

REPUBLIC OF TURKEY
YILDIZ TECHNICAL UNIVERSITY
GRADUATE SCHOOL OF SCIENCE AND ENGINEERING

**INVESTIGATION OF SEDIMENT DYNAMICS IN RIVER
DELTA COASTS: SAKARYA RIVER DELTA**

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Master of Science Thesis

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July, 2022

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This study was supported by the Scientific and Technological Research Council of
Türkiye (TUBITAK) Grant No: 117Y333.



Dedicated to my family

ACKNOWLEDGEMENTS

I would like to express my deepest gratitude to my esteemed advisor Cihan Şahin for his excellent supervision, for broadening my perspective by teaching the subjects that I enjoyed the most in my education life without getting bored for hours, and for offering me the opportunity to participate in this extensive project, and most importantly, for giving me the freedom to make mistakes and assisting me in correcting them by teaching me the right way.

I would like to thank Prof. Dr. Yalçın Yüksel for not just teaching the university courses he was an expert in but sharing his experiences with us so that we could become well-equipped graduate engineers.

I want to express my gratitude to my cherished Assoc. Prof. Bergüzar Özbahçeci for her assistance in helping me recognize my enthusiasm for and interest in the field of coastal engineering.

I would like to thank my dear primary school teacher, Nilgün Gargın Mert, who taught me how to read and write and made me love numbers (by teaching math even in physical education classes).

Thanks to the TÜBİTAK (The Scientific and Technological research Council of Türkiye) for sponsoring this comprehensive project at the Yıldız Technical University.

I wish to extend my deepest gratitude to my lovely family for their support and encouragement.

Lastly, and above all, I give thanks to Allah, whose first advice for humanity is to learn and discover, and who most generously taught humanity what they did not know, for instilling in me the desire to learn and for motivating me more with each new lesson.

Kerem GÜNER

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LIST OF SYMBOLS

f_f	A form function describing the backscattering characteristics of a particle relative to its geometrical size (<i>dimensionless</i>)
I_{dB}	ABS signal intensity (<i>decibel</i>)
k	Acoustic wave number
τ	Acoustic pulse duration
α	Attenuation coefficient (<i>Nepers 1/m</i>)
k_t''	Calibration parameter ($V m^{3/2}$)
K_c	Decibel inversion factor
ρ	Density
ε	Dimensionless fluid heuristic formula coefficient
ψ	Dimensionless near-field correction factor describing the departure from spherical spreading in the near-field of the transducer
k_s	Embodies the scattering properties of sediment (m/kg^2)
η	Free surface variation
H_f	Freshwater thickness
M	Mass concentration of sediment in suspension (kg/m^3)
T_m	Mean wave period
χ	Normalized total scattering cross-section of suspended particles Radius of sediment in suspension (m)
m_n	n^{th} power of momentum of frequency spectrum
a_t	Radius of the active area of the transducer
r	Range from the transceiver along the acoustic beam (m)
E	Received acoustic backscatter signal intensity

ξ	Sediment attenuation constant
$\rho(a)$	Sediment density (kg/m^3)
H_s	Significant wave height
α_c	Sound speed in water
ζ	Sound velocity ratio



LIST OF ABBREVIATIONS

ABS	Acoustic Backscatter
ADCP	Acoustic Doppler Current Profiler
CTD	Conductivity, Temperature and Depth Sensor
DFT	Discrete Fourier Transform
ECMWF	European Centre for Medium-Range Weather Forecasts
FFT	Fast Fourier Transform
DSI	General Directorate of State Hydraulic Works
NTU	Nephelometric Turbidity Unit
PSU	Practical Salinity Unit
SSC	Suspended Sediment Concentration

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Investigation of Sediment Dynamics in River Delta Coasts: Sakarya River Delta

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Department of Civil Engineering

Master Thesis

Advisor: Assist. Prof. Dr. Cihan ŞAHİN

Deltaic areas are low-lying regions where the river's fresh water and sediment content discharges into the sea. These regions are highly dynamic in terms of salinity, temperature and sediment content and many other parameters. Interventions in these delta regions and their basins alter the dynamics of water and solid matter. Construction of dams, sediment holding structures, flood prevention dams and deforestation, which are made to facilitate human life, negatively affect these natural areas. In addition to all of these, sudden and severe impacts of natural disasters related to climate change, whose effects are gradually becoming more pronounced, also affect delta and estuarine environments.

Sakarya river, which flows into the sea in the Karasu district of Sakarya province, and its delta are classified as vulnerable regions to the potential effects of climate change due to their nature. The Sakarya River delta is home to wide beaches in the east and the west of the river mouth, fossilized coastal dunes, and the Acarlar Floodplain which is the world's largest single-piece floodplain. In addition to the 7.5 m annual coastal erosion already seen on the Karasu beaches, more intense erosion rates are expected in the future due to the possible effects of climate change.

Sediment dynamics and hydrodynamic behavior studies of delta and estuarine regions assist to examine the change in the morphodynamical structure of these regions over time. Investigations on the solid matter dynamics of these regions with field studies form a basis for model studies in order to reveal the effects of infrastructure projects and various scenarios of climate change on the region. Understanding the relationship between hydrodynamic conditions, suspended sediment dynamics and bed material transport in these regions, and their seasonal variations is important for determining the protection measures in these vulnerable areas.

In this study, morphodynamical variations under the influence of hydrodynamics and sediment dynamics in the Sakarya River delta region were investigated with field studies carried out in different seasons (February, July, and November in 2019) to capture the dynamics in summer, winter and autumn seasons under different forcing conditions. The field campaigns were conducted in the vicinity of the Sakarya River region of influence, covering different meteorological and hydrological conditions. In winter, the fresh water and riverine sediments are transported several kilometers to the sea. The region of river water influence in the sea was much narrower in summer and autumn during which the river discharge was relatively low. While the river mouth was wide open (100 meters wide and 4.4 meters deep) in winter due to high river discharge, the width and the depth of the river mouth section gradually decreased during seasons with low discharge. The median sediment grain size, D_{50} , becomes 556 μm , 4 μm and 74 μm due to the seasonal flow characteristics occurred in the river mouth in February, July and November respectively. The base material gets finer from coast toward the open sea in all seasons. In all stations, D_{50} values are averaged around 150 μm , 205 μm and 216 μm in February, July and November respectively.

Keywords: Delta, Sakarya River Delta, sediment dynamics, delta hydrodynamics, coastal erosion

Akarsu Delta Kıyılarında Sediment Dinamiğinin İncelenmesi: Sakarya Nehri Deltası

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İnşaat Mühendisliği Bölümü

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Delta alanları, nehir tarafından taşınan su ve katı madde içeriğinin denizlere ulaştığı düşük eğimli bölgelerdir. Bu bölgeler tuzluluk, sıcaklık ve sediment içeriği ve diğer pek çok parametre açısından oldukça dinamik bölgelerdir. Bu bölgelerde ve bölge havzasında insan yaşamını kolaylaştırmak için yapılan baraj, sediment tutma yapıları, taşkın kontrol havuzları ve ormansızlaştırma çalışmaları gibi su ve katı madde dinamiğini değiştiren müdahaleler bu doğal alanları olumsuz yönde etkilemektedir. Tüm bunlara ek olarak, etkisi giderek artan iklim değişikliği nedeniyle ortaya çıkan doğal afetler de delta ve haliç bölgelerinde ani ve yıkıcı etkilere yol açmaktadır.

Sakarya ilinin Karasu ilçesinde denize dökülen Sakarya Nehri ve deltası, doğası gereği iklim değişikliğinin olası etkilerine karşı kırılgan bölge olarak sınıflandırılmaktadır. Sakarya Nehri deltası, nehir ağzının doğusunda ve batısında geniş plajlara, fosilleşmiş kıyı kumullarına ve dünyanın en büyük tek parça longozu olan Acarlar Longozuna ev sahipliği yapmaktadır. Karasu sahillerinde halihazırda gözlenen yıllık 7.5 m kıyı erozyonuna ek olarak iklim değişikliğinin olası etkileri nedeni ile bölgedeki erozyonların daha da yoğunlaşacağı öngörülmektedir.

Delta ve haliç bölgelerinin sediment dinamiği ve hidrodinamik davranışı araştırmaları bu bölgelerin morfodinamik yapısının zaman içerisindeki değişimini incelemeye yardımcı olmaktadır. Saha çalışmaları ile bu bölgelerdeki katı madde dinamiğinin incelenmesi, altyapı projeleri ve iklim değişikliğinin bölgeye etkilerini çeşitli senaryolar çerçevesinde ortaya koymak amacıyla hazırlanacak model çalışmalarına temel teşkil etmektedir. Bu bölgelerdeki hidrodinamik koşullar, askıdaki katı madde dinamiği ve taban malzemesi taşınımı arasındaki ilişkiyi ve bunların mevsimsel değişimlerini anlamak, bu hassas bölgelerde koruma önlemlerinin belirlenmesi için önemlidir.

Bu çalışmada Sakarya nehri deltası bölgesinde hâkim olan hidrodinamik ve sediment dinamiği etkisi ile yaz, kış ve sonbahar mevsimlerinde (Şubat, Temmuz ve Kasım 2019) görülen morfodinamik değişimler saha çalışmaları ile mevsimsel olarak gözlemlenmiştir. Farklı meteorolojik ve hidrolojik koşulları kapsayan saha çalışmaları Sakarya Nehri etki bölgesinde gerçekleştirilmiştir. Kış mevsiminde akarsuyun taşıdığı sediment ve tatlı su denizde birkaç kilometre ilerlemektedir. Yaz ve sonbahar mevsimlerinde ise görece daha düşük akarsu deşarjı nedeniyle nehir sularının deniz içindeki etki alanı küçülmektedir. Kış mevsiminde yüksek akarsu deşarjı etkisindeki nehir ağzı bölgesi geniş bir açıklığa sahipken (100 metre genişlik ve 4.4 metre derinlik) bu bölgenin genişliği ve derinliği düşük deşarj görülen mevsimlerde giderek daralmaktadır. Mevsimsel akış karakteristiğindeki değişimler nedeni ile nehir ağzında sediment medyan dane boyutu, D_{50} , Şubat, Temmuz ve Kasım aylarında sırasıyla $556\mu\text{m}$, $4\mu\text{m}$ ve $74\mu\text{m}$ olmaktadır. Tüm mevsimlerde kıyı bölgesinden açık denize doğru ilerledikçe taban malzemesi incelmektedir. Şubat, Temmuz ve Kasım aylarında tüm istasyonlardaki ortalama medyan dane boyutları sırasıyla $150\mu\text{m}$, $205\mu\text{m}$ ve $216\mu\text{m}$ olmaktadır.

Anahtar kelimeler: Delta, Sakarya Nehri Deltası, sediment dinamiği, delta hidrodinamiği, kıyı erozyonu

1.1 Literature Review

Deltas and estuaries where river fresh water meets salty sea water are dynamic and complex environments in terms of salinity, temperature, sediment content, and even biological and chemical variety. (Flores et al., 2022). The dynamical features resulting from the mixing of sea water and river water in estuaries can be seen in the water channel before the river water reaches the sea (Otero et al., 2021). However, in environments under river current dominance, the mixing process can occur in the region where the fresh water flows into the sea (Dagg et al., 2004).

In the region where the river and sea waters of different densities meet, encounter-specific conditions develop until a complete mixture occurs (Piton *et al.*, 2020). Rivers, in addition to transporting water, also discharge the sediment load of the river basin into the sea. The amount of sediment carried is influenced by numerous factors such as the area of the basin, amount of precipitation in the region, amount of river discharge and flow velocities (Milliman and Syvitski, 1992).

Human-caused interventions have a negative impact on the delta and estuary ecosystems. While dams act as a barrier to the conveyed sediment load (Zhang *et al.*, 2008), dam-induced deforestation, on the other hand, induces erosion and hence increases the transported sediment load (Milliman and Syvitski, 1992). Furthermore, as a result of climate change, extreme natural disasters including storms and floods disturb deltaic and estuarine regions, and predicted rises in water levels increase the risk of these damages (Wang *et al.*, 2010; Le *et al.*, 2007). Since the deltaic and estuarine environments are naturally low-lying zones, the potential impacts of climate change emphasize the vulnerability of these coastal areas in the world as well as in Turkey (Alpar, 2009).

Examining the sediment material dynamics and hydrodynamics of a coastal region can be a useful indicator for revealing the morphological changes of the delta and estuary systems through time. In a study on the Fly River Delta in Papua New Guinea in 1991 (Harris *et al.*, 1993), the samples belonging to the bottom sediment material were compared with the seismic profiles and sediment facies of the region, and projections for the future were established by revealing the hydrodynamic conditions that occurred in the past.

In the tide-dominated Mekong River estuary, the behavior of river-carried sediment material under various hydrodynamic conditions as well as the effects of human constructions such as dams and sediment barriers on the mixing of river and seawater in the estuary region were investigated (Wolanski *et al.*, 1996). In the Bohai Strait region, which connects the Bohai Sea and the Yellow Sea, the seasonal hydrodynamic changes of the region were modeled, and the sediment transport mechanism was revealed using the Moderate Resolution Imaging Spectrometer (MODIS) images and the concentration of suspended sediment data collected in field studies (Bi *et al.*, 2011). Seasonal fluctuations between winter and summer were explored by field investigations in the Misa River estuarine at Senigallia, Italy, and the relationship between seasonal hydrodynamic conditions, suspended sediment material, and bedload sediment movement was highlighted (Brocchini *et al.*, 2017). To examine climate change and human-induced changes in the delta-bay system in San Francisco, a study (Achete *et al.*, 2017) monitored suspended sediment material dynamics and sediment budgets on the bottom as an input for the Delf-3D model that evaluates various scenarios and presents a base study for the coming years.

1.2 Objective of the Thesis

In the Sakarya River Delta system, river sediment is a source that morphologically forms the river mouth, wide beaches close to the river mouth and dunes at the backside of these beaches. The Sakarya River delta is a natural lowland, hence, it is vulnerable to the potential effects of climate change. The natural morphological equilibrium will be disrupted if there is a lack of sediment or severe erosion due to seasonal or long-term hydrodynamical variations. As a result, erosion of the

beaches and dunes in the region would intensify (TMMOB, 2012). In this context, the interactions of the river and sea water at the Sakarya River mouth, suspended sediment dynamics and the morphology of the region were examined seasonally by field studies in order to provide input data for the models to analyze the long-term morpho and hydro-dynamic structure of the region.

Datasets collected in this study cover hydrodynamics (waves and currents), bottom sediment material properties, suspended sediment concentration measurements, and bathymetrical measurements. This study presents the results in terms of seasonal variations of;

- River water discharges and sediment discharges
- Salinity, temperature, and suspended sediment concentrations
- River and sea interaction
- River cross-section and river mouth morphology
- Sea bottom morphology

The second section introduces the case study site, where the Sakarya River flows into the Black Sea, the in-situ measurements, and laboratory experiments conducted using samples from the field. In the third chapter, the water and sediment discharge data of the river, the analysis methods applied to the turbidity sensor data, the suspended sediment concentration data, the acoustic backscatter data, and the methods used for spectral wave analysis are explained. All the obtained results are presented in the fourth section. The fifth section includes a discussion, followed by the conclusion in the sixth section.

1.3 Original Contribution

Sakarya River Delta system is a vulnerable deltaic area in Karasu province on the Black Sea coast of Turkey. The coastal region is under the impact of the Sakarya River plume and is located near the southern coast of the Black Sea, east of Istanbul, where environmental, economic, and societal issues are concentrated. The shoreline is under the influence of high anthropogenic modification. The erosion problem threatens the coastal area and also the Acarlar Floodplain Forest on the west side of the river behind the dunes on the coast which support a very

rich ecosystem. The previous studies reported a significant erosion on the east side of the river, with the 7.5m per year retreat of the coastal line due to the decrease of the sediment runoff to the coast, and also a construction of a harbor on the west side of the river mouth (Yüksel et al., 2013; Tan, 2013). However, no detailed field measurement effort has been initiated so far to investigate the hydrodynamics and the suspended matter dynamics of the Sakarya River delta coast in terms of seasonal variability. The present study aims at documenting the high-resolution in-situ observations regarding the hydro-sedimentary processes in the Sakarya river delta coast. The findings of this study help understand the sediment dynamics of the delta and provide valuable inputs for possible future numerical model studies.



Melting of the glaciers which were formed about 15,000 years ago, the time of the last glaciation, naturally caused the sea level to rise more than 100 m until 5,000 years ago and afterward brought the sea level as it is today by a few meters of fluctuations. Nature has created various coastal formations nearshore within the last 5,000 years. These formations are mainly river deltas, marine-dominated lagoons and estuaries dominated by both river and marine. It is clearly in sight that the deltas are wide and low-lying coastal creations. They have formed by the deposition of river sediment in shallow coastal areas (Day *et al.*, 1997). Deltas can be classified according to dominant forces on their locations.

River currents, waves, and tides have been active in shaping the delta coasts throughout the years, either as an individual predominant force or with a diverse combination of these hydrodynamic phenomena (Olariu, 2014).

Deltas are coastal landforms that involve subaqueous and subaerial sediment accumulations adjacent to river sources (Wright, 1985). Rivers are the main sources of sediment discharge in delta regions (Vörösmarty *et al.*, 2009). Hydrodynamic conditions at the river mouth where the river flow meets wave-dominated or tide-dominated marine environment determine the sediment flow behavior throughout the outer reach of the river mouth (Wright, 1977).

Since the earliest ages, human civilization has been situated in river valleys and delta regions. These regions, which had been fertile zones in terms of hunting and gathering in early ages, were later been home to ancient civilizations because of the abundance of accessibility to basic needs such as water, agricultural activities, and constructing materials. The alteration of river and delta zones can be traced back to these ages (Evans, 2012).

Being in close vicinity to coastal zones has been beneficial throughout human history (Kummu *et al.*, 2016). According to a human population study conducted

by Cohen and Small (1998), the global population ratio under 100 m elevation was 33.5% in 1994. Another study by Kummu et al. (2016) indicates the global population ratio under 100 m elevation was 39% in 1990. In the near-coast region within 100 km of the coast and under 100 m elevation, the global population ratio was 28%, and this ratio is estimated as 5.4% for elevations under 5 m. The study propounds these values are highly conservative until 2030. Furthermore, 42% of global domestic production is achieved in the near-coast zone in 2010 according to their study.

With interventions by humankind, fertile shores have been more fragile for decades. Considering the accelerated loss of lands and coasts due to unconscious practices and climate change, a better understanding of sediment transfer mechanisms is even more critical for governing sustainable administrations. Nevertheless, the awareness about these fragile zones keeps pace with the increase in research and regulations about coastal zone management. Thanks to the advancement of science and technology, data acquisition from the environment has become more reliable, easy, and quick. Today, sophisticated sensors and sonar systems allow high-frequency data sampling without any destruction of the environment (Thorne and Hurther, 2014).

The ADCPs (Acoustic Doppler Current Profilers) assist to achieve a wide variety of data belong the water bodies from freshwater and saltwater environment. Constitutively, they transmit certain frequencies of sound through the water column, also called "pings" and listen for echoes. The essential ability of these devices is that they utilize the doppler effect on backscattered pulses to provide highly accurate current speed and current direction data along a water column. Additionally, suspended sediment concentration along the water column can be reached by manipulation of backscattered pulse intensities. Wave parameters can be calculated from recorded pressure data when the ADCP is positioned far enough below the water surface. Concurrently, bathymetric data may also be provided from downward-looking ADCPs, however, its precision will depend on the cell size resolution of ADCP's beams. As a result of these features, researchers gather information on the hydro and morpho-dynamics of the environment.

Many studies approve that the ADCP is effective in investigating the flow and sediment characteristics along a water column. A comprehensive study that examines the 3D spatial variation of river flow in an engineered channel at the lower junction of the Sacramento River was performed to observe the effect of the channel on fish migration (Dinehart and Burau, 2005). Besides, it allows for an investigation of hydrodynamics and sediment dynamics even around complicated tidal estuaries (Piton *et al.*, 2020; Monismith *et al.*, 2005; Yuan *et al.*, 2021).

Conductivity, temperature, and depth (CTD) sensors provide salinity and temperature data at the device's location underwater. It also allows gathering data along a water column when plunged from the water surface to the bottom. Since the device is suitable for a turbidity sensor installation, turbidity data can be obtained throughout the water column. With these abilities, CTDs serve to observe freshwater and plume mixing activities during flood and ebb cycles at estuaries (Yankovsky and Voulgaris, 2019; Nowacki *et al.*, 2015; Filizola *et al.*, 2011).

2.1 Hydrodynamics at Coastal Depositional Systems

Coastal depositional areas are regions that host the process of mixing fresh water and salt water (Prandle, 2009). The complex combination of waves, currents, tides, rivers, and meteorologic phenomena are the main energy sources that influence the estuary shores. Naturally, these energies have dynamic effects on morphology (Bosboom and Stive, 2022).

2.1.1 Classification of Coasts

Deposition of the river sediment is the main source of the coasts. However, the abundance or scarcity of sediment load can affect the shape of the coast in various ways. Typical shapes of these coasts vary according to the dominant forces in the region (Figure 2.1) including waves, tides, and river discharge (Bosboom and Stive, 2022).

The effect of waves on bottom sediment is inversely proportional to depth. Coastal sediments are more responsive to wave action in shallower water because the wave bottom can feel the bed at an appropriate water depth. A variety of disturbances might start a movement in the bottom sediment. This initial

movement can be caused by a periodical change in the hydrodynamic pressure of a naturally oscillating wave or by exceeding maximum bottom shear stress due to wave breaking and orbital movement in an extreme wave condition. Storm surges, which are high-energy waves corresponding to significant wave heights typically greater than 1.5m (Figure 2.2), cause the state of sediment particles unstable, further they can also increase the volume of sediment transported (Bosboom and Stive, 2022). The mass movement by the nature of tides has significant consequences on sedimentation especially if the area is in a macrotidal zone. Besides, as the water depth decreases while the tidal current proceeds to the shore, the maximum tidal current speed is reached at the shore because decreasing water depth restricts the area that the volume passes. The bedload of sediment depositional environment can highly be disturbed by tidal currents that reach the maximum speed, resulting in net sediment transfer by the periodic flood and ebb currents (Dalrymple, 1992).

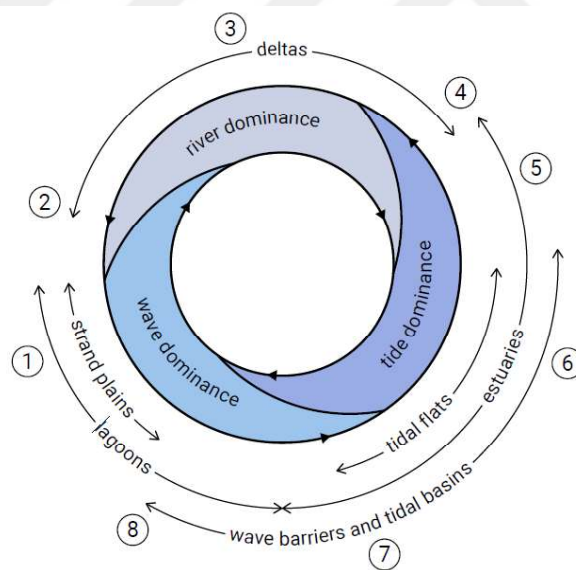


Figure 2.1 The dominant forces that shape coasts (Bosboom and Stive, 2022)

The region where river freshwater and salty sea water combine at the river mouth is quite dynamic in terms of salinity, temperature, and solids content. This region, also known as the transition zone, is typically formed in deltas' and estuaries' mouths. The location of this transition zone can vary according to river discharge. River water, which is less dense than sea water progress above the sea water at the entrance of the transition zone. Thus, the density difference between seawater and

river water results in a pressure gradient that generates stratification (Figure 2.3). A vertical circulation of seawater and freshwater is created by this pressure gradient (Bosboom and Stive, 2022). In the presence of tide, the ebb and flow cycles of seawater under the freshwater lead this transition zone to be observable over a larger area. This is a typical characteristic of tidal estuary regions which has wide channels by the nature. This zone becomes even more complex when the differences in the parameters like temperature, suspended sediment concentration, and others are included in the research.

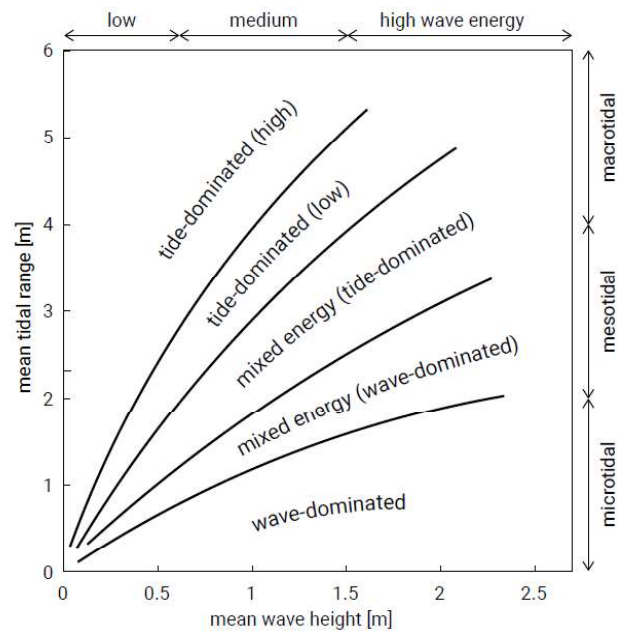


Figure 2.2 Dominant factors at delta shores (Bosboom and Stive, 2022)

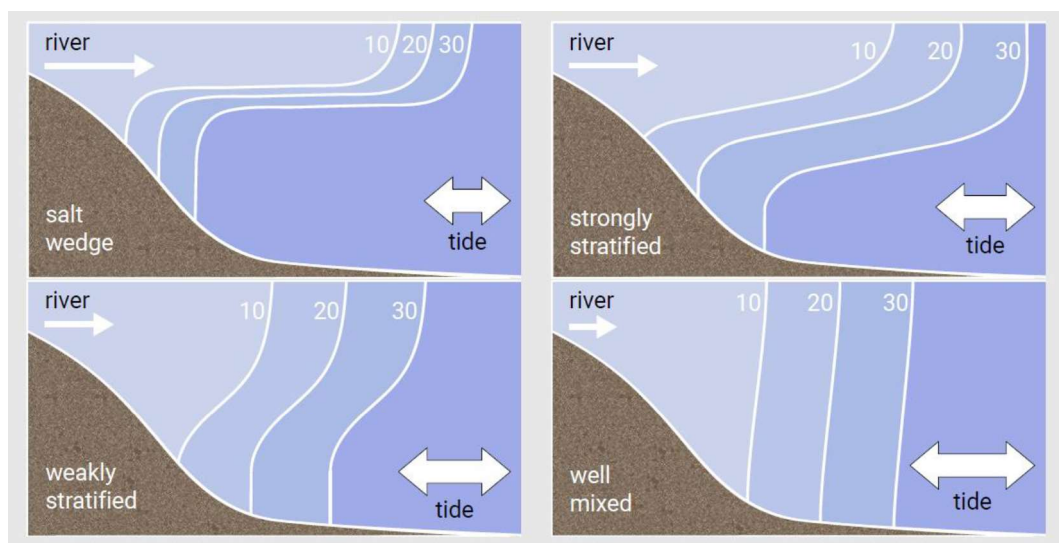


Figure 2.3 Stratification in river mouth (Bosboom and Stive, 2022)

2.2 Sediment Dynamics in Deltas

Since all deltas are sourced from rivers, deltas are the zone where river flow and standing water body mix. During flood times, rivers sweep out their bedload (Barrell, 1912) and progress throughout the channel to enter a body of water where rivers lose their ability to convey the sediment load, hence the carried sediment load settles along the outer reach of the channel. In a year-long period, morphology becomes a typical delta form with a net increase in the amount of settling sediment load. In the case of powerful coastal activities, sediment will become swashed and moved away which indicates they are vulnerable to coastal processes, thus, they are more regressive than other depositional coastal systems. (Bhattacharya, 2006).

