EVALUATING THE USE OF SATELLITE OPTICAL DATA FOR MAPPING AND MONITORING LAKES AND THEIR SALINITY IN KONYA AND BURDUR CLOSED BASINS SUBJECTED TO INCREASING WATER ABSTRACTION AND CLIMATE CHANGE.

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ABSTRACT

EVALUATING THE USE OF SATELLITE OPTICAL DATA FOR MAPPING AND MONITORING LAKES AND THEIR SALINITY IN KONYA AND BURDUR CLOSED BASINS SUBJECTED TO INCREASING WATER ABSTRACTION AND CLIMATE CHANGE.

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Global warming and climate change have been affecting the conditions and future of inland waters. Turkey's important two closed basins, Konya, and Burdur Closed Basins (KCB and BCB) are facing with drought and many of the lakes in these basins are drying or already dried out. Monitoring the lakes and mapping lake parameters (e.g., surface water area, electrical conductivity - EC) are important to increase the awareness about the situation of these lakes. Modified Normalized Difference Water Index (MNDWI) is used to map the surface area of the lakes from Landsat 5-8 and Sentinel-2 data. Sentinel-2 has better areal mapping due to its ground resolution advantage over Landsat-8. On the other hand, Landsat legacy provides great opportunity to monitor the lakes since 1984. Using this legacy, several lakes in KCB and BCB are monitored over the past 35 years. Combining these changes with the meteorological parameters, like Standardized Precipitation Evapotranspiration Index (SPEI), it is showed that the change in the surface area is related to the change in precipitation and evaporation. In addition, budget calculations showed that, Lake Burdur will reach the critical water level in the next 60 years and face with the possibility of dried out if the water use in the basin remains the same. Water EC is another important parameter for the lakes because it is related with the biodiversity. To map the EC of lakes, field measurements were used which were collected from the lakes in June 2020, July 2021 and May 2022. A significant relation between Sentinel bands 1, 2 and 3 with the EC values were obtained. Also, a case study conducted on Lake Salda presents the uniform variation of EC over the lake except at the locations of river contributing to the lake.

Keywords: optical remote sensing, Sentinel-2, Landsat, water index, salinity

ÖZ

ARTAN SU KULLANIMINA VE İKLİM DEĞİŞİKLİĞİNE MARUZ KALAN KONYA VE BURDUR KAPALI HAVZASI'NDAKİ GÖLLERİN OPTİK UYDU GÖRÜNTÜLERİ İLE BELİRLENMESİ, İZLENMESİ VE TUZLULUĞUNUN TESPİT EDİLMESİ

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Küresel ısınma ve iklim değişikliği iç suların koşullarını ve geleceğini etkilemektedir. Türkiye'nin iki önemli kapalı havzası olan Konya ve Burdur Kapalı Havzaları (KKH ve BKH) kuraklıkla karşı karşıyadır ve bu havzalardaki göllerin çoğu kurumak üzere veya çoktan kurumuştur. Göllerin izlenmesi ve göl parametrelerinin (örn. yüzey suyu alanı, iletkenlik) haritalanması, bu göllerin durumu hakkındaki farkındalığı artırmak için önemlidir. Modifiye Normalleştirilmiş Su Fark İndisi (MNDWI), Landsat 5-8 ve Sentinel-2 verilerinden göllerin yüzey alanını haritalamak için kullanılmıştır. Sentinel-2, Landsat-8'e göre yer çözünürlüğü avantajı nedeniyle daha iyi alan haritalamasına sahiptir. Öte yandan, Landsat mirası, 1984'ten beri gölleri izlemek için harika bir fırsat sunmaktadır. Bu mirası kullanarak, son 35 yılda KKH ve BKH'deki birçok göl izlenmiştir. Bu değişiklikler Standardize Yağış Evapotranspirasyon İndisi (SPEI) gibi meteorolojik parametrelerle birleştirildiğinde, yüzey alanındaki değişikliğin yağış ve buharlaşmadaki değişiklikle ilişkili olduğu gösterilmiştir. Ayrıca göl suyu bütçe hesapları, Burdur Gölü'nün önümüzdeki 60 yıl içinde kritik su seviyesine ulaşacağını ve havzadaki su kullanımının aynı kalması halinde kuruyabileceği ihtimalini ortaya koymuştur. Su iletkenliği, biyoçeşitlilik ile ilgili olduğu için göller için bir diğer önemli parametredir. Göllerin iletkenliğini haritalamak için Haziran 2021 ve Haziran 2022'de göllerden toplanan saha ölçümleri kullanılmıştır. Sentinel-2'nin 1., 2. ve 3. bantları ile elektriksel iletkenlik değerleri arasında anlamlı bir ilişki elde edilmiştir. Ayrıca, Salda Gölü üzerinde yürütülen bir saha çalışması, göle katkıda bulunan nehir girişleri dışında, göl üzerindeki homojen iletkenlik değişimini ortaya koymaktadır.

Anahtar Kelimeler: optik uzaktan algılama, Sentinel-2, Landsat, su indisi, tuzluluk

To my dearest family and my precious Betül...

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BOA	Bottom of Atmosphere
TOA	Top of Atmosphere
KCB	Konya Closed Basin
BCB	Burdur Closed Basin
GEE	Google Earth Engine
NDWI	Normalized Difference Water Index
MNDWI	Modified Normalized Difference Water Index
TM	Thematic Mapper
OLI	Operational Land Imager
EC	Electrical Conductivity

CHAPTER 1

INTRODUCTION

Global warming and change in precipitation patterns are predicted to intensify water loss in semi-arid and arid regions (IPCC, 2014, 2021). Among the eastern Mediterranean countries, Turkey will likely experience major increases in summer drought (Barcikowska et al., 2020). A recent study, based on global circulation models (GCMs) Bağçaci et al. (2021), showed that there will be at least a 2 °C increase in spring and summer mean temperatures and a 10% decrease in annual total precipitation in Turkey by 2100. Moreover, water abstraction, not least for irrigation purposes, is expected to increase markedly (Rodríguez Díaz et al., 2007; Yano et al., 2007). These changes are major threats to the water balance of many lakes that may dry out temporarily or permanently, with the shallower areas being particularly vulnerable. The magnitude of the future changes poses a major threat to the functioning and biodiversity of inland aquatic ecosystems. Many lakes especially in closed basins may dry out temporarily or permanently with rising temperature, while salinization in the remaining waterbodies may lead to reduced biodiversity (Flöder & Burns, 2004; Jeppesen et al., 2015; Schallenberg et al., 2003; Williams et al., 1990) and loss of ecosystem functioning (Lin et al., 2017; Vidal et al., 2021).

Salinity is one of the most important and essential parameters for the sustainability of the ecosystem. Both in the lackness and fullness might be harmful for the ecosystem. For example, there are some halocline bacteria that need a saline environment to live. In the reverse scenario, which is the fullness of the salinity, there are many types of crops, animals that are negatively affected. For example, some species, like flamingos, need to have saline, shallow lakes for breeding (Yılmaz et al., 2021). Hence, from micro- to macro-scale, creatures need a saline environment to live up to a level.

The dynamic change in the amount of water in the inland water bodies makes the importance of monitoring them frequently. The water level of big natural lakes and reservoirs of the dams are monitored by State Water Works (DSI) in Turkey. However, there are no records about the water level of the small ones. Besides the water level, the chemical properties of the lakes cannot be monitored frequently. Because, measuring on-site is not always possible or practical. However, one can make these measurements more easily with the technological improvements in the remote sensing area. For remote sensing, land monitoring satellites like Landsat 8, Sentinel-2 and Sentinel-3 are used, mostly because of their ease of use and open data access properties. There are several advantages of the remote sensing stated by Hellweger et al. (2004); the first one is remote sensing images cover large areas. Second, it allows one to reach inaccessible areas. Lastly, it has a long time series of images. Hellweger et al. (2004) also said that combining the ground and the satellite estimates is the most effective approach.

Positive and negative ions in the water causing the conductivity. There are several types of ions, such as Na^{+}, Ca^{+2}, K^{+}, Mg^{+2}, Cl^{-}, SO_4^{-2}, etc. which causes conductivity. Salinity is a converted parameter by measuring the conductivity of the water. Salinity is one of the optically active parameters due to changing the surface reflectance of the water, such as turbidity, phytoplankton, etc. which enable the optical satellites to monitor the surface of the water (Giardino et al., 2013).

There are six closed basins with different size of lakes in Turkey. Among these basins, two of them, namely Konya Closed Basin (KCB) and Burdur Closed Basin (BCB) are selected as study area. The semiarid Konya Closed Basin (KCB), the largest closed basin of Turkey, is spanning almost 50 000 km^2 and covering 7% of the country's land area. It has a population of 3.2 million and supports extensive agricultural activities that depend heavily on surface water and groundwater abstraction, implying that many natural streams have been regulated and channelized for dam construction to provide water for irrigation. The basin is hosting to several globally threatened waterbird species and is an important area for breeding, wintering, and migrating (Kirwan et al., 2010). A recent study, describing the predicted changes in the hydrogeological reserve of the basins in Turkey, reveals that the BCB will be the most affected Anatolian basin (The Ministry of Foresty and Water Affairs, 2016) . The

BCB is the smallest of the closed basins in Turkey. At the end of the present century, due to the effects of climate change, the hydrogeological reserve of the BCB will decrease by 14% and the possible reserve by 26% (The Ministry of Foresty and Water Affairs, 2016) compared with 3% and 6% in the KCB, which has already faced dramatic changes in recent decades (Yılmaz et al., 2021). In the BCB, there are extensive agricultural activities (as in the KCB) that depend heavily on surface water and groundwater abstraction, and the surface water has been controlled by constructing dams that provide water for irrigation. The BCB includes the second- and third-deepest lakes in Turkey, while the lakes in the KCB are mainly shallow. In both areas, the lakes host large and diverse waterbird and fish populations. Some of the shallow lakes in both basins have already dried out, and the deeper lakes in the BCB have shown signs of shrinkage due to increased evaporation and water abstraction (Davraz et al., 2019a).

The main goal of this thesis is to present the use of optical remote sensing data to map the inland waters, to monitor the change of lake surface area and to investigate the possibility of mapping water salinity of the lakes from the satellite images. The study is performed in KCB and BCB.

In Chapter 1, the aim of the thesis is given. In Chapter 2, the literature and background information on the use of optical remote sensing data in identifyinginland water bodies, monitoring the surface area of the lakes and retrieving the salinity information from satellite data are presented. By this search, while we can see the accumulation information, we also see what we can provide to the literature. In Chapter 3, materials and methods used in this study are provided in detail. In Chapter 4, the results of the study are presented and discussed. In addition, a case study on the Lake Salda is presented in Chapter 4. In Chapter 5, the work done in this thesis is summarized, conclusions and recommendations are provided.

CHAPTER 2

BACKGROUND INFORMATION AND LITERATURE REVIEW

In this chapter, background information about used material and later, the studies in the literature which are related to the study area are reviewed.

In the past, airborne imagery has been chosen as a better tool for the remote sensing due to its better spatial properties (Dekker et al., 1996). However, with the development of spaceborne remote sensing technologies with improved spectral and spatial resolution, studies have shifted to this area.

Remote sensing technology offers effective ways to observe the dynamics of surface water. Remote sensing datasets provide spatially explicit and temporally frequent observations of a number of physical attributes on the Earth's surface that can be appropriately leveraged to map the extent of water bodies at regional or even global scale, and to monitor their dynamics at regular and frequent time intervals. There are generally two categories of sensors that can serve the purpose of measuring surface water, the optical sensor and the microwave sensor. Microwave sensors, due to their usage of long wavelength radiation, have the ability to penetrate cloud coverage and certain vegetation coverage. Independent of solar radiation, they can work day and night under any weather condition. Optical sensors have been widely applied in this field due to high data availability, as well as suitable spatial and temporal resolutions (Huang et al., 2015). Huang et al. (2018) present a review of using remote sensing in mapping water areas on the Earth surface and state that the number of publications has increased steadily after 2000.

Another study noted that remote sensing is an advantageous tool for the management of shallow waters (Kutser et al., 2020). They also state that shallow lakes are mostly located in places where it is hard to reach. Also, due to their shallowness, it is very dangerous for hydrographic ships and bathymetry surveys (Kutser et al., 2020). Karpatne et al. (2016) showed the importance of remote sensing of inland waters because they have a dynamic structure and are exposed to external impacts such as human effects, climate change, etc.

Another study stated that there is clearly reflectance difference between deep and shallow water surface (Albert & Mobley, 2003). The study by Stefanidis and Papastergiadou (2012) showed that morphometry has an undeniable effect on the water quality. Furthermore, Blix et al. (2018) stated that local studies are required for each lake due to their different optical properties that can cause large deviations.

Soomets et al. (2020) stated that there is very important knowledge about why Multi-Spectral Imager (MSI) of Sentinel-2 can be used as a water observer. Also, Operational Land Imager (OLCI) of Landsat-8 is designed for ocean and lake imager. However, the ground resolution of OLCI is 30 m, which makes it harder to observe small lakes, which are very important (Soomets et al., 2020; Tyler et al., 2006). They also recommend that preprocessing is an essential step for the analysis.

One the contrary, an initial study on Sentinel-2 used the Sen2Cor tool which is not designed for the water bodies and explore that Top of Atmosphere (TOA) results are better than the ones obtained from the Bottom of Atmosphere (BOA) reflectance values in the case of water qualities (Toming et al., 2016). Subsequently, Medina-Lopez and Ureña-Fuentes (2019) did not perform pre-processing steps and observed better results compared to the atmospherically corrected results. Also, by not applying the image preprocessing stage, time is shortened for the whole process.

2.1 Water Detection

Every matter has different spectral characteristics like signatures as seen in Figure 2.1. As nature of water, there is very low reflectance in the Near-Infrared (NIR) range of the spectrum.

The principle of extracting surface water from optical images is obviously based on the lower reflectance of water, compared to that of other land cover types, in infrared channels. Many methods have been developed for extracting water areas from optical remote sensing imagery (Acharya et al., 2016; Frazier, Page, et al., 2000; Manavalan et al., 1993; Olthof, 2017; Ozesmi & Bauer, 2002; Sun et al., 2011). An easy and effective way to identify water is to use water indices, which are calculated from two or more bands, to identify the differences between water and non-water areas.

