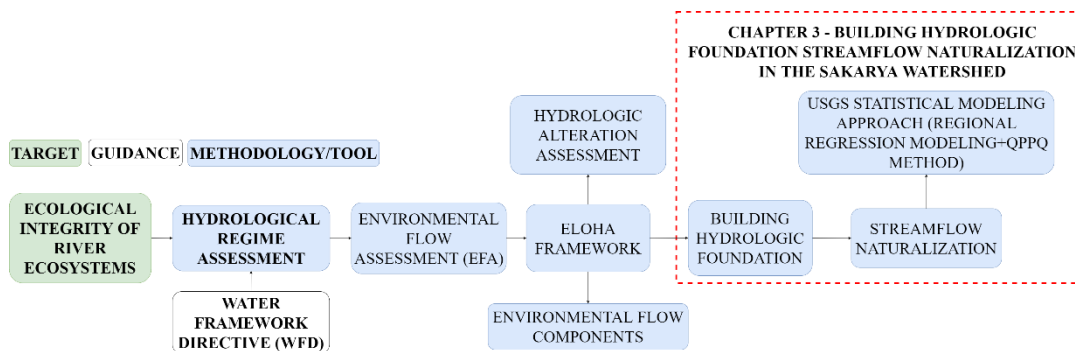


Figure 3.1. The details of Chapter 3 within the framework of this thesis study

3.1 Introduction

Section 3.1.1 includes detailed literature research on hydrologic foundation, and its importance in terms of environmental flow assessment studies. On the other hand, since natural streamflow time series needs to be generated at this step of the ELOHA framework, streamflow naturalization literature is elaborated in the section 3.1.2.

3.1.1 1st step of the ELOHA Framework: Building a Hydrologic Foundation

To successfully manage water resources in a watershed or any region of interest, water availability should be understood well. The knowledge of where, when and how much water exists within a watershed is required to inform sustainable water management decisions. More specifically, environmental flow management decisions also depend on this kind of information to be accurately implemented. In the case of ELOHA framework, the water availability information is proposed by building a database called ‘hydrologic foundation’.

It is a database consisting of two different types of streamflow information (Figure 3.2), which is used as a tool for this study to inform both regional environmental flow needs and hydrologic alteration assessment (The Nature Conservancy, n.d.).

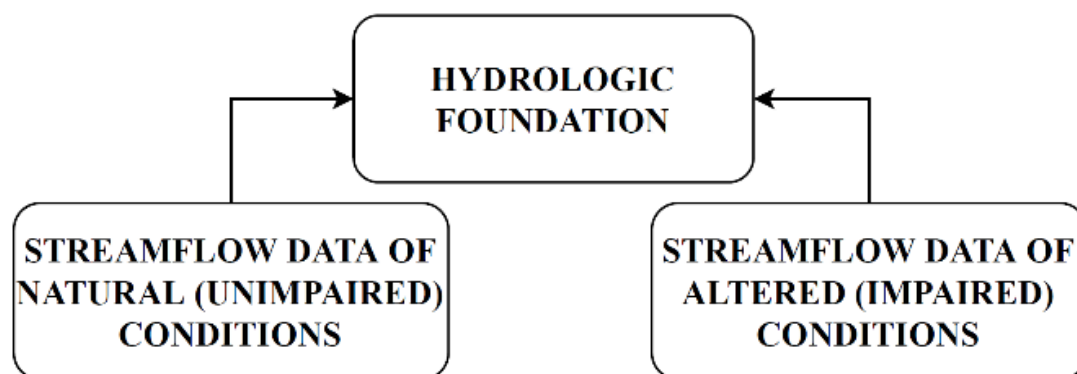


Figure 3.2. The main components of a hydrologic foundation

The data feeding hydrologic foundation, shown in Figure 3.2, needs to be obtained for every analysis node (i.e., the locations where this streamflow information is

aimed to be constructed) over a common period of time. The time period should be at least 20 years as recommended by the literature, however, it may be as short as 10 years due to practical challenges. The analysis nodes should be identified based on:

- stakeholders (e.g. water managers), who will use this foundation as they make their decisions on water management,
- data availability (for example, availability of the ecological data to be used in formulating the relationships between streamflow alteration and corresponding ecological responses or geomorphic data to be included in physical habitat assessments expressed for a defined flow regime), and
- likelihood of the future data collection at the location of interest.

Unimpaired (natural) conditions of this database typically refer to **minimally altered** or **best-available streamflow conditions**, i.e. major water abstractions, diversions or any other major human impact on the water either do not exist at the upstream or do not majorly affect the natural hydrologic condition. It is fundamental to understand natural variation (Figure 3.3) in the streamflow regime at the region of interest since the environmental flow needs, degree of deviations in the current flow regime from the natural conditions, and ecological responses to this deviation are investigated only by knowing the natural flow behavior. Altered (impaired) conditions, on the other hand, represents a streamflow regime where cumulative effects of the impoundments, diversions, groundwater abstractions, return flows and other flow alteration factors are observed in the hydrograph (Kendy et al., 2012; Poff et al., 2010).

Aquatic biodiversity and natural flow regimes

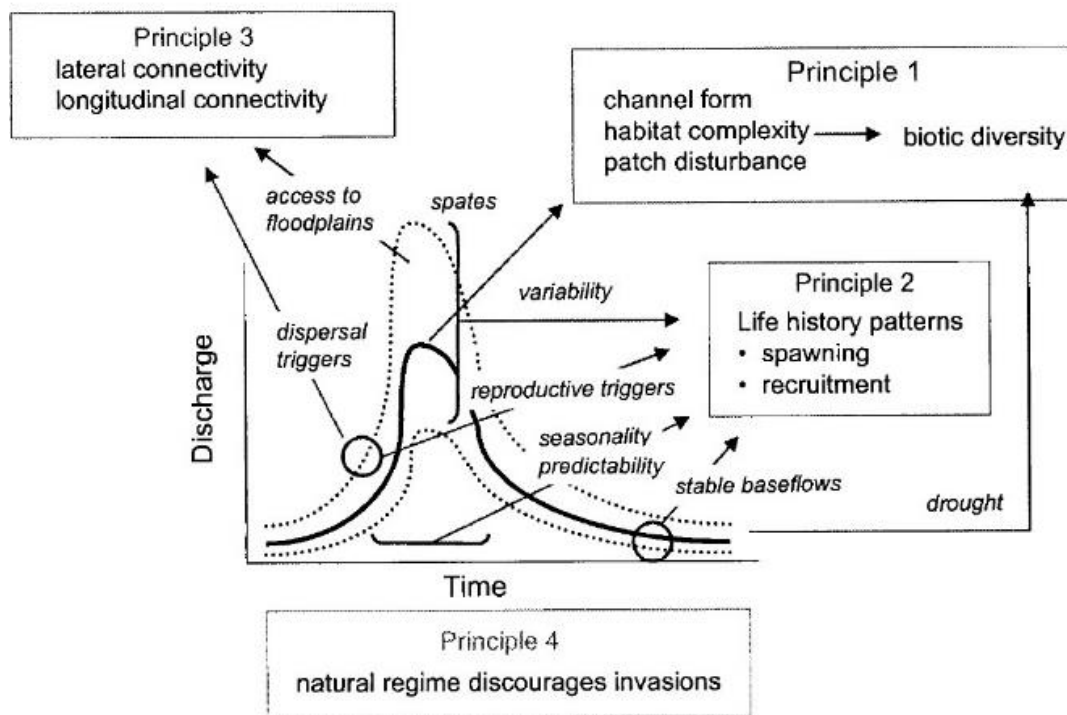


Figure 3.3. Natural streamflow variation and corresponding principles to sustain native aquatic biodiversity (Bunn & Arthington, 2002)

It is a requirement to build models for development of a hydrologic foundation regardless of types of the application. There are various approaches for both gauged and ungauged sites to model catchment hydrology and create flow data of the natural (unimpaired) and/or altered (impaired) conditions of the region. Different factors play a key role in the selection of the appropriate model, which are project budget and schedule, data availability, hydrologic and ecologic condition and level of experiences of modelers (Kendy et al., 2012). Ideal temporal resolution of the data to construct a hydrologic foundation is daily streamflow data according to Poff et al. (2010) since this resolution provide sufficient information to understand the relationship between hydrologic alteration and the corresponding ecological responses. In case of data scarcity, coarser resolution of data, such as weekly or monthly, could be used.

In this study, a hydrologic foundation of the Sakarya watershed was built by combining the natural and altered streamflow databases (Figure 3.4).

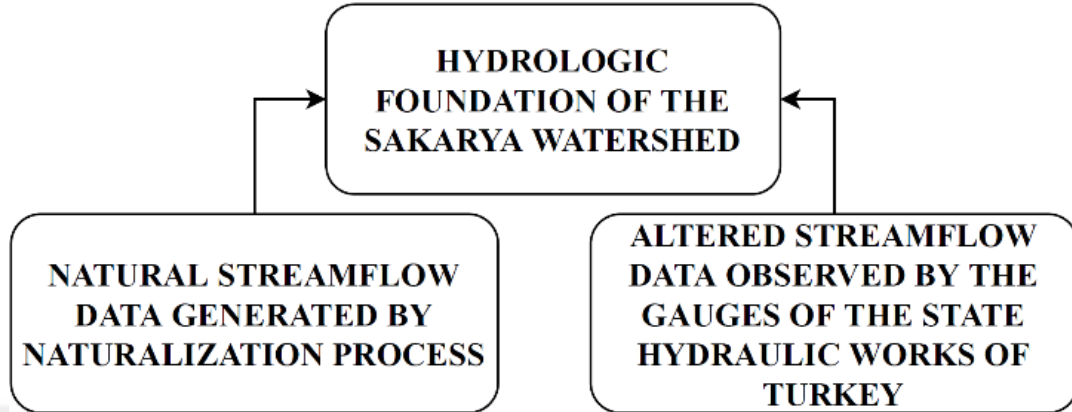


Figure 3.4. Main components of the hydrologic foundation of the Sakarya watershed

It should be noted that the altered (impaired) streamflow data is already available thanks to the streamflow gauge measurements of the State Hydraulic Works (DSI) of Turkey. Therefore, there is no calculation related to the altered streamflow time series data of the Sakarya watershed. However, the natural streamflow data was needed to be generated due to its unavailability. Thus, it was calculated using statistical modeling approach whose detailed literature research are given in section 3.1.2.

3.1.2 Streamflow Naturalization

As indicated earlier, natural (i.e., unimpaired) hydrologic processes provide the ideal conditions for native aquatic and riparian ecosystems of rivers, whereas both climate change and human activities have dramatically altered the natural dynamics of river hydrology worldwide (Blythe & Schmidt, 2018; Carlisle et al., 2010; Homa et al., 2013; Poff et al., 1997; Wen, 2009). Semi-arid to arid regions like the Sakarya watershed are especially the most vulnerable regions of the world to these alterations. Hence, the knowledge of river's natural behavior is investigated depending on the environmental water management objectives ranging from river restoration or maintenance of current conditions to governmental water allocation planning. All of

these management approaches need the natural streamflow information. The natural streamflow regime attributes provide benchmarks for these altered river systems. Therefore, because the natural streamflow data cannot be directly measured, it needs to be estimated using ‘streamflow naturalization’ methods. In this regard, a number of scientific tools and methods are developed.

As pointed out by Terrier et al. (2021) different definitions of natural flow regime are provided in the streamflow naturalization literature. It is seen that there is no common definition for the ‘natural’ state, which resulted in different approaches have been developed and adopted in time. For example, predictions of this flow regime are often based on pre-disturbance of an event, historical conditions or an ideal condition modeled from nearby natural streamflow gauges (Carlisle et al., 2010).

According to Terrier et al. (2021) there are six main naturalization methods in the literature: (1) Reconstitution, (2) Water balance, (3) Routing, (4) Extension, (5) Paired catchment, (6) Regionalization

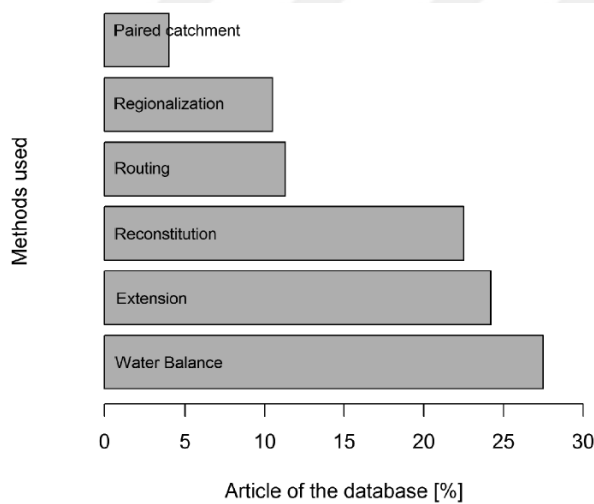


Figure 3.5. Total percentage of the literature studies using the streamflow naturalization methods reviewed by Terrier et al. (2021)

The water balance and reconstitution methods are based on anthropogenic alterations, such as irrigation abstractions, impoundments by dams and reservoirs,

water supply diversions, industrial and drinking abstractions, etc. In the water balance method naturalized streamflow is calculated by adding or subtracting the alteration from the observed streamflow data. For example, suppose there is a discharge into the stream at the upstream of a gauge of interest. In that case, the volume of water (ΔV) during the time interval Δt is subtracted from the observed streamflow value to find the natural streamflow value. On the other hand, the reconstitution method uses hydrological models by applying a two-step methodology. At the first step, the hydrological model is developed using input data of climate, abstractions, discharges, soil, etc. It is calibrated based on a set of parameters to calculate the altered streamflow time series. At the second step, all of the human alterations are removed from the model and the simulated natural streamflow time series is obtained (Terrier et al., 2021).

The extension and paired catchment methods are using the observations from the pre-influence period of an anthropogenic alteration such as a dam construction. In the extension method, a two-step methodology is applied like in the case of reconstitution method. However, there is a pre-alteration streamflow data is available for this method. At the first step the hydrological model parameters are calibrated using the pre-alteration period streamflow values. Then, at the second step, altered period is modelled using the same set of calibrated parameters and corresponding input data. The paired catchment method does not apply a hydrological modeling but statistical flow-rate relationships between the destination station and its natural donor station(s) over the pre-influence period simulate the natural streamflow data (Terrier et al., 2021).

The last two naturalization methods, on the other hand, depend on regional information. Routing modeling method estimates natural streamflow information using hydraulic models. Upstream streamflow which is unimpaired (natural) is propagated to obtain the downstream natural streamflow. In the case of the upstream flow is not natural, it can be first naturalized then the routing is applied. On the other hand, the regionalization method is the one applied mostly for ungauged or poorly

gauged basins. The natural neighbor basins are used to estimate natural flow characteristics (Terrier et al., 2021).

Since the study conducted by Terrier et al. (2021) is the first review on streamflow naturalization literature, this classification is not verified by another study. Yet, it is an invaluable contribution to the naturalization literature. However it needs to be enhanced by a more comprehensive research because, for example, the method implemented in this study does not belong to only one class. It can be classified under both paired catchment and regionalization methods. Thus, this indicates that further research is needed for the streamflow naturalization literature.

A literature research on the streamflow naturalization was conducted considering the objectives of this study and data availability of the study area (Table 3.1). Since the main objectives of this study is to assess hydrological alteration degrees of the selected locations within the Sakarya watershed and to determine environmental flow needs at the same locations, daily natural streamflow is required. Moreover, the Sakarya watershed does not have a well-established streamflow database. In fact, the available streamflow gauges have very limited data. However, the daily natural streamflow estimation is still possible. It was seen that rainfall-runoff or hydrological modeling approach is the most suggested one according to the literature. At a watershed scale, simulation of physical hydrological models (like parameterized rainfall-runoff models) are both costly and information & time-consuming approach at a daily resolution although they provide high flexibility. In addition, their model structure, inputs and calibration are likely to have high uncertainty (Homa et al., 2013). Also, statistical models especially regional regression models are commonly used tools to estimate natural streamflow by making use of geospatial and climatic characteristics of the watersheds (Table 3.1). Therefore, it is decided that statistical regional regression modeling approach is more appropriate to create baseline conditions for this study at a daily time resolution. Specifically, the regional regression modeling methodology and the QPPQ method implemented by the U.S. Geological Survey has been adopted and modified regarding data availability and characteristics of the Sakarya River at the selected gauged locations (Archfield &

Vogel, 2010; Archfield et al., 2012; Archfield S. A. et al., 2013; Ssegane et al., 2013; Stuckey et al., 2014). The models of this method require input data from reference sites where streamflow regime has been least or minimally altered by human activities. All the details of the USGS approach are given in section 3.2 as the methodology of this study.

Table 3.1 A summary of the literature review of streamflow naturalization methodologies conducted in this study

Purpose of the study	Method used for naturalization	Flow data resolution	Country	Reference
Assessment of water availability at ungauged locations	Regional regression modeling + QPPQ method	Daily	U.S.A	Archfield & Vogel (2010)
Estimation of unimpaired daily streamflow	Regional regression modeling	Daily	U.S.A.	Archfield et al. (2012)
Estimation of unregulated daily streamflow at ungauged locations	Regional regression modeling + QPPQ method	Daily	U.S.A	Archfield S. A. et al. (2013)
Estimation of unimpaired daily streamflow	Mass balance – algebraic calculations	Daily	U.S.A.	Blythe & Schmidt (2018)
Hydrologic alteration assessment	Random Forests (RF) – a robust statistical model	Daily	U.S.A.	Carlisle et al. (2010)
Natural and environmental flow determination	Regional regression modeling	Monthly	Canada	El-Jabi & Caissie (2018)
Independent variable selection for the models	Regional regression modeling	Daily	U.S.A.	Fouad et al. (2018)
Hydrologic alteration assessment	Regression modeling	Daily	U.S.A.	Homa et al. (2013)
Designing a naturalized streamflow regime	The Corps of Engineers' Daily Routing Model (DRM)	Daily	U.S.A.	Jacobson & Galat (2008)
Assessment of the impacts of dams on the flood frequency	Physical Model (SWAT)	Daily	South Korea	Lee et al. (2017)
Integrated water resources management	Rainfall-Runoff Model - Water Resources Simulation Model-90 (WRSM90)	Monthly	South Africa	McCartney et al. (2004)
Estimation of baseline daily streamflow at ungauged locations	Regression modeling + QPPQ method	Daily	U.S.A.	Stuckey et al. (2014)
Reconstruction of natural streamflow regime	Regression modeling	Monthly	Australia	Wen (2009)
Streamflow naturalization at both gaged and ungauged sites	River-Reservoir System Water Allocation Model (WRAP)	Monthly	U.S.A.	Wurbs (2006)
Estimation of monthly natural flows	Regional regression modeling	Monthly	U.S.A	Zhang et al. (2020)

3.2 Materials and Methods

The hydrologic foundation of the Sakarya watershed was built by:

- unimpaired (natural) streamflow data generated by statistical modeling, and
- Altered (impaired) streamflow data obtained from the gauge measurements.

Because natural streamflow data of the Sakarya watershed is not available as gauge measurements like altered streamflow data, it was modelled by adopting a statistical approach where regional regression modeling is performed.

The USGS approach includes regional regression modeling which is one of the most commonly used methodology in the naturalization literature (Table 3.1). Besides, the QPPQ method developed by Fennessey (1994) is integrated into the regression modeling in the USGS methodology to complete naturalization of the Sakarya River in daily time resolution. Brief step-by-step methodology of the USGS streamflow naturalization process adopted for the Sakarya watershed is given in Figure 3.6. There are two main components of this methodology: 1) multiple linear regression analysis and 2) QPPQ method, which are explained in the following sections.

STREAMFLOW NATURALIZATION METHODOLOGY IN SAKARYA WATERSHED

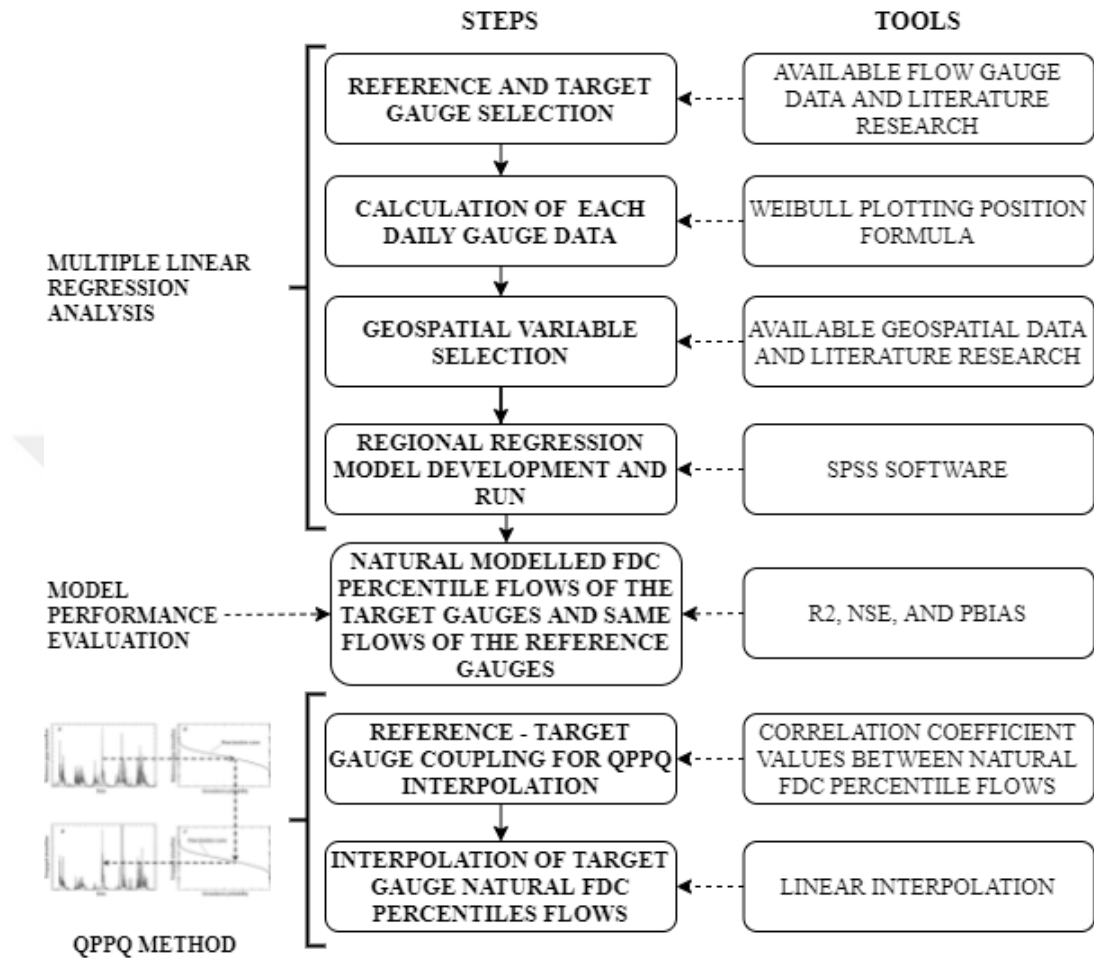


Figure 3.6. Flowchart of the streamflow naturalization methodology of Sakarya Watershed, Turkey

3.2.1 U.S. Geological Survey (USGS) Streamflow Naturalization Methodology Part 1 – Multiple Linear Regression Analysis

Regional regression models were developed using the methodology implemented by the U.S. Geological Survey with a few modifications based on data availability and characteristics of the Sakarya watershed. These models are ‘multiple linear regression models’, also named as ‘regional regression log-transformed models’,

which use parameter-based regression equations. In these equations, geospatial and climatic characteristics of the upstream drainage areas of the reference gauges are fed into the models as independent variables while the FDC exceedance percentile flows of these reference gauges are dependent variables. Even though 18 exceedance percentiles were calculated for all streamflow gauges included, only 12 exceedance percentiles along the FDCs are introduced to the regression equations (1, 5, 10, 15, 20, 30, 40, 50, 60, 70, 80 and 85) as dependent variables. The reason behind excluding the remaining percentiles (i.e., 0.1, 0.5, 90, 95, 99 and 99.9) is because they represent the highest and lowest flows on the FDC and they cannot be properly modelled using regression modeling approach. Therefore, they were included in the naturalization using drainage area ratio (DAR) method and regression of the lowest end percentiles against each other. The details of calculations of these percentile flows are explained in Section 3.2.2.2. The modelled exceedance percentile flows of the observed reference hydrographs were related to their watershed characteristics having possible effects on streamflow dynamics. Mathematical expression of the regression models are in the following form:

$$\ln(Q_i) = \beta_0 + \beta_1 * \ln(Ch_1) + \beta_2 * \ln(Ch_2) + \beta_3 * \ln(Ch_3) + \dots + \beta_n * \ln(Ch_n) \quad \text{Eq-1}$$

where Q_i is the streamflow having exceedance probability i ; β_i values are model coefficients; Ch_j is the watershed characteristics selected to be used as independent variable. All dependent and independent variables are converted to natural logarithms of their actual values to linearize the model variables. The watershed characteristics (the independent variables), also known as geospatial and climatic metrics, are selected based on critical thinking on the literature applications and conditions of the watershed (data availability).

In the following, reference and target streamflow gauge selection, calculation of the FDC exceedance probability flows, geospatial & climatic metrics selection and model development procedures are given in detail.

3.2.1.1 Reference and Target Streamflow Gauge Selection

The first step of the streamflow naturalization process in Sakarya watershed is selection of gauged sites having two different flow dynamics: natural/almost natural (reference gauges) and altered (target gauges). Reference streamflow gauges represent the sites with least or minimal hydrologic alteration under natural (e.g. climate change) and anthropogenic (e.g. dam operations) pressures, while target streamflow gauges are the sites with streamflow regimes cumulatively affected by major water abstractions, impoundments, diversions, mining, etc. at the upstream drainage area. The reference gauges are used to construct the multiple linear regression models and are coupled with the target gauges having highest correlation values (they will be named source gauges after this). Target gauges are the locations where the naturalization process and hydrologic alteration assessment are performed.

Before determining reference and target streamflow gauges within Sakarya watershed boundaries, all gauges were screened. There are 347 streamflow gauges (Figure 3.7) in the watershed and their numbers in each subwatershed can be seen in Table 3.2. It has to be noted that Lower Sakarya and Goksu subwatersheds are not included in the naturalization process because these areas are located on a different climate zone according to the Köppen-Greiger Climate Classification (section 3.2.1.1.2). It is known that distinct climate characteristics adversely affect regional regression models and their results, so both subwatersheds were decided to be excluded from Sakarya watershed regional regression model development.

Table 3.2 Total number of streamflow gauges screened within Sakarya watershed

Subwatershed	Total number of gauges
Upper Sakarya subwatershed	60
Porsuk subwatershed	74
Ankara subwatershed	65
Middle Sakarya subwatershed	64
Göksu subwatershed	38
Lower Sakarya subwatershed	46
TOTAL	347

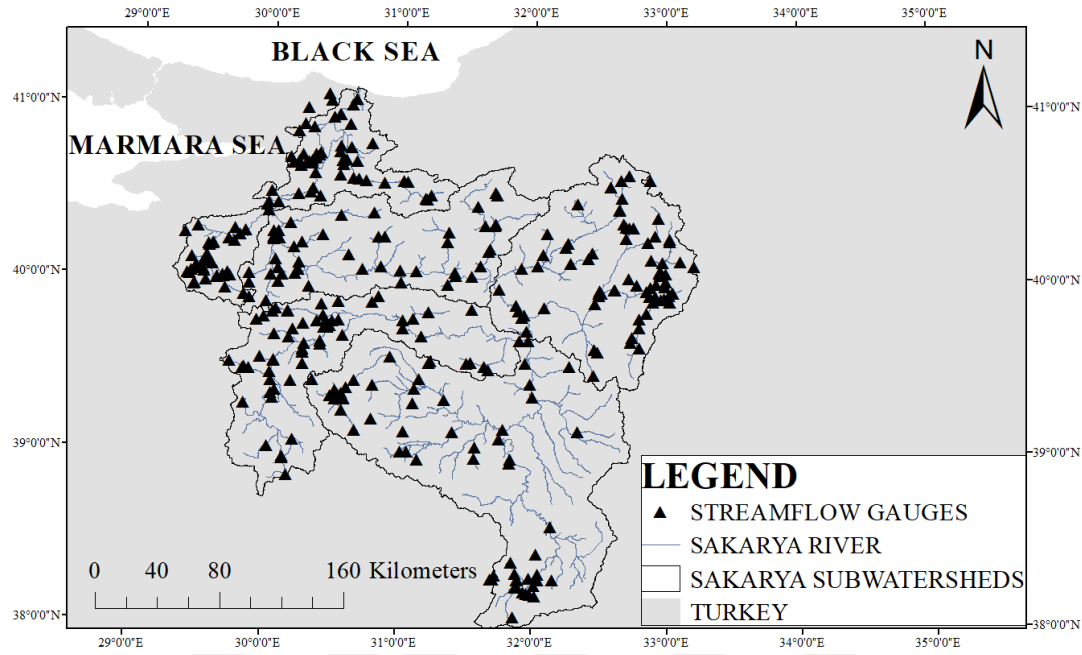


Figure 3.7. Streamflow gauges located within the Sakarya watershed, given subwatershed boundaries

3.2.1.1.1 Target Gauge Selection

In this study, ‘target streamflow gauges’ are the sites impacted by cumulative anthropogenic alterations. Further hydrologic alteration and environmental flow assessments will be performed at these locations after naturalization process (Chapters 4 and 5). As it is aimed to calculate environmental flow needs and hydrologic alteration levels at these locations, target gauges should provide sufficient data about geomorphology, ecology and hydrology of its upstream region. Moreover, candidate target gauges were coupled with closest candidate source gauges to implement QPPQ methodology. Whether these couples have a common time period to apply QPPQ was questioned. In this regard, the final target gauge locations were selected depending on their long-term data availability, representativeness of the altered conditions and existence of an appropriate reference gauge to be coupled with.

3.2.1.1.2 Reference Gauge Selection

Reference streamflow gauge selection procedure for the Sakarya watershed has been developed depending on similar research studies (Archfield et al., 2009; Armstrong et al., 2008; Carlisle et al., 2010; Falcone et al., 2010; Falcone et al., 2011; Fox & Magoulick 2019; Homa et al., 2013; Leasure et al., 2016; Stuckey et al., 2014). The final steps of the procedure are given in Table 3.3. These criteria has been selected regarding data availability and watershed conditions of the Sakarya River.

Table 3.3 Sakarya watershed reference gauge selection step-by-step procedure and the criteria list

REFERENCE GAUGE SELECTION CRITERIA	
1.	Data availability at least 10 years (mostly 15 to 20 years) to extend spatial coverage, some exceptions exist due to same reason
2.	Gauges coded as canal/ditch/pipeline have been eliminated.
3.	Gauges located right downstream of dams/reservoirs/HPPs have been eliminated.
4.	Substantial regulation has been checked by upstream reservoir impoundments controlling at least 10 percent of the contributing drainage area. – Even though major dam structures are present in the drainage area.
5.	If a dataset before operation of the impoundment has been used in the selection process, to check whether there is questionable regulation in that dataset range and median of flows before and after the impoundment have been compared.
6.	Visual inspection has been done in the case of any unusual characteristics hydrologically and obligation to the previous steps.
7.	Hydrologic classification (main classification) under 3 classes: perennial, intermittent and ephemeral - only perennial sites but extreme drought years have been selected.
8.	Climate classification based on Köppen-Geiger Climate Classification System at a 1-km spatial resolution (Beck et al., 2018)

In the following, the subwatershed level reference gauge selection process is given in detail. All gauges within the Sakarya watershed other than the ones in the Göksu and Lower Sakarya subwatersheds were screened and eliminated according to these criteria given in Table 3.3. The reason why the two subwatersheds are excluded at

the beginning of this process is because it was detected that these subwatersheds have distinct climatic behaviour than the rest of the area (i.e. wetter climate) according to the World Maps of the Köppen-Geiger Climate Classification at a 1-km spatial resolution (Beck et al., 2018). Since naturalization is performed using regional regression modeling approach, all gauges should reflect similar climatic and hydrologic characteristics in the region. In the following, the reference gauge selection procedure is elaborated.

1st criterion: Data availability at least 10 years (mostly 15 to 20 years) to extend spatial coverage, some exceptions exist due to same reason

At the beginning, all potential streamflow gauges were selected based only on the availability and length of their period of records. After screening literature sources and taking regional characteristics of each subwatershed into account, it has been decided to take at least 10 years as a minimum criterion. 10 years of data availability extended spatial coverage. Also, a couple of exceptions having less than 10 years of data were included to increase spatial representativeness of the watershed for model development. Table 3.4 - Table 3.7 show all potential gauges complying with the data availability criterion at subwatershed-level.

Table 3.4 Potential gauges in Upper Sakarya subwatershed

Gauge Code	Number of years available	Range of years available	Gauge Code	Number of years available	Range of years available
D12A132	11	1976-1986	D16A081	45	1968-2016
D12A138	36	1977-2016	D16A092	46	1971-2016
D12A159	28	1982-2011	D16A109	35	1976-2016
D12A176	24	1985-2015	D16A114	27	1977-2005
D12A183	20	1986-2016	D16A123	22	1979-2016
D12A184	26	1986-2016	D16A135	32	1985-2018
D12A185	30	1986-2016	D16A136	29	1985-2016
D12A192	24	1988-2016	D16A137	32	1985-2016
D12A193	14	1988-2009	D16A149	24	1987-2016
D12A194	24	1990-2016	D16A151	25	1991-2016
D12A205	17	1991-2013	E12A023	44	1953-1997
D12A132	11	1976-1986	E12A024	53	1963-2016
D16A017	18	1961-1981	E12A041	26	1963-1988
D16A020	12	1958-1969	E16A016	17	1957-1974

Table 3.5 Potential gauges in Porsuk subwatershed

Gauge Code	Number of years available	Range of years available	Gauge Code	Number of years available	Range of years available
D12A002	11	1960-1971	D12A114	10	1973-1982
D12A003	11	1961-1971	D12A124	14	1974-1987
D12A006	34	1961-1999	D12A134	18	1977-1998
D12A033	49	1962-2016	D12A143	17	1977-1996
D12A034	51	1963-2016	D12A144	11	1977-1993
D12A049	48	1964-2013	D12A149	24	1981-2013
D12A053	14	1965-1977	D12A150	19	1979-2010
D12A054	52	1964-2016	D12A152	30	1980-2016
D12A055	45	1965-2016	D12A170	29	1984-2016
D12A063	52	1965-2016	D12A171	18	1984-2007
D12A067	31	1965-1995	D12A172	30	1983-2016
D12A087	33	1966-2000	D12A173	14	1984-2000
D12A088	11	1969-1979	D12A181	28	1986-2016
D12A090	16	1967-1983	D12A182	24	1988-2017
D12A093	44	1967-2016	D12A225	14	1998-2015
D12A101	31	1971-2016	E12A003	76	1935-2011
D12A103	19	1973-1996	E12A012	34	1962-1986
D12A105	13	1972-1992	E12A048	32	1973-2003
E12A051	21	1989-2010			

Table 3.6 Potential gauges in Ankara subwatershed

Gauge Code	Number of years available - total	Range of years available	Gauge Code	Number of years available - total	Range of years available
D12A017	53	1959-2018	D12A189	29	1987-2016
D12A030	18	1961-1989	D12A238	12	2003-2014
D12A075	39	1965-2013	E12A016	34	1962-1995
D12A126	14	1999-2013	E12A039	43	1956-2002
D12A139	23	1979-1999	E12A044	36	1963-1999
E12A053	24	1991-2018			

Table 3.7 Potential gauges in Middle Sakarya subwatershed

Gauge Code	Number of years available - total	Range of years available	Gauge Code	Number of years available - total	Range of years available
D12A091	21	1967-2014	D12A188	29	1988-2016
D12A098	18	1968-1986	E12A006	33	1938-1972
D12A120	21	1973-1995	E12A018	44	1953-2003
D12A146	34	1979-2013	E12A033	56	1959-2016
D12A160	23	1984-2012	E12A042	39	1961-1999
D12A167	24	1983-2013	E12A049	33	1973-2005
E12A058	11	2004-2015			

2nd criterion: Gauges coded as canal/ditch/pipeline have been eliminated

This criterion is where all potential reference streamflow gauges selected at the first step are screened to eliminate the ones which does not comply with the natural streambed characteristics. The gauges coded as canal/ditch/pipeline were eliminated from the potential reference gauge list because these do not exhibit natural streambed characteristics and they cannot be included in the naturalization process of Sakarya watershed. In Table 3.8, eliminated gauges at this step are listed based on subwatershed level.

Table 3.8 Sakarya watershed canalized/piped/etc. gauges eliminated at the second step of reference gauge selection process

Upper Sakarya	Porsuk	Ankara	Middle Sakarya	Göksu
D16A081 D16A123 D16A149 D16A020	D12A101	No canalized beds	E12A049	No canalized beds

3rd criterion: Gauges located right downstream of dams/reservoirs/HPPs have been eliminated.

Since naturalization requires unimpaired characteristics of streambeds and their hydrology, the gauges located at the outlet of dams/reservoirs/hydropower plants were eliminated at this step of the reference gauge selection procedure. Table 3.9 shows the eliminated gauges in each subwatershed based on this third criterion.

Table 3.9 Sakarya watershed gauges eliminated at the third step of the reference gauge selection process

Upper Sakarya	Porsuk	Ankara	Middle Sakarya	Göksu
D12A184 D12A192 D12A205 D16A092 D16A109	D12A124 D12A149 D12A170 D12A172	No gauges eliminated	E12A018 E12A033 E12A058 E12A042 E12A006 D12A098	D12A157

4th and 5th criteria: Substantial regulation check by reservoir control and questionable regulation check by comparing dataset

4th and 5th steps in Table 3.3 are combined since they reinforce each other by providing supporting information. At this step, upstream substantial regulation by reservoir control was checked using a quantitative measure specified by Stuckey et al. (2014). The measure taken into account is if an impoundment controls at least 10 percent of the contributing drainage area, the gauge of interest is eliminated. Even though major dam structures are present in the drainage area, if they control less than 10 percent of the area, they can be used as a reference gauge. In addition to impoundment control on the upstream area, questionable regulation was also checked. If a dataset before operation of the impoundment was used in the selection process, whether there is questionable regulation in that dataset range and median of flows before and after the impoundment should be checked. The eliminated gauges are shown in Table 3.10.

Table 3.10 Sakarya watershed gauges eliminated at the fourth step of the reference gauge selection process

Upper Sakarya	Porsuk	Ankara	Middle Sakarya	Göksu
D12A193	D12A034	D12A126	D12A167	No gauges eliminated
	D12A054	D12A238		
	D12A063	E12A016		
	D12A134			
	D12A173			
	E12A012			
	E12A048			
	E12A051			

6th criterion: Visual inspection in case of any unusual characteristics hydrologically and obligation to the previous steps

This step eliminates the gauges exhibiting any unusual hydrologic and/or morphologic behaviors. Visual tools, such as Google Earth images and shape/raster files of the region, and available information obtained from governmental sources

are used to detect these types of unusual characteristics. Table 3.11 presents the gauges eliminated at this step based on subwatershed level.

Table 3.11 Sakarya watershed gauges eliminated at the sixth step of the reference gauge selection process

Upper Sakarya	Porsuk	Ankara	Middle Sakarya	Göksu
D12A138	D12A103	No gauges	E12A018	No gauges
	D12A105	eliminated		eliminated
	D12A114			
	D12A143			
	D12A144			
	D12A150			
	D12A225			

7th criterion: Hydrologic classification under 3 classes: perennial, intermittent and ephemeral – only perennial sites but extreme drought years were selected.

According to the literature, there are 3 main classes of streamflow regime: perennial, intermittent and ephemeral; and all these classes should be individually assessed when regional regression models are developed, Carlisle et al. (2010) states. Therefore, in this study, these classes were defined using quantitative threshold values. Since there are no strict criteria for distinguishing between these stream types, the quantitative limits mentioned by Svec et al. (2005) were used to define perennial, ephemeral and intermittent streams in Sakarya watershed. The fact that perennial streams are the ones having water present 90% of the time is one of the quantitative criterion mentioned in the source. Because only perennial sites are decided to be modelled in the Sakarya watershed, 90% threshold value was selected to eliminate both intermittent and ephemeral streams from the dataset. The eliminated gauges are given in Table 3.12 based on subwatershed level.

Table 3.12 Sakarya watershed gauges eliminated at the seventh step of the reference gauge selection process

Upper Sakarya	Porsuk	Ankara	Middle Sakarya	Göksu
D12A183	D12A002	D12A075	D12A120	No gauges
D12A194	D12A067			eliminated
D12A204	D12A087			
D16A017	D12A171			

Table 3.12 Sakarya watershed gauges eliminated at the seventh step of the reference gauge selection process (continued)

Upper Sakarya	Porsuk	Ankara	Middle Sakarya	Göksu
D16A114				
D16A151				

8th criterion: Climate classification based on Köppen-Geiger Climate Classification System at a 1-km spatial resolution (Beck et al., 2018)

As a final step of the reference gauge elimination process, climate classification based on the Köppen-Geiger Climate Classification System was used. Beck et al. (2018) published worldwide climate data at a high spatial resolution (1-km) for the present day period (1980-2016). This dataset was included in the selection process by calculating each gauge's climate classes in ArcMap 10.7 software (Table 3.13- Table 3.17). According to this dataset, the dominant climate classes in Upper Sakarya, Porsuk, Ankara, and Middle Sakarya subwatersheds are coded as 7 and 18. 7 represents arid, steppe and cold climate while 18 does cold, dry summer and warm summer climate types. As a result of this evaluation, the entire Göksu and Lower Sakarya subwatersheds and two gauges in the Middle Sakarya subwatershed (Table 3.18) were eliminated from the dataset since it has warmer and wetter climate than the rest.

Table 3.13 Upper Sakarya subwatershed climate zone percentages (%)

The Köppen-Geiger classes*	7	8	9	14	15	18	19	26
D12A058	45.8	-	-	-	-	54.2	-	-
D12A132	42.4	-	-	-	-	57.6	-	-
D12A159	93.2	-	-	-	-	6.8	-	-
D12A176	92.6	-	-	-	-	7.4	-	-
D12A185	21.1	-	-	-	-	78.9	-	-
D12A217	-	-	-	-	-	100.0	-	-
D16A135	70.2	-	-	-	-	29.8	-	-
D16A136	61.9	-	-	-	-	38.1	-	-
D16A137	40.3	-	-	-	-	59.7	-	-
E12A023	60.2	-	-	-	-	39.8	-	-
E12A024	83.3	-	-	-	-	16.7	-	-
E12A041	92.4	-	-	-	-	7.6	-	-
E16A016	48.0	-	-	-	-	52.0	-	-

* Numeric values and their legends on the Köppen-Geiger classes map (Beck et al., 2018). 7: Arid, steppe, cold, 8: Temperate, dry summer, hot summer, 9: Temperate, dry summer, warm summer, 14: Temperate, no dry season, hot summer, 15:

Temperate, no dry season, warm summer, 18: Cold, dry summer, warm summer, 19: Cold, dry summer, cold summer, 26: Cold, no dry season, warm summer

Table 3.14 Porsuk subwatershed climate zone percentages (%) (a)

The Köppen-Geiger classes*	7	8	9	14	15	18	19	26
D12A003	16.6	0.1	0.1	-	-	83.2	-	-
D12A006	26.8	-	-	-	-	73.2	-	-
D12A033	18.8	0.1	0.2	-	-	81.0	-	-
D12A049	-	-	-	-	-	100.0	-	-
D12A053	-	-	-	-	-	100.0	-	-
D12A055	4.3	-	0.3	-	-	95.4	-	-
D12A088	54.7	-	-	-	-	45.4	-	-
D12A090	17.1	0.1	0.1	-	-	82.8	-	-
D12A093	-	-	-	-	-	100.0	-	-
D12A152	-	-	-	-	-	100.0	-	-
D12A171	-	-	-	-	-	100.0	-	-
D12A181	18.6	0.1	0.1	-	-	81.2	-	-
D12A182	100.0	-	-	-	-	-	-	-
E12A003	16.5	0.1	0.1	-	-	83.3	-	-

* Numeric values and their legends on the Köppen-Geiger classes map (Beck et al., 2018). 7: Arid, steppe, cold, 8: Temperate, dry summer, hot summer, 9: Temperate, dry summer, warm summer, 14: Temperate, no dry season, hot summer, 15: Temperate, no dry season, warm summer, 18: Cold, dry summer, warm summer, 19: Cold, dry summer, cold summer, 26: Cold, no dry season, warm summer

Table 3.15 Ankara subwatershed climate zone percentages (%)

The Köppen-Geiger classes*	7	8	9	14	15	18	19	26
D12A017	-	-	-	-	-	100.0	-	-
D12A030	-	-	-	-	-	100.0	-	-
D12A139	10.0	-	-	-	-	89.6	-	0.4
D12A189	1.0	-	-	-	-	99.0	-	-
E12A039	0.4	-	-	-	-	99.6	-	-
E12A044	0.0	-	-	-	-	100.0	-	-
E12A053	0.0	-	-	-	-	100.0	-	-

* Numeric values and their legends on the Köppen-Geiger classes map (Beck et al., 2018). 7: Arid, steppe, cold, 8: Temperate, dry summer, hot summer, 9: Temperate, dry summer, warm summer, 14: Temperate, no dry season, hot summer, 15: Temperate, no dry season, warm summer, 18: Cold, dry summer, warm summer, 19: Cold, dry summer, cold summer, 26: Cold, no dry season, warm summer

Table 3.16 Middle Sakarya subwatershed climate zone percentages (%)

The Köppen-Geiger classes*	7	8	9	14	15	18	19	26
D12A091	6.5	1.3	35.8	3.2	18.6	33.6	-	1.0
D12A146	0.4	12.7	-	1.2	25.9	57.2	-	2.7
D12A160	51.8	-	-	-	-	48.2	-	-
D12A188	23.5	-	1.0	-	-	73.9	-	1.6

* Numeric values and their legends on the Köppen-Geiger classes map (Beck et al., 2018). 7: Arid, steppe, cold, 8: Temperate, dry summer, hot summer, 9: Temperate, dry summer, warm summer, 14: Temperate, no dry season, hot summer, 15: Temperate, no dry season, warm summer, 18: Cold, dry summer, warm summer, 19: Cold, dry summer, cold summer, 26: Cold, no dry season, warm summer

Table 3.17 Göksu subwatershed climate zone percentages (%)

The Köppen-Geiger classes*	7	8	9	14	15	18	19	26
D12A135	-	2.5	35.4	-	-	55.3	6.8	-
D12A153	23.4	10.6	32.8	-	-	32.5	0.8	-
D12A156	1.1	6.8	38.6	-	-	53.4	-	-
D12A158	20.9	3.3	37.0	-	-	38.9	-	-
D12A164	41.7	1.7	56.5	-	-	-	-	-
D12A175	-	21.0	51.9	-	-	24.7	2.5	-
D12A177	-	5.9	49.0	-	-	45.1	-	-
D12A231	-	56.5	43.5	-	-	-	-	-
E12A028	27.8	4.9	33.1	-	-	34.2	-	-

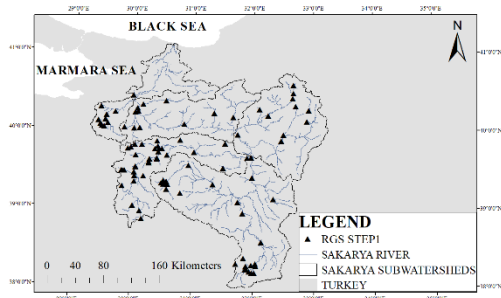
* Numeric values and their legends on the Köppen-Geiger classes map (Beck et al., 2018). 7: Arid, steppe, cold, 8: Temperate, dry summer, hot summer, 9: Temperate, dry summer, warm summer, 14: Temperate, no dry season, hot summer, 15: Temperate, no dry season, warm summer, 18: Cold, dry summer, warm summer, 19: Cold, dry summer, cold summer, 26: Cold, no dry season, warm summer

Table 3.18 Sakarya watershed gauges eliminated at the eighth step of the reference gauge selection process

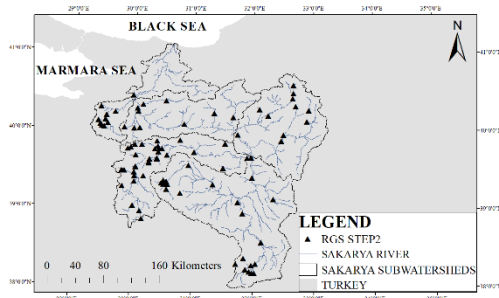
Göksu Subwatershed	Middle Sakarya Subwatershed
D12A135	D12A091
D12A153	D12A146
D12A156	
D12A158	
D12A164	
D12A175	
D12A177	
D12A231	
E12A028	

A summary graph showing the reference gauge elimination procedure is given in Figure 3.8.

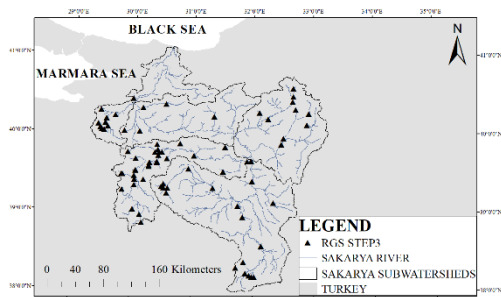
STEP 1



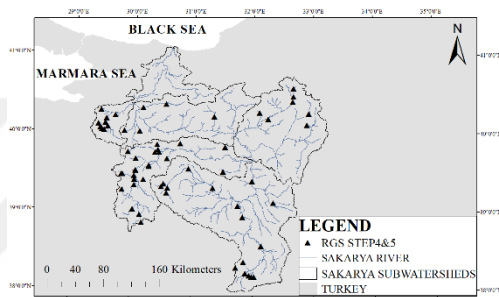
STEP 2



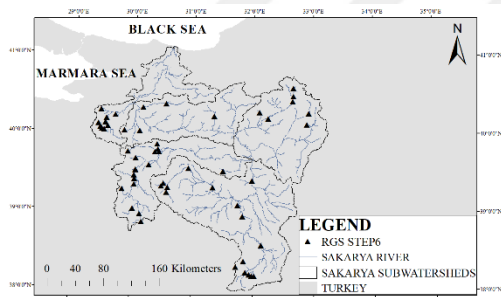
STEP 3



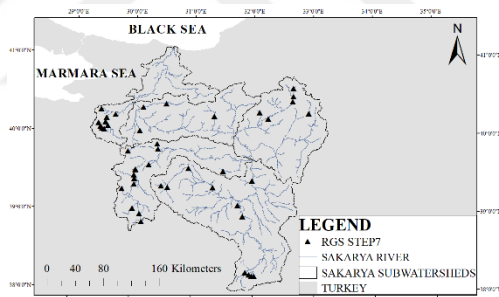
STEP 4-5



STEP 6



STEP 7



STEP 8

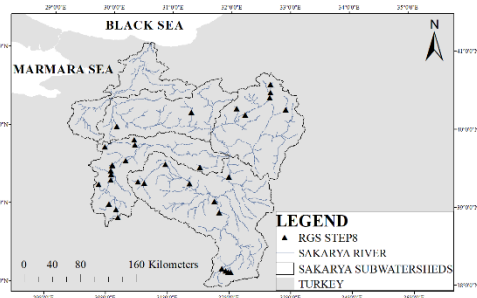


Figure 3.8. Reference gauge selection procedure maps showing gauges remained after each step

3.2.1.2 Determination of the Flow Exceedance Percentiles

The 18 exceedance probability flows of each reference and target streamflow gauge were calculated to feed into the regression models as dependent variables and into the QPPQ application. In order to calculate these exceedance probability flows, the most commonly used equation in the naturalization literature was detected and used in this study. The equation is named as ‘Weibull plotting position formula’ (Stedinger et al., 1993) and it gives unbiased exceedance probabilities for all distributions (Eq-2).

$$P_i = \frac{i}{n + 1} \quad \text{Eq-2}$$

3.2.1.3 Geospatial and Climatic Metric Selection – Independent variables of the regression models

As indicated in the section 3.2.1, geospatial and climatic metrics are possible watershed characteristics affecting streamflow dynamics. They are selected based on the independent variables used in various studies and data availability of the Sakarya watershed. Because such geospatial characteristics are poorly documented in quantitative manner and data are scarce across the study region, following eleven characteristics were calculated and fed into the regression models:

- 1- Mean annual precipitation calculated from total daily precipitation values,
- 2- Mean maximum daily temperature,
- 3- Longitude at the outlet of drainage area,
- 4- Drainage area,
- 5- Percentage of impervious area,
- 6- Percentage of carbonate bedrock,
- 7- Percentage of forest cover,
- 8- Percentage of woodland cover,
- 9- Percentage of grassland cover, and

10- Mean basin elevation.