In general, delta systems contain three characteristic aggregation subsets that configure each delta form with some variety of shapes. By the nature of the fine suspension material in the river plume that potentially travels much further than coarser sediment materials, it accumulates at a point far from the river mouth and forms the delta bottomset (Figure 2.4). Similarly, foreset is constituted by diminishing the coarser sediment material transported by the river discharge at a distance where wave and current cannot sway the material anymore. The topset, as the name signifies, lies at the top of the bottomset and foreset and is located mainly in the posterior region compared to the foreset but slightly covers the foreset as well. The topset is also separated into two parts, the subaerial part that lies above the water and the subaqueous part that lies under the water and is hence still exposed to wave and current activities (Barrell, 1912).

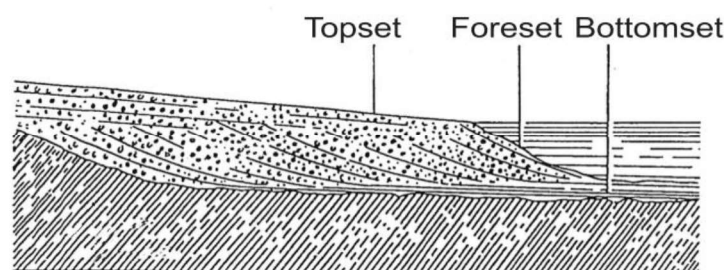


Figure 2.4 Delta subsets: Bottomset, foreset and topset (Bhattacharya, 2006)

Tide and wave have a destructive effect on the delta front. They have the ability to swash and resuspend fine sediment and transport the suspended sediment to the deep water. In the presence of a current parallel to the shore, the current may carry the suspended sediment far enough to break its connection with the delta. When the wave effect is also combined in this lateral movement, it causes further dispersion of the suspended material (Barrell, 1912).

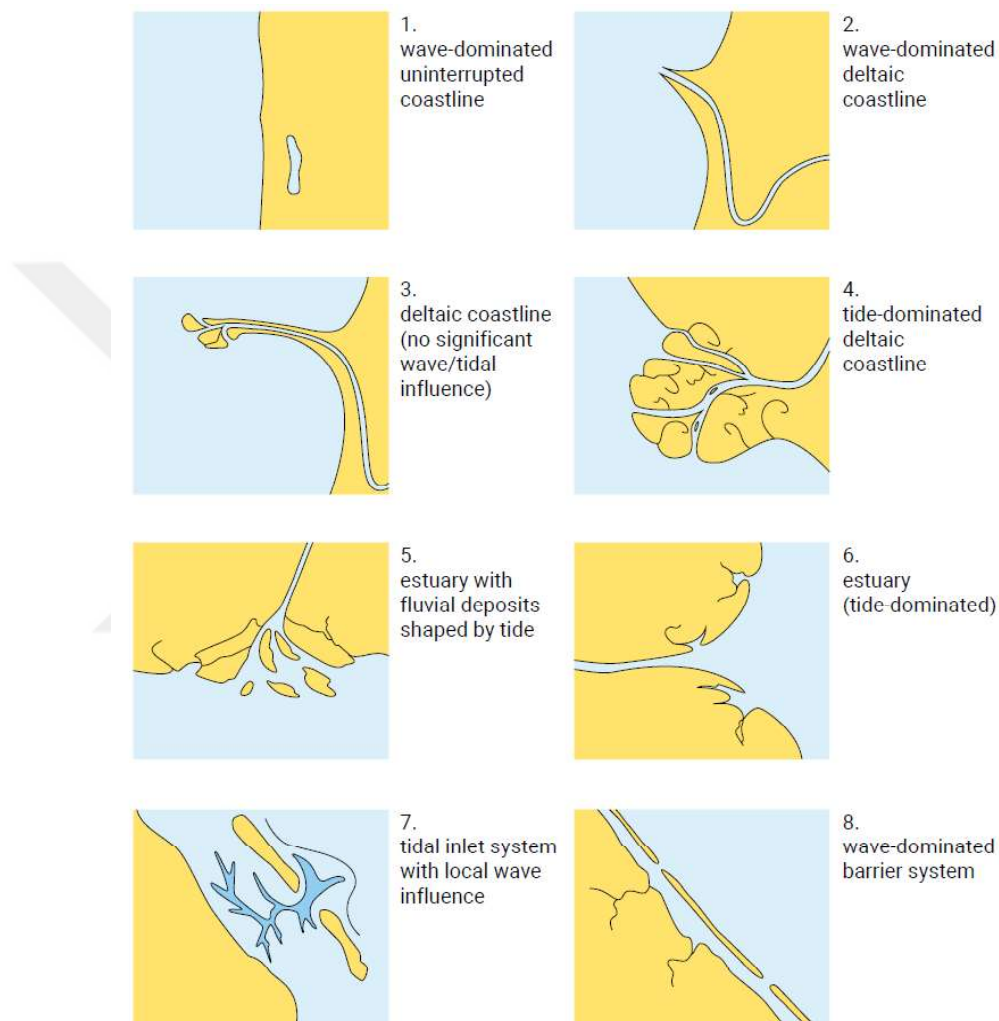


Figure 2.5 Coastal depositional systems (Bosboom and Stive, 2022)

One of the most fundamental methods for classifying sediment depositional environments is to assess whether the coastal region is transgressive or regressive (Boyd *et al.*, 1992). These terms cover over a thousand years of a period that can be observed in facies analysis. A transgressive movement represents a shoreline shift through the land whereas a regressive movement is supposed to mean a shoreline shifting through the sea (Bokuniewicz, 2005; Cattaneo and Steel, 2003).

Despite deltas, which are primarily sourced from rivers, estuaries are fed from both oceans and rivers. Therefore, deltas are assessed as being regressive as opposed to estuaries which are transgressive (Bhattacharya, 2006).

Since coastal areas have significant coastal landform types depending on the prevailing forces, remote sensing can be utilized to classify these regions. Figure 2.5 illustrates typical coastal landforms that are naturally constructed over long periods by the dominating forces indicated in Figure 2.1. The lagoons, depicted in Figure 2.5 (panel 1), are salty water bodies restricted by coastal sediments that are under the influence of dominant waves. In systems where river water and sediment enter the coastal environment, sediment banks can be formed in the channel that progresses towards the sea. Sediment depositional banks can progress freely seaward without being suppressed by wave or tide (Figure 2.5 panel 3), however, in the presence of prevalent wave or tide, the propagation of sand banks is restrained (Figure 2.5 panel 2). Typical delta and estuary patterns in the presence of dominant tide are shown in Figure 2.5 (panels 4, 5 and 6). Wave-dominated tidal inlet and barrier systems are illustrated in Figure 2.5 (panels 7 and 8, respectively).

3.1 Study Site: Karasu

Karasu coast is located in the north of the Sakarya province where the city meets the Black Sea (Figure 3.1). The coastline stretches out approximately 25 km west and east side of the Sakarya River mouth (41.127N 30.649E). The sediment load of the Sakarya River is the primary source that provides the formation of the Karasu coastline geomorphology (TMMOB, 2012).

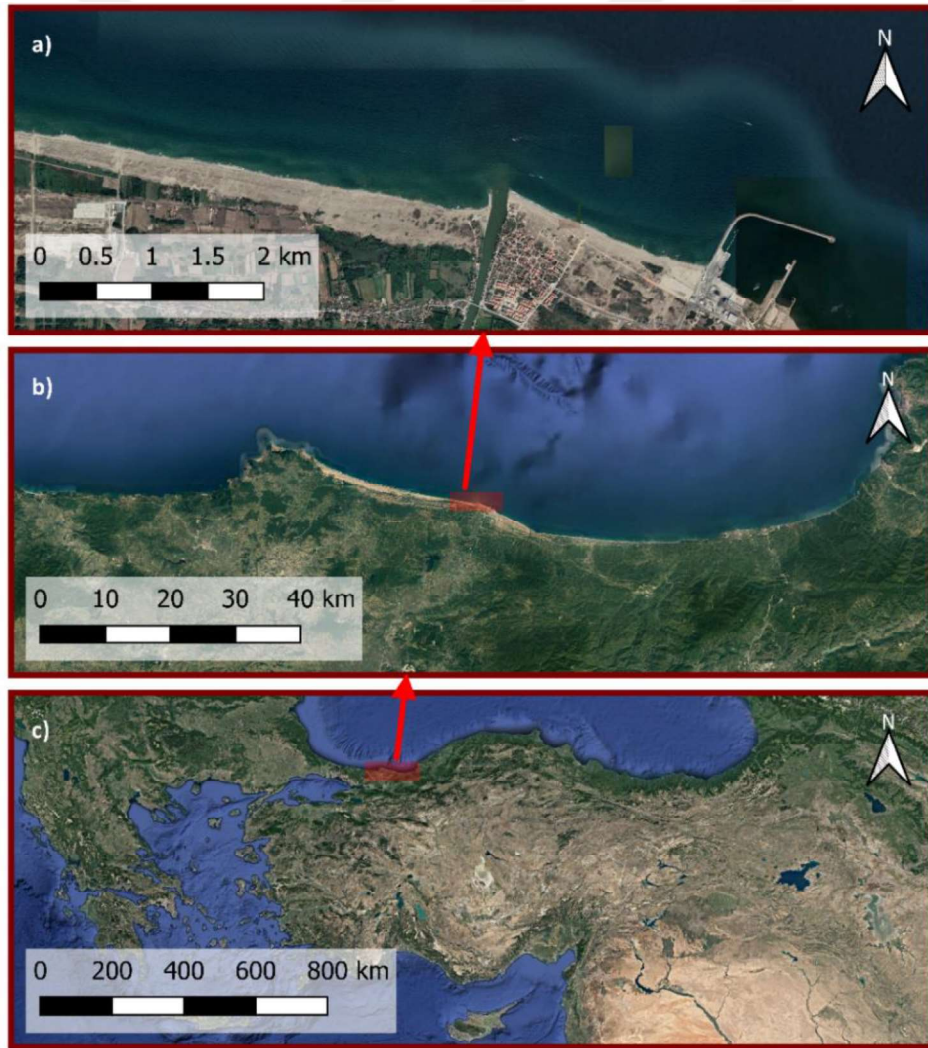


Figure 3.1 Study site, Karasu (Sentinel2 satellite). a) 1:70,000 scale
b) 1:1,200,000 scale c) 1:20,000,000 scale

The morphological structure of the river mouth and nearby coasts is formed by the sand delivered by the Sakarya River to the Black Sea under the influence of waves and currents. The formation of very large beaches, which are formed over thousands of years from young dunes to fossilized dunes beyond the beach, are evidence of this morphological structure. The coastal dunes in this morphological structure, which have an average height of 6-7 m and structures creating a 50–300 m strip to the west of the river mouth, act as a vital sand budget for erosion to take place in the coastal area (TMMOB, 2012). The wave structure in the region causes a significant amount of cross-shore sediment transport in the coastal area. Furthermore, the coastline is quite dynamic in terms of longshore sediment transport with significant transport rates from west to east and east to west. This situation is also observed from the sand accumulations at the mouth of the Sakarya River and the morphological structure of the coast (Figure 3.2).

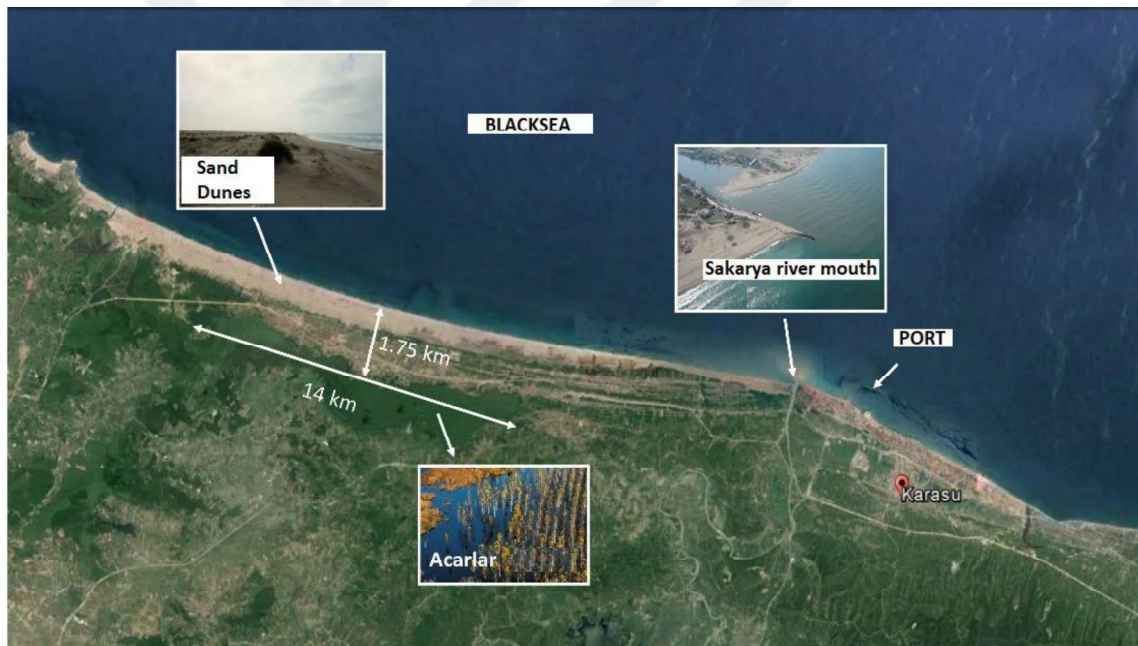


Figure 3.2 Sakarya river delta environment (Google Earth, 2015)

On the west coast of the Sakarya River mouth, Acarlar floodplain and floodplain forest are located at 1.5 km inland, extending 12 kilometers parallel to the shore, 1.5 meters deep, and covering an area of approximately 1560 hectares. The Acarlar floodplain has the feature of being the largest one-piece floodplain in the world. It is also covered in sedge, reed, aquatic plants, and flowers, as well as ash, alder, elm, and willow trees (Figure 3.3). Nearly 200 bird species can be found annually in the

Acarlar floodplain forest. The Acarlar Lake is home to several fish species including eels, carp, catfish, rudd, pike, and mullet. Due to the combination of all these characteristics, it has been designated as 1st Degree Natural Protected Area. The Acarlar Lake, which is surrounded by ash trees, is formed as a result of the flooding of the area behind the dunes on the shore. The lake floor is covered in a dense forest structure that is hard to cross, which sets Acarlar lake apart from many lagoons or wetlands. In addition to being habitat to a unique natural structure, the Karasu coastal region shields the Acarlar Floodplain and the adjacent coastal sand dunes from the destructive impacts of the sea (Figure 3.4). With this delicate composition, Karasu is one of the rare coastal regions not only in our country but also in the world (TMMOB, 2012).

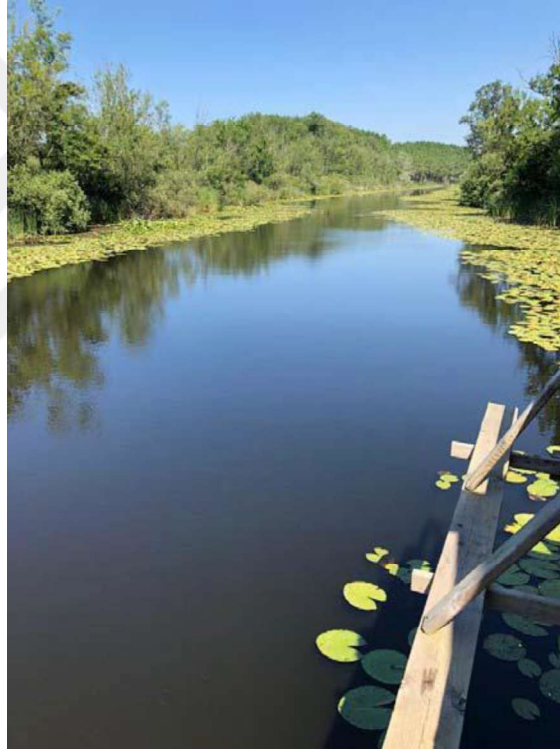


Figure 3.3 Acarlar floodplain

The population living in the provinces located in the Sakarya River Basin and the activities carried out directly affect the Sakarya River and the coastal part formed by the river. However, this effect is reflected cumulatively on the Karasu in Sakarya province, where the basin meets the Black Sea. The area is the tourist attraction point of the region due to its 40 km uninterrupted coastline and its proximity to Istanbul. As a result, the shoreline is host to several tourist facilities.

Due to the dams constructed on the Sakarya River, sand intakes, and coastal constructions, coastal erosion has been visible and persists on the Karasu coastline for the last few decades, and it has recently reached a point where it poses a serious threat to the residential areas (TMMOB, 2012).



Figure 3.4 Sand dunes at the coast

The Sakarya River with its tributaries has a length of 720 km and it drains the water and sediment load of the Sakarya Basin to the Black Sea (TÜBİTAK-MAM, 2013). The Sakarya River emerges from two springs, one near the Çifteler district in Eskişehir and the other one at the Bayat Plateau in the northeast of Afyonkarahisar (TMMOB, 2012), and the river grows with tributary channels as the altitude decreases until it reaches the river mouth. Sakarya Basin is the 3rd largest basin among 26 basins in Turkey with a watershed (or catchment) of 58160 km², which corresponds to Turkey's 7.5% surface area (T.C. Orman ve Su İşleri Bakanlığı, 2014; TMMOB, 2012). The Basin covers all the surface areas of Sakarya and Eskişehir provinces, 97% of Bilecik, 70% of Ankara, 42% of Bolu, 35% of Kütahya, 26% of Afyonkarahisar, 20% of Konya, 17% of Bursa, 10% of Kocaeli and less than 2% of Düzce, Çankırı and Uşak provinces (TÜBİTAK-MAM, 2013).

Three dams that have been built on the river since 1956 caused a major decrease in the amount of water and sediment load carried by the river (Işık et al., 2006). According to data taken from DSI, for the last 2 decades annual water discharge and suspended sediment load of the Sakarya River are 4.40×10^9 m³/year and

1.15×10^6 t/year, respectively (Figures 5.5a and Figure 5.6a). However, before the construction of Gökçekaya Dam in 1972, these values were 6.17×10^9 m³/year and 4.6×10^6 t/year, respectively (Yüksel *et al.*, 2014; TMMOB, 2012). Dramatical decreases in the sediment load of the river negatively affect the coastline and lead to 7.5 m erosion per year (Yüksel *et al.*, 2014; Şahin, 2020).

3.2 Field Campaign

Hydrodynamics and sediment dynamics along the Karasu coastline under the influence of Sakarya River discharge were investigated using the field observations conducted in different seasons covering different meteorological and hydrological conditions and therefore allowing for observations under different forcing conditions in the vicinity of the Sakarya River region of influence. The objective of the field study is to observe the seasonal behavior of suspended sediments and variations of hydrodynamics and morphodynamics on the delta coast. For this purpose, three field campaigns in 2019 representing the winter, summer, and autumn seasons (1-7 February, 5-13 July, and 2-13 November, respectively) were conducted. Measurements of waves, vertical structures of currents, turbidity, temperature, and salinity were collected.

In the field studies, vertical salinity, temperature, and turbidity profile measurements were carried out along one cross-shore (A) and two long-shore transects (B and C). Transect A involves 12 stations (except the field study in November which has 17 stations) along a 4 km distance between the river mouth and the deepest station at 40 m depth. The transect B includes 9 stations at a constant depth of approximately 5m, and the transect C includes 8 stations at a constant depth of 10m, and both stretch out approximately 2.9 km parallel to the shoreline. The number and depth of measurement stations in the transects may vary slightly depending on the measurement season. The measurement locations used in different seasons are seen in Figures 3.5-3.9.

The wintertime field study included 12 stations on transect A, 9 stations on transect B, and 8 stations on transect C, and was conducted between February 1st and 7th to represent the dynamics in the winter season (Figure 3.5). Station A12 was used for in-river CTD and turbidity measurements, as well as the collection of

bottom sediment material and water samples. In addition to CTD and turbidity measurements, along transect A perpendicular to the shoreline, water samples were collected at stations A11, A9, A7 and A5. On transects B and C parallel to the shoreline, bottom sediment materials and water samples were collected at stations B5 and C4. The wintertime shoreline has been extracted from the Sentinel-2 satellite data of February 4, 2019.

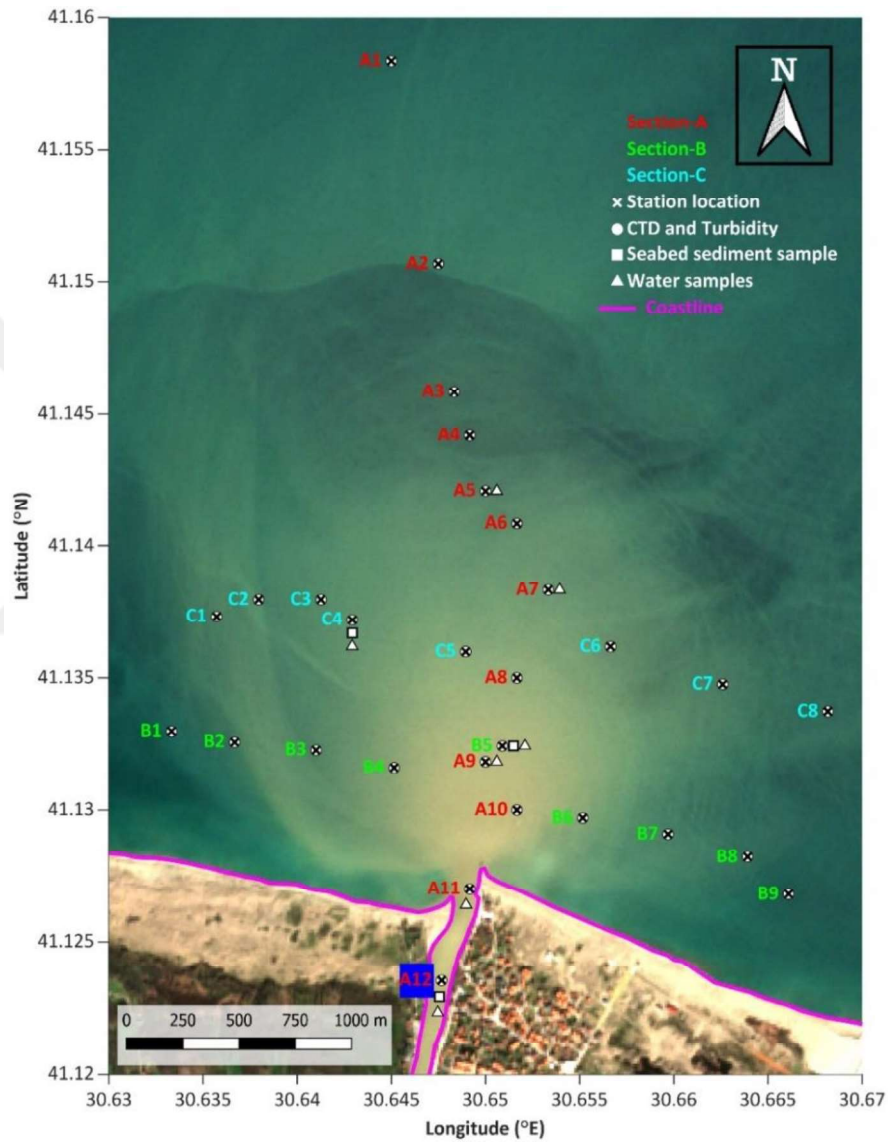


Figure 3.5 February field measurement stations

The summertime field study was conducted between July 5th and 13th to reflect the summer season dynamics with 12 stations on transect A, 9 stations on transect B, and 8 stations on transect C, and the station at around 15 m depth where an ADCP device was deployed (Figure 3.6). The CTD and turbidity profiles were

collected in all the stations. Station A12 was used for in-river CTD and turbidity measurements, as well as the collection of water samples. The water sample collection was carried out at stations A10, A9, A7 and A4, and additional bottom sediment materials were taken at station A9. On transect B, bed material was taken at station B9, and water samples were taken at station B6. On transect C, bed material was taken at station C1. The summertime shoreline has been extracted from the Sentinel-2 satellite data of July 9, 2019.

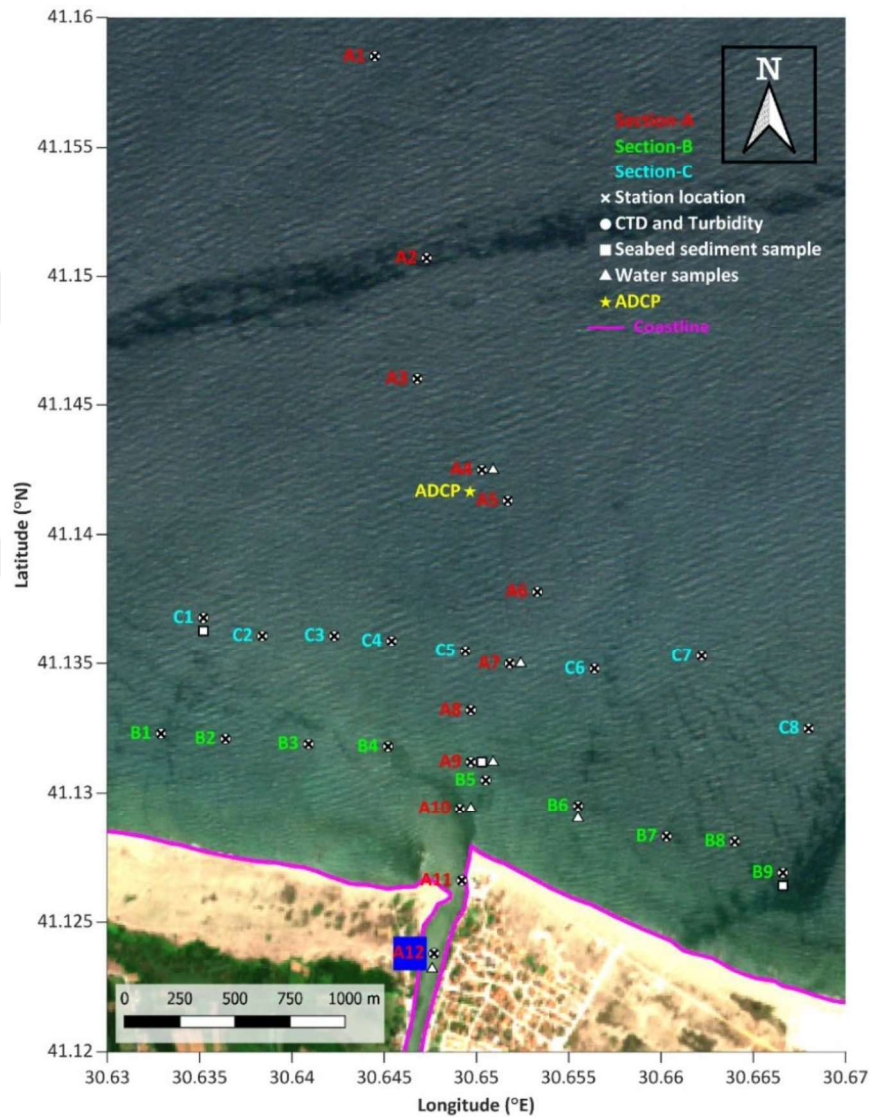


Figure 3.6 July field measurement stations

The field study carried out between November 2nd and 13th representing the autumn season covers 17 stations on transect A, 9 stations on transect B, 8 stations on transect C, and the station where the ADCP device was placed around 15 m

depth (Figure 3.7). For in-river measurements, CTD and turbidity measurements and water sample collection were carried out at station A17. In addition to the CTD and turbidity measurements carried out at all stations; water sample collection was performed at A13, A8 and A4, and bottom sediment material and water samples were taken at stations B1 and B9 on transect B and stations C1 and C8 on transect C. For the shoreline in November 2019, the Sentinel-2 satellite data of November 6, 2019, was used.