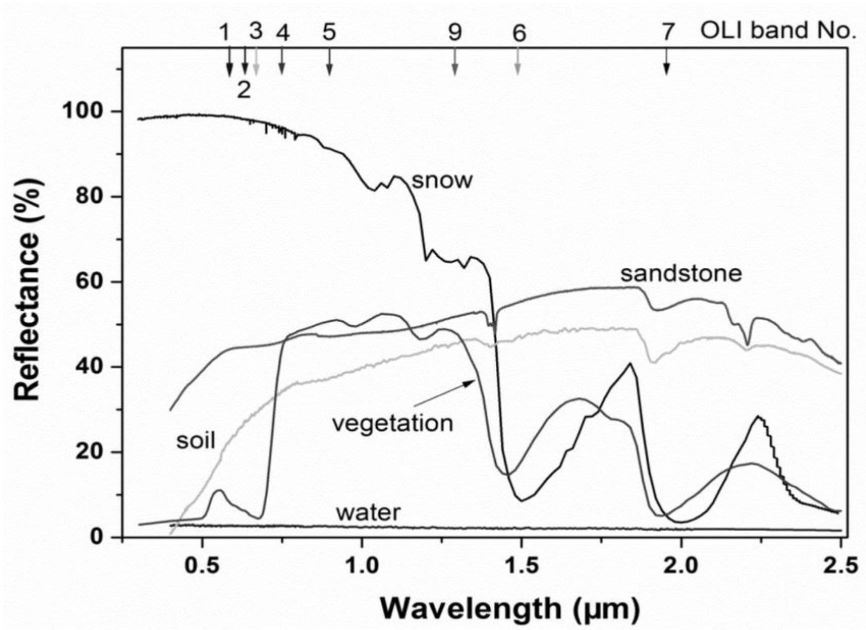

Figure 2.1: Spectral responses of different land covers. Figure retrieved from (Huete, 2004)

Gao (1996) proposed an index (Eq. 2.1) to find the water content in vegetation, which is called the Normalised Difference Water Index (NDWI) by using the NIR and Mid-Infrared (MidIR) parts of the spectrum.

$$NDWI_{Gao,1996} = \frac{NIR - MidIR}{NIR + MidIR} \tag{2.1}$$

McFeeters (1996) also proposed an index (Eq. 2.2), different than $\mathrm{NDWI}_{\mathrm{Gao,1996}}$, to extract the water bodies, which is also called NDWI. In Figure 2.1, one can clearly see that, in NIR part of the spectrum, there is a huge reflectance difference between vegetation and water. On the other hand, in the visible (green) part of the spectrum, there is no clear difference. This principle is used while creating the indices.

$$NDWI_{McFetters,1996} = \frac{Green - NIR}{Green + NIR} \tag{2.2}$$

Our study aimed to detect the salinity of the water, so as the first step we need to find the water pixel. Xu (2006) modified the NDWI by using Green and the Short-Wave Infrared (SWIR) parts of the spectrum and created Modified Normalised Difference Water Index (MNDWI) Eq. 2.3 which is a useful tool for extracting the water body, especially for inland waters.

$$MNDWI = \frac{Green - SWIR}{Green + SWIR} \tag{2.3}$$

Du et al., 2016 realised that MNDWI gave a better result in mapping the water pixels than the $\mathrm{NDWI}_{\mathrm{McFetters,1996}}$.

Besides that, there are many studies that used MNDWI to detect the water bodies and their seasonal changes (Hereher, 2015; Nair & Babu, 2016; Tebbs et al., 2013). Moreover, Hui et al. (2008) and later, Deus and Gloaguen (2013), combined these changes with hydrological and land use studies. Land use effects on lake surface area changes are also studied with MNDWI (Zhang et al., 2015). The surface area of the water in shallow lakes shows a strong correlation with climate effects and lake hydrology (Tebbs et al., 2013). Also, for Lake Burdur, which is the largest lake in BCB, MNDWI is the best index to obtain the change in lake surface area among three different water detection indices (Sarp & Ozcelik, 2017).

2.2 Water Quality and Salinity Detection

In literature, the specific salinity measurements by optical sensors are not common. However, salinity is considered as a parameter that is a part of water quality in general. Ansari and Akhoondzadeh (2020) have tried to measure the salinity of the Karun River, in Iran, using Landsat-8 OLI.

Ritchie et al. (2003) state that empirical models are widely used in remote sensing studies in water quality studies. Dekker et al. (1996) stated that mathematical models obtained by using remote sensing data may provide time series data depending on the quality of the model. With the help of this, one can use the past data on the study area if the model is good. Furthermore, prediction studies can be the next step by using this model. Mukhtar et al. (2021) used different empirical models to find salinity and other parameters .

As a sampling method, a study in China used different-sized average filters, such as 3 x 3 or 5 x 5, to sample pixels. Also, they sampled using the one-pixel method and saw that there is no best sampling method for remote sensing data (He et al., 2008). Wong et al. (2007) selected only offshore pixels to prevent the mixed pixel effect. Also, they generate an equation from the correlation of the bands with the sea surface salinity ground measurements. The correlations of the bands are not very reliable, but after modelling, they obtained higher correlations. Wang and Xu (2008) studied the salinity of the US Gulf in Mexico. They sampled the lake surface in horizontal and vertical directions. Again, they created a model and mapped the salinity. A similar study was conducted in Lake Balaton, which is the largest lake in central Europe, and suspended solid samples were taken horizontally and vertically from the lake surface and calibrated with Landsat TM (Tyler et al., 2006). Dewidar and Khedr (2001) conducted a similar study in the Egyptian lagoon to explore water quality parameters and salinity with a variety of salinities from low to high.

Hu et al. (2004) tried to find the salinity by Coloured Dissolved Material (CDOM) as an indirect method and they obtained linear, negative correlation.

CHAPTER 3

MATERIALS AND METHODS

In this chapter, the materials and methods are described in details. In the materials section, information about the study area, *in-situ* data and related satellite images are given. Then, the ground truth data are presented. In the methodology part, the methods used in the study are explained in sub-sections. Field samplings, satellite image selection, classification of water pixels, retrieving values from satellite images, and statistical analysis are also given in detail in this section.

3.1 Materials

3.1.1 Study Area

Lakes in central Anatolia are facing drought problems due to the change in precipitation and temperature as a result of climate change. A 25%–30% decrease in precipitation and increased evaporation are expected by the end of the 21^{st} century in the Mediterranean region, to be accompanied by an even stronger reduction in runoff of up to 30%–40%, (IPCC, 2014; Parry et al., 2007). It is known that this will lead to increased salinization of the lakes in these areas (Jeppesen et al., 2020). Among the eastern Mediterranean countries, Turkey will likely experience major increases in summer drought (Barcikowska et al., 2020). A recent study, based on global circulation models (GCMs) (Bağçaci et al., 2021), showed that there will be at least 2 °C increase in spring and summer mean temperatures and a 10% decrease in annual total precipitation in Turkey by 2100 (A.2). Moreover, water abstraction, not least for irrigation purposes, is expected to increase significantly (Rodríguez Díaz et al., 2007; Yano et al., 2007). The natural lakes in KCB (A.1-Figure 1) as being the largest, and

BCB (A.2-Figure 1) as being one of the smallest closed basins in Turkey are selected in the scope of this thesis. The lakes in both basins host large and diverse populations of waterbirds and fish. Some of the shallow lakes in both basins have already dried out. The study areas are shown in Figure 3.1.

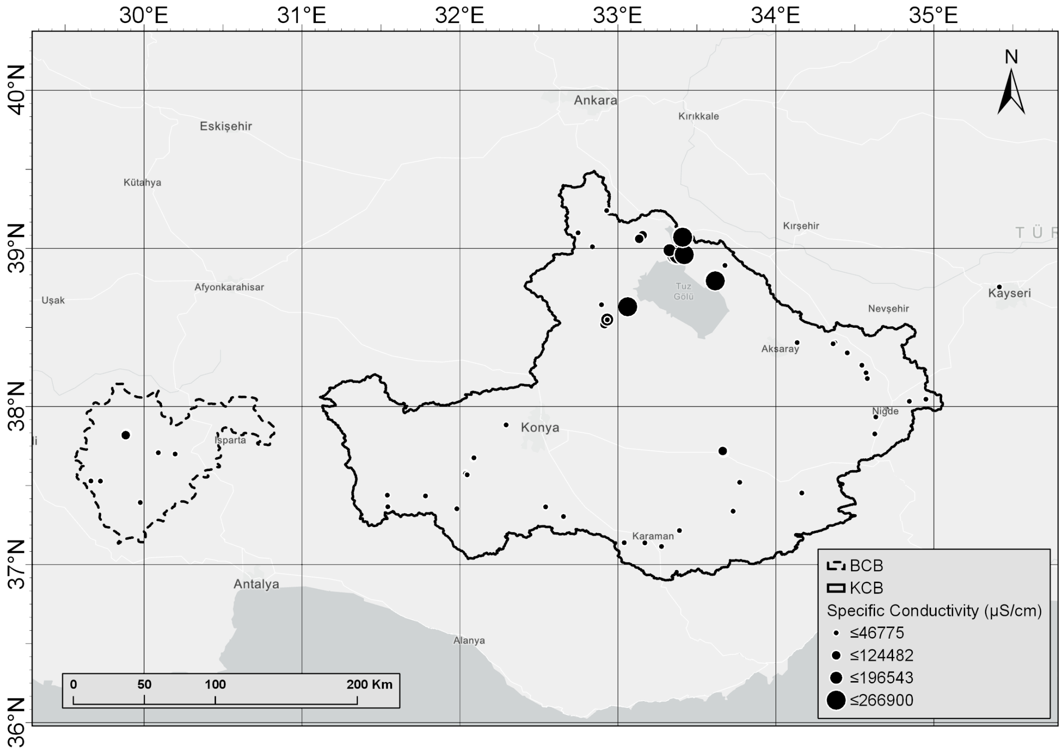

Figure 3.1: Locations of selected closed basins and field sampling points in KCB and BCB.

3.1.2 *In-situ* Data and Sampled Lakes

The water salinity of selected lakes in two different basins was measured in the years 2015-2016 of the entire season, 2020-2022 of field trips of the summer season within the scope of the 118C250 BIDEB project.

In the measured of field data parameters, conductivity ($\mu S/cm$) (also used as Electrical Conductivity - EC), salinity (converted from EC, ppt - parts per thousand), dissolved oxygen ($\%$), temperature ($^{\circ}C$) etc. are included. The pysical parameters were measured by using calibrated YSI multiprob (YSI 556-02, YSI Company, USA) (Figure 3.2) during whole sampling campaign. However, EC is the only common parameter for the all field works. Therefore, we decided to use only the EC parameter.

Figure 3.2: YSI Multiprob (YSI 556-02, YSI Company, USA).

The coordinates of all the samples obtained from the GPS where WGS84 datum and UTM coordinate system are used.

During these field trips, different types of lakes like shallow, deep, natural, artificial, saline, or alkaline lakes were included in the target list.

In field trip FS, saline lakes which have usually high and moderate salinities are selected and sampled periodically in KCB. 101 points are selected from 4 different lakes (Lake Tuz, Tersakan, Bolluk and Acıgöl) in different periods of the year 2016. The range of conductivity values in FS is 9,044 - 251,768 µS/cm.

Natural, artificial dams, and saline lakes are sampled in a short date range in the KCB. 43 sample points are selected from various lakes. The range of conductivity values in FT1 is 64 - 240,000 µS/cm.

Lakes have different contents, sampled in a short date range in KCB and BCB. The range of conductivity values in FT2 is 398 - 237,300 µS/cm.

High-salinity lakes are sampled in a short date range in KCB in BCB. 3 of the sample points selected in KCB, remaining one is selected in BCB. The range of conductivity values in FT3 is 72,440 - 266,900 µS/cm.

During the field trips 165 points are sampled in total and summary of field trips are given in Table 3.1.

Table 3.1: Field Sampling Summary

Field Trip Code	Start Date	End Date	Number of Samples	Basin	EC Range (µS/cm)	Notes
FS	12.12.2015	10.12.2016	101	KCB	9,044-251,768	Periodical
FT1	23.06.2020	27.06.2020	43	KCB	64-240,000	Snapshot
FT2	05.07.2021	26.07.2021	18	KCB-BCB	398-237,300	Snapshot
FT3	18.05.2022	21.05.2022	4	KCB-BCB	72,440-266,900	Snapshot

3.1.3 Remote Sensing Data: Sentinel-2 and Landsat-5 & 8 Images

Sentinel-2 is one of the missions of the European Space Agency (ESA). It is a twin satellite constellation which has wide-swath, high-resolution, multi-spectral imaging capabilities. These twin satellites are placed at 180° in the orbit. The temporal resolution of the satellites is 5 days/cycle. Sentinel-2 carries a MultiSpectral Instrument (MSI) passive imager. Sentinel-2 has 13 bands that are shown in Table 3.2. Bands 1, 9, and 10 are designed for atmospheric corrections. Also, bandwidth of the band 8A is in the range of band 8, which has better spatial resolution. Therefore, these bands are excluded in this study.

The Landsat programme was initiated by the National Aeronautics and Space Administration (NASA) and the United States Geological Survey (USGS) about 50 years ago. Landsat legacy has provided very important data to monitor the changes in earth. Landsat-5 is one of the important members of this legacy by its longest-served satellite (29 years) title. Moreover, it has temporal resolution of 16 days and ground resolution of 30 meters. Landsat-5 carries Thematic Mapper (TM) sensor. Band properties of Landsat-5 are given in Table 3.3

The other important optical imager is Landsat-8. It is one the milestone in this legacy and it was launced in 2013. Temporal and ground resolutions are the same as Landsat-5. Landsat-8 carries two sensors, one is Operational Land Imager (OLI) and the other is Thermal Infrared Sensor (TIRS). The Landsat-8 band designation is provided in Table 3.4.