Mean annual precipitation and mean maximum daily temperature data were calculated from the daily data collected by Turkish State Meteorological Service (MGM). Longitude at the outlet of drainage was taken from the Google Earth software. Drainage area and mean basin elevation were calculated using Geographic Information System (GIS) – ArcMap 10.7 software from the Digital Elevation Model (DEM) data of USGS (<https://earthexplorer.usgs.gov/>). Percentage of impervious area, forest, grassland and woodland covers were calculated using the ArcMap 10.7 software from the data of CORINE Land Cover database (<https://land.copernicus.eu/pan-european/corine-land-cover>). Percentage of carbonate bedrock was obtained from the shapefiles generated by State Hydraulic Works of Turkey (DSI), calculated by the ArcMap 10.7 software.

3.2.1.4 Regression Model Development

Multiple linear regression models were developed, and model coefficients, R^2 , and adjusted R^2 values were obtained using SPSS software.

Different combinations of the independent variables were used to develop regression models and the performance of the regression models were evaluated using standard statistical parameters. The model performances were evaluated using validation gauges selected among the reference gauges. The model performance evaluation methodology is given in Section 3.2.1.5. Other than model performance evaluation, the model summary table, ANOVA table and model coefficients tables were evaluated to select the best performing models. Example outputs of these tables are given in Figure 3.9 below.

Model Summary					
Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	
1	.929 ^a	0.862	0.825	0.49722	
a. Predictors: (Constant), ELEVLN, CARBLN, MAPLN, IMPCOVLN,					

ANOVA ^a						
Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	34.118	6	5.686	23.000	.000 ^b
	Residual	5.439	22	0.247		
	Total	39.557	28			
a. Dependent Variable: Q5LN						
b. Predictors: (Constant), ELEVLN, CARBLN, MAPLN, IMPCOVLN, DRAREALN, FORLN						

Coefficients ^a						
Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-24.016	7.405		-3.243	0.004
	DRAREALN	0.666	0.068	0.965	9.730	0.000
	IMPCOVLN	0.057	0.080	0.068	0.718	0.480
	CARBLN	-0.328	0.113	-0.249	-2.896	0.008
	MAPLN	0.920	0.621	0.130	1.480	0.153
	FORLN	0.346	0.107	0.323	3.245	0.004
	ELEVLN	2.409	0.831	0.294	2.898	0.008
a. Dependent Variable: Q5LN						

Figure 3.9. Example SPSS outputs of the Sakarya Watershed Regional Regression Model Runs

3.2.1.5 Model Performance Evaluation using Statistical Parameters

Model and prediction performances were evaluated using evaluation parameters commonly used in the naturalization literature. They are NSE, R^2 , and PBIAS, where NSE: Nash-Sutcliffe Efficiency, R^2 : Coefficient of Determination, and PBIAS: Percent bias. The model performance was evaluated using 30 reference gauges while the predictive performance of the models was evaluated using five reference validation gauges.

The equations used for the calculations of these parameters are:

$$NSE = 1 - \frac{\sum_{b=1}^n (O_b - P_b)^2}{\sum_{b=1}^n (O_b - \bar{O})^2} \quad \text{Eq-3}$$

$$R^2 = \left(\frac{\sum_{b=1}^n (O_b - \bar{O})(P_b - \bar{P})}{\sqrt{\sum_{b=1}^n (O_b - \bar{O})^2} \sqrt{\sum_{b=1}^n (P_b - \bar{P})^2}} \right)^2 \quad \text{Eq-4}$$

$$PBIAS = \left[\frac{\sum_{b=1}^n (O_b - P_b) * 100}{\sum_{b=1}^n (O_b)} \right] \quad \text{Eq-4}$$

where, O_b and P_b are the observed and predicted flows of gauge b , $\bar{O}$ and $\bar{P}$ are the observed and predicted mean flow values, and n is the number of gauges.

3.2.2 U.S. Geological Survey (USGS) Streamflow Naturalization Methodology Part 2 – QPPQ Method

After obtaining the coefficients from the regional regression models, the 12 natural exceedance probability flows of the target gauges were calculated using Eq-1.

Since daily natural streamflow time series cannot be obtained by developing and running only regional regression models, QPPQ method was applied. As indicated by Archfield et al. (2012), Ssegane et al. (2013) and Stuckey et al. (2014), the QPPQ method was first proposed by Fennessey (1994) and published by various authors – Archfield & Vogel (2010), Hughes & Smakhtin (1996), Shu & Ouarda (2012), Smakhtin et al. (1997), Smakhtin V. Y. (1999). The method is named different by each author, for example Ssegane et al. (2013) refer to the method as ‘Streamflow Separation (SFS) Technique’, Smakhtin V. Y. (1999) refers as ‘Non-linear Spatial Interpolation Method’ and, on the other hand, Archfield et al. (2009), Fennessey

(1994), and Stuckey et al. (2014) refer to the method as ‘QPPQ Method’. The method is referred to as ‘QPPQ Method’ in this study.

QPPQ method has a technique to translate daily flow information from a source (reference) site to a destination site depending on a linear interpolation technique (Smakhtin V. Y., 1999; Ssegane et al., 2013). Even though it points out that only single source site is used to apply this method, here exist some other studies using more than one neighbouring gauges (source sites) to generate daily flow time series of target sites (Shu & Ouarda, 2012; Ssegane et al., 2013).

Smakhtin V.Y. (1999) presents the general steps of this non-linear spatial interpolation method as follows:

- 1- Possible source site identification and weighting based on the similarity between source and destination site flow regimes
- 2- Generation of 17 fixed percentage points on the FDCs (from 0.01 to 99.99%) at each site (both source and destination sites)
- 3- Determining source site daily flow time series and their corresponding flow exceedance percentages
- 4- Estimation of flows for destination site by weighted averaging of all estimated flow values of source sites

In the USGS methodology of naturalization, this method is modified and applied using the following approach.

- 1- A reference gauge which has the similar flow regime characteristics to the target site of interest is selected.
- 2- Its daily flow time series and corresponding daily flow exceedance percentiles are found.
- 3- The streamflows corresponding to fixed 17 percentiles at the target site (which are estimated using the parameterized regression models) are linearly interpolated equating the percentiles of the reference gauge time series for a particular day.

A visual representation of the QPPQ Method is given in Figure 3.10, prepared by Stuckey et al. (2014).

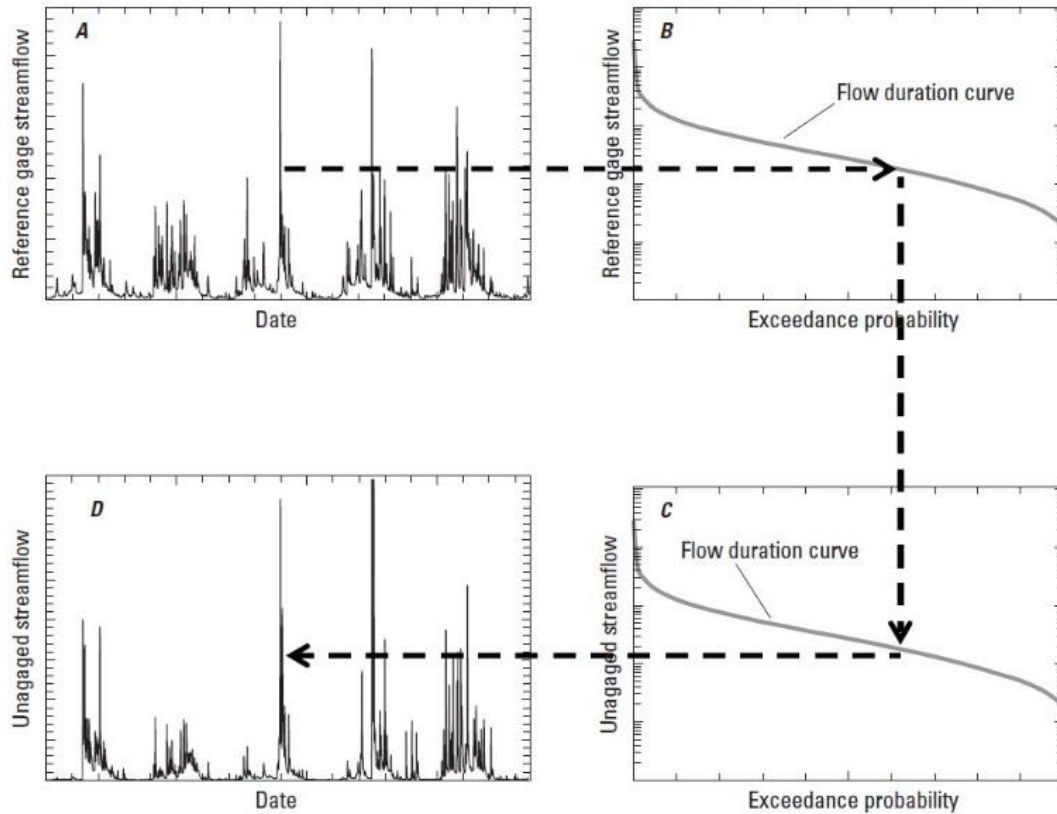


Figure 3.10. QPPQ Method used for constructing natural streamflow daily time series of target sites in the Sakarya watershed (the figure was taken from Stuckey et al., 2014)

3.2.2.1 Coupling Source and Target Gauges

In this study, the source gauges selected to complete daily natural streamflow time series of the target gauges were chosen among the reference gauges based on a distance threshold. This threshold value is 20 km between source sites and the target sites, which has been adopted from the study of Ssegane et al. (2013). If 20 km threshold could not be applied due to issues such as data unavailability and/or

regional differences, subsequent sites in terms of closest distance was taken into account and used for the process.

After implementation of the distance threshold method at the previous step, Pearson's correlation coefficient (r) values between the 18 log-linear natural exceedance probability percentile flows of the candidate source and target gauges were calculated within their common period of time. In order to decrease estimation uncertainties, data imputation adopted by the USGS was not performed to complete missing years. Instead, the available data years of both reference and target sites are used to create daily natural streamflow time series. The highest correlation coefficient value between the log-linear natural percentile flows yields the best source and target gauge couple to be selected for QPPQ method implementation.

3.2.2.2 Calculation of the Extreme End Exceedance Percentile Flows on the Flow Duration Curve (FDC)

Since only 12 exceedance probability percentile flows were modelled against the geospatial and climatic parameters of the reference gauges, the remaining 6 percentile flows were calculated using different approaches.

Using different approaches for the extreme ends of the FDC exceedance probability flows was suggested by Archfield et al. (2013) to prevent physical impossibility caused by the uncertainties in the flow estimates of the regression models. Archfield et al. (2013) states when all streamflow quantiles were regressed against watershed characteristics, no constraint to ensure that estimated streamflows decreased with increasing exceedance probability was observed. Also, some estimated streamflow values were larger at higher exceedance probabilities than streamflows estimated at lower exceedance probabilities, resulting in physical impossibility. Thus, they suggested to use the drainage area ratio (DAR) method for the exceedance probabilities less than 1% and the linear regression against exceedance probability percentiles for greater than 85% (Table 3.11).

The DAR method was implemented using the coupled reference gauge's information. On the other hand, the linear regression against exceedance probability percentile flows was recursively performed between 85% (modelled by the regional regression model) and 90%, 90% and 95%, 95% and 99%, and 99% and 99.9%. Therefore, 90, 95, 99 and 99.9% flow values were estimated using the linear regression against subsequent percentile flow value.

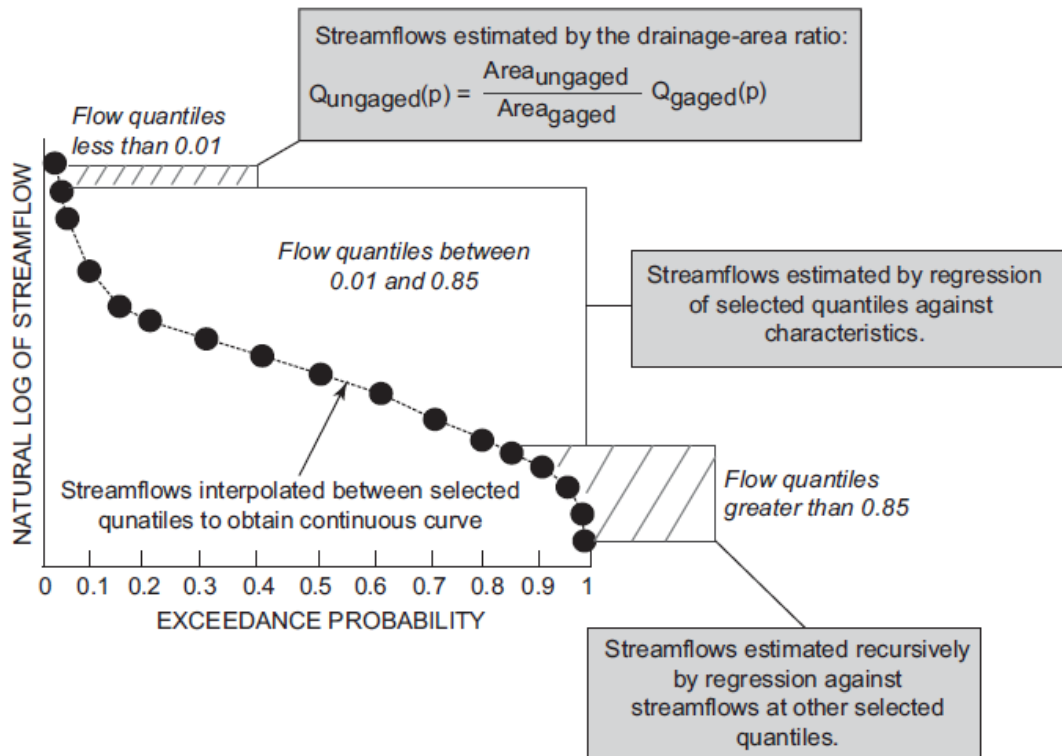


Figure 3.11. The methodology proposed by Archfield et al. (2013) for calculating the natural exceedance probability percentile flows (The figure was adopted from Archfield et al. (2013))

3.2.2.3 Generating Daily Streamflow Time Series of the Target Gauges

At this step, as the literature emphasizes, the assumption is that the target site of interest has the same exceedance probability in the same day with the corresponding source site. By adopting this assumption, the daily flow time series of target sites

were estimated using the coupled source flows and their corresponding exceedance probabilities for the common period of time between the coupled source and target gauges.

First, entire streamflow time series and corresponding daily FDC percentiles of the corresponding source gauges were calculated using the Weibull Plotting Position formula (Eq-2). Then, daily FDC percentiles of the target sites were accepted to be the same as the ones calculated at the previous step from their coupled source gauge data. Since the daily FDC percentiles of the target sites were obtained, linear interpolations between the 18 natural FDC percentile flows of the target sites were performed to find corresponding daily flow values.

3.3 Results

In this section, the results of Multiple Linear Regression Modeling – QPPQ Methodology are given. Section 3.3.1 presents selected reference and target gauges, dependent variables, independent variables and performance evaluation parameters of the multiple linear regression models. On the other hand, in section 3.3.2, the QPPQ method source-target gauge couples, correlation results and natural daily streamflow time series of the target locations generated are given.

3.3.1 Results of Multiple Linear Regression Modeling

In the following subsections, results of the multiple linear regression modeling results are given.

3.3.1.1 Reference and Target Streamflow Gauge Selection Results

According to the considerations given in 3.2.1.1.1, target gauges where streamflow naturalization process was implemented were selected and shown in Table 3.19. The

locations of these target gauges within the Sakarya watershed can be seen in Figure 3.12.

Table 3.19 Target gauges selected across Sakarya watershed

Subwatershed	Map no	Gauge Code	Data year range
Upper Sakarya	1	E12A024	1986-2016
Ankara	2	E12A045	1987-2002
Porsuk	3	D12A034	1963-2011

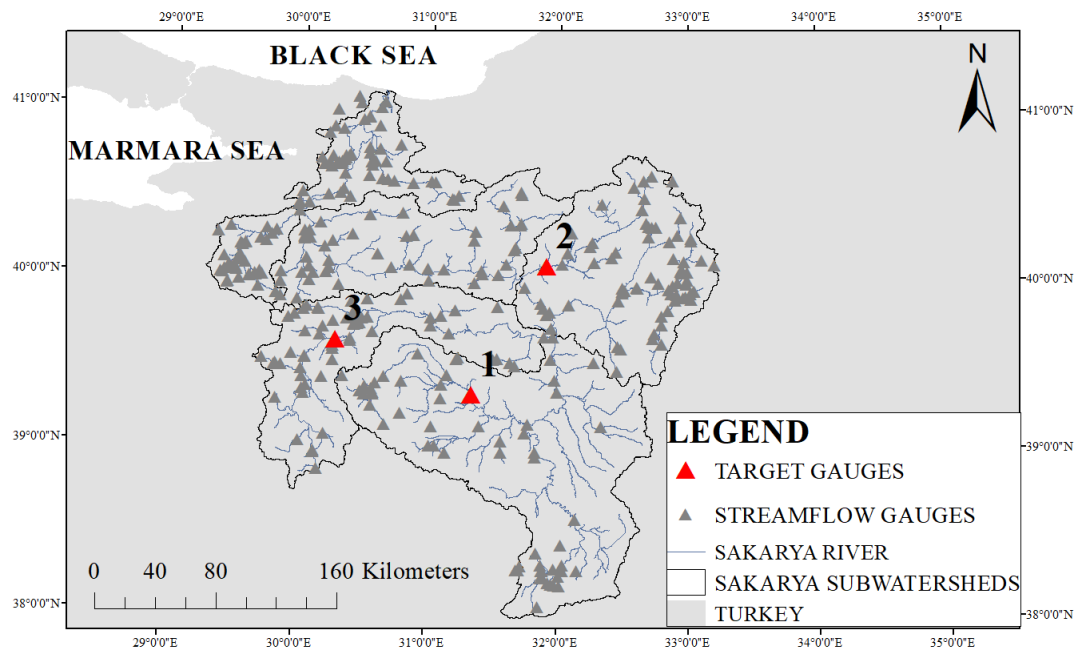


Figure 3.12. The target streamflow gauges selected

In addition to the target gauges, the reference gauges whose hydrological, climatological and geospatial data were used to construct multiple linear regression models were selected based on the criteria given in section 3.2.1.1.2. The final list of these selected reference gauges are given in Table 3.20 and their locations within the Sakarya watershed can be found in Figure 3.13.

Table 3.20 Final reference gauge list of Sakarya watershed

Upper Sakarya	Porsuk	Ankara	Middle Sakarya
D12A058	D12A003	D12A017	D12A160
D12A132	D12A006	D12A030	D12A188
D12A159	D12A033	D12A139	
D12A185	D12A049	D12A189	
D12A217	D12A053	E12A039	
D16A135	D12A088	E12A044	
D16A136	D12A090	E12A053	
D16A137	D12A093		
E12A023	D12A152		
E12A024	D12A181		
E12A041	D12A182		
E16A016	E12A003		

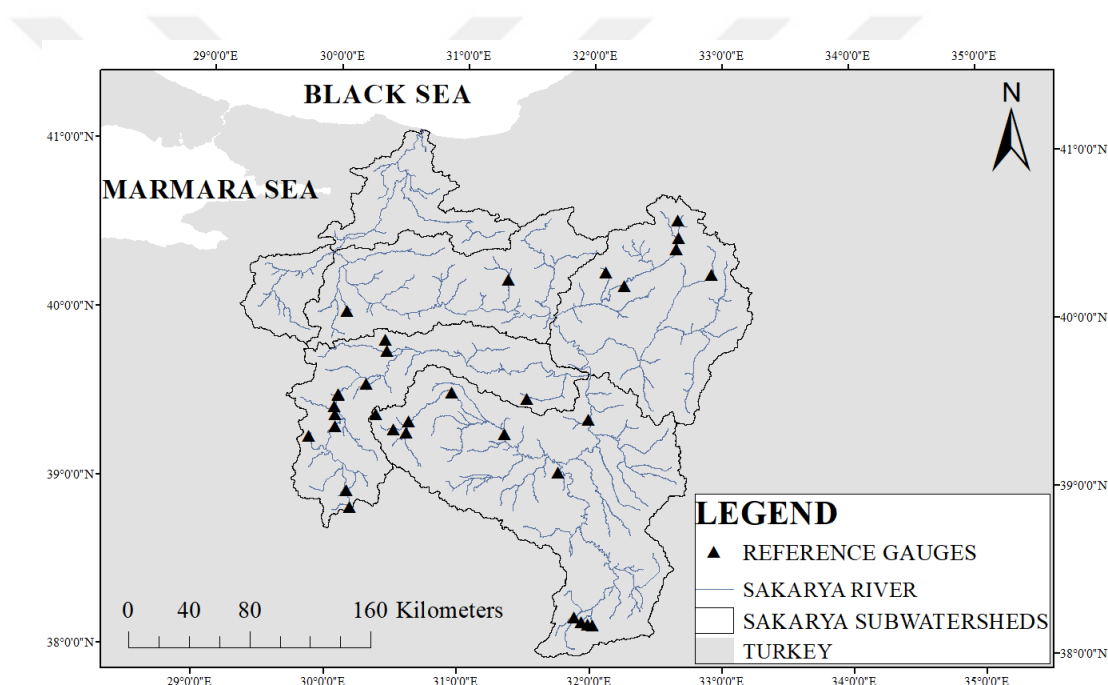


Figure 3.13. The map showing reference gauges selected for the streamflow naturalization procedure in the Sakarya watershed

3.3.1.2 Determination of the Flow Exceedance Percentiles

The 18 FDC exceedance probability percentile flows calculated by the Weibull plotting position formula (please see Section 3.2.1.2) from the observed daily

streamflow time series of each reference and target gauge of the Sakarya watershed are given in between Table 3.21 and Table 3.23.

Table 3.21 Reference Gauge Flow-Duration Curve Exceedance Probability Percentile Flow Values (m^3/s) – Q_{50} - $Q_{99.9}$

Subwatershed	Gauge Code	Q99.9	Q99	Q95	Q90	Q85	Q80	Q70	Q60	Q50
Upper Sakarya	D12A058	-	0.00	0.04	0.08	0.15	0.25	0.52	0.80	1.48
	D12A132	-	0.01	0.08	0.18	0.31	0.46	0.77	1.28	2.20
	D12A159	-	0.78	1.24	1.98	2.55	3.10	3.81	4.29	4.90
	D12A185	-	0.00	0.05	0.14	0.25	0.40	0.80	1.55	2.38
	D12A217	-	-	0.00	0.01	0.02	0.04	0.09	0.18	0.31
	D16A135	-	0.02	0.09	0.20	0.29	0.37	0.54	0.73	0.97
	D16A136	-	-	0.00	0.01	0.03	0.04	0.10	0.20	0.33
	D16A137	-	0.001	0.01	0.03	0.05	0.08	0.19	0.36	0.63
	E12A023	0.0038	0.07	0.18	0.33	0.48	0.64	1.02	2.14	3.34
	E12A024	-	2.78	3.51	4.10	4.61	5.06	5.95	6.97	7.96
	E12A041	-	11.64	14.20	16.80	19.40	22.00	27.20	32.40	37.60
	E16A016	-	0.01	0.08	0.18	0.29	0.43	0.84	1.69	2.80
Porsuk	D12A003	-	1.98	2.61	3.71	4.47	5.22	6.73	8.24	9.75
	D12A006	-	0.00	0.04	0.07	0.11	0.17	0.37	0.65	0.89
	D12A033	-	0.17	0.32	0.49	0.69	0.89	1.78	3.15	4.84
	D12A049	-	0.01	0.07	0.11	0.18	0.25	0.40	0.62	0.81
	D12A053	-	0.00	0.02	0.04	0.07	0.09	0.18	0.36	0.58
	D12A088	-	0.00	0.01	0.03	0.04	0.06	0.11	0.22	0.38
	D12A090	-	1.45	2.05	2.79	3.54	4.28	5.77	7.26	8.75
	D12A093	-	0.01	0.05	0.12	0.23	0.38	0.69	1.13	1.90
	D12A152	-	0.0023	0.01	0.06	0.18	0.30	0.65	1.40	2.23
	D12A171	-	0.0005	0.02	0.05	0.09	0.12	0.25	0.47	0.71
	D12A181	-	0.66	1.09	1.72	2.27	3.06	4.60	6.32	8.18
	D12A182	-	0.00	0.02	0.04	0.06	0.07	0.12	0.19	0.30
	E12A003	1.012	1.17	1.71	2.36	3.01	3.63	4.92	6.28	7.60
Ankara	D12A017	-	0.09	0.23	0.45	0.71	1.07	3.18	5.85	8.60
	D12A030	-	0.00	0.02	0.05	0.09	0.18	0.48	0.84	1.75
	D12A139	-	0.00	0.02	0.06	0.13	0.22	0.70	2.00	6.70
	D12A189	-	0.03	0.09	0.19	0.31	0.46	0.94	2.01	3.41
	E12A039	0.0003	0.012	0.07	0.14	0.23	0.33	0.64	1.19	2.72
	E12A044	-	0.13	0.30	0.59	0.87	1.33	2.93	5.15	7.92
	E12A053	-	0.01	0.05	0.10	0.18	0.28	0.57	0.93	1.74
Middle Sakarya	D12A160	-	-	0.02	0.05	0.09	0.14	0.38	0.65	0.91
	D12A188	-	0.02	0.10	0.24	0.44	0.68	1.23	2.12	2.97

Table 3.22 Reference Gauge Flow-Duration Curve Exceedance Probability
Percentile Flow Values (m^3/s) – $Q_{0.1}$ - Q_{40}

Subwatershed	Gauge Code	Q40	Q30	Q20	Q15	Q10	Q5	Q1	Q0.5	Q0.1
Upper Sakarya	D12A058	3.50	6.05	8.80	10.88	17.25	27.25	48.35	53.63	-
	D12A132	3.64	5.18	6.98	8.48	9.92	14.20	24.80	-	-
	D12A159	5.42	6.01	6.95	7.45	8.00	8.58	9.76	-	-
	D12A185	3.35	4.58	6.35	7.70	8.91	10.97	15.59	-	-
	D12A217	0.51	0.77	1.16	1.41	1.94	2.54	-	-	-
	D16A135	1.38	2.10	2.98	3.64	4.44	5.82	10.16	-	-
	D16A136	0.49	0.73	1.09	1.53	1.76	2.18	-	-	-
	D16A137	1.00	1.47	1.96	2.27	2.92	4.57	7.14	-	-
	E12A023	4.72	6.37	8.27	9.51	14.17	20.87	37.89	49.02	-
	E12A024	8.90	10.00	16.98	20.49	24.09	29.49	45.30	61.43	-
	E12A041	42.80	48.40	54.60	58.70	62.70	69.30	98.86	-	-
	E16A016	4.17	5.77	8.03	9.64	14.20	20.80	39.42	-	-
Porsuk	D12A003	15.30	24.70	39.80	47.35	54.90	71.35	144.70	-	-
	D12A006	1.59	2.96	4.84	6.26	7.84	9.76	31.56	-	-
	D12A033	7.03	9.82	17.16	21.79	28.38	42.03	56.06	64.61	-
	D12A049	1.07	2.17	2.30	2.73	3.65	4.92	7.39	-	-
	D12A053	0.86	1.38	2.50	3.55	5.10	7.20	11.70	-	-
	D12A088	0.57	0.85	1.29	1.62	2.38	3.42	7.60	-	-
	D12A090	11.20	18.15	31.20	38.65	49.10	57.55	132.55	-	-
	D12A093	2.64	3.59	4.78	5.54	6.50	7.88	10.08	13.74	-
	D12A152	3.01	4.55	6.46	7.60	9.55	12.01	17.94	19.31	-
	D12A181	10.44	16.48	24.24	29.18	35.26	42.13	50.63	54.87	-
	D12A182	0.43	0.59	0.86	1.00	1.26	1.58	2.30	-	-
	E12A003	9.05	14.84	26.16	32.82	39.86	50.58	78.20	98.13	143.81
Ankara	D12A017	14.42	24.64	41.96	49.79	65.80	95.50	161.70	332.60	-
	D12A030	4.14	6.88	9.92	15.70	23.60	37.80	65.24	81.20	-
	D12A139	18.00	33.00	56.00	71.00	92.00	142.50	267.00	339.00	-
	D12A189	5.14	7.89	11.52	15.37	19.62	26.37	39.56	44.31	-
	E12A039	4.53	6.69	9.27	13.42	20.28	30.38	46.70	64.89	85.07
	E12A044	12.80	22.10	32.80	40.60	51.40	64.50	124.50	163.20	-
	E12A053	2.70	4.21	5.84	6.85	8.47	10.97	21.01	25.08	-
Middle Sakarya	D12A160	1.38	2.21	3.14	3.61	4.14	5.19	-	-	-
	D12A188	4.27	5.84	8.07	10.34	12.87	16.77	27.64	31.48	-

Table 3.23 Target Gauge Flow-Duration Curve Exceedance Probability Percentile Flow Values (m³/s)

Subwatershed	Upper Sakarya	Ankara	Porsuk
Gauge Code	E12A024	E12A045	D12A034
Q99.9	-	-	-
Q99	0.27	0.05	0.01
Q95	0.94	0.26	0.02
Q90	1.43	0.62	0.06
Q85	2.04	0.98	0.14
Q80	2.48	1.75	0.28

Table 3.24 Target Gauge Flow-Duration Curve Exceedance Probability Percentile Flow Values (m³/s)

Subwatershed	Upper Sakarya	Ankara	Porsuk
Gauge Code	E12A024	E12A045	D12A034
Q70	3.39	3.44	0.92
Q60	4.50	5.70	2.27
Q50	5.68	9.35	4.30
Q40	6.94	20.90	6.62
Q30	8.18	35.65	8.95
Q20	9.90	54.40	14.80
Q15	11.20	66.33	24.70
Q10	12.90	83.95	39.80
Q5	14.40	127.25	55.80
Q1	21.22	222.95	71.98
Q0.5	22.72	263.08	79.47
Q0.1	-	413.79	-

3.3.1.3 Geospatial and Climatic Metrics of Regional Regression Models

The geospatial and climatic metrics calculated for each reference and target gauge of the Sakarya watershed are given in Table 3.25 and Table 3.27.

Table 3.25 Sakarya watershed independent variables of reference gauges*

	Gauge Code	LONG (°)	DRAREA (km ²)	IMP (%)	CARB (%)	MAP (mm)	MMT (°C)	FOR (%)	GRASS (%)	WOOD (%)	ELEV (m)
Upper Sakarya	D12A058	30.60	1141	1.11	75.44	362.6	16.13	45.58	5.67	21.22	1289.9
	D12A132	30.58	702	1.61	80.73	352.2	16.02	49.82	5.25	19.97	1290.1
	D12A159	31.75	6589	1.35	62.83	453.9	17.56	3.14	8.31	3.18	1117.5

Table 3.25 Sakarya watershed independent variables of reference gauges*
(continued)

	Gauge Code	LONG (°)	DRAREA (km ²)	IMP (%)	CARB (%)	MAP (mm)	MMT (°C)	FOR (%)	GRASS (%)	WOOD (%)	ELEV (m)
Porsuk	D12A185	30.48	219	0.01	65.43	361.0	16.95	49.66	6.59	16.48	1377.3
	D12A217	30.35	19.3	0.01	26.28	440.7	16.36	84.14	5.92	9.69	1575.6
	D16A135	32.03	65.7	1.63	78.47	434.4	17.14	18.12	1.95	32.45	1448.4
	D16A136	31.99	28.4	1.44	94.77	441.0	17.16	11.18	9.92	32.24	1453.9
	D16A137	31.94	89.1	0.33	31.01	434.4	17.15	26.13	12.79	26.07	1490.1
	E12A023	30.93	1579	1.06	68.08	363.2	16.05	34.84	7.15	17.40	1223.8
	E12A024	31.34	4296	1.28	48.04	363.2	16.21	15.82	8.22	10.76	1087.6
	E12A041	31.98	20005	1.29	51.80	393.1	16.71	4.88	11.34	4.66	1069.0
	E16A016	31.88	585	0.84	33.57	361.1	17.45	21.79	4.14	15.69	1390.2
	D12A003	30.05	3912	2.78	61.19	534.1	17.60	13.97	4.12	15.64	1160.4
	D12A006	30.27	320	0.10	49.06	618.3	16.79	36.02	2.72	20.58	1157.3
	D12A033	30.03	2407	1.14	62.11	468.4	16.99	14.55	4.04	14.00	1177.5
	D12A049	29.83	114.6	0.24	84.08	556.8	17.13	18.20	2.84	20.15	1279.7
	D12A053	30.42	195	0.75	28.58	488.2	17.01	24.24	3.24	21.79	1257.2

Table 3.26 Sakarya watershed independent variables of reference gauges*

	Gauge Code	LONG (°)	DRAREA (km ²)	IMP (%)	CARB (%)	MAP (mm)	MMT (°C)	FOR (%)	GRASS (%)	WOOD (%)	ELEV (m)
Ankara	D12A088	30.40	63.7	0.49	12.07	582.5	17.46	0.65	13.97	0.11	1068.8
	D12A090	30.03	3751	2.47	62.17	476.1	17.30	14.47	4.00	14.61	1162.6
	D12A093	30.17	143	1.43	35.14	506.9	14.88	6.55	9.05	4.60	1288.3
	D12A152	30.13	202	1.39	51.76	480.5	15.42	5.16	15.05	14.28	1261.69
	D12A181	30.03	3288	1.31	64.15	503.3	16.88	14.53	3.99	15.72	1167.5
	D12A182	31.50	206	0.95	16.02	408.8	17.00	1.46	18.80	14.58	1137.5
	E12A003	30.05	3901	2.78	61.31	456.0	16.86	14.00	4.13	15.49	1160.8
	D12A017	32.65	878	0.69	9.08	565.3	15.05	38.89	26.34	24.64	1464.0
	D12A030	32.67	337	0.23	17.26	548.2	16.15	40.36	22.84	22.13	1538.3
	D12A139	32.24	2226	0.94	17.47	442.7	15.11	29.85	28.82	21.97	1346.6
	D12A189	32.10	194	0.47	7.89	396.8	18.71	53.79	25.71	17.60	1496.0
	E12A039	32.92	322	0.07	1.67	449.9	17.50	21.51	32.07	14.22	1545.75
	E12A044	32.65	877	0.65	9.09	476.7	14.55	38.93	26.37	24.61	1464.4
	E12A053	32.66	137	0.34	25.00	419.7	14.02	46.89	24.42	17.40	1570.1
Middle Sakarya	D12A160	30.10	95.7	2.70	2.66	528.8	17.70	21.20	4.05	15.51	842.8
	D12A188	31.34	602	0.11	83.18	415.9	18.21	26.27	3.05	47.75	1106.3

* LONG (°): Longitudes of the target gauge location, DRAREA (km²): Upstream drainage areas of the gauges, IMP (%): Impervious land cover percentage of the gauge upstream drainage areas, CARB (%): Carbonate bedrock percentage of the gauge upstream drainage areas, MAP (mm): Mean annual precipitation at the gauge location, MMT (°C): Mean maximum temperature at the gauge location, FOR (%): Forest land cover percentage of the gauge upstream drainage areas, GRASS (%): Grassland cover percentage of the gauge upstream drainage areas, WOOD (%): Woodland cover percentage of the gauge upstream drainage areas, ELEV (m): Mean elevation of the upstream drainage area

Table 3.27 Sakarya watershed independent variables of target gauges*

	Gauge Code	LONG (°)	DRAREA (km ²)	IMP (%)	CARB (%)	MAP (mm)	MMT (°C)	FOR (%)	GRASS (%)	WOOD (%)	ELEV (m)
Upper Sakarya	E12A024	31.34	4296	1.28	48.04	402.58	16.71	15.82	8.22	10.76	1087.58
Ankara	E12A045	31.91	4081	1.06	36.08	443.49	15.80	19.38	27.49	14.69	1195.42
Porsuk	D12A034	30.28	4568	2.78	56.38	441.93	16.79	14.45	4.10	16.35	1147.73

* LONG (°): Longitudes of the target gauge location, DRAREA (km²): Upstream drainage areas of the gauges, IMP (%): Impervious land cover percentage of the gauge upstream drainage areas, CARB (%): Carbonate bedrock percentage of the gauge upstream drainage areas, MAP (mm): Mean annual precipitation at the gauge location, MMT (°C): Mean maximum temperature at the gauge location, FOR (%): Forest land cover percentage of the gauge upstream drainage areas, GRASS (%): Grassland cover percentage of the gauge upstream drainage areas, WOOD (%): Woodland cover percentage of the gauge upstream drainage areas, ELEV (m): Mean elevation of the upstream drainage area

3.3.1.4 Performance Evaluation of the Regional Regression Models Using Statistical Parameters

Both *the performance of the Sakarya watershed multiple linear regression models* and *the predictive performance of them* were evaluated using NSE, R^2 and PBIAS parameters. These values are shown in two tables: 1) model performance of the Sakarya watershed regional regression models (Table 3.28 and Figure 3.14) and 2) predictive performance of the models (Table 3.29).

Table 3.28 R^2 and adjusted R^2 values between estimated and measured flow-duration curve percentile flows of the 29 reference gauges

Percentile	R^2	Adjusted R^2	Percentile	R^2	Adjusted R^2
Q85	0.841	0.815	Q30	0.870	0.841
Q80	0.844	0.810	Q20	0.875	0.848
Q70	0.842	0.808	Q15	0.872	0.837
Q60	0.841	0.798	Q10	0.876	0.842
Q50	0.844	0.818	Q5	0.863	0.825
Q40	0.875	0.854	Q1	0.813	0.767

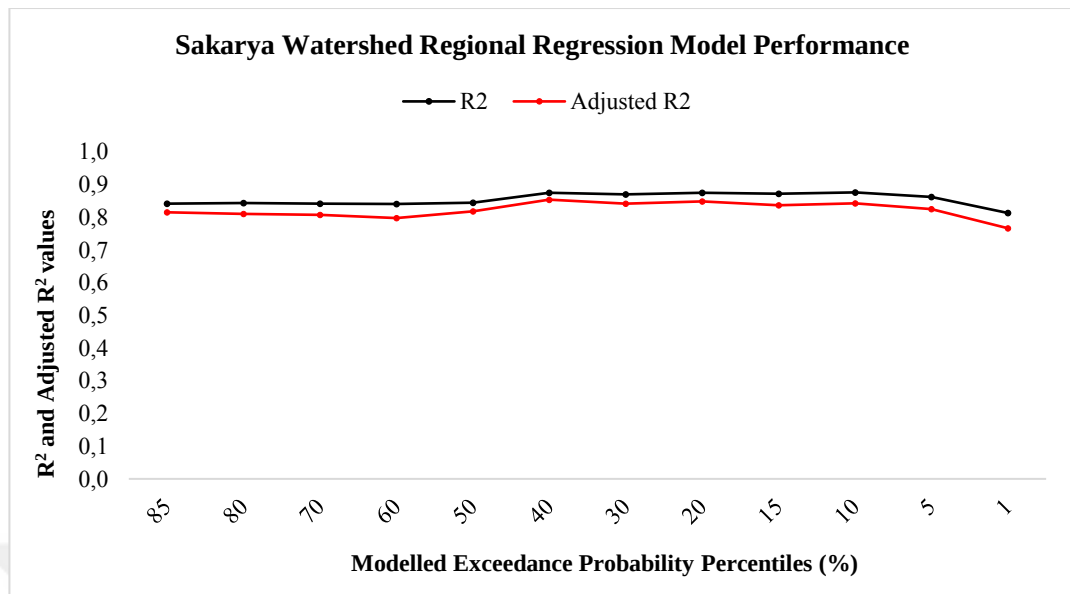


Figure 3.14. R^2 and adjusted R^2 values between estimated and measured flow-duration curve percentile flows of the 29 reference gauges

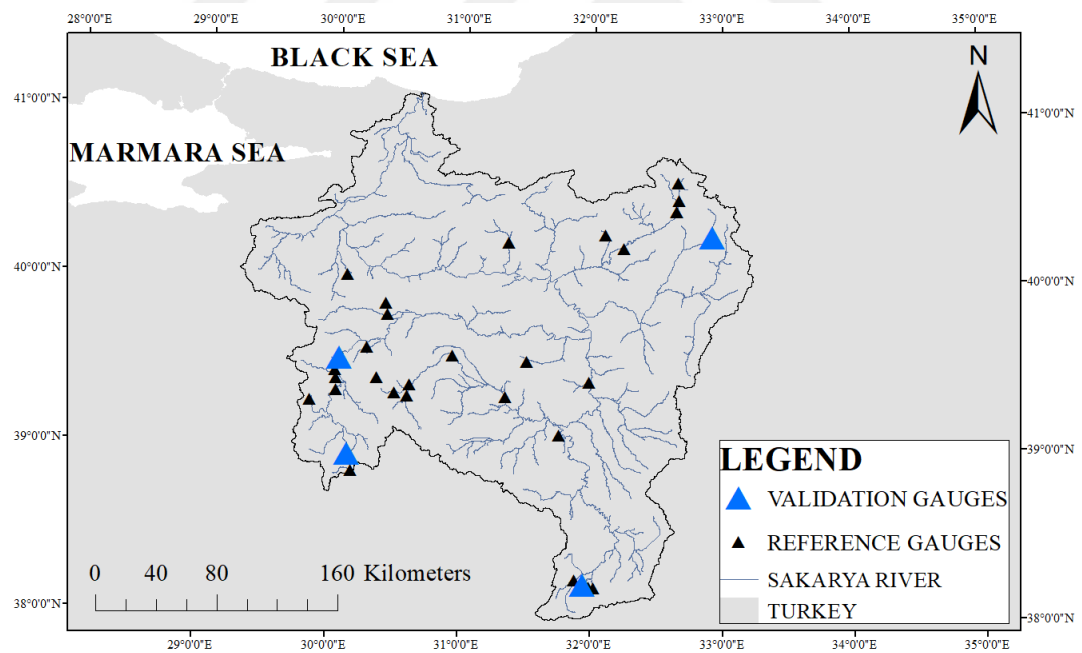


Figure 3.15. Sakarya watershed regional regression models validation gauge locations

Table 3.29 Predictive performance parameters of the Sakarya watershed regression models

Percentile	NSE	PBIAS (%)	Percentile	NSE	PBIAS (%)
Q85	0.85	-3.6	Q30	0.61	-7.4
Q80	0.85	-2.5	Q20	0.56	-8.5
Q70	0.88	-6.2	Q15	0.60	-9.2
Q60	0.88	28.0	Q10	0.61	-8.6
Q50	0.73	1.1	Q5	0.65	-5.4
Q40	0.67	-3.3	Q1	0.37	-7.3

3.3.2 Results of the QPPQ Method

In this section, the results of the natural daily streamflow generation using the QPPQ method are presented.

3.3.2.1 Performance of the Regional Regression-QPPQ methodology

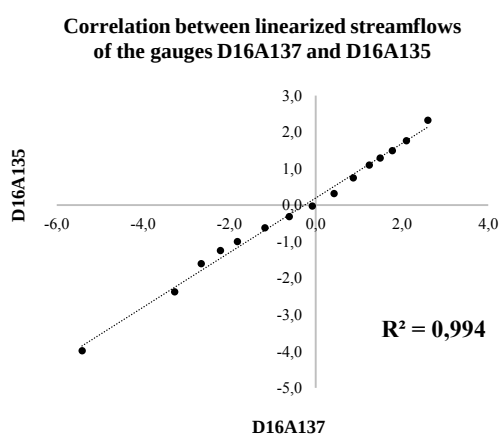
Before applying QPPQ method to the target gauges, the performance of the whole methodology applied in this study (i.e. Regional regression modeling + QPPQ method) was evaluated using Nash-Sutcliffe Efficiency (NSE) coefficient values calculated from the daily predicted and measured natural streamflows of the four validation gauges (Figure 3.17).

First, the source and validation gauge couples were found to make the evaluation. The correlation coefficients between the log-linear values of the 15 flow-duration curve exceedance probability flows (i.e., Q1-Q99) were calculated. It should be noted that the remaining 3 FDC exceedance probability flows (i.e., Q0.1, Q0.5 and Q99.9) could not be included in the calculation of the correlations because they could not be obtained from their daily observed flows using Weibull Plotting Position formula. The correlation graphs of these source-validation gauge couples are given in Table 3.30 and Figure 3.16.

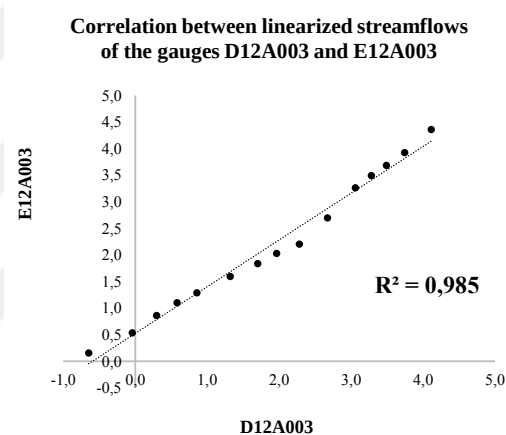
Table 3.30 Correlations between the Sakarya watershed validation and corresponding source gauge couples in the QPPQ application for performance evaluation of the whole methodology

Subwatershed	Validation Gauge	Reference Gauge	Common period of application	Correlation coefficient (r)
Upper Sakarya	D16A137	D16A135	1985-2016	0.997
Porsuk	D12A003	E12A003	1961-1971	0.993
Porsuk	D12A152	D12A093	1980-2010	0.989
Ankara	E12A039	D12A030	1967-1994	0.991

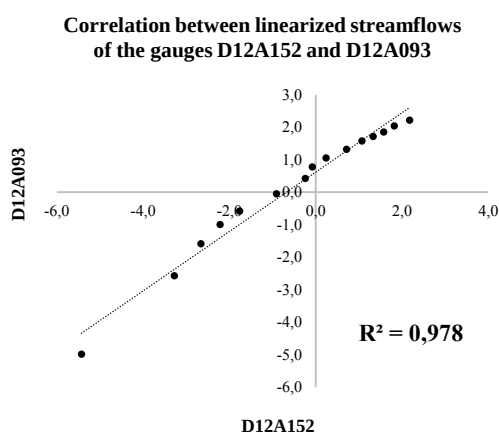
a)



b)



c)



d)

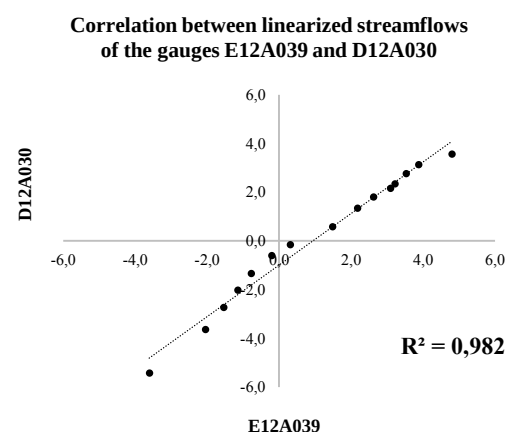
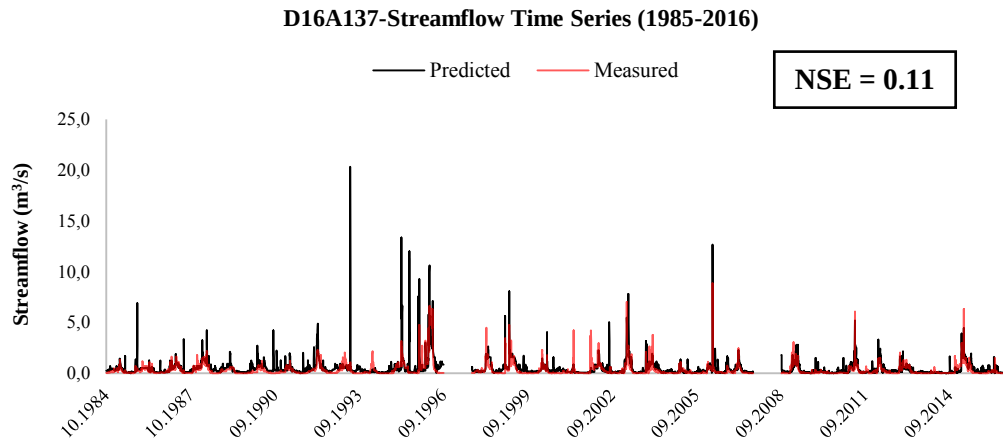


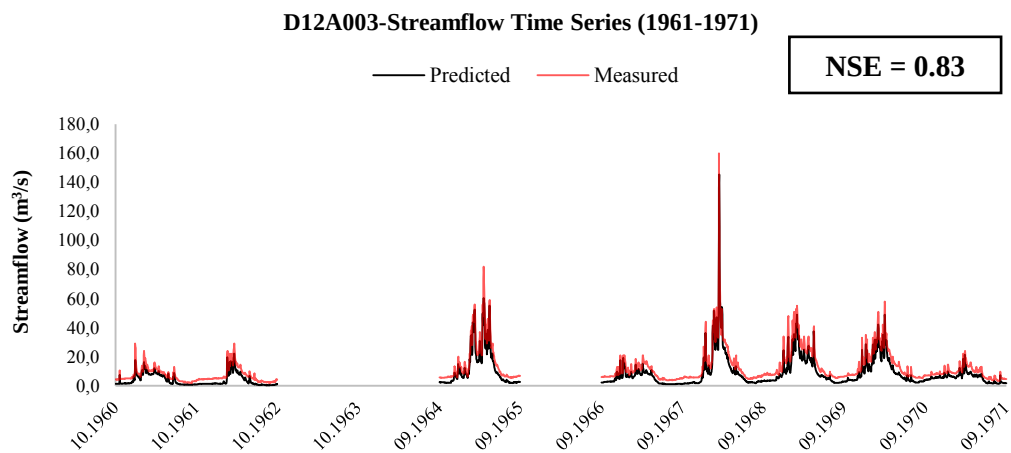
Figure 3.16. Correlation graphs between the linearized natural streamflow percentile flows of the validation and their coupled source gauges in the Sakarya watershed. a) D16A137, b) D12A003, c) D12A152 and d) E12A039

After implementing the QPPQ methodology to the validation gauges, the following daily flow time series were generated (Figure 3.17).