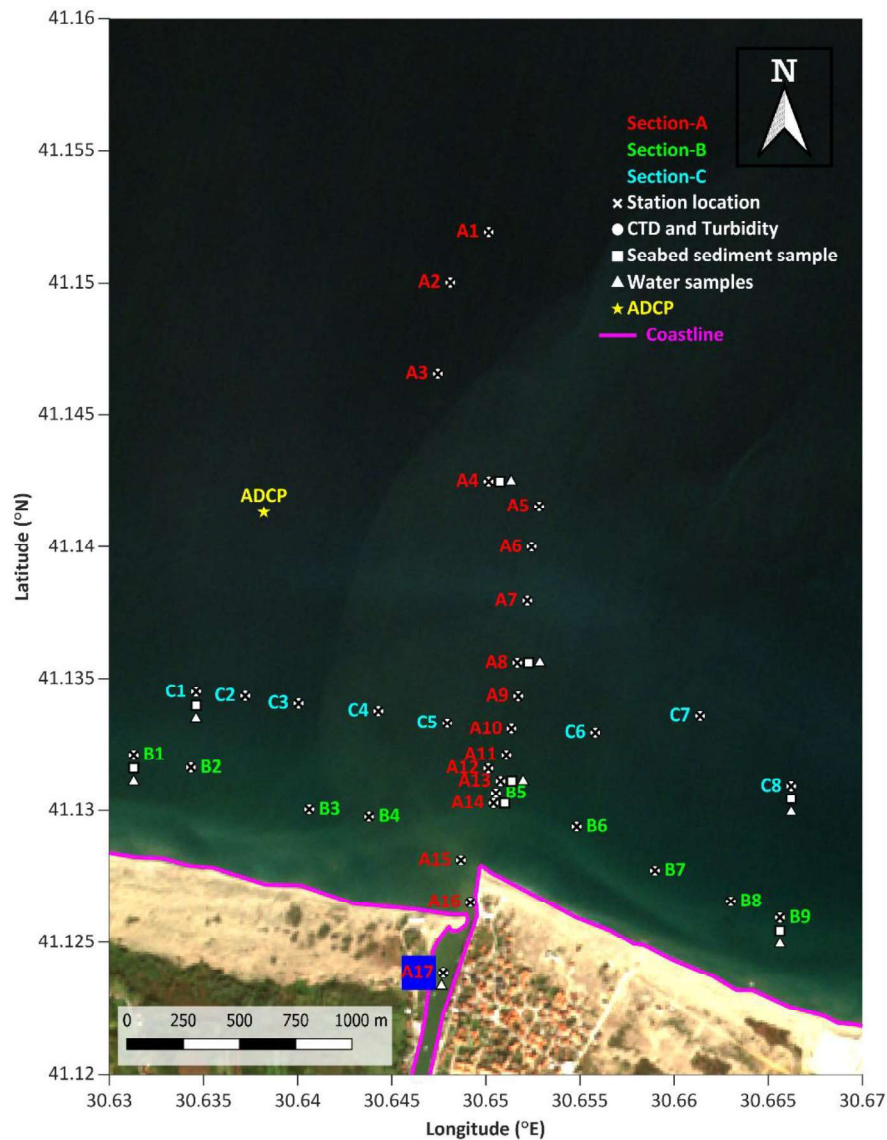


Figure 3.7 November field measurement stations

In order to determine the seasonal variation of the river cross-section, water depths were measured in a section 400 m behind the river mouth during the February, July and November field campaigns (Figure 3.8).



Figure 3.8 Location of measurement station for river cross-section approximately 400m distance behind the river mouth

In addition to the measurement of hydrodynamics and suspended sediment dynamics, a total of 6 bathymetry profiles perpendicular to the shore up to 50 m depth were acquired. One of these bathymetric profiles was between the river and the port in the east of the river mouth, and 5 profiles of 5 km intervals were in the 25 km-long part in the west of the river mouth. The locations of these bathymetric measurements are given in Figure 3.9.

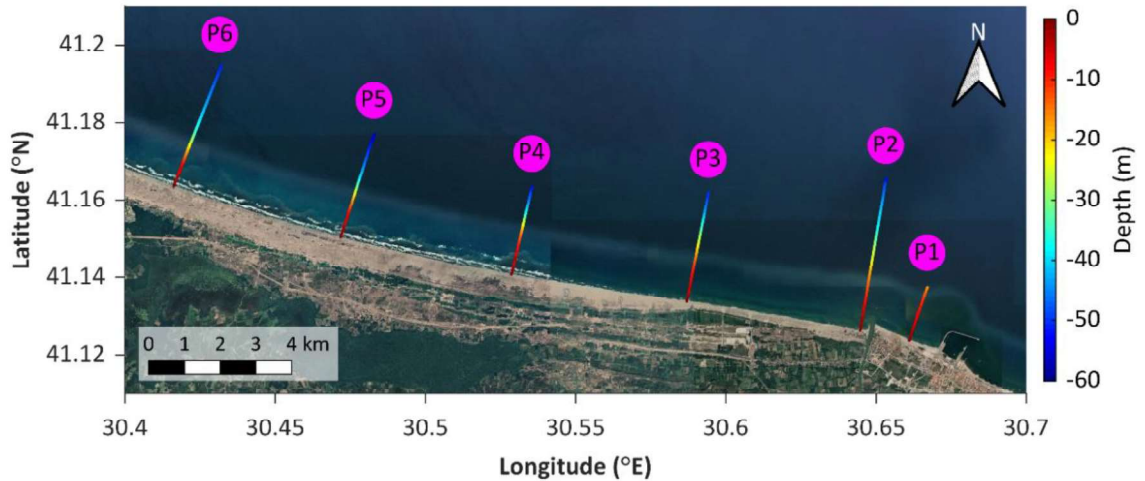


Figure 3.9 Location of the seabed level measurements

3.3 Instrumentation

Salinity and temperature measurements were carried out with CTD sensors (Conductivity, C.Xchange Sensor; Temperature, T.Xchange Sensor; Pressure, P.Xchange Sensor; Minos X, AML Oceanographic) (Figure 3.10). Turbidity Sensors (Tu.Xchange Sensor; Minos X, AML Oceanographic) were used to estimate the suspended sediment concentration. The sampling frequency of the two profiling instruments was defined as 4 Hz. Instruments evenly profiled the whole water column twice (from surface to bottom and from bottom to surface) with a constant speed of 0.2 – 0.4m/s.



Figure 3.10 Temperature, salinity and turbidity data acquired with CTD sensor

To observe the vertical current profiles and surface waves, two upward-looking 600 kHz ADCPs (FlowQuest 600, LinkQuest Inc., and Aquapro, NortekGroup) were deployed at the seafloor with a depth of approximately 15 m (Figure 3.12). The vertical spatial resolution (cell size) of the Aquapro ADCP was 1.0 m, whereas the Flowquest ADCP sampled in 0.5 m vertical bins. Both devices operate at 600 kHz and have a 0.5 m blanking distance (Figure 3.13c).

Water samples from the near bottom, middle, and top of the water column were taken at the stations presented in Figures 3.5-3.7. Additionally, bottom sediment samples were taken at stations where turbidity measurement was made (Figure 3.11).



Figure 3.11 Bottom sediment sampling during the field study



Figure 3.12 ADCP installation using a crane system during fieldwork (February 2019)

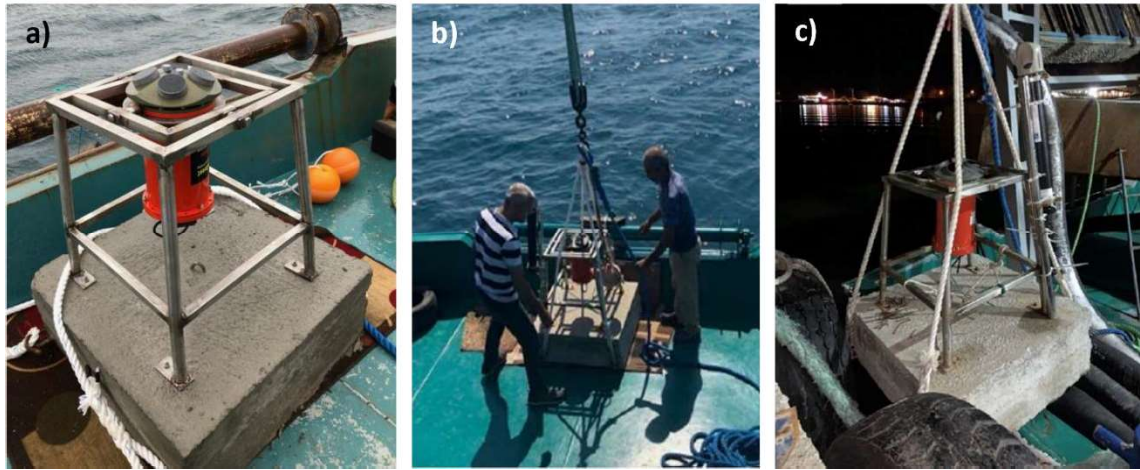


Figure 3.13 ADCP frame deployment. a) February, b) July and c) November

Inside the river, vertical salinity, temperature, and turbidity profile measurements, water sampling at three different depths (near the bottom, middle and near the top portion of the water column) and bottom sediment sampling were made at a station approximately 400 m distance from the river mouth. A point current meter (Valeport Single Point Current Meter) was deployed about 1.5 m below the water surface to obtain the approximate river current velocity during the field measurements. Additionally, sequential depth measurements were carried out along the river width to determine the river cross-section.

4.1 Laboratory Analysis of Water and Sediment Samples

To produce gradation curves of sediment samples taken from the riverbed and seabed, sieve analysis was done on all samples collected. In the laboratory, the materials were put into the stove to dry for 24 hours and finally sorted with sieves (Figure 4.1). The materials were sieved using 250, 170, 115, 80, 60, 42 and 32 Tyler/Mesh, corresponding to 63, 90, 125, 180, 250, 355 and 500 μm mesh opening sizes (Figure 4.2a). Hydrometer analysis was done on fine material ($\leq 63\mu\text{m}$) (Figure 4.2b).



Figure 4.1 a) Bottom sediment sample, b) oven drying the samples

The amount of suspended sediment in the water samples collected at different measurement stations and depths (bottom, middle, and near-surface levels) was obtained by using gravimetric analysis that separates the liquid phase from the solid phase in a water sample. The gravimetric analysis was performed in the Yıldız Technical University Environmental Engineering Laboratory. In the gravimetric method, suspended sediment in a known sample volume is filtered out using a vacuum filtration process (Figure 4.3). The filter with the suspended sediment is oven-dried to remove water from the filter. Suspended sediment

concentration (SSC) is determined based on the difference between the weight of the filter with suspended sediment (final weight) and the weight of the filter itself (first weight) using the following expression:

$$SSC \left(\frac{mg}{l} \right) = \frac{\text{Final weight (mg)} - \text{First weight (mg)}}{\text{Sample volume (l)}} \quad (4.1)$$

Suspended sediment concentrations obtained by the gravimetric analysis of water samples were used to calibrate the turbidity sensors that were used to measure the SSC profiles at the measurement stations.



Figure 4.2 a) Sieve analysis, b) Hydrometer test

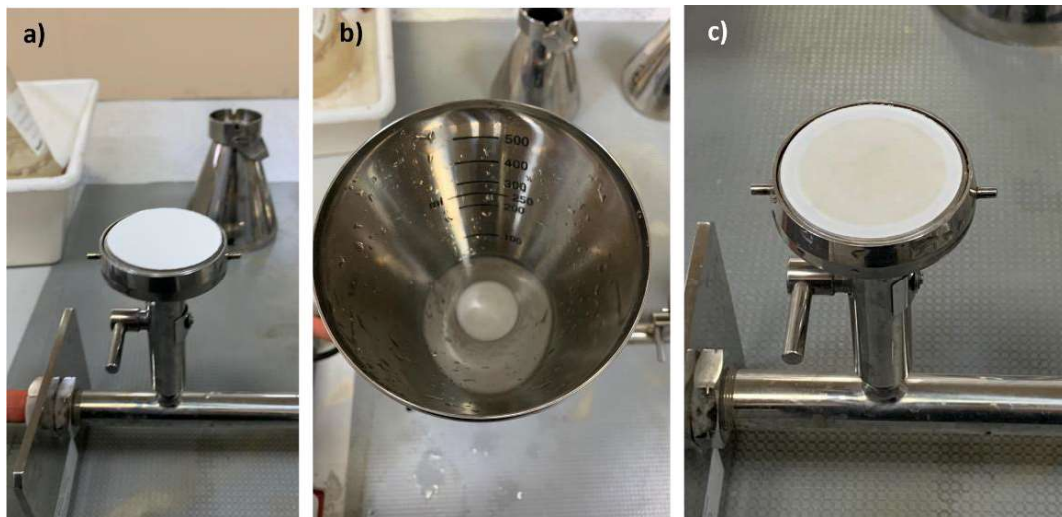


Figure 4.3 Separation of suspended sediment from water samples.
a) Before filtration b) filtration of water sample c) after filtration

4.2 Turbidity Sensor Data Calibration for SSC

The commercial turbidity measurement instruments provide access to the processed output signal in the manufacturer-specified unit (NTU: Nephelometric Turbidity Units) of the received signal strength indicator. It is known that there is an empirical relationship between the suspended sediment concentration in the water column and the turbidity value recorded by the instrument (Downing et al., 1995; Sahin et al., 2013; Sahin et al., 2017) as $SSC = a * NTU^b$, where a and b are the regression coefficients (Arora et al., 2022). To determine the coefficients in this relationship, the turbidity measurements should be calibrated using the concentrations obtained from the water samples collected in the field or in the laboratory. In the present study, calibration was performed using the water samples collected during the field campaigns.

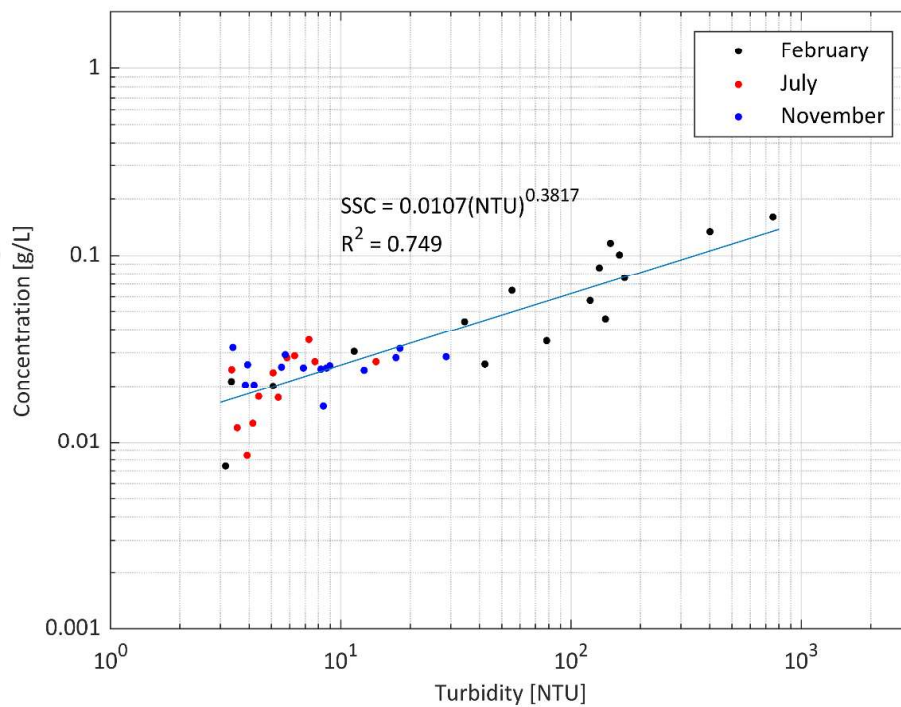


Figure 4.4 Suspended sediment concentration and turbidity correlation

In the field studies in February, July and November, turbidity data in NTU units were obtained with the turbidity sensors. To calibrate the NTU data with the true suspended sediment concentration (SSC), a filtration study (Figure 4.3) was carried out using water samples obtained from the bottom, middle, and surface levels of the water column at certain stations (Figures 3.5-3.7). The relationship

between the turbidity in NTU and the suspended sediment concentration from water samples is given in Figure 4.4.

The calibration equation to calculate suspended sediment concentration (SSC) in g/L was obtained with the determination coefficient of $R^2 = 0.749$ as following:

$$SSC = 0.0107(NTU)^{0.3817} \quad (4.2)$$

Suspended sediment concentration data at each station was gathered in each season from the turbidity sensor using this equation. The spatial distribution of SSC in the vicinity of the river mouth was determined using the data collected at each station in different seasons. These data, on the other hand, have a limitation of being available for only as long as the measurement time at the measurement station.

4.3 Acoustic Backscatter Data Calibration for SSC

ADCPs also measure the intensity of backscattered acoustic signal as well as flow velocity and direction. This feature allows researchers to obtain continuous suspended sediment concentration data by converting the acoustic backscatter data (ABS) collected by an ADCP (Sahin et al., 2017).

Using recorded backscatter data throughout a one-week period during which the ADCP measurements were taken at each season, a suspended sediment concentration acquisition was carried out as part of this study. Since the backscattered intensity data are under the influence of stratification layer and mixing processes, especially in the presence of river flow and biological and chemical factors in the water, the estimated concentrations do not directly represent the true concentrations (Dinehart and Burau, 2005).

Acoustic backscatter intensity data from the ADCP is converted to the vertical distribution of mass concentration of suspended sediment, M (kg/m^3) as (Sahin et al., 2017).

$$M(r) = \left\{ \frac{10^{\frac{I_{dB}}{20}} z \psi}{k_s k_t''} \right\}^2 e^{4r\alpha} \quad (4.3)$$

The calibration parameter, k_t'' is;

$$k_t'' = \left\{ \frac{3\tau c}{16} \right\}^{1/2} \frac{0.96}{k\alpha_t} \frac{p_0}{p_{ref}} \quad (4.4)$$

The system constant k_t'' which does not depend on suspension characteristics and the range is required for estimating SSC from time series of vertical backscatter profiles (Betteridge et al., 2008). In the present study, the value of k_t'' that minimizes the RMS error between the SSC observations obtained from the water samples and calculations was searched, and the resulting value of k_t'' was used as the calibration coefficient.

Received signal intensity E can be converted to signal intensity I_{dB} using as follows (Gostiaux and van Haren, 2010)

$$I_{dB} = 10 \log_{10}(10^{K_c E/10} - 10^{K_c E_r/10}) \quad (4.6)$$

K_c is the count to decibel conversion factor ($dB/count$) which ranges from 0.4 to 0.5 $dB/count$. The sum of water attenuation and sediment attenuation gives the attenuation coefficient, $a = a_w + a_s$, where water attenuation is a function of acoustic frequency, water temperature, pressure, and salinity. The sediment attenuation term a_s can be calculated as

$$a_s(r) = \frac{1}{r} \int_0^r \xi(r) M(r) dr \quad (4.7)$$

with

$$\xi(r) = \frac{3\langle\chi(r)\rangle}{4\langle a(r)\rangle\rho(\alpha)} \quad (4.8)$$

where ξ is the sediment attenuation constant (m^2/kg)

χ is the normalized total scattering cross-section for the particles in suspension (dimensionless)

$$f_f = \frac{k_f f \chi^2}{1 + \varepsilon_1 \chi^2} \quad (4.9)$$

$$\chi_s = \frac{k_{fa}x^4}{1-\varepsilon_2x+\varepsilon_3x^2+k_{fa}x^4} \quad (4.10)$$

where $x = ka$

$$\begin{aligned} k_{ff} &= 2 \left(\frac{\gamma\zeta^2-1}{3\gamma\zeta^2} + \frac{\gamma-1}{2\gamma+1} \right) \\ k_{fa} &= 2 \left(\left(\frac{\gamma\zeta^2-1}{3\gamma\zeta^2} \right)^2 + \frac{1}{3} \left(\frac{\gamma-1}{2\gamma+1} \right)^2 \right) \end{aligned} \quad (4.11)$$

The suspended sediment concentration data obtained from the filtration process using water samples taken from the station closest to the deployed ADCP was used to calibrate the SSC data from ADCP backscatter intensities in the field study in July. The calibration resulted in the value of $k_t'' = 3.098 \times 10^{17}$, which gives the minimum error value over a wide range of k_t'' parameters. An example of an SSC profile converted from ADCP backscatter is seen in Figure 4.5 for the field experiment conducted in July.

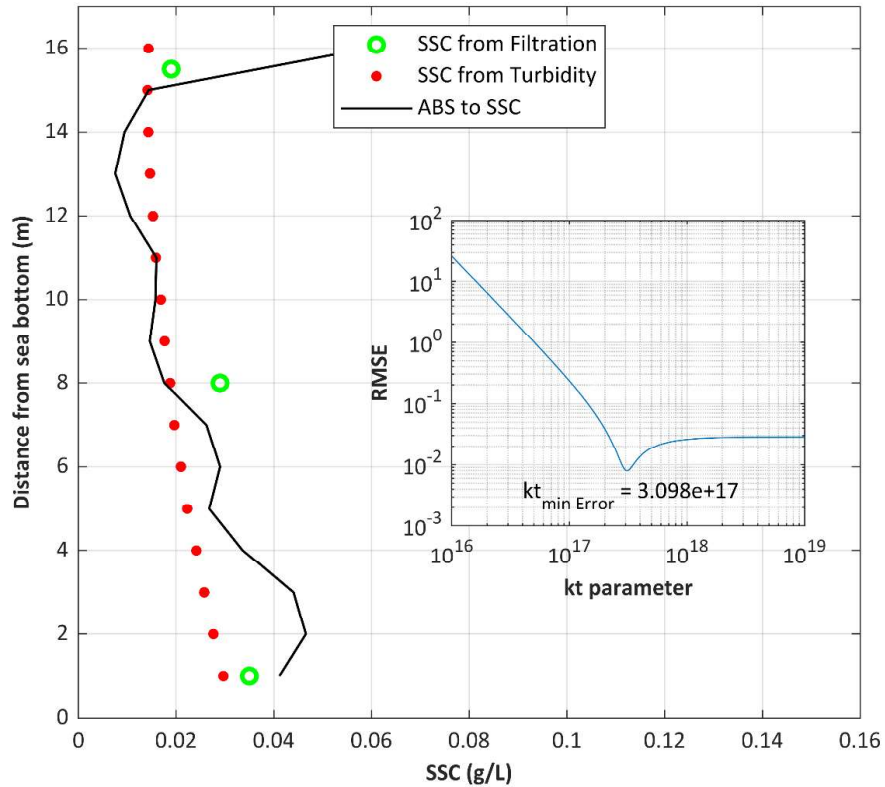


Figure 4.5 Acoustic backscatter data calibration, July

For the calibration of the November data, the suspended solids concentration data obtained by the filtration process with the water samples taken from the station closest to the ADCP device was used. The calibration process was completed for $k_t'' = 8.829 \times 10^{18}$, which yielded the minimum error value from a wide range of mean squared errors. An example of an SSC profile converted from ADCP backscatter is seen in Figure 4.6 for the field experiment conducted in November.

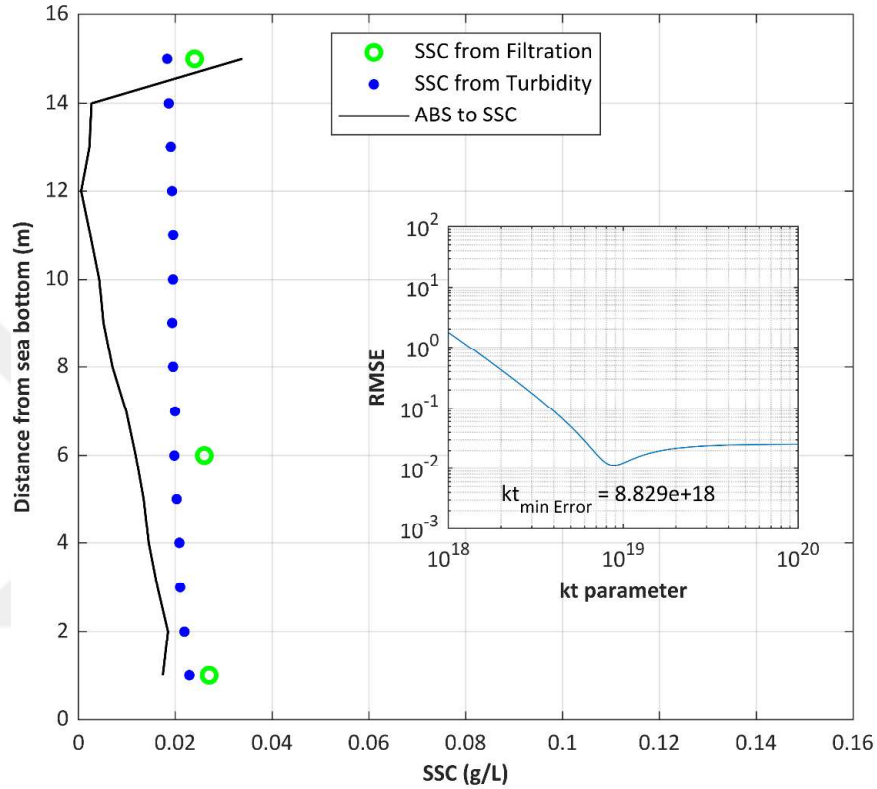


Figure 4.6 Acoustic backscatter data calibration, November

4.4 Spectral Wave Analysis

Frequency spectrum analysis is widely used to determine the statistics of the data that oscillates unpredictably around a certain mean. For the ocean waves in deep water, the data is the wind-generated water surface elevation which fluctuates around zero mean. In deep water, ocean waves are classified as normally distributed waves that obey the Gaussian (normal) distribution (Ochi, 1998). In more detail, the subject of the distribution is the fluctuated surface elevation distance from zero mean in time series. Fourier transform helps to separate naturally superposed waves (Figure 4.7) to its infinite number of basic sines or

cosines wave forms. Further, it also allows to convert time-domain data to frequency-domain data and examine data statistics by constructing a wave spectrum. As a result, by analyzing the wave spectral density function (wave frequency spectrum), the total energy of random waves can be determined.

$$\eta(t) = \frac{a_0}{2} + \sum_{n=1}^{\infty} a_n \cos(2\pi nft) + b_n \sin(2\pi nft) \quad (4.12)$$

Although natural data is continuous, data recorded on digital devices has a discrete structure due to the sampling process. Fourier transform can also handle the discrete data with the implementation of the discrete Fourier transform (DFT) algorithm. Thus, wave frequency spectrum analysis can be performed with discrete water surface data recorded as time series.