Landsat-5 & 8 and Sentinel-2 data are used in mapping the waterpixels and monitoring the change in water surface area of the lakes in this study.

Table 3.2: Sentinel-2 bands

Bands	Sentinel-2A Central wavelength (nm)	Sentinel-2A Bandwidth (nm)	Sentinel-2B Central wavelength (nm)	Sentinel-2B Bandwidth (nm)	Spatial resolution (m)
Band 1 – Coastal aerosol	442.7	21	442.2	21	60
Band 2 – Blue	492.4	66	492.1	66	10
Band 3 – Green	559.8	36	559.0	36	10
Band 4 – Red	664.6	31	664.9	31	10
Band 5 – Vegetation red edge	704.1	15	703.8	16	20
Band 6 – Vegetation red edge	740.5	15	739.1	15	20
Band 7 – Vegetation red edge	782.8	20	779.7	20	20
Band 8 – NIR	832.8	106	832.9	106	10
Band 8A – Narrow NIR	864.7	21	864.0	22	20
Band 9 – Water vapour	945.1	20	943.2	21	60
Band 10 – SWIR – Cirrus	1373.5	31	1376.9	30	60
Band 11 – SWIR	1613.7	91	1610.4	94	20
Band 12 – SWIR	2202.4	175	2185.7	185	20

Table 3.3: Landsat-5 bands

Bands	Central wavelength (nm)	Bandwidth (nm)	Spatial resolution (m)
Band 1 - Blue	485.0	70	30
Band 2 - Green	560.0	80	30
Band 3 - Red	660.0	60	30
Band 4 - NIR	830.0	140	30
Band 5 - SWIR	1650.0	200	30
Band 6 - Thermal Infrared	11450.0	2100	120
Band 7 - SWIR	2215.0	270	30

Sentinel-2 MSI Level-1C data is used for EC data analysis. (Medina-Lopez & Ureña-Fuentes, 2019) stated that non-preprocessed images give better results for water quality studies. Google Earth Engine repository is used for both image selection and pixel extraction. The Sentinel-2 data contain 13 spectral bands which have 16-bit unsigned integer (UINT16) data type representing TOA reflectance scaled by 10,000.

Table 3.4: Landsat-8 bands

Bands	Central wavelength (nm)	Bandwidth (nm)	Spatial resolution (m)
Band 1 - Coastal Aerosol	443.0	16	30
Band 2 - Blue	482.0	60	30
Band 3 - Green	561.0	57	30
Band 4 - Red	655.0	37	30
Band 5 - NIR	865.0	28	30
Band 6 - SWIR	1609.0	85	30
Band 7 - SWIR	2201.0	187	30
Band 8 - Pan	590.0	172	15
Band 9 - Cirrus	1373.0	20	30
Band 10 - Thermal Infrared	10895.0	590	100
Band 11 - Thermal Infrared	12005.0	1010	100

3.2 Methods

3.2.1 Image Selection

In order to decide the satellite images, the following conditions are required;

- Cloud free pixel (Checked from QA60 - Cloud Mask - obtained from GEE Sentinel-2 Level-1 product)
- Minimum date difference with the field sampling date (manual selection from image list)

After applying these conditions, 71 Sentinel-2 (years between 2015-2020), 112 Landsat-5 (years between 1984-2011), and 32 Landsat-8 (years between 2013-2020) images are selected.

3.2.2 Finding water pixels

As mentioned in Chapter 2 in detail, MNDWI can be used to find the water pixels. However, the ground resolution of the Sentinel-2 bands are different as seen in Table

3.2. Therefore, Du et al. (2016) suggest band 3 and resampled band 11 (to 10 m). As a result we modified the Eq. 2.3 for Sentinel-2 images as given in Eq. 3.1, for Landsat-5 as given in Eq. 3.2, and for Landsat-8 images as given in Eq. 3.3.

$$MNDWI_{S2} = \frac{Band3 - Band11}{Band3 + Band11} \tag{3.1}$$

$$MNDWI_{L5} = \frac{Band2 - Band5}{Band2 + Band5} \tag{3.2}$$

$$MNDWI_{L8} = \frac{Band3 - Band6}{Band3 + Band6} \tag{3.3}$$

As a result of MNDWI image, range of pixel values are -1 to 1. Positive values of MNDWI indicate water pixels. An example MNDWI image can be seen in Figure 3.3c and 3.3d.

Figure 3.3 shows that water areas of Lake Uyuz obtained by Landsat-8 and Sentinel-2 in similar dates. Lake Uyuz has very dense marches near the shore indicated by red colour. MNDWI method clearly separates vegetation and water pixels, as seen in Figures 3.3c and 3.3d.

As area detection method, negative NDVI values (3.3a, 3.3b) and MNDWI values which is larger than 0.1 (3.3c, 3.3d) interpreted as water pixels. And the water areas are polygonized and measured in km^2. As clearly seen in Figure 3.3, Sentinel-2 has better area detection due to its higher spatial resolution.

3.2.2.1 Field Sampling Point Correction

While *in-situ* sampling, the common approach is to take samples from the lake shore. Therefore, we used the one pixel sample from where the water is observed for the sampling point. Thus, the first criterion for pixel selection is MNDWI ≥ 0.1. On the other hand, due to possible reflectance errors, the selected pixels cannot be located in deep water as well. Due to projection and GPS errors, most of the sample points are located in the land side of the shore. Also, the kernel methods used in the study of He

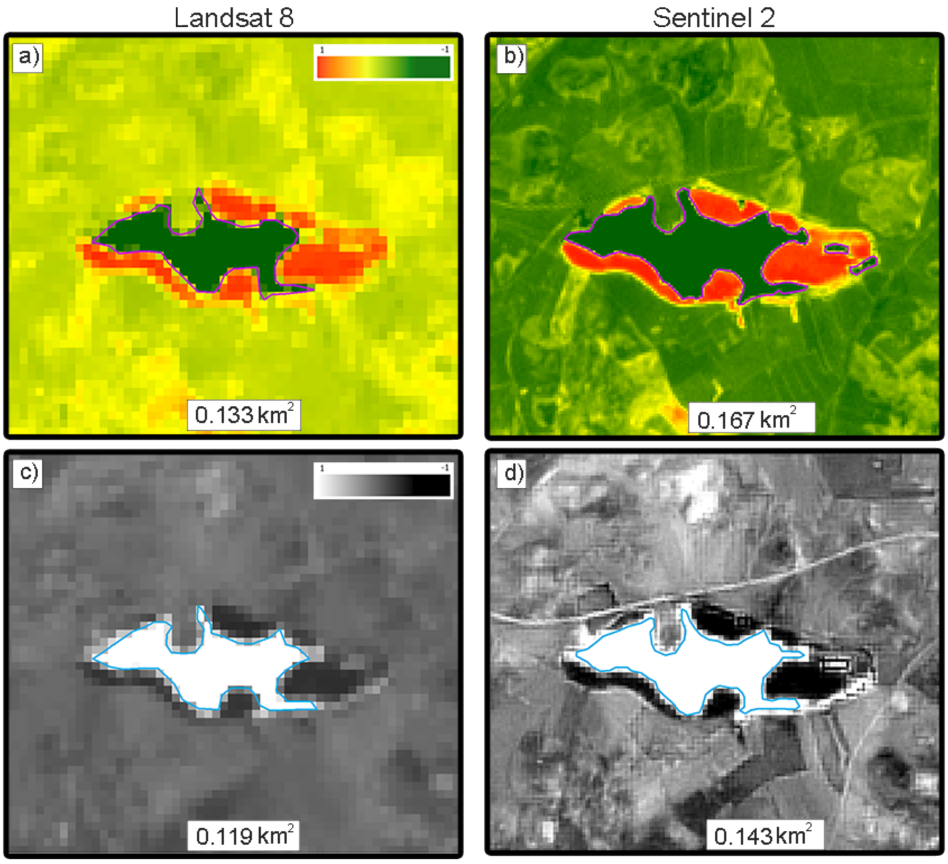

Figure 3.3: a) and b) show Normalised Difference Vegetation Index (NDVI) images of Lake Uyuz obtained from Landsat-8 (date of image-27.08.2019) and Sentinel-2 (date of image-30.08.2019) respectively. c) and d) shows the MNDWI images. The water surface areas obtained by the images are presented in km^2 for each image.

et al. (2008) cannot be performed due to a possible mixed-pixel problem which means land and water reflectances can mix and this may cause a possible error. Therefore, manual correction of field sampling points is essential. An example of a sampled point location is given in Figure 3.4a. Original and corrected field sample points are shown in Figures 3.4b and 3.4c, respectively.

A different method was applied for the case study and is explained in section 4.4.6.

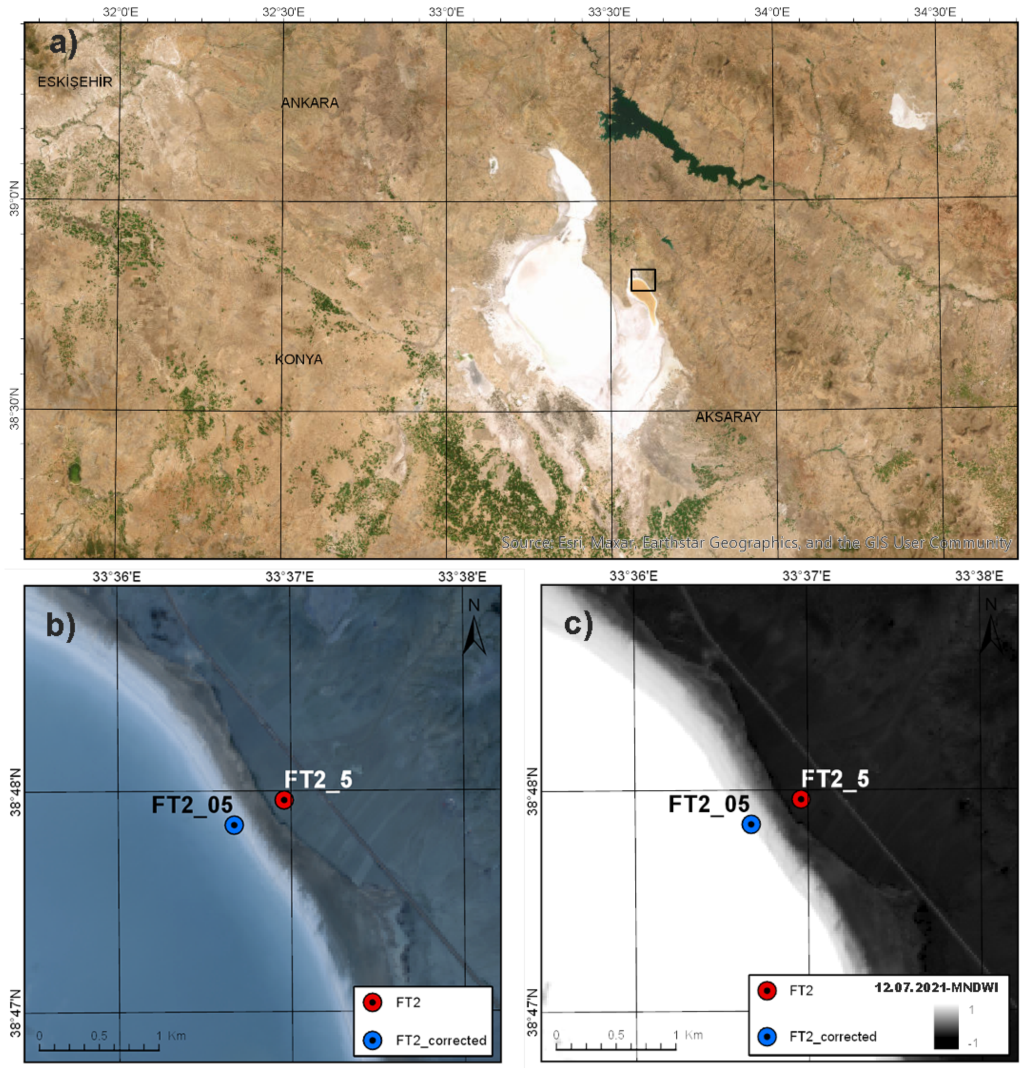

Figure 3.4: a) Point correction example of field sampling points. b) the original sampling point showed as red, the corrected sampling point is blue. c) MNDWI image is presented.

3.2.2.2 Coherent Noise Problem

During this study, there are some stripes observed on the lake surface areas (Figure 3.5, Figure 3.6). These stripes are the result of an artefact called Coherent Noise (CN). Helder and Ruggles (2004) defined the CN as a periodic pattern with low amplitude generally seen in homogenous areas like water surfaces and deserts.

Pahlevan et al. (2017) stated that this artifact is related with the Signal to Noise Ratio (SNR). SNR is inversely correlated with the CN. Also, they found that, in turbid waters, this noise is reducing. Pahlevan et al. (2018) also said that this problem occurs more strongly in the blue (480 - 490 nm) band.

There are some studies to reduce this CN. There are mainly two approaches. First one is using the median filter to the bands (Nichol & Vohora, 2004; Pahlevan et al., 2018) and the other one is filtering the image in the Fourier domain (Tilton et al., 1985).

In this study, both median and Fourier filtering methods are tried for several lake images. However, because of the huge variation of the images and the application difficulties, it is not found feasable to apply the correction, therefore none of them are applied in this study.

In order to see the differences between the Sentinel-2 and Landsat-8 CN characteristics, monthly images are selected for 2016, for Lake Salda. Non-cloudy blue band is considered for the analysis. Unfortunately, less number of Landsat images were found due to cloudness problem. No significant seasonality is observed according to the results of the analysis shown in Table 3.5.

3.2.3 Band Value Extraction

Sentinel-2 has 13 bands as mentioned in Table 3.2. Values of selected bands of Sentinel-2 from the field sampling points are automatically extracted from the images in Google Earth Engine (GEE). After extraction, criterias mentioned in Section 3.2.1 are applied while selecting the appropriate band values. The band values corresponding to field sampled conductivity values are obtained as a flat file.