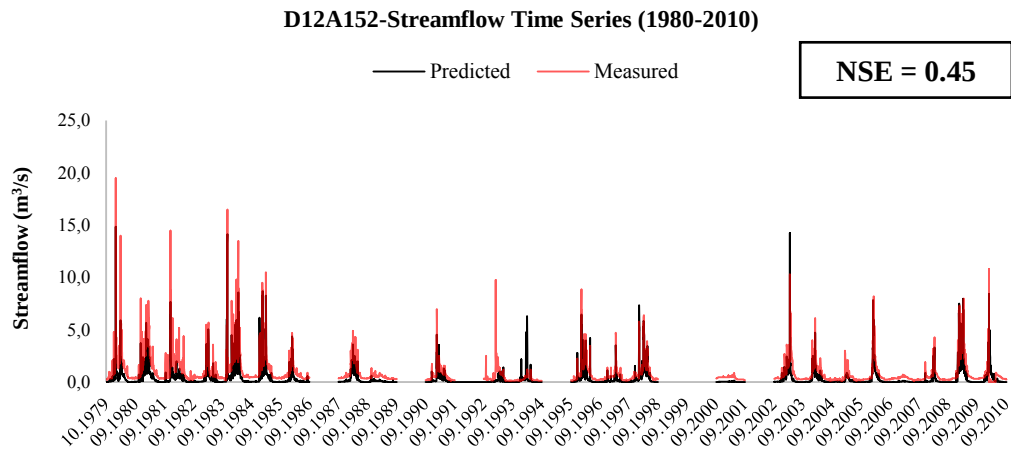
a)



b)



c)



d)

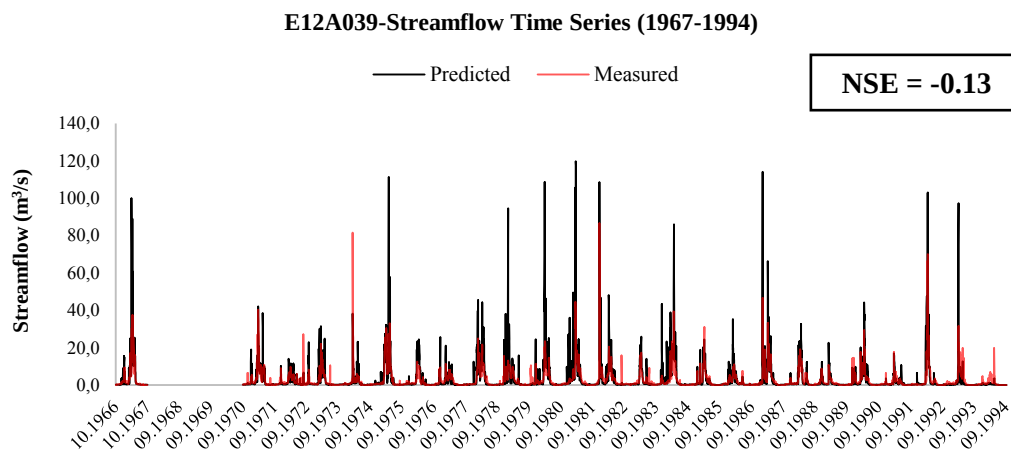


Figure 3.17. Predicted and measured daily streamflow time series of the validation gauges and their corresponding NSE values. a) D16A137, b) D12A003, c) D12A152 and d) E12A039

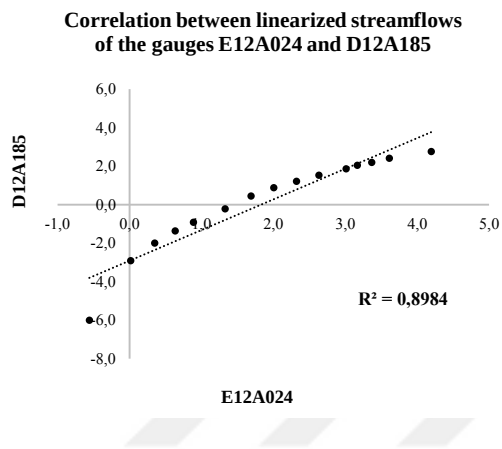
3.3.2.2 Coupling Source and Target Gauges

Source gauges having highest correlation with the corresponding target gauges based on their 18 log-linear natural FDC percentile flows are given in Table 3.31. The correlation between them are visualized in Figure 3.18.

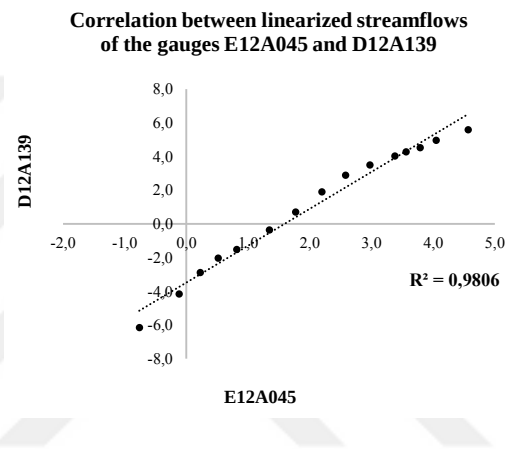
Table 3.31 Correlation details of the Sakarya watershed source and target gauge couples in the QPPQ application

Subwatershed	Target Gauge	Source Gauge	Common period of application	Correlation coefficient (r)
Upper Sakarya	E12A024	D12A185	1986-2016	0.948
Ankara	E12A045	D12A139	1979-1999	0.990
Porsuk	D12A034	E12A003	1963-1996	0.994

a)



b)



c)

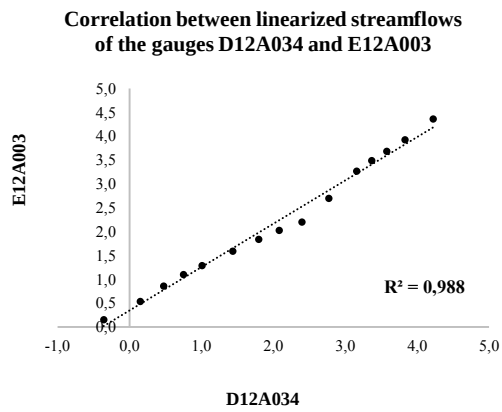


Figure 3.18. Correlation graphs between the linearized 15 natural FDC exceedance probability percentile flows of the target and coupled source gauges in the Sakarya watershed. a) E12A024-D12A185, b) E12A045-D12A139 and c) D12A034-E12A003

3.3.2.3 Estimation of the Natural FDC Exceedance Probability Percentile Flows of Target Gauges

The 18 natural FDC percentile flows (Table 3.34) of the target locations within the Sakarya watershed were generated (Table 3.32 and Table 3.33). The 12 percentile flows (i.e., between Q85 and Q1) was calculated using the following regional regression model coefficients while the remaining 6 percentile flows (i.e., Q_{0.5}, Q_{0.1}, Q₉₀, Q₉₅, Q₉₉, and Q_{99.9}) were calculated by the DAR method and the linear regression against percentiles.

Table 3.32 Model coefficients obtained from the multiple linear regression models of the Sakarya watershed

	Q85	Q80	Q70	Q60	Q50	Q40
A	-21.23	-20.24	-14.94	-12.05	-13.51	-15.47
LONG (°)	-	-	-	-	-	-
DRAREA (km²)	0.87	0.83	0.75	0.69	0.70	0.69
IMP (%)	-	-	-	-	-	-
CARB (%)	-	-	-	-	-0.22	-0.29
MAP (mm)	-	-	-	-	-	-
MMT (°C)	2.92	2.35	0.87	-0.03	-	-
FOR (%)	-	-	-	-	0.13	0.19
GRASS (%)	-	-	-	-	-	-
WOOD (%)	-	-	-	-	-	-
ELEV (m)	0.91	1.08	1.08	1.15	1.45	1.80

*A: Constant term, LONG (°): Longitudes of the target gauge location, DRAREA (km²): Upstream drainage areas of the gauges, IMP (%): Impervious land cover percentage of the gauge upstream drainage areas, CARB (%): Carbonate bedrock percentage of the gauge upstream drainage areas, MAP (mm): Mean annual precipitation at the gauge location, MMT (°C): Mean maximum temperature at the gauge location, FOR (%): Forest land cover percentage of the gauge upstream drainage areas, GRASS (%): Grassland cover percentage of the gauge upstream drainage areas, WOOD (%): Woodland cover percentage of the gauge upstream drainage areas, ELEV (m): Mean elevation of the upstream drainage area

Table 3.33 Model coefficients obtained from the multiple linear regression models of the Sakarya watershed

	Q30	Q20	Q15	Q10	Q5	Q1
A	-19.99	-20.67	-22.46	-23.64	-24.02	-8.55
LONG (°)	-	-	-	-	-	-
DRAREA (km²)	0.69	0.70	0.68	0.67	0.67	0.57
IMP (%)	-	-	0.04	0.04	0.06	-
CARB (%)	-0.28	-0.31	-0.30	-0.31	-0.33	-0.52
MAP (mm)	0.66	0.81	0.95	0.99	0.92	1.39

Table 3.33 Model coefficients obtained from the multiple linear regression models of the Sakarya watershed (continued)

	Q30	Q20	Q15	Q10	Q5	Q1
MMT (°C)	-	-	-	-	-	-
FOR (%)	0.26	0.28	0.31	0.32	0.35	0.59
GRASS (%)	-	-	-	-	-	-
WOOD (%)	-	-	-	-	-	-
ELEV (m)	1.90	1.91	2.08	2.25	2.41	-

*A: Constant term, LONG (°): Longitudes of the target gauge location, DRAREA (km²): Upstream drainage areas of the gauges, IMP (%): Impervious land cover percentage of the gauge upstream drainage areas, CARB (%): Carbonate bedrock percentage of the gauge upstream drainage areas, MAP (mm): Mean annual precipitation at the gauge location, MMT (°C): Mean maximum temperature at the gauge location, FOR (%): Forest land cover percentage of the gauge upstream drainage areas, GRASS (%): Grassland cover percentage of the gauge upstream drainage areas, WOOD (%): Woodland cover percentage of the gauge upstream drainage areas, ELEV (m): Mean elevation of the upstream drainage area

Table 3.34 Target Gauge Natural FDC Percentile Flow Values (m³/s)

	E12A024	E12A045	D12A034
Q99.9	0.26	0.18	0.38
Q99	0.57	0.47	0.70
Q95	1.02	0.88	1.16
Q90	1.42	1.25	1.60
Q85	1.88	1.67	2.12
Q80	2.42	2.26	2.73
Q70	3.77	3.82	4.20
Q60	5.42	5.84	6.02
Q50	7.41	8.98	7.98
Q40	10.19	13.14	10.99
Q30	13.89	19.55	15.94
Q20	20.24	29.32	23.43
Q15	23.72	35.19	28.98
Q10	28.95	44.04	35.72
Q5	36.97	57.17	45.94
Q1	66.12	96.14	67.98
Q0.5	-	621.47	119.55
Q0.1	-	-	169.80

An example calculation for Q₈₀ of the target gauge D12A034 is given below:

$$\ln(Q_{80}) = -20.24 + 0.83 * \ln(4568.24) + 2.35 * \ln(16.79) + 1.08 * \ln(1147.73) = 1.01$$

$$Q_{80} = 2.73 \text{ m}^3/\text{s}$$

Q0.5 and Q0.1 could not be calculated for the gauges E12A024 and E12A045 because their coupled reference gauges did not have these values in their flow duration curves their data structure.

Measured and natural (i.e., calculated by the naturalization methodology of this study) flow duration curves of the target sites are given in Figure 3.19.

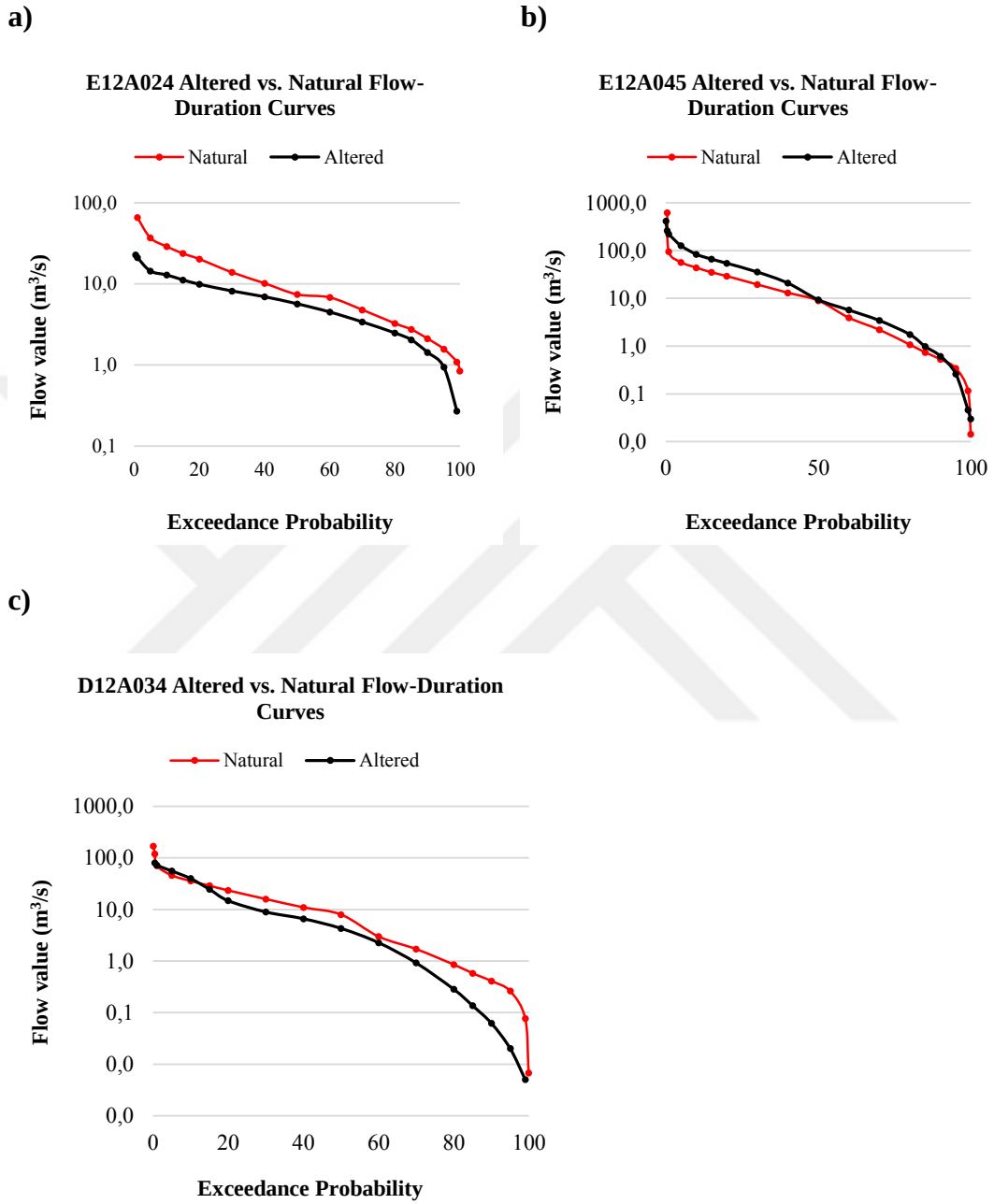
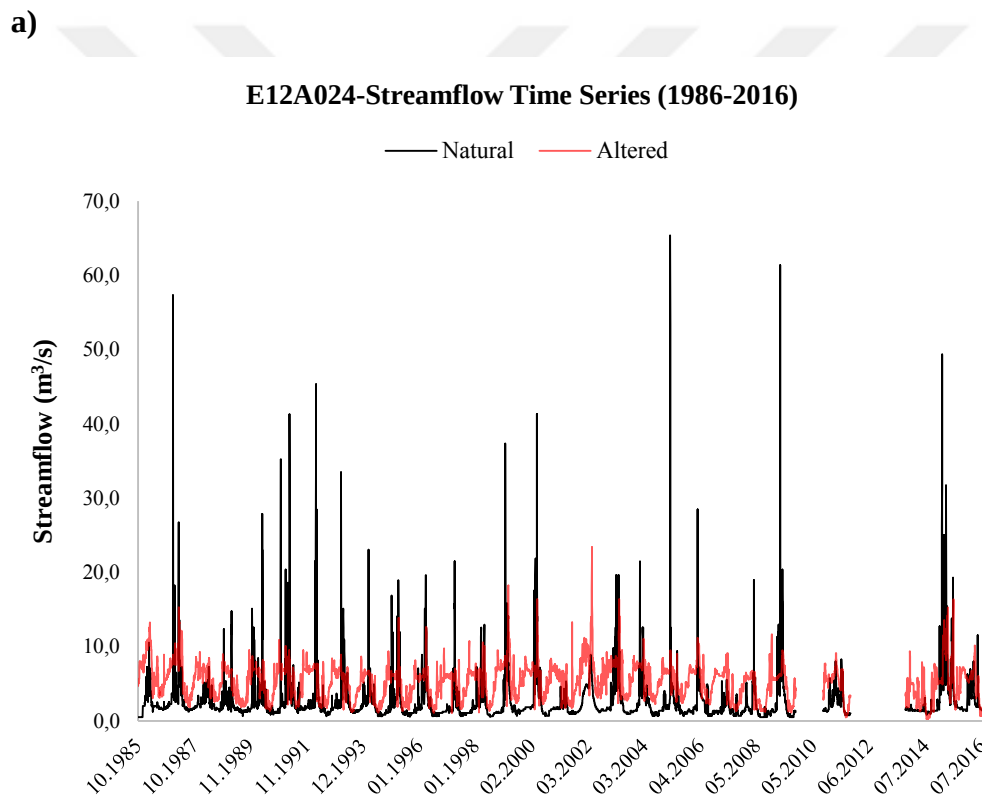


Figure 3.19. Natural and altered FDCs of the target gauges in the Sakarya watershed.
a) E12A024, b) E12A045 and c) D12A034

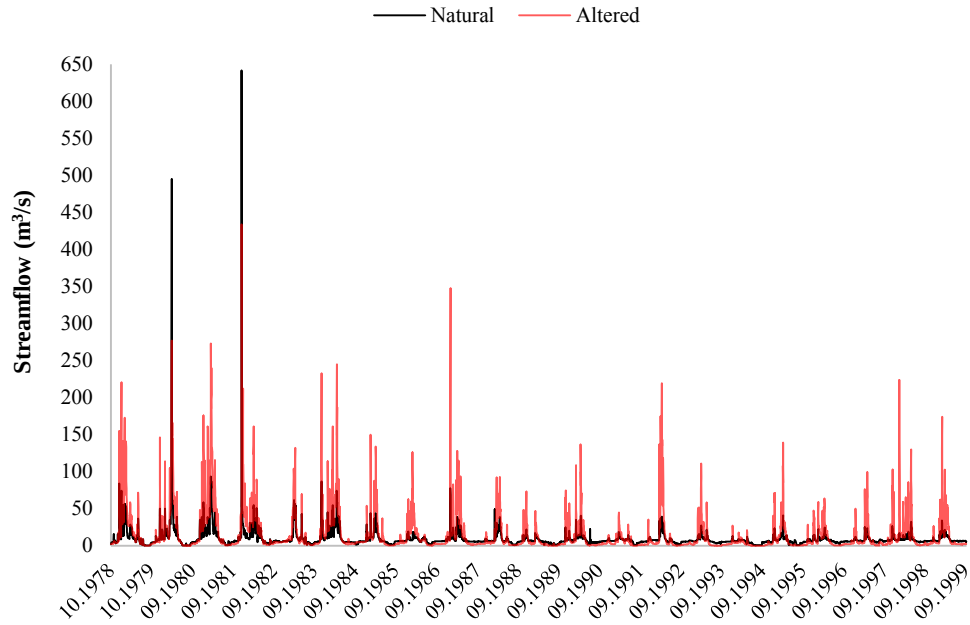
3.3.2.4 QPPQ Application

After selecting corresponding source gauges to naturalize the target gauge flows, natural target daily flows were calculated in their period of naturalization based on the corresponding reference daily exceedance probability percentiles. Linear interpolation between the fixed (i.e., the 18 percentiles) natural flow duration curve exceedance probability flows of the target gauges (Table 3.34) was performed. The resulting measured and natural daily flow time series of the target gauges are presented in Figure 3.20.



b)

E12A045-Streamflow Time Series (1979-1999)



c)

D12A034-Streamflow Time Series (1963-1996)

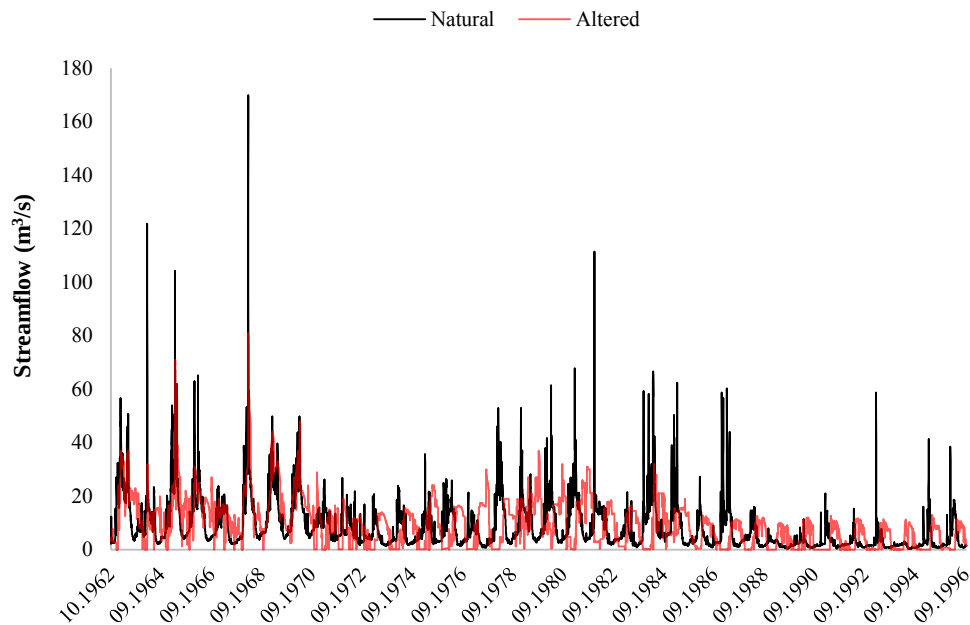


Figure 3.20. Daily flow time series of both altered and natural conditions at the target gauge locations. a) E12A024, b) E12A045 and c) D12A034

3.4 Summary and Discussion

In this chapter, a hydrologic foundation of the Sakarya watershed was developed, consisting of natural and altered daily streamflow time series at the selected target gauge locations. Since altered conditions are represented by the streamflow gauge measurements obtained from the State Hydraulic Works (DSİ) of Turkey, the daily streamflow data of the altered conditions were not included in the calculations. Therefore, the natural daily streamflow data of the target locations were produced using a statistical approach named 'Regional regression modeling and QPPQ method' commonly used by the USGS. According to this streamflow naturalization approach,

12 regression models were developed based on selected FDC exceedance probability percentile flows (i.e., 85%, 80%, 70%, 60%, 50%, 40%, 30%, 20%, 15%, 10%, 5% and 1%) by 29 reference streamflow gauges within the Sakarya watershed. Each natural exceedance probability percentile flow of the target locations was estimated using the model coefficients and gauge-based climatic and geospatial characteristics. After obtaining these 12 percentile flow values, the remaining FDC exceedance probability percentile flows (i.e., 90%, 95%, 99% and 99.9% and 0.5% and 0.1%) were completed using the linear regression against exceedance probability percentiles for greater than 85% and the Drainage Area Ratio (DAR) method for the exceedance probabilities less than 1%. The closest and linearly correlated reference gauge was considered to be used in the DAR method for target locations. In addition to the regression modeling, the QPPQ method was applied to generate daily sequence of the natural streamflows of the target locations. After coupling source and target gauges based on their linear natural FDC exceedance probability percentile flows, the daily source gauge flow-percentile information was translated into the target gauge daily flow information.

Among 10 climatic and geospatial independent variables introduced to the regional regression models, 7 variables were found to be the most statistically significant parameters for selected ones. The remaining 3 parameters were found as statistically

non-significant, which means the variability of these 3 variables do not define the variability of dependent variables. Thus, they were eliminated from the list. However, all of these 7 variables were not used for each 12 models (please see Table 3.35). It was detected that drainage area is the most significant variable.

Table 3.35 Statistically significant independent variables of the Sakarya watershed regional regression models

PERCENTILES	85	80	70	60	50	40	30	20	15	10	5	1
LONGITUDE												
DRAINAGE AREA	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
IMPERVIOUS COVER									✓	✓	✓	
CARBONATE ROCK					✓	✓	✓	✓	✓	✓	✓	✓
MEAN ANNUAL PRECIPITATION (MAP)							✓	✓	✓	✓	✓	✓
MEAN DAILY MAXIMUM TEMPERATURE (MMT)	✓	✓	✓	✓								
FOREST COVER					✓	✓	✓	✓	✓	✓	✓	✓
GRASSLAND COVER												
WOODLAND COVER												
MEAN BASIN ELEVATION	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	

The model performance and its predictive performance were evaluated using the commonly used statistical parameters. The model performance parameters were coefficient of determination (R^2) and adjusted coefficient of determination (**Adjusted R^2**). On the other hand, the predictive performance parameters of the models are **NSE** and **PBIAS** calculated by the linearized FDC exceedance probability percentile flow values. The predictive performance of the models was evaluated depending on the information provided by four validation gauges which were not included in the regression models. In addition, the performance of regional regression modeling + QPPQ method was evaluated by **NSE** which was calculated from the daily natural streamflow values.

At this point, the exceedance percentile flow range from $Q_{0.1}$ to $Q_{99.9}$ was divided into three classes showing different environmental flow regions in a flow duration

curve. Low flows are Q_{85} , Q_{90} , Q_{95} , Q_{99} , $Q_{99.9}$, medium flows are between Q_{10} and Q_{80} , and high flows are selected to be $Q_{0.1}$, $Q_{0.5}$, Q_1 , and Q_5 . The concept of low, medium, and high flow regions allows us to see whether the Sakarya watershed regional regression models would be sufficient to help making environmental flow decisions depending on the “Natural Flow Regime Paradigm” (Poff, et al., 1997).

The most challenging part of this study was to develop regression models with a limited database. Since Sakarya watershed have limited climatological, hydrological and geospatial data, input of the regression models has less number of data than the ones seen in the literature studies. To illustrate this, there are 347 gauges in Sakarya watershed (Table 3.2) however only 36 of them (i.e., 33 of them are reference, and 3 of them are target) have long-term data and could be used in this study. Yet, according to Moriasi et al. (2015), model and predictive performance evaluations yield good results for the three flow classes (i.e., low, medium, and high flow regions), indicating the regional regression models perform well (Table 3.36 and Table 3.36).

Table 3.36 Sakarya watershed regional regression model performance evaluation

%	R^2	Adjusted R^2	Performance Evaluation*
1	0.81	0.78	G
5	0.86	0.83	VG
10	0.88	0.84	VG
15	0.87	0.84	VG
20	0.88	0.85	VG
30	0.87	0.84	VG
40	0.87	0.85	VG
50	0.84	0.82	G
60	0.79	0.76	G
70	0.78	0.75	G
80	0.77	0.74	G
85	0.77	0.74	G

* G: good model performance, VG: very good model performance according to Moriasi et al. (2015)

The predictive performance evaluation of the regional regression models revealed that the model is partly satisfactory for the 60% and 70% flows along the modelled 12 FDC exceedance probability percentiles (Table 3.37). However, this does not

mean that the models cannot be used to predict these flows. Their uncertainty should be carefully taken into account while using this information. The remaining 11 models' predictive performances were found to range from satisfactory to very good. On the other hand, prediction performance of the linear regressions against exceedance probability percentiles was also satisfactory and good. The exceedance probability percentiles 99.9, 0.1 and 0.5 could not be statistically evaluated because they could not be calculated for validation gauges using the Weibull plotting formula. Thus, the Sakarya watershed regional regression models developed in this study and the linear regressions against exceedance probability percentiles can be implemented anywhere within the boundaries defined, however 60, 70 and 95% flows should be carefully taken into consideration.

Table 3.37 Sakarya watershed regional regression models' predictive performance evaluation based on NSE and PBIAS parameters

%	NSE	Performance Evaluation*	PBIAS	Performance Evaluation*
1	0.51	S	-0.1	VG
5	0.72	G	1.3	VG
10	0.69	S	-0.3	VG
15	0.67	S	-0.2	VG
20	0.57	S	-0.1	VG
30	0.61	S	1.8	VG
40	0.61	S	4.3	VG
50	0.69	S	9.1	G
60	0.87	VG	28.0	NS
70	0.87	VG	-52.2	NS
80	0.83	VG	-10.0	G
85	0.84	VG	-7.6	G

Table 3.38 Predictive performance evaluation of the linear regressions against exceedance probability percentiles for greater than 85% based on NSE and PBIAS parameters

%	NSE	Performance Evaluation*	PBIAS	Performance Evaluation*
90	0.85	VG	7.0	G
95	0.79	G	18.4	NS
99	0.86	VG	10.1	S

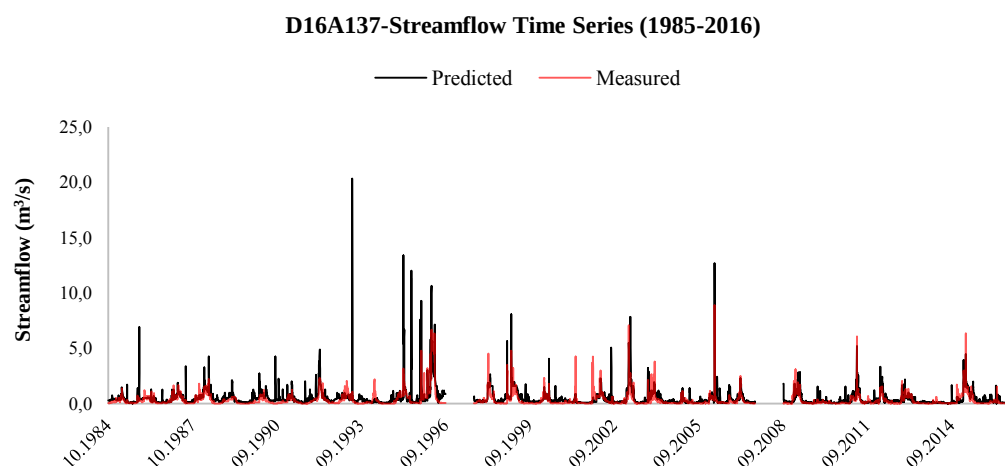
Table 3.39 A summary table of the validation-source gauge couples with their key characteristics

Characteristics	D16A137-D16A135	D12A003-E12A003	D12A152-D12A093	E12A039-D12A030
Drainage area (km²)	89.1-65.7	3912.01-3901.05	202.0-142.78	321.7-336.5
Elevation (m)	1076-1077	903-942	1155-1164	1039-1007
Reach name	Bulcuk Stream-Tekke Stream	Porsuk Creek-Porsuk Creek	Kokar Stream-Kokar Stream	Ova Stream-Sey Stream
Distance between (km)	8	1	11	31
Climate ch.*	7-7	7-7	18-18	7-18
Flow range (m³/s)	[0-15]-[0-8.9]	[1.95-160]-[1.7-145]	[0-19.5]-[0-10.5]	[0-86.5]-[0.01-40]

*Climate classes according to Beck et al. (2018); 7: arid steppe cold, 18: cold, dry summer, warm summer

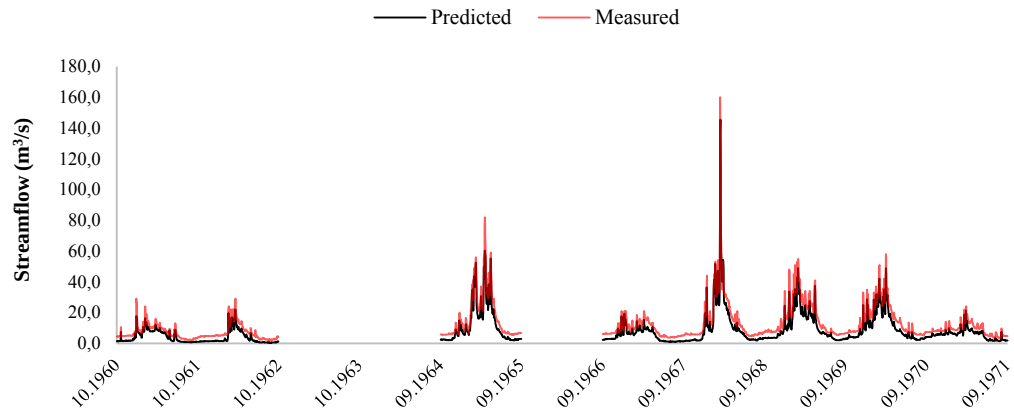
In addition to the performance evaluations given, the predictive performance of the whole methodology (regional regression modeling + QPPQ method) was evaluated using the four validation gauges' daily streamflow data (Figure 3.21). The performances change in terms of geomorphological setting of the validation gauges. As given in Section 3.3.1.4, the four validation gauges (Figure 3.15) were randomly selected to represent different landscape structures and subwatersheds within the watershed. One is in an arid part of the Upper Sakarya subwatershed, another one is in a wet part of the Ankara subwatershed, and the remaining two validation gauges are located in the headwater and mid-catchment areas of the Porsuk subwatershed.

a)



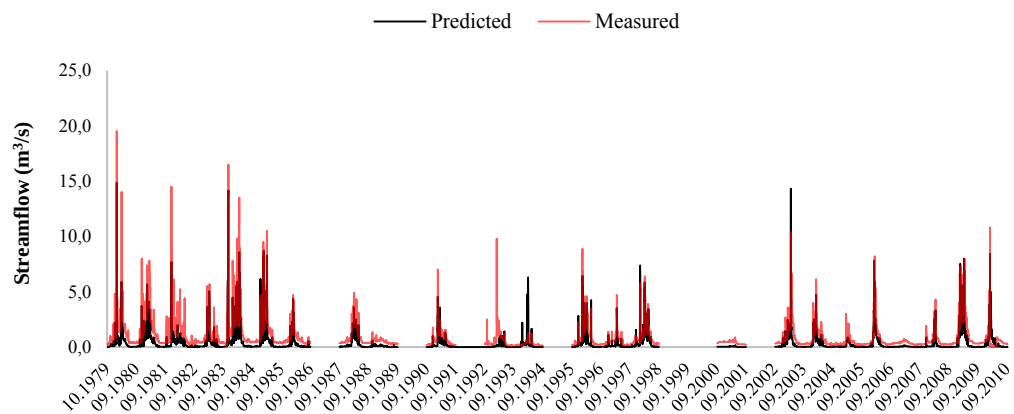
b)

D12A003-Streamflow Time Series (1961-1971)



c)

D12A152-Streamflow Time Series (1980-2010)



d)

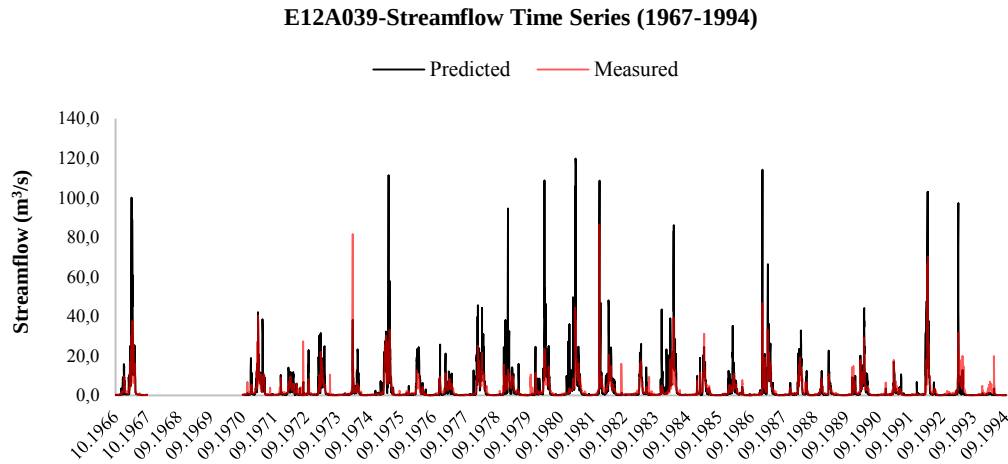


Figure 3.21. Predicted and measured daily streamflow time series of the validation gauges. a) D16A137, b) D12A003, c) D12A152 and d) E12A039

The NSE values calculated by the daily streamflow time series of the validation gauges were 0.11 for the arid Upper Sakarya validation gauge (D16A137), 0.83 for the Porsuk middle catchment validation gauge (D12A003), 0.45 for the Porsuk headwater validation gauge, and -0.13 for the Ankara headwater validation gauge (E12A039). These NSE values showed that the source gauge selection procedure is critical because as the difference between the characteristics of the gauges increases (Table 3.39), the prediction performance decreases. Moreover, since the main assumption behind the QPPQ method is that target site of interest has the same exceedance probability in the same day with the corresponding reference site, timing of the daily streamflows depends only on the selected source gauge. Another limitation of the QPPQ method is that there should be a common time period for both gauges. It should also be emphasized that the methodology used in this study should be only applied to the perennial streams, not ephemeral or intermittent flow regimes.

Each hydrograph and FDC built in this study indicate a different source of human alteration or pressure on the river because each drainage area has one or more dominating anthropogenic factor(s) such as irrigational water abstractions,

hydropower generation, cooling water abstractions, drinking water supply, etc.). With the help of the visual aids and their high temporal resolution data, future environmental flow and hydrologic alteration assessments would be guided.

In addition to the hydrologic alteration and environmental flow assessments, ecological/urban river restoration can be supported by this database with an additional and sufficient biological/morphological/water quality data collected. The ecological river restoration is a broad research area including sediment transport, physical habitat, biological, longitudinal-lateral-vertical connectivity, riparian vegetation assessments. A high resolution (means daily here) hydrological database plays a key role providing these assessments important supportive information.

Moreover, risk assessment studies can be conducted using this hydrological foundation to take measures to comply environmental management framework. One of the most common risk assessment type is flood risk assessment because the climate change deteriorates the global hydrological cycle and causes the frequency of extreme water conditions to increase (such as flooding) or decrease (for example drought). Thus, scientists around the world are working on this issue to comprehend its risks to the society, economy, ecosystem, and psychology by using this kind of hydrological database. On the other hand, drought risk assessment studies can be conducted using hydrological approaches. The hydrological drought assessments based on streamflow indices can be given as an example to the other extreme event analysis using streamflow information.

As can be seen in the above, the hydrologic foundation is a very functional tool to perform various future research about the hydrological conditions of the Sakarya watershed or Turkey. This study would guide the critical decision making processes related to the streamflow allocation assessments. Also, the database is used to assess hydrological alterations and environmental flows in the Sakarya watershed in the context of this study. Chapter 4 and 5 present these assessments depending on this high resolution streamflow database.

CHAPTER 4

HYDROLOGIC ALTERATION ASSESSMENT: IMPLEMENTATION OF THE INDICATORS OF HYDROLOGIC ALTERATION (IHA)/ RANGE OF VARIABILITY (RVA) METHOD

In this chapter, hydrologic alteration assessments conducted at the streamflow naturalization target sites selected in Chapter 3 are presented. The overview of this chapter as part of this thesis study is shown in Figure 4.1. This chapter basically presents the third step of the ELOHA framework where hydrological alterations are calculated and related to ecological responses. This chapter does not focus on this ecological response – hydrological alteration relationship because the required ecological data is either not available or not sufficient to make such an evaluation. However, the hydrologic alterations are found and their possible reasons are investigated in the Sakarya watershed. The tool used in the evaluation is the ‘Indicators of Hydrologic Alteration (IHA)/Range of Variability (RVA) approach’, which is the most commonly used method and software to evaluate the alteration level of hydrological regimes in river basins. In the following sections, literature research, methodology and results of the Sakarya watershed IHA/RVA assessment are given.

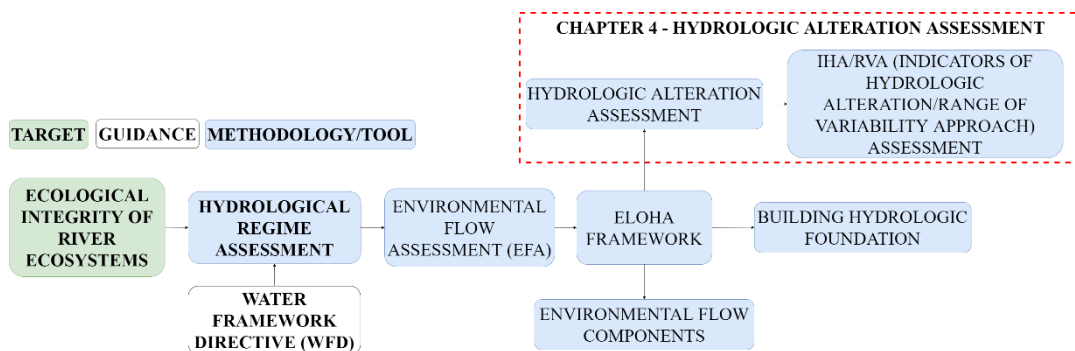


Figure 4.1. The details of Chapter 4 within the framework of this thesis study

4.1 Introduction

The natural flow regime paradigm (Poff et al., 1997) identified five critical components of streamflow regime: magnitude, frequency, duration, timing, and rate of change (Figure 4.2).

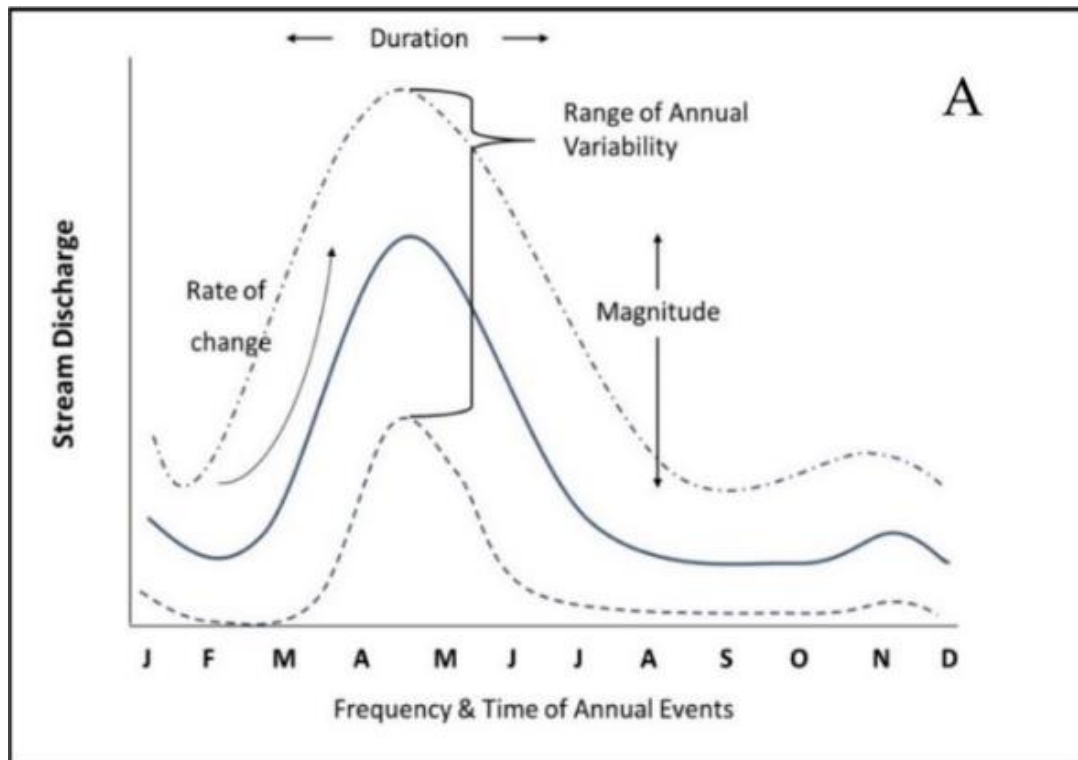


Figure 4.2. The natural streamflow regime components (Poff et al., 1997)

The entire range of streamflows and specific hydrologic occurrences (such as floods or low flows) of a riverine corridor can be defined using these five components. They have ecologically relevant meanings and play a key role in sustaining ecosystem services. Moreover, these components both directly and indirectly influence other primary regulators of ecological integrity, for example, water quality or physical habitat (Figure 4.3). As Poff et al. (1997) stated, ‘flow regime’ is the master variable affecting the biotic integrity of riverine ecosystems (Figure 4.3).

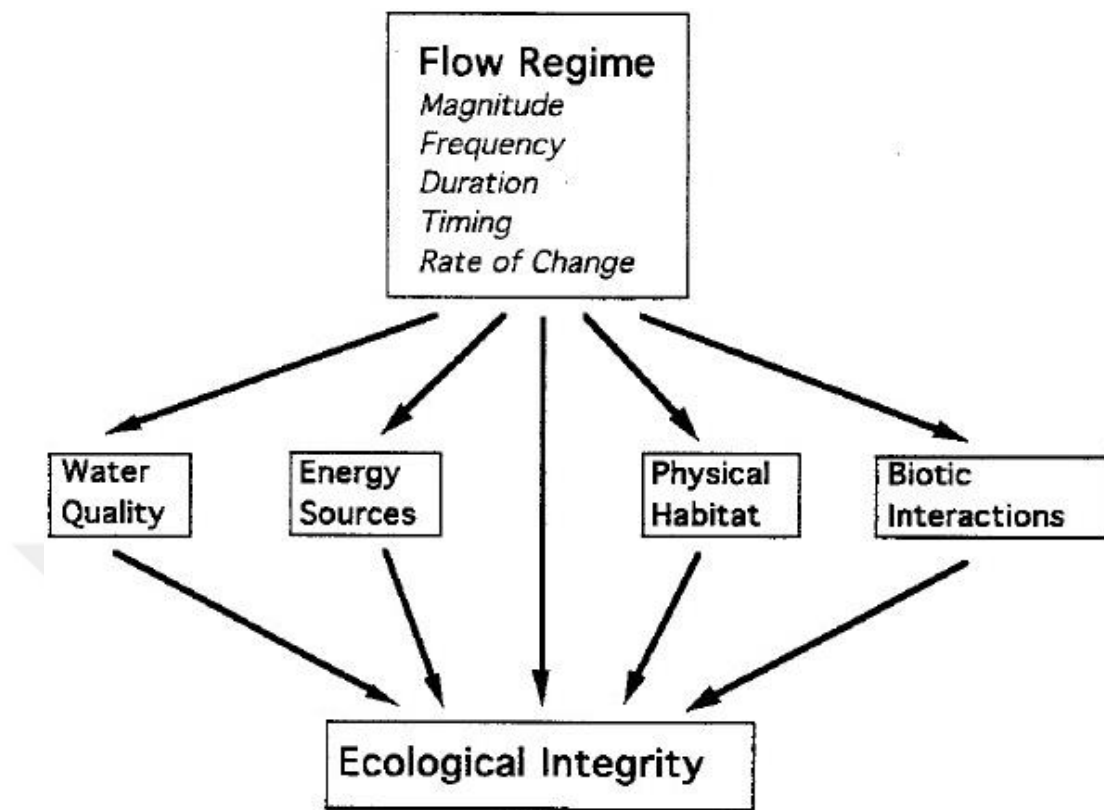


Figure 4.3. Components affecting the ecological integrity of natural river ecosystems (Poff et al., 1997)

By defining the streamflow regime in terms of these five components helps to consider the ecological consequences of any alteration explicitly. Before referring to the importance and methodologies of hydrologic alteration assessments, what is meant by hydrologic alteration should be highlighted. **Hydrologic alteration**, also named as flow alteration, is any climatic (for example, suprasedseasonal droughts) and human-induced (such as dam operations, flow diversion, intensive land-use change, flood control, irrigation, hydropower, transportation, recreation or water supply) modifications in natural streamflow characteristics leading to impairments in native biodiversity and their physical habitats in the riverine ecosystems (Carlisle et al., 2010; Department of Environmental Conservation, 2020; Poff et al., 1997; Ruhi et al., 2019; Zhang et al., 2018).

As stated by Whiting (2002), alterations in hydrological regime of riverine ecosystems directly affect both biological and geomorphic composition. Geomorphic alterations, then, lead to indirect ecological adjustments. These geomorphic alterations range from changes in streambed sediment size and physical dimensions (width, depth, etc.) of the channel to changes in the soil moisture content of floodplain (Figure 4.4).

Direct and indirect biological effects are well-explained by a new term called 'Hydrological Alteration and Biological Invasion Nexus' (Ruhi et al., 2019). According to this understanding, alterations in the natural flow regimes lead to invasions in aquatic habitats and biological species living in these habitats (Figure 4.5). Ruhi et al. (2019) explain the alteration-invasion nexus using three broad flow types explaining how native biodiversity is affected due to modifications in these flows:

- 1- Changes in scouring floods > Changes in channel form, habitat complexity, and patch disturbance; effects on natural physical habitats of native species
- 2- Changes in flow spates > Changes in dispersal and access of riverine organisms and subsidies (nutrients, organic particles, and larvae) to floodplain zone
- 3- Changes in natural disturbance regimes (changes in the five components – magnitude, frequency, duration, timing, and rate of change – of disturbance flows) > Changes in critical life cycle steps of organisms (such as spawning, recruitment, and seed dispersal)

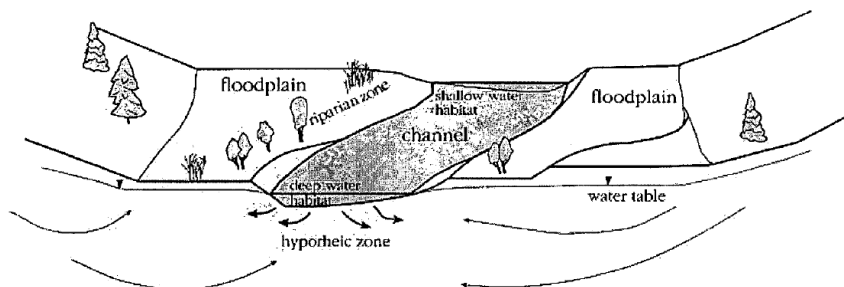


Figure 4.4. A sketch of riverine corridor components by Whiting (2002)

In Figure 4.5, an example is given to illustrate hydrologic alteration – biological invasion nexus. In the figure, natural flow dynamics of a location changed because of some human-induced activities (such as dams and diversions) and climate change. These factors caused duration of high flows to increase, magnitude of low flows to decrease dramatically, and base flows to shift in a decreasing trend. In addition to these factors, propagule pressure, which means introducing nonnative species to the environment, created a mixed environment with native and nonnative species. The ecological consequences of these alterations are:

- A decrease in the persistence of native species,
- A reduction of biotic resistance of native species,
- Increase in competition between native and nonnative species,
- Increase in the establishment and spread of nonnative organisms.

Finally, the river's ability to store energy and materials changed the availability and heterogeneity of resources that impaired native biodiversity and improved nonnative organisms' survival.