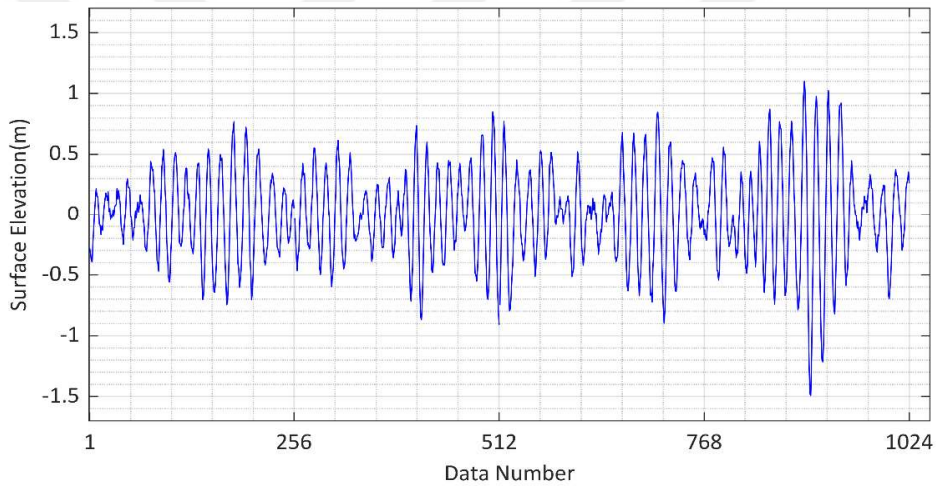


Figure 4.7 Water surface elevation (02/11/2019 21:30-21:39)

Pressure data gathered with the ADCP, which was deployed to a depth of roughly 15 meters in November, was used to perform wave spectrum analysis. Within the 30-minute burst intervals, water pressure was recorded at 2 Hz for 8 minutes, 32 seconds burst durations yielded 1024 data for each ensemble (Figure 4.7).

Since performing spectrum analysis on all of the data produces a noisy result, the data is separated into four equal pieces to make the spectrum diagram more comprehensible. Each data group in this study has 256 data points. Chebyshev windowing (Figure 4.8) was applied to each data subset to diminish the side lobe

effects that occur when the Fourier transform is applied to discontinuous data (Smith, 2011), thus the data is made more suitable for the Fourier transform.

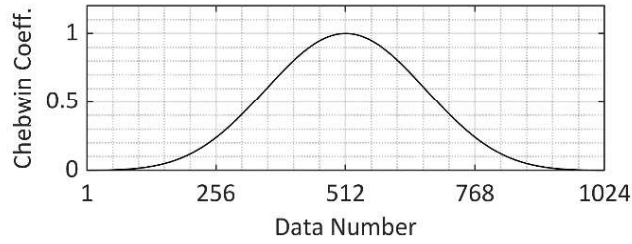


Figure 4.8 Chebyshev window coefficients

To compensate for data losses at the beginning and end of each sub-data group, the segments are overlapped by 50% (Figure 4.9). Since the variances of the subdivisions were consequently altered by manipulating the subdivided data with windowing, all individual data groups multiplied with the desired coefficient to fix the deviation in the variations.

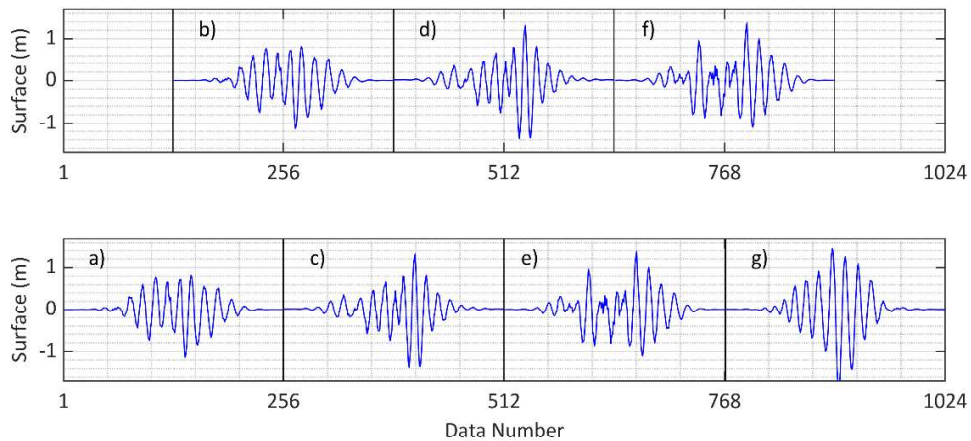


Figure 4.9 Chebyshev window process on data subsets

The wave spectrum obtained by averaging the spectrograms produced by the FFT analysis of all subdivisions in Figure 4.9 is shown in Figure 4.10. Wave parameters of the spectrum are derived based on the total wave energy, m_0 .

The swell waves are assessed as frequencies under 0.094 Hz in this study. Above this frequency are determined as the wind-generated waves. T_p is the peak period of the wave spectrum. The significant wave period, T_s , cannot be calculated directly from a wave spectrum, but its relation between both T_p and T_m assist to derive it empirically. As the spectrum gets sharper around the T_p , variation between the wave period parameters becomes narrow (Goda, 2000).

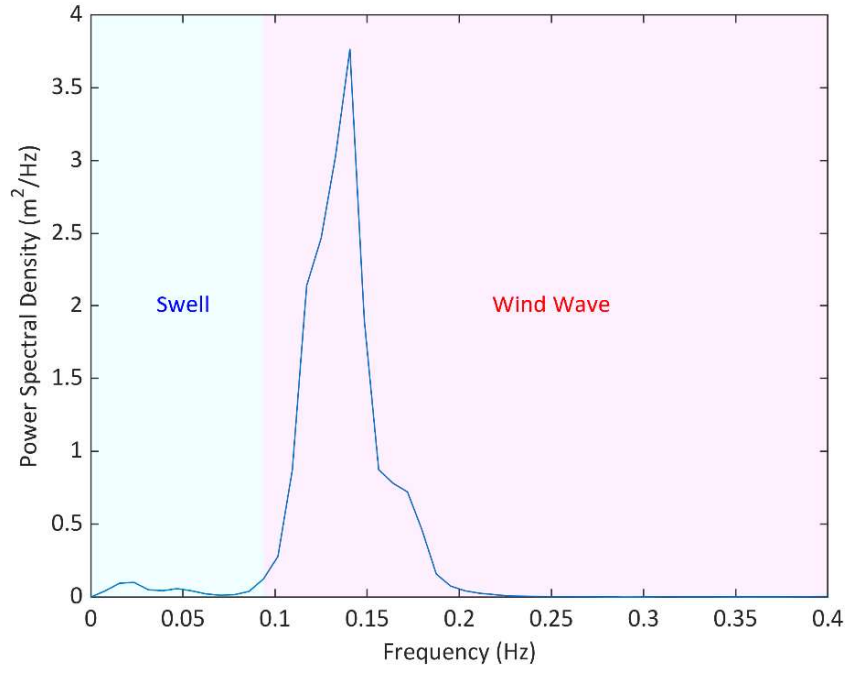


Figure 4.10 Wave frequency spectrum (02/11/2019 21:30)

Wave parameters, H_s and T_m are derived from the deserved power momentum of the wave spectrum in equation 4.13,

$$m_n = \int_0^{\infty} f^n S(f) df \quad (4.13)$$

where m_n is the n^{th} power of the spectrum moment and the f is the frequency array.

The significant wave height, H_s ,

$$H_s = 4.004 \sqrt{m_0} \quad (4.14)$$

The mean wave period, T_m ,

$$T_m = \sqrt{\frac{m_0}{m_2}} \quad (4.15)$$

The wave parameters for the frequency spectrum that is illustrated in Figure 4.9 and 4.10 calculated by the equation 4.14 and 4.15 as $H_{s(swell)} = 0.24m$, $H_{s(wind)} = 1.07m$, the total $H_s = 1.10m$, $T_p = 7.11s$ and $T_m = 6.60s$.

5.1 Water and Sediment Discharge of Sakarya River

The sediment and water discharge data between 2002 and 2019 were obtained from the DSI Adatepe station (located on the river and approximately 20 km behind the river mouth), to conduct a comprehensive analysis of flow dynamics in previous years. DSI river sediment department provides monthly sediment discharge data and water discharge data (Figure 5.1a). The water discharges measured by the sediment department had a high degree of agreement with those measured by the DSI water department ($R^2 = 0.992$) as expected (Figure 5.1b).

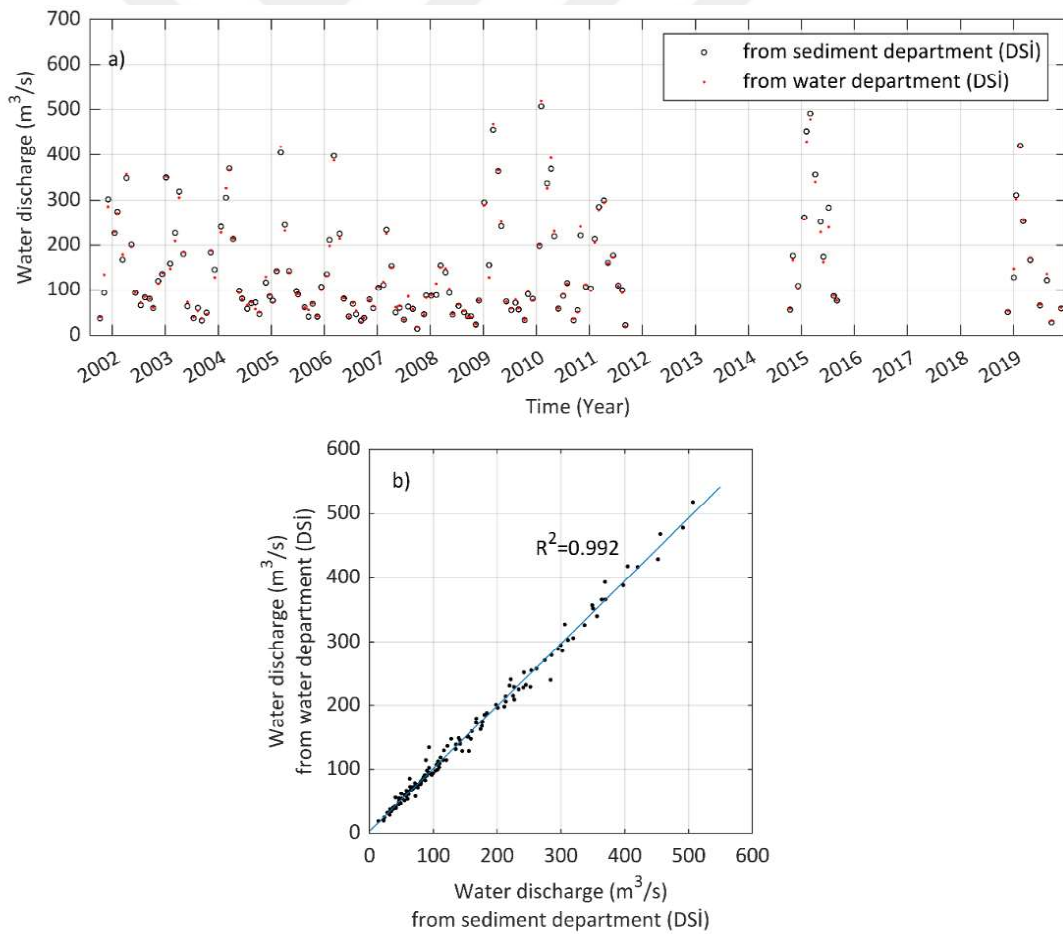


Figure 5.1 Water discharges from the water and sediment department of DSI. a) between October 2001 and October 2019, b) Correlation of water discharges

The relationship between sediment discharge and water discharge data collected approximately every 30 days by the DSI river sediment department is shown in Figure 5.2. The sediment rating curve was obtained with a determination coefficient of $R^2 = 0.867$.

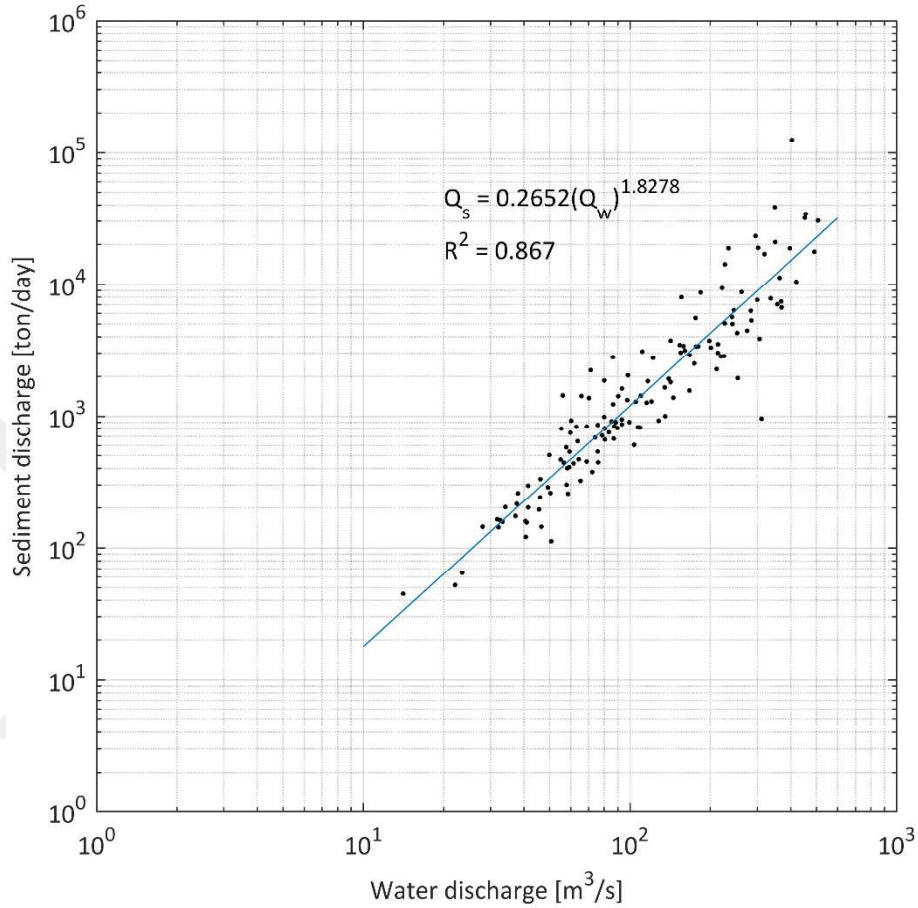


Figure 5.2 Sediment rating curve of Adatepe station between 2002 and 2019

The daily sediment discharge was determined from equation 5.1 by substituting the daily river discharges by the DSI river water department in the sediment rating curve. Thus, the sampling frequency of sediment flow data (approximately 30 days) was improved to daily data. Daily sediment discharge data allows us to determine the sediment discharges during the field survey dates.

$$Q_s = 0.2652Q_w^{1.8278} \quad (5.2)$$

The flow velocity inside the river where the river cross-section was extracted was also recorded using a single-point current meter from Valeport. The velocimeter was placed about 2 meters from the right bank of the channel and about 1.8 meters

below the water surface. Since this location does not represent the average speed of the river section, a correlation was made between the data obtained from the velocimeter and the daily flow data obtained from DSI.

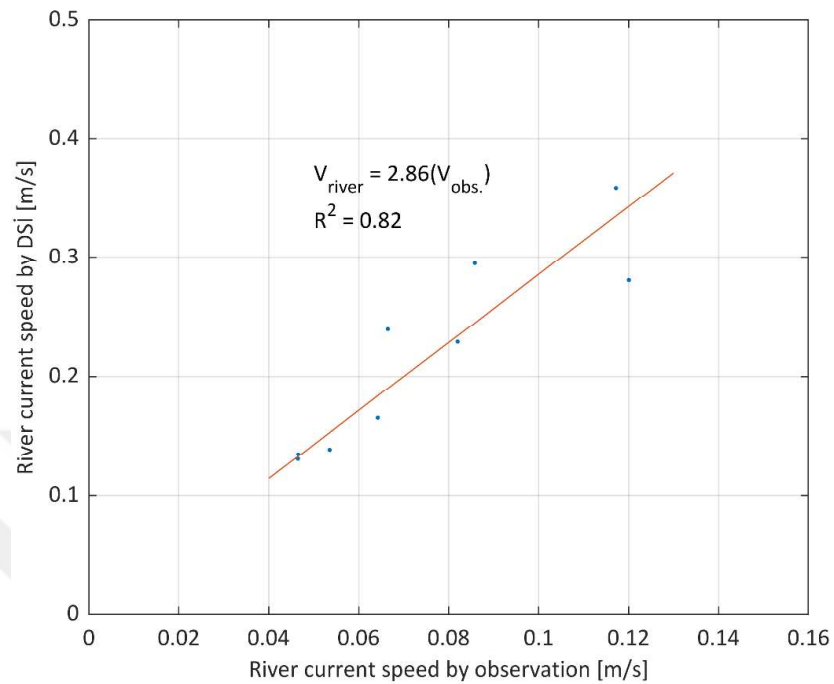


Figure 5.3 River daily current speed correlation between observation and DSI data, July 2019

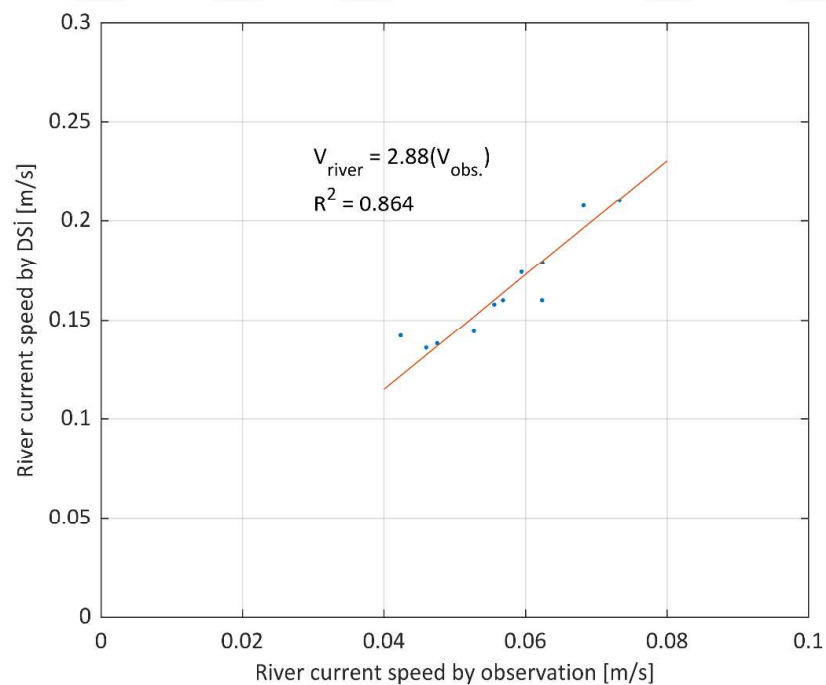


Figure 5.4 River daily current speed correlation between observation and DSI data, November 2019

As a result of this correlation study, it was observed that river velocities measured approximately 2.86 and 2.88 times less than the average velocity of the river section in July and November respectively (Figures 5.3 and 5.4). These correlations have been utilized for the calculation of the river discharge data that is not measured hourly or daily by the DSI water department.

5.2 River Water and Sediment Analysis

The river discharge data collected at Adatepe station are shown in Figure 5.5a to examine yearly and monthly river discharges between October 2001 and October 2020. Due to the maintenance works carried out at the station in some years, the flow data for those hydraulic years could not be obtained. The average river flow rate for the last 20 hydraulic years is 139.4 m³/s. The average river flow rates for the hydraulic years 2019 and 2020 (between October 2018-October 2020), during which the field studies were carried out within the scope of this study, are 142.1 m³/s and 123.8 m³/s, respectively.

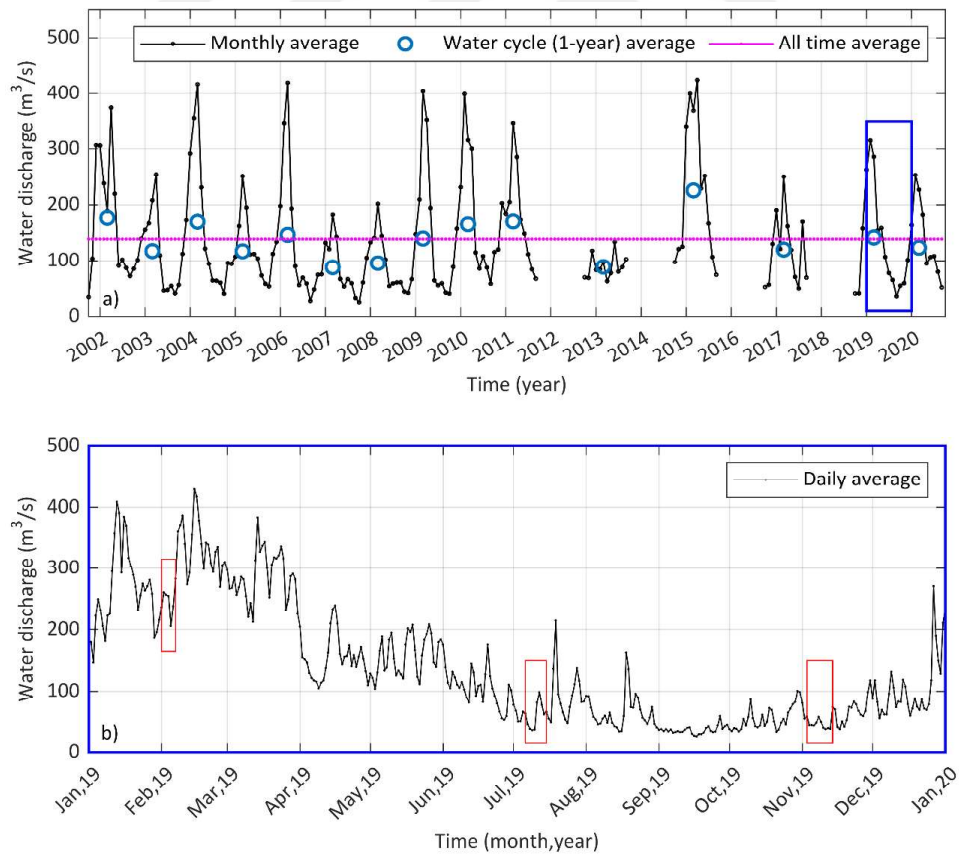


Figure 5.5 Sakarya River discharge. a) Monthly and yearly water discharge between October 2002-2020, b) Daily water discharge, January 2019-2020

The river discharges corresponding to the dates of field trips are shown in red boxes in Figure 5.5b. The average river flow rates in winter (February 1-6, 2019), summer (July 5-13, 2019) and autumn (November 2-13, 2019), during the field studies, are 242.5 m³/s, 60.4 m³/s and 46.2 m³/s, respectively.

Sediment discharge data produced from the sediment rating curve using equation 5.1 in Section 3.1 are shown in Figure 5.6a. The average sediment flow rate for the last 20 hydraulic years is 3268 tons/day. The average sediment flow rates for the 2019 and 2020 hydraulic years are 3304 tons/day and 2380 tons/day, respectively. The sediment flow rates occurring between the dates of the field studies in February, July and November are 6282.4 tons/day, 515.6 tons/day and 292.5 tons/day, respectively (Figure 5.6b).

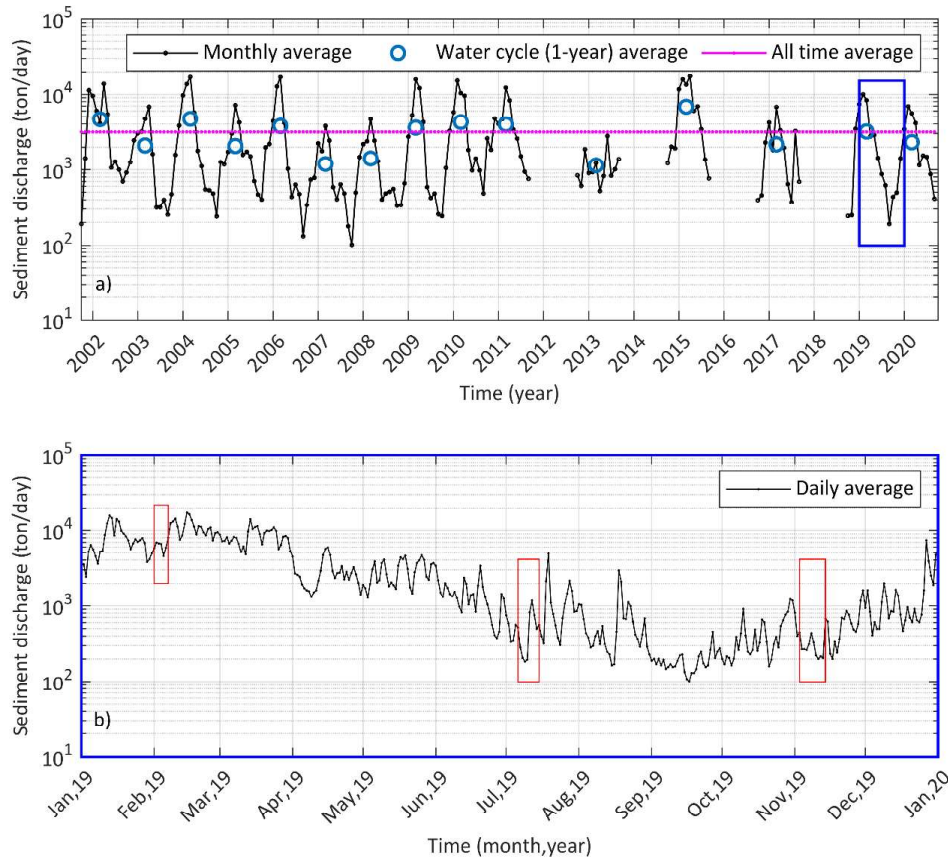


Figure 5.6 Sakarya River sediment discharge. a) Monthly and yearly sediment discharges between 2002-2020, b) Daily sediment discharge between January 2019-2020

5.3 Near-surface Salinity, Temperature, Suspended Sediment Concentration and Fresh Water Thickness

The near-surface variation plots for salinity, freshwater thickness, temperature and suspended sediment material obtained along the transects perpendicular and parallel to the coast during the field surveys in different seasons are shown in Figures 5.7-5.9. Surface salinity in the river mouth, which is below 12 PSU, increases along the transect perpendicular to the shore (transect A) as depth increases and reaches approximately 18 PSU, which is the typical salinity value of the Black Sea, as shown in Figure 5.7a-c. Salinity values lower than 18 PSU can reach 1.5 km away from the river mouth due to the influence of fresh river water in February, during which the river discharge is quite high. Salinities lower than 18 PSU are observed within 1 km from the mouth in July and November since discharges are lower. From inside the river to deep regions, the salinity values vary between 0.3-18.2 PSU in February, and between 0.6-18.2 PSU in July and November.