3.2.4 Statistical Data Analysis and Correlations

First of all, K-Means method is selected for clustering the dataset proposed by MacQueen (1967) according to their conductivity levels. Before applying the K-means method, the optimal number of clusters is decided using the elbow method proposed by Tibshirani et al. (2001). According to the result of optimal cluster number, K-means clustering is applied. After clustering, correlation between band values and conductivity values is calculated for the whole dataset and for each cluster. As a cor-

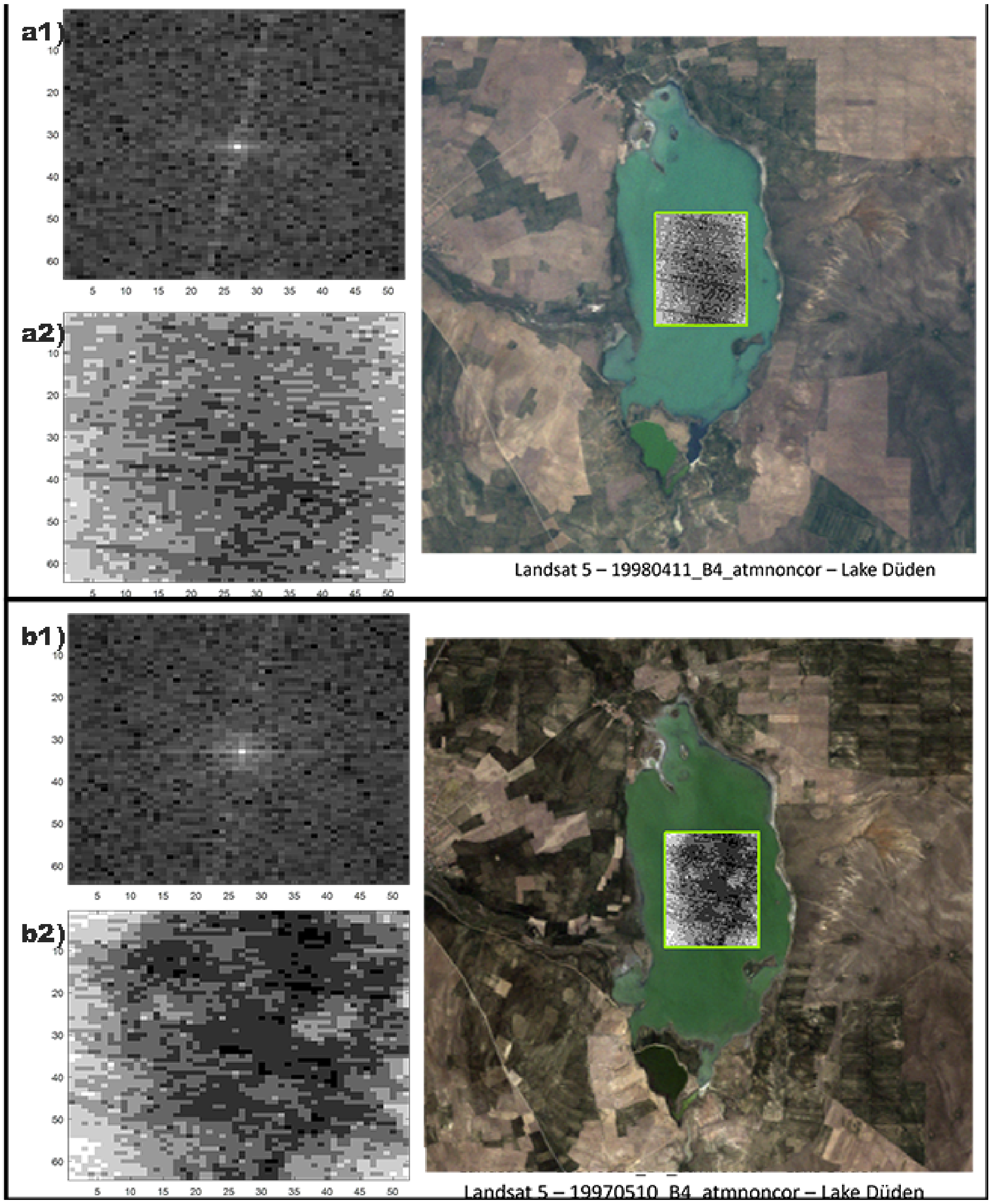

Figure 3.5: Landsat-5 images of Lake Düden. Bands are not atmospherically corrected. Figures a1) and b1) are Fourier domians of the selected areas on the lake surface. Figures a2) and b2) are close-up images of band 4 and the stripes on the lake surface can be interpreted visually.

relation method, Pearson's correlation coefficient (Pearson, 1895) is used and results of R^2 values are obtained. R language is used for statistical analyses.

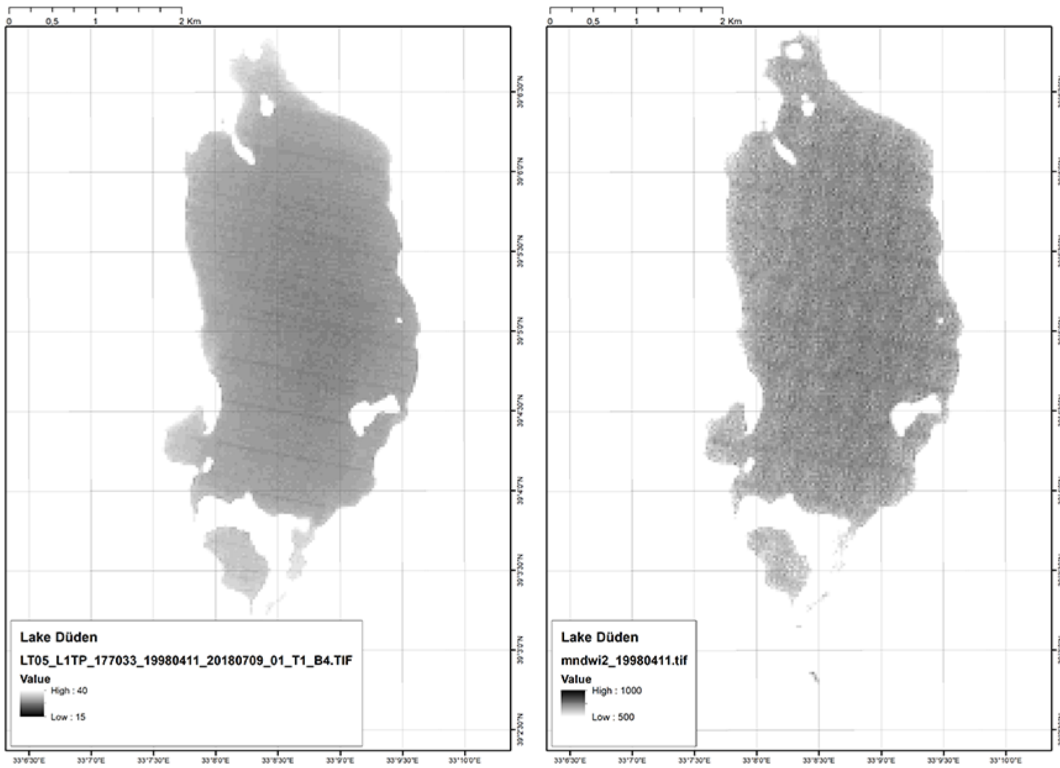

Figure 3.6: Coherent noise over the Lake Düden. Left, CN of band 4. Right, CN of MNDWI image.

Table 3.5: Zonal statistics of rectangular area on the surface of the Lake Salda on different dates of blue bands of Sentinel-2 and Landsat-8 images.

Date	Median	Mean	Std. Dev.	Min	Max
Sentinel-2					
06-03-16	1005.00	1005.88	22.46	936.00	1100.00
05-04-16	857.00	854.20	15.71	781.00	896.00
25-05-16	1207.38	1258.34	257.90	838.00	4390.00
24-06-16	1091.56	1109.14	127.73	851.00	1913.00
14-07-16	929.51	973.22	96.24	867.00	1489.00
23-08-16	1150.00	1150.63	15.48	1090.00	1215.00
12-09-16	935.00	936.67	12.56	891.00	1014.00
02-10-16	818.00	819.36	11.40	780.00	872.00
21-11-16	758.50	789.95	84.22	669.00	981.00
11-12-16	850.00	849.77	11.06	798.00	897.00
Landsat-8					
22-02-16	7636.53	7628.77	64.48	7470.00	7836.00
10-04-16	9118.46	9126.25	43.11	9032.00	9294.00
15-07-16	9418.48	9440.81	73.75	9288.00	9794.00
16-08-16	11014.45	11027.73	83.31	10793.00	11299.00
17-09-16	8196.00	8200.77	21.80	8151.00	8297.00
19-10-16	7984.00	7987.75	25.44	7930.00	8115.00
20-11-16	7422.00	7422.61	17.24	7372.00	7482.00

CHAPTER 4

RESULTS AND DISCUSSION

In this chapter, the results obtained from the proposed methodology are given. Also, Lake Salda is investigated in more detail as a case study. The average date difference between sample dates and the satellite images is 3 days. The maximum difference is 16 days because of the cloudy periods over the area.

4.1 Mapping the water

The lake surface area is determined from MNDWI data. The performance of this index is evaluated in published papers in which Landsat-5 and 8 data were used to monitor the changes in lake surface areas (Appendix A.1, Appendix A.2) . The index performed very well in mapping the lakes in KCB and BCB. As an example lake from KCB, Lake Düden is mapped for the years between 1985-2020 in 5-year periods as presented in Figure 4.1.

In further detailed studies on the KCB, meteorological and hydrological parameters are included and discussed in details on the published paper presented in the Appendix A.1. For KCB, Figure 5b in A.1 shows the SPEI which is highly related with meteorological parameters temperature and precipitation, and the surface areas of the lakes Düden and Uyuz. The results of this study showed that about 50% of the surface area of these three lakes was lost during the 35-year period. Also, Lake Uyuz has a lower dependence on groundwater than the other two and this shows the hydrological differences of the lakes. After 2000, there is a significant decrease in SPEI values and surface areas which indicated the water deficit in the KCB. In addition to this, the uncontrolled use of groundwater for irrigation purposes causes a significant decrease

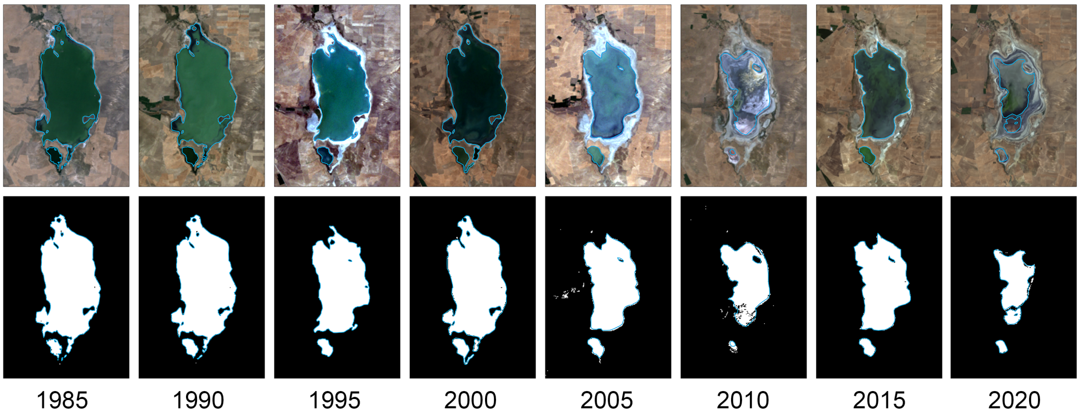

Figure 4.1: The True Color Image (TCI) of Lake Düden (above), surface water boundary detected using the MNDWI binary image (Landsat-5 and 8 is used.) Retrieved from (Yılmaz et al., 2021).

in groundwater levels in KCB (Appendix A.1).

Other published paper on BCB showed that there is a trend of increasing temperature while no-change in precipitation (Appendix A.2 - Figure 8). As a result of this, water loss is increasing due to the increase in evaporation and transpiration. Also, negative SPEI values indicate dry conditions, which has an additional effect on water loss (Appendix A.2 - Figure 5). As discussed in the paper (Appendix A.2), each lake has different responses to the SPEI. For example, while changes in deep lakes (e.g. Lake Burdur and Salda) depend on meteorological events, shallower lakes (e.g. Lakes Acıgöl and Akgöl) depend on groundwater and streamflow (Appendix A.2).

The climate projection models used for the BCB predict an increase in annual mean temperature of up to 1.18 °C, an increase in annual precipitation of 10 mm per year where the long term mean annual precipitation is 413 mm. Also, an increase in the potential annual evaporation of 200 mm per year (Appendix A.2) is predicted. The budget analysis of Lake Burdur (the third deepest lake in Turkey) and the projected SPEI values (Appendix A.2-Eq. 1, Figure 9, Figure 10) show that there is a high risk that the lake may reach the critical level due to excessive evaporation and water abstraction for irrigation until 2080 (Appendix A.2-Figure 9). Lake Acıgöl also faces great shrinkage, since its water balance is highly controlled by the water use of the salt and sulfate facilities around the lake.

Table 4.1: A sample view of flat file.

FCODE	Name	EC	B2	B3	B4	B5	B6	B7	B8	B11	B12
FT1_01	Godet_Dam	357.50	910	806	762	718	764	795	745	281	488
FT1_02	Ibrala_Dam	293.60	1203	1153	830	814	853	908	796	441	557
FT1_03	Ayranci_Dam	306.00	1384	1567	1155	992	948	995	909	327	567
FT1_04	Ivriz_Dam	261.80	1123	1102	2157	2239	2640	2939	2731	322	2548
FT1_05	Akgol	3039.00	1055	1054	896	1178	1876	2206	1644	613	541
FT1_06	Yollarbasi_Dam	302.20	1146	1181	1542	1598	1783	2007	3109	480	1588
FT1_07	Delicay_Dam	383.10	1343	1477	1046	912	831	872	870	379	534
FT1_08	Aydogmus_Dam	386.30	1016	989	765	693	664	707	653	268	358
FT1_09	Apa_Dam	217.30	1099	1011	627	597	575	597	536	418	346
FT1_10	Sugla_Lake	231.30	1326	1286	649	695	680	662	527	813	430

4.2 Field and Satellite Data

The spectral band values (B2, B3, B4, B5, B6, B7, B8, B11, and B12) from Sentinel-2 MSI Level-1C data corresponding to the EC values sampled at the field are generated as a flat file. A sample view is given in Table 4.1 and all data are presented in Appendix B.1.