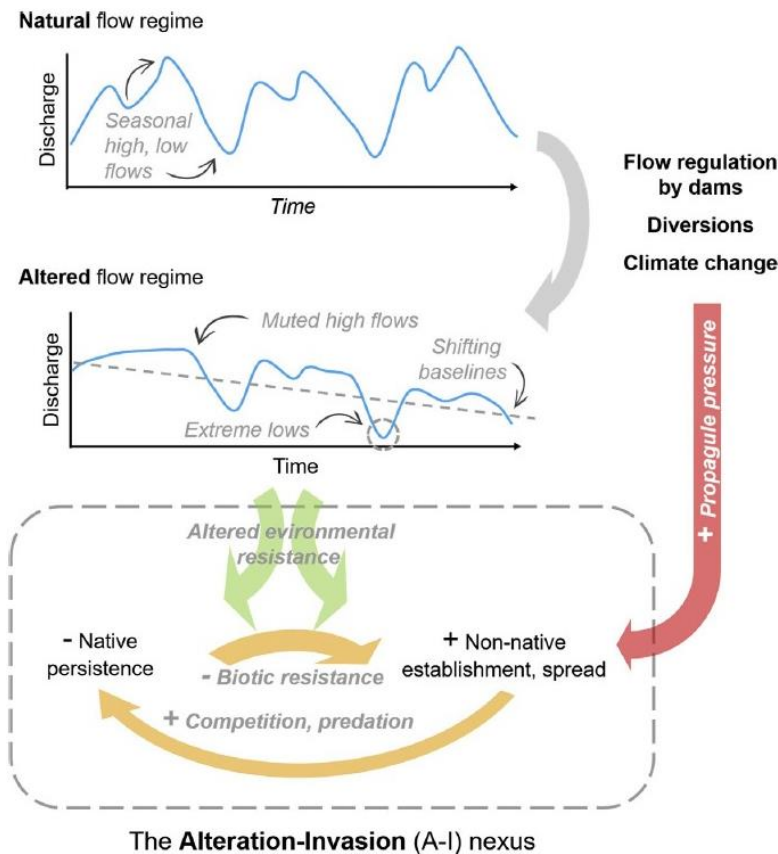


Figure 4.5. Hydrologic Alteration and Biological Invasion Nexus* (Ruhi et al., 2019)

**propagule pressure (also termed introduction effort): is a composite measure of the number of individuals of a species released into a region to which they are not native (Propagule pressure, 2018).*

The dynamic equilibrium between water and sediment movements is disrupted by any alteration in the natural hydrological regime. Aquatic and riparian habitats composed of various geomorphic features which depend on the natural behaviors of the system are altered because of this disruption. It is known that a new dynamic equilibrium of this system is attained for long periods – it may even take centuries for some type of riverine systems, and it is possible that some systems may never reach their equilibrium (Poff et al., 1997).

Because this study is based on the general framework of ELOHA, hydrologic alteration step is a must to determine environmental flows in Sakarya watershed. The assumption behind this step of the method is that increase in the flow alteration

degree from baseline conditions (i.e., natural flow regime) leads to an increase in ecological change and degradation of the biotic integrity of riverine ecosystems.

By using available software, hydrologic alteration degree can be calculated for each target site by comparing baseline and developed conditions of their flow dynamics. The 'Indicators of Hydrological Alteration' method is selected because it is the most commonly used method to interpret hydrological alterations (Black et al., 2005; Butchart-Kuhlmann et al., 2018; Gao et al., 2009; Ge et al., 2018; Kannan et al., 2018; Mathews & Richter 2007; McDaniel & O'Donnell, 2019; Pfeiffer & Ionita, 2017; Richter et al., 1996; Richter et al., 1997; Zhang et al., 2018).

Richter et al. (1996) first presented IHA as a statistical approach for characterization of the temporal variability in hydrological regimes using biologically relevant statistical attributes representing the needs of not only one or few species but the entire community living in aquatic, wetland and riparian ecosystems on the riverine corridors. Also, the method is developed to calculate hydrologic alterations compared to the natural conditions in a quantitative manner. This method is only for determining hydrologic alteration level. It does not consider any biological response relationship with these hydrological modifications.

The design of the methodology was based on the comparison between pre- and post-time frames of perturbations in the system (for example pre- and post- periods of operation of a dam). However as streamflow naturalization science is improved, these periods can become natural condition versus developed condition of any hydrologic regime. This study used the latter approach, and hydrologic alterations were calculated taking the natural conditions of the Sakarya River and its tributaries as a reference.

The computation of alteration level is done using IHA hydrologic parameters, which represent entire streamflow events of a hydrograph. These parameters show both intra-annual variations to characterize the water conditions introduced to the software and inter-annual variations to compare periods of different water conditions. They are also called indicators, where the name of the method comes

from. The authors classify these indicators into five groups having different regime characteristics (Table 4.1).

Table 4.1 Indicators of Hydrologic Alteration Method Groups of Indicators (Richter et al., 1996; The Nature Conservancy, 2009)

IHA statistics group	Regime characteristics	Hydrologic parameters
Group1: Magnitude of monthly water conditions	Magnitude Timing	1-12. Mean or median value for each calendar month
Group2: Magnitude and duration of annual extreme water conditions	Magnitude Duration	13. Annual minima 1-day mean
		14. Annual maxima 1-day mean
		15. Annual minima 3-day means
		16. Annual maxima 3-day means
		17. Annual minima 7-day means
		18. Annual maxima 7-day means
		19. Annual minima 30-day means
		20. Annual maxima 30-day means
		21. Annual minima 90-day means
		22. Annual maxima 90-day means
Group3: Timing of annual extreme water conditions	Timing	23. Number of zero-flow days
		24. Base flow index: 7-day minimum flow/mean flow for year
Group4: Frequency and duration of high and low pulses	Magnitude Frequency Duration	25. Julian date of each annual 1-day maximum
		26. Julian date of each annual 1-day minimum
		27. Number of high pulses within each water year
		28. Number of low pulses within each water year
Group5: Rate and frequency of water condition changes	Frequency Rate of change	29. Mean or median duration of high pulses (days)
		30. Mean or median duration of low pulses (days)
		31. Rise rates: Mean or median of all positive differences between consecutive daily values
		32. Fall rates: Mean or median of all negative differences between consecutive daily values
		33. Number of hydrologic reversals

The 33 IHA parameters represent a detailed structure of a hydrological regime to be able to make alteration assessment based on a separation technique. This technique combines the information provided by modification degree of each important natural variability component described by Poff et al. (1997) – magnitude, duration, frequency, timing, and rate of change. In the following, descriptions and ecological meanings of each IHA group are presented (Table 4.2).

IHA Statistics Group 1: Magnitude

12 of the total 33 parameters are in this group, which calculate the central tendency (mean or median) of each month using daily mean flow values of a given month. “Normal” daily conditions for a given month is described by these 12 parameters, providing indications for habitat availability or suitability.

IHA Statistics Group 2: Magnitude and Duration of Annual Extreme Conditions

12 parameters are in the second group of IHA statistics, which measure the magnitude and duration of extreme annual flow conditions. Magnitudes of the extremes are defined by minimum and maximum values, while duration is measured by a range of periods from daily to seasonal. These durations are 1-day and 3-day which are daily measure, 7-day which is weekly measure, 30-day which is monthly measure, and 90-day which is seasonal measure of extremes. Also, zero-flow days and baseflow index are computed in this group. Environmental stress and disturbance in a given year are measured using this group of statistics.

IHA Statistics Group 3: Timing of Annual Extreme Conditions

The same ecological processes as the ones in Group 2 are measured using this group of IHA statistics, which are environmental stress and disturbances. There are two parameters out of 33, which are Julian dates of the 1-day annual minimum and the 1-day annual maximum. Timings of the highest and lowest water conditions in a year provides measures for describing any stress or disturbance. As Poff et al. (1997) stated, there may be links between key life-cycle phases of ecological species (such as reproduction) and timing of the annual extremes.

IHA Statistics Group 4: Frequency and Duration of High and Low Pulses

Group 4 includes four parameters measuring frequency and duration of high and low flow pulses exceeding and remaining below their thresholds set by the decision-maker. Two of these four parameters provide information about the number of annual occurrences of each condition, while the remaining parameters measure the

mean or median duration of these pulses. The high and low pulses together obtain information on the hydrologic pulse nature of the area.

IHA Statistics Group 5: Rate and Frequency of Change in Conditions

In this group, three parameters measure the number and mean rate of both positive and negative changes from one day to the next. Intra-annual changes are evaluated using these parameters, giving an idea about the rate and frequency of these changes.

Table 4.2 IHA statistics groups and their ecosystem influences, adapted from The Nature Conservancy (2009)

IHA Statistics Group	Ecosystem Influences of the Group
Group 1: Magnitude of monthly water conditions	- Availability of habitats for aquatic organisms - Availability of soil moisture for plants - Water availability for terrestrial animals - Availability of food/cover for fur-bearing mammals - Reliability of water supplies for terrestrial animals - Access by predators to nesting sites - Influences on water temperature, chemistry (oxygen level), and photosynthesis process in the water
Group 2: Magnitude and duration of annual extreme water conditions	- Balancing competitive, ruderal, and stress-tolerant organisms - Creating sites for plant colonization - Structuring of aquatic ecosystems by abiotic vs. biotic factors - Structuring of river channel morphology and physical habitat conditions - Soil moisture and anaerobic stresses in plants - Dehydration in animals - Voluming nutrient exchanges between rivers and floodplains - Duration of stressful conditions such as low oxygen and concentrated chemicals in aquatic environments - Distribution of plant communities in lakes, ponds, floodplains - Duration of high flows for waste disposal, aeration of spawning beds in channel sediments

Table 4.2 IHA statistics groups and their ecosystem influences, adapted from The Nature Conservancy (2009) (continued)

IHA Statistics Group	Ecosystem Influences of the Group
Group 3: Timing of annual extreme water conditions	- Compatibility with life cycles of organisms - Predictability/avoidability of stress for organisms - Provision of accessibility to special habitats during reproduction or to avoid predation - Provision of spawning cues for migratory fish - Evolution of life history strategies, behavioral mechanisms
Group 4: Frequency and duration of high and low pulses	- Frequency and magnitude of soil moisture and anaerobic stresses for plants - Availability of floodplain habitats for aquatic organisms - Exchange of nutrients and organic matters between river and floodplain - Availability of soil mineral - Accessibility for waterbirds to sites of feeding, resting, and reproduction - Influences on bedload transport, channel sediment textures, and duration of substrate disturbance (high pulses)
Group 5: Rate and frequency of water condition changes	- Drought stress on plants (falling levels) - Entrapment of organisms on islands, floodplains (rising levels) - Desiccation stress on low-mobility streamedge (varial zone) organisms

In the year of 2009, The Nature Conservancy published the Manual of IHA software version 7.1, when they published 34 additional parameters to be integrated into the method, named Environmental Flow Components (EFCs) (The Nature Conservancy, 2009). These parameters measure the most essential environmental flow types affecting ecological integrity and its components (Figure 4.3). They are:

- Monthly low flows – mean or median of low flows during each calendar month (*12 parameters in total*)

- Extreme low flows – frequency, duration, peak, and timing of extreme low flow event of each year or season (*4 parameters in total*)
- High flow pulses – frequency, duration, peak, timing, and rise and fall rates of high flow pulses during each year or season (*6 parameters in total*)
- Small floods – frequency, duration, peak, timing, and rise and fall rates of small floods during each year or season (*6 parameters in total*)
- Large floods – frequency, duration, peak, timing, and rise and fall rates of large floods during each year or season (*6 parameters in total*)

Providing these flow types with their alteration level, ecological consequences of these alterations would be drawn explicitly, which is helpful to make multicriteria decisions within a sustainable water management context (Table 4.3).

Table 4.3 Environmental flow components of the IHA method and their ecosystem influences on river ecosystems, adapted from The Nature Conservancy (2009)

Environmental Flow Component	Ecosystem Influences of the Flow Component
Monthly low flows	- Adequate habitat for aquatic organisms
	- Acceptable water chemistry, water temperature, and dissolved oxygen concentration
	- Maintenance of soil moisture for floodplain zone
	- Provision of drinking water for terrestrial animals
	- Provision of space for fish and amphibian eggs
	- Provision of spaces for fish movement to feed and spawn
	- Provision of living spaces for hyporheic organisms which are the organisms live in sediment bottom of streambed
Extreme low flows	- Recruitment of certain floodplain plant species
	- Prevention of invasion of introduced aquatic and riparian species
	- Concentration of prey into limited areas to benefit predators

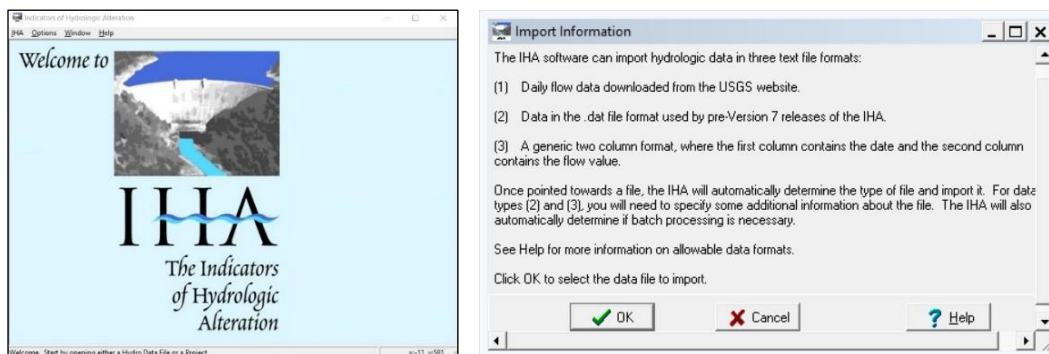
Table 4.3 Environmental flow components of the IHA method and their ecosystem influences on river ecosystems, adapted from The Nature Conservancy (2009) (continued)

Environmental Flow Component	Ecosystem Influences of the Flow Component
High flow pulses	- Shaping physical habitats of stream channels (including pools and riffles) - Characterizing streambed substrates (size of the substrates) - Prevention of encroaching of riparian vegetation into stream channel - Restoring normal water quality conditions after prolonged low flows by flushing away waste products and water pollutants - Preventing siltation, which helps to aerate eggs in spawning gravel areas
Small floods	- Provision of migration and spawning cues for fish - Triggering new phase in life-cycle (i.e. insects) - Provision of nursery area for juvenile fish by enabling fish to spawn in floodplain - Provision of new feeding opportunities for fish, waterfowl - Recharging floodplain zone groundwater table - Maintenance of floodplain forest biodiversity through prolonged inundation (meaning different plant species have different tolerances) - Controlling distribution and abundance of floodplain plant species - Depositing nutrients on floodplain
Large floods	- Maintenance of balance of species in aquatic and riparian communities - Creating sites for recruitment of colonizing plants - Shaping physical habitats of floodplain zone - Carrying and depositing gravel and cobbles in spawning areas - Flushing both organic materials (food) and woody debris into channel - Prevention of invasion of introduced aquatic and riparian communities - Dispersal of seeds and fruits of riparian plants - Driving lateral movement of river channel, forming new habitats like secondary channels, oxbow lakes - Provision of plant seedlings with prolonged access to soil moisture

4.2 Materials and Methods

The Indicators of Hydrologic Alteration (IHA) method involves two parameter groups consisting of 67 parameters (please refer to section 4.1 and 5.1 for the details) to determine hydrologic alterations and environmental flow requirements in a quantitative manner: IHA (33 parameters) and Environmental Flow Components (EFCs) (34 parameters). 33 of these parameters provide essential information on flow modifications due to various anthropogenic factors and possible ecological impacts caused by these modifications. Since this chapter includes the hydrologic alteration assessment in the Sakarya watershed, only IHA parameters are used to calculate hydrologic alteration levels at the target locations.

The Nature Conservancy (TNC) improved the efficiency of the method by developing a software. The interface of this software can be seen in Figure 4.6. The data required to feed this software is daily streamflow data which should be prepared for two conditions: natural and altered flow conditions. Altered flow conditions refer to the impacted hydrological regimes due to human modifications such as dam operations while natural conditions are defined by no impacts of any external factor to the river ecosystems. The natural and altered streamflow data are statistically compared to determine flow deviations from the unimpaired conditions. Thus, the hydrologic alteration levels were calculated using this software.



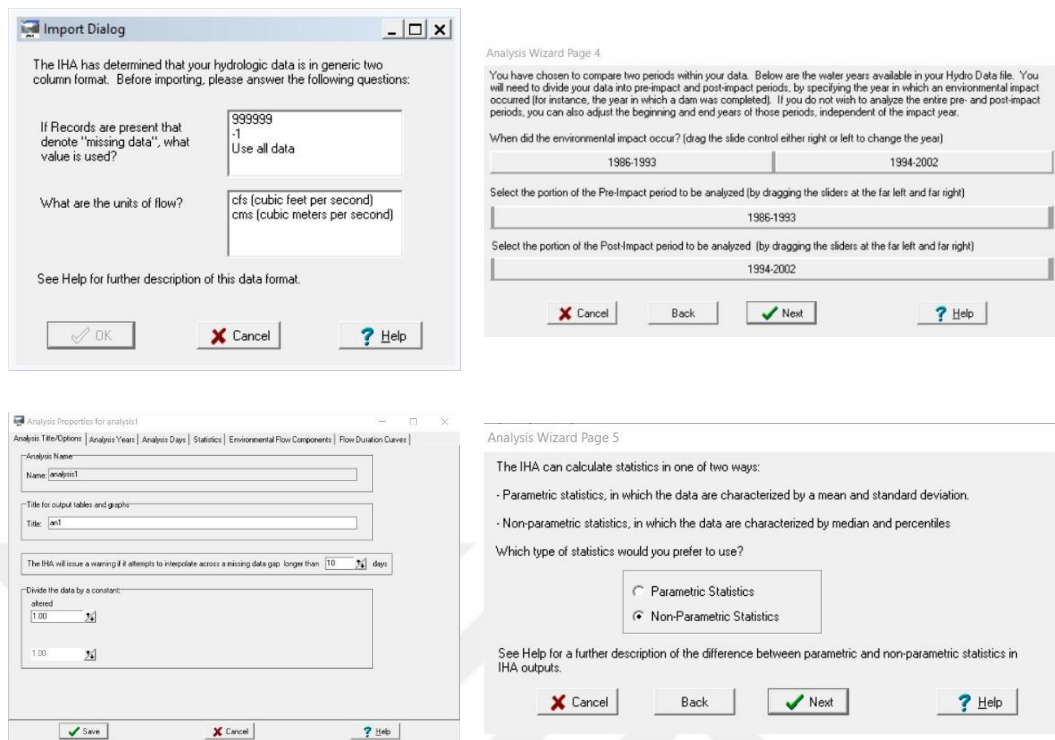


Figure 4.6. Example pop-up windows of the Indicators of Hydrologic Alteration (IHA) Software

Richter et al. (1997) introduced an approach called ‘Range of Variability (RVA)’ to identify river management targets regarding ecological flow needs of the river ecosystems and environmental flow decisions. According to this approach, there are three RVA zones defining low, middle and high frequency ranges of the streamflow events defined by the IHA parameters. Among these three, the middle RVA zone is the target for environmental flow management since it defines a range where the number of occurrences of the flow events are naturally and commonly observed. As emphasized by the Nature Conservancy (2009), Richter et al. (1997) stated that it would be ideal that the any water decision maker should keep the annual IHA parameter values as close to the natural distributions as possible. Thus, the frequency of the occurrences of each flow event within this RVA zone determines the management goals in the context of environmental flow assessment (Figure 4.7). Moreover, the hydrologic alteration levels can be defined within all these RVA zones and can be related to each other to comprehend the modifications in a holistic way.

In this study, the middle (target) RVA range was not individually evaluated since the changes occurred within this RVA range appeared in different ways within either low or high RVA ranges. For example, a 100% decrease in the target RVA range can cause a 100% increase in the low range, and the hydrological alterations can comprehensively be interpreted with this change.

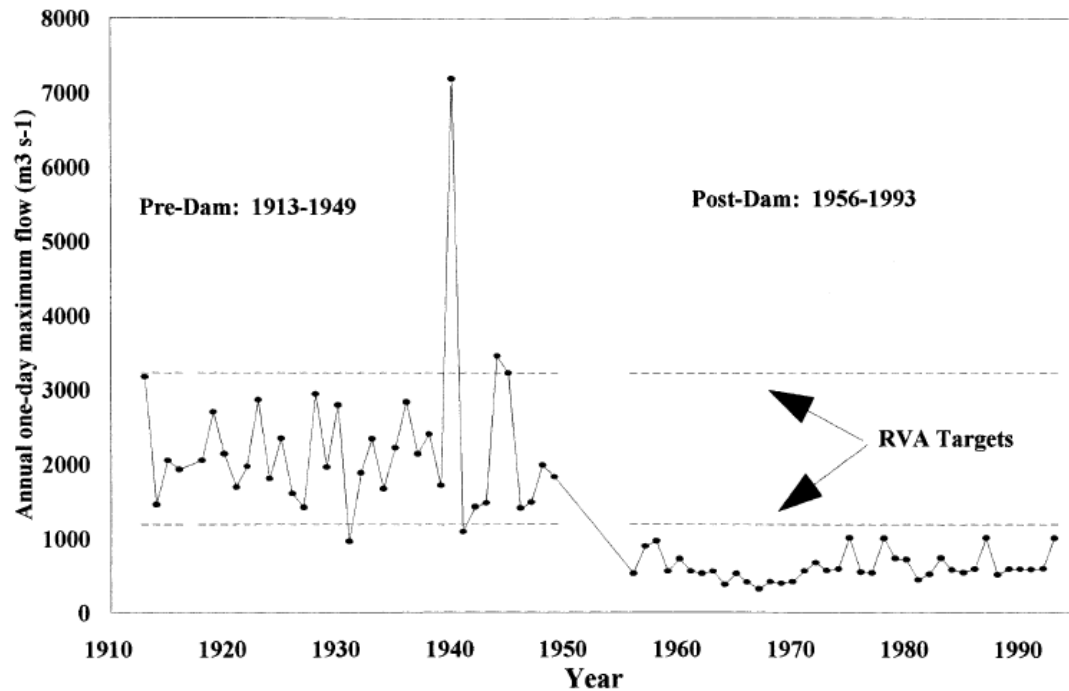


Figure 4.7. An example IHA/RVA assessment figure showing target boundaries by Richter et al. (1997)

Two statistical analysis types are available to determine the boundaries defining these RVA zones: non-parametric and parametric analyses. In non-parametric analysis, percentile values are used while a number of standard deviations away from the mean are the criteria for parametric analysis. Since it is suggested to use the non-parametric analysis in the IHA manual document (The Nature Conservancy, 2009), it was selected for this study. In this analysis, the values of 17 percentiles from the median of each IHA parameter are used as the boundaries. In other words, 33rd percentile and 67th percentile of each IHA parameter delineate the middle RVA zone upper and lower boundaries and automatically the low and high RVA zones. After

determination of these two boundaries, the expected number of occurrences (frequencies) in terms of annual data are calculated within each RVA range during natural conditions. Same calculations are performed for the frequencies during altered conditions to see actual number of occurrences of these flow events.

Finally, the calculations of the hydrologic alteration degrees within each RVA zone are performed based on these natural and altered frequency information. The hydrologic alterations are calculated using the formula given below:

$$HA = \frac{N_A - N_N}{N_N}$$

HA = hydrologic alteration percentage, N_A = the number of water years observed within an RVA range of the altered conditions, N_N = the number of water years observed within an RVA range of the natural conditions

In this section, the results of the IHA parameter groups are individually given as hydrologic alteration degrees. As given in the methodology section, the hydrologic alteration degrees are presented in three ranges defined by the RVA methodology: low, middle (target), and high. These ranges indicate how each IHA parameter has changed by taking the natural middle frequencies as the reference condition. For example, the February median monthly flow value of the expected natural flow regime of the gauge D12A034 decreased 67% in both the middle and high RVA ranges while it is observed in the low RVA range under altered conditions with an increase by 118% (Figure 4.8). This means that the February median flows of the location has so dramatically decreased that this flow is mostly observed below the lower RVA threshold (i.e., 7.37 m³/s) due to the upstream human perturbations. All RVA boundaries specified by the IHA software are summarized in Table 4.8 for each target gauge location in the Sakarya watershed.

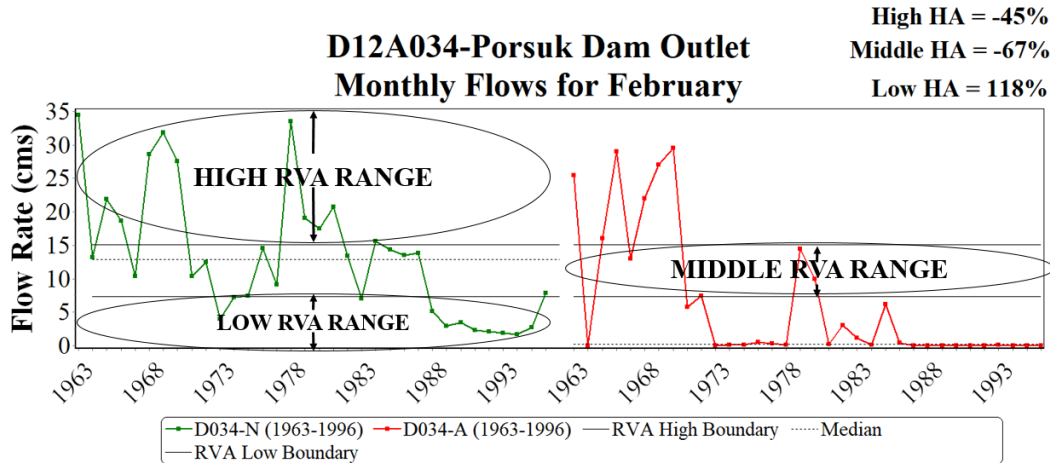


Figure 4.8. An example to the IHA/RVA range representations – February median flows of the gauge D12A034. Green line shows the natural occurrence of the event and the red line reflect the altered February median flows.

4.3 Results

The hydrologic alteration assessment results of the three target gauges (Figure 4.9) are presented in this section. Also, potential pressure factors causing these significant hydrologic changes are analyzed at each upstream drainage area. It was determined at what degree the natural streamflow variability and dynamics have adversely been influenced due to various human perturbations in the watershed. Each gauge reflect one or more adverse effects of the anthropogenic activities taken place at the upstream drainage area, such as long-term dam operations, massive agricultural water abstractions/diversions for irrigation practices, heavy urbanization, etc.

The results are presented as 1) changes in the average annual statistics within the assessment periods (Table 4.4), 2) the hydrologic alteration degrees in each RVA range, and 3) overall hydrologic alterations of the Sakarya River.

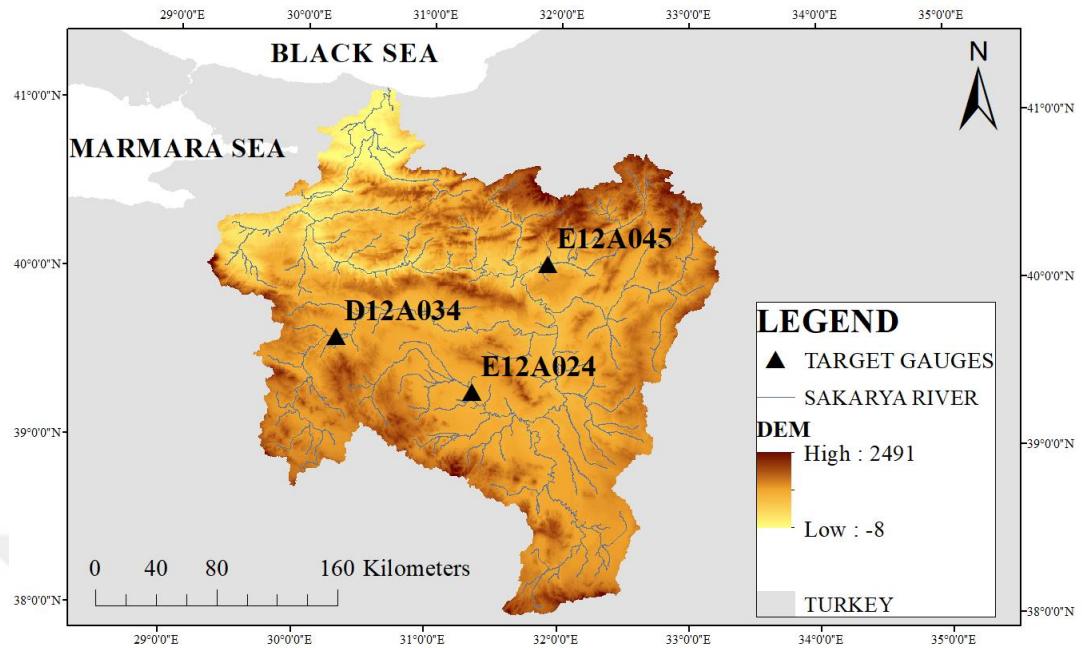


Figure 4.9. Locations of the target gauges on the Sakarya River and its tributaries

The target gauges included in this assessment are selected based on the streamflow naturalization process performed in Chapter 3 of this study. Their hydrologic foundations were established on a daily basis. Thus, daily natural and altered streamflow information of these gauges were provided to the IHA/RVA methodology to obtain hydrologic alteration levels in this chapter of the study. The assessment periods of the target sites (Table 4.4) were selected based on the length of the common time period of daily natural and altered datasets.

Table 4.4 IHA/RVA assessment time periods of the target locations in the Sakarya watershed

Subwatershed	Target gauge	IHA/RVA period
Upper Sakarya	E12A024	1986-2016
Ankara	E12A045	1979-1999
Porsuk	D12A034	1963-1996

Before hydrological modifications are discussed at each target location (Table 4.4), the existing hydromorphological pressures were detected. Thus, the possible causes of the alterations could be evaluated with and related to the alteration information.

Each target gauge upstream area was analyzed to detect all human perturbations resulting in hydromorphological modifications in the river ecosystems. Ultimately, it has been found that there are certain dominant sectors requiring water from both surface and subsurface of the Sakarya River system at each drainage area. These sectors are: agriculture (i.e., irrigation and livestock watering), energy production (mostly hydropower generation with big reservoirs), drinking and utility, industry, and mining. The most dominant ones within each target drainage area are given in Table 4.5 as a summary.

Agriculture is undoubtedly the most dominant sector using water from the Sakarya River, and its groundwater reserves, which is around 70% of all water uses in the watershed (Alp et al., 2019). Especially in the Upper Sakarya subwatershed target location (i.e., E12A024), agricultural lands are irrigated by diversion weirs, big dams, and small reservoirs with open and piped channel systems. On the other hand, a big portion of these lands are irrigated by groundwater abstractions of both individual and public wells. There are two big impoundments (i.e., dams) which are operated to supply irrigational water in this area. At this point, it should be highlighted that almost all irrigated lands are located on the floodplains!

In Porsuk subwatershed target location (i.e., D12A034), three dominant sectors are seen: agriculture, drinking water, and industry/mining. The biggest contribution to the hydrological modifications in the area is because of the Porsuk dam. This dam is operated to prevent flooding, supplying drinking water to the Eskişehir province, and supplying irrigational water to the downstream agricultural lands. Since the D12A034 target gauge is located at the outlet of this dam, it is known that the streamflow regime at the downstream area is directly affected by the dam operation rules. And these operation rules are determined mostly by the upstream and downstream human activities which take place in the Kütahya and Eskişehir provinces. Since a significant portion of the population in Kütahya lives upstream of the D12A034 gauge, the drinking and utility water of this population is supplied from the Porsuk creek system. In addition to Kütahya, Eskişehir receives its drinking and utility water from the same source by the Porsuk dam. Many industrial and mining

activities occur in the area, and they abstract water for their processes. Also, irrigational water is supplied by diversion structures and small reservoirs. Thus, it is more likely that these human perturbations would cause hydrological alterations in the area however there is another adverse effect that should be emphasized here, which is deterioration of the water quality. When assessing the environmental flows, this water quality degradation should also be taken into consideration since hydrological conditions do not individually reflect the ecological conditions in an assessment region.

At the upstream drainage area of the target gauge E12A045, the most significant water allocation is to drinking water system. This is because Ankara is the capital city of Turkey and almost 6 million people (5,639,076 people in 2019) live in this province according to the Turkish Statistical Institution (TÜİK) (2019). Several sizes of reservoirs are operated to supply drinking water requirements. The highlight at this point is that these impoundments are mostly located at the upstream of the Ankara subwatershed. Also, irrigational and industrial activities use the Ankara creek surface and groundwater sources for their activities.

Table 4.5 The dominant hydromorphological pressures* at the target locations in the Sakarya watershed as a summary table

Gauge no	A (I)	D	E	I/M
E12A024	✓			
D12A034	✓	✓		✓
E12A045		✓		✓

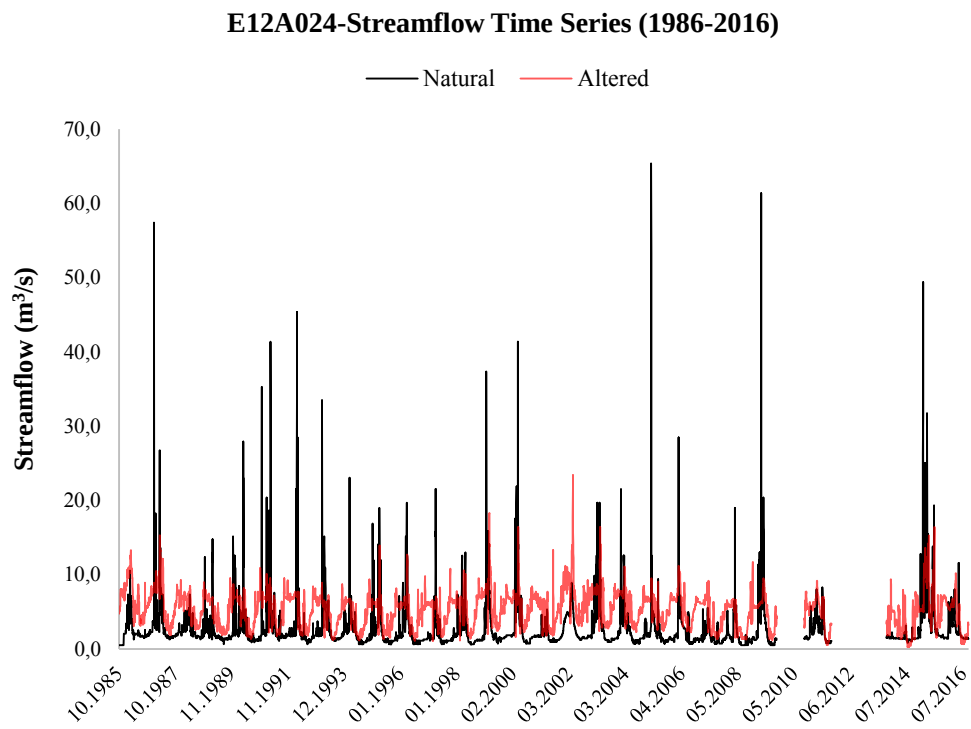
* A (I): Agriculture (Irrigation), D: Drinking water, E: Energy production, I & M: Industry and Mining. Other sectors also demand water at each region however they are not the major sector using water.

4.3.1 Results of average statistics within the assessment periods

The natural range of variations introduced to the IHA software were characterized by predicted daily mean unregulated (natural) flow records ranging from 21 to 34 years. On the other hand, regulated (altered) characteristics of the streamflow of the

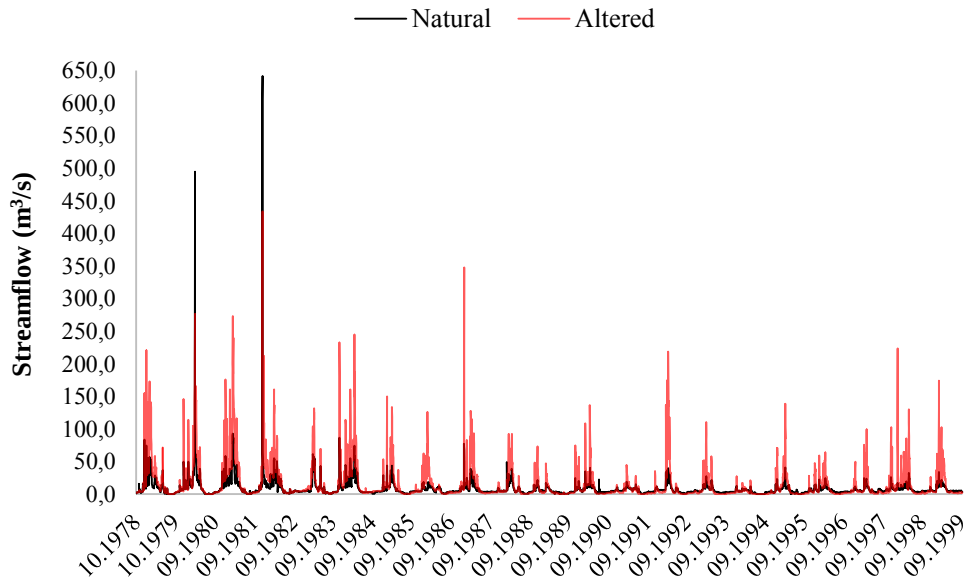
target gauges were determined using the gauge measurement data in the same period. These two daily streamflow time series during the assessment periods of the target locations are given in Figure 4.10 for each target gauge.

a)



b)

E12A045-Streamflow Time Series (1979-1999)



c)

D12A034-Streamflow Time Series (1963-1996)

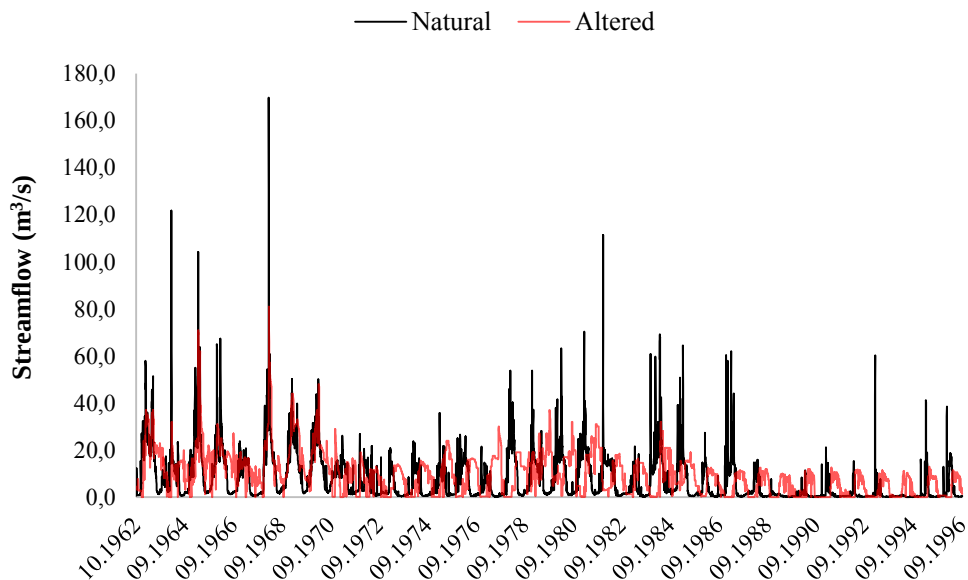


Figure 4.10. Daily natural and altered streamflow time series of the target gauges in the Sakarya watershed to introduce to the IHA software. a) E12A024, b) E12A045 and c) D12A034

These two flow datasets for each target gauge are used to generate a non-parametric scorecard table demonstrating average annual statistical characterizations. Table 4.6 presents this characterization by comparing mean annual flows, annual coefficient of variation, flow predictability, the ratio between constancy and predictability, % of floods, and flood-free season length of each gauge.

Table 4.6 Non-parametric scorecard table of the target gauges included in the Sakarya watershed IHA/RVA assessment

		NF*	MAF*	NMAF*	ACV*	P*	C/P*	PF60*	FFS*
E12A024	Natural conditions	1	2.56	2.56	1.69	0.62	0.74	0.45	45
	Altered conditions	1	5.28	5.28	0.45	0.71	0.75	0.45	0
E12A045	Natural conditions	1	9.18	9.18	1.55	0.62	0.7	0.38	117
	Altered conditions	1	14.03	14.03	1.89	0.4	0.34	0.38	104
D12A034	Natural conditions	1	8.29	8.29	1.11	0.42	0.67	0.38	52
	Altered conditions	1	9.63	9.63	0.93	0.42	0.67	0.38	0

*NF = Normalization factor, MAF=Mean annual flow (cms), NMAF = Non-normalized mean flow (cms), ACV = Annual coefficient of variation, P = Flow predictability, C/P = Flow constancy/predictability ratio, PF60 = % of floods in 60d period (%), FFS = Length of flood free season (day)

Table 4.7 Percent of changes in the flood free season lengths of target sites in the Sakarya watershed

	Flood free season (days)	% of change
E12A024	Natural conditions	45
	Altered conditions	0
E12A045	Natural conditions	117
	Altered conditions	104
D12A034	Natural conditions	52
	Altered conditions	0

In Upper Sakarya and Porsuk subwatersheds, even though % of floods in 60 day period did not changed, the flood-free season has the most notable results (Table 4.7), which are zero! E12A024 is at the downstream of a massive irrigational activity supplied by two dams and several weirs. On the other hand, D12A034 is located at the outlet of the Porsuk dam – which is a big impoundment having a major impact on the streambed, bank and floodplain ecosystems at the downstream. This is very important to be highlighted here because the natural condition shows us that these streambeds were not always under flood conditions. The aquatic and terrestrial

organisms adapted to live in an ecosystem where there are times when flood events occur time to time according to the natural flow conditions.

In Ankara subwatershed, the change in the flood free season did not change like in the Upper Sakarya and Porsuk subwatersheds. Even though there is a decrease in the flood free season length, it is not as high as the changes observed at other gauges. Since it is known that this region has various types of anthropogenic factors deteriorating natural balance in the stream ecosystems, the changes calculated as average statistics within their whole assessment time periods might not reflect the changes expected regarding flood free season parameter. Therefore, the IHA group-based alterations should be further analyzed to see the big picture in the areas.

At this point, it should be emphasized that these statistics should not be used alone to understand hydrologic alteration levels, even though they give a general idea about the changes. A more detailed assessment using the IHA group parameters should be included to gain more comprehensive information. Thus, in the following, the IHA group parameter changes are analyzed for the Sakarya watershed.

The hydrologic alteration degrees of each RVA range are summarized for every target location in the Sakarya watershed in section 4.3.2. On the other hand, the IHA groups of parameters are individually assessed in section 4.3.2 to discuss the cause-effect relationships between possible factors at the upstream and the changes in these parameters.

Table 4.8 RVA boundaries of the Sakarya watershed target gauges – Upper Sakarya and Porsuk subwatersheds

	E12A024		D12A034		E12A045	
	RVA Low	RVA High	RVA Low	RVA High	RVA Low	RVA High
Parameter Group #1						
October	1.19	1.46	2.61	4.55	5.24	5.84
November	1.41	1.61	2.72	5.44	5.71	6.55
December	1.61	2.28	3.96	8.34	6.55	9.31
January	1.85	2.56	4.38	13.77	7.04	9.54
February	2.08	4.21	7.37	15.08	7.03	11.92
March	3.65	4.93	13.07	15.88	10.32	13.34
April	2.92	5.22	11.51	15.72	11.83	20.53
May	2.14	2.76	6.19	13.66	7.34	9.68

Table 4.8 RVA boundaries of the Sakarya watershed target gauges – Upper Sakarya and Porsuk subwatersheds (continued)

	E12A024		D12A034		E12A045	
	RVA Low	RVA High	RVA Low	RVA High	RVA Low	RVA High
June	1.49	1.98	3.55	7.69	5.75	7.25
July	1.10	1.41	1.59	3.85	4.09	5.16
August	0.95	1.39	1.27	2.72	1.49	3.86
September	0.95	1.34	1.65	3.80	2.89	4.88
Parameter Group #2						
1-day minimum	0.64	0.91	0.92	2.11	1.23	2.13
3-day minimum	0.71	0.95	1.01	2.23	1.23	2.17
7-day minimum	0.72	0.96	1.10	2.29	1.27	2.76
30-day minimum	0.84	1.13	1.26	2.54	1.51	3.63
90-day minimum	1.01	1.26	1.62	3.43	3.18	4.51
1-day maximum	14.02	35.18	25.10	57.54	28.47	58.56
3-day maximum	10.85	20.49	21.31	50.01	27.18	51.39
7-day maximum	8.25	13.93	18.78	39.66	22.55	35.94
30-day maximum	5.70	8.43	14.67	26.14	15.32	26.86
90-day maximum	4.20	5.80	11.06	19.09	11.82	17.13
Number of zero days	0.00	0.00	0.00	0.00	0.00	0.00
Base flow index	0.30	0.39	0.20	0.26	0.15	0.32
Parameter Group #3						
Date of minimum	199.1	223.6	227.6	240.5	215.8	236.7
Date of maximum	62.6	105.4	64.0	96.2	75.3	98.7
Parameter Group #4						
Low pulse count	2.0	4.4	1.6	3.5	2.0	3.7
Low pulse duration	5.5	19.9	5.0	11.5	12.8	35.4
High pulse count	3.0	6.4	4.0	6.0	4.0	5.0
High pulse duration	4.0	17.4	4.0	6.0	7.0	11.9
Parameter Group #5						
Rise rate	0.26	0.37	0.24	0.46	0.41	0.62
Fall rate	-0.30	-0.26	-0.40	-0.24	-0.53	-0.40
Number of reversals	46.0	58.4	87.6	102.5	44.0	55.5

4.3.2 Overall results of IHA/RVA analysis in the Sakarya watershed

In this section, hydrologic alteration degrees of the target locations in the Sakarya watershed region calculated based on IHA/RVA groups are given. Since the natural middle RVA range (Figure 4.8) is the target condition, hydrologic alteration degrees projected on the maps (Figure 4.21) indicate these alteration levels. However, the low and high RVA ranges are also presented to interconnect the results and to show the whole picture. The summary of the alteration percentages are given in between Table 4.9 and Table 4.11 indicating changes in the low, middle and high RVA ranges. The alteration degrees were classified into 4 classes which are: low or little

or no alteration (0-33%), moderate alteration (34-67%), high alteration (68-100%), and severe alteration - S (> 100%). These classes have been developed using the approach proposed by Gierszewski et al. (2020); Hayes et al. (2018); Richter et al. (1998); Zimmerman et al. (2018). Each target gauge was analyzed based on their hydrologic alteration results and the possible anthropogenic pressures resulting in these alterations at their upstream drainage areas.

Table 4.9 Low RVA range hydrologic alteration values (%) of the Sakarya watershed target locations

*	E12A024	E12A045	D12A034
Parameter Group #1	-100.0 (H)	200.0 (S)	-36.4 (M)
October	-100.0 (H)	350.0 (S)	18.2 (L)
November	-100.0 (H)	116.7 (S)	100.0 (H)
December	-100.0 (H)	42.9 (M)	90.9 (H)
January	-100.0 (H)	14.3 (L)	118.2 (S)
February	-100.0 (H)	-50.0 (M)	136.4 (S)
March	-88.9 (H)	-42.9 (M)	127.3 (S)
April	-100.0 (H)	57.1 (M)	-90.9 (H)
May	-100.0 (H)	85.7 (H)	-100.0 (H)
June	-75.0 (H)	200.0 (S)	-100.0 (H)
July	-75.0 (H)	128.6 (S)	-100.0 (H)
August	-100.0 (H)	185.7 (S)	-90.9 (H)
September	-100.0 (H)	200.0 (S)	-36.4 (M)
Parameter Group #2			
1-day minimum	-40.0 (M)	157.1 (S)	200.0 (S)
3-day minimum	-50.0 (M)	142.9 (S)	181.8 (S)
7-day minimum	-66.7 (M)	142.9 (S)	181.8 (S)
30-day minimum	-66.7 (M)	157.1 (S)	118.2 (S)
90-day minimum	-100.0 (H)	200.0 (S)	81.8 (H)
1-day maximum	144.4 (S)	-85.7 (H)	72.7 (H)
3-day maximum	88.9 (H)	-85.7 (H)	54.6 (M)
7-day maximum	-44.4 (M)	-85.7 (H)	45.5 (M)
30-day maximum	-88.9 (H)	-85.7 (H)	18.2 (L)
90-day maximum	-100.0 (H)	-85.7 (H)	0.0 (L)
Number of zero days	0.0 (L)	0.0 (L)	0.0 (L)
Base flow index	0.0 (L)	200.0 (S)	190.9 (S)
Parameter Group #3			
Date of minimum	66.7 (M)	-28.6 (L)	63.6 (M)
Date of maximum	-55.6 (M)	14.3 (L)	-72.7 (H)
Parameter Group #4			
Low pulse count	187.5 (S)	-100.0 (H)	-45.5 (M)
Low pulse duration	0.0 (L)	-16.7 (L)	71.4 (H)
High pulse count	0.0 (L)	0.0 (L)	162.5 (S)
High pulse duration	-71.4 (H)	50.0 (M)	-77.8 (H)
Parameter Group #5			

Table 4.9 Low RVA range hydrologic alteration values (%) of the Sakarya watershed target locations (continued)

*	E12A024	E12A045	D12A034
Rise rate	166.7 (S)	-71.4 (H)	-100.0 (S)
Fall rate	-75.0 (H)	142.9 (S)	154.5 (S)
Number of reversals	-100.0 (H)	-85.7 (H)	209.1 (S)

*These alteration degrees were classified into 4 classes which are: low or little or no alteration (0-33%), moderate alteration (34-67%), high alteration (68-100%), and severe alteration - S (> 100%). These classes have been developed using the approach proposed by Gierszewski et al. (2020); Hayes et al. (2018); Richter et al. (1998); Zimmerman et al. (2018).

Table 4.10 Middle RVA range hydrologic alteration values (%) of the Sakarya watershed target locations

*	E12A024	E12A045	D12A034
Parameter Group #1			
October	-100.0 (H)	-100.0 (H)	-69.2 (H)
November	-100.0 (H)	-81.8 (H)	-38.5 (M)
December	-100.0 (H)	-87.5 (H)	-58.3 (M)
January	-100.0 (H)	-85.7 (H)	-41.7 (M)
February	-90.0 (H)	-71.4 (H)	-66.7 (M)
March	-90.0 (H)	-100.0 (H)	-100.0 (H)
April	-50.0 (M)	-71.4 (H)	-91.7 (H)
May	-58.3 (M)	-85.7 (H)	53.9 (M)
June	-80.0 (H)	-85.7 (H)	-83.3 (H)
July	-91.7 (H)	-100.0 (H)	-100.0 (H)
August	-100.0 (H)	-28.6 (L)	-100.0 (H)
September	-100.0 (H)	-85.7 (H)	-75.0 (H)
Parameter Group #2			
1-day minimum	-100.0 (H)	-57.1 (M)	-100.0 (H)
3-day minimum	-100.0 (H)	-42.9 (M)	-83.3 (H)
7-day minimum	-100.0 (H)	-42.9 (M)	-91.7 (H)
30-day minimum	-100.0 (H)	-57.1 (M)	-83.3 (H)
90-day minimum	-90.0 (H)	-100.0 (H)	-75.0 (H)
1-day maximum	-40.0 (M)	-85.7 (H)	8.3 (L)
3-day maximum	0.0 (L)	-85.7 (H)	25.0 (L)
7-day maximum	90.0 (H)	-100.0 (H)	16.7 (L)
30-day maximum	80.0 (H)	-85.7 (H)	-8.3 (L)
90-day maximum	-90.0 (H)	-71.4 (H)	-8.3 (L)
Number of zero days	0.0 (L)	0.0 (L)	-11.8 (L)
Base flow index	-20.0 (L)	-100.0 (H)	-100.0 (H)
Parameter Group #3			
Date of minimum	-40.0 (M)	14.3 (L)	-100.0 (H)
Date of maximum	0.0 (L)	-14.3 (L)	-75.0 (H)
Parameter Group #4			
Low pulse count	-54.6 (M)	0.0 (L)	16.7 (L)
Low pulse duration	-77.8 (H)	57.1 (M)	0.0 (L)

Table 4.10 Middle RVA range hydrologic alteration values (%) of the Sakarya watershed target locations (continued)

*	E12A024	E12A045	D12A034
High pulse count	8.3 (L)	-10.0 (L)	-68.4 (H)
High pulse duration	25.0 (L)	-75.0 (H)	-84.6 (H)
Parameter Group #5			
Rise rate	-72.7 (H)	0.0 (L)	-66.7 (M)
Fall rate	-100.0 (H)	-75.0 (H)	-50.0 (M)
Number of reversals	-83.3 (H)	-42.9 (M)	-100.0 (H)

*These alteration degrees were classified into 4 classes which are: low or little or no alteration (0-33%), moderate alteration (34-67%), high alteration (68-100%), and severe alteration (> 100%). These classes have been developed using the approach proposed by Gierszewski et al. (2020); Hayes et al. (2018); Richter et al. (1998); Zimmerman et al. (2018).