The freshwater thickness, H_f , was used to characterize freshwater spreading from the river (Yankovsky and Voulgaris, 2019):

$$H_f = \int_D^0 \frac{s_r - s}{s_r} dz \quad (5.2)$$

where s is the salinity, s_r is the reference salinity value defined by the offshore CTD measurements, which is 18.2 PSU for the Black Sea (water salinity from CTD measurements at the deepest point), z is the vertical coordinate (positive upwards), and D is the total depth of water.

Figure 5.7d-f represent the spatial distribution of the freshwater thickness derived using equation 5.2. The greatest freshwater thicknesses are observed at the stations nearest to the river mouth, and it generally spreads in response to wind stress. The amount of fresh water provided by the river is the largest and spreads over a wide area in February, consistent with the high river discharge. In February, it is observed that the freshwater thickness can reach up to 0.6 m even at stations 1.5 kilometers away from the river mouth. The amount of freshwater reduces as

the distance from the river mouth increases. In July, the rain during the field measurements resulted in lower salinities and higher freshwater thicknesses than expected in the measurement stations at the deep locations.

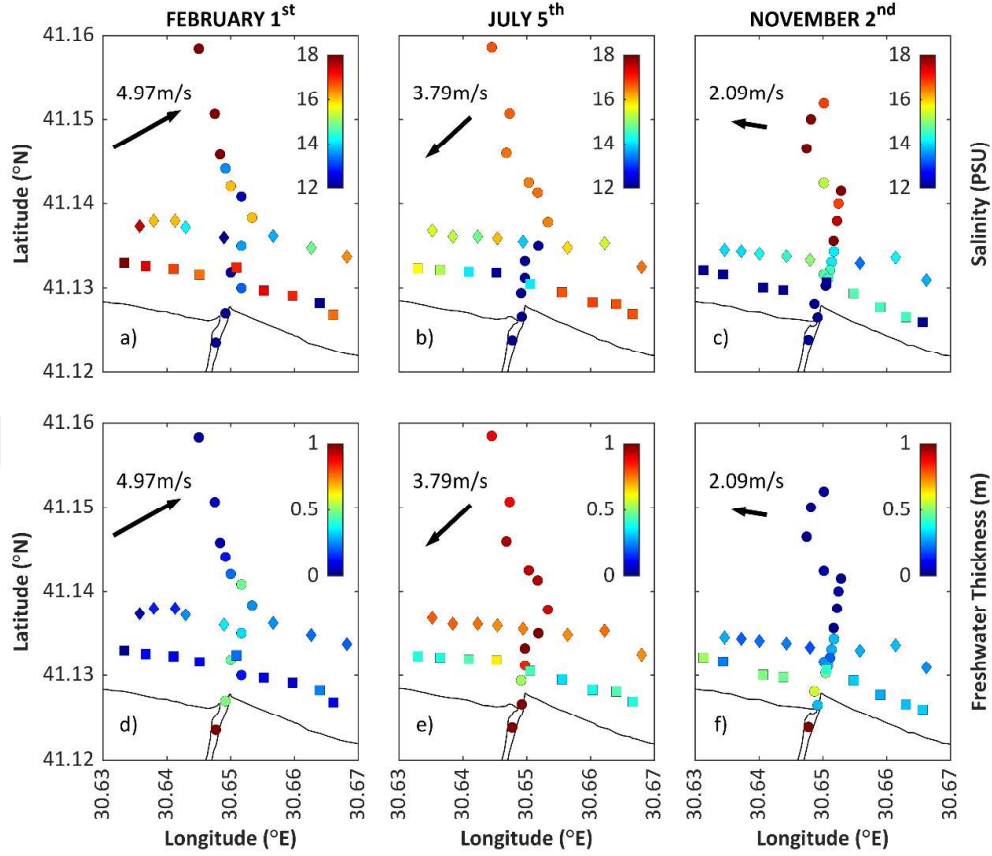


Figure 5.7 Surface salinity and freshwater thickness maps.

a) February, b) July and c) November salinity

d) February, e) July and f) November freshwater thickness

Figure 5.8a-c demonstrates the spatial temperature distributions near the water surface in different seasons. The sea temperature varies seasonally and is distributed in accordance with wind stress. Sea water temperatures in February, July, and November are 8°C, 26.4°C and 17°C, respectively. The fresh water in the river has been recorded warmer than the seawater in February and colder than the seawater in November. In July, there is no major temperature difference between freshwater in the river and saltwater in the sea.

Suspended sediment concentrations near the surface in different seasons are presented in Figure 5.9a-c. The concentrations of suspended sediment were calculated by converting turbidity values measured in NTU to g/L using the

calibration equation 4.2 provided in Section 4.2. As a result, a much larger concentration of suspended sediment is delivered from the river to the sea in February, when the strong river flow occurs, than in the other field study seasons. With the influence of wind stress, the material with a concentration of more than 0.16 g/L at the river mouth is transported to the east of the coastline. In the field studies during the seasons when the river flow is low, suspended sediment concentration is correspondingly reduced. The suspended material concentration values near the surface are typically lower than 0.015 g/L in July, and they are lower than 0.02 g/L in November.

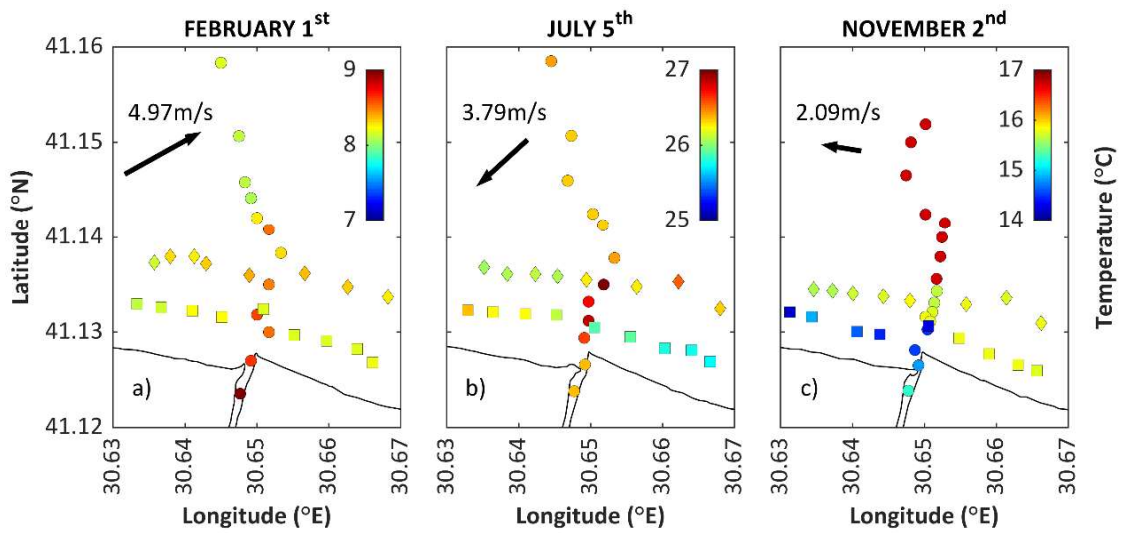


Figure 5.8 Surface temperature. a) February, b) July and c) November

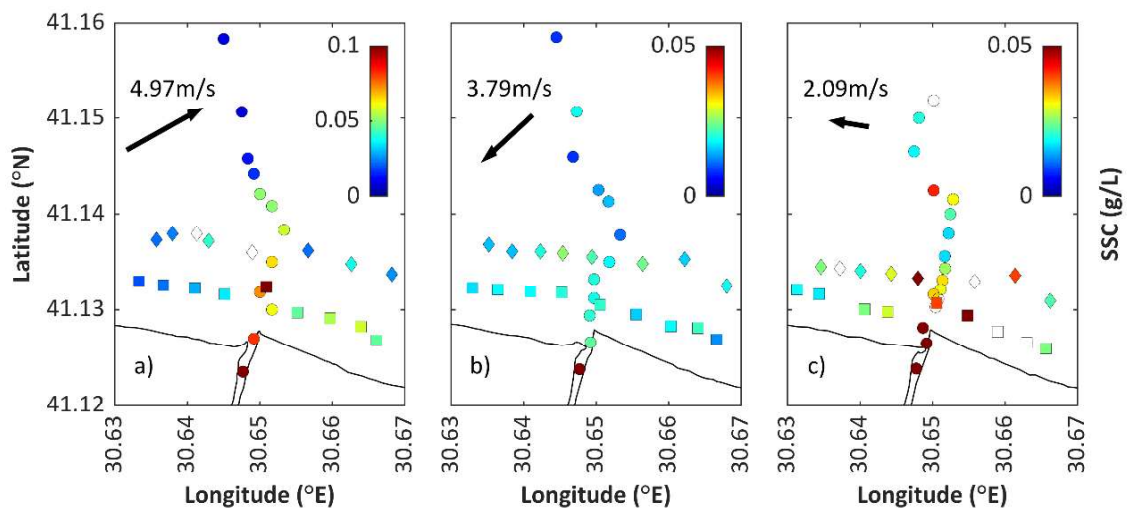


Figure 5.9 Surface suspended sediment concentrations.
a) February, b) July and c) November

5.4 Vertical Profiles of Salinity, Temperature, SSC

5.4.1 Salinity Profiles

Vertical salinity profiles in transect A (perpendicular to the shore) in Figure 5.10 show that the effect of the river discharge in February can progress more than 1.5 km from the river mouth, especially near the water surface. In July and November, the cross-shore river discharge impact was approximately within a distance of 1 km from the river mouth. As the distance from the river mouth increases, the salinity values near the surface and the depth of impact from the surface decrease.

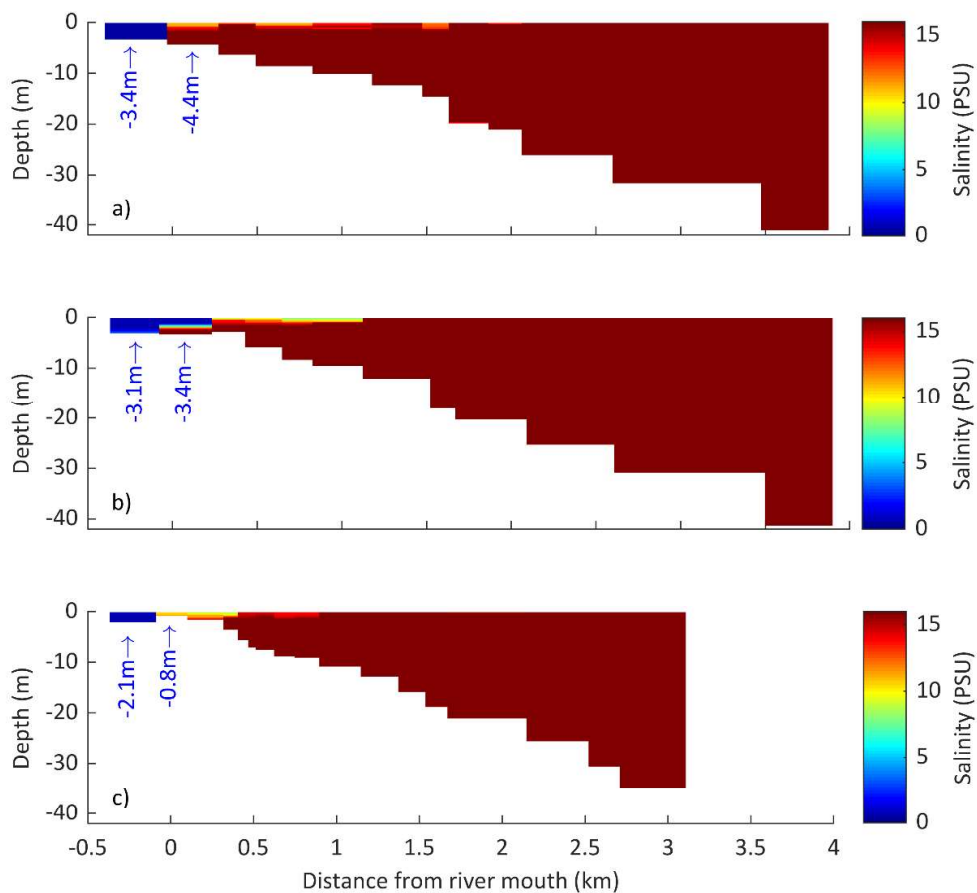


Figure 5.10 Salinity profiles along transect A.
a) February, b) July and c) November

The reference seawater salinity was measured as 18.2 PSU in all three measurement seasons. Because no seaward variation in salinity, temperature, or concentration was recorded in deep regions in November, the observations were ended about 3 kilometers from the river mouth. In the station inside the river, which is approximately 400 m behind the river mouth, seasonal changes in the

seabed level are also observed. The depth at this station is 3.4m in February, and it decreases to 3.1m in July and 2.1m in November. At the river mouth, it is seen that the depths are 4.4m in February, 3.4m in July and 0.8m in November.

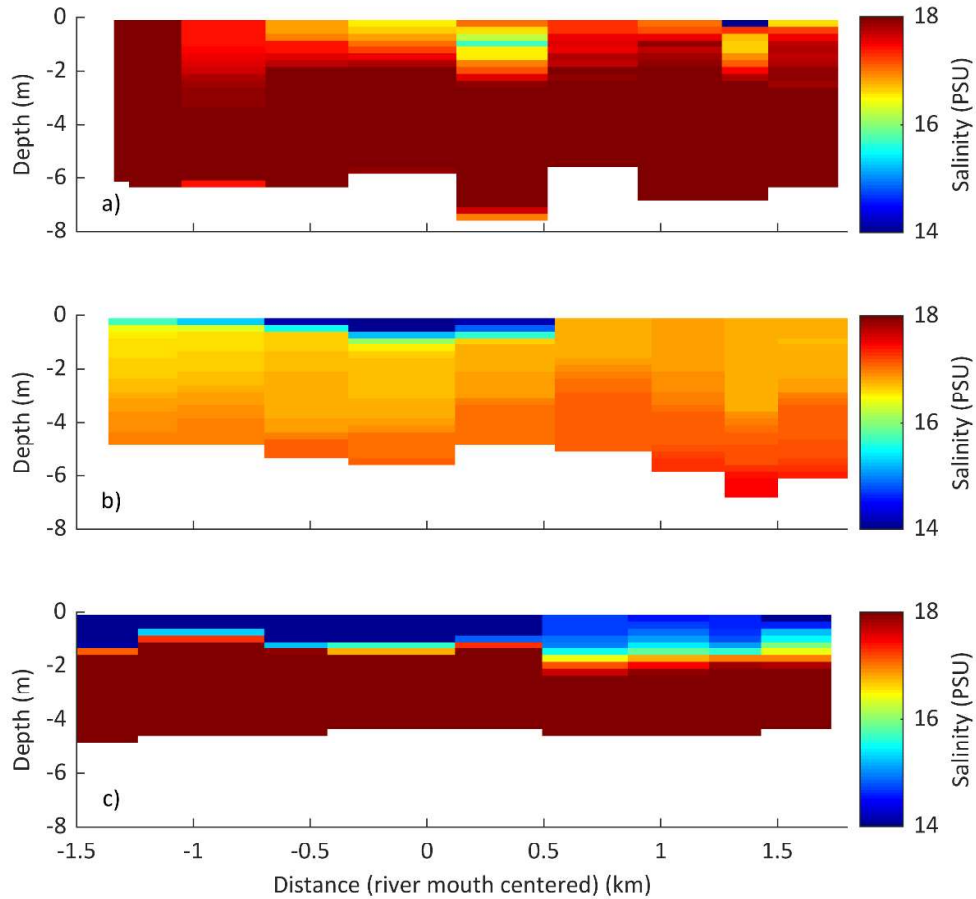


Figure 5.11 Salinity profiles along transect B.
a) February, b) July and c) November

Variation of vertical salinity profiles along transect B (parallel to the coastline, 5 m depth) is presented in Figure 5.11. The effect of the freshwater from the river is observed in a region close to the surface in all three seasons. Low-salinity river water is distributed over a considerably wider area in February due to the high river discharge with a weekly average river discharge of $234 \text{ m}^3/\text{s}$ during the field measurement. In July, the freshwater dispersion is significantly smaller than that in February as the average river discharge in the week before the measurement day is $74 \text{ m}^3/\text{s}$. Additionally, in July, the salinity is lower than the expected 18 PSU value throughout the water column due to rainy conditions during the field study. In November, the distribution of river salinity is wider than that in July, as the

average river discharge in the week before the measurement day is $81 \text{ m}^3/\text{s}$. The effect of freshwater is significantly more obvious in November because the primary wind direction is much more parallel to the coast compared to the other seasons. The distance of transect B from the shore is greater in February than in other months with greater water depths. Therefore, the spreading of salinity in response to high river discharge in February seems less than expected. However, the impact of high river discharge in February is clearer in transect C which is deeper than transect B.

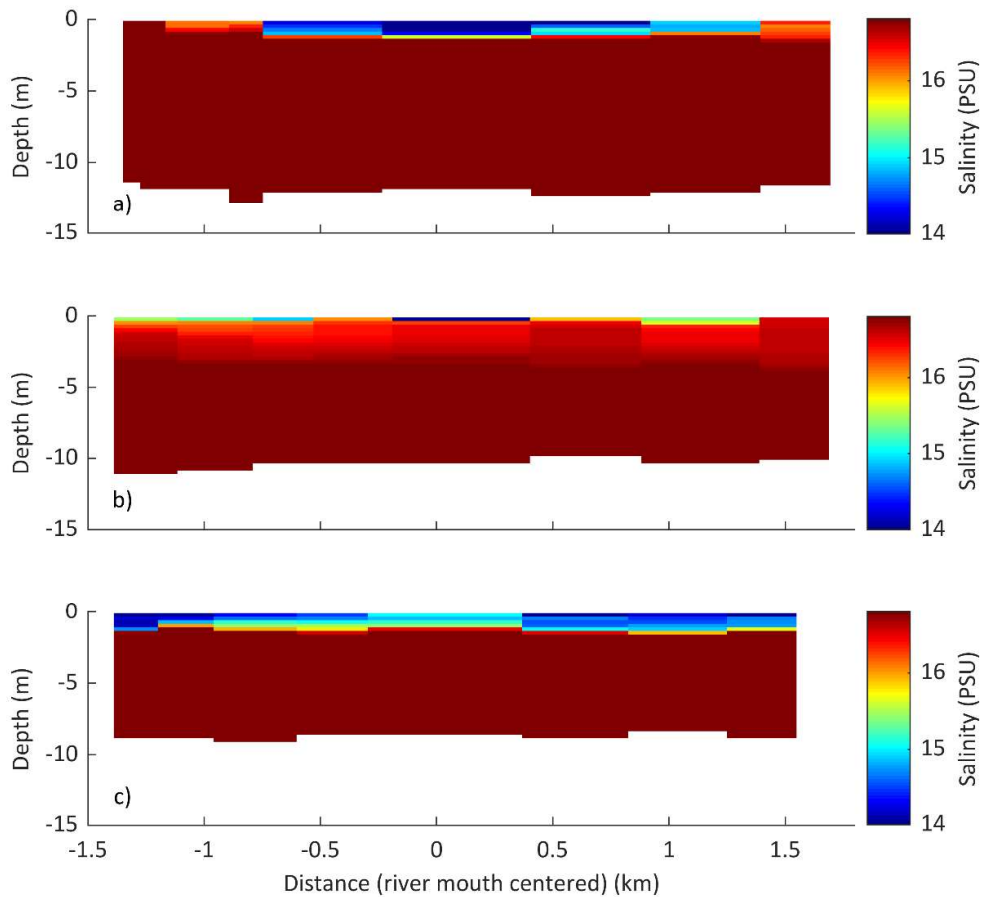


Figure 5.12 Salinity profiles along transect C. a) February, b) July and c) November Variation of vertical salinity profiles in transect C (parallel to the coastline, 10 m depth) is shown in Figure 5.12. There are high near-surface salinity gradients in all the measurement seasons. Salinities of around 12 PSU near the surface propagate towards the wind direction in February. While there are no significant salinity variations in July due to the low flow rate, the influence of the rain is noticeably more visible in the depths close to the surface. In November, freshwater is widely

dispersed in transect C since the river discharge is slightly greater and the transect is closer to the river mouth than those in July and the wind blows parallel to the shore. While the flow rate is slightly higher in November than in July, the fact that the wind is parallel to the coast implies that freshwater is widely dispersed along transect C.

5.4.2 Temperature Profiles

In the field studies, significant variations in water temperatures were observed between seasons (Figures 5.13-15). In February, the river water temperature is 9.2°C and the sea temperature is 8.1°C, and the relatively warm river water that enters the sea from the surface area has an influence within around 2 kilometers from the shore to the sea.

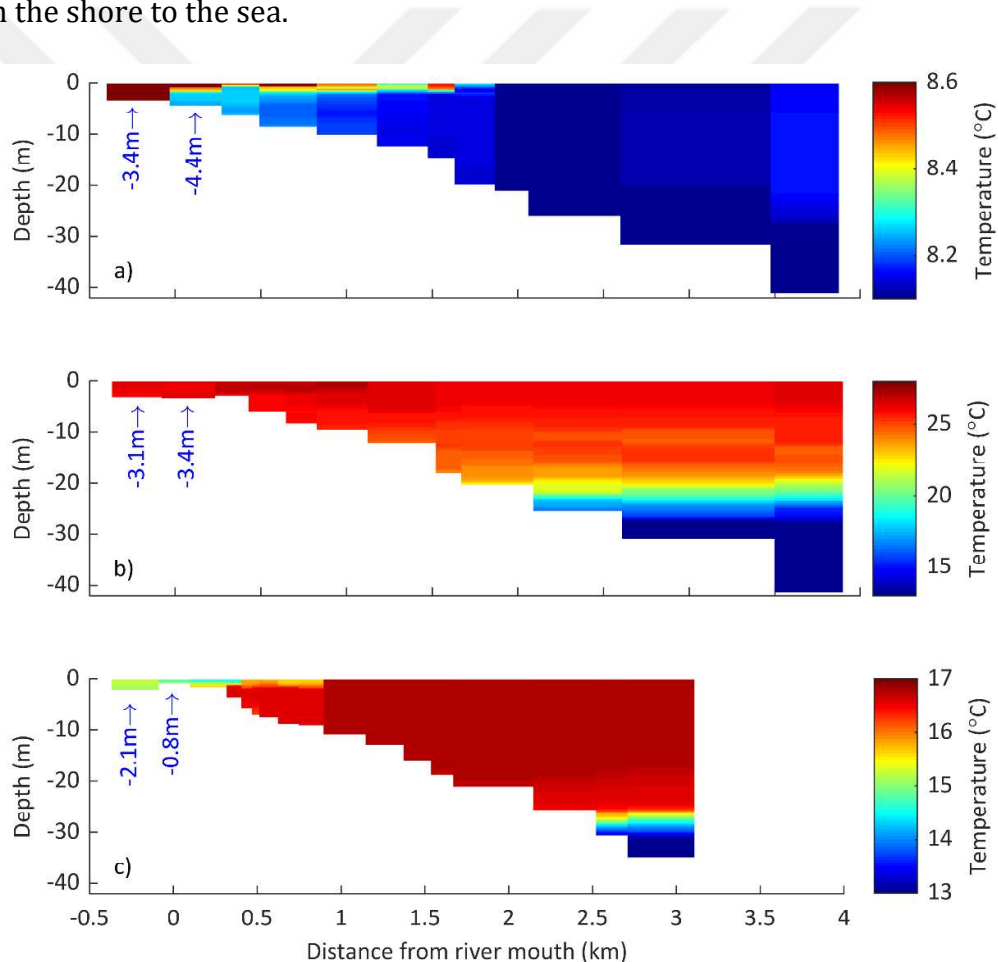


Figure 5.13 Temperature profiles along transect A.
a) February, b) July and c) November

In July, there are no significant differences between the water carried by river flow and the seawater. The water temperature in the river flow and sea surface was

around 26°C. However, in deep stations, the water temperature changes with the depth. As depth increases, especially in regions deeper than around 15 m, a considerable drop in temperature is noted. The water temperature decreases to around 13°C at the deepest sites observed. In November, the surface temperature of river and sea water is approximately 15°C and 17°C, respectively, and the river is colder than seawater. The relatively warm water brought by the river shows its effect near the surface within a distance of about 1 km. In November, a decrease in seawater temperature at depths greater than 20 m is observed, similar to the observations in July, and the water temperature drops to about 12°C at the deepest points measured.

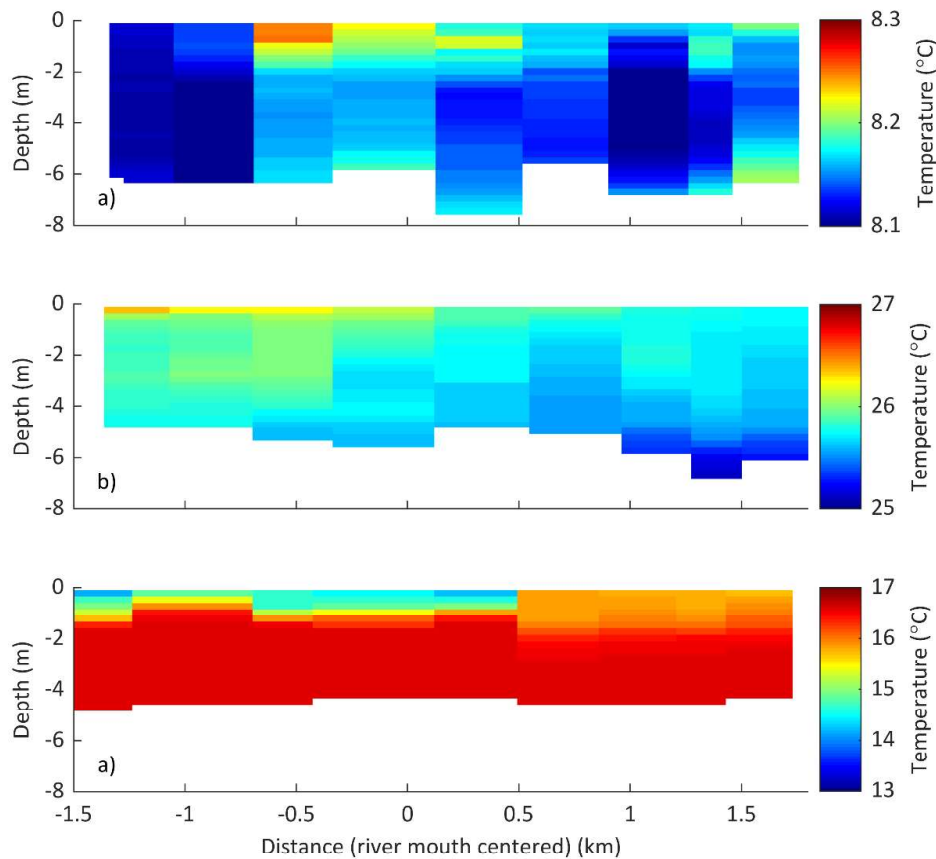


Figure 5.14 Temperature profiles along transect B.
a) February, b) July and c) November

Water temperature measurements in transect B (5m depth) are presented in Figure 5.14. In February, the river water which is 1°C warmer than sea water disperses in the direction of the wind. In July, the river water which is 0.5°C warmer than the sea, is distributed windward. In November the distribution of

river water, which is colder than the sea, is dispersed toward the west in the direction of the dominant wind which is parallel to the coast.