4.3 Clustering

The dataset used in the clustering consists of the EC values sampled at the lake and the associated Sentinel-2 band values. The clustering is applied for 165 sample points since the sampled lakes have different characteristics and conductivity values. K-means clustering method is used after deciding the number of clusters from the result of Elbow method (Tibshirani et al., 2001). According to the elbow method, the optimal clustering number is obtained as 4 (Figure 4.2) since beyond 4 cluster, the effect of the clustering is negligible. When dataset is sorted, the pattern can be seen in Figure 4.3. The dataset has very wide conductivity properties. This means that there are different types of lakes in terms of conductivity. Naturally, different lakes have different colours and dynamics. Therefore, reflectance spectrums may be different. Spatial distribution of the clusters is mapped in Figure 4.4. In this figure, we can see that there is a wide spread of the lakes over the basins KCB and BCB.

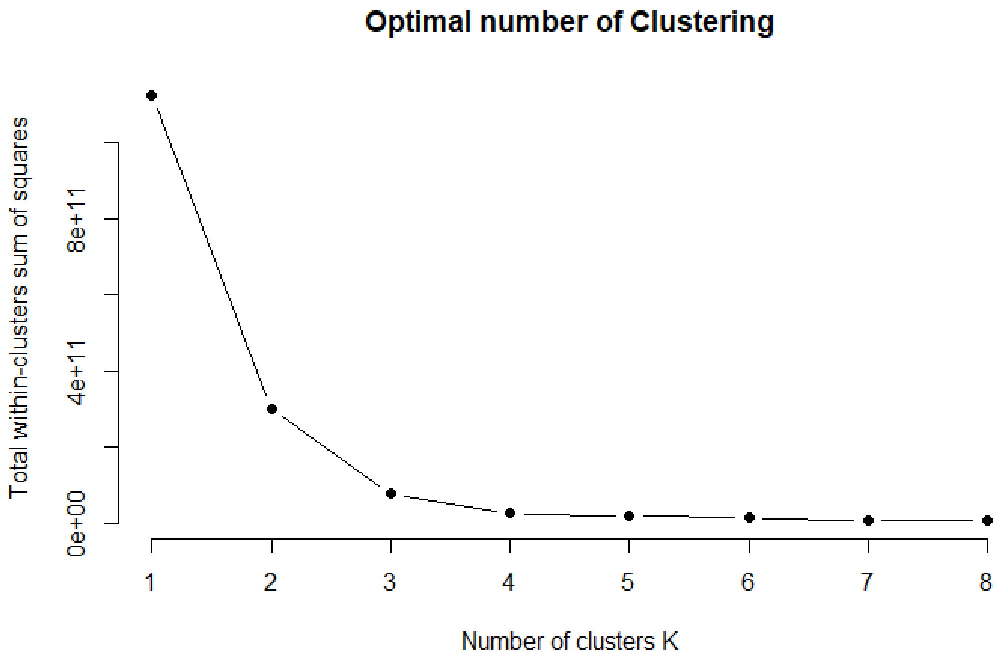

Figure 4.2: Optimal number of cluster after obtained by Elbow method.

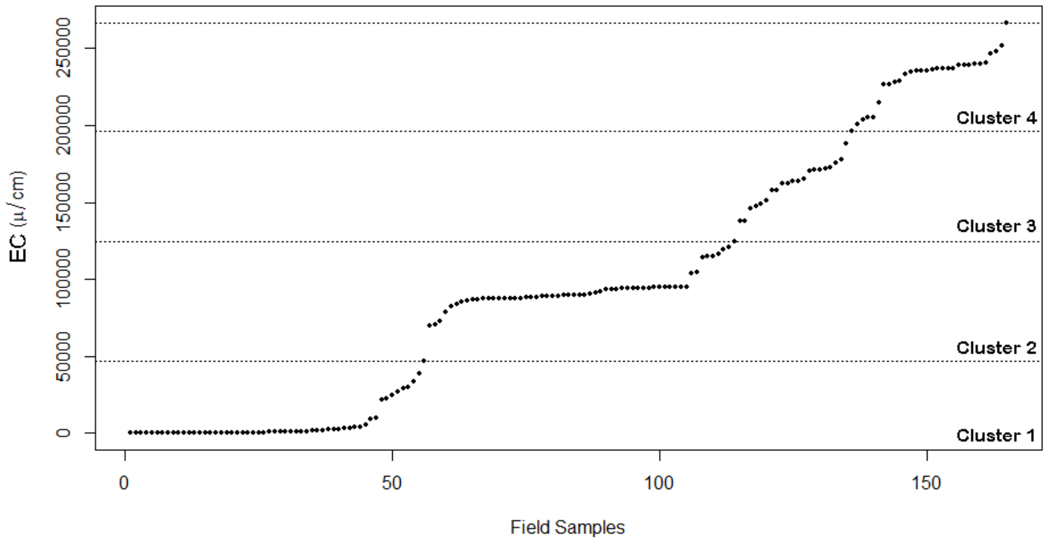

Figure 4.3: EC and cluster groups.

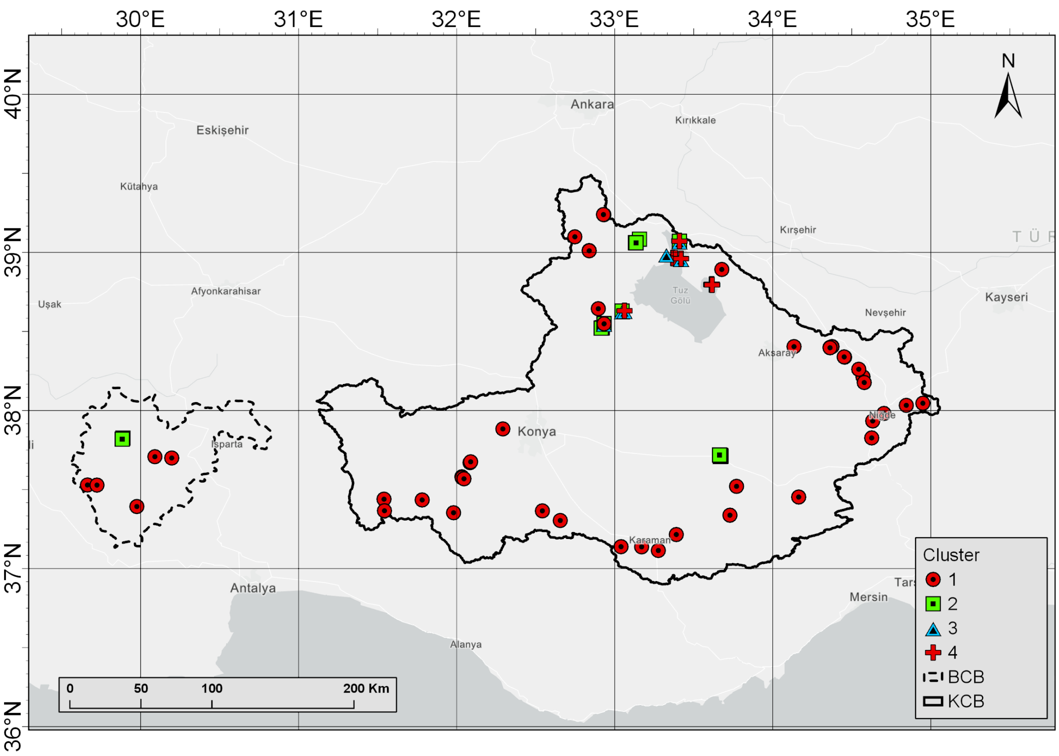

Figure 4.4: The cluster groups

4.4 Correlations between field measurements and Sentinel-2 band values

In this section, correlations between field measurements and datasets without clustering, different cluster groups are investigated.

4.4.1 Without Clustering

When all data are taken into consideration without clustering by conductivities, R^2 of the highest correlations found for Band 2 and Band 3 as 0.60 and 0.61 respectively. All R^2 values are presented in Table 4.2 and Figure 4.5. In the figure, we can see that there is a difference between Band 2, 3 and others. The correlation between the first three bands and the remaining nine bands is very low.

Table 4.2: R^2 values for both non-clustered and clustered data.

	B2	B3	B4	B5	B6	B7	B8	B11	B12
Non-cluster	0.602	0.617	0.213	0.205	0.094	0.086	0.069	0.093	-0.222
Cluster 1	0.640	0.640	-0.002	0.035	0.033	0.041	-0.019	0.581	0.066
Cluster 2	0.123	0.256	0.143	0.155	0.010	0.011	-0.016	-0.075	-0.117
Cluster 3	0.007	-0.021	0.013	0.040	0.009	-0.011	0.003	-0.143	-0.166
Cluster 4	-0.114	-0.076	-0.009	0.007	0.016	0.037	0.062	0.157	0.169

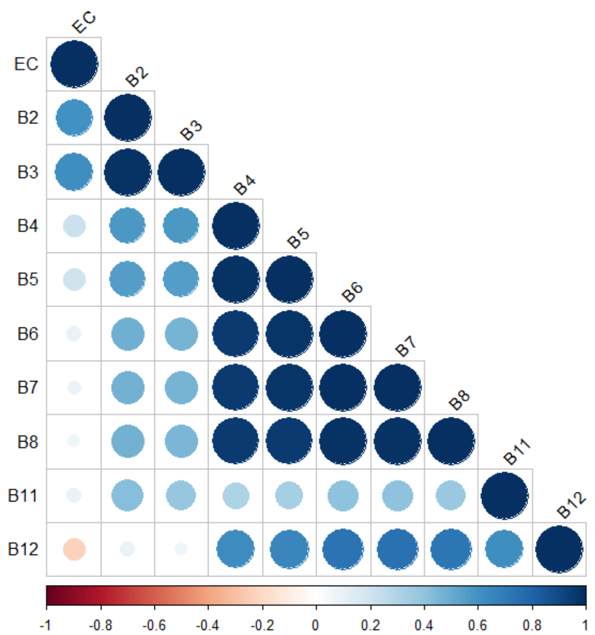

Figure 4.5: Correlation between non-clustered EC and Sentinel-2 band values

4.4.2 Cluster 1

Cluster 1 has the lowest conductivity range between 64.79 - 46775.00 µS/cm. Mostly, freshwaters, artificial lakes, and dams are in this cluster. After cluster, 56 points are placed in this group. In Table 4.2, the correlations between low conductivity cluster and Band 2, 3 and 11 is the highest among others. Furthermore, the correlations between other bands can be seen in Figure 4.6a. Bands 2, 3 and 11 has low correlation between the other 6 bands.

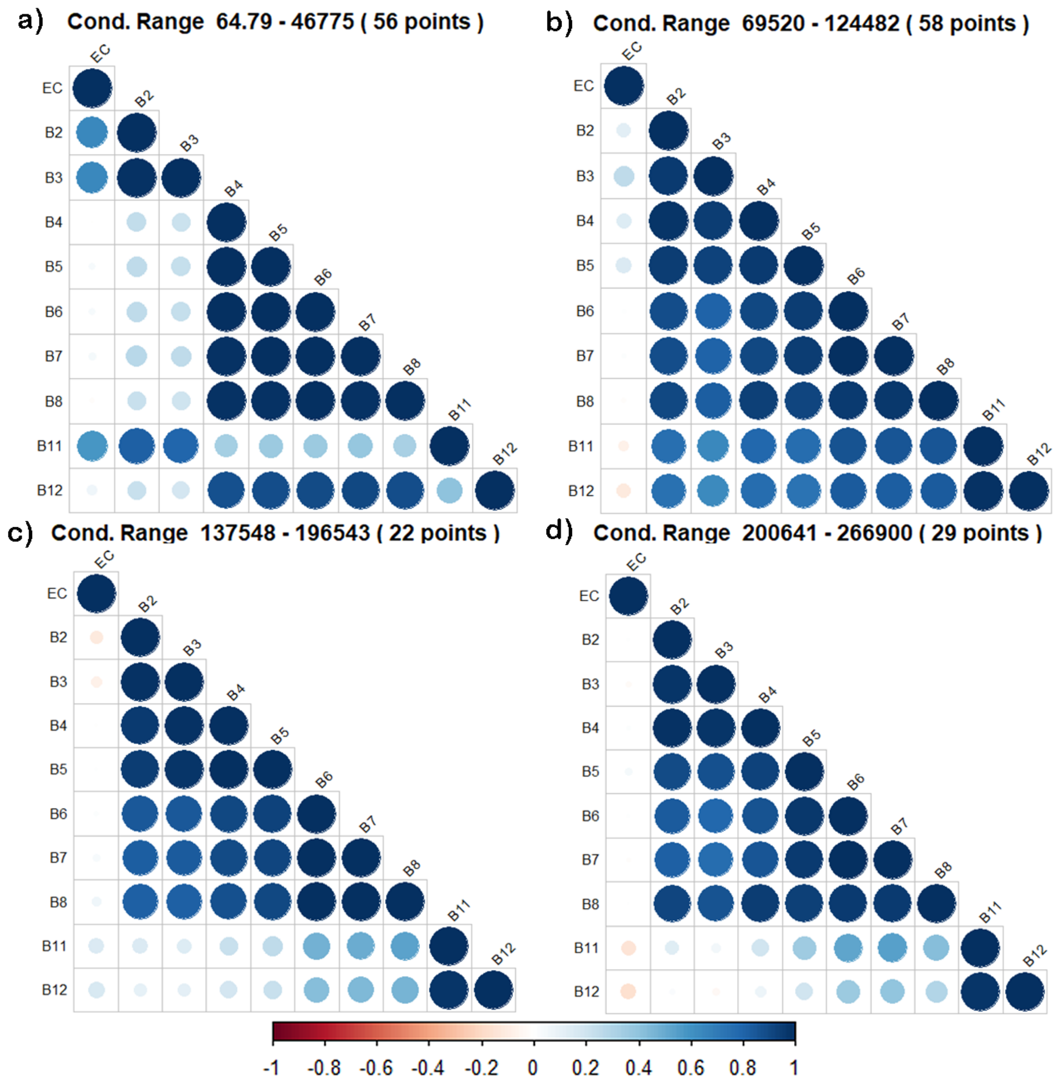

Figure 4.6: Correlation between the EC and Sentinel-2 band values for different clusters.