Table 4.11 High RVA range hydrologic alteration values (%) of the Sakarya watershed target locations

*	E12A024	D12A034	E12A045
Parameter Group #1			
October	366.7 (S)	130.0 (S)	-100.0 (H)
November	300.0 (S)	30.0 (L)	-83.3 (H)
December	460.0 (S)	-36.4 (M)	0.0 (L)
January	211.1 (S)	-45.5 (M)	42.9 (M)
February	200.0 (S)	-45.5 (M)	57.1 (M)
March	200.0 (S)	-27.3 (L)	157.1 (S)
April	144.4 (S)	-27.3 (L)	114.3 (S)
May	228.6 (S)	30.0 (L)	28.6 (L)
June	188.9 (S)	190.9 (S)	0.0 (L)
July	212.5 (S)	209.1 (S)	-100.0 (H)
August	188.9 (S)	209.1 (S)	-100.0 (H)
September	211.1 (S)	172.7 (S)	-100.0 (H)
Parameter Group #2			
1-day minimum	177.8 (S)	-90.9 (H)	-100.0 (H)
3-day minimum	257.1 (S)	-90.9 (H)	-100.0 (H)
7-day minimum	177.8 (S)	-81.8 (H)	-100.0 (H)
30-day minimum	177.8 (S)	-27.3 (L)	-100.0 (H)
90-day minimum	200.0 (S)	0.0 (L)	-100.0 (H)
1-day maximum	-100.0 (H)	-81.8 (H)	171.4 (S)
3-day maximum	-88.9 (H)	-81.8 (H)	171.4 (S)
7-day maximum	-55.6 (M)	-63.6 (M)	185.7 (S)
30-day maximum	0.0 (L)	-9.1 (L)	171.4 (S)
90-day maximum	200.0 (S)	9.1 (L)	157.1 (S)
Number of zero days	0.0 (L)	0.0 (L)	0.0 (L)
Base flow index	22.2 (L)	-81.8 (H)	-100.0 (H)
Parameter Group #3			
Date of minimum	-22.2 (L)	45.5 (M)	14.3 (L)
Date of maximum	55.6 (M)	154.5 (S)	0.0 (L)

Table 4.11 High RVA range hydrologic alteration values (%) of the Sakarya watershed target locations (continued)

*	E12A024	D12A034	E12A045
Parameter Group #4			
Low pulse count	-100.0 (H)	27.3 (L)	71.4 (H)
Low pulse duration	-71.4 (H)	62.5 (M)	-16.7 (L)
High pulse count	-11.1 (L)	0.0 (L)	16.7 (L)
High pulse duration	11.1 (L)	122.2 (S)	42.9 (M)
Parameter Group #5			
Rise rate	-87.5 (H)	172.7 (S)	71.4 (H)
Fall rate	188.9 (S)	-100.0 (H)	-66.7 (M)
Number of reversals	188.9 (S)	-100.0 (H)	128.6 (S)

*These alteration degrees were classified into 4 classes which are: low or little or no alteration (0-33%), moderate alteration (34-67%), high alteration (68-100%), and severe alteration (> 100%). These classes have been developed using the approach proposed by Gierszewski et al. (2020); Hayes et al. (2018); Richter et al. (1998); Zimmerman et al. (2018).

4.3.2.1 Upper Sakarya subwatershed

As indicated in section 4.3, the target gauge E12A024 (Figure 4.9 and Table 4.4) is on the very upstream of the Sakarya River at the Upper Sakarya subwatershed. The most dominant water user in the upstream drainage area of this gauge is agriculture including irrigational practices and livestock watering (Alp et al., 2019). Since irrigation is applied using both surface and groundwater resources in the region, the hydrologic alteration results were evaluated regarding their possible impacts in between 1986 and 2016. Also, a couple of images (Figure 4.12) and observations obtained from the field surveys conducted between 2017 and 2018 were taken into consideration. As the images belong to 2018, they were included in the assessment as the most current streambed, banks and floodplain morphological conditions. For further assessments in this region, the field outputs of this study are thought to be valuable for this existing database.

As can be demonstrated in Figure 4.12, a majority of the floodplain areas at the upstream of E12A024 were converted to agricultural lands. While these agricultural activities are taken place, irrigational water is transferred via either open channels or closed pipe systems. If the system is open channel, farmers and the authorities either

changed the streambed by forcing natural bed structure to a straighter channel or conveyed the water with artificial channels. Because between 1986 and 2016 is the assessment period for this gauge, two big dam structures being operated since 1986 were taken into consideration as the major anthropogenic pressures on the hydrological regime. Their monthly operation time series (Figure 4.11) were used as supporting tools to understand their behavior and possible impacts. These dams and several smaller reservoirs in the region are operated to supply irrigational water. In addition to the impoundments, groundwater irrigation is a major activity supplied by irrigation pumps. Also, a couple of major water diversion structures are present for the same reason in the area. Figure 4.12 shows images of the streambed, banks and floodplain in this location, which were taken in 2017 and 2018. These images and field survey observations are used to prove the current situation of this target location.

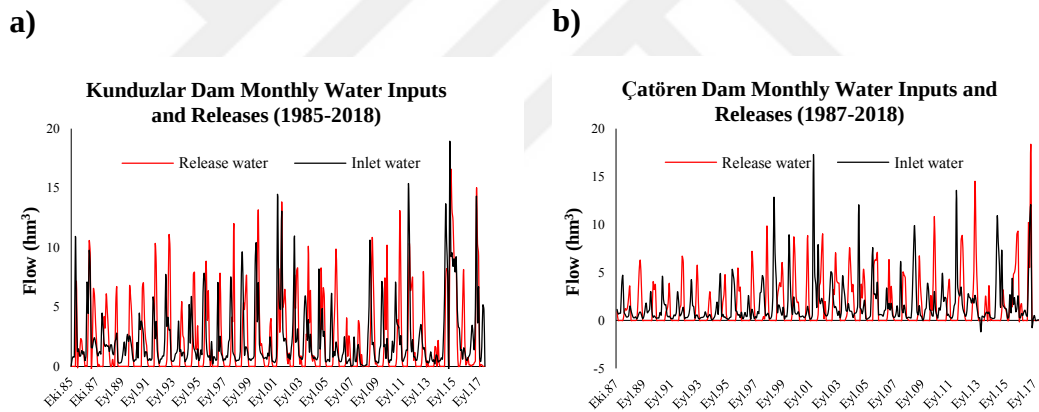


Figure 4.11. a) Kunduzlar dam and b) Catoren dam being operated at the upstream drainage area of the target gauge E12A024 between 1985 and 2018

Figure 4.11 indicates that the water released from the dams follows a repetitive pattern and causes extreme changes in time. Even though they generally release more water than the amount coming into the reservoir, their operations depend on the incoming water dynamics. In other words, if they release water, they generally do it in compliance with timing and magnitude of the incoming water. Since the incoming water reflects what have been done to alter natural water dynamics at the upstream

area, its pattern gives important insights about the possible reasons to the alterations calculated here.



Figure 4.12. The current riverbed, banks and floodplain conditions of the target location E12A024 and its upstream – Images taken in between December 2017 and August 2018

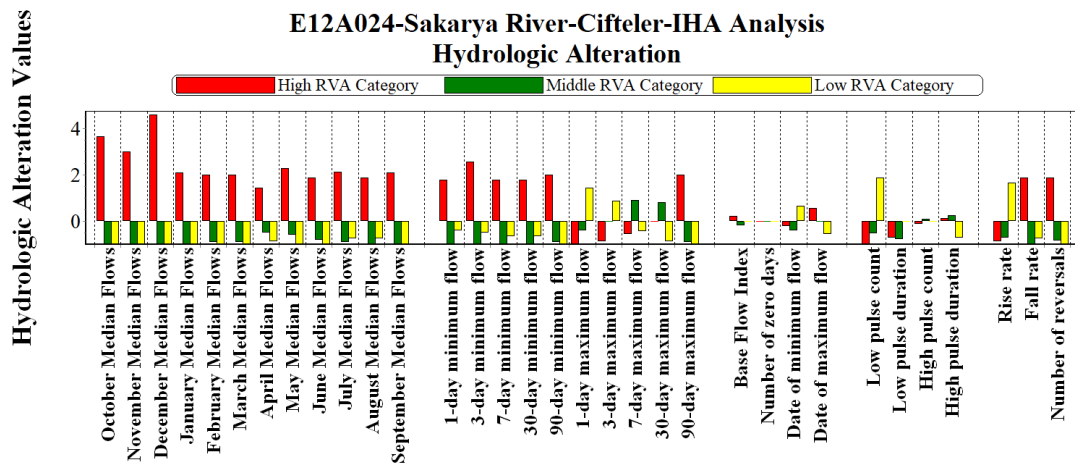


Figure 4.13. Hydrologic alteration bar chart of the target gauge E12A024 in three RVA ranges

Figure 4.13 shows overall hydrologic alteration levels of the 5 groups of IHA parameters at this location. As can be seen from this figure and all the individual alteration graphs given in between Appendices B and F, the average monthly flow magnitudes of this target location severely increased (from 144% up to 460% increases). Also, 1-, 3-, 7-, 30- and 90-day moving averages of the annual minimum flow magnitudes severely increased (up to 257% increase in the occurrence of these events in the high RVA range). On the other hand, the annual maxima calculated in the same time periods yielded a different behavior. For example, 1- and 3-day moving averages of the annual maximum so decreased that their hydrologic alteration degrees +144% and +89% in the low RVA ranges. However, it is the opposite for 7-, 30- and 90-day moving average values. Therefore, it can be inferred that the maximum flows are more uncertain than the ones under the natural conditions. In addition to the annual extreme flow changes, base flow of this target location showed a slight increase.

Another change was detected for the timing of the annual minimum and maximum flow values. In average, it was found that the annual minimum flow occurs 15 days earlier than it should be. On the other hand, the annual maximum flow is observed 7.5 months later within the assessment period, in average. Especially the latter should

be immediately taken into consideration for the water management decisions in the region.

Moreover, low and high pulse flow events significantly altered according to the results. It was found that the number of low pulses severely decreased (i.e., 188% increase in the frequency in the low RVA range) under the influence of upstream human activities because zero low pulse was observed almost 61% of the time during the altered period. Even though high pulse events slightly changed, it was detected that sometimes high pulse durations were so high that it could go up to 639 days at once.

In addition to these changes, daily rise and fall values severely decreased (166.7% for daily rises and 188.9% for daily falls). On the other hand, the number of reversals so increased that its hydrologic alteration is 189% in the high RVA range.

All of these hydrologic alterations indicate that this region needs a sustainable water management approach. It is thought that the ecosystem is under serious pressures which would get worse in time because of the population growth and the corresponding irrigational and livestock water demands. The biggest pressures are the water releases from the Kunduzlar and Çatören dams, other water releases from the several small reservoirs and water diversions for the same purpose (i.e., irrigation). These structures supply irrigational water for an agricultural land having a surface area greater than 19200 ha which is a huge area!

4.3.2.2 Ankara subwatershed

In Ankara subwatershed, the target gauge E12A045 (Figure 4.9 and Table 4.4) was included in the IHA/RVA assessment, as mentioned earlier. There are two main branches within the subwatershed, which are Ankara Creek and Kirmir Creek. The target gauge is located at the very downstream of Kirmir Creek. Thus, the hydrologic alteration assessments conducted at this location reflect the cumulative impacts of the human pressures existing throughout the creek. Even though the most dominant

water user at the upstream drainage areas of this gauge is drinking and utility, irrigation and watering livestock is the second biggest water consumption in the subwatershed. The water used for irrigating agricultural lands and watering livestock is not negligible compared to other sectors. Therefore, their cumulative effects are the main focus of this assessment. The water needed by these sectors are supplied by big and small reservoirs/dams/diversion structures. These structures put various pressures on the streambed, bank and floodplain ecosystems in terms of hydrology and geomorphology. To find out what kind of hydromorphological issues the stream corridor has, hydromorphological field surveys were conducted for five periods in the years of 2017 and 2018. The photographs seen in Figure 4.14, were taken at the field surveys and help to support findings of hydrological alterations regarding the current morphologic conditions. Each water condition were represented by these photographs since they belong to maximum, minimum and high pulse periods during 2017 and 2018.





Figure 4.14. The current riverbed, banks and floodplain conditions of the target location E12A045 and its upstream – Images taken in between December 2017 and August 2018

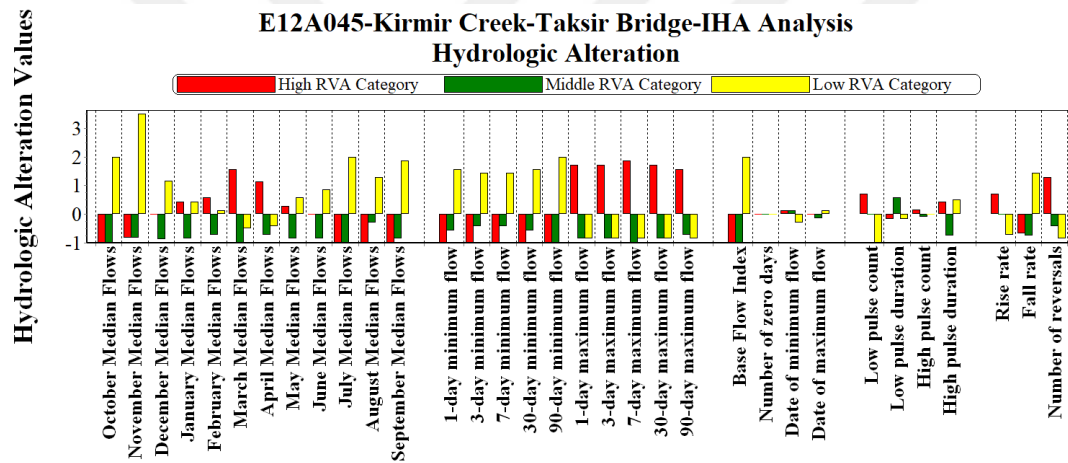


Figure 4.15. Hydrologic alteration bar charts of the target gauge E12A045 in three RVA ranges

Figure 4.15 shows overall hydrologic alteration levels of the 5 groups of IHA parameters at this location. As can be seen from this figure and all the individual alteration graphs given in between Appendices C and G, the hydrologic conditions of the Kirmir Creek were degraded due to several upstream pressures. The first group of IHA parameters indicated that summer and autumn months experienced decreases in magnitude. The hydrologic alteration levels calculated for the months of these two seasons range between +142.9% and +200% in the low RVA range. So, the average monthly flow conditions during summer and autumn are observed more frequently

below the lower RVA threshold value. On the other hand, winter and spring months, which are the high flow periods of the study region, have highly variable flow pattern. According to the alteration calculations, it was found that the changes in the average monthly flow magnitudes of winter and spring seasons resulted in more uncertainty in the flow behavior.

As expected, 1-, 3-, 7-, 30- and 90-day moving averages of the annual minimum flow magnitudes severely decreased (their frequency of occurrence during the altered period is up to 200% increase in the low RVA range). On the other hand, the annual maxima calculated in the same time period shows similar change however their magnitudes severely increased. Thus, their hydrologic alteration levels were found as +157.1% and +185.7% in the high RVA range of the IHA graphs. In addition to the annual extreme flow changes, base flow of this target location showed a slight increase.

There is no major alteration in the timings of annual daily maximum and minimum flow conditions.

Moreover, low and high pulse flow events highly altered according to the results. It was found that the number of low pulses highly increased (i.e., 71.4% increase in the frequency in the high RVA range) while their durations moderately decreased. The number of high pulse events changed less compared to the low pulse events. However, the durations of high pulses are more variable than the natural conditions. Their occurrences increased both in the low and high RVA ranges.

In addition to these changes, daily rise and fall values highly and severely increased (71.4% for daily rises and 142.9% for daily falls). It can be seen that daily decreases in the flow magnitude is more severe, which is due to upstream water abstractions and impoundments to supply drinking and irrigational waters. On the other hand, the number of reversals severely increased (i.e., the hydrologic alteration levels of this parameter is +128.6% in the high RVA range).

4.3.2.3 Porsuk subwatershed

The target gauge D12A034 (Figure 4.9 and Table 4.4) is on the Porsuk Creek which is one of the biggest tributary of the Sakarya River. At the upstream drainage area of this gauge, various human activities take place. For example, industrial zones (including ceramic factories, sugar plants, car factories, mineral fertilizer factories and milk factories) are abstracting freshwater either via surface abstraction or groundwater pumping. They also discharge their wastewater into the creek and its tributaries. In addition to these industrial water loops, two populous centers (i.e., Kütahya and Eskişehir provinces) are located at the upstream and downstream, where drinking water demands are high (Alp et al., 2019). Also, the biggest pressure on the Porsuk Creek streambeds, banks and floodplains is the Porsuk dam. This dam has almost 450 hm³ total volume and 50 meters height, which applies a high pressure on both stream hydrology and morphology by blocking natural sediment and stream flows. Since the gauge D12A034 is right at the outlet of the Porsuk dam, it gives direct information about the hydrologic alterations caused by dam operations. Also, it reflects indirect cumulative impacts of the pressures.

The current streambed, banks and floodplain conditions of the gauge are presented in Figure 4.16. The images shown in the figure belong to the field surveys made in distinct flow events expected in the region. For example, first two images of each figure indicate the high pulse period hydromorphological conditions, which were taken in December 2017. Other images were taken in April and June 2018 (naturally expected maximum flow periods) and August 2018 (naturally expected dry period).



Figure 4.16. The current riverbed, banks and floodplain conditions of the target location D12A034 and its upstream – Images taken in between December 2017 and August 2018

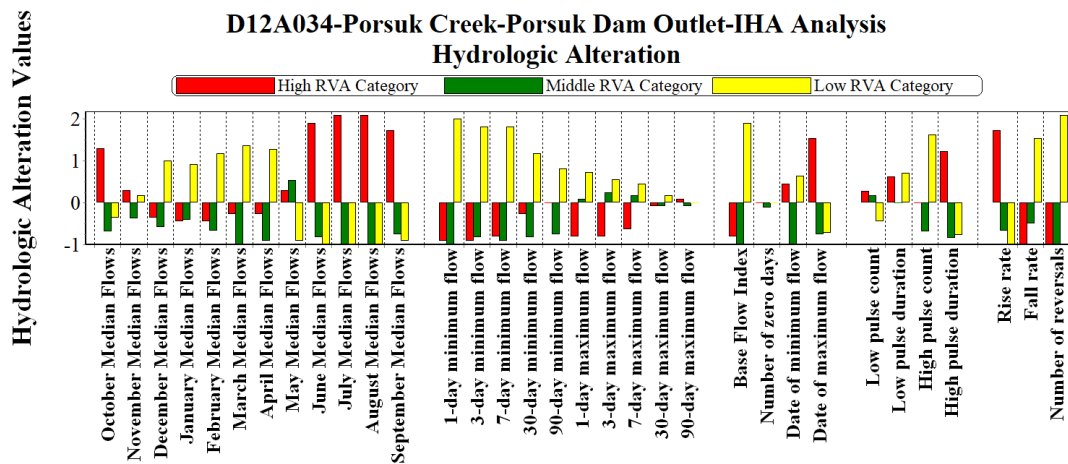


Figure 4.17. Hydrologic alteration bar charts of the target gauge D12A034 in three RVA ranges

Figure 4.17 shows overall hydrologic alteration levels of the 5 groups of IHA parameters at this location. As can be seen from this figure and all the individual alteration graphs given in between Appendices C and G, the hydrologic conditions of the Porsuk Creek deteriorated due to the biggest upstream pressure, the Porsuk Dam. The first group of IHA parameters revealed that winter and spring months except for May experienced severe decreases in magnitude, i.e, from +90.9% to +136.4% changes in the number of occurrences in the low RVA ranges. The average May flows indicated there is a moderate increase in the magnitude. A similar situation was detected for the summer and autumn months. June, July, August, September and October experienced severe increases in their magnitude due to the dam operations (i.e., +130% up to +209.1% increases in the frequency of the high RVA ranges). Like May, November yielded lower alteration compared to the summer and autumn months.

As expected, 1-, 3-, 7-, 30- and 90-day moving averages of the annual minimum flow magnitudes severely decreased (their frequency of occurrence during the altered period is up to 200% increase in the low RVA range). On the other hand, the annual maxima calculated with the same moving average time resolutions shows lower alteration levels. Monthly and seasonal moving averages showed low alterations

while 1-, 3- and 7-day moving average values moderately and highly (i.e., +45.5% and +72.7% changes in the low RVA ranges) decreased due to the dam operations. Unlike the other target gauges, D12A034 experienced zero flow days during its altered time period. According to the results, there were 4 incidents the streambed had no streamflow for up to 11 days of duration. This is important because there were no zero flow in the streambed under natural conditions. In addition to the annual extreme flow changes and zero days, base flow magnitudes severely decreased (+190.9% increase in the frequency of base flow event in the low RVA range), as expected.

The third group of IHA parameters yielded significant changes in the annual daily minimum and maximum flow timings. In average, it was found that the minimum event occurs 4 months later than the natural timing while the shift for the maximum event is almost 3 months later. The whole altered period showed the uncertainty of the minimum flow event increased because it was observed in a wider time range than the natural one.

The number of low pulse events moderately increased according to the results (-45.5% in the low RVA range). Their durations exhibited the same alteration. On the other hand, the number of high pulse events severely decreased (i.e., severe increases in the low RVA range by 162.5%). However, the durations of these pulse events are increased by 122.2% in the high RVA ranges. It is clearly seen that the low and high pulse dynamics were adversely affected by the dam operations (Figure 4.18).

In addition to these changes, daily rise and fall values severely increased (+172.7% for daily rises and +154.5% for daily falls). On the other hand, the number of reversals severely decreased (i.e., the hydrologic alteration levels of this parameter is +209.1% in the low RVA range).

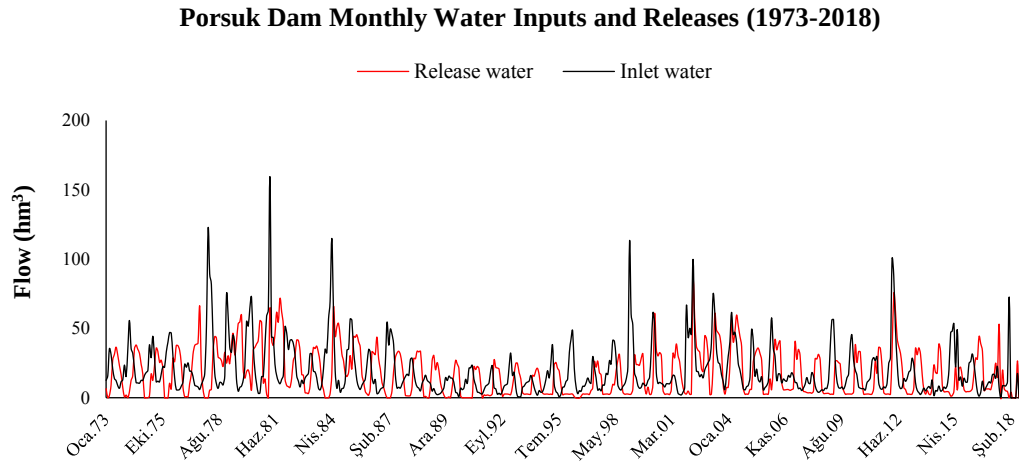


Figure 4.18. The Porsuk dam operations – monthly – between 1973 and 2018

4.4 Summary and Discussion

Three representative target locations across the Sakarya watershed (Figure 4.9) were selected to implement IHA/RVA methodology. Various anthropogenic pressures, such as impoundments of the water for flood prevention, irrigational water abstractions and diversions, industrial water pumping, etc. are in excessive amounts at these locations. Also population in the area is increasing in time, which put extra pressure on the water resources for the purpose of drinking and utility (e.g. 83% increase in the population at the upstream area of D12A034, which can be seen in Table 4.12). These pressures cause a major stress on the Sakarya river ecosystems where the biggest share of the water abstractions and regulations belong to the agriculture sector. Especially intensive irrigational activities take place in certain regions of the watershed (Table 4.13 and Figure 4.19). However, all of the upstream pressures have cumulatively detrimental impacts on the natural variability of the streamflow regime and the ecological integrity of the Sakarya River ecosystems as it was detected in this study.

Table 4.12 Total population change between 1965 and 2011 at the upstream area of D12A034

Year	Population (cap)				Year	Population (cap)			
	Kutahya	Bilecik	Afyon	Total		Kutahya	Bilecik	Afyon	Total
1965	147702	28863	22590	199155	2000	251764	60863	33220	345847
1970	162954	29725	24783	217462	2007	273214	64514	30550	368278
1975	180081	30368	25719	236168	2008	261371	65369	30055	356795
1980	192045	33346	26232	251623	2009	270674	65799	29060	365533
1985	215229	40588	28346	284163	2010	292019	66255	28438	386712
1990	223596	48193	30034	301823	2011	269836	67524	28407	365767

Table 4.13 The percentage shares of each sector having pressure on water resources in the Sakarya watershed (Alp et al., 2019)

Sector	Upper Sakarya	Porsuk	Ankara	Middle Sakarya
Agriculture	89.4	60.2	9.9	23.0
Drinking water	10.4	23.4	90.1	29.7
Industry	0.0	1.8	0.0	2.3
Energy	0.2	14.6	0.0	45.1

The percentage shares of water use sectors in Sakarya watershed

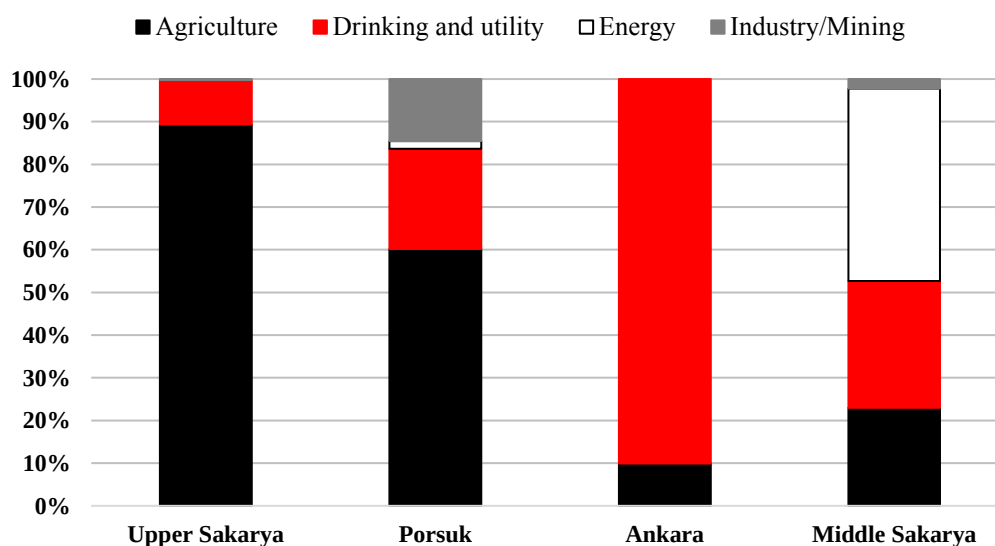
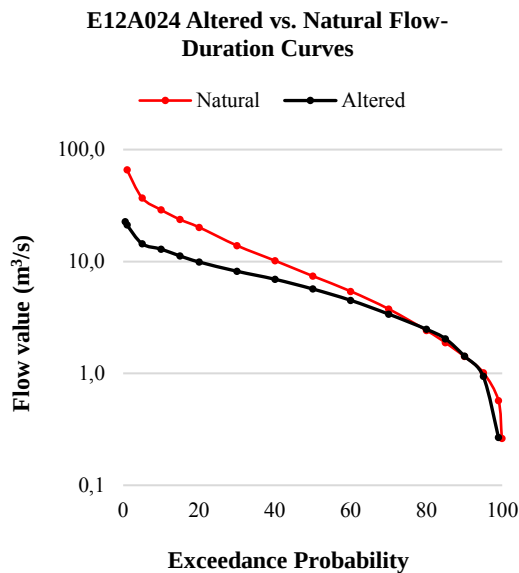


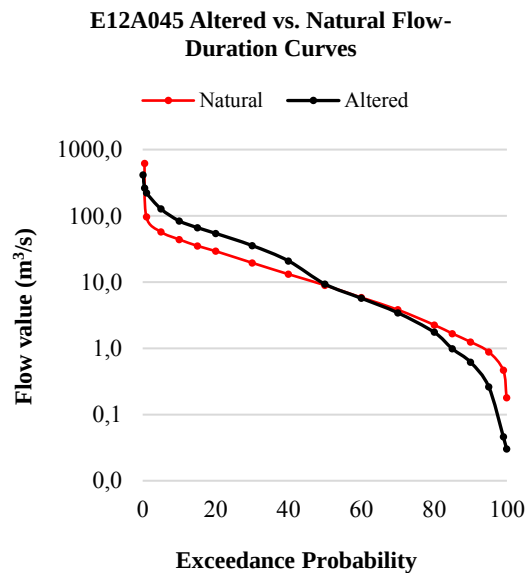
Figure 4.19. Bar graph of the percentage shares of each sector having pressure on water resources in the Sakarya watershed (Alp et al., 2019)

The flow duration curves of the target gauges are presented in Figure 4.20 to first give the overall picture in the area in terms of low (85%-99.9%), medium (between 10% and 80%) and high (0.1%-5%) flows. As can be seen in the figure, the anthropogenic pressures resulted in decreases in the low flows at every target location. On the other hand, high flows changed depending on the dominant sector. For example, the high flows decreased at the Upper Sakarya target location while it is vice versa at the Porsuk target gauge. On the other hand, the highest flow decreased and the other high flows increased at Ankara target location. It is considered that the main reason for these changes in the high flows is because the major upstream dams are operated depending on the downstream demands and upstream water uses. Also, several water abstractions and discharges cause these alterations, for example, by increasing the surface runoff or decreasing the peaks. Finally, the middle zone of the FDCs show various changes in different flows within the range due to the effects of the same pressures (Figure 4.19 and Figure 4.20).

a)



b)



c)

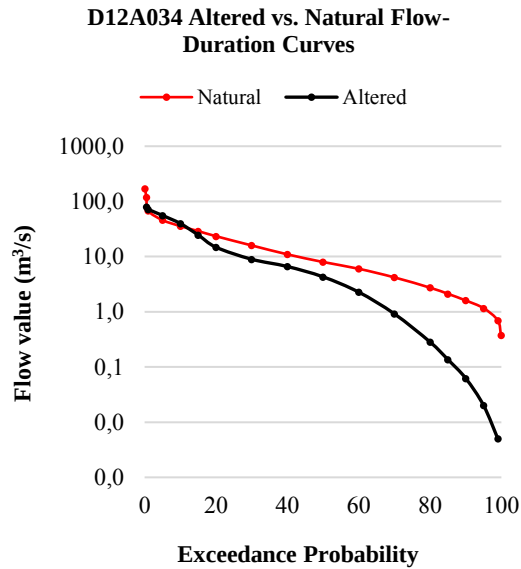
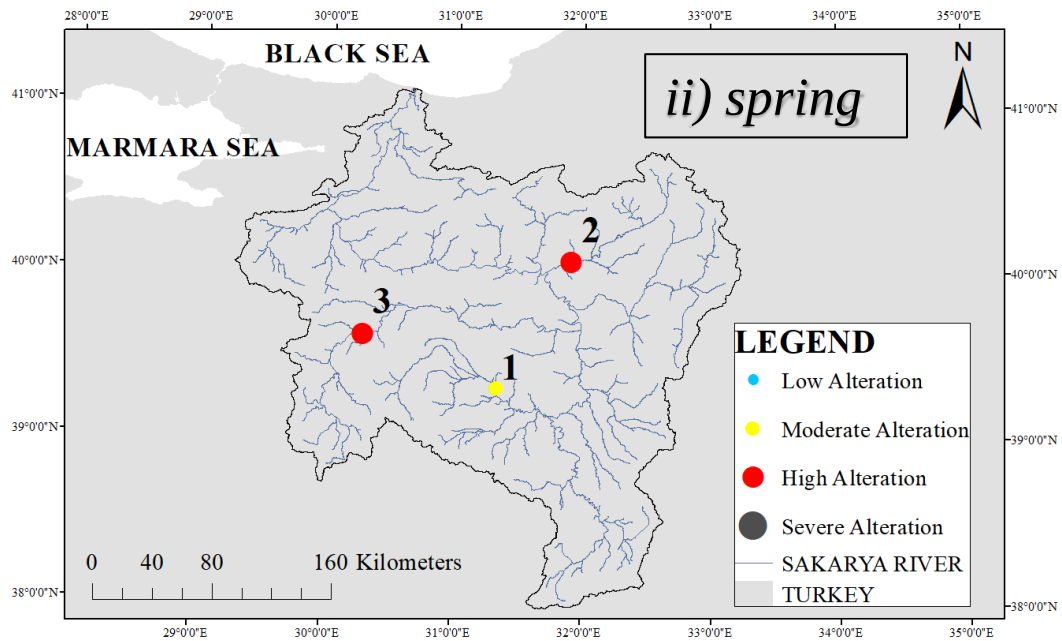
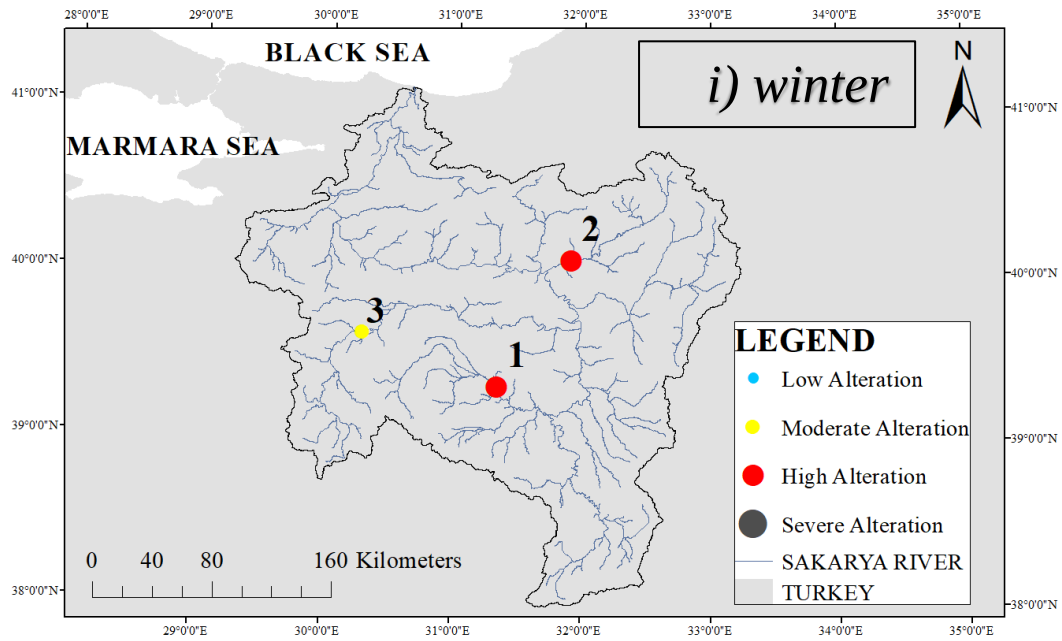
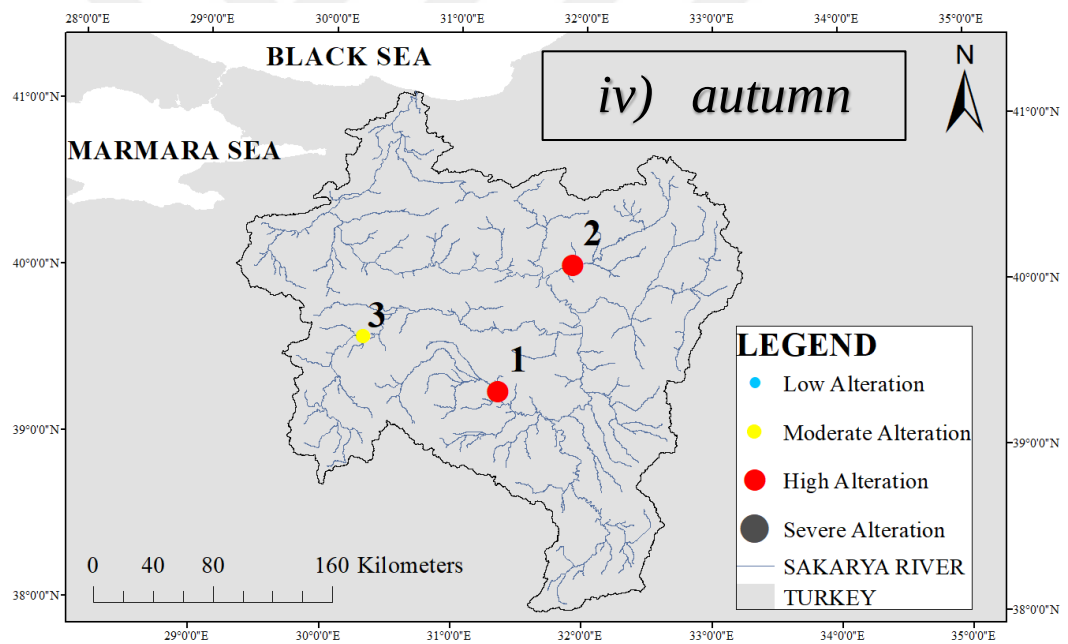
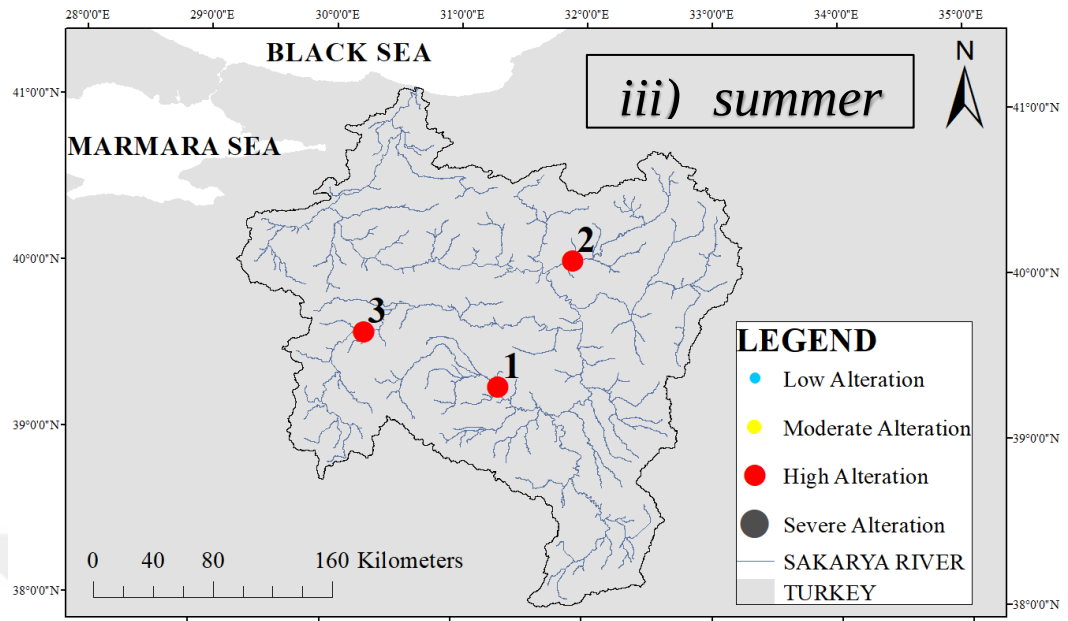
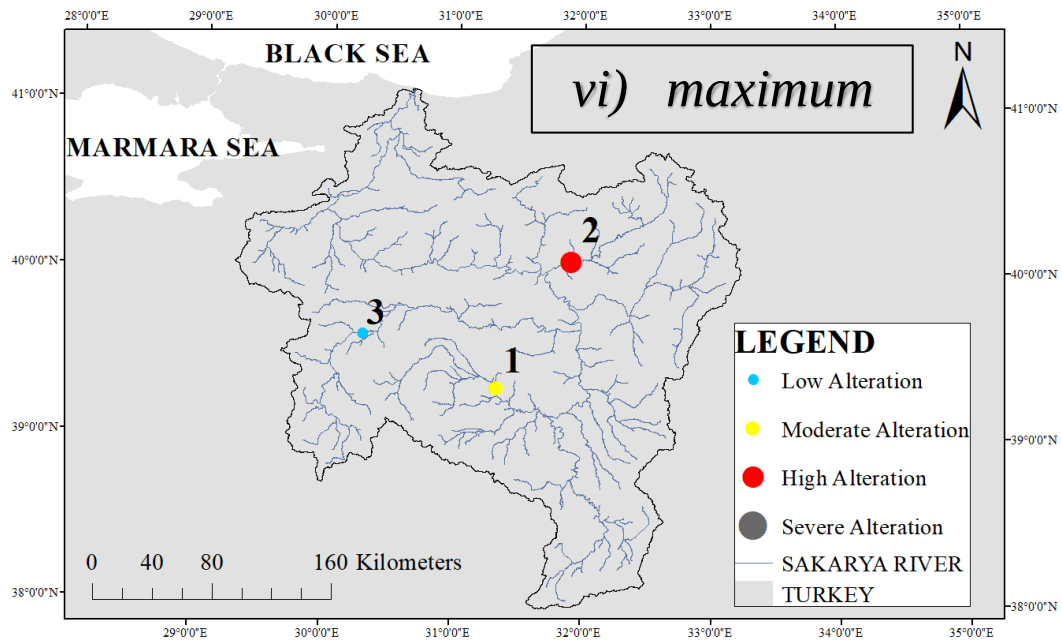
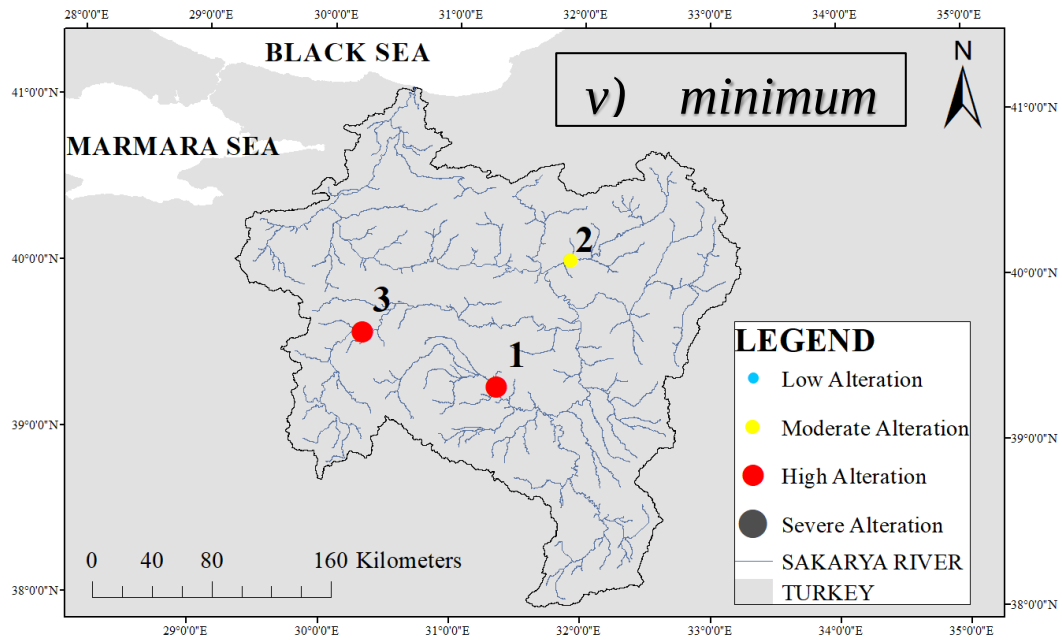


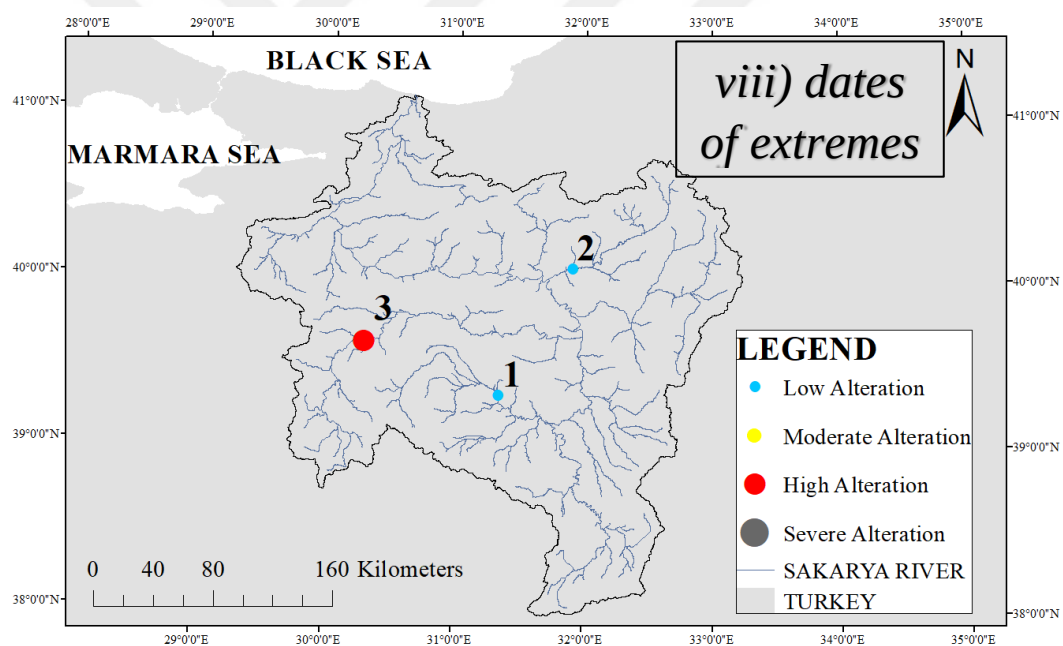
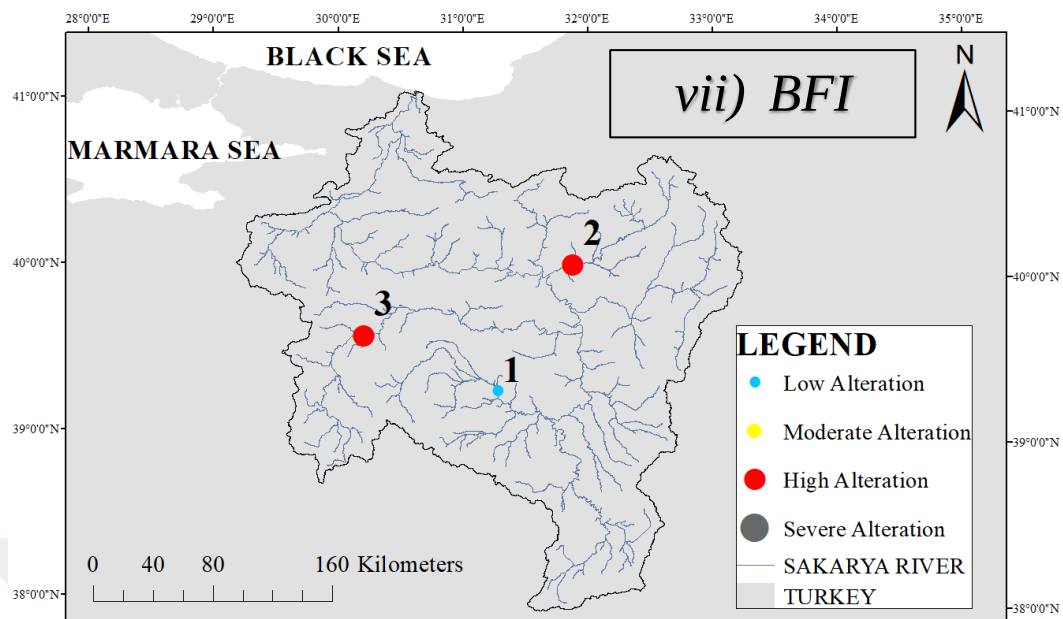
Figure 4.20. Natural and altered flow duration curves of the target gauges in the Sakarya watershed. a) E12A024, b) E12A045 and c) D12A034

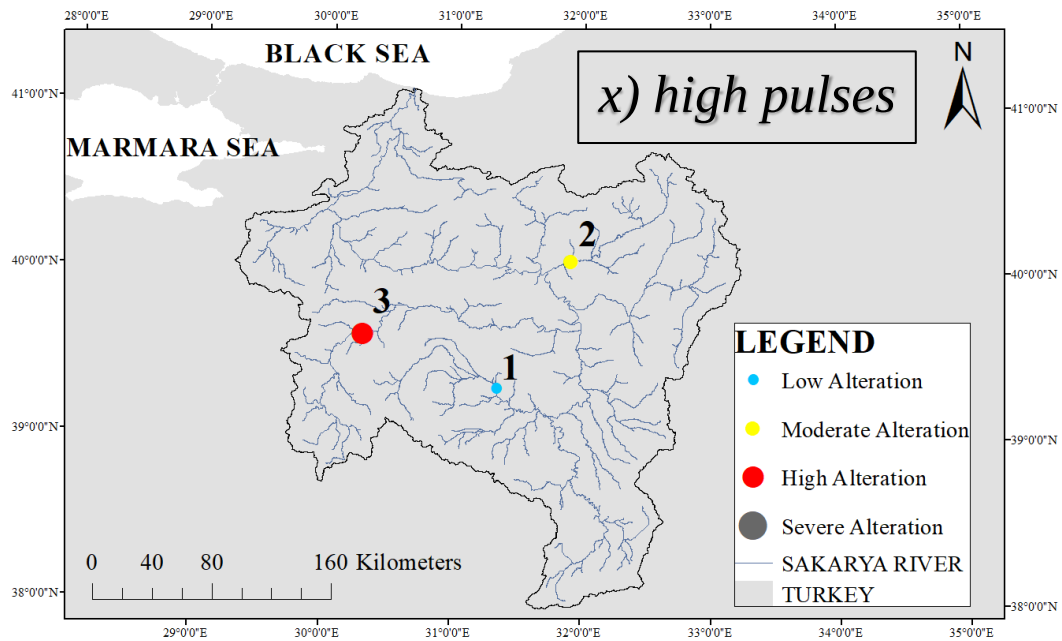
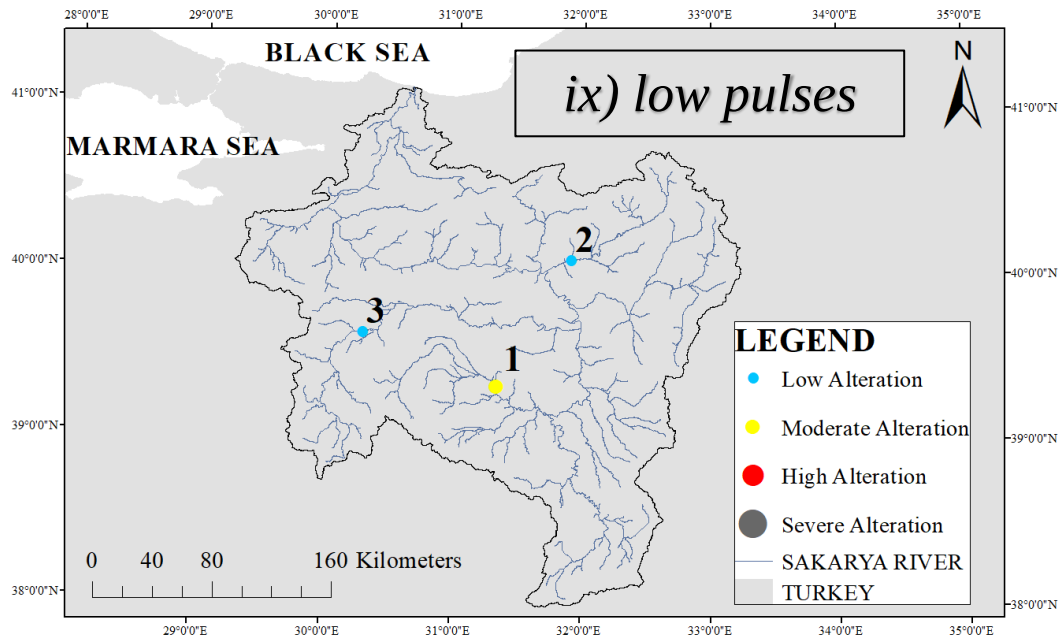
The IHA/RVA results were assessed within each group of parameters however a couple of modifications were carried out to better comprehend the alterations in the region (Figure 4.21). The modifications based on the IHA parameter groups are 1) evaluating seasonal hydrologic alterations by taking averages of corresponding monthly alteration degrees 2) analyzing minimum and maximum flow conditions separately by taking averages of daily, weekly, monthly and seasonal moving averages of the extreme events' alteration degrees instead of evaluating them individually 3) evaluating alterations in the dates of annual extreme events by taking average of both annual minimum and maximum events 4) assessing changes in the low and high pulse events taking average of the count and duration alterations and 5) assessing intra-annual variation by averaging rise and fall rates and hydrologic reversals parameters. Therefore, 11 assessments were performed to characterize hydrologic alteration results in the Sakarya watershed.