Vertical variation of temperature in transect C (10m depth) is provided in Figure 5.15. River water, which is 1 °C warmer than sea water, spreads on the surface in the direction of the wind in February. In this season, the river discharge is high, and the temperature of the river water is correspondingly dispersed over a relatively larger area. In July, it is observed that the river water, which is 0.5 °C warmer than the sea, spreads in the opposite direction of the wind direction in transect C, which is the deepest parallel section of the field study. In November, with a slightly stronger river flow than that in July, the river water, which is cooler than the seawater, spreads entirely on the surface.

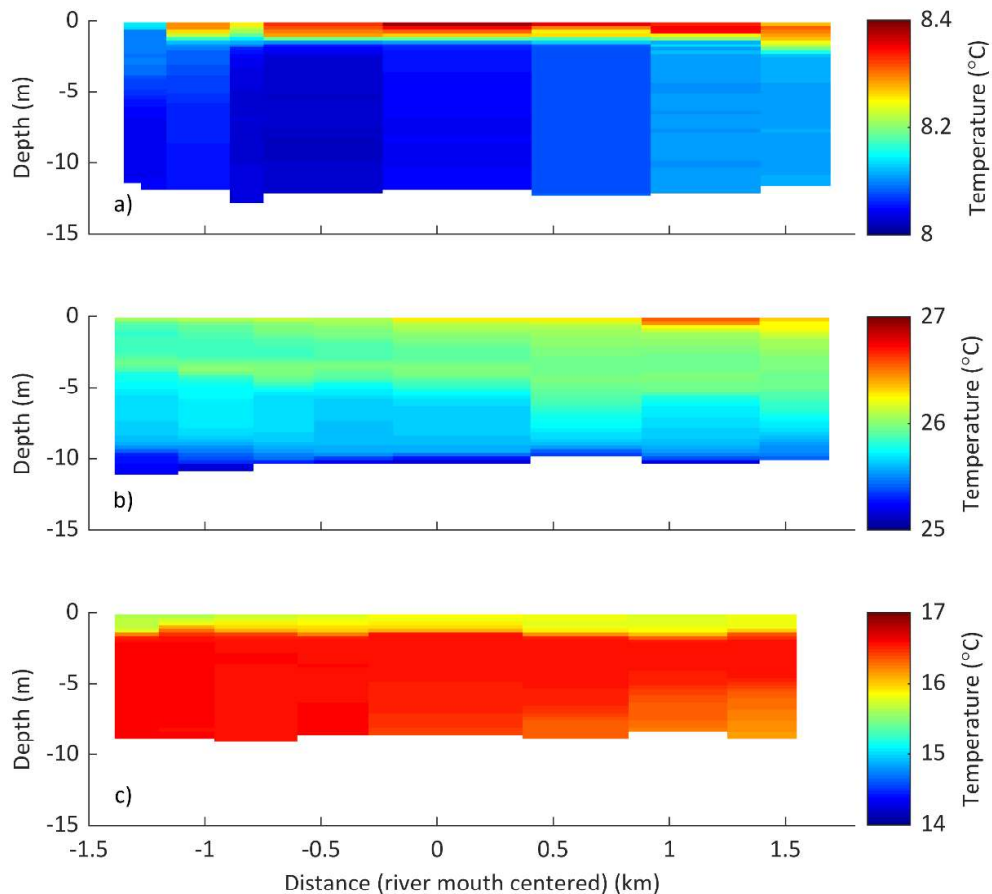


Figure 5.15 Temperature profiles along transect C.
a) February, b) July and c) November

5.4.3 SSC Profiles

In field studies, significant seasonal fluctuations in SSC were recorded due to the seasonal variation in the suspended sediment discharge of the Sakarya River (Figures 5.16-18). In February, the suspended material brought by the river has dispersed up to 2 kilometers from the river mouth likewise the salinity and temperature, and as the distance from the river mouth increases, the concentration of suspended material reduces. The amount of suspended material entering the sea from the river mouth exceeds 0.16 g/L. Due to low flow rates, this value drops below 0.05 g/L and 0.075 g/L in July and November, respectively. Besides, suspended solids can only travel 200 meters from the river mouth in July, sediments can travel up to 750 meters in November with a slightly higher flow rate.

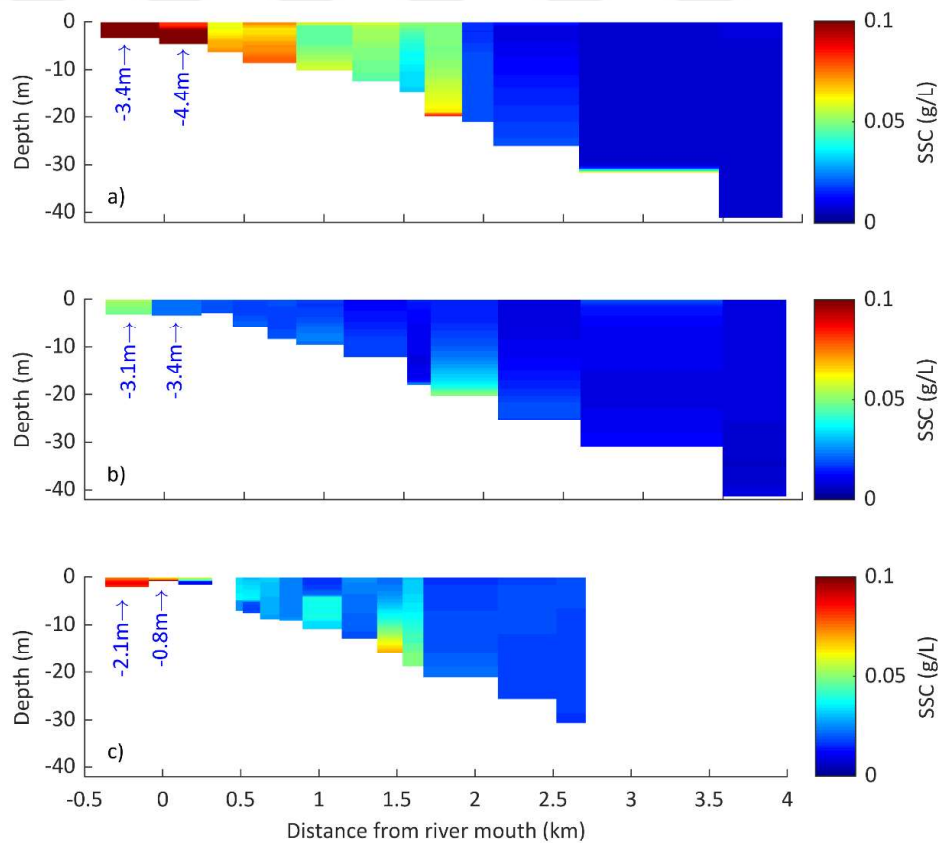


Figure 5.16 SSC profiles along transect A. a) February, b) July and c) November

The vertical variations of suspended sediment concentration in transect B (5m depth) are given in Figure 5.17a-c. The sediment concentration carried by the high river discharge in February is dispersed in the wind direction. In July, because of

the low flow rate and amount of sediment material carried by the river, the dispersion of sediment concentration is relatively modest. In November, compared to July, the slightly higher flow rate and amount of suspended sediment material carried by the river spread weakly in the dominant wind direction parallel to the coast. The suspended sediment material at several stations could not be shown due to data loss in the turbidity sensor and lack of good quality data.

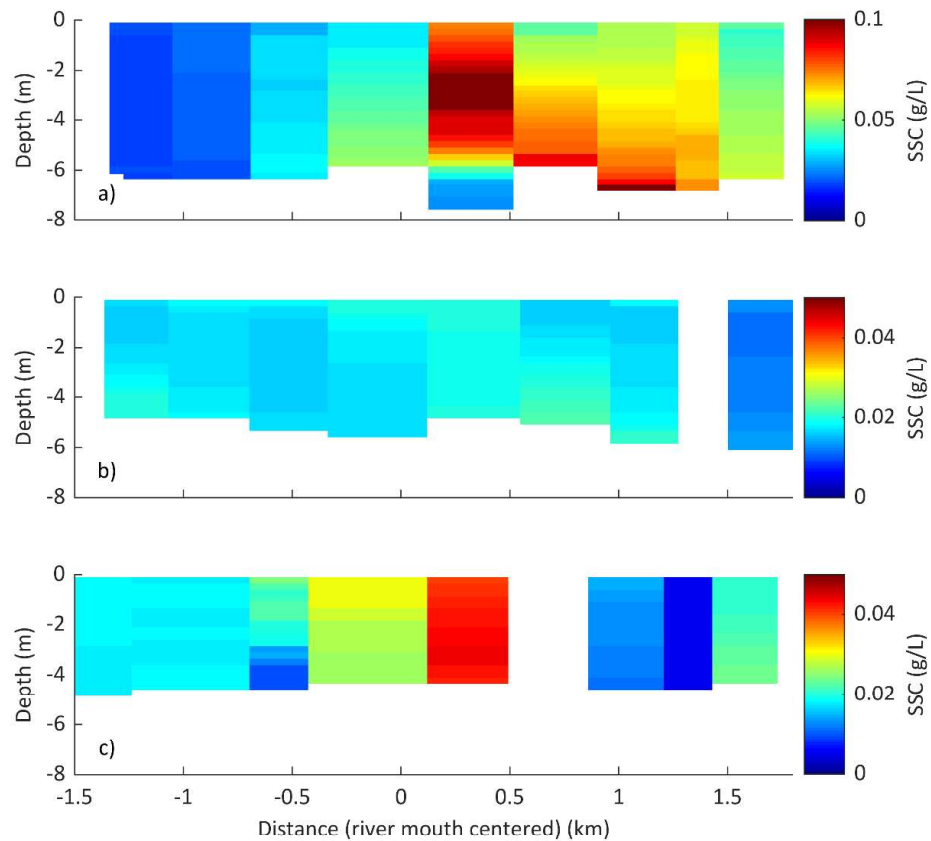


Figure 5.17 SSC profiles along transect B. a) February, b) July and c) November

Suspended solids change graphs in transect C (10m depth) are shown in Figure 5.18a-c. In February, it is seen that the highest suspended concentration is on the surface with 0.7 g/L which is carried by the river flow up to the location of transect C. In July, due to the low flow rate of the river and the amount of suspended solid transported by the river, the presence of material and spread of concentration is highly limited, just as observed in transect B. In November, the river's solid matter is determined to be transported in the dominant wind direction towards the west, parallel to the coast. The solids concentrations of several stations in transect C could not be shown due to data loss in the turbidity sensor.

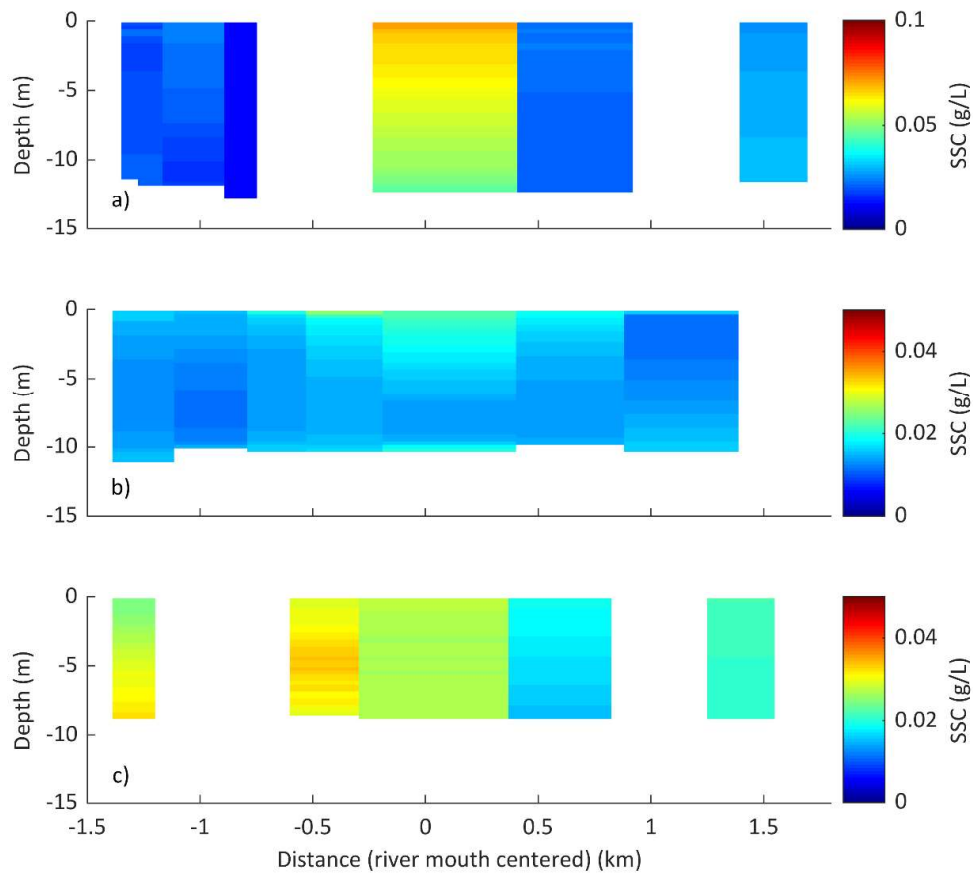


Figure 5.18 SSC profiles along transect C. a) February, b) July and c) November

5.5 Hydrodynamics

The wind conditions, river flow and sediment discharge, measurements of significant wave height, current speed and direction, and SSC profiles at the station around 15 m water depth in July are summarized in Figure 5.19. In July, wind statistics from the closest available ECMWF wind data to the river mouth are shown in Figure 5.19a. The wind directions are mainly around 250° (SSW), with average wind speeds of 4 m/s. The in-river water and sediment flow rates at the dates of the field study are shown in Figure 5.19b. The river flow is around $50 \text{ m}^3/\text{s}$ generally, and it reaches $100 \text{ m}^3/\text{s}$ on the first day for 2 hours and in the last 40 hours of field study. While the SSC values are usually less than 0.1 g/L , it rises above 0.15 g/L for 12 hours on the first day and the last 48 hours of field study. In comparison to earlier days of the field study, the flowrate and suspended sediment concentration are higher in the last 48 hours of the study.

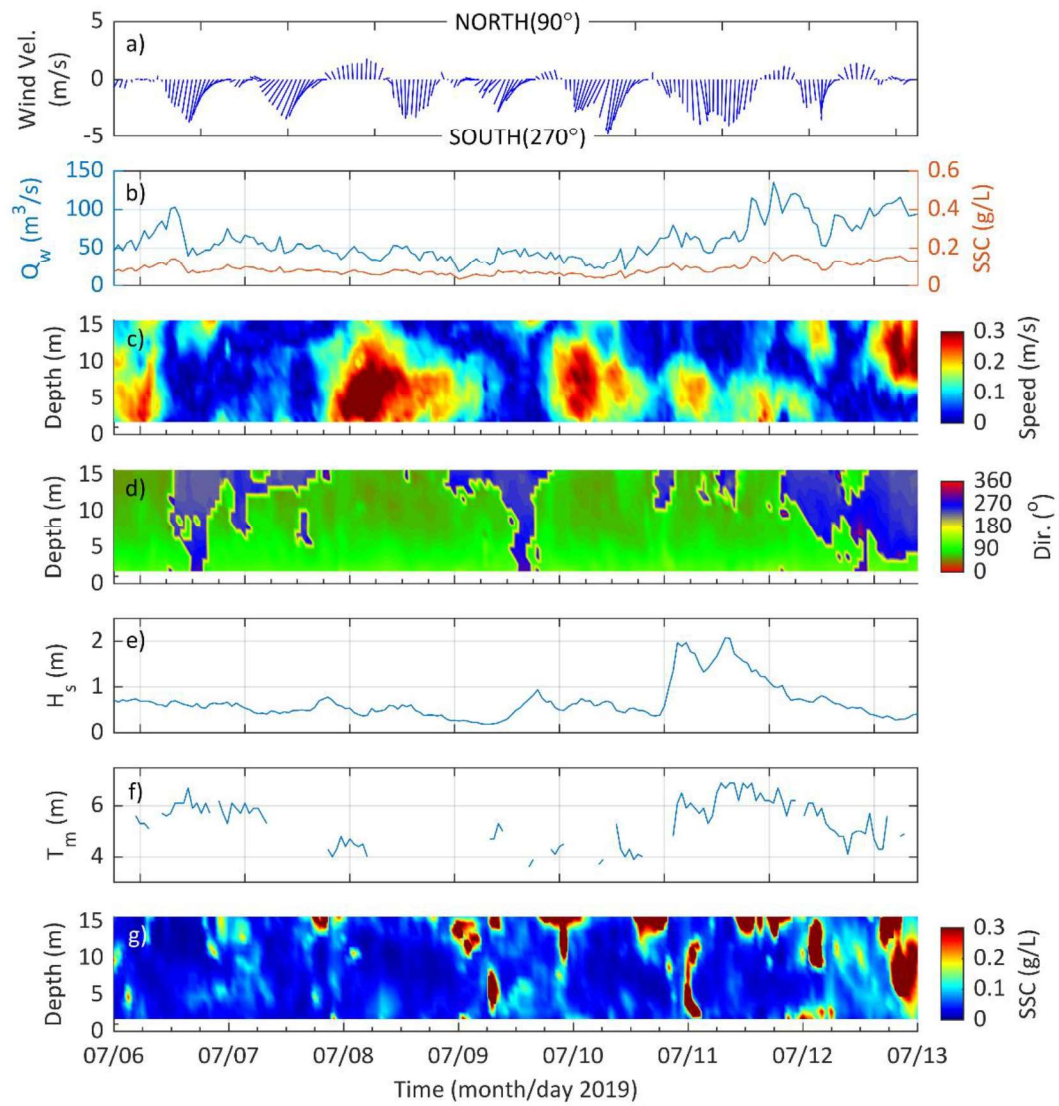


Figure 5.19 Hydrodynamics of delta between 6-13 July, 2019. a) wind velocity from ECMWF data, b) river water and sediment discharge, c) water flow speed from ADCP d) water flow direction from ADCP, e) Significant wave height, f) Wave period and g) Suspended sediment concentration

In Figure 5.19c and d, wave and current profiles are presented that were measured by an ADCP deployed on the seabed facing upwards at a water depth of approximately 15 m. When the current profiles are examined, it can be noted that the current speed occasionally exceeds 0.3 m/s. On July 8, the current velocity reached 0.3 m/s and did not drop below 0.2 m/s for about 24 hours within the first 10 m depth from the seabed (Figure 5.19c). When the directions of currents exceeding 0.3 m/s are examined, the current direction is roughly 70° (NNE) between the 6th and 12th of July, however, after July 12, the current direction is nearly 250° (SSW). In the measurements in July, it is seen that the significant wave

height was around 0.55m on average until July 11, but thereafter suddenly increased to 2m and did not fall below 1m for about 24 hours (Figure 5.19e). Correspondingly, after the 11th of July, the average wave period rose to around 7 seconds (Figure 5.19f). The suspended sediment concentration data obtained by calibration of acoustic backscatter acquired by the ADCP are provided in Figure 5.19g. Throughout the measurement, the amount of suspended sediment material occasionally rises above 0.2 g/L, and generally, it is below 0.1 g/L. The suspended sediment concentration rises over 0.1 g/L around 4 hours after the flow velocity (Figure 5.19c) rises above 0.2 m/s.

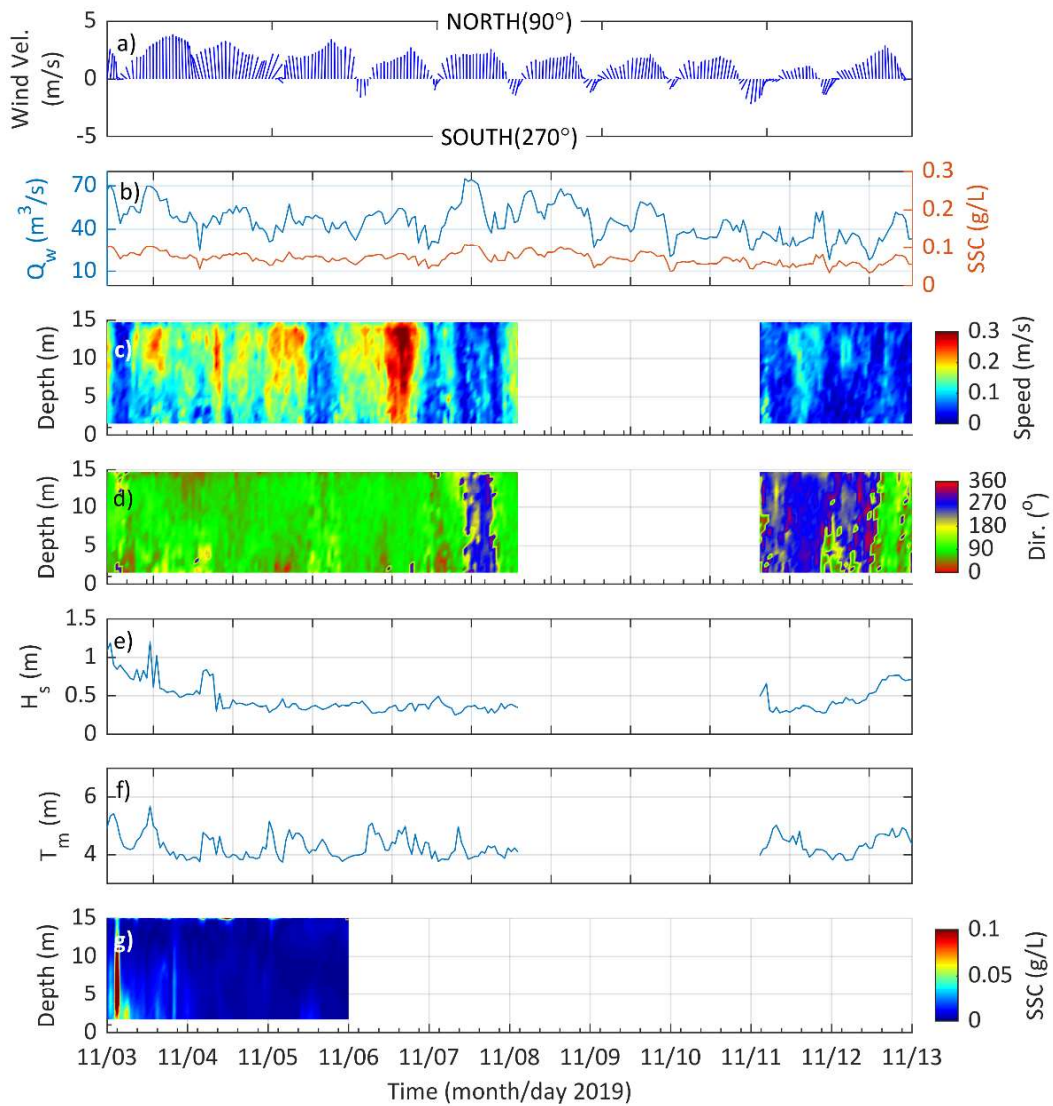


Figure 5.20 Hydrodynamics of delta between 3-13 November, 2019. a) Wind velocities, b) River water and sediment discharge, c) water flow speed from ADCP d) water flow direction from ADCP, e) Significant wave height, f) Wave period and g) Suspended sediment concentration

The hydrodynamic activities in November are represented in Figure 5.20. According to wind data from the ECMWF nearest to the river mouth in November, wind directions are mainly in the North direction (90°). An average wind speed of 4m/s on the first day decreases to an average of 1 m/s until the last day and continues to blow in the same direction (Figure 5.20a). The in-river water and sediment flow rates along the fieldwork dates are shown in Figure 5.20b. The river flow rate surged to 70 m³/s on the first day of the field study, then dropped to 50 m³/s on average until November 7th.

The suspended sediment concentration is mainly around 0.05 g/L, occasionally reaching 0.1 g/L. Current velocity profiles in Figure 5.20c show that current velocities have been above 0.1 m/s for the first 4 days and sometimes have even exceeded 0.3 m/s. The current velocity is often less than 0.1 m/s after the first 4 days. On November 6, the current velocity reached 0.3 m/s and remained above 0.2 m/s for approximately 8 hours throughout the entire water column. In Figure 5.20d, the current direction is roughly 75° (NNE) when current velocities are greater than 0.15 m/s. However, when current velocities are less than 0.1 m/s, the current direction changes 180 degrees and becomes 255° (SSW). Due to data loss in the Flowquest ADCP device between November 8 and 11, the current speed and direction data cannot be presented. The significant wave height was above 0.5 m in November measurements until November 4th, after which it remained below 0.5 m until the last 12 hours of fieldwork when it rose over 0.5m again (Figure 5.20e).

Throughout the field measurements, the average wave period stayed over 4s and occasionally approached 5s (Figure 5.20f). Although the suspended sediment concentration remained below 0.025 g/L throughout the measurement period, it was above 0.1 g/L along a 12 m water column from the bottom for 2 hours in the first hours of data collection. Suspended sediment concentration data cannot be presented after November 6 due to data loss in the AquaPro ADCP (from Nortek) instrument.

Figure 5.21 presents the comparison between the wave data obtained from two different ADCPs (Flowquest ADCP and Nortek ADCP). Since the NORTEK ADCP provided pressure data at a 2Hz frequency, we were able to perform spectral

analysis and separate wind waves (seas) and swells. Total wave data from the Flowquest ADCP, and sea and swell heights estimated from the Nortek ADCP water surface elevation data, are shown in Figure 5.21. The energy of the swell wave is low on the spectrum, therefore it has little effect on the total wave height for the measurement duration. Due to data loss after November 5 of the Nortek ADCP and between November 8 and 11 of the Flowquest ADCP, the wave parameters cannot be shown. However, the correlation between wave data from the two instruments can be observed during the first two days of field measurements.

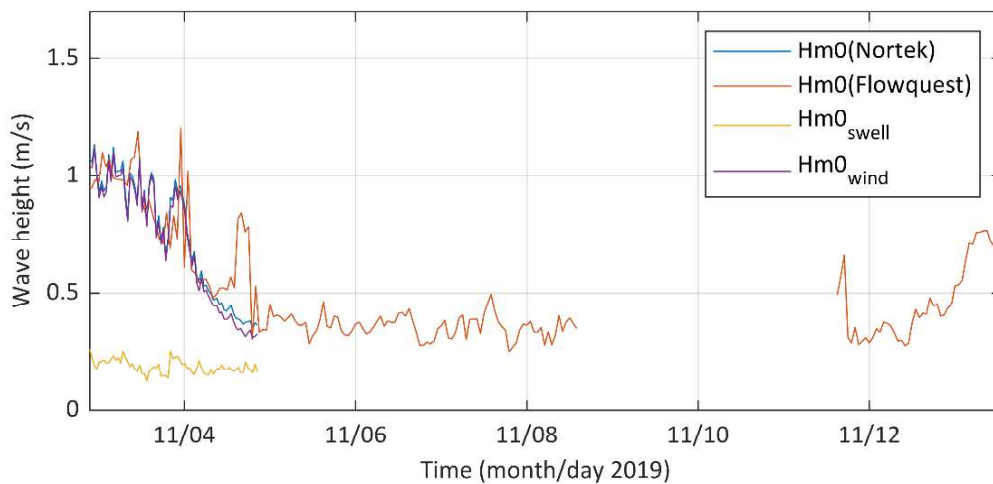


Figure 5.21 Wave height from Nortek and Flowquest devices, November

5.6 Morphodynamics

5.6.1 River Mouth

The morphology of the river mouth shows significant seasonal variability as seen in satellite pictures of the field study dates (Figure 5.22). In February with the highest flow rates (Figure 5.5b) among the measurement seasons, the river mouth section has a 100 m width (Figure 5.22a) and 4.4m depth (Figure 5.10a). As a result of continuously decreasing discharge after February, the width of the mouth decreased to 70 m (Figure 5.22b) with a 3.4 m depth (Figure 5.10b) during the measurements in July. Among the three field campaigns, the lowest discharges occurred in November with calm river conditions within the previous 3 months (Figure 5.5b). This caused the accumulation of sand (Figure 5.25) at the mouth of

the river, and the river mouth became the narrowest in field campaigns with a 20 m width (Figure 5.22c) and 0.8m depth (Figure 5.10c).