4.4.3 Cluster 2

Cluster 2 has the conductivity range between 69,520 - 124,482 µS/cm. After cluster, 58 points are placed in this group. The correlations between conductivity cluster and Band 3 is the highest among others. However, it is not a high correlation. On the other hand, in Figure 4.6b, the correlations between bands are significant.

4.4.4 Cluster 3

Cluster 3 has the conductivity range between 137,548 - 196,543 µS/cm. After cluster, 22 points are placed in this group.There is no significant correlation observed between EC and Sentinel-2 bands. On the other hand, there is good correlation between all bands, except Bands 11 and 12, as seen in Figure 4.6c.

4.4.5 Cluster 4

Cluster 4 has the highest conductivity range between 200,641 - 266,900 µS/cm. After cluster, 29 points are placed in this group. Mostly, iconic Lake Tuz and some salt production areas like Lakes Bolluk and Tersakan are in this cluster. There is no significant correlation between conductivity and band values. On the other hand, in Figure 4.6d, the correlations between bands are significant, except Bands 11 and 12.

As seen in the non-clustered and clustered results, there are no significant correlations between the conductivity and the Sentinel-2 band reflectances. For the whole dataset, Bands 2-3 show high correlation with conductivity values. However, results of the clusters show that there is no correlation between the bands except the Cluster 1, which is the lowest conductivity cluster.

As seen in Table 3.1, lakes were periodically visited and sampled between 2015 and 2016. There are 4 lakes in this category, Acıgöl, Bolluk, Tersakan and Lake Tuz. Therefore, we look at these lakes in a time-series (Appendix - Figure B.1). For Acıgöl and Lake Tuz there were 3 different sample locations, whereas for Bolluk and Tersakan there are 2 sample locations. There are different characteristics of sampling locations of the lakes. This is the reason behind why conductivities of the same lakes show different values. As seen in the Appendix - Figure B.1, there are missing data at some dates because of cloud contamination or sampling difficulties. There are no seasonality and meaningful correlations obtained from these samples.

4.4.6 Case Study: Lake Salda

Lake Salda is one of the important inland waters in Turkey. Lake Salda is selected as natural protected environment in 2019 because of its ecological features (Dereli & Tercan, 2020). It has some unique properties. Lake Salda is one of the deepest lakes in Turkey by its depth up to 100 m. However, there are some other comments on the depth which emphasised that the depth is up to 190 m (Dereli & Tercan, 2020). The composition of the lake is mostly alkaline with the EC range 1690 - 2124 µS/cm (Davraz et al., 2019b). Davraz et al. (2019b) compared the EC of Lake Salda in dry and wet periods, and realized that conductivity is increasing in dry period.

Lake Salda has a special place among the sampled lakes because the methodology of sampling is different. The sampling path on the surface is selected. The sampling is started at P01 (Figure 4.7a) which is located near the inlet of the lake. A similar method applied to the Lake Pontchartrain as selecting vertical and horizontal paths over the lake surface in Wang and Xu (2008). The main expectation from this study is to identify if there is any difference in the surface salinity and related band values of Sentinel-2. Therefore, we sampled the surface water with the multiprob as described in Chapter 3.1.2, approximately in each 100 meters and 50 cm depth. The date difference between sampling date (27.07.2021) and the nearest-time Sentinel-2 image (25.07.2021) is 2 days.

The buffered (8 x 8 pixels) and the exact pixel points are extracted from the images. In Figure 4.7a, the path of sampling can be seen.

4.4.6.1 Results of the Case Study

EC and extracted band values for 27 sample points are given in the Appendix B.2, B.3. The conductivity values are also presented in Figure 4.8. As expected, conductivity values are not changing dramatically over the lake surface area, as seen in Figure 4.8. Salda has an inlet near the field sample point (P01) (Figure 4.7). Sikora and Kjerfve (1985) and Wang and Xu (2008) commented that there are fluctuations in the estuarine lakes which implies the existence of an inlet river. In Figure 4.8a, first point is a sample from the inlet of the lake. Also, Sentinel-2 band values are grapically

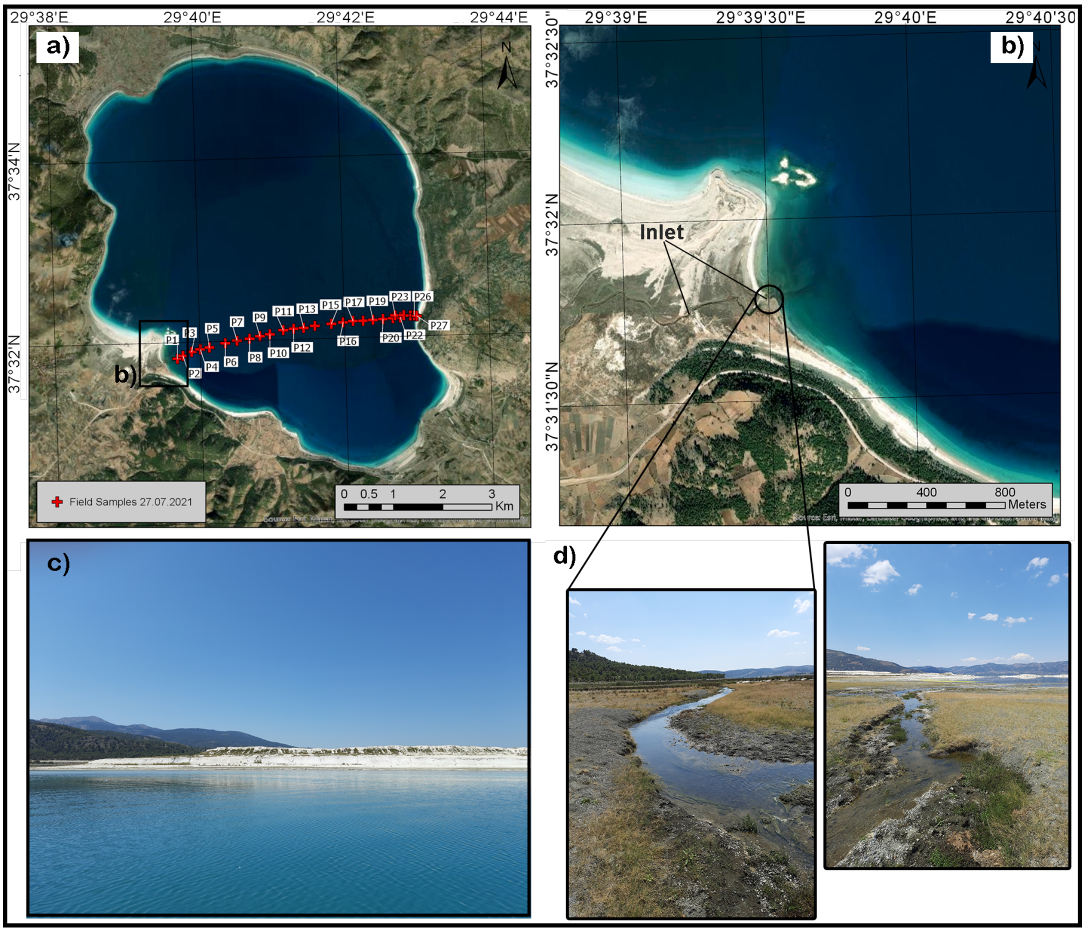

Figure 4.7: a) Sample points over surface path, b) Close look up to the inlet area. Below, photograph is shoot on sampling date (25.07.2021) and place. Photos from Lake Salda; c) shoreline, d) inlet area.

presented in Figure 4.8.

The correlations between conductivities of sampled points and the Sentinel-2 data are given in the Table 4.3. Also, correlations with respect to Sentinel-2 bands can be seen in Figure 4.9.

The results of this case study showed that, except bands 2 and 3, there are small correlation between the conductivity and the exact band reflectance values. The method of buffering has slightly lower correlation results than exact point method. As a contradiction to the all conductivity data over the KCB and BCB (Figure 4.5), the bands, except bands 2 and 3, have very low correlation. Also, as seen in Figure 4.9 there are no significant correlation.

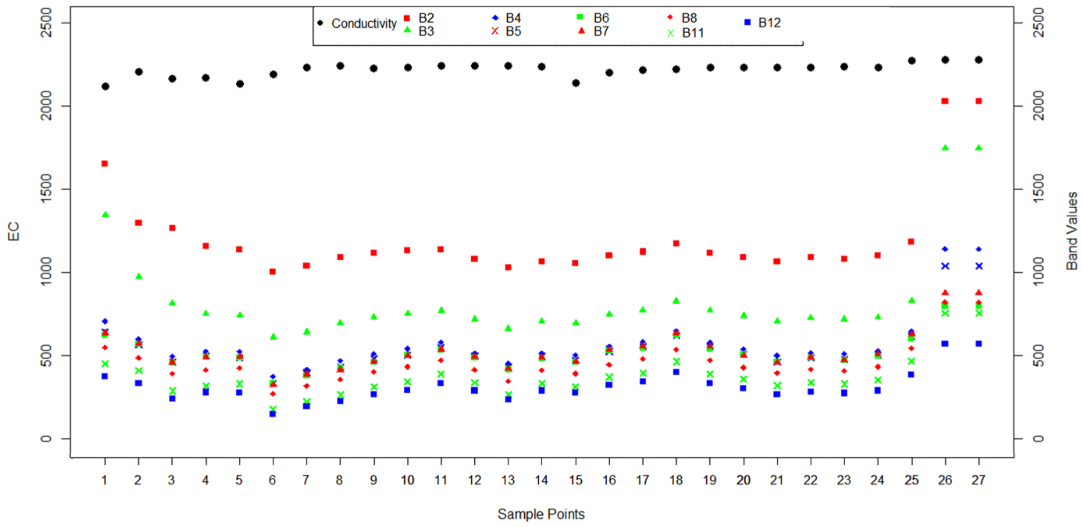

Figure 4.8: EC and Sentinel-2 band values of exact sampled points in 25.07.2021.

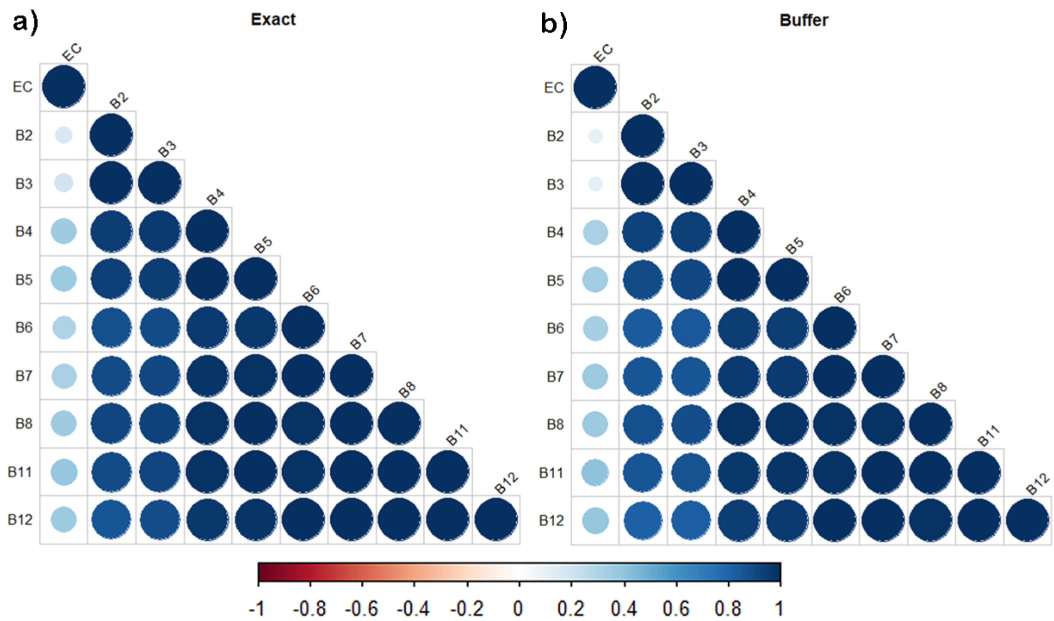

Figure 4.9: a) Correlation of conductivity and exact pixel values of field points, b) 8 x 8 median filtered pixel values.

Lake Salda is in the first cluster (Figure 4.6a) with respect to its conductivity. However, the correlation results in Table 4.3 show different pattern than the first cluster. While bands 2, 3 and 11 show highest correlation with conductivity values in the first cluster, bands 2 and 3 has the lowest correlation with surface conductivity of Lake

Salda in the case study.

Dörnhöfer and Oppelt (2016) emphesized that different lake properties affect the reflectances of the surface of the lakes. Therefore, there are many emprical studies for specific area and sensors are developed, rather than general aspect (Dörnhöfer & Oppelt, 2016).

In our dataset, there are many different types of lakes. For the low conductivity classes, there are mostly freshwater dams and freshwater natural lakes exist. Also, chemical compositions of the lakes show variations. For example, Lake Burdur is an alkaline and very deep lake with high ion compositon, whereas Lake Acıgöl is hypersaline soda and very shallow lake situated in a tectonic depression (Çolak et al., 2022). Therefore, in this study, it was found that raw band and conductivity correlations is not enough to develop a general relationship between electrical conductivity and reflectance values of optical bands.

Table 4.3: R^2 values for exact and buffered pixels.