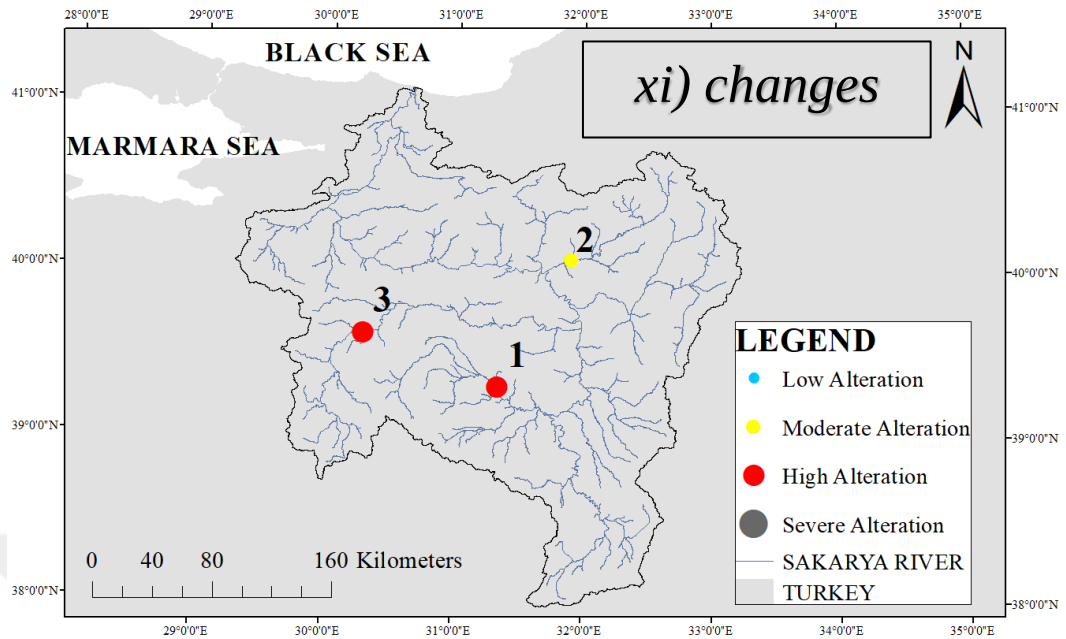


Figure 4.21. Overall hydrologic alteration maps representing: **i)** winter season (December-January-February) **ii)** spring season (March-April-May) **iii)** summer season (June-July-August) **iv)** autumn season (September-October-November) **v)** daily, weekly, monthly and seasonal minimum flow conditions (1-, 3-, 7-, 30- and 90-day minimum flows) **vi)** daily, weekly, monthly and seasonal maximum flow conditions (1-, 3-, 7-, 30- and 90-day maximum flows) **vii)** base flow index (BFI) **viii)** timings of the annual extreme events (dates of the 1-day minimum and maximum flows) **ix)** low pulses **x)** high pulses **xi)** hydrologic changes (rise and fall rates and hydrologic reversals)

Table 4.14 Summary of the hydrologic alteration assessments at the Sakarya watershed target locations

Parameter Gr.	Assessment Summary
Winter	The average winter flows of the target gauges responded different to the dominant human pressure(s) of the corresponding drainage area. The hydrologic alteration levels of the Sakarya River headwater and Kirmir Creek are high in terms of magnitude however they experienced different types of alterations. Because the Upper Sakarya subwatershed has an intensive agricultural activity, the winter streamflows severely increased in magnitude. On the other hand, the Kirmir Creek is at the downstream of several dams and reservoirs with different volumes constructed for drinking, utility and irrigation water demands. That is why, the change in the winter flows is highly variable (i.e., both increasing and decreasing in magnitude), which increases the uncertainty. Lastly, the Porsuk Dam, the only pressure on the corresponding target location, caused winter flows highly decrease in magnitude while the average alteration level is moderate.

Table 4.14 Summary of the hydrologic alteration assessments at the Sakarya watershed target locations (continued)

Parameter Gr.	Assessment Summary
Spring	Spring months of the Upper Sakarya and Ankara subwatersheds' target locations have similar alteration behaviors as the winter months. However, it is a little different at the Porsuk subwatershed target location. Even though March and April flows severely decreased like in the case of winter flows, the average flow of May increased in magnitude.
Summer	The alteration of summer monthly flows is one of the most significant results obtained from this study because all target locations yielded high hydrologic alteration degrees. The Upper Sakarya and Porsuk target streambeds receive much more water than required during these months while the Ankara subwatershed target location cannot access sufficient water for a healthy stream ecosystem.
Autumn	Autumn average monthly flow alteration degrees on the map given in Figure 4.21 are the same as winter and spring months but the changes occurred are different. According to the calculations, the average monthly flows at the Upper Sakarya target location severely increased due to the irrigational activities. However, this is severe decreases in magnitude for the Ankara subwatershed target location. The Porsuk dam effect was observed as low to severe increases in magnitude of these flows.
Annual minima	The long-term trends of the annual minimum flows yielded significant results in terms of flow magnitude. Even though moderate to high flow alteration degrees were observed for the Sakarya watershed, impoundments at the upstream area caused severe decreases in the minimum flow amounts (i.e., Ankara and Porsuk subwatersheds). On the other hand, intensive irrigational activities using both surface and groundwater resources in the Upper Sakarya resulted in severe increases in these flows.
Annual maxima	The long-term trends of the annual maximum flows are one of the most complicated results obtained in this study because all target locations experienced different types of alterations. For example, the maximum flows sometimes increased sometimes decreased due to high uncertainty in the demand for food.
BFI	The changes in base flows at the target locations are changing between low and high as indicated on the map given in Figure 4.21. It was detected that the base flow magnitudes severely decreased in the Ankara and Porsuk subwatersheds. The Upper Sakarya subwatershed target location has a low alteration for this parameter.
Timing of the annual extremes	Timings of the annual extreme events showed that significant shifts in time were detected in average. But there is no pattern for the changes observed. Therefore, it can be stated that the anthropogenic pressures on a river system cause unpredictable extreme events.
Low and high pulses	Their alteration results offer the same statements as the timings of annual extremes.

Table 4.14 Summary of the hydrologic alteration assessments at the Sakarya watershed target locations (continued)

Parameter Gr.	Assessment Summary
Changes	Another one of the most important parameter group is the changes in daily flow conditions. As can be seen in Figure 4.21, Ankara and Porsuk target locations has higher daily changes of the streamflows. However, there

CHAPTER 5

ENVIRONMENTAL FLOW ASSESSMENTS (EFA) IN THE SAKARYA WATERSHED

Environmental flow assessments (EFAs) of the Sakarya watershed are presented in this chapter (Figure 5.1). The approach adopted here is the holistic environmental flow assessment approach because not only a specific part of the river ecosystems are targeted to be maintained or restored but the whole system is taken into consideration. As previously mentioned, the ELOHA framework is the overall methodology used in this thesis study so the environmental flow determination step of this framework was modified to be implemented for the Sakarya watershed. As the watershed does not have sufficient supporting information/data in terms of biology or geomorphology, the available hydrological data was assessed with the information and data obtained from our field surveys. The integrated assessment of the hydrological and other available data yielded holistic environmental flow values at the target locations within the Sakarya watershed. This chapter includes 3 subsections: introduction, methodology, and results&discussion. The introduction part presents the evolution of the environmental flow assessment procedure, holistic approaches to the EFs and the environmental flow determination step of the ELOHA framework in detail. The methodology used in this chapter is the Environmental Flow Components (EFCs) of the Indicators of Hydrologic Alteration (IHA) method. In the results&discussion part, environmental flow assessment suggestions for the target locations are discussed for a sustainable environmental water management.

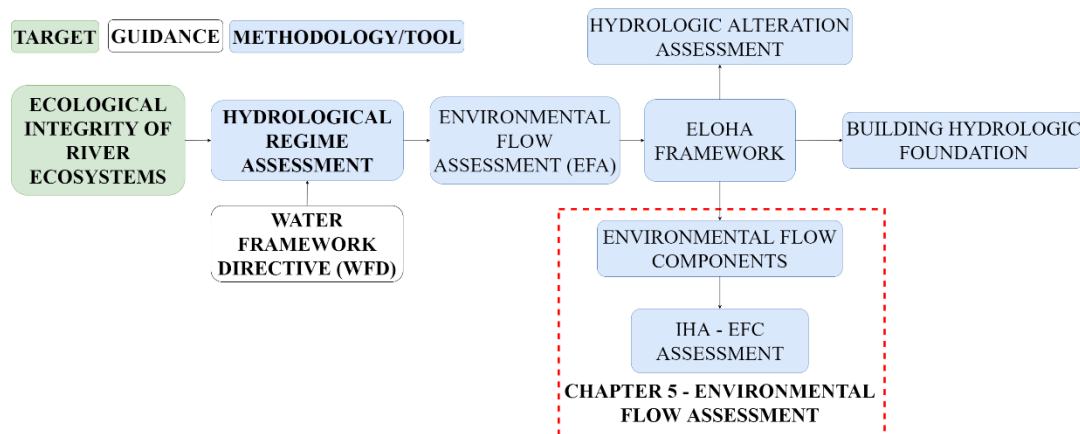


Figure 5.1. Main focus of Chapter 4 within the overall framework of this thesis study

5.1 Introduction

“Environmental flows describe the quantity, timing, and quality of freshwater flows and levels necessary to sustain aquatic ecosystems which, in turn, support human cultures, economies, sustainable livelihoods, and well-being” by Arthington et al. (2018).

Sustainable water management provides a smart water allocation where water for both direct and indirect uses is balanced without conflicting trade-offs between these two parties. Direct water uses are, for example, public supply, irrigation, and industrial applications; on the other hand, water for the ecosystem needs is an indirect use of water. Even though water allocated to direct uses provides many benefits to humankind (flood protection, food supply, drinking water, energy generation, etc.), the allocation of water to natural ecosystems should not be avoided because of two reasons.

One of the reasons is that natural ecosystems are as valuable as humankind. As Whiting (2002) states, *‘rivers and associated biological communities are among our most valuable natural resources’*. All the living organisms in these ecosystems have a right to access a healthy environment where clean and enough water is available and accessible. As humankind is not the center of the universe, environmental ethics

should be taken into consideration carefully at this point. The second reason is that freshwater ecosystems have many tangible benefits to human well-being. These benefits are summarized by Forslund et al. (2009) in Figure 5.2. As shown in the figure, human well-being depends on all the supporting, provisioning, regulation, and cultural services of freshwater ecosystems. To illustrate this, human security, living essentials, and health are strongly correlated with the regulation services, such as climate regulation, flood regulation, and self-purification of water bodies, of the freshwater ecosystems.

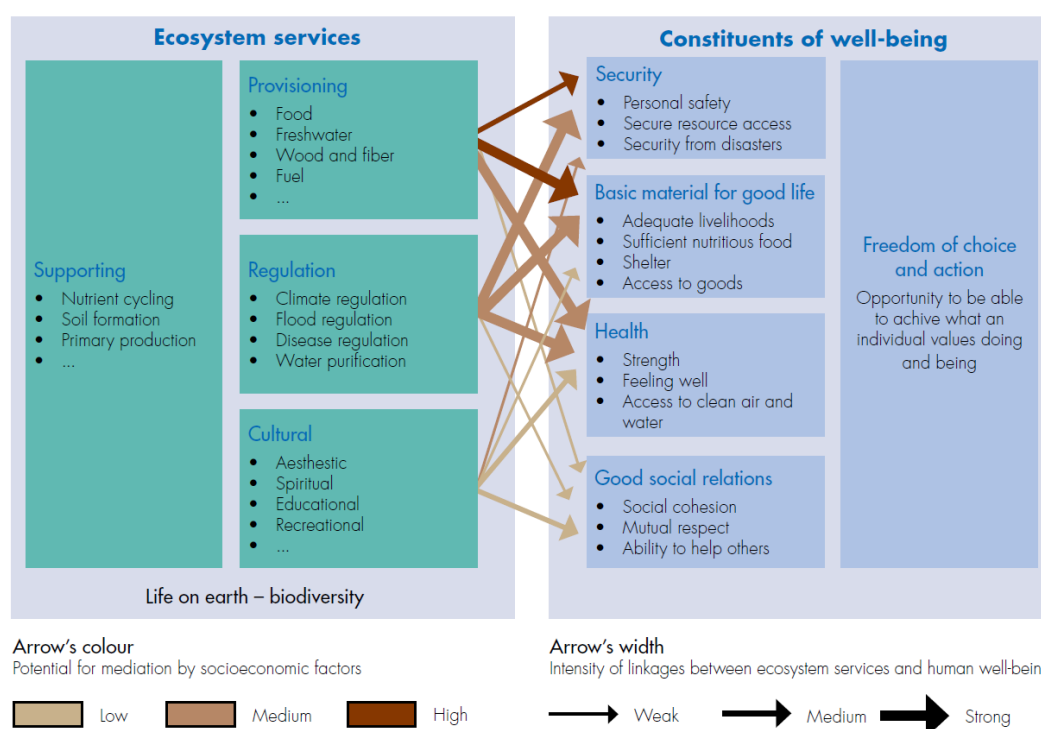


Figure 5.2. Links between freshwater ecosystem services and human well-being (Forslund et al., 2009)

Also, Whiting (2002) gives solid examples to the freshwater ecosystem services to humankind. Agriculture is sustained by fertile soils of floodplain areas of riverine corridors, where nutrient-rich floodwaters are stored and recharge groundwater, while river waters provide fisheries itself. Moreover, a major proportion of drinking water is supplied by rivers and river-fed lakes (Whiting, 2002). On the other hand,

recreational purposes like boating, fishing, and swimming are provided by riverine corridors. Thus, environmental flow allocations play a vital role in a sustainable environment and health.

After recognition of the fact that minimum low flows individually do not support the ecosystem-based environmental water management, all the elements of an annual hydrograph – including floods (small and large), low and extremely low flows, zero flows, high and low pulses, etc. – were taken into consideration. These elements of the flow regime drive critical riverine processes maintaining the biodiversity and functions of riverine ecosystems. It is essential to know that magnitude, duration, timing, frequency, and rate of change in these environmental flow components should be considered as a whole so that detrimental effects of the alterations can be eliminated or minimized. For example, too much flow at the wrong time of a period (this period can be a year or a season) is just as detrimental as too low flow. Also, early environmental flow assessment methods assumed that if water conditions were appropriate for some valued indicator species, i.e., the most sensitive of these organisms, other organisms would also be conserved. However, it was realized that food webs and feedback loops in river ecosystems are so complex that it necessitates targeting a range of species spanning broad ecological requirements – plants, fish, algae, invertebrates, reptiles, amphibians, and birds (Acreman et al., 2014; Williams et al., 2019). Thus, environmental flow elements (low, high, floods, etc.) must be determined regarding both stream processes and their functions on the ecosystem. In this study, the Indicators of Hydrologic Alteration (IHA) Assessment methodology Environmental Flow Components (EFCs) were used to determine the environmental flow requirements of the Sakarya watershed. 34 parameters demonstrating magnitude, frequency, duration, timing, and rate of change components of the following five environmental flows exist in this approach:

- 1- Extremely low flows
- 2- Low flows
- 3- High pulses
- 4- Small floods

5- Large floods

The ecological roles of these parameters are given in Table 5.1.

Table 5.1 Environmental flow components of the IHA method and their ecosystem influences on river ecosystems, adapted from The Nature Conservancy (2009)

EFC	Ecosystem Influences of the Flow Component
Monthly low flows	-Adequate habitat for aquatic organisms -Acceptable water chemistry, water temperature, and dissolved oxygen concentration -Maintenance of soil moisture for floodplain zone -Provision of drinking water for terrestrial animals -Provision of space for fish and amphibian eggs -Provision of spaces for fish movement to feed and spawn -Provision of living spaces for hyporheic organisms which are the organisms live in sediment bottom of the streambed
Extreme low flows	-Recruitment of certain floodplain plant species -Prevention of invasion of introduced aquatic and riparian species -Concentration of prey into limited areas to benefit predators
High flow pulses	-Shaping physical habitats of stream channels (including pools and riffles) -Characterizing streambed substrates (size of the substrates) -Prevention of encroaching of riparian vegetation into a stream channel -Restoring normal water quality conditions after prolonged low flows by flushing away waste products and water pollutants -Preventing siltation, which helps to aerate eggs in spawning gravel areas

Table 5.1 Environmental flow components of the IHA method and their ecosystem influences on river ecosystems, adapted from The Nature Conservancy (2009) (continued)

EFC	Ecosystem Influences of the Flow Component
Small & large floods	-Provision of migration and spawning cues for fish -Triggering new phase in life-cycle (i.e., insects) -Provision of nursery area for juvenile fish by enabling fish to spawn in the floodplain -Provision of new feeding opportunities for fish, waterfowl -Recharging floodplain zone groundwater table -Maintenance of floodplain forest biodiversity through prolonged inundation (meaning different plant species have different tolerances) -Controlling distribution and abundance of floodplain plant species -Depositing nutrients on floodplain -Maintenance of balance of species in aquatic and riparian communities -Creating sites for recruitment of colonizing plants -Shaping physical habitats of floodplain zone -Carrying and depositing gravel and cobbles in spawning areas -Flushing both organic materials (food) and woody debris into channel -Prevention of invasion of introduced aquatic and riparian communities -Dispersal of seeds and fruits of riparian plants -Driving lateral movement of river channel, forming new habitats like secondary channels, oxbow lakes -Provision of plant seedlings with prolonged access to soil moisture

Whiting (2002) made a different classification of the environmental maintenance flows under eight classes, which include all IHA environmental flow elements. The author classified these flows under specific broad functioning of the riverine corridors, unlike IHA methodology. To better demonstrate the roles of environmental flow components, these eight classes of the maintenance flows are listed in Table 5.2. As can be seen in the table, holistic environmental flow components provide essential functions and processes occurring in the riverine ecosystems.

Table 5.2 Environmental maintenance flows defined by Whiting (2002)

Flow type no	The function of the flow
Flow type-1	Maintaining recreation and aesthetics
Flow type-2	Maintaining sediment sizes on the bed and their mobility
Flow type-3	Channel maintenance
Flow type-4	Maintaining longitudinal continuity of the channel
Flow type-5	Maintaining features and habitat
Flow type-6	Floodplain maintenance
Flow type-7	Hyporheic zone maintenance
Flow type-8	Maintaining riparian vegetation

Therefore, the critical streamflow events that support all these aquatic, riparian, terrestrial, and wetland functions of the riverine corridors should be included in the management context of the environmental water allocation procedure, which is ideally dealt with the holistic environmental flow methodologies.

The main objective of the environmental flow determination step within the ELOHA framework is to develop and test determined hypotheses on ecological response degree to alterations in a range of flow conditions. Although the prediction of direct ecological responses to flow alterations using empirical models is the goal of environmental flows science, these models are not readily available. It can be accomplished by developing these models with making hypotheses based on published studies documenting response-alteration relationships, where this relationship can be illustrated with an increase in the frequency of flow fluctuations or stream flashiness – for example a flow regime induced by dam operations or urbanization – favor fish species that are habitat generalists (nonnative species). An example of a hypothesis is given as: an increase in the duration of extreme low flow events will cause riparian canopy die-back in arid to semi-arid landscapes (Poff et al., 2010).

The flow alteration-ecology response relationships may be expressed in various forms:

- An ecosystem attribute (E) as a function of the change in hydrologic condition (Q) from baseline $> \frac{\Delta Q}{E}$,
- A change in ecosystem attribute from a reference condition as a function of change in hydrologic condition $> \frac{\Delta Q}{\Delta E}$,
- An expected status of an ecosystem attribute as a function of the value of a hydrologic metric $> \frac{Q}{E}$.

As previously stated, this study adopts the Ecological Limits of Hydrologic Alteration (ELOHA) framework as the holistic environmental flow assessment methodology for the Sakarya watershed. Thus, this chapter presents the 4th step of this framework, where the determination of environmental flows is supported by hydrologic alteration and ecological response relationships. It should be noted that since a comprehensive biological dataset is not available for the Sakarya watershed target locations selected in this study, these flow alteration and ecology relationships could not be made. All the environmental flow suggestions are based on only hydrological assessments.

Environmental flow assessment is defined as the process of estimating streamflow requirements such that environmental water needs are determined, effects of the streamflow modifications on both ecosystems and human well-being are evaluated and water projects are informed to make decisions while improving environmental conditions. Water is directly used by allocating it for different sectors, such as energy, irrigation, industry and public supply. On the other hand, indirect uses of water is available as it is indicated in the ‘environmental flow’ definition of the Brisbane declaration. This indirect use of water is for ecosystem well-being, religious activities, improvement of water quality, etc., which in turn provides services to people named as ‘ecosystem services’. These ecosystem services have been classified under different categories, for example, supporting services (e.g. nutrient cycling), provisioning services (e.g. freshwater), regulation services (e.g. climate regulation) and cultural services (e.g. spiritual) (Forslund et al., 2009). Thus,

environmental flow requirement ought to be central issue in a sustainable water allocation.

In the United States of America, environmental flow assessment was first regarded as a way to protect certain fish species. California was in the forefront and section 5937 of the Fish and Game Code of California law stated that sufficient water to pass through a fishway of a dam shall be released by the owner of the dam. In the absence of fishway, again sufficient water shall be released to keep the conditions good for fish just below the dam. As time passed, environmental movements have changed the politics and applicable laws in 1960s and 1970s. The Clean Water Act which is enacted in 1972 and the Endangered Species Act in 1973 were the most solid achievements in the environmental water management field. Other countries and regions were also working on their legal protections for environmental flow management (Williams et al., 2019).

In 2007, at the 10th International Riversymposium and International Environmental Flows Conference held in Brisbane, Australia, more than 750 scientists, economists, engineers, resource managers and policy makers from more than 50 countries declared their summary findings on environmental flow management and called a global action on this topic, which was presented as 'The Brisbane Declaration'. In this document, a global definition for 'environmental flows' was introduced as 'the quantity, timing, and quality of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems'. Also, their global action agenda was involving immediate action call on environmental flow quantification, integration of environmental water management into every aspect of land and water management, establishing institutional frameworks, building capacity etc. After 10 years, at the 20th International Riversymposium and International Environmental Flows Conference held in Brisbane, Australia, this declaration has been revisited and a new declaration and a new global action agenda has been published in 2018. In 2018's declaration, environmental flow definition from 2007's declaration has been revisited and it has been changed to (Arthington et al., 2018):

“Environmental flows describe the quantity, timing, and quality of freshwater flows and levels necessary to sustain aquatic ecosystems which, in turn, support human cultures, economies, sustainable livelihoods, and well-being.”

With these declarations, environmental water requirement has been highlighted as an essential part of water allocations and a key element of integrated water resources management. In addition, they were first steps to build a common vision and direction for environmental flow management by making a consensus view from diverse experiences across regions and disciplines.

Two different ways of achieving environmental flows are mostly adopted and they are in line with the approach specified in the Water Framework Directive for ecological status definitions. First is environmental flows for limiting hydrologic alterations from the unimpaired condition, which is applicable to the natural or semi-natural waterbodies where primary concern of the water management is preserving or improving the ecologic condition. While, second way of achieving environmental flows is the design approach (Figure 5.3). In this approach, heavily modified or artificial water bodies are the concern where streamflow regime can be adjusted to obtain a specific ecologic condition with ecosystem services it provides without regard to returning natural conditions (Acreman et al., 2014).

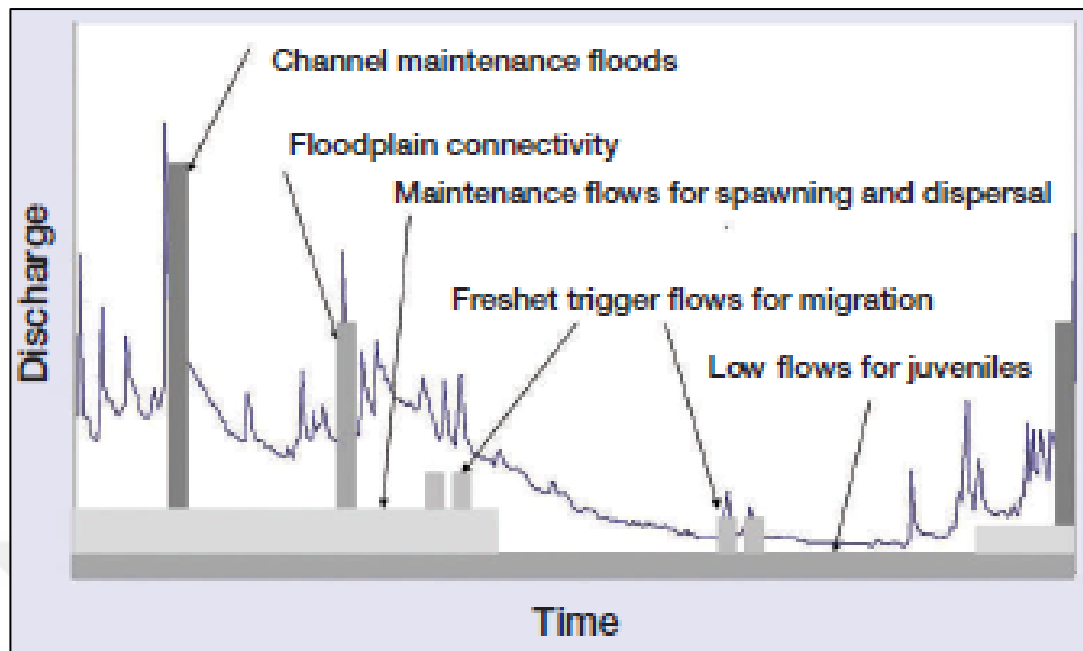


Figure 5.3. An example designer approach environmental flow assessment figure

As it is recognized that natural and anthropogenic modifications result in changes in the streamflow variability and biotic integrity of river ecosystems, environmental flow assessment methodologies have been improved appropriately.

Environmental flow assessment methodologies include many different kind of individual methods as well as frameworks being composed of various individual methods combined. These methodologies have been evolved from the certain minimum flows maintaining river biota to more comprehensive approach reflecting the dynamic nature of the ecological flow regime. Tharme (2003) reviewed all the present environmental flow methodologies in 2003 across the world and found that there are 207 individual methodologies of environmental flow assessment. However, it is surely known that she missed some and new methods have been developed since then (Williams et al., 2019). She classified these methodologies into four classes:

- 1- Hydrological,
- 2- Hydraulic rating,
- 3- Habitat simulation, and
- 4- Holistic methodologies.

Williams et al. (2019) mentions that this is not the only classification of environmental flow assessment methodologies. For example, top-down and bottom-up approaches; sample-based methods and whole-system methods; standard-setting and incremental approaches are some of these methodologies mentioned.

Holistic methodologies are in line with the idea of natural flow paradigm proposed by Poff et al. (1997) where flow regime has 5 important components creating natural flow variability. As Williams et al. (2019) noted, important and/or critical flow events are identified in holistic methodologies to understand this flow variability. Examples of these critical flow events are given by the authors as four features of the annual hydrograph providing distinct geomorphic and ecological functions in the river ecosystems:

- Wet season initiation flows
- Peak magnitude flows
- Spring recession flows and
- Dry-season low flows.

5.2 Materials and Methods

As indicated in Chapter 4, The Indicators of Hydrologic Alteration (IHA) method involves two groups consisting of 67 parameters (please refer to section 4.1 and 5.1 for the details) to determine hydrologic alterations and environmental flow requirements in a quantitative manner. 34 of these parameters provide information about the natural environmental flow types and their ecological integrity components (i.e., magnitude, duration, frequency, timing and rate of change). Since this chapter presents the environmental flow assessment in the Sakarya watershed, only these EFC parameters are used to determine environmental flow components at the target locations.

Similar to the IHA/RVA assessment, the EFA was performed using the IHA software of The Nature Conservancy (TNC). There are threshold values and couple of settings

to identify each EF component in the software. The tab where these information is provided to the software is illustrated in Figure 5.4. The data required to feed the software is daily natural streamflow data estimated in the Chapter 3 of this study.

Analysis Properties for D12A034-Porsuk Creek-Porsuk Dam Outlet-IHA Analysis

Analysis Title/Options | Analysis Years | Analysis Days | Statistics | **Environmental Flow Components** | Flow Duration Curves

Environmental Flow Component (EFC) analysis computes statistics for up to five different flow components: Extreme Low Flows, Low Flows, High Flow Pulses, Small Floods, and Large Floods. If you wish, this analysis may be performed for two separate seasons (see Analysis Days tab). The parameters used to define EFCs can be set below.

☒ Use Advanced Calibration Parameters

Initial High Flow/Low Flow Separation

All flows that exceed: % of daily flows for the period will be classified as High Flows.

All flows that are below: % of daily flows for the period will be classified as Low Flows.

Between these two flow levels, a High Flow will begin when flow increases by more than: percent per day, and will end when flow decreases by less than: percent per day.

High Flow Pulse and Flood Definition

☒ A small flood event is defined as an initial High Flow with a peak flow greater than: year return interval event.

☒ A large flood event is defined as an initial High Flow with a peak flow greater than: year return interval event.

All initial high flows not classified as Small Floods or Large Floods will be classified as High Flow Pulses.

Extreme Low Flow Definition

☒ An Extreme Low Flow is defined as an initial low flow below % of daily flows for the period.

All initial low flows not classified as Extreme Low Flows will be classified as Low Flows.

Figure 5.4. The interface of IHA software EFC tab to define the thresholds and set up parameters

For the environmental flow components calculations in the Sakarya watershed, the following threshold values are used (Table 5.3). These thresholds are set by the software as a default.

Table 5.3 The threshold values introduced to the Sakarya watershed IHA software in the EFC tab

EFC name	Threshold defined to the software
Extreme low flows	10% of daily flows for the period
Low flows	50% of daily flows for the period
High flow pulses	75% of daily flows for the period
Small floods	2-year return interval value
Large floods	10-year return interval value

An extreme low flow event starts with a low flow peaking below 10% of daily flows of the period (i.e., minimum) and end if the next flow event has a peak greater than this threshold value. On the other hand, a low flow event is defined by flow values with a peak (i.e., maximum) below 50% of the daily flows of the period. The low flows should be above the extreme low flow threshold value.

A high flow pulse event exceeds 75% of daily flows for the period and has a peak below the small flood threshold. The initiation of a high flow between low and high flow threshold values is with a rise rate of 25% per day. And it ends with a fall rate of 10% per day.

Small and large flood events are defined by the initial high flows with a peak flow value above their thresholds which are 2-year return flow for the small flood and 10-year return flow for the large flood.

The software creates a graph showing each EFC with colored lines and their initial and last values can be distinguished. An example to these graphs is given in Figure 5.5.

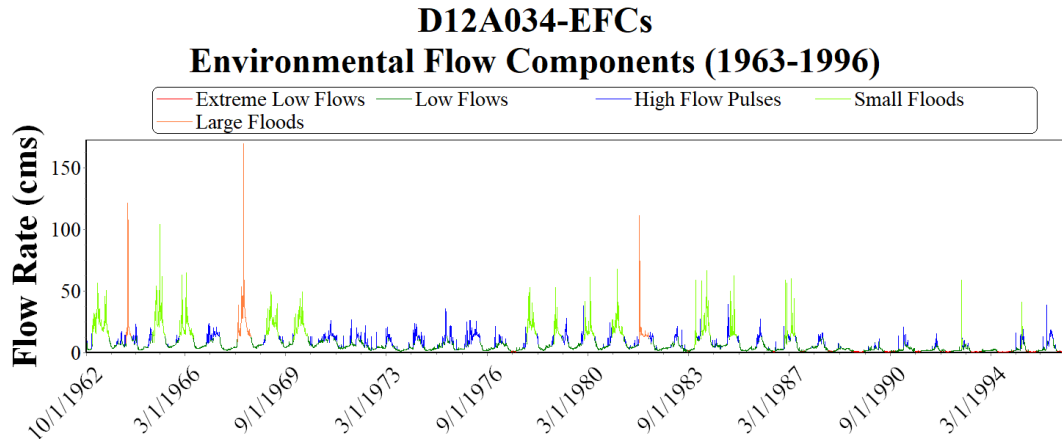


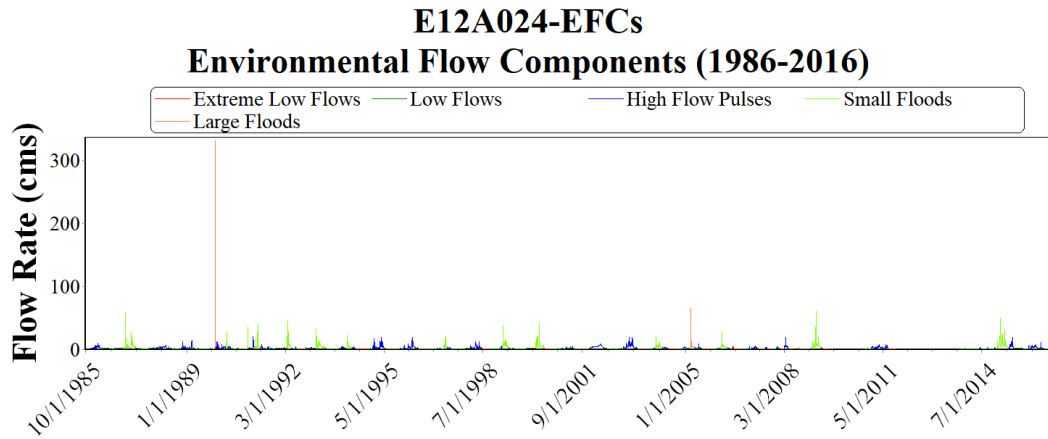
Figure 5.5. Daily environmental flow components (EFCs) graph of the target gauge D12A034*

*Orange: Large floods, Light green: Small floods, Blue: High flow pulses, Dark green: Low flows, Red: Extreme low flows

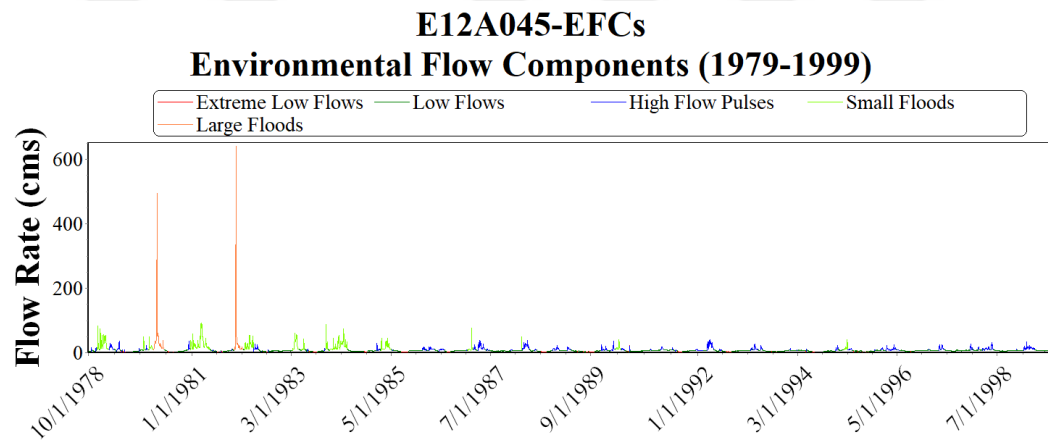
5.3 Results & Discussion

According to the Environmental Flow Components (EFCs) of the IHA methodology, 34 environmental flow parameters of the Sakarya watershed (Table 4.3) were calculated using the daily natural time series and they are given in Figure 5.6 for each target location. Since the parameters ‘rise and fall rates’ were not used for the environmental flow component suggestions to decrease the complexity of the assessment, they were excluded from the suggested parameters lists. The selected parameter values are presented in percentiles ranging from 10% to 90% (Table 5.4-Table 5.6). Since a single value for the environmental flow components would not be realistic for a proper water resources management, the mentioned range of values was proposed for each parameter.

a)



b)



c)

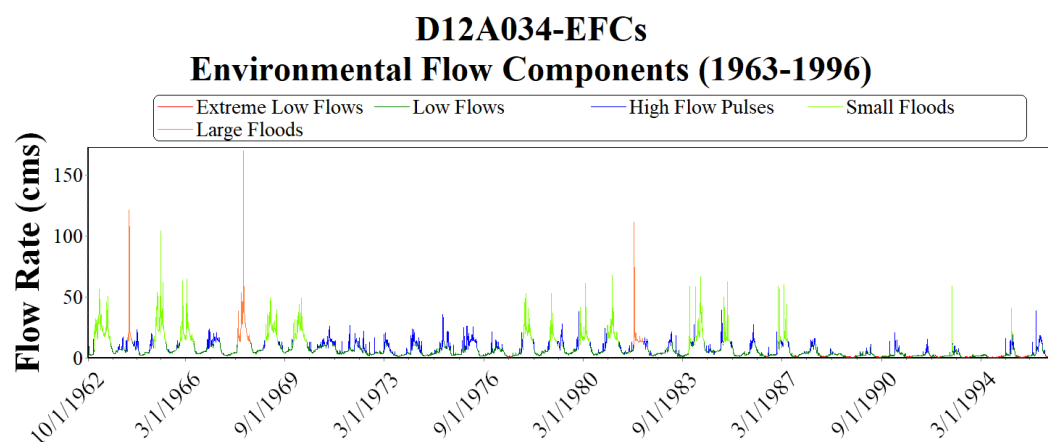


Figure 5.6. Daily natural hydrographs of the target gauges with EFC representations as colored lines: *Orange: Large floods, Light green: Small floods, Blue: High flow*

pulses, Dark green: Low flows, Red: Extreme low flows. a) E12A024, b) E12A045 and c) D12A034

In this study, only natural environmental flow components were taken into consideration as the literature emphasizes. The reason why this is the case is that altered environmental flow components show resulting flow magnitudes and other components under the effect of human pressures. The natural EFCs of each target gauge are given in between Table 5.4 and Table 5.6. According to these tables, there are four components calculated for extremely low flows, high flow pulses, small and large floods. However, only magnitude component was calculated for the low flows because the software gives only monthly magnitude values of this event.

The magnitude means peak values for the extremely low flows, high flow pulses, small and large floods. These peak values are the lowest for the extremely low flows and the highest for the other three flow events (high flow pulses, small and large floods).

On the other hand, durations mean median total number of days in which these events occur in a year. In other words, the median of all specific flow events occurring in a year yields the annual input dataset of the duration parameter in this analysis. For example, at the target location of the gauge D12A034 the high flow pulse event occurred four times in 1979 where their durations are variable. First event lasted 5 days, second does 5 days, third is 65 days and the last one lasted 4 days in a row. With these durations, it was found that the median duration of high pulse events in 1979 is 5 days. After obtaining all the yearly duration values, the cumulative percentiles in the following tables were calculated. The same calculation algorithm was applied to all parameters.

Timing of a flow event is defined by the Julian date number in a year. Also, the Julian date number is selected as the time when the peak flow was observed. For example, the lowest flow during an extreme flow event is flagged as the day and its Julian date number is taken.

On the other hand, the frequency of a flow event is defined by the total number of occurrence of this event in a year. To illustrate, the high flow pulse events at the D12A034 location in 1979 was observed four times in this year and its frequency was introduced to the software as four. The cumulative percentiles given in the following tables were calculated from the annual dataset of these total number of occurrences for each parameter.

Table 5.4 The Environmental Flow Components (EFCs) Values of the Target Gauge E12A024 as cumulative percentiles ranging from 10 to 90

Flow Type	Component	10%	25%	50%	75%	90%
Extremely low flows	Magnitude	0.64	0.71	0.89	0.95	0.95
	Duration	1.1	3.3	6.5	20.0	39.5
	Timing	192.2	210.6	223.5	231.8	247.2
	Frequency	0.0	0.0	2.5	6.0	9.1
Low flows	October	1.10	1.19	1.41	1.46	1.78
	November	1.10	1.37	1.41	1.66	2.04
	December	1.19	1.41	1.64	2.10	2.28
	January	1.41	1.66	1.87	2.25	2.28
	February	1.41	1.64	1.93	2.28	2.33
	March	1.43	2.04	2.28	2.28	2.54
	April	1.44	1.77	2.16	2.31	2.40
	May	1.55	1.82	2.16	2.31	2.52
	June	1.19	1.41	1.66	1.88	2.10
	July	1.10	1.19	1.28	1.54	1.66
	August	1.10	1.12	1.28	1.54	1.66
	September	1.10	1.15	1.28	1.44	1.79
High flow pulses	Magnitude	2.25	2.84	3.43	4.49	8.21
	Duration	2.4	4.0	5.0	12.0	30.7
	Timing	1.2	37.0	72.0	120.0	171.2
	Frequency	1.9	3.0	4.5	7.0	9.0
Small floods	Magnitude	21.54	25.49	37.37	43.73	56.59
	Duration	25.2	45.3	77.0	98.5	126.6
	Timing	26.8	44.5	57.0	95.5	111.2
	Frequency	0.0	0.0	0.0	1.0	1.1
Large floods	Magnitude	65.40	65.40	198.20	331.00	331.00
	Duration	15.0	15.0	38.0	61.0	61.0
	Timing	334.0	334.0	15.0	62.0	62.0
	Frequency	0.0	0.0	0.0	0.0	0.1

Table 5.5 The Environmental Flow Components (EFCs) Values of the Target Gauge D12A034 as cumulative percentiles ranging from 10 to 90

Flow Type	Component	10%	25%	50%	75%	90%
Extremely low flows	Magnitude	0.91	1.10	1.24	1.32	1.37
	Duration	1.8	3.0	4.0	8.0	12.0
	Timing	149.8	202.8	232.8	302.6	340.5
	Frequency	0.0	0.0	0.0	5.0	7.5
Low flows	October	1.50	2.43	3.20	4.89	6.20
	November	1.57	2.56	3.44	5.57	6.90
	December	1.61	2.96	4.60	7.57	9.53
	January	1.94	2.82	5.37	9.04	10.45
	February	1.91	2.72	6.27	9.93	11.87
	March	2.50	3.29	7.07	9.98	10.41
	April	2.45	5.23	7.98	10.83	11.62
	May	2.32	4.03	6.34	10.02	11.52
	June	2.05	2.46	4.70	8.46	10.30
	July	1.51	1.77	2.55	4.24	6.91
	August	1.47	1.85	2.29	3.54	4.63
	September	1.51	1.92	2.90	4.15	5.32
High flow pulses	Magnitude	8.25	12.48	13.52	14.06	15.62
	Duration	2.4	4.0	5.0	7.0	8.8
	Timing	338.4	3.5	71.0	119.5	179.7
	Frequency	2.0	3.0	5.0	7.0	9.5
Small floods	Magnitude	45.49	52.09	58.70	63.45	85.95
	Duration	10.5	60.3	129.5	170.0	194.5
	Timing	24.0	45.9	63.5	91.5	101.0
	Frequency	0.0	0.0	0.0	1.0	1.0
Large floods	Magnitude	111.40	111.40	121.80	169.80	169.80
	Duration	68.0	68.0	123.0	170.0	170.0
	Timing	353.0	353.0	70.0	75.0	75.0
	Frequency	0.0	0.0	0.0	0.0	0.5

Table 5.6 The Environmental Flow Components (EFCs) Values of the Target Gauge E12A045 as cumulative percentiles ranging from 10 to 90

Flow Type	Component	10%	25%	50%	75%	90%
Extremely low flows	Magnitude	0.96	1.37	1.55	1.78	2.99
	Duration	1.9	5.1	11.5	40.0	57.2
	Timing	177.6	191.3	221.5	242.0	250.6
	Frequency	0.0	0.5	2.0	3.0	4.8
Low flows	October	4.83	5.13	5.45	5.90	6.29
	November	5.34	5.65	5.90	6.58	7.20
	December	5.40	5.84	6.96	8.17	9.15
	January	5.93	6.20	6.85	7.74	8.53
	February	5.85	6.45	6.96	7.92	9.33
	March	6.47	7.26	7.87	9.25	9.53
	April	7.05	7.65	9.11	9.38	9.57
	May	5.34	6.35	7.56	8.27	8.83
	June	4.52	5.39	6.35	6.96	8.60
	July	3.78	4.48	4.87	5.58	5.71
	August	3.71	3.80	4.05	5.18	6.85
	September	4.03	4.33	4.84	5.50	6.03
High flow pulses	Magnitude	10.19	11.46	14.38	16.55	21.69
	Duration	3.5	5.3	9.0	14.0	42.0
	Timing	342.4	18.8	61.0	113.5	205.2
	Frequency	2.0	3.0	4.0	5.0	7.8
Small floods	Magnitude	40.73	44.04	52.39	79.17	90.79
	Duration	7.7	29.0	41.0	80.0	140.2
	Timing	361.8	30.0	63.0	93.0	120.0
	Frequency	0.0	0.0	1.0	1.0	2.0
Large floods	Magnitude	495.00	495.00	568.30	641.60	641.60
	Duration	74.0	74.0	78.5	83.0	83.0
	Timing	351.0	351.0	36.5	88.0	88.0
	Frequency	0.0	0.0	0.0	0.0	0.8

The environmental flow suggestions based on the values shown in Table 5.4 and Table 5.6 are visualized through Figure 5.7 and Figure 5.9. In these figures, each environmental flow component is shown on a monthly time scale where gray zones represent the possible timings of the occurrence of the related event. In addition to the timings of each component, their magnitudes, durations and frequencies are given. It should be emphasized that these environmental flow suggestions are based

on the natural required values. There are no or little impact of operational or management-related factors.

These suggested environmental flow components should be used in accordance with a natural river restoration perspective. By implementing these values, the Sakarya River would provide its near-natural conditions where human pressures and alterations are minimal. It was found that each location within the watershed require a comprehensive environmental flow assessment like in this study. Each EF figure shows different timings, magnitudes, durations and frequencies of the environmental flow components specific to the upstream drainage area characteristics and hydromorphological dynamics.

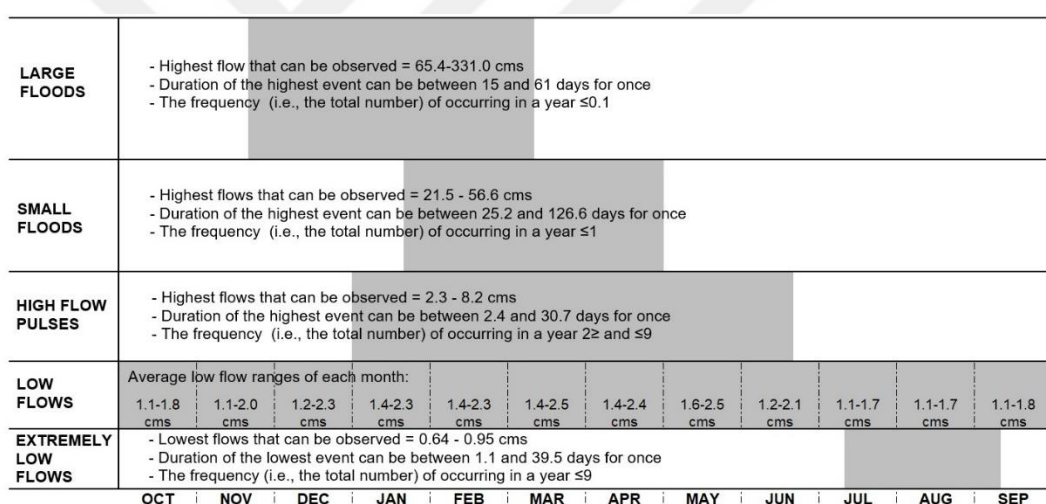


Figure 5.7. EFC suggestions for the target gauge E12A024

LARGE FLOODS	- Highest flow that can be observed = 495.0-641.6 cms - Duration of the highest event can be between 74 and 83 days for once - The frequency (i.e., the total number) of occurring in a year ≤ 0.8											
SMALL FLOODS	- Highest flows that can be observed = 40.7 - 90.8 cms - Duration of the highest event can be between 7.7 and 140.2 days for once - The frequency (i.e., the total number) of occurring in a year ≤ 2											
HIGH FLOW PULSES	- Highest flows that can be observed = 10.2 - 21.7 cms - Duration of the highest event can be between 3.5 and 42 days for once - The frequency (i.e., the total number) of occurring in a year $2 \geq$ and < 8											
LOW FLOWS	Average low flow ranges of each month:											
	4.8-6.3 cms	5.3-7.2 cms	5.4-9.2 cms	5.9-8.5 cms	5.8-9.3 cms	6.5-9.5 cms	7.1-9.6 cms	5.3-8.8 cms	4.5-8.6 cms	3.8-5.7 cms	3.7-6.9 cms	4.0-6.0 cms
EXTREMELY LOW FLOWS	- Lowest flows that can be observed = 0.96 - 2.99 cms - Duration of the lowest event can be between 1.9 and 57.2 days for once - The frequency (i.e., the total number) of occurring in a year < 5											
	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP

Figure 5.8. EFC suggestions for the target gauge E12A045

LARGE FLOODS	- Highest flow that can be observed between 111.4 and 169.8 cms - Duration of the highest event can be between 68 and 170 days for once - The frequency (i.e., the total number) of occurring in a year ≤ 0.5											
SMALL FLOODS	- Highest flows that can be observed = 45.5 - 86.0 cms - Duration of the highest event can be between 10.5 and 194.5 days for once - The frequency (i.e., the total number) of occurring in a year ≤ 1											
HIGH FLOW PULSES	- Highest flows that can be observed = 8.3 - 15.6 cms - Duration of the highest event can be between 2.4 and 8.8 days for once - The frequency (i.e., the total number) of occurring in a year $2 \geq$ and < 10											
LOW FLOWS	Average low flow ranges of each month:											
	1.5-6.2 cms	1.6-6.9 cms	1.6-9.5 cms	1.9-10.5 cms	1.9-11.9 cms	2.5-10.4 cms	2.4-11.6 cms	2.3-11.5 cms	2.0-10.3 cms	1.5-6.9 cms	1.5-4.6 cms	1.5-5.3 cms
EXTREMELY LOW FLOWS	- Lowest flows that can be observed = 0.91-1.37 cms - Duration of the lowest event can be between 1.8 and 12 days for once - The frequency (i.e., the total number) of occurring in a year < 8											
	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP

Figure 5.9. EFC suggestions for the target gauge D12A034

CHAPTER 6

CONCLUSION AND FUTURE RECOMMENDATIONS

The environmental flows have been recognized as one of the most important concept for the integrated water resources management. Even though the environmental flows offer significant solutions to the challenges encountered while making decisions of the sustainable water allocations, no legal basis was formed and no common methodology was developed. However, there are attempts to create a baseline for the implementation of environmental flows. For example, the Water Framework Directive (WFD) published in 2000 by the European Commission refers to hydromorphological quality elements for freshwater resources. Throughout the time, the scientific knowledge of the environmental flows evolved. It was understood that these flows do not only provide a healthy river corridor for the organisms living in but also provide a sustainable development services to humankind. These freshwater services include socioeconomic security, basic materials for living, health, regulation services, and self-purification. Therefore, they need to be included in any of the water resources management plan. With this regard, a gap in the holistic environmental flow assessment was detected for Turkey's water management strategies.