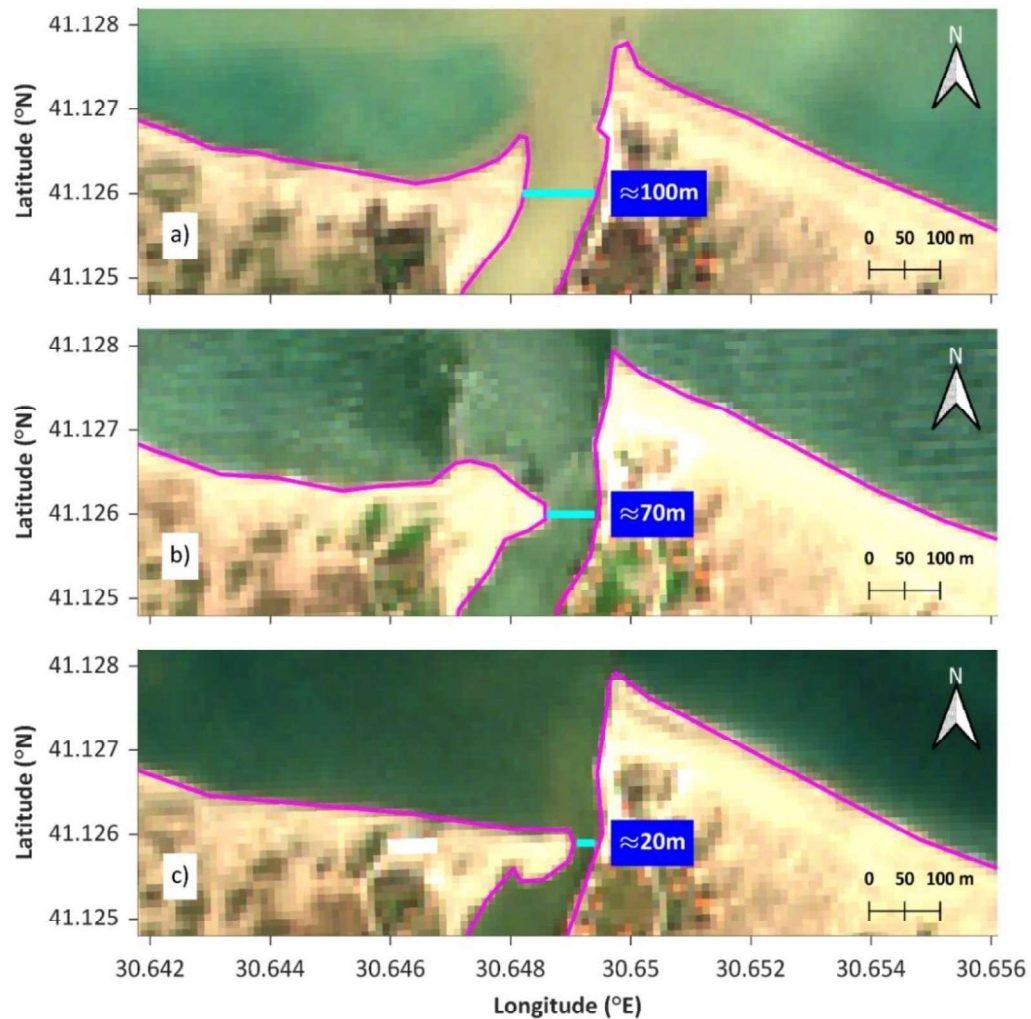


Figure 5.22 River mouth changes. a) February, b) July, c) November

The narrowing of the river mouth and the decrease in depth are clearly visible in photos captured during the field measurements in addition to satellite imagery. Figures 5.23-5.25 show the river mouth's situation during the measurements in February, July, and November. After February, it is noticed that sediments were transported from west to east along the coast, and with the low discharges, the sediment could not reach the sea and accumulated in the river mouth, causing the river mouth to get narrower. In November, the width of the river mouth was down to about 20 meters and its depth was around 0.8 meters, making it difficult for boats to enter and exit the river (Figure 5.25).

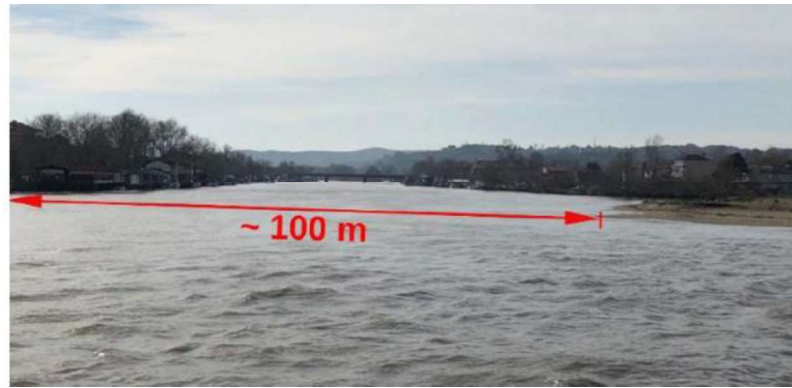


Figure 5.23 River mouth from the vessel, February



Figure 5.24 River mouth from the vessel, July

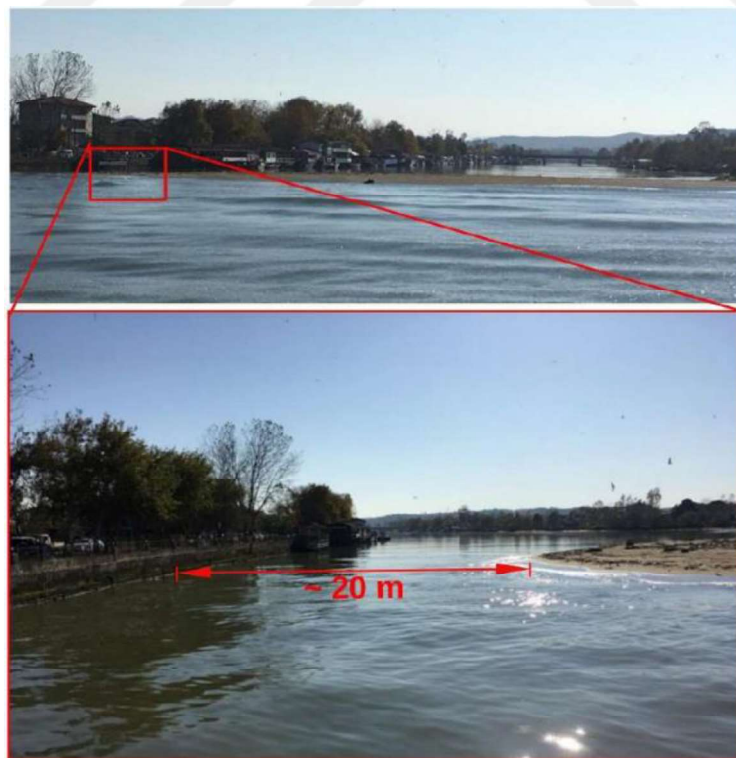


Figure 5.25 River mouth from the vessel, November

5.7 River Section

Bathymetric measurements were performed to examine the change in the river section at a specified location 400 meters behind the river mouth in February, July, and November (Figure 5.26). The largest river cross-sectional area occurred in February due to a strong current impact that moved the bed sediment to the sea, while the smallest cross-sectional area occurred in November due to relatively weak currents. Based on the cross-sectional areas, the suspended sediments settled and accumulated on the riverbed after February due to decreasing river discharge and carrying capacity. As a result, the cross-sectional area of the river section decreased by 24% until July. Between July and November, it was observed that the accumulation of the sediment on the bed became slower, and therefore the cross-section of the river did not change significantly. The total decrease in the cross-sectional area of the river section was 31% between February and November.

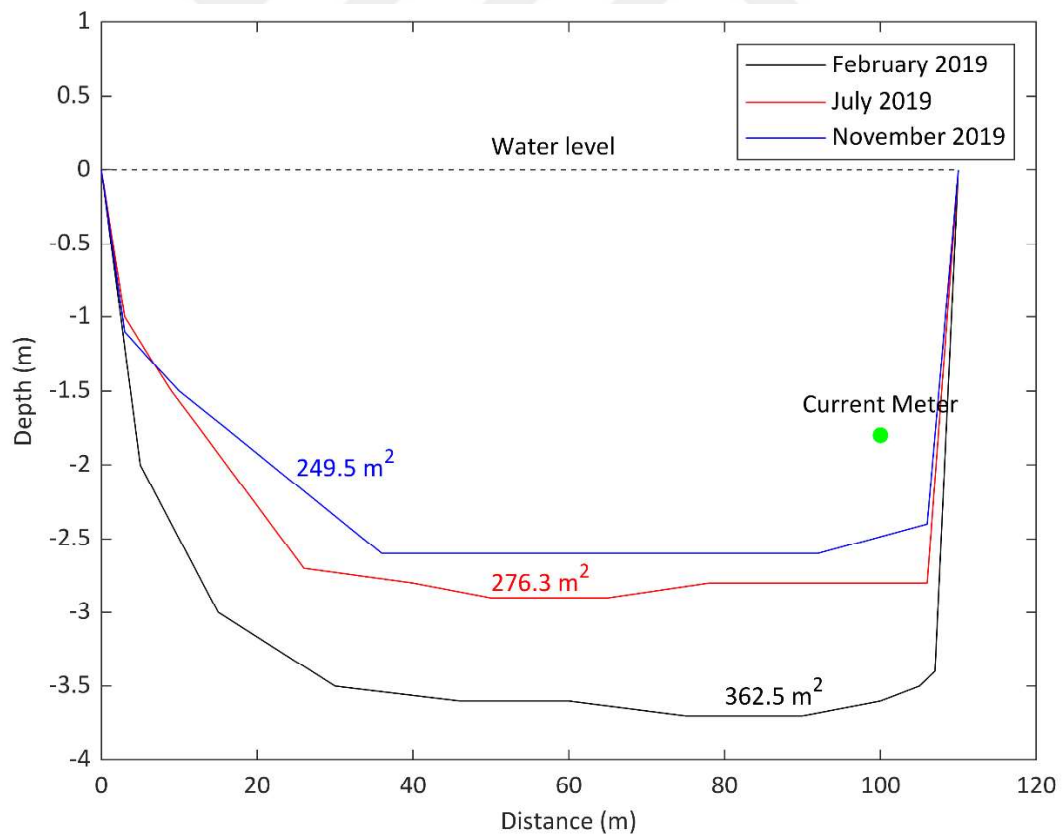


Figure 5.26 Sakarya river sections at a particular station approximately 400m distance from the river mouth

5.7.1 Seasonal Seabed Changes

Figure 5.27 shows the bathymetric measurements made up to a depth of 50 meters in the sea and topographic measurements made up to 50 meters behind the shore to observe seasonal changes. The locations of the bathymetric profile measurements can be seen in Figure 3.9. It is obvious that the seasonal variation of the bathymetry decreases as the depth increases at all the profiles (P1 at the east of the river mouth and P2, P3, P4, P5, and P6 from the west of the river mouth). When the sea floor is investigated in more detail, it is seen that seasonal variations have an effect up to 500 meters from the shoreline, corresponding to up to 10 meters depth in the water.

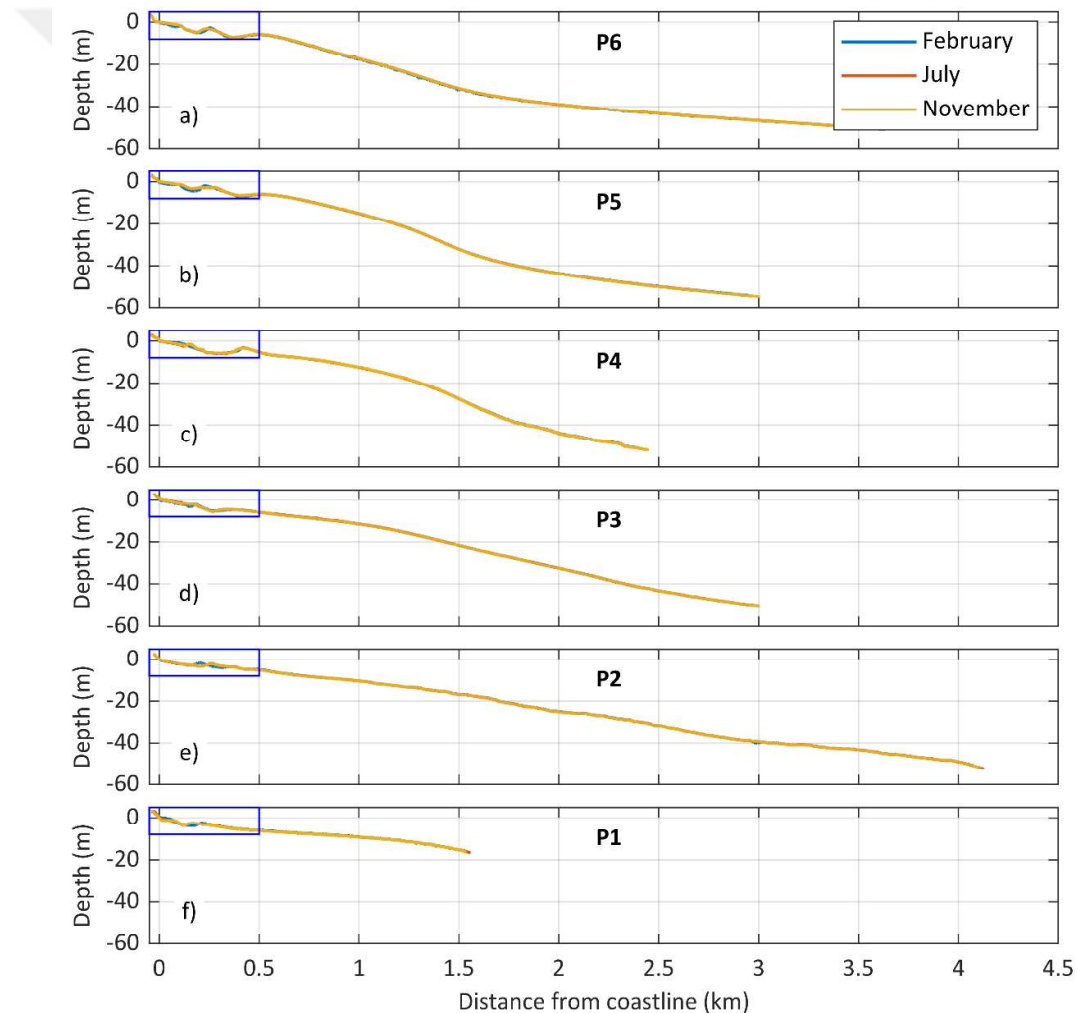


Figure 5.27 Seabed level changes from coastline to 4.5km

Morphological variations between P1 in the east of the river mouth and P2 which is the first measurement profile in the west indicate that the western part of the

river is more dynamic than the eastern part (Figure 5.28e and f). The sand dune in the west of the river, which is observed at a distance of about 200 meters from the beach in February, is transported 75 meters further away in July and formed at a distance of about 275 meters from the shoreline (Figure 5.28e). The sand dune, which is seen on the sea bottom in the east of the river at about 225 meters in February, is transported to the shore by 50 meters in July and is about 175 meters away from the shoreline (Figure 5.28f).

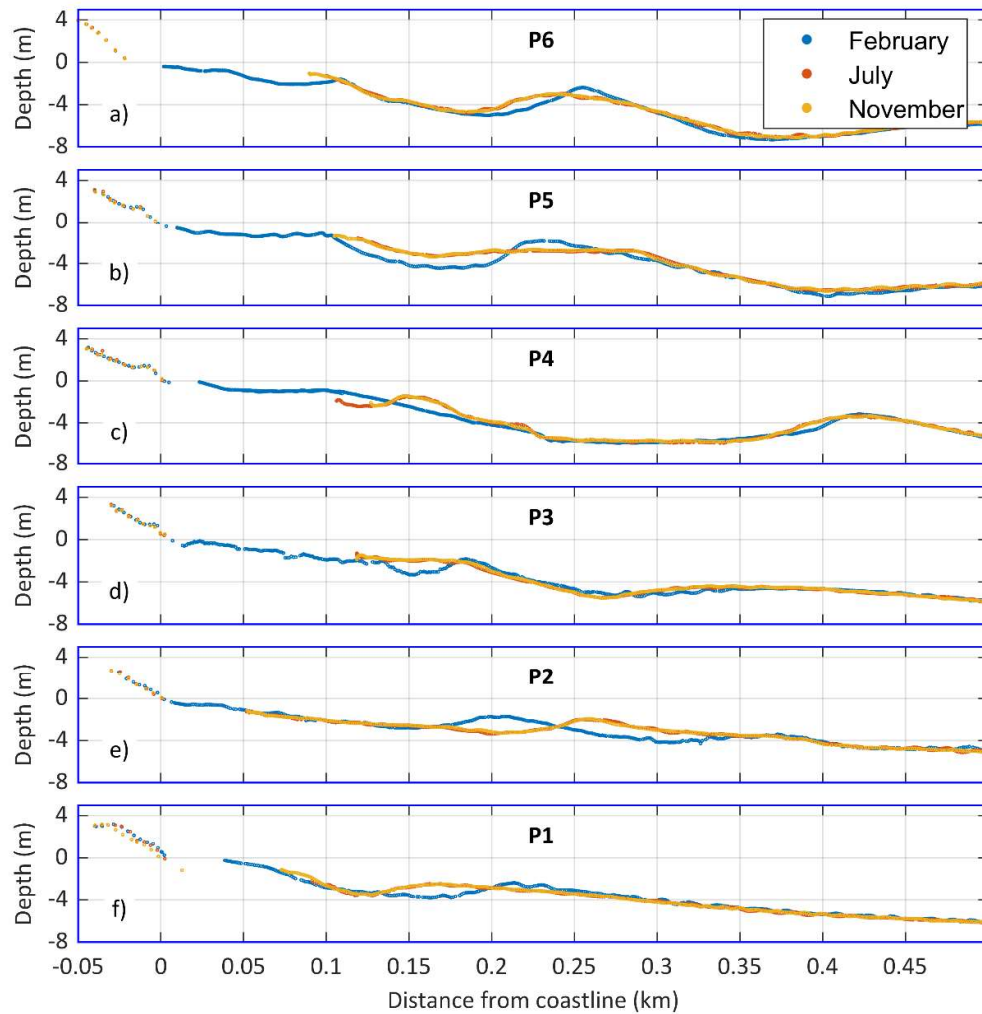


Figure 5.28 Seabed level changes from coastline to 500m

Towards further west from the river mouth, it is observed that it is less dynamic and undergoes fewer changes (Figure 5.28a-d). In Figure 5.26, the cross-shore section of the river shows that between July and November, the sea floor reflects no recognizable change (Figure 5.28).

5.7.2 Seasonal Bottom Sediment Material Change

The gradation curves of the bottom sediment material collected from the specified stations in February, July and November are shown in Figure 5.29. In February, the gradation curve indicates that about 95% of the sediment material inside the river is larger than 75 μm (sand). In July, inversely, around 95% of the material is smaller than 75 μm (silt and clay). In November, it is seen that the ratio of fine and coarse materials is almost the same. The median diameter (D_{50}) of the material at the bottom of the river was determined to be 556 μm , 4 μm and 74 μm in February, July and November, respectively.

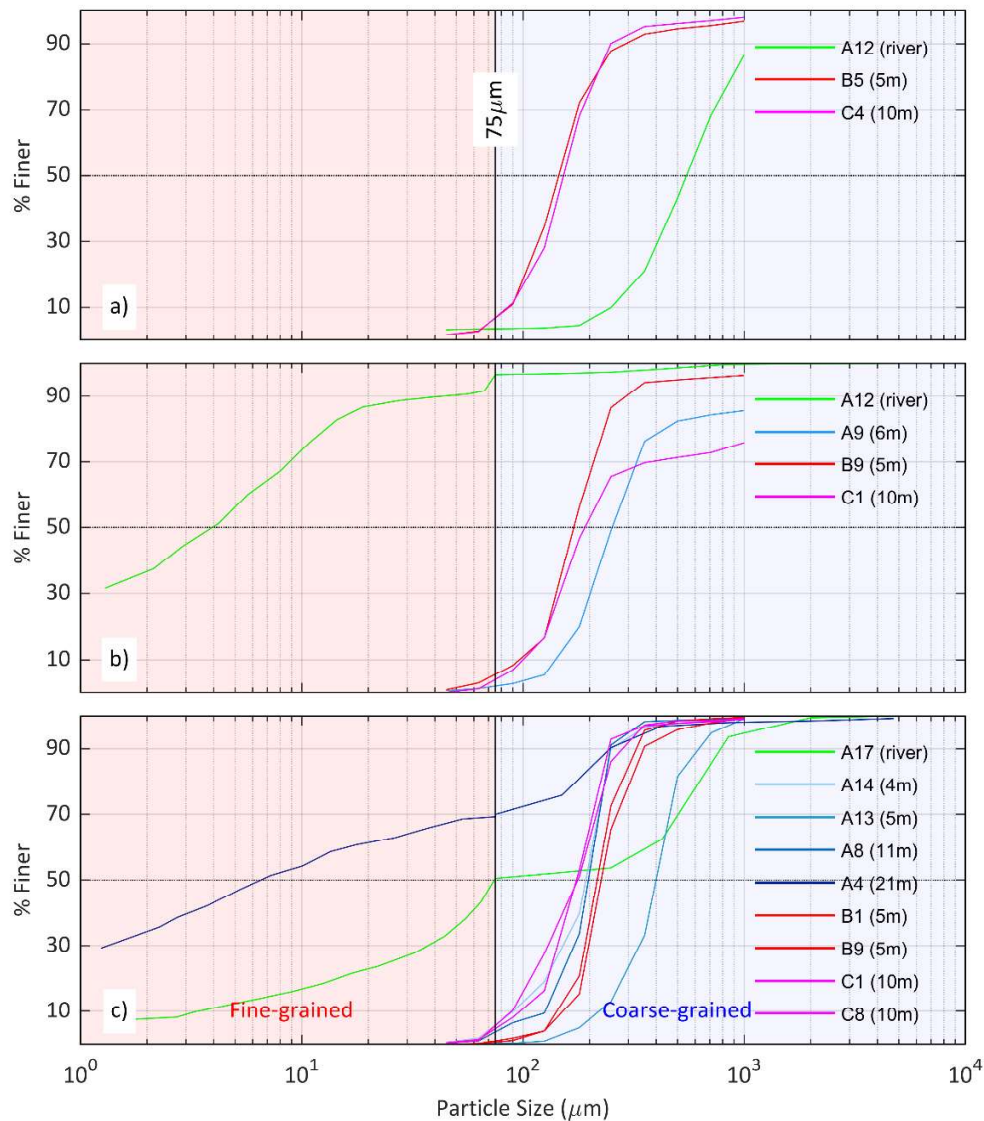


Figure 5.29 Sediment gradation curves. a) February, b) July, c) November

For the sea bottom samples, the sediment gradation curves obtained in February at different locations are nearly identical with D_{50} values of around $150\ \mu\text{m}$ (Figure 5.30). In July, the sediment material becomes coarser around the river mouth than in the other locations, with D_{50} values averaging $205\ \mu\text{m}$. It has been observed that the solid material in February is finer than the material taken in July. In November, a seaward fining of the bed material is observed, reaching an average of $216\ \mu\text{m}$ (except for the A4 station at 21m depth). The solid material obtained from station A4 in November at a depth of 21 meters is very fine with a D_{50} value of $7\ \mu\text{m}$.

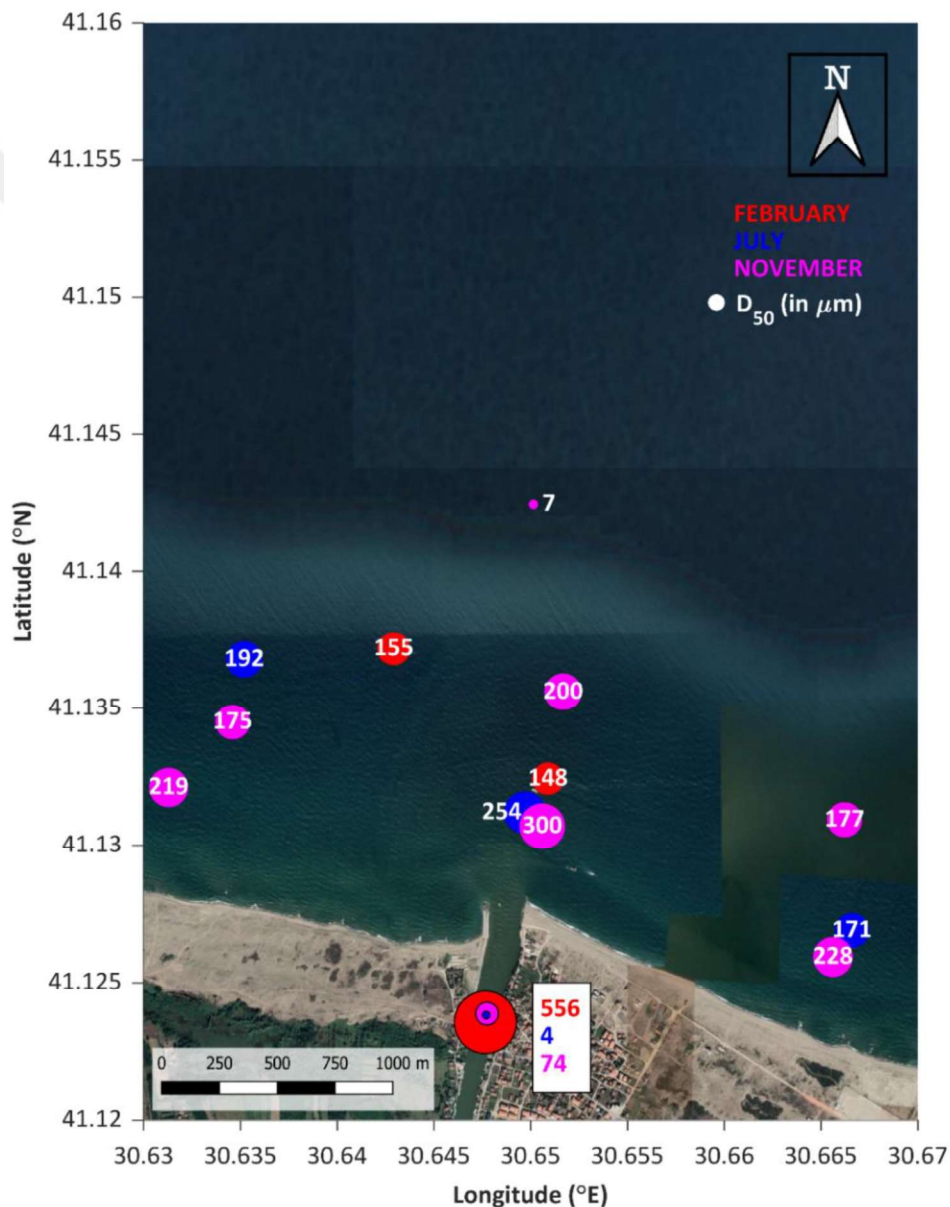


Figure 5.30 D_{50} data of sediment sampled stations

The bottom sediment samples taken in the river section in different field campaigns indicate significant variation in the cross-sectional area and the sediment properties. The data indicate that seasonal differences in the amount of water and solids carried by the river are responsible for the variations in sediment properties collected in the river during different seasons. The weekly average flow rates during measurements are 234 m³/s in February, 74 m³/s in July, and 81 m³/s in November, as shown in Figure 5.5b. The average velocities in the river section when the cross-sectional areas are measured in Figure 5.26 are 0.65 m/s in February, 0.27 m/s in July, and 0.32 m/s in November. In February, high bottom shear stresses induced by high stream velocities erode the river bottom material (Figure 6.1), and therefore the depth increases (Figure 5.10a). In this season, the resuspended material due to erosion is transported into the sea until the river bottom is composed of coarser material which is more resistant to erosion (Figure 5.30). In summer and autumn, the carrying capacity of the river decreases due to decreasing river discharge and stream velocity, and therefore suspended fine material settles and depth decreases (Figure 5.26). The riverbed is composed of cohesive fine material during these seasons (Figures 5.29 and 5.30).