	B2	**B3**	**B4**	**B5**	**B6**	**B7**	**B8**	**B11**	**B12**
Exact point	0.168	0.194	0.351	0.368	0.300	0.329	0.353	0.385	0.366
Buffered point	0.160	0.176	0.249	0.253	0.246	0.253	0.250	0.304	0.361

CHAPTER 5

CONCLUSION

Studies showed that with climate change and an increase in temperature patterns, lakes are getting in target. As a semi-arid region; KCB and BCB are in this target list. In KCB, the surface areas of the lakes are significantly decreased, as observed in Lake Düden. In the studied dataset, there are huge variety in lakes in terms of area, depth, composition, colour, conductivity etc. Therefore, monitoring of these lake is an important target for the better environmental future.

Optical satellite imagers are very powerful at mapping the water surface area even in vegetative lakes using MNDWI. In this study, time-series of many lake surface areas are measured. Also, Landsat legacy provides land images since 1984 and this is a very important tool for monitoring the changes in the land cover. Sentinel-2 has some advantages over the Landsat-8 in terms of its spatial and temporal resolutions.

Naturally, in all optical imagers, there are some artefacts. One of them is Coherent Noise problem, which occurs mainly on homogenous surfaces such as lakes, seas, and desserts. Therefore, for surface analyses, this noise effect should be considered. In this study, the sample pixels were selected according to this as one point and its neighbours, rather than averaging the band values for all the surface area of the lake under investigation.

The lakes are clustered according to their conductivity levels. Sentinel-2 bands are compared with each cluster. Unfortunately, there are no meaningful correlations between the bands and the *in-situ* conductivity measurements. In addition, during the field trip in 2021, surface conductivity values of Lake Salda were measured, and then, correlation between measurements and Sentinel-2 bands are calculated. Unfortunately, again there is no meaningful correlations obtained. Generally, field samples are taken from the shores of the lakes, so this may cause the mismatch with the lake surface conductivity. For example, in Lake Salda, conductivity values are uniformly distributed while, in the estuarine part of the lake, conductivity values are slightly lower.

Different lakes show different reflectance properties, and their conductivity levels depend on many other parameters; therefore, the construction of a general correlation without considering these parameters is not applicable in this level of study.

For future steps, more field studies should be conducted periodically in different types of inland waters. Also, many other parameters such as depth, colour, turbidity, temperature, precipitation, and hydrological dynamics of the lakes should be included in the analyses. These parameters can be investigated using artificial intelligence methods, as the number of samples increases.

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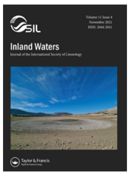
Appendix A

APPENDIX A

A.1 Paper A



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Decadal changes in size, salinity, waterbirds, and fish in lakes of the Konya Closed Basin, Turkey, associated with climate change and increasing water abstraction for agriculture

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ABSTRACT
The Konya Closed Basin (KCB) in Turkey has a cold semiarid to warm Mediterranean climate and hosts the largest Turkish freshwater lake, Lake Beyşehir, and the iconic saline Lake Tuz. Using published as well as our own ground-truth and remote sensing data, we provide (1) a brief description of the paleoenvironmental changes in the KCB; followed by (2) a detailed description of the changes in land use, crop farming, groundwater and surface water levels, and climate; and (3) associated changes in lake water surface area and salinity as well as in waterbird and fish communities during the past 40 years. The KCB is intensively farmed, and the farming of mainly water intensive crops has increased substantially, especially since 2000. This, combined with climate warming, has led to a substantial rate of reduction of the groundwater level (up to 1 m/yr) and the surface area of the lakes and wetlands, followed by an increase in salinisation, and even complete loss of several wetlands. Three globally threatened waterbird species face extinction in the basin, and 18 of the 62 previous breeding species have already been lost. The KCB has 38 fish species, of which 74% are endemic and 61% are considered threatened or near threatened. Modelling projections using various climate and land use scenarios predict serious additional reductions of the water level in the future due to climate change, leading to deterioration (or complete loss) of lake ecosystems and the services they provide.

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Introduction

Globally, temperature and precipitation patterns are predicted to change markedly as a result of climate change (IPCC 2007, 2014). Particularly regions with a cold or hot semiarid to arid and Mediterranean climate are expected to be strongly affected (Giorgi 2006, Vicente-Serrano et al. 2014). In the Mediterranean region, a major increase of land in drought is expected (Pegion 2012, Russo et al. 2019), and water abstraction, not least for irrigation purposes, is predicted to increase markedly (Rodriguez Diaz et al. 2007, Yano et al. 2007) because of reduced net precipitation. In addition, a global increase in the demand for food by a growing population and a shift to more water intensive crops will accelerate the agricultural water use and may cause salinisation of lakes and soils (IPCC 2007, Jeppesen et al. 2020).

The magnitude of the future changes poses a major threat to the functioning and biodiversity of inland aquatic ecosystems. Many lakes may dry out temporarily or permanently with rising temperature, while salinisation in the remaining waterbodies may lead to reduced biodiversity (Williams et al. 1990, Schallenberg et al. 2003, Flöder and Burns 2004, Jeppesen et al. 2015) and loss of ecosystem functioning (Lin et al. 2017, Vidal et al. 2021). To date, however, knowledge of the effects of warming on saline lakes is fragmented and far from

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the level achieved for freshwater lakes (Jeppesen et al. 2015, Cañedo-Argüells et al. 2019).

Closed basins in semiarid or arid regions often respond rapidly to geological and climatic changes because any slight alteration may have significant consequences for their water balance. Moreover, a few years of prolonged drought may lead to enhanced salinity and, consequently, alteration of the ecosystem characteristics of the lakes (Levi et al. 2016, Beklioğlu et al. 2018). We focus on the semiarid Konya Closed Basin (KCB), the largest closed basin of Turkey, spanning almost 50 000 km^2 and covering 7% of the country's land area. It has a population of 3.2 million and supports extensive agricultural activities that depend heavily on surface water and groundwater abstraction, implying that many natural streams have been regulated and channelised for dam construction to provide water for irrigation. Despite this, the KCB still exhibits an astonishing biodiversity and a high degree of endemism, which reflects its role as a refuge during the ice ages in the Quaternary period (Eken et al. 2006, Şenkul and Kaya 2017). The basin is home to several globally threatened waterbird species and is an important area for breeding, wintering, and migrating waterbirds (Kirwan et al. 2010). The KCB has large freshwater and saline lakes as well as extensive marshes, some of which are the remnants of a paleolake, Lake Konya, which dried out in the early Holocene (Roberts 1983). The region is located at the intersection of 3 ecoregions and comprises 2 national parks, 1 strict nature reserve, 2 Ramsar sites, 10 Important Plant Areas (IPAs; Özhatay et al. 2003), 11 NATURA 2000 areas (Republic of Turkey Ministry of Agriculture and Forestry 2018a), and 16 Important Bird Areas (IBAs; Eken et al. 2006, Kirwan et al. 2010, BirdLife International 2020).

In this overview, we first provide a brief paleoecologically based description of the KCB since the last glacial maximum. We then focus on the changes in climate, land use (mainly agriculture), and groundwater level that have occurred in the past 4–6 decades and reveal how these changes have affected the lakes in terms of size, salinity, and fish and waterbird communities using remote sensing, field data, literature, and existing databases. Included are also 2 case studies focusing on the recent drastic transformations occurring in the large wetlands, the Ereğli, Eşmekaya, and Hotamış marshes, as well as the future of Lake Beyşehir, the largest freshwater lake in the basin and in the whole Mediterranean region. Finally, we discuss the future of the KCB lakes seen in the light of global change, with emphasis on the need for mitigation initiatives.

Material and methods

Remote sensing analyses and agricultural data

We used Sentinel-2 MSI and Landsat data on the long-term (>40 years) changes in the lake surface area and salinity of 3 lakes in the region, Lakes Düden, Little Düden, and Uyuz. These lakes represented a wide range of salinity (48.4, 65.3, and 1.2 ppt of measured salinity, respectively) while having similar meteorological/climatic conditions due to their spatial proximity. Optical satellite images (Landsat and Sentinel data) including 80 noncloudy Landsat 1–3 MSS, Landsat 4-5-7-8 TM, ETM+, OLI data, and 6 noncloudy Sentinel 2A images (for 2016–2019) were downloaded from www.earthexplorer.usgs.gov. The Sentinel images were processed using Sen2Cor (software processing Sentinel 2 data, ESA). For the Landsat image series, Dark-Object Subtraction atmospheric correction technique was applied using the Semi-Automatic Classification plugin in QGIS (Congedo 2016). Images were preprocessed (radiometric and geometric corrections) before determining the lake surface areas. The Normalised Water Index and the Modified Normalised Water Index (Xu 2006) were used to assign the water pixels, which were subsequently checked for correctness against the normalised vegetation index for the vegetation-covered lake surface area.

Because water is highly absorptive within the near and shortwave infrared spectrum, the majority of water-leaving radiance occurs within the visible spectrum with slight variations dependent on temperature and salinity (Topp et al. 2020). Shortwave infrared (SWIR) and red-edge spectral bands were used to improve the salinity detection of the spectral indices (Bannari et al. 2018, Wang et al. 2019). Thus, SWIR bands (2.2 µm of Landsat 8, 2.205 µm of Landsat 5, and 2.194 µm of Sentinel data), near infrared (NIR) bands (0.865 µm of Landsat 8, 0.835 µm of Landsat 5), and a red-edge band (0.78 µm) of Sentinel data were used to create the salinity index (SWIR-NIR)/(SWIR + NIR). The salinity index was calibrated using ground truth data (using a YSI ProDSS Multiparameter Water Quality Meter, Yellow Springs, OH, USA) obtained for 14 lakes in the region in June 2020 having a salinity between 0.5 and 230 ppt.

Monthly mean air temperature and annual precipitation data were obtained from Turkish State Meteorological Service for the period 1970–2020. After testing the normality and homogeneity of the data, Mann Kendall and Şen's trend analysis (Şen 2011) were applied. We used the Thornthwaite method (Thornthwaite and Mather 1955) to estimate evapotranspiration and the standardised precipitation evapotranspiration index (SPEI; Vicente-Serrano et al. 2010) for the time scales

3, 9, 12, 24, 36, and 48 months to determine which time periods best describe the hydrologic response of small waterbodies in the study area. The groundwater levels at the observation wells located in the basin were obtained from the State Hydraulic Works.

Data on agricultural land area, crop patterns, and their biomass production (i.e., crops, vegetables, fruits) for 1980–2019 were obtained from the database of the Turkish Statistical Institute (TUIK 2020).

Populations of globally threatened waterbird species and fish

We compiled population estimates and observation records for globally threatened waterbird species in the region for 1960–2020, including common pochard (*Aythya ferina*), marbled teal (*Marmaronetta angustirostris*), white-headed duck (*Oxyura leucocephala*), slender-billed curlew (*Numenius tenuirostris*), and red-breasted goose (*Branta ruficollis)*, supplemented with sighting records in Cornell Lab of Ornithology's databases (Cornell Lab of Ornithology 2019) as well as midwinter waterbird censuses (DKMP 2019) to evaluate population changes in the KCB. A full list of the resources used and a detailed description of the methodology followed for our final abundance estimates is in Supplemental Material S1.

We also quantified the change in the species richness of breeding waterbirds in the KCB by analysing data gathered in 2 breeding bird atlases from the period 1998–2018 when the wetlands of the basin underwent substantial degradation. The first breeding bird atlas survey of the KCB was conducted in 1998 (Eken and Magnin 2000). The second survey for the atlas was conducted at a national scale between 2014 and 2018 (Boyla et al. 2019). Because the surveys for the 2 atlases used the same coordinate and grid systems and similar methodologies, they are practically comparable. We chose 50 km × 50 km spatial resolution because the most recent atlas survey did not report results at the finer resolution. For the atlas squares coinciding with the KCB border, only bird sightings obtained within the borders of the KCB were included in the analyses (see Supplemental Material S2 for detailed descriptions of methods).

We collected information on fish species and their status in the KCB from a wide range of literature (Supplemental Material S3). The validity of fish names was checked using Fishbase (Froese and Pauly 2020) and Catalog of Fishes (Fricke et al. 2020). The conservation status of species was obtained from the IUCN Red List (IUCN 2020).

Results

Konya basin – paleoenvironmental history

The KCB is located at a mean elevation of 900–1050 m in the south Central Anatolian Plateau (Fig. 1). The flat and mostly marl and limestone terrain of the basin, formed as a result of lacustrine deposition during the Quaternary (Roberts 1983), is enclosed by the Taurus Mountains (>3000 m) to the south and the west and the uplands of the Anatolian plateau to the east and the north. The basin housed the extensive Paleolake Konya (Fig. 1), during most of the Quaternary until the end of the last glacial period, but with intermittent dry-outs (Kuzucuoğlu et al. 1999). Although the basin is endorheic with no surface outflows, the southern basin has a few karstic outlets to the deeper strata, which probably prevented complete salinisation of the basin during the paleo-history (Roberts 1983, Kuzucuoğlu et al. 1999).

The KCB lakes display complex responses to climate change. High water levels have appeared in cold and dry periods with prominent ice cover when evaporation was low (Roberts 1983). In addition, despite the limited precipitation in the basin in the cold periods, the seasonal snow build-up and consequent thawing of the glacial formations in the Taurus Mountains to the south, where precipitation was presumably higher than in the northern basin, have contributed to the positive water balance of the lakes (Fontugne et al. 1999). Whether the water levels are principally determined by changes in precipitation or evaporation has been debated (Roberts et al. 1999), but recent research using stable isotope signals indicates a strong role of evaporation, especially during the interglacial periods and in the early Holocene (Roberts et al. 2016).

In the last glacial maximum (25–20 ka BP), Paleolake Konya reached its largest surface area >4000 km^2 and a maximum depth of 30 m (Roberts 1983, Fontugne et al. 1999, Roberts et al. 1999), and Lake Tuz was 15 m deeper than today (Kashima 2002). The lakes started to recede between 17 to 13 ka BP (Roberts 1983, Kuzucuoğlu et al. 1999, Roberts et al. 1999) but exhibited markedly higher water levels than the current level during the Younger Dryas (13 ka BP). The cold intermittent period marked the last high stand of Paleolake Konya, which fragmented into smaller isolated waterbodies in the following millennia, not least when warmer conditions predominated at the beginning of the Holocene (Roberts 1983).