Sakarya watershed, the study area, is under the cumulative pressure of various sectors demanding water. Agriculture, drinking and utility water, industry and energy are the main sectors in the watershed. Because it is a socioeconomically developed region and the environmental flow management strategies is limited to the minimum flow approach, there is a gap to be filled with a sustainable and integrated environmental flow management approach. This study was carried out to address this gap detected for the environmental flow needs of the Sakarya River at selected strategic locations using the ELOHA framework approach. It was performed

as a level-1 and partly 2 (Opperman et al., 2018) study where both desktop methodologies and field surveys were conducted to make a holistic assessment. First, a hydrologic foundation of the watershed was developed, consisting of natural and altered daily streamflow time series at the selected gauged locations. The natural daily streamflow data of the target gauge locations were produced using a statistical approach named ‘Regional regression modeling and QPPQ method’ adopted by the USGS (Chapter 3). Even though the most challenging part of this step was to develop regression models with a very limited database, it was achieved to obtain good model and prediction performance results. Since Sakarya watershed have limited climatological, hydrological and geospatial data, input of the regression models has less number of data than the ones seen in the literature studies. Nevertheless, model and predictive performance evaluations yield good results for the three flow classes of the FDC (i.e., low, medium, and high flow regions), which indicates the regional regression models perform well. Yet, it should be noted that the daily streamflow estimation at the validation gauges revealed that the regional regression model development and QPPQ method applied in this study is less suitable to the arid areas of the watershed and headwaters.

Each hydrograph and FDC built and field survey results indicate the sources of human alteration or pressure on the river corridor because each drainage area has one or more dominating anthropogenic factor(s) (Chapter 4). Various anthropogenic pressures, such as impoundments of the water for hydropower plant (HPP) operations, irrigational water abstractions and diversions, industrial water pumping, etc. are in excessive amounts in the watershed. Also population in the area is increasing with time, which put extra pressure on the water resources for the purpose of drinking and utility. For example, Ankara, Eskişehir and Kütahya are such highly populated cities. These pressures cause a major stress on the Sakarya river ecosystems where the biggest share of the water abstractions and regulations belong to the agriculture sector. Especially intensive irrigational activities take place in certain regions of the watershed. Also, there are consequential morphological pressures and alterations of these hydrological activities. All of these pressures have

cumulative detrimental impacts on the natural variability of streamflow regime and the ecological integrity of river ecosystems as it was detected in this study. In the light of these information, the hydrologic alteration and environmental flow assessments were performed.

The average IHA results (Figure 4.21 and Table 4.14) revealed that dam operations, agricultural activities (irrigation and livestock watering), industrial and mining water abstractions and discharges, and drinking water demands have significantly changed the natural streamflow dynamics. The aquatic, terrestrial and wetland ecosystems within this region are considered to be seriously degraded regarding the hydrologic alteration and ecological integrity framework (Poff et al., 1997). Therefore, it is suggested that an immediate action should be taken to rehabilitate the hydrologic conditions in the region. In this regard, environmental flow suggestions were made in Chapter 5. The environmental flows were calculated by the Environmental Flow Components (EFCs) methodology of the IHA framework. It is believed that these environmental flow suggestions would guide the environmental authorities to enhance hydrologic conditions in the Sakarya watershed. Also, the methodology selected for this study can be applied to anywhere in Turkey with sufficient hydrologic and geospatial data. It should also be emphasized that this is the first study to make such a comprehensive environmental flow assessment in Turkey. Also, it is believed that the methodology implemented in this thesis study would help to create a national environmental flow legislation.

In addition to the hydrologic alteration and environmental flow assessments, the following studies can be conducted using the same information. The ecological/urban river restoration can be supported with an additional and sufficient biological/morphological/water quality data collected. The ecological river restoration is a broad research area including sediment transport, physical habitat, biological, longitudinal-lateral-vertical connectivity, riparian vegetation assessments. A high resolution (means daily here) hydrological database plays a key role to provide important supportive information for these assessments. Moreover, risk assessment studies can be conducted to take serious measures in legal

environmental management framework. One of the most common risk assessment type is flood risk assessment because climate change and anthropogenic activities deteriorate the global hydrological cycle. These pressures cause the frequency of extreme water conditions to increase (such as flooding) or decrease (for example drought), which is supported by the hydrologic alteration assessment findings of this study. Thus, scientists around the world are working on these issues to comprehend the risks to the society, economy, ecosystem, and psychology by using high resolution hydrological database. On the other hand, drought risk assessment studies can also be conducted using hydrological approaches. The hydrological drought assessments based on streamflow indices can be given as an example to the other extreme event analysis using high resolution streamflow information. As can be realized, the hydrologic foundation is a very functional tool to perform research about the hydrological conditions. Thus, this study would also guide different critical decision making processes in the Sakarya watershed.

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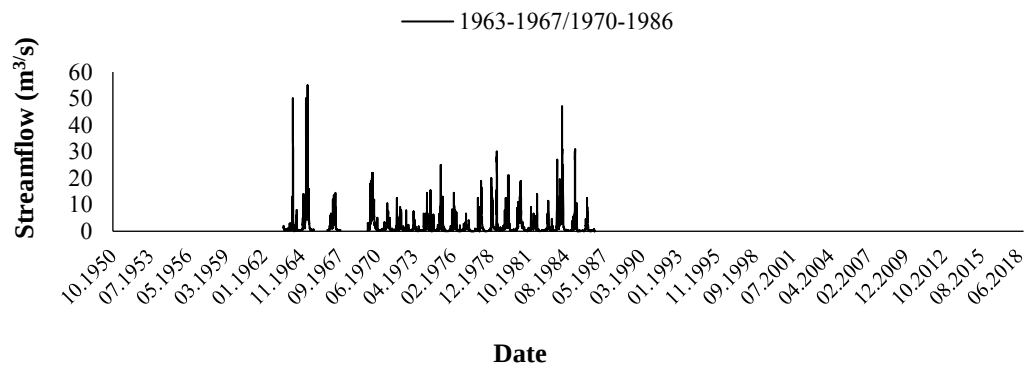
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APPENDICES

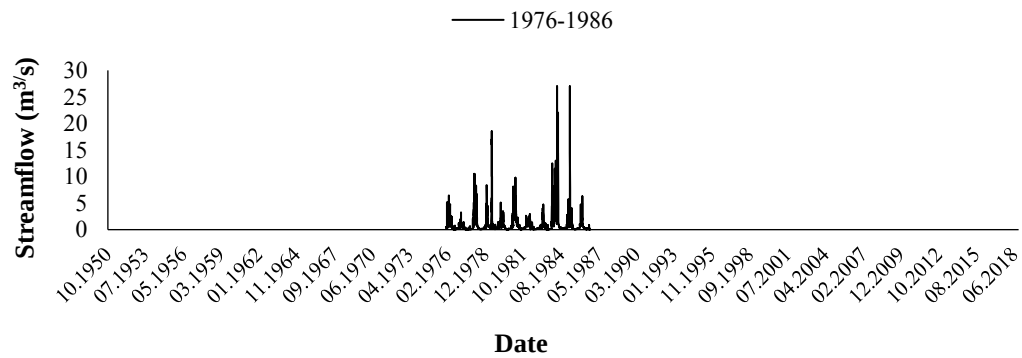
A. Sakarya watershed – Streamflow Gauges Time Series Graphs

Upper Sakarya Subwatershed

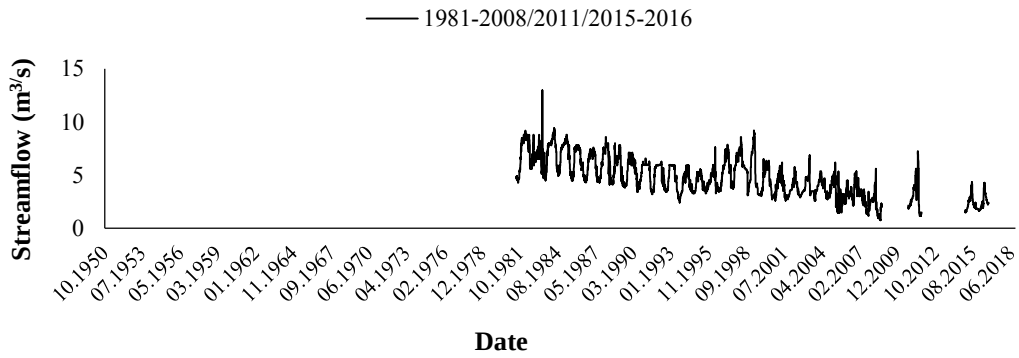
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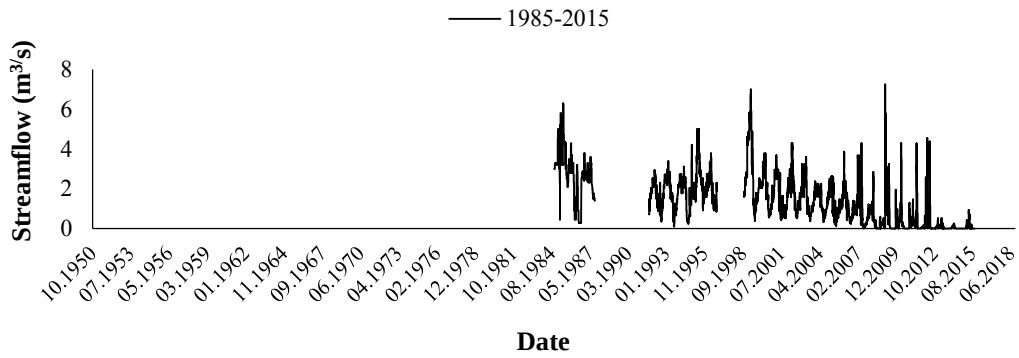
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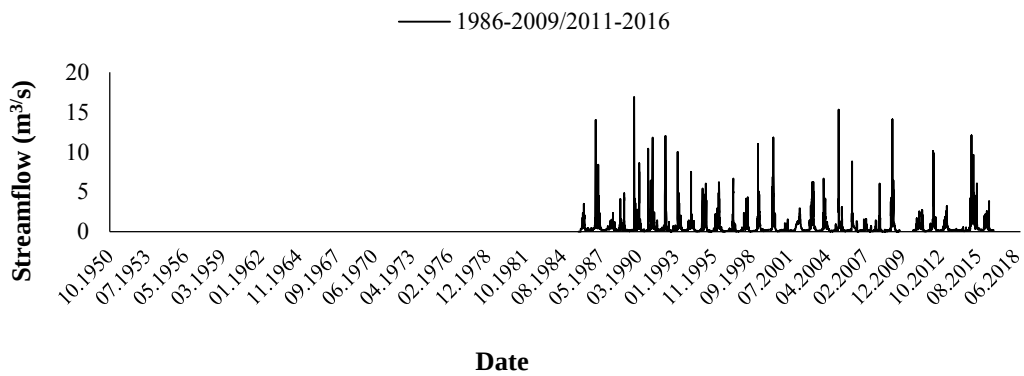
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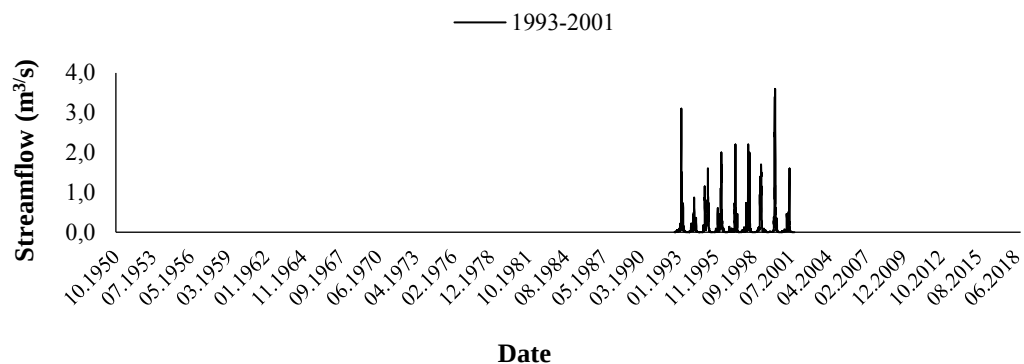
D12A176 - AKGOL CIKISI - KUCUKHASAN BRIDGE



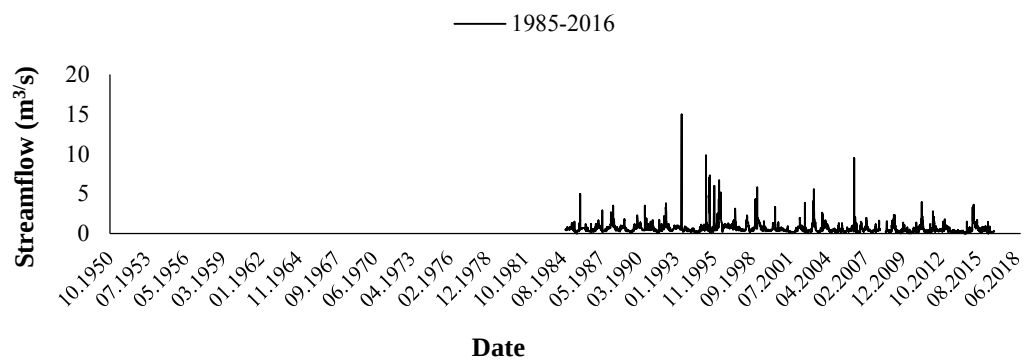
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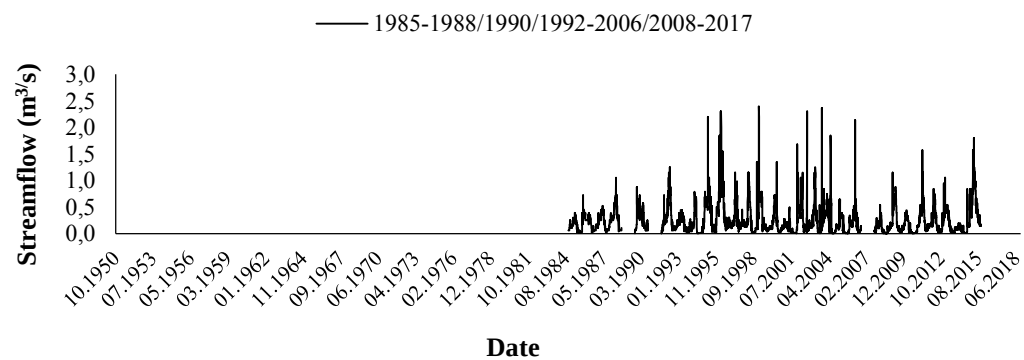
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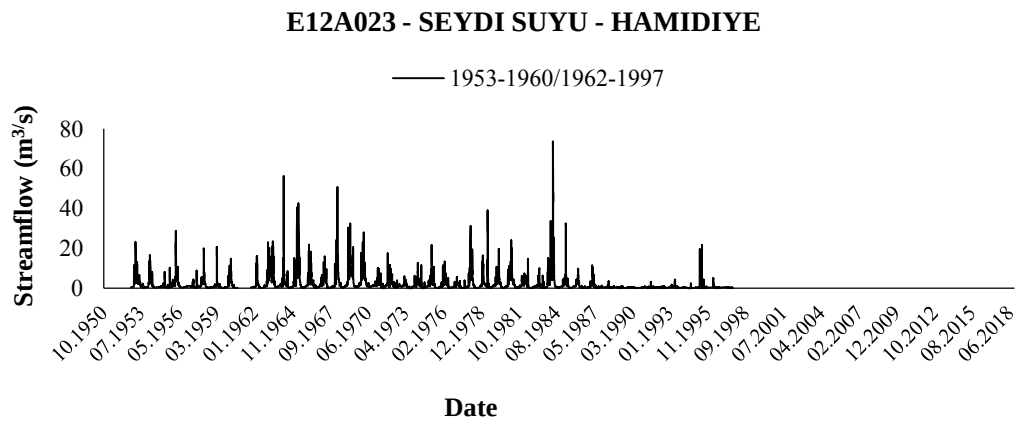
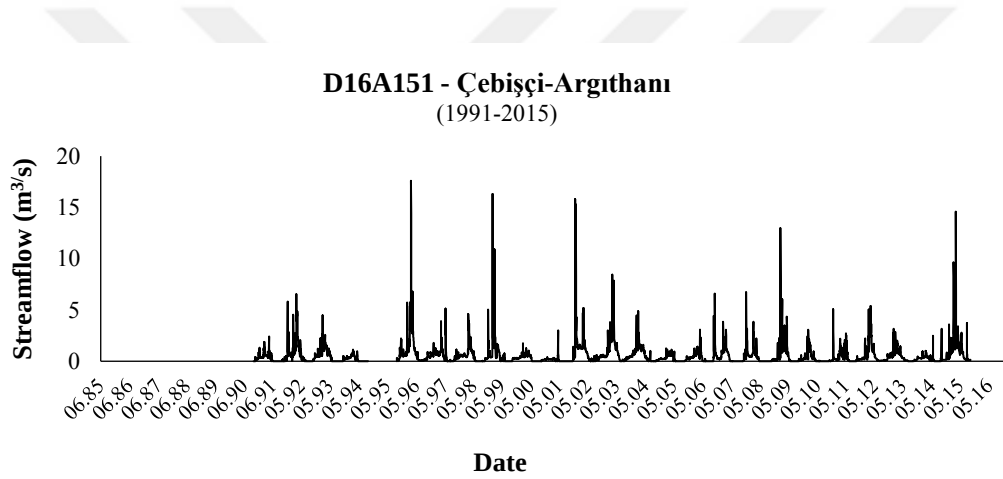
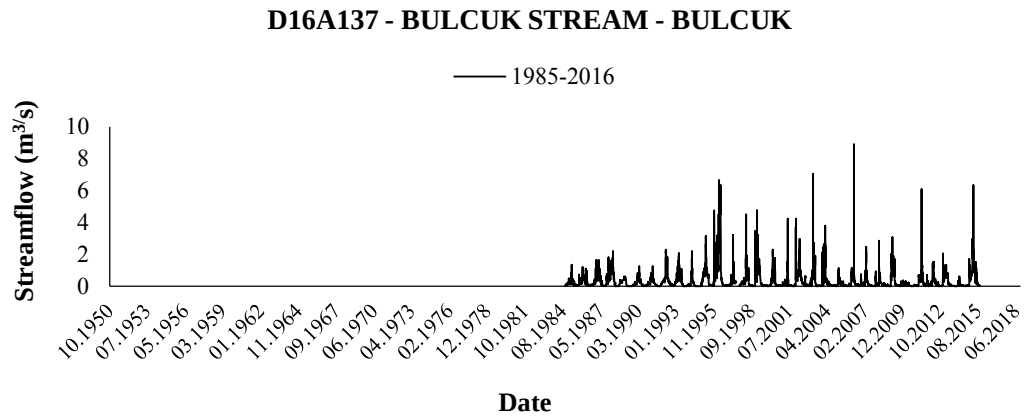


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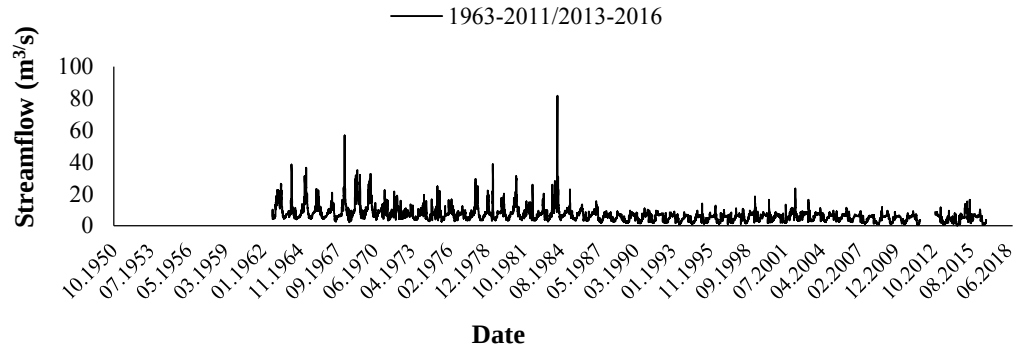


D16A136 - ELDES CREEK - ELDES

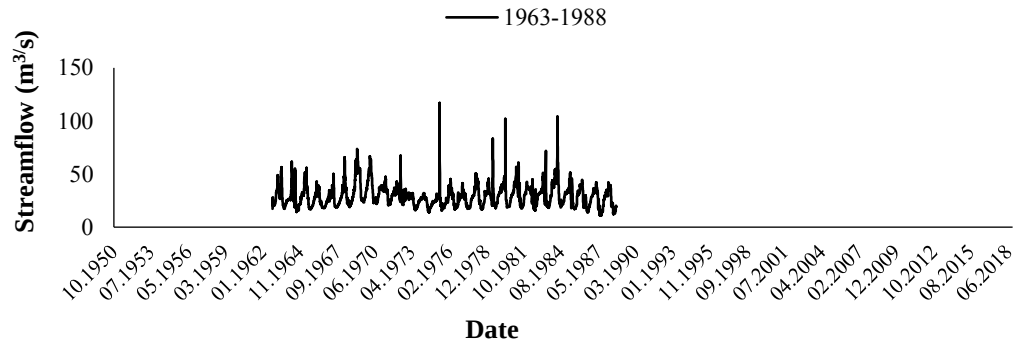




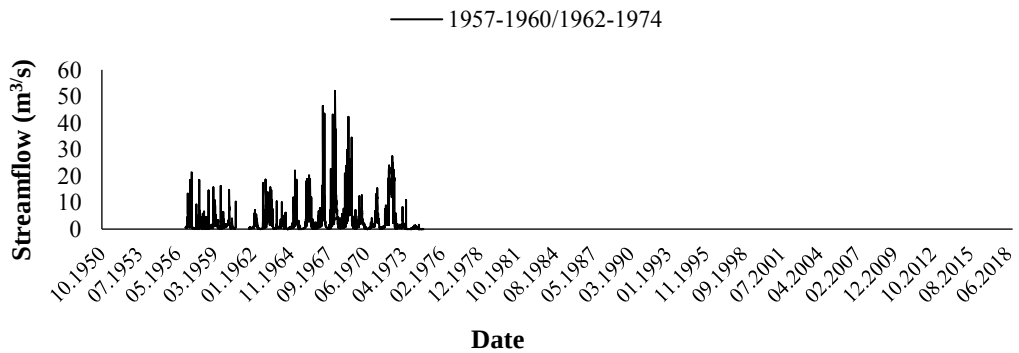
E12A024 - SAKARYA RIVER - AKTAS



E12A041 - SAKARYA RIVER - KAVUNCU BRIDGE

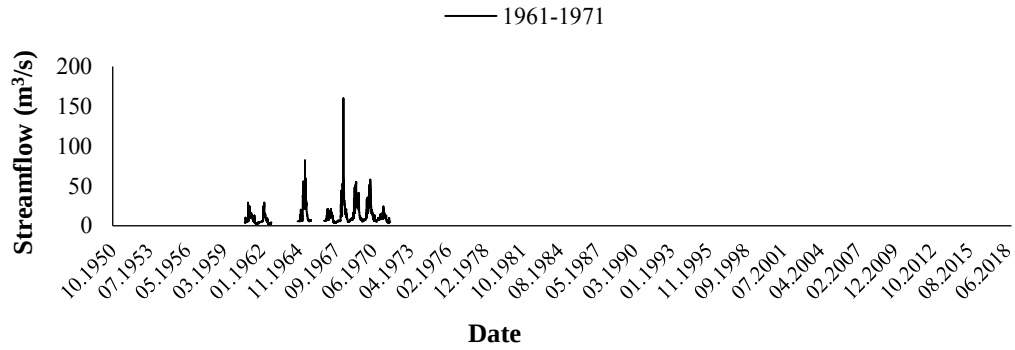


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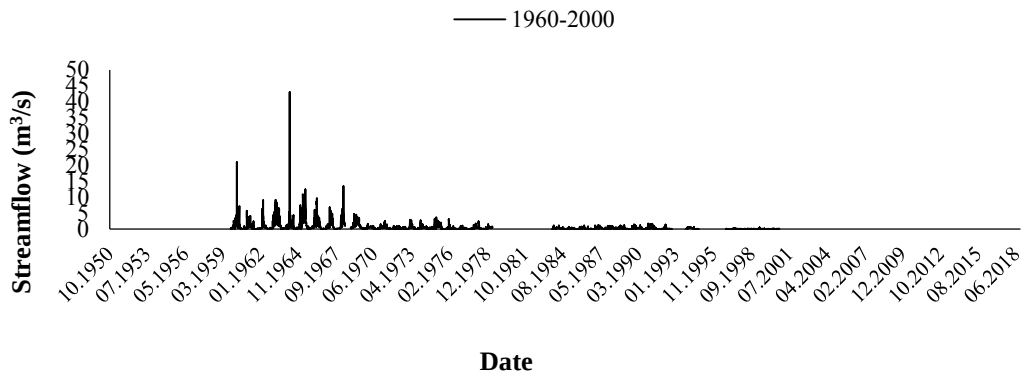


Porsuk subwatershed

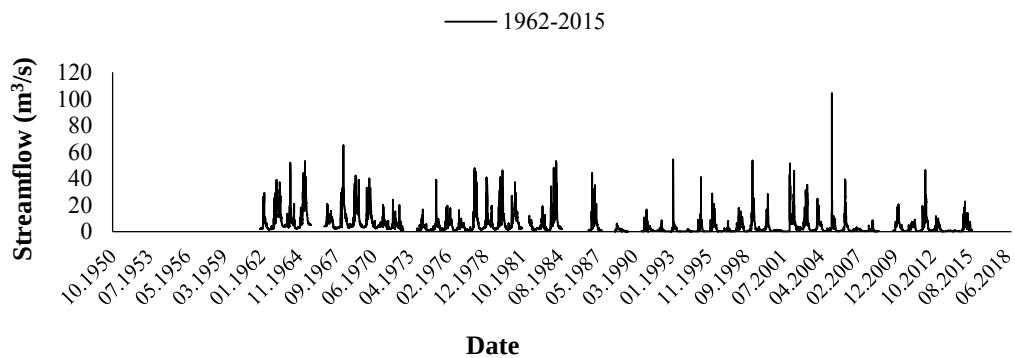
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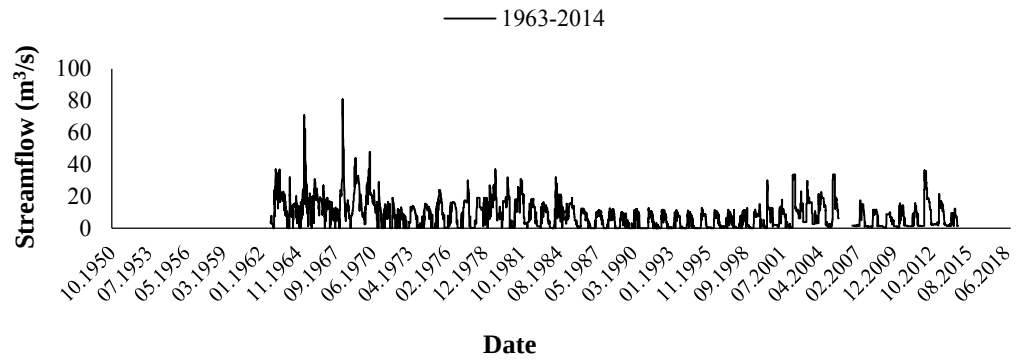
D12A006 - KARGIN STREAM - PORSUK DDY STATION



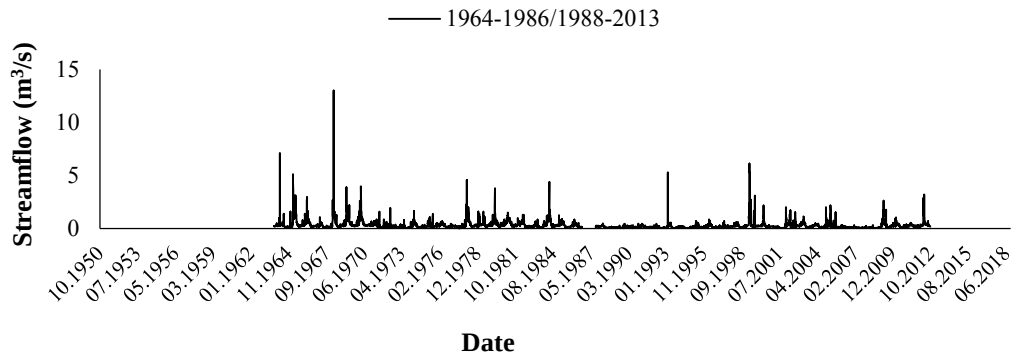
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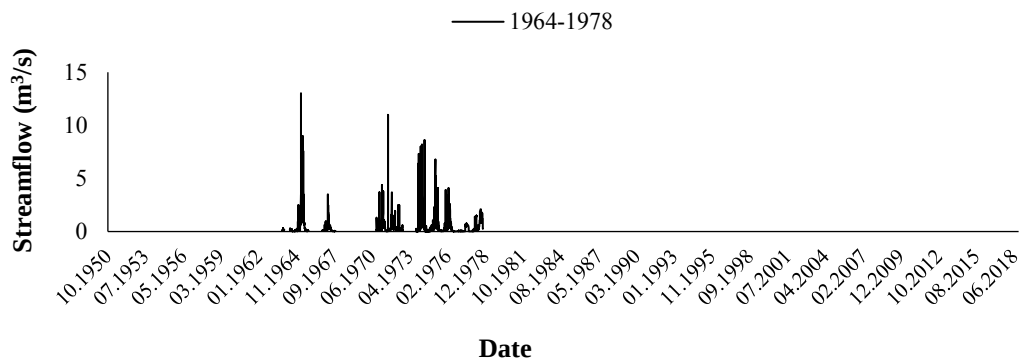
D12A034 - PORSUK DAM OUTLET



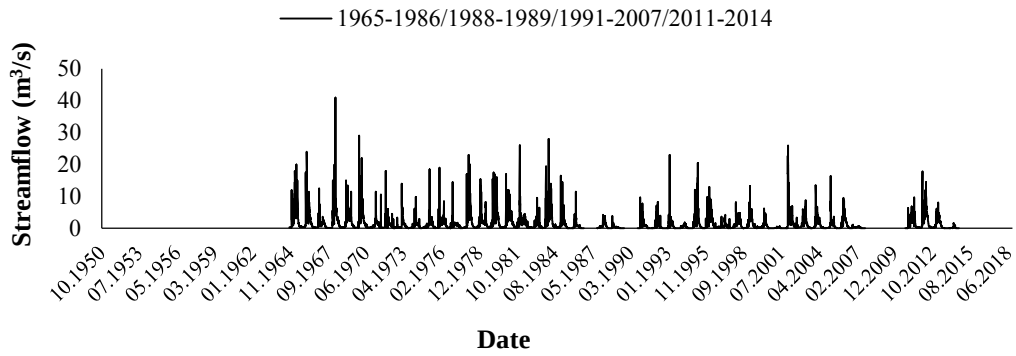
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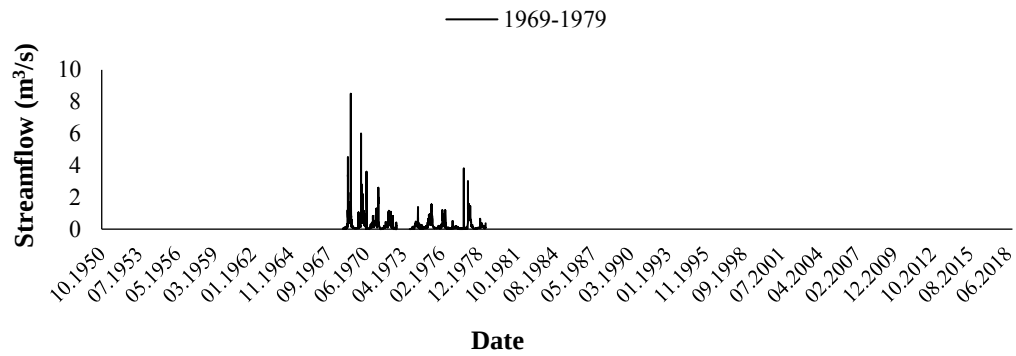
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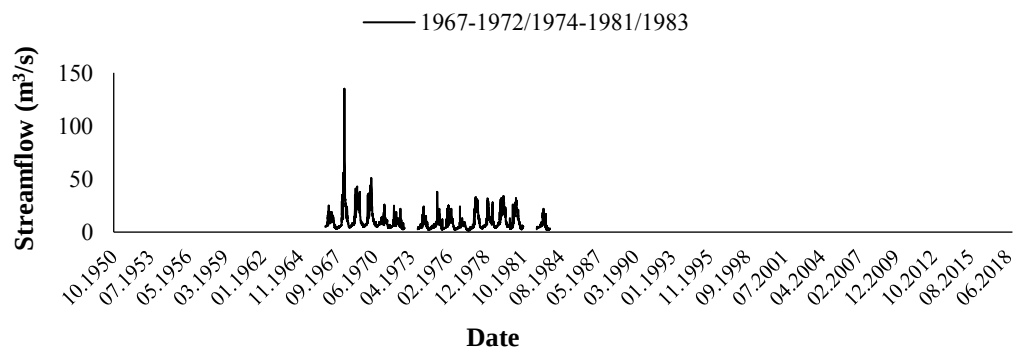
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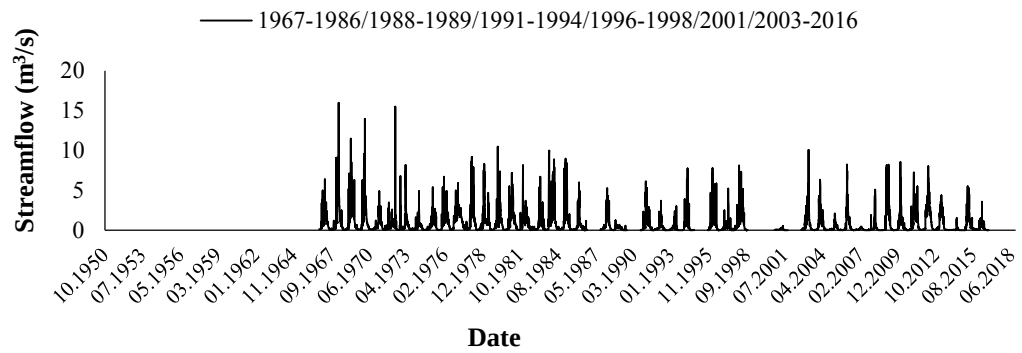
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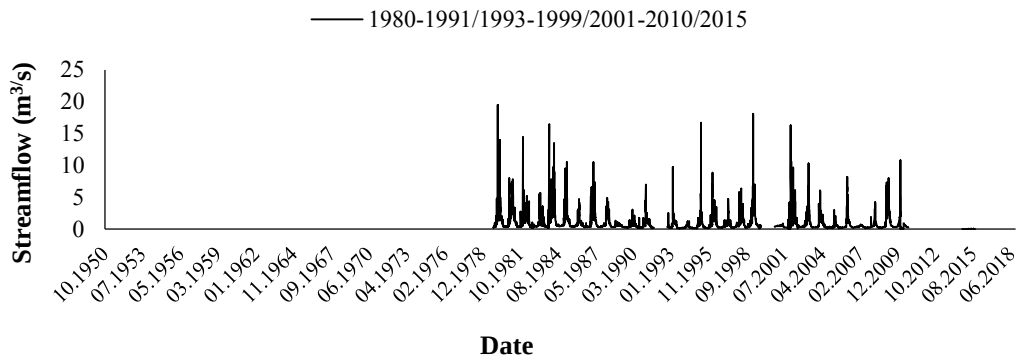
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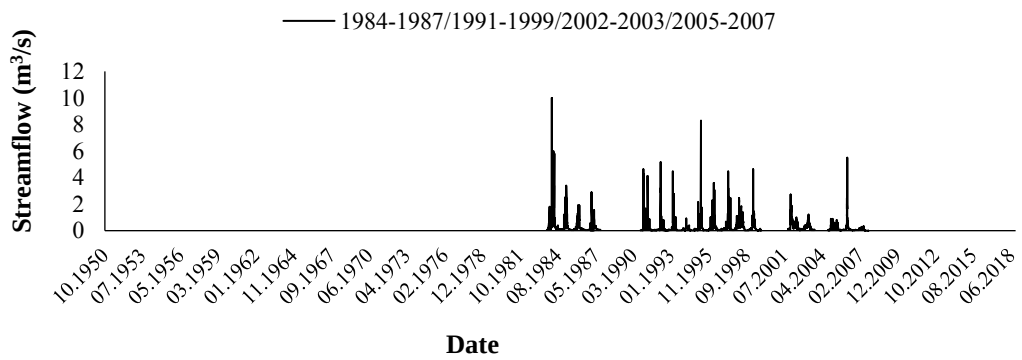
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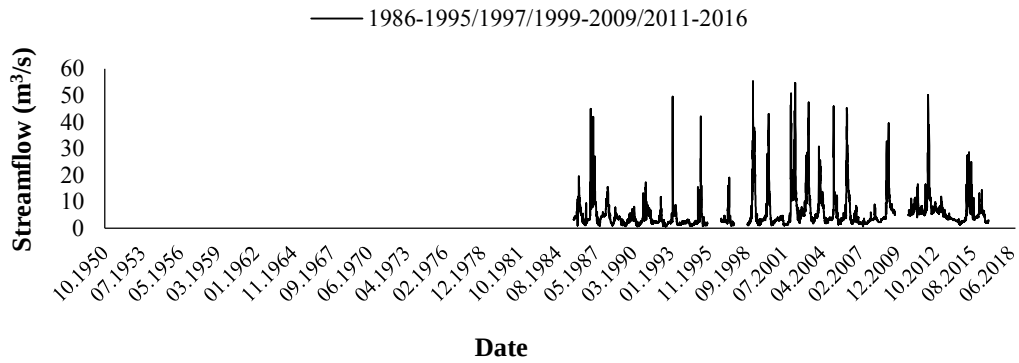
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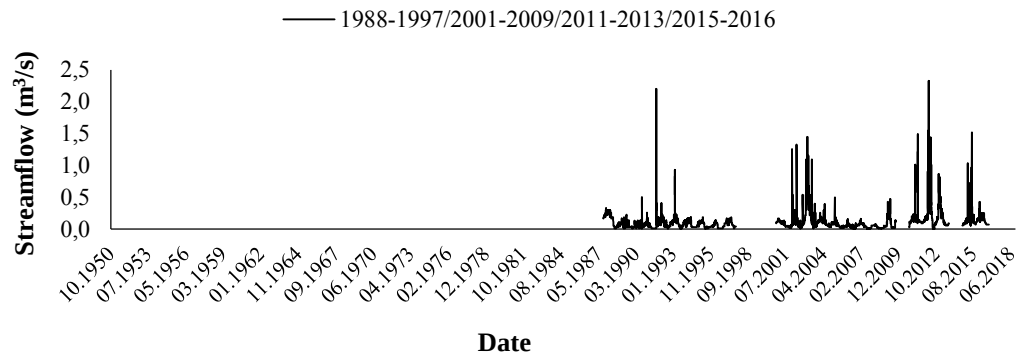
D12A171 SARISU - YENIDODURGA



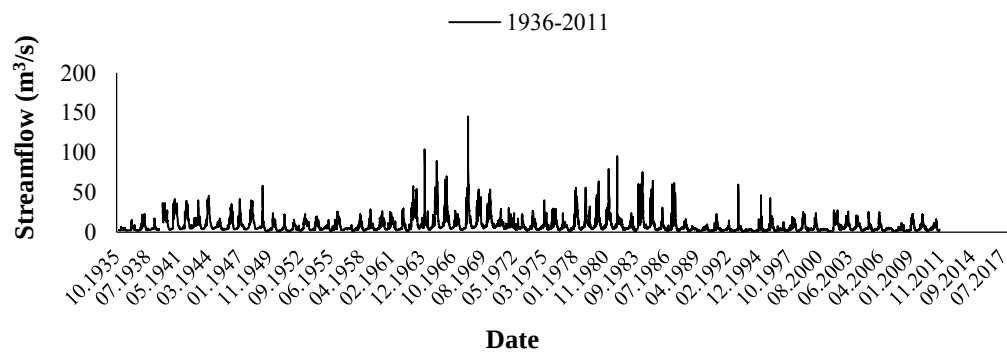
D12A181 - PORSUK CREEK - YENIBORSA



D12A182 - PURTEK STREAM - MEMIK

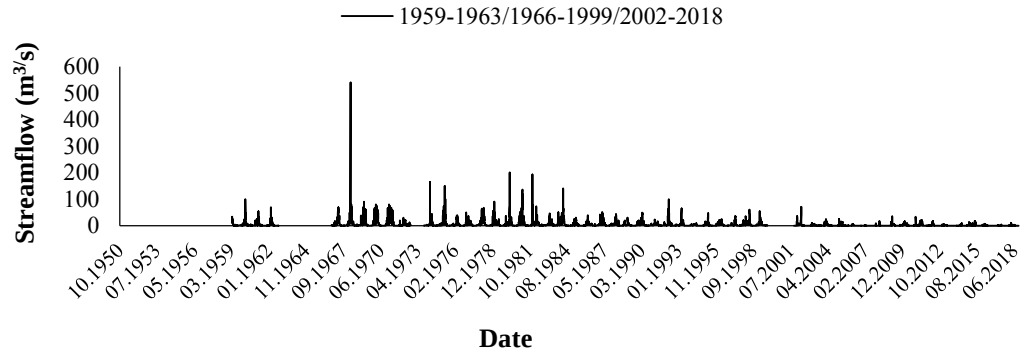


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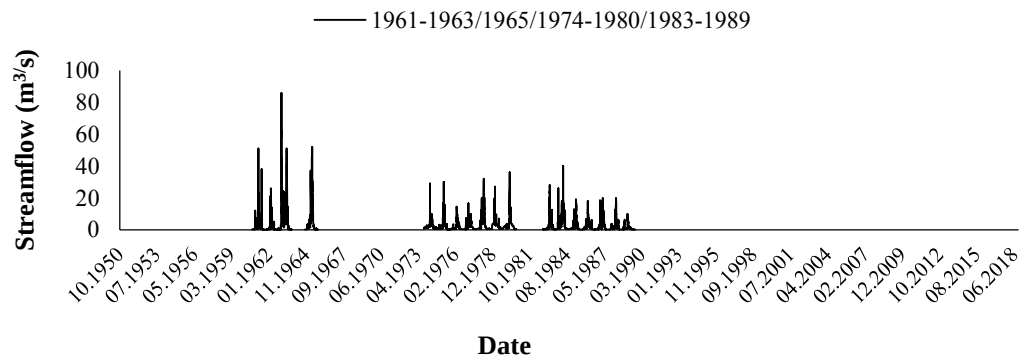


Ankara subwatershed

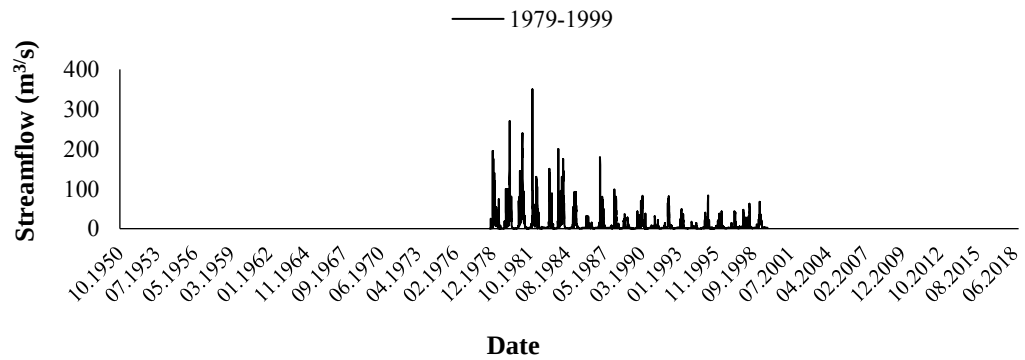
D12A017 - KIZILCAHAMAM STREAM - MANDIRA



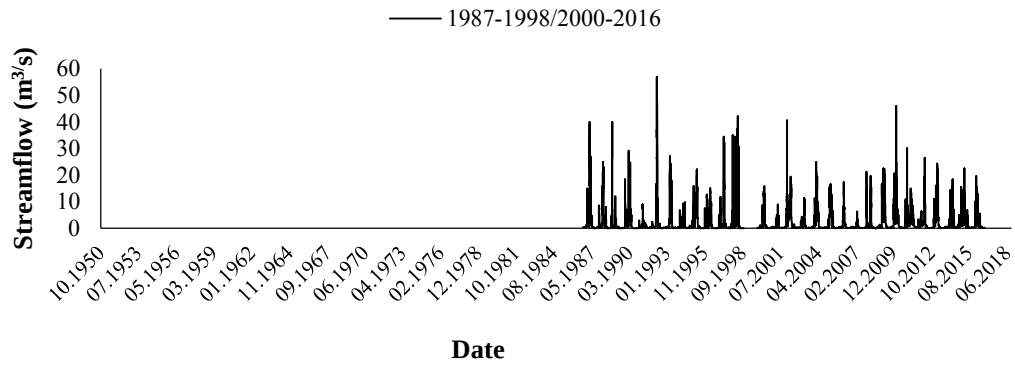
D12A030 - SEY STREAM - SARAY



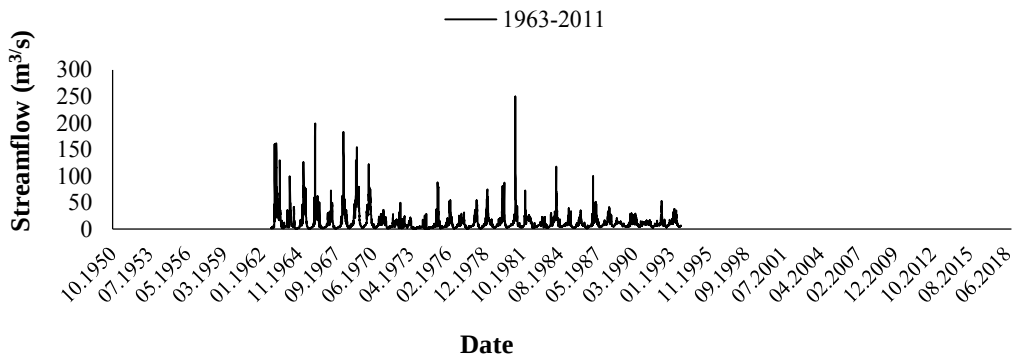
D12A139 - KIRMIR CREEK - GUDUL



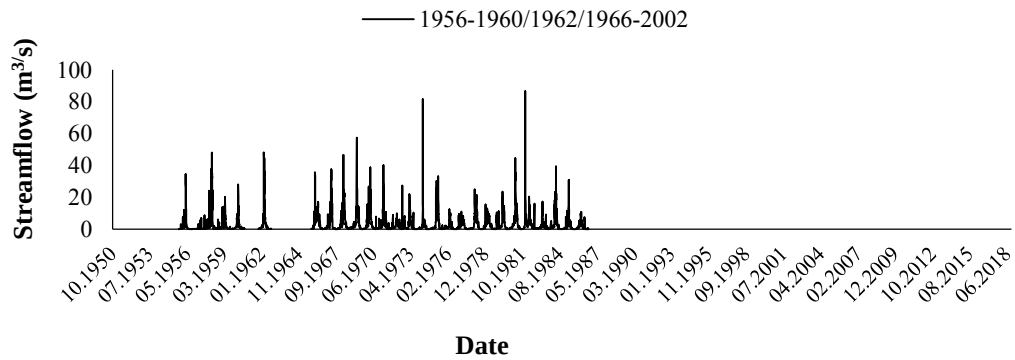
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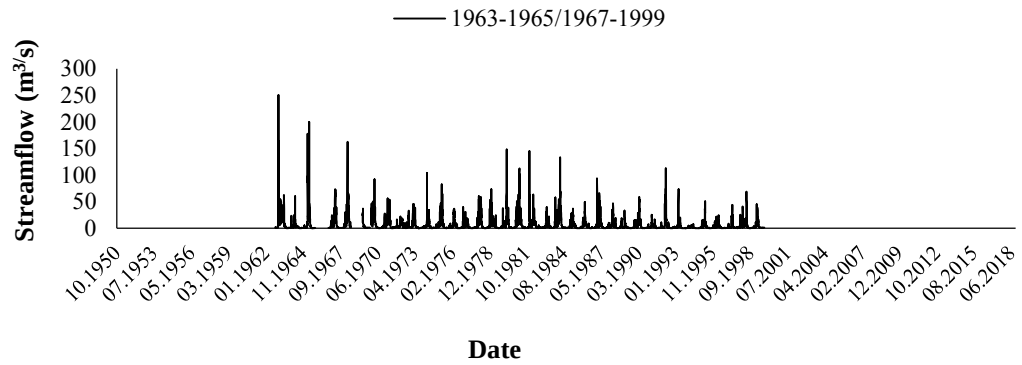
E12A026 - ANKARA CREEK - MESECIK



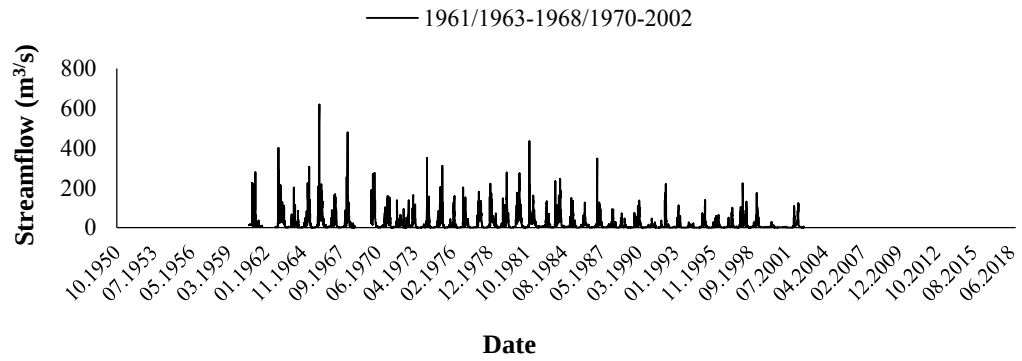
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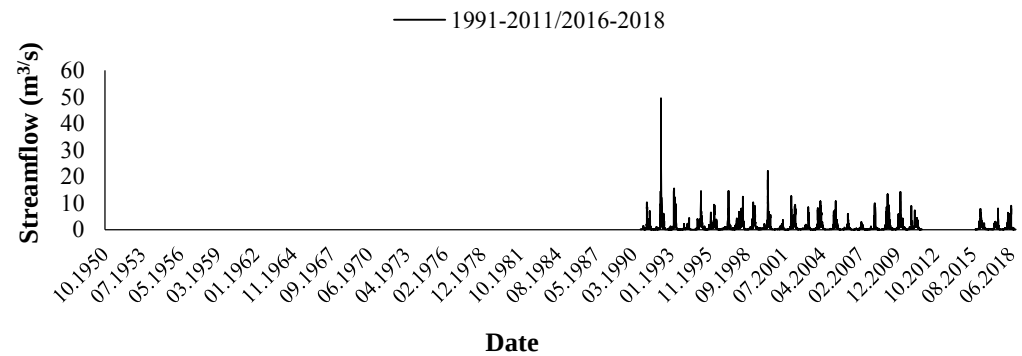
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E12A045 - KIRMIR CREEK - TAKSIR BRIDGE