Further, short-term flow variations, such as one-week period, might cause changes in the gradation curves of materials from the river. Although the river discharges from July to November cause a slight change in the river section (Figure 5.26), the same flow rates did not modify the sea morphology in November, as seen in Figure 5.28 in the marine environment, the variability in the characteristics of the bottom sediment material is low, particularly in locations far from the river mouth with high water depth.

The observations during the field experiments and the satellite images taken in different seasons suggest a significant narrowing (around 80 m) of the river mouth in 9 months from February to November. During the field studies, it was learned

during the interviews with the local people that the closure of the river mouth was prevented by regular dredging in this region. Our field observations suggest that the study site would require a significant amount of dredging for longer periods.



Figure 6.1 The view of the Sakarya River mouth and the carried fine material during the fieldwork in February

In order to estimate the amount of long-term sand accumulation in the Sakarya River mouth, Şahin et al. (2021) conducted numerical simulations with a one-line shoreline evolution model LITLINE (DHI, 2008). They forced the model with the winds from the ECMWF database, numerically simulated waves, and defined the river discharge measurements obtained from DSI as a source. As a result of the study, it was concluded that the study area is a significantly active coast with an average annual net longitudinal sediment transport of 70000 m³/year. The direction of the transport has been observed to be from west-northwest (WNW) (upstream) to east-southeast (ESE) (downstream) (from the left shore to the right shore). Additionally, according to the model results (Figure 6.2) during the period between 1980 and 2018, the yearly average maximum sedimentation was +4.2 m, and based on field observations, it was determined that the largest accumulation occurred just west of the river mouth.

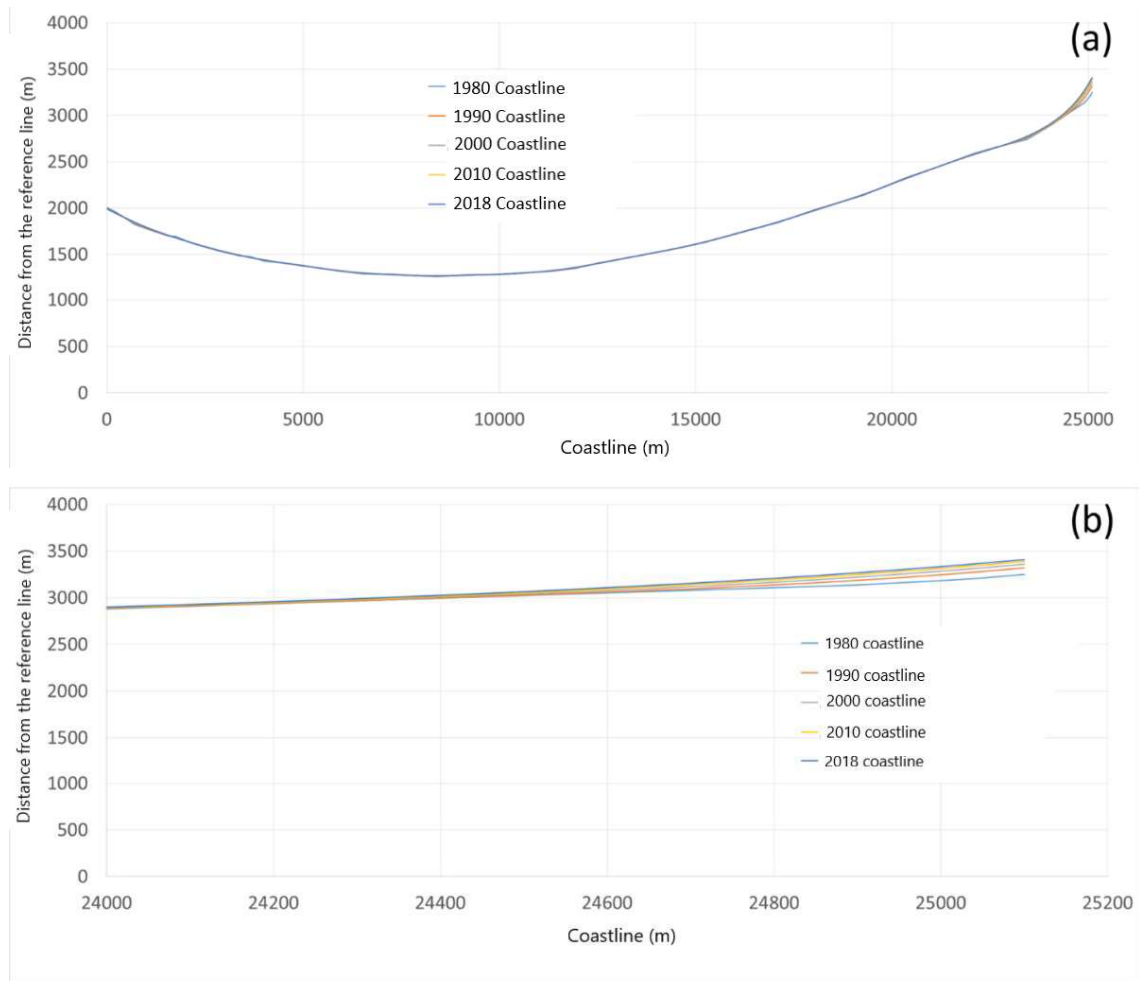


Figure 6.2 Coastline changes expected to occur between 1980 and 2018 according to the results of the numerical model a) The entire coast b) close-up view just west of the river mouth (Sahin et al., 2021)

Şahin et al. (2021) stated that the 25 km length of the shoreline, which also includes the Acarlar deep spot, did not experience any significant long-term (38 years) alteration according to the numerical model results. In the field study carried out in November 2019, preparations for construction of a jetty were observed on the west bank of the river mouth in order to prevent this solid material accumulation. The constructed jetty can be seen in up-to-date satellite images (Figure 6.3). After the Jetty was constructed, the river mouth was roughly 150 meters wide.



Figure 6.3 Google Earth image of the river mouth (June 2021)

Future studies should focus on the possible impact of the newly constructed groin on the future sediment transport dynamics of the coast, especially in the region that protects the Acarlar deep spot.

Delta areas being lowland regions where the water and sediment material delivered by the river flow into the sea, are highly dynamic regions in terms of salinity, temperature and sediment content and many other parameters. By altering the dynamics of water and solids, the engineering projects constructed in these areas have a severe impact on these natural ecosystems. In addition, natural disasters caused by climate change, the impact of which is gradually increasing, also cause sudden and destructive effects in delta and estuary regions.

The Sakarya River Delta, which is a vulnerable region to the effects of climate change by its nature, is home to large beaches, fossilized coastal dunes, and the Acarlar Floodplain, the biggest single-piece floodplain in the world. The Karasu shores currently experience 7.5 m of annual coastal erosion, however, it is anticipated that erosion in the area would worsen owing to potential climate change consequences.

Sediment dynamics and hydrodynamic behavior studies of delta and estuary regions help to examine the change in the morphodynamic structure of these regions over time. Examination of the sediment dynamics in these regions with field studies forms a basis for model studies that will reveal the effects of infrastructure projects and climate change within the framework of various scenarios. Understanding the relationship between hydrodynamic conditions, suspended sediment dynamics, base material transport and their seasonal is important for determining conservation measures in these sensitive areas.

In this study, the seasonal variability of hydrodynamics and sediment dynamics in the Sakarya river delta were examined with field studies in the summer, winter and autumn seasons (February, July and November 2019). Data from DSI shows that before the dams were built in the past, the river water and sediment discharges were 6.17×10^9 m³/year and 4.6×10^6 t/year, respectively. However, in

the last 20 years, these flow rates have decreased to $4.40 \times 10^9 \text{ m}^3/\text{year}$ and $1.15 \times 10^6 \text{ t/year}$. While the region is protected from floods by the constructed dams, the sediment flow rate was reduced by three-fourths as a result. Delta shores are severely eroding as a result of this drastic reduction in sediment flow rate.

The water and sediment discharges over the previous 20 years are $139.4 \text{ m}^3/\text{s}$ and 3268 tons/day, respectively. Between February 1-6, July 5-13, and November 2-13, when the field studies were conducted, the water discharge was $242.5 \text{ m}^3/\text{s}$, $60.4 \text{ m}^3/\text{s}$, and $46.2 \text{ m}^3/\text{s}$, while the sediment discharge was 6282.4 tons/day, 515.6 tons/day, and 292.5 tons/day, respectively. During winter, river water and sediments can travel for long distances into the sea with the high flow rates of the river. Due to the relatively lower river discharge in summer and autumn, the impact area of river waters in the sea decreases. In February, the river's fresh water is effective up to 1.5 km from its mouth, however, in July and November, this distance drops to 500 meters.

Sea water temperatures in February, July, and November are 8°C , 26.4°C and 17°C , respectively. The fresh water in the river has been recorded warmer than the seawater in February and colder than the seawater in November. In July, there are no major temperature changes between freshwater in the river and saltwater in the sea. Due to the high sediment discharge in February, the suspended sediment concentration (SSC) in the river mouth was at most 0.16 gr/L , whereas in July and November, when sediment discharge is reduced, the SSC drops below 0.05 gr/L .

According to the sediment rating curve, there is a strong relation between river water flow and sediment flow which obey the $Q_s = 0.2652Q_w^{1.8278}$ equation. The river flow, which was $60 \text{ m}^3/\text{s}$ on average in July, occasionally reached $100 \text{ m}^3/\text{s}$ in the ADCP records dates, hence, the suspended sediment concentration which was below 0.05 g/L , surged to 0.18 g/L with this relatively high river flow. In November, the river water discharge which has an average of $46 \text{ m}^3/\text{s}$, increased to $65 \text{ m}^3/\text{s}$ from time to time. As a result, this relatively high river discharge increased the SSC to 0.08 gr/L , which was below 0.05 gr/L . The maximum current speeds in the water column at the ADCP stations in July and November are 0.3 m/s ,

and the current directions induced by the river flow generally coincide with the local wind directions.

A correlation study was performed between the bottom sediment material from certain stations and the turbidity data of the same stations, and the equation of $SSC = 0.0107(NTU)^{0.3817}$ was obtained for turbidity sensor calibration. Furthermore, the calibration parameter, k_t'' , was iterated to determine the concentration of suspended particles by using the acoustic backscatter intensity data collected from the ADCP device. The calibration parameters, which offer the minimum errors, were found to be 3.098×10^{17} for July, and 8.829×10^{18} for November.

Using the pressure data obtained from the ADCP device, frequency spectrum analysis was performed. In the analysis, water surface profiles were obtained by using the pressure data, and the spectrums of the profiles with certain time intervals were calculated by the FFT method. The requisite moment calculations were done on the obtained spectrums, and the significant wave heights and average wave periods of each spectrum were determined.

In February, July, and November seasonal surveys were conducted to determine the river cross-sections at the station 400 meters behind the river mouth. The river cross-section at this station expanded to 363 m^2 as a result of the eroded base material due to the high flow rate in February. The cross-section gradually narrowed due to the weak river discharges in July and November that were insufficient to move the base material and unable to prevent sediment accumulation. The river cross-section at this station was 276 m^2 in July and 250 m^2 in November. While the high flow rate in February widened the river mouth by about 100 m, this width decreased to 70 m in July and 20 m in November.

In cross shore seabed level measurements, there is no seasonal difference in measurements 500 m further from the shore, while seasonal variations are generally within the first 500 m from the shore or up to a depth of 10 meters. Additionally, the western part of the river mouth is more dynamic than the eastern part. The sand dune, which is formed on the sea bottom in the east of the river mouth at about 225 meters in February, comes closer to the shore by 50 meters in

July and stands at a distance of about 175 meters. The sand dune in the west of the river mouth, which is formed at a distance of roughly 200 meters from the shore in February, is transported 75 meters further away in July and forms at a distance of around 275 meters from the shoreline. While there are significant seabed level changes between the summer and autumn or winter, a remarkable difference is not observed between the summer and autumn seasons.

In February, the majority (roughly 95%) of the sediment sample from the river bed is coarser than 75 μm (sand). In July, on the other hand, approximately 95% of the material is finer than 75 μm (silt and clay). The amount of fine and coarse materials are nearly equal in November. The material at the bottom of the river had a median diameter (D_{50}) of 556 μm , 4 μm , and 74 μm in February, July, and November, respectively. On the sea bottom, sediment samples from various locations had nearly identical D_{50} values of about 150 μm in February. In July, while all D_{50} values are averaged around 205 μm , the sediment material becomes coarser at the river mouth. The sediment samples collected in July are coarser than it is in February. The base material gets finer toward the open sea in November, reaching an average D_{50} of 216 μm (except the station A4 at 21 m). The sediment sample that was extracted from the A4 station at a depth of 21 meters in November, is very fine, with a D_{50} value of 7 μm .

References

- Achete, F. *et al.* (2017) 'How can climate change and engineered water conveyance affect sediment dynamics in the San Francisco Bay-Delta system?', *Climatic Change*. Climatic Change, 142(3–4), pp. 375–389. doi: 10.1007/s10584-017-1954-8.
- Alpar, B. (2009) 'Vulnerability of Turkish coasts to accelerated sea-level rise', *Geomorphology*. Elsevier B.V., 107(1–2), pp. 58–63. doi: 10.1016/j.geomorph.2007.05.021.
- Arora, N., Kumar, A. and Kumar Singal, S. (2022) 'Technological advancement in measurements of suspended sediment and hydraulic turbine erosion', *Measurement: Journal of the International Measurement Confederation*. Elsevier Ltd, 190(December 2021), p. 110700. doi: 10.1016/j.measurement.2022.110700.
- Barrell, J. (1912) 'Criteria for the recognition of ancient delta deposits', *Geological Society of America Bulletin*, 23, pp. 377–446.
- Betteridge, K. F. E., Thorne, P. D. and Cooke, R. D. (2008) 'Calibrating multi-frequency acoustic backscatter systems for studying near-bed suspended sediment transport processes', *Continental Shelf Research*, 28(2), pp. 227–235. doi: 10.1016/j.csr.2007.07.007.
- Bhattacharya, P. J. (2006) 'Deltas', *Society for Sediment Geology*. Edited by H. W. Posamentier and R. G. Walker. SEPM Society for Sedimentary Geology, pp. 237–292. doi: <https://doi.org/10.2110/pec.06.84.0237>.
- Bi, N. *et al.* (2011) 'Seasonal variation of suspended-sediment transport through the southern Bohai Strait', *Estuarine, Coastal and Shelf Science*. Elsevier Ltd, 93(3), pp. 239–247. doi: 10.1016/j.ecss.2011.03.007.
- Bokuniewicz, H. (2005) 'Ingression, Regression, and Transgression', in Schwartz, M. L. (ed.) *Encyclopedia of Coastal Science*. Dordrecht: Springer Netherlands, pp. 564–565. doi: 10.1007/1-4020-3880-1_181.
- Bosboom, J. and Stive, M. J. F. (2022) *Coastal Dynamics*. 1.1. TU Delft Open.

- Boyd, R., Dalrymple, R. and Zaitlin, B. A. (1992) 'Classification of clastic coastal depositional environments', *Sedimentary Geology*, 80(3–4), pp. 139–150. doi: 10.1016/0037-0738(92)90037-R.
- Brocchini, M. *et al.* (2017) 'Comparison between the wintertime and summertime dynamics of the Misa River estuary', *Marine Geology*. Elsevier B.V., 385, pp. 27–40. doi: 10.1016/j.margeo.2016.12.005.
- Cattaneo, A. and Steel, R. J. (2003) 'Transgressive deposits: A review of their variability', *Earth-Science Reviews*, 62(3–4), pp. 187–228. doi: 10.1016/S0012-8252(02)00134-4.
- Cohen, J. E. and Small, C. (1998) 'Hypsographic demography: The distribution of human population by altitude', *Proceedings of the National Academy of Sciences of the United States of America*, 95(24), pp. 14009–14014. doi: 10.1073/pnas.95.24.14009.
- Dagg, M. *et al.* (2004) 'Transformation of dissolved and particulate materials on continental shelves influenced by large rivers: Plume processes', *Continental Shelf Research*, 24(7–8), pp. 833–858. doi: 10.1016/j.csr.2004.02.003.
- Dalrymple, R. W. (1992) 'Tidal Depositional Systems', in Walker, R. G. and James, N. P. (eds) *Facies Models 4: Response to Sea Level Change*. Newfoundland: Geological Association of Canada, pp. 195–218.
- Day, J. W. *et al.* (1997) 'System functioning as a basis for sustainable management of deltaic ecosystems', *Coastal Management*, 25(2), pp. 115–153. doi: 10.1080/08920759709362315.
- Dinehart, R. L. and Burau, J. R. (2005) 'Repeated surveys by acoustic Doppler current profiler for flow and sediment dynamics in a tidal river', 314, pp. 1–21. doi: 10.1016/j.jhydrol.2005.03.019.
- Dinehart, R.L. and Burau, J. R. (2005) 'Repeated surveys by acoustic Doppler current profiler for flow and sediment dynamics in a tidal river', *Journal of Hydrology*. Elsevier, 314(November), pp. 1–21. doi: 10.1016/j.csr.2013.10.017.
- Downing, A., Thorne, P. D. and Vincent, C. E. (1995) 'Backscattering from a

suspension in the near field of a piston transducer', *Journal of the Acoustical Society of America*, 97(March 1995), pp. 9–13.

Evans, G. (2012) 'Deltas: The fertile dustbins of the continents', *Proceedings of the Geologists' Association*. The Geologists' Association., 123(3), pp. 397–418. doi: 10.1016/j.pgeola.2011.11.001.

Filizola, N. *et al.* (2011) 'The Significance of Suspended Sediment Transport Determination on the Amazonian Hydrological Scenario', in Manning, A. J. (ed.) *Sediment Transport in Aquatic Environments*. London, United Kingdom: IntechOpen. doi: 10.5772/827.

Flores, R. P. *et al.* (2022) 'Spatio-temporal variability of turbid freshwater plumes in the Inner Sea of Chiloé, northern Patagonia', *Journal of Marine Systems*. Elsevier B.V., 228(August 2021). doi: 10.1016/j.jmarsys.2022.103709.

Goda, Y. (2000) *Random Seas and Design of Maritime Structures*. World Scientific Publishing Co. Pte. Ltd.

Gostiaux, L. and van Haren, H. (2010) 'Extracting meaningful information from uncalibrated backscattered echo intensity data', *Journal of Atmospheric and Oceanic Technology*, 27(5), pp. 943–949. doi: 10.1175/2009JTECH0704.1.

Harris, P. T. *et al.* (1993) 'A preliminary study of sedimentation in the tidally dominated Fly River Delta, Gulf of Papua', *Continental Shelf Research*, 13(4), pp. 441–472. doi: 10.1016/0278-4343(93)90060-B.

Işık, S., Şaşal, M. and Doğan, E. (2006) 'Sakarya nehrinde barajların mansap etkisinin araştırılması', *Gazi Üniversitesi Mühendislik Mimarlık Fakültesi Dergisi*, 21(3), pp. 401–408.

Kummu, M. *et al.* (2016) 'Over the hills and further away from coast: Global geospatial patterns of human and environment over the 20th-21st centuries', *Environmental Research Letters*. IOP Publishing, 11(3). doi: 10.1088/1748-9326/11/3/034010.

Le, T. V. H. *et al.* (2007) 'The combined impact on the flooding in Vietnam's Mekong River delta of local man-made structures, sea level rise, and dams upstream in the

river catchment', *Estuarine, Coastal and Shelf Science*, 71(1–2), pp. 110–116. doi: 10.1016/j.ecss.2006.08.021.

Milliman, J. D. and Syvitski, J. P. M. (1992) 'Geomorphic/tectonic control of sediment discharge to the ocean: the importance of small mountainous rivers', *Journal of Geology*, 100(5), pp. 525–544. doi: 10.1086/629606.

Monismith, S. *et al.* (2005) 'Hydrodynamics and sediment dynamics in Elkhorn Slough', *A report to Monterey Bay Sanctuary Foundation*, (December), pp. 1–83. Available at: http://sanctuarysimon.net/regional_docs/site_build/elkhorn_slough_hydrodynamics.pdf.

Nowacki, D. J. *et al.* (2015) 'Sediment dynamics in the lower Mekong River: Transition from tidal river to estuary', *Journal of Geophysical Research: Oceans*, 120(9), pp. 6363–6383. doi: 10.1002/2015JC010754. Received.

Ochi, M. K. (1998) *Ocean Waves: The Stochastic Approach*. Cambridge University Press (Cambridge Ocean Technology Series). doi: 10.1017/CBO9780511529559.

Olariu, C. (2014) 'Autogenic process change in modern deltas: lessons for the ancient', *International Association of Sedimentologists*, 46, pp. 149–166.

Otero, L. J. *et al.* (2021) 'Interannual and seasonal variability of stratification and mixing in a high-discharge micro-tidal delta: Magdalena River', *Journal of Marine Systems*, 224(August). doi: 10.1016/j.jmarsys.2021.103621.

Piton, V. *et al.* (2020) 'Seasonal and tidal variability of the hydrology and suspended particulate matter in the Van Uc estuary, Red River, Vietnam', *Journal of Marine Systems*. Elsevier, 211(July 2019), p. 103403. doi: 10.1016/j.jmarsys.2020.103403.

Prandle, D. (2009) *Estuaries: Dynamics, Mixing, Sedimentation and Morphology*. Cambridge: Cambridge University Press.

Sahin, C. *et al.* (2013) 'Observations of suspended sediment stratification from acoustic backscatter in muddy environments', *Marine Geology*. Elsevier B.V., 336, pp. 24–32. doi: 10.1016/j.margeo.2012.12.001.

- Sahin, C. *et al.* (2017) 'Acoustic backscatter by suspended cohesive sediments: Field observations, Seine Estuary, France', *Continental Shelf Research*. Elsevier, 134(September 2016), pp. 39–51. doi: 10.1016/j.csr.2017.01.003.
- Şahin, C. (2020) 'Sakarya Nehri Deltası'nda uzun süreli rüzgar ve dalga iklimi değişimleri', *Dokuz Eylül University Faculty of Engineering Journal of Science and Engineering*, 22(65), pp. 353–368. doi: 10.21205/deufmd.2020226505.
- Şahin, C. *et al.* (2021) *Akarsu Delta Sistemlerinin İklim Değişikliği Etkilerine Karşı Kırılganlığı: Sakarya Nehri Deltası Örneği*.
- Smith, J. O. (2011) *Spectral Audio Signal Processing*. W3K Publishing.
- T.C. Orman ve Su İşleri Bakanlığı (2014) *Ulusal havza yönetim stratejisi*. Ankara.
- Tan, R. İ. (2013) *Risk Altındaki Kıyı Alanlarının Yönetimi ve Karasu Örneği*. Yıldız Technical University.
- Thorne, P. D. and Hurther, D. (2014) 'An overview on the use of backscattered sound for measuring suspended particle size and concentration profiles in non-cohesive inorganic sediment transport studies', *Continental Shelf Research*. Elsevier, 73, pp. 97–118. doi: 10.1016/j.csr.2013.10.017.
- TMMOB (2012) *Karasu kıyı alanı kıyı daralması raporu, Türk Mühendis ve Mimarlar Odası Birliği*.
- TÜBİTAK-MAM (2013) *Havza koruma eylem planlarının hazırlanması projesi: Sakarya havzası*. Kocaeli.
- Vörösmarty, C. J. *et al.* (2009) 'Battling to save the world's river deltas', *Bulletin of the Atomic Scientists*, 65(2), pp. 31–43. doi: 10.2968/065002005.
- Wang, H. *et al.* (2010) 'Recent changes in sediment delivery by the Huanghe (Yellow River) to the sea: Causes and environmental implications in its estuary', *Journal of Hydrology*, 391(3–4), pp. 302–313. doi: 10.1016/j.jhydrol.2010.07.030.
- Wolanski, E. *et al.* (1996) 'Fine-sediment dynamics in the Mekong River Estuary, Vietnam', *Estuarine, Coastal and Shelf Science*, 43(5), pp. 565–582. doi: 10.1006/ecss.1996.0088.

- Wright, L. D. (1977) 'Sediment transport and deposition at river mouths: A synthesis', *Bulletin of the Geological Society of America*, 88(6), pp. 857–868. doi: 10.1130/0016-7606(1977)88<857:STADAR>2.0.CO;2.
- Wright, L. D. (1985) 'River Deltas', in Davis, R. A. (ed.) *Coastal Sedimentary Environments*. 2nd edn. New York: Springer, New York, NY. doi: 10.1007/978-1-4612-5078-4.
- Yankovsky, A. E. and Voulgaris, G. (2019) 'Response of a coastal plume formed by tidally modulated estuarine outflow to light upwelling-favorable wind', *Journal of Physical Oceanography*, 49(3), pp. 691–703. doi: 10.1175/JPO-D-18-0126.1.
- Yuan, S. *et al.* (2021) 'Hydrodynamics, Sediment Transport and Morphological Features at the Confluence Between the Yangtze River and the Poyang Lake', *Water Resources Research*, 57(3). doi: 10.1029/2020WR028284.
- Yüksel, Y. *et al.* (2013) 'A coastal management case study in Karasu at black sea region', *Proceedings of the International Offshore and Polar Engineering Conference*, pp. 1244–1250.
- Yüksel, Y. *et al.* (2014) 'KARASU KIYI ALANININ BÜTÜNLEŞİK MODELİ', pp. 71–88.
- Zhang, S. *et al.* (2008) 'Recent changes of water discharge and sediment load in the Zhujiang (Pearl River) Basin, China', *Global and Planetary Change*, 60(3–4), pp. 365–380. doi: 10.1016/j.gloplacha.2007.04.003.

Project

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TÜBİTAK 1001 Proje No: 117Y333