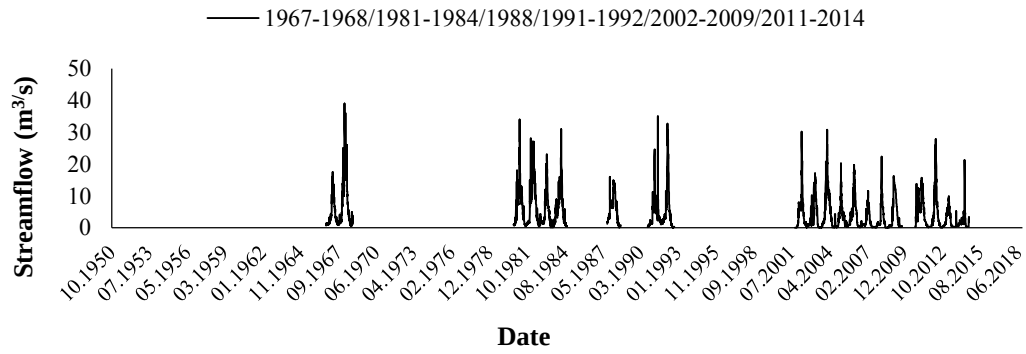


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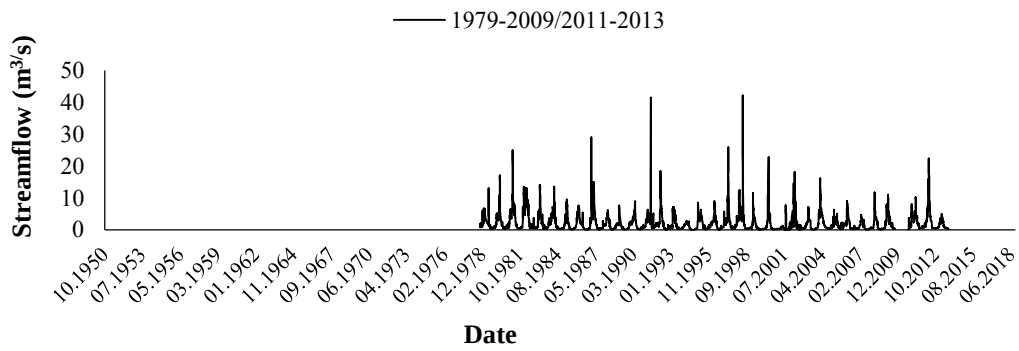


Middle Sakarya subwatershed

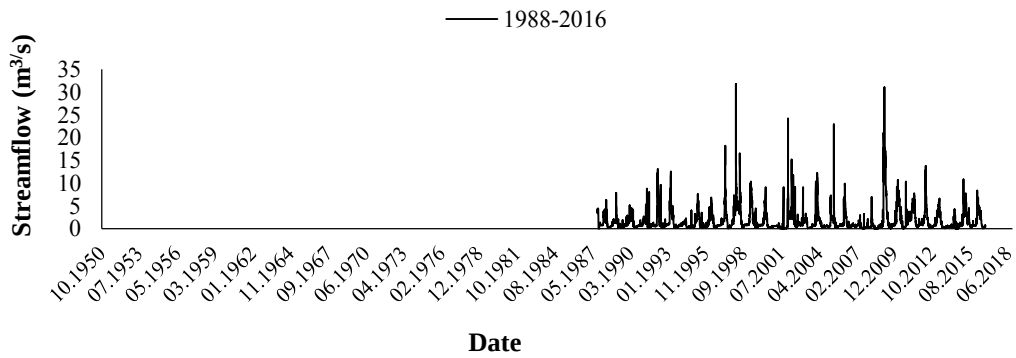
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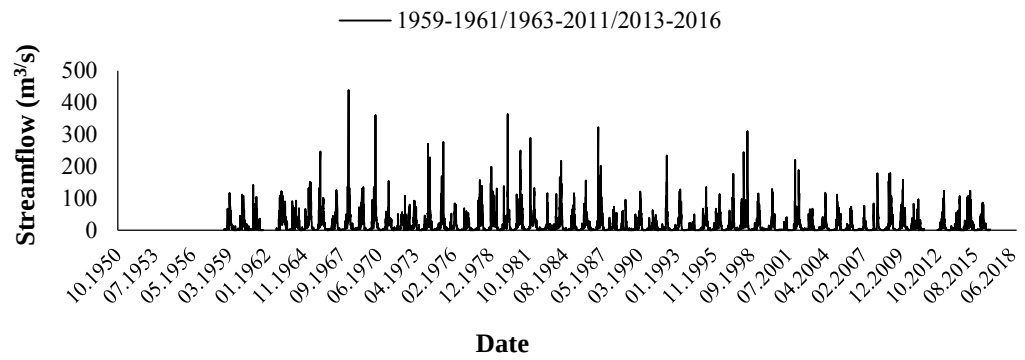
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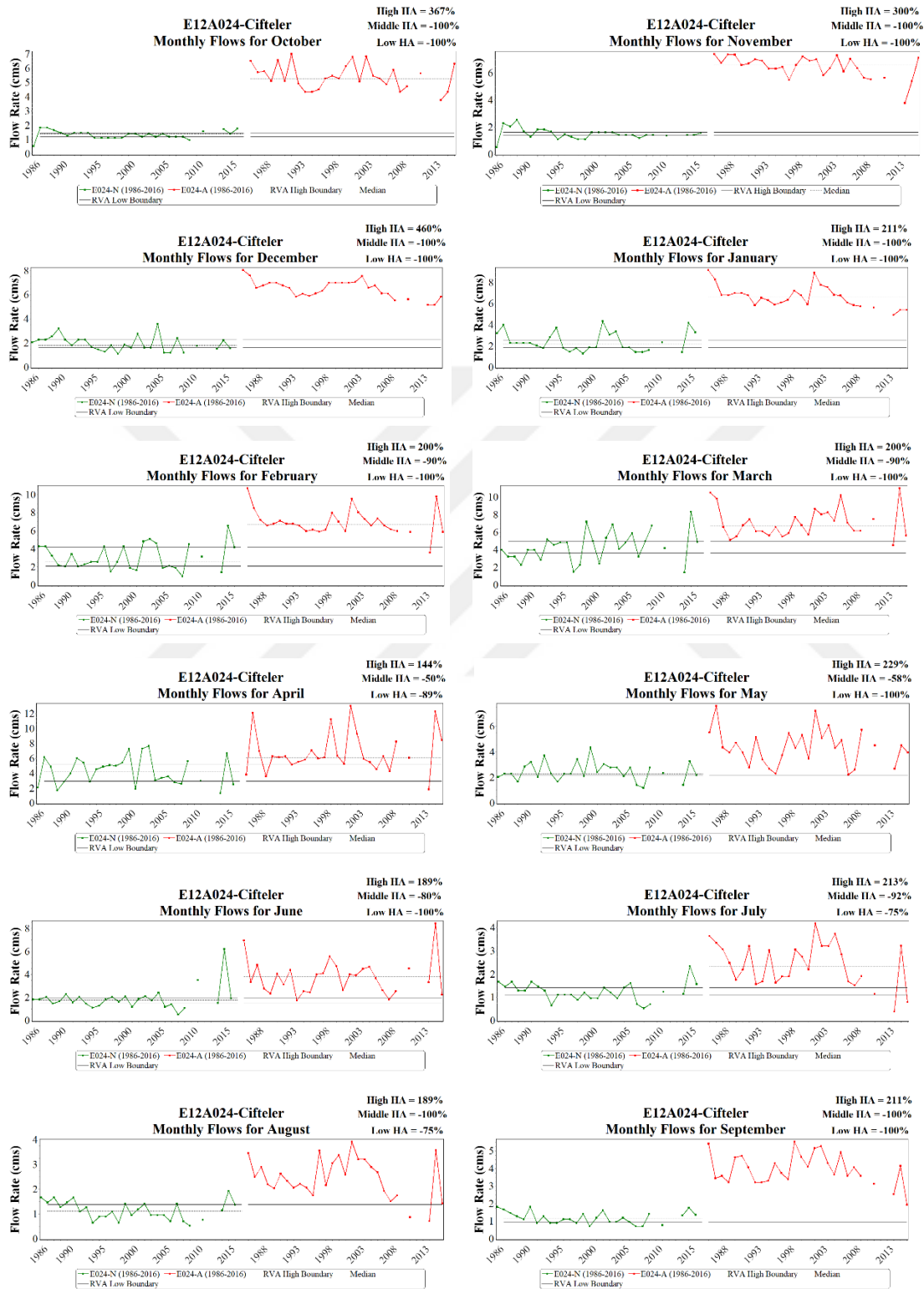
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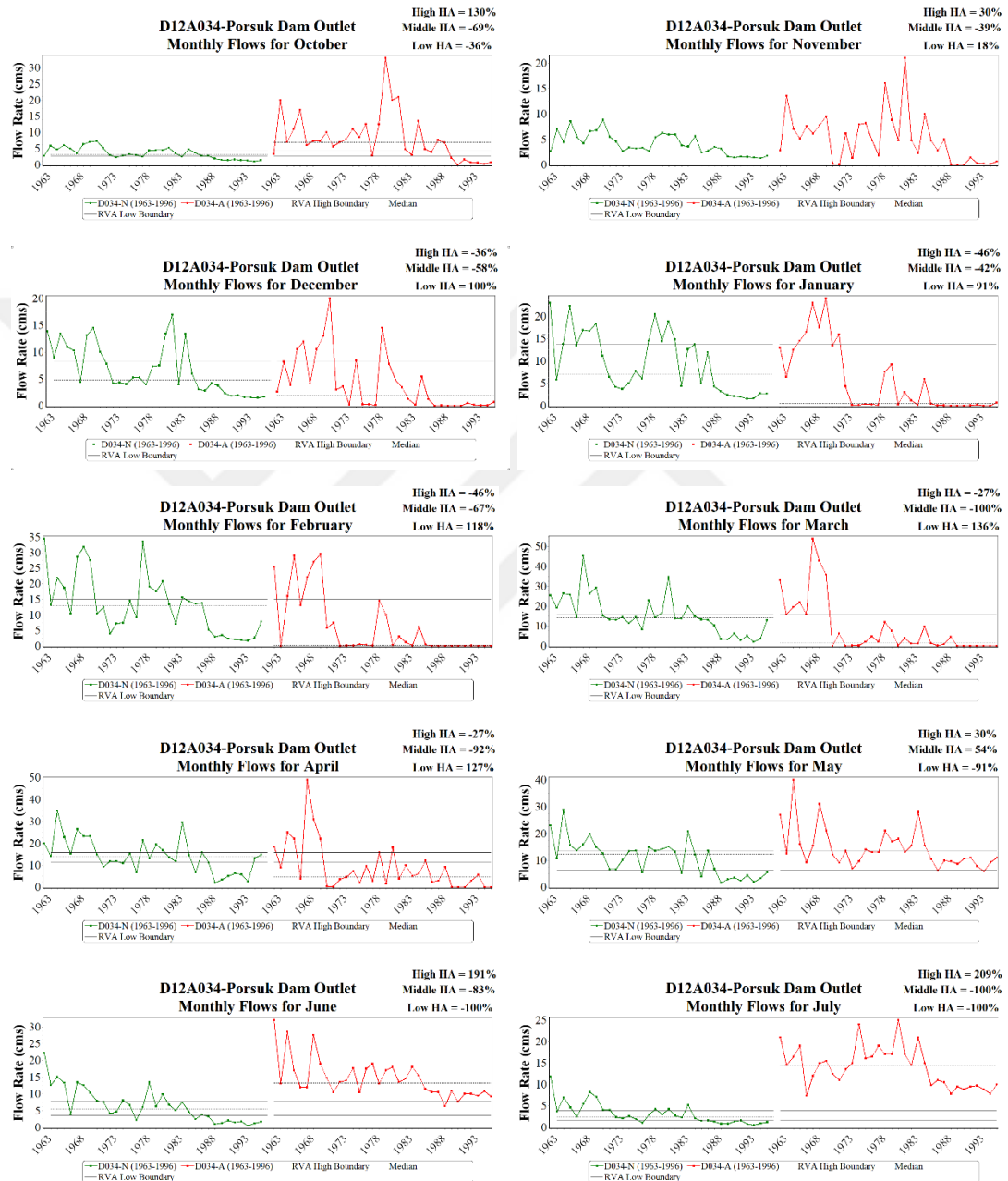
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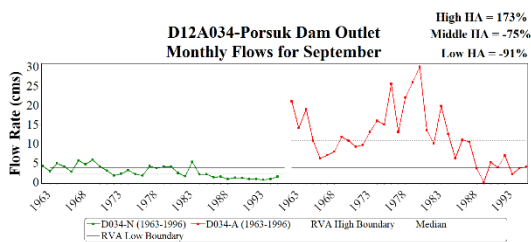
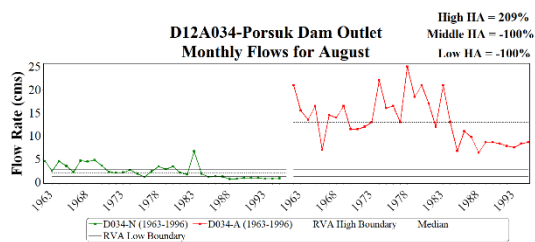


B. Indicators of Hydrologic Alteration (IHA) Output Graphs – Group 1

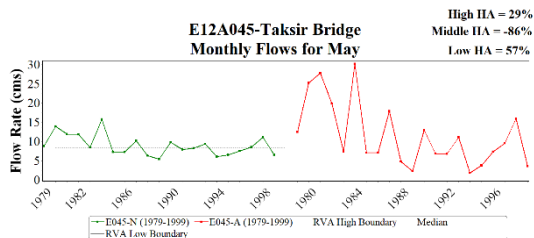
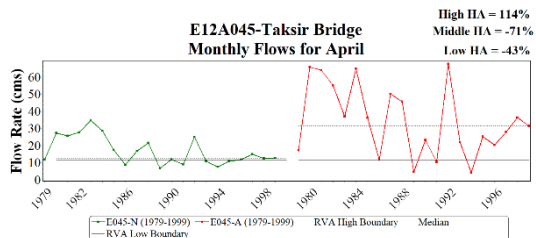
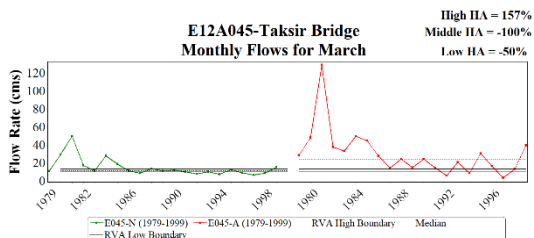
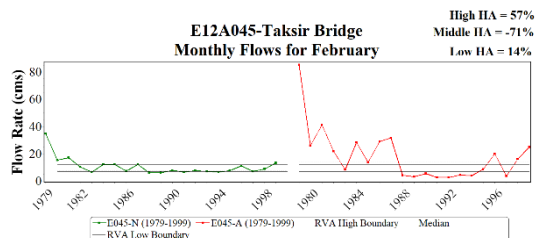
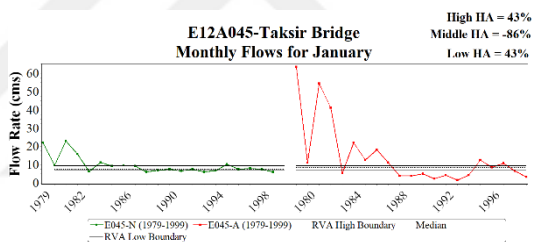
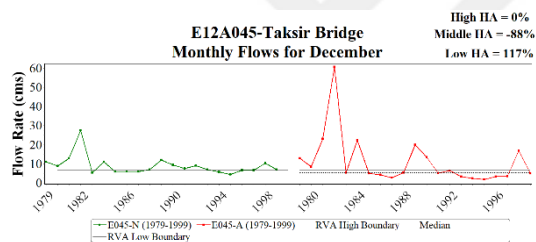
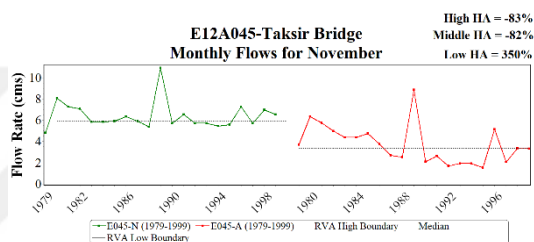
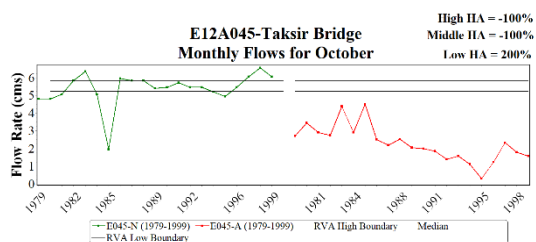


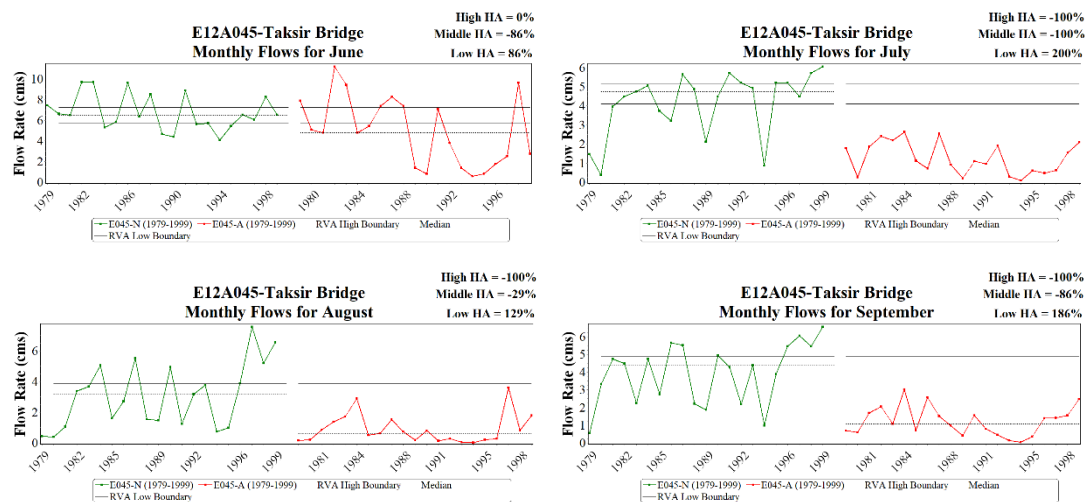
The monthly water condition (IHA Group 1) alteration graphs of the target gauge E12A024 (The green line on the graphs represents the natural condition between 1986 and 2016 while the red line shows altered number of occurrences in the same period. Black horizontal lines are the lower and higher RVA boundary levels dividing the graph area into the three RVA ranges, i.e., low, middle (target) and high RVA ranges.)





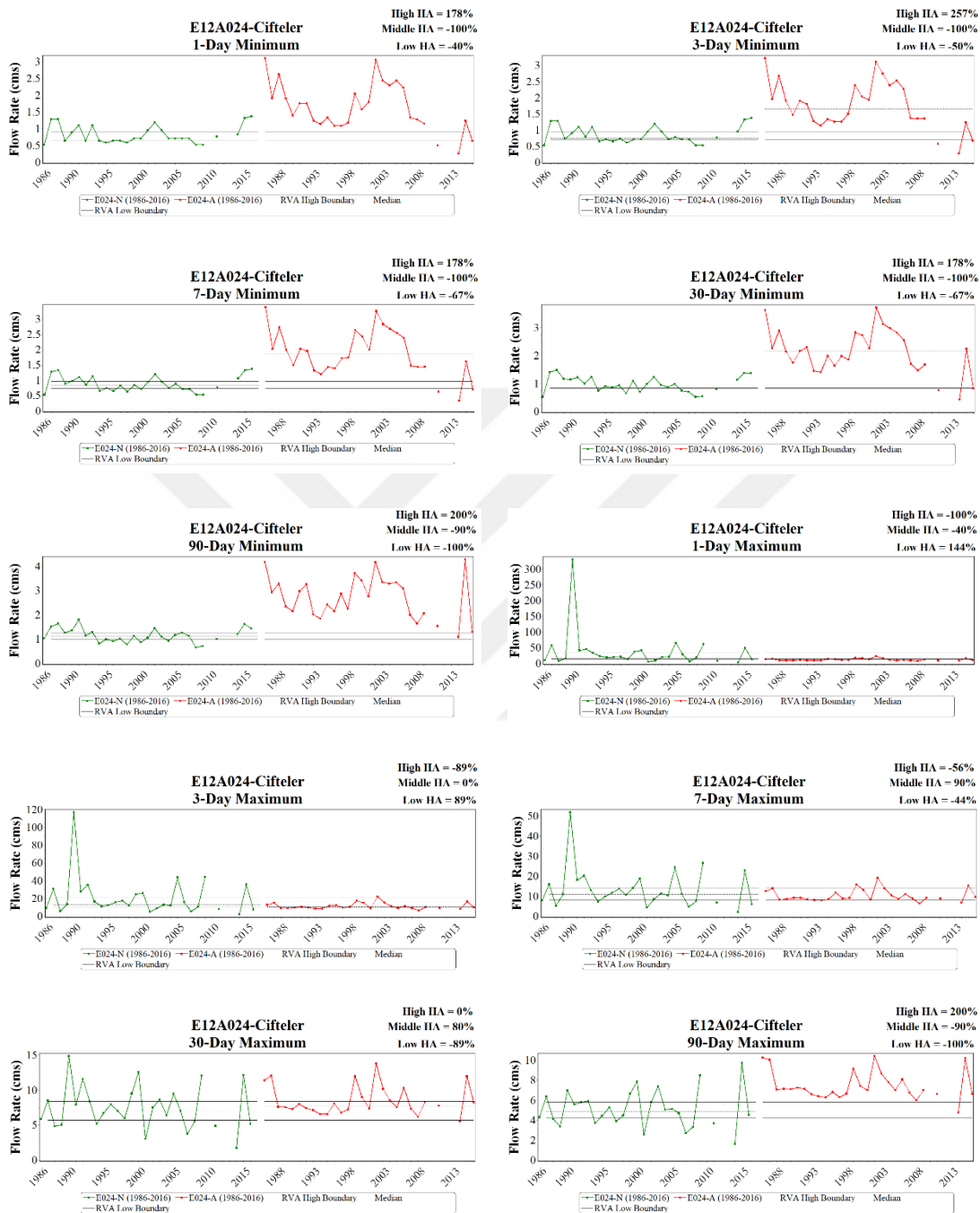
The monthly water condition (IIA Group 1) alteration graphs of the target gauge D12A034 (The green line on the graphs represents the natural condition between 1963 and 1996 while the red line shows altered number of occurrences in the same period. Black horizontal lines are the lower and higher RVA boundary levels dividing the graph area into the three RVA ranges, i.e., low, middle (target) and high RVA ranges.)

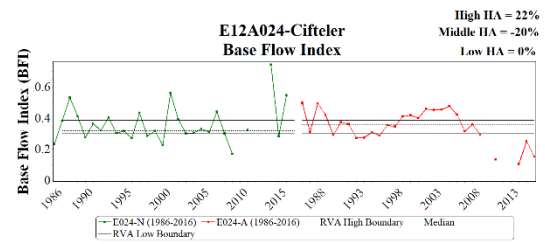
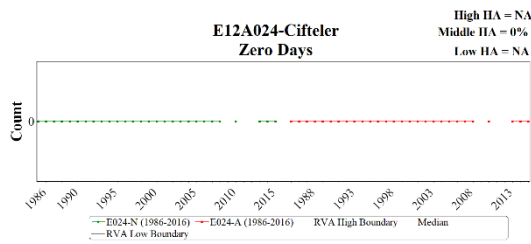




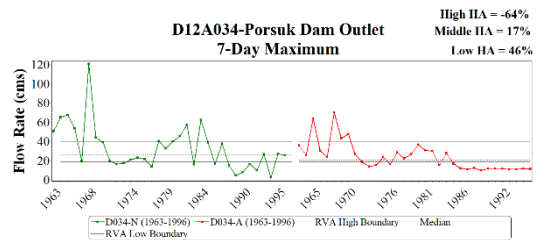
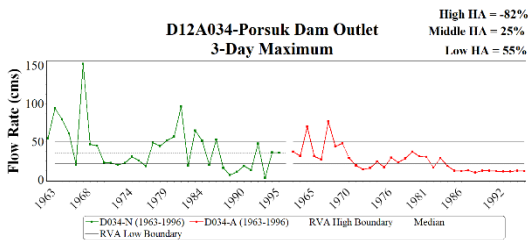
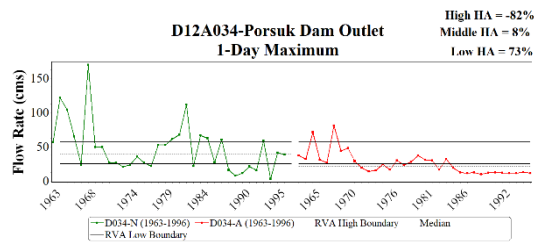
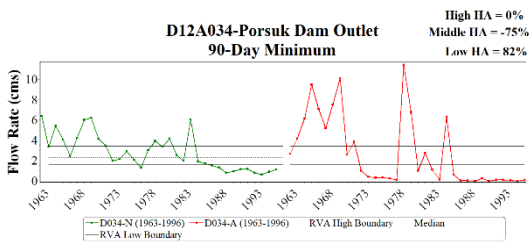
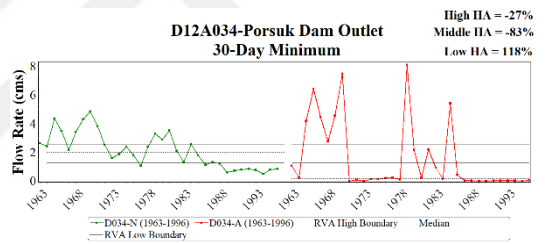
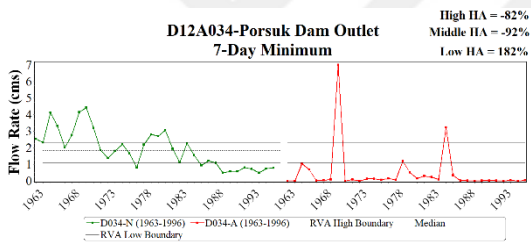
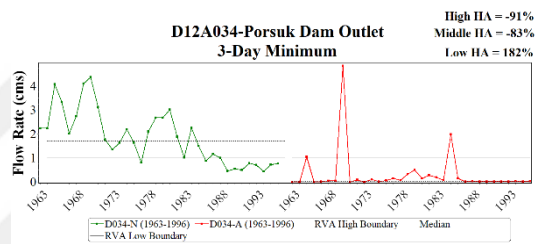
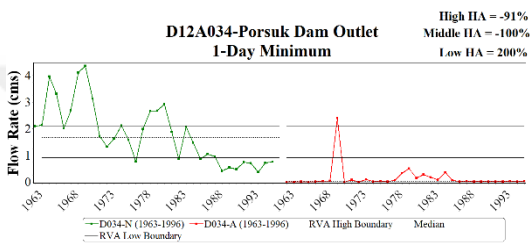
The monthly water condition (IIA Group 1) alteration graphs of the target gauge E12A045 (The green line on the graphs represents the natural condition between 1979 and 1999 while the red line shows altered number of occurrences in the same period. Black horizontal lines are the lower and higher RVA boundary levels dividing the graph area into the three RVA ranges, i.e., low, middle (target) and high RVA ranges.)

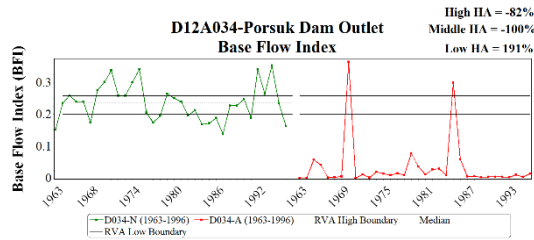
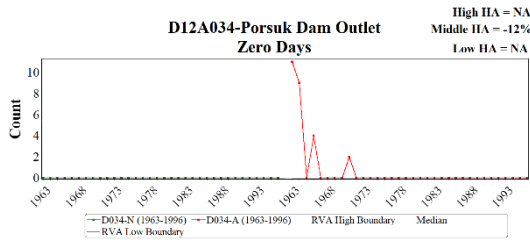
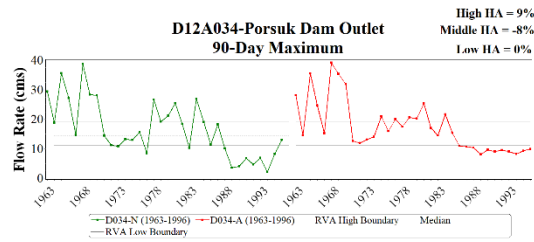
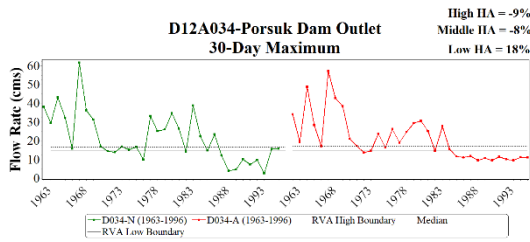
C. Indicators of Hydrologic Alteration (IHA) Output Graphs – Group 2



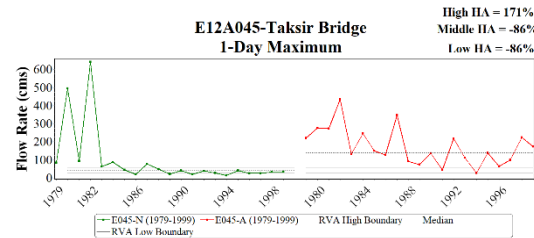
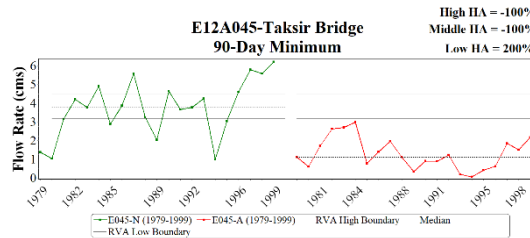
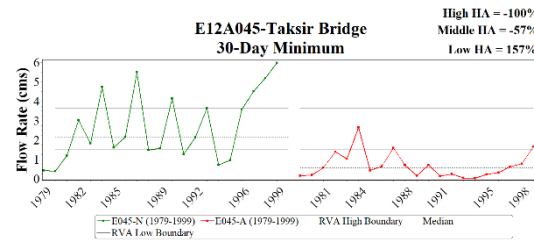
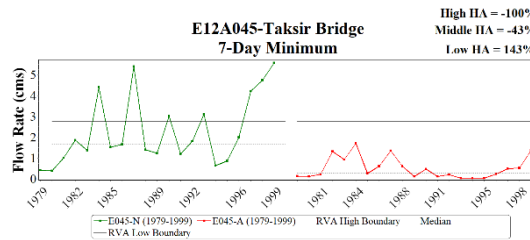
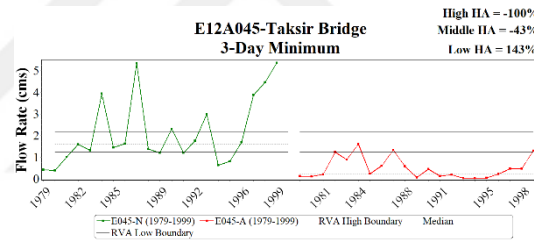
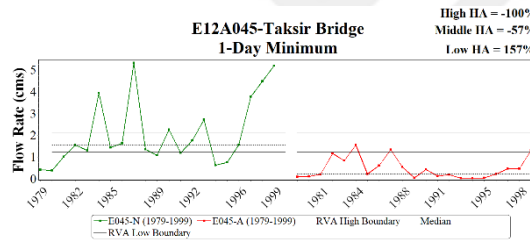


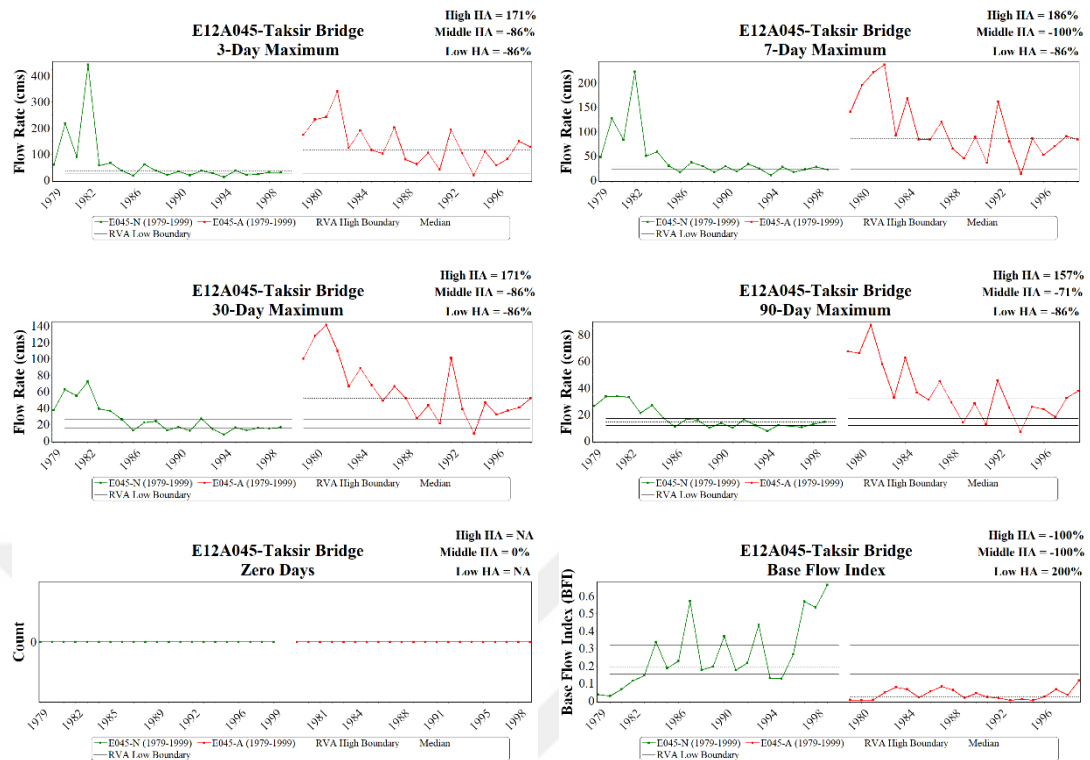
The extreme water condition (IIA Group 2) alterations of the target gauge E12A024 (The green line on the graphs represents the natural condition between 1986 and 2016 while the red line shows altered number of occurrences in the same period. Black horizontal lines are the lower and higher RVA boundary levels dividing the graph area into the three RVA ranges, i.e., low, middle (target) and high RVA ranges.)





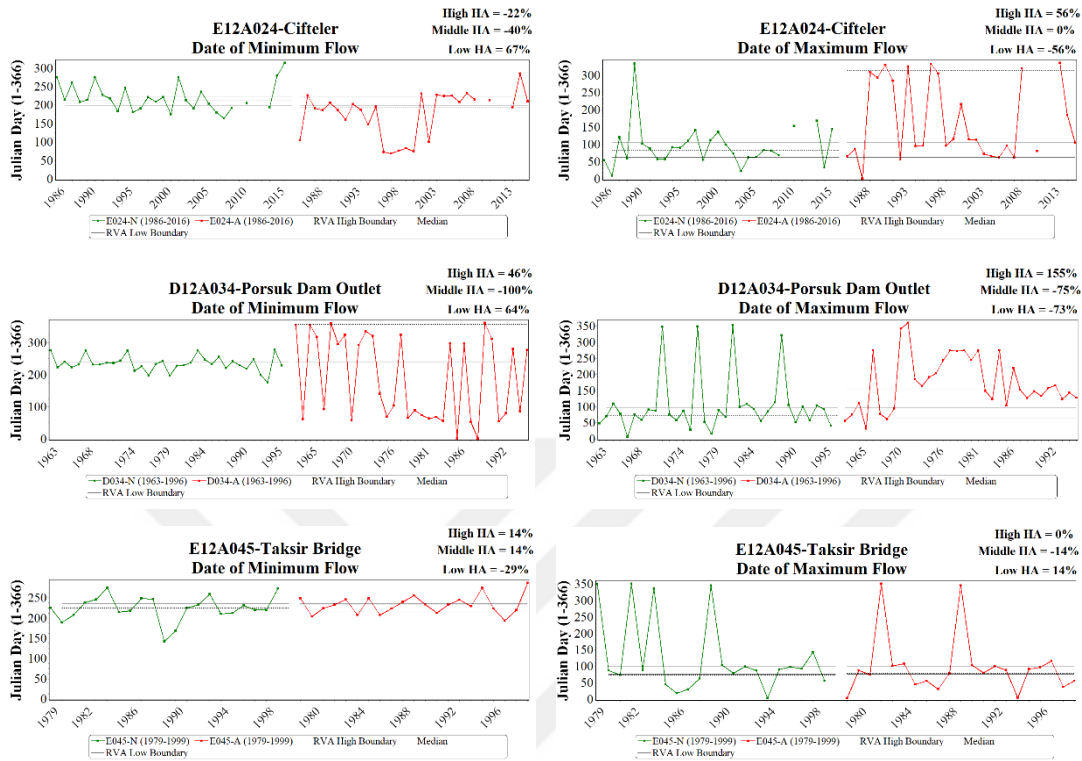
The extreme water condition (IIA Group 2) alterations of the target gauge D12A034 (The green line on the graphs represents the natural condition between 1963 and 1996 while the red line shows altered number of occurrences in the same period. Black horizontal lines are the lower and higher RVA boundary levels dividing the graph area into the three RVA ranges, i.e., low, middle (target) and high RVA ranges.)





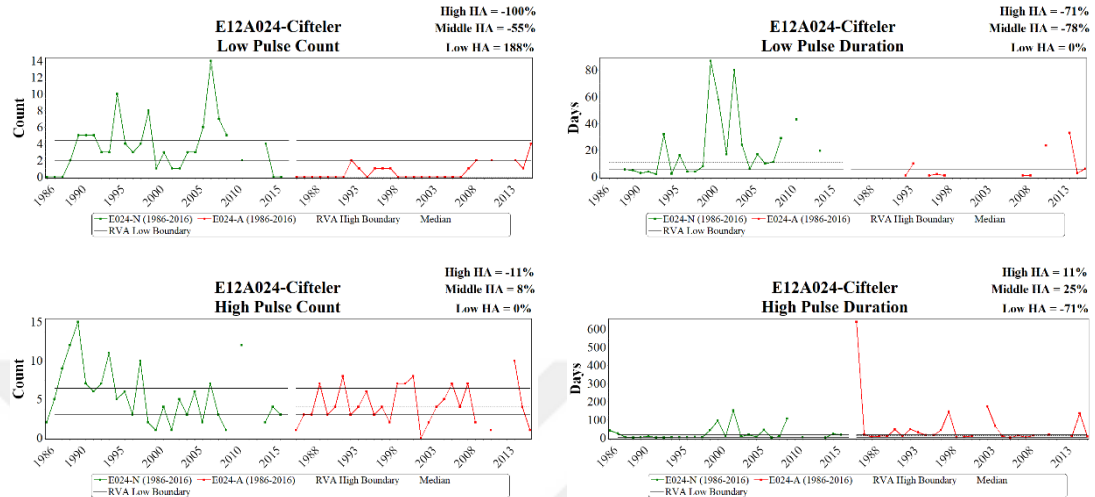
The extreme water condition (IIA Group 2) alterations of the target gauge E12A045 (The green line on the graphs represents the natural condition between 1979 and 1999 while the red line shows altered number of occurrences in the same period. Black horizontal lines are the lower and higher RVA boundary levels dividing the graph area into the three RVA ranges, i.e., low, middle (target) and high RVA ranges.)

D. Indicators of Hydrologic Alteration (IHA) Output Graphs – Group 3

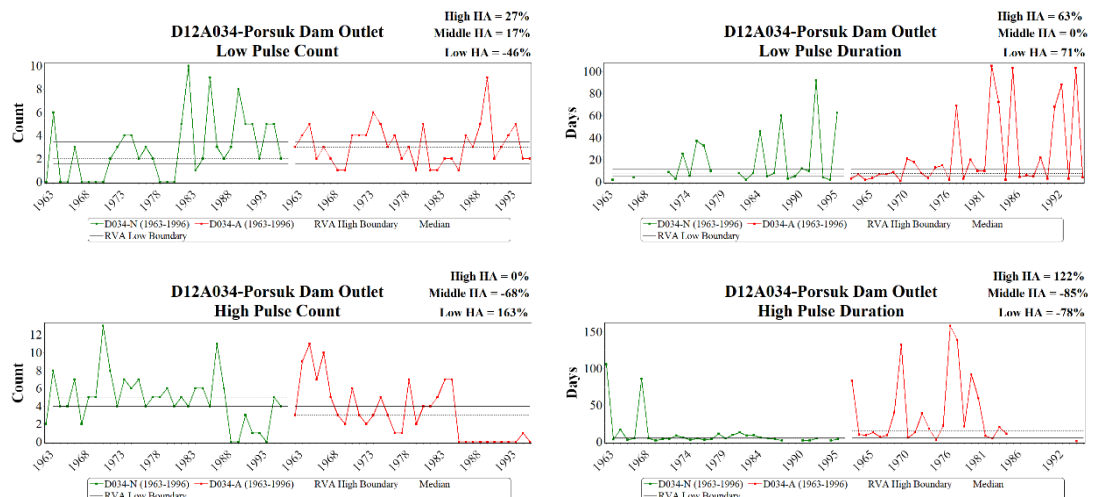


The timing of extreme water condition (IHA Group 3) alterations of the target gauges (The green line on the graphs represents the natural condition while the red line shows altered number of occurrences. Black horizontal lines are the lower and higher RVA boundary levels dividing the graph area into the three RVA ranges, i.e., low, middle (target) and high RVA ranges.)

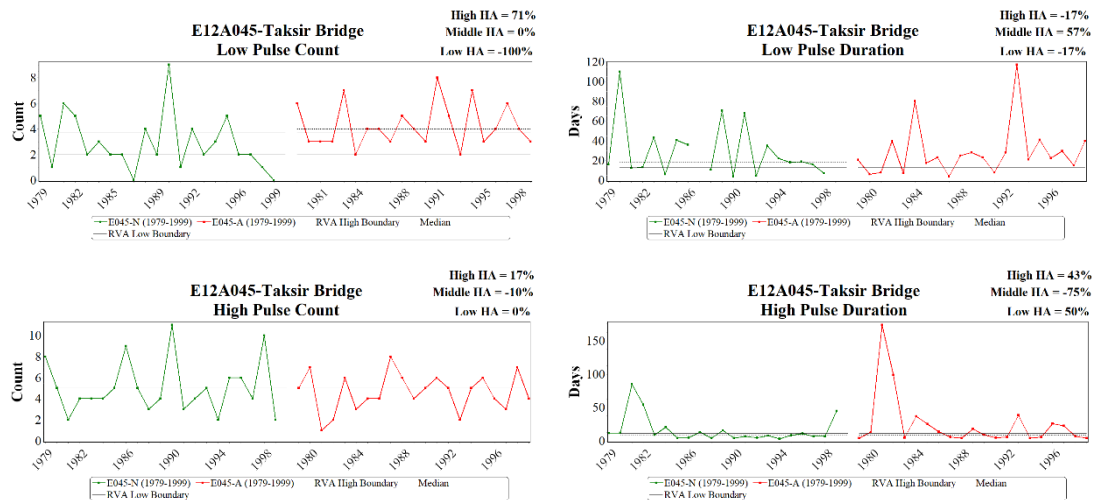
E. Indicators of Hydrologic Alteration (IHA) Output Graphs – Group 4



The counts and durations of low and high pulses (IHA Group 4) alterations of the target gauge E12A024 (The green line on the graphs represents the natural condition between 1986 and 2016 while the red line shows altered number of occurrences in the same period. Black horizontal lines are the lower and higher RVA boundary levels dividing the graph area into the three RVA ranges, i.e., low, middle (target) and high RVA ranges.)

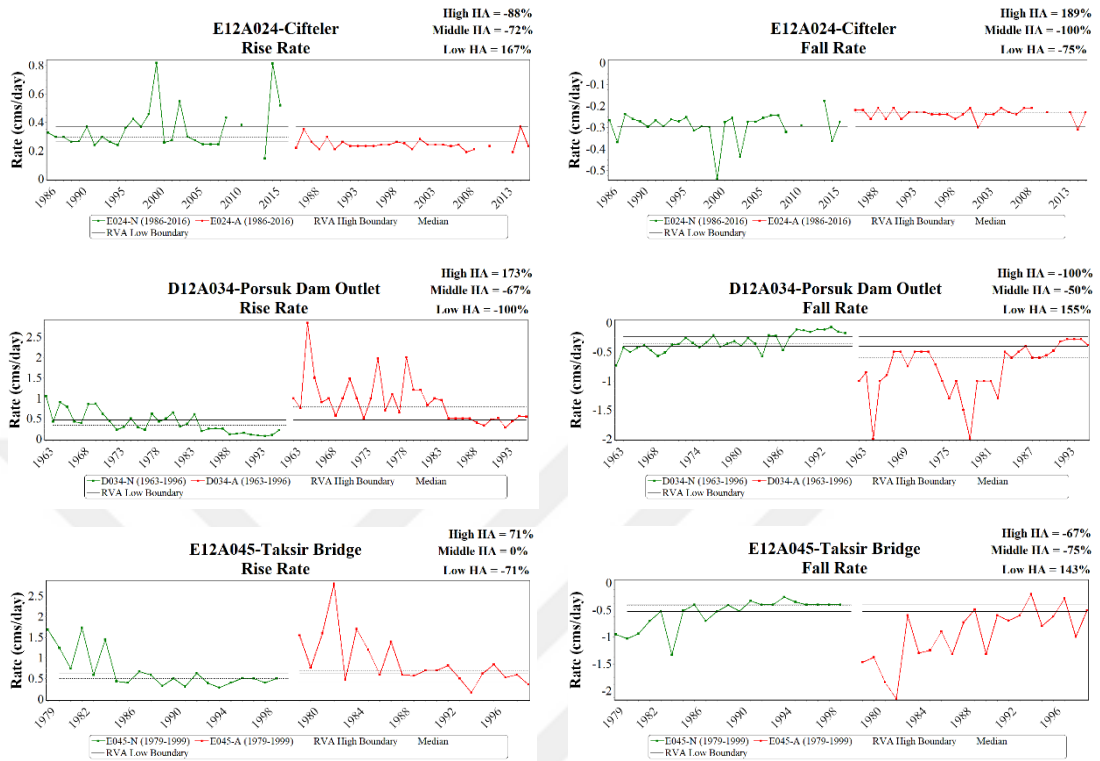


The counts and durations of low and high pulses (IHA Group 4) alterations of the target gauge D12A034 (The green line on the graphs represents the natural condition between 1963 and 1996 while the red line shows altered number of occurrences in the same period. Black horizontal lines are the lower and higher RVA boundary levels dividing the graph area into the three RVA ranges, i.e., low, middle (target) and high RVA ranges.)

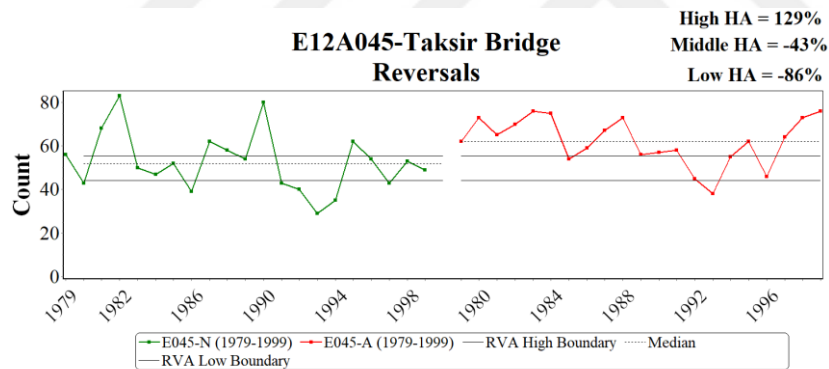
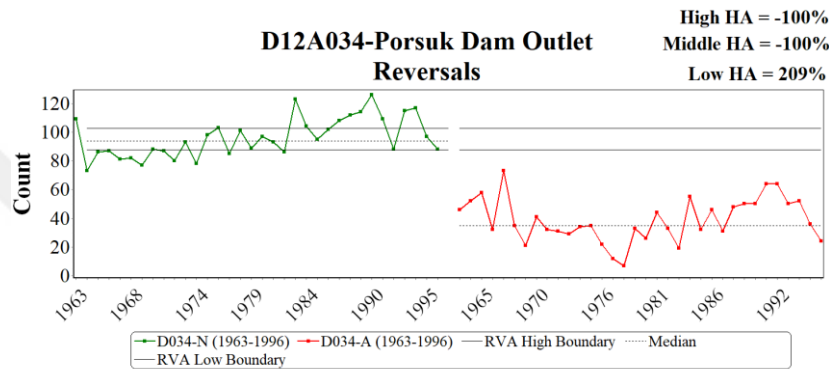
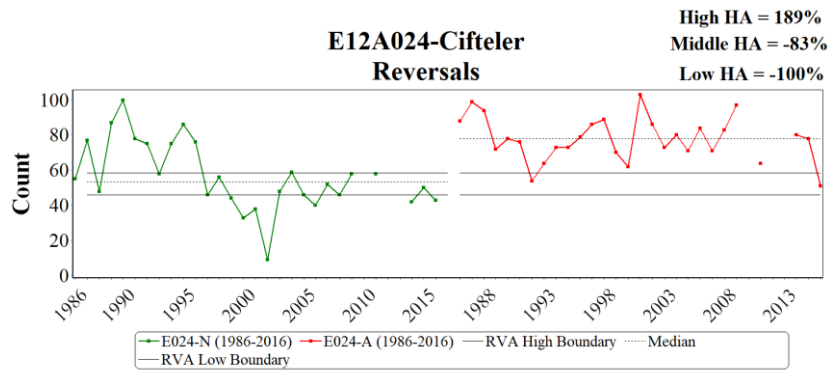


The counts and durations of low and high pulses (IIA Group 4) alterations of the target gauge E12A045 (The green line on the graphs represents the natural condition between 1979 and 1999 while the red line shows altered number of occurrences in the same period. Black horizontal lines are the lower and higher RVA boundary levels dividing the graph area into the three RVA ranges, i.e., low, middle (target) and high RVA ranges.)

F. Indicators of Hydrologic Alteration (IHA) Output Graphs – Group 5



The rise and fall rate (IHA Group 5) alterations of the target gauges (The green line on the graphs represents the natural condition while the red line shows altered number of occurrences. Black horizontal lines are the lower and higher RVA boundary levels dividing the graph area into the three RVA ranges, i.e., low, middle (target) and high RVA ranges.)



The reversals (IHA Group 5) alterations of the target gauges (The green line on the graphs represents the natural condition while the red line shows altered number of occurrences. Black horizontal lines are the lower and higher RVA boundary levels dividing the graph area into the three RVA ranges, i.e., low, middle (target) and high RVA ranges.)