In the early Holocene, warmer and wetter conditions prevailed in the region (Dean et al. 2015, Roberts et al. 2016) and the landscape shifted from steppe plant

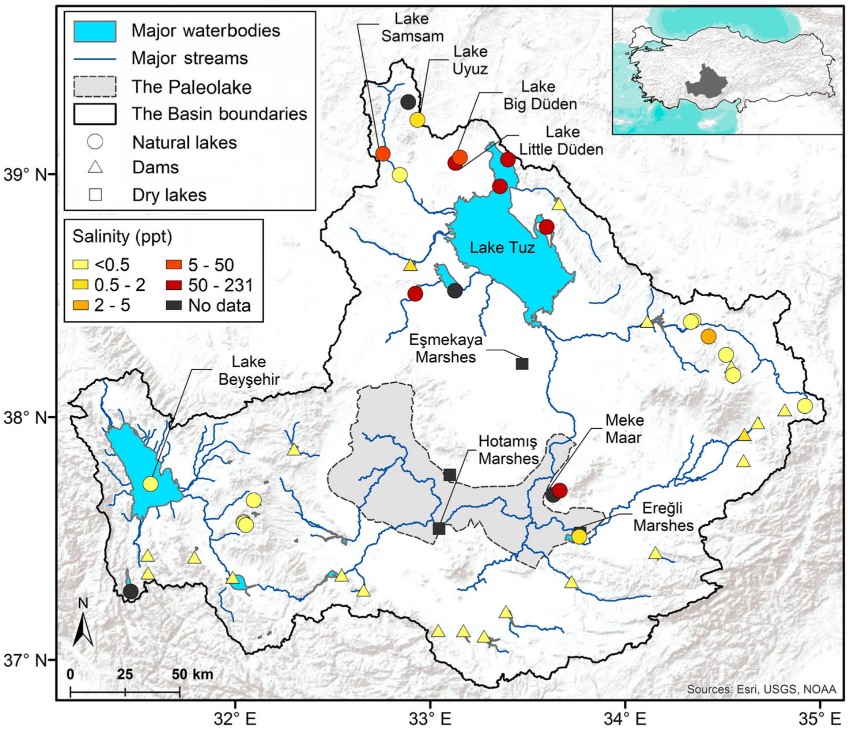

Figure 1. Konya Closed Basin (KCB) showing the location of KBC in Turkey (inset), its boundaries, its major watebodies; salinity (ppt) of its lakes and reservoirs based on YSI ProDSS multiprobe measurements taken in June 2020, and the greatest extent of the Paleolake Konya during the last glacial maximum.

dominance (e.g., *Chenopodiaceae*, *Artemisia*; Roberts et al. 2016, Woodbridge et al. 2019) to (oak) tree dominance (Roberts et al. 2011). However, the simultaneous dry-out of Paleolake Konya suggested that the precipitation pattern changed less than the temperature-induced increase in evaporation (Roberts 1983). The early Holocene was also the first period in which human activity had an unequivocal impact on the environmental landscape and altered the vegetation (Asouti and Hather 2001), likely as a result of animal herding and early crop farming activities. Çatalhöyük, one of the most populous Neolithic settlements so far discovered, with a population of 10 000 at its height, was founded in the southern alluvial margins of the basin and remained there for more than one millennium (Hodder 1996, Roberts 2002, Roberts et al. 2011, Asouti and Kabukcu 2014). After the Holocene climatic optimum (9000–5000 BP), a period of gradual aridification occurred in the mid-Holocene (Dean et al. 2015). The late Holocene witnessed a climatic amelioration accompanied by an increase in settlement numbers (Allcock and Roberts 2014) in the region, called the Beyşehir Occupation (BO) phase (~3000–1300 BP). The basin was repopulated, with widespread arboreal agricultural areas with fruit trees (Eastwood et al. 1999). Following the centennial hiatus after the BO phase, agricultural activities regained momentum in the area, but this time with a greater emphasis on cereal farming and pastoralism during the last millennia (England et al. 2008). This pattern of agro-pastoralism remained stable well into the modern period; thus, by the mid-19th century and afterward in the Republic period, cereals, especially rye (*Secale cereale*), markedly increased in the pollen record (England et al. 2008). In the more recent past, with the development of irrigation techniques, water intensive crops (e.g., sugar beet and legumes) increased their share while livestock production became restricted to the mountainous regions where irrigation was not possible (Fontugne et al. 1999).

Konya Closed Basin – recent history

Climate, precipitation, evaporation, and temperature changes

Today the KCB has a diverse climate. Thus, in the southwest basin the climate is Mediterranean while a cold-dry steppe climate prevails in the northern basin and a desert climate in the central Karapınar region.

Long-term annual mean precipitation in the basin was 340 mm during 1970–2020; the lowest (289 mm) was observed in the Karapınar and the highest (747 mm) in the Seydişehir region (Fig. 2). Mann Kendall and Şen's trend analysis (Şen 2011) of existing data indicated an increase in annual mean temperatures (~0.045 °C/yr) at most of the stations used in our study and a decrease in annual precipitation at some, but not all, sites (Fig. 2). Evaporation from the water surfaces is measured by pan evaporation by DSI in the basin for months April–October. A maximum of 262 mm in July and a minimum of 100 mm in October were recorded during 1970–2013.

Changes in land and water use

According to the Coordination of Information on the Environment Land Cover 2012 first-level classification database, produced by visual interpretation of high-resolution satellite imagery to create land cover/use maps, ~56% of the KCB area was used for crop farming across 27×10^3 km^2, of which 8×10^3 km^2 were irrigated (Republic of Turkey Ministry of Agriculture and Forestry 2018b). Although a semiarid climate prevails in most of the KCB, with 70% of the precipitation occurring outside the crop-growing period, cultivation of water intensive crops has been widespread in the KCB farmlands (Berke et al. 2014).

The municipalities of Konya and Karaman cover most of the KCB (40×10^3 and 9×10^3 km^2, respectively). From 1995 to 2019, the total agricultural area of Konya and Karaman decreased by 27% (from ~30×10^3 to 22×10^3 km^2; TUIK 2020). Despite these reductions in cultivated area, the crop production increased substantially after 2000, coinciding with increased use of fertilisers and water for irrigation (Konya Directorate of Provincial Agriculture and Forestry 2019; Fig. 3). In 2019, the dominant crops were sugar beet, maize, wheat, alfalfa, and barley, accounting for 28%, 18%, 9%, 9%, and 6%, respectively, of the >22×10^6 tonne of agricultural production (TUIK 2020).

As the total production increased, the extent of irrigated land and water use also increased (Fig. 3). In 2019, >3×10^3 hm^3 of water was used to irrigate 6×10^3 km^2 in Konya, more than the calculated amount needed if multiplying the irrigation demand of each crop with their cultivated area (Republic of Turkey Ministry of Environment and Urbanisation 2020), which is a conservative value. In 2008, sprinkler and drip irrigation methods were introduced for irrigation as a water saving potential at the expense of the more primitive surface irrigation (Republic of Turkey Ministry of Environment and Urbanisation 2020).

Although sugar beet is the second most water intensive crop, its production in the KCB has increased with the establishment of new sugar factories (i.e., Konya, Çumra Sugar Factory with a capacity of 0.3×10^6 tonne/yr) and privatisation of existing ones (i.e., Konya Sugar Factory in 1991 and Turkish Sugar Factory in 2008), a result of the new "Sugar Law" (Türkşeker 2020) that facilitates sugar beet production in the area, with major implications in the form of enhanced water use for irrigation (Fig. 3).

Change in groundwater resources

The water potential of the basin is estimated at 4.7×10^3 hm^3/yr, 42.8% of which comes from groundwater resources (Dolsar 2015). The basin has 22 reservoirs, mostly designed and operated for irrigation purposes. In 2015, the annual amount of water used in the KCB was 5.0×10^3 hm^3, of which 95% was used for irrigation, 4% for domestic water supply, and 1% for industrial purposes.

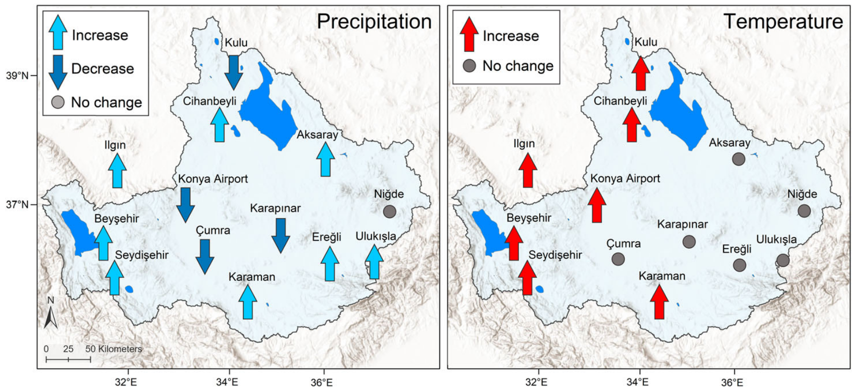

Figure 2. Trend analysis of annual precipitation and mean annual air temperature for selected meteorological stations for the period 1970–2020 in Konya Closed Basin based on data from the Turkish State Meteorological Service.

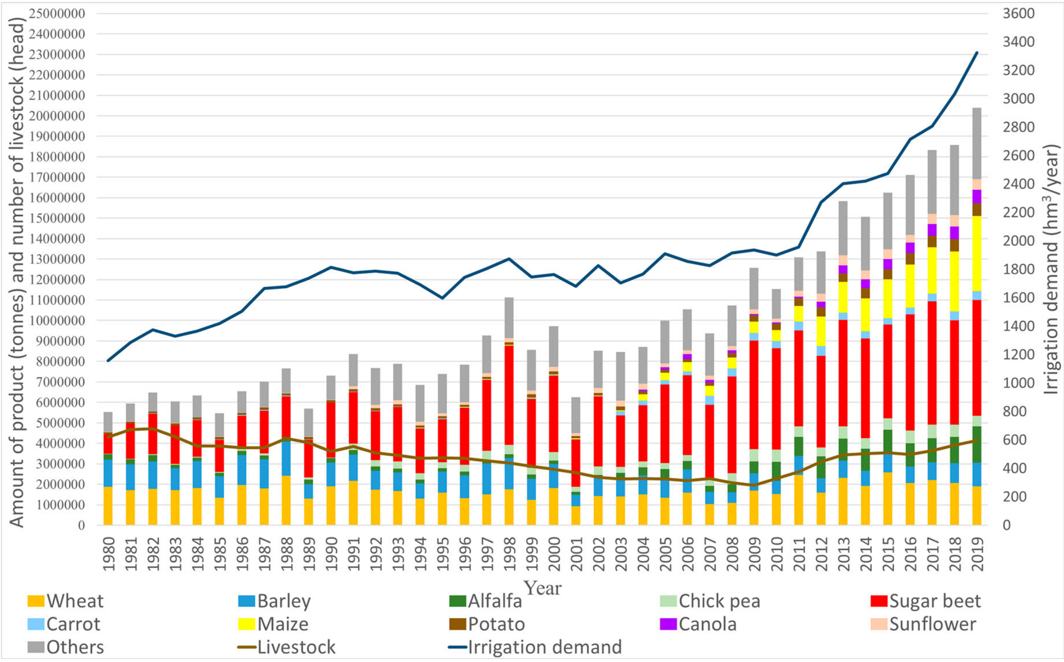

Figure 3. Total agricultural products, number of livestock, and estimated irrigation amount in the Konya and Karaman provinces between 1980 and 2019 (data taken from TUIK 2020). Net amount of irrigation water for crops largely cultivated in the Konya Closed Basin (upper left) (Berke et al. 2014) and estimated total irrigation demand of main crops. Estimates were obtained by multiplying the area in which the crop was cultivated with the net irrigation requirements, assuming that 85% of KBC's winter cereals were fed by rainfall (Topak et al. 2008).

The extra water needed was provided by transfer from neighbouring catchments (Gembos and Blue Tunnel projects, 0.5×10^3 hm^3/yr; Dolsar 2015). A 5–10% decrease in precipitation is estimated to result in a 34% decrease in surface water (Dolsar 2015). Of the 88 394 wells in the KCB used for irrigation, 41% were unlicensed in 2013 (Dolsar 2015). Overall, the average groundwater level decrease from the wells was 1 m/yr during the 20-year period from 1995 to 2015, although there are a few exceptions from this general pattern (Fig. 4).

Change in lake surface area and salinity

The KCB holds many lakes, including the iconic saline Lake Tuz and the largest Turkish freshwater lake, Lake Beyşehir. To illustrate the changes in lake surface areas during the last 35 years caused by the reduction in groundwater level and surface water amount, we used surface area data derived from remote sensing data from May (wettest month) and August (driest month) on 3 representative lakes and combined these data with monthly temperature and precipitation data on the entire catchment (Fig. 5). About 50% of the

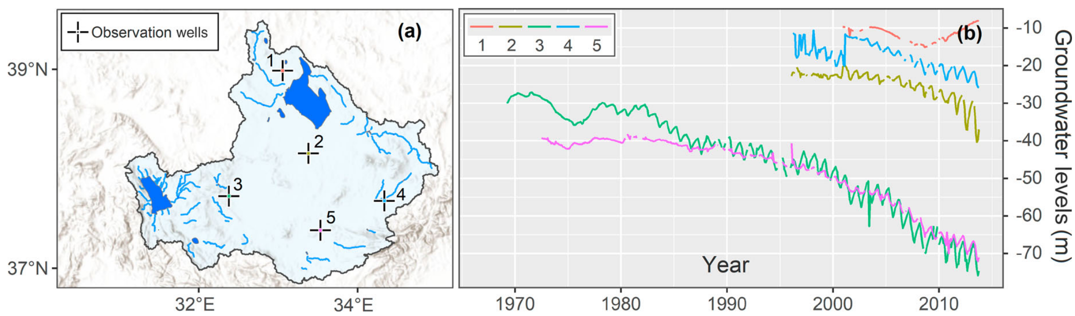

Figure 4. (a) The 5 selected observational wells numbered from 1 to 5 and (b) long-term changes in the groundwater levels of the 5 selected wells in the Konya Closed Basin.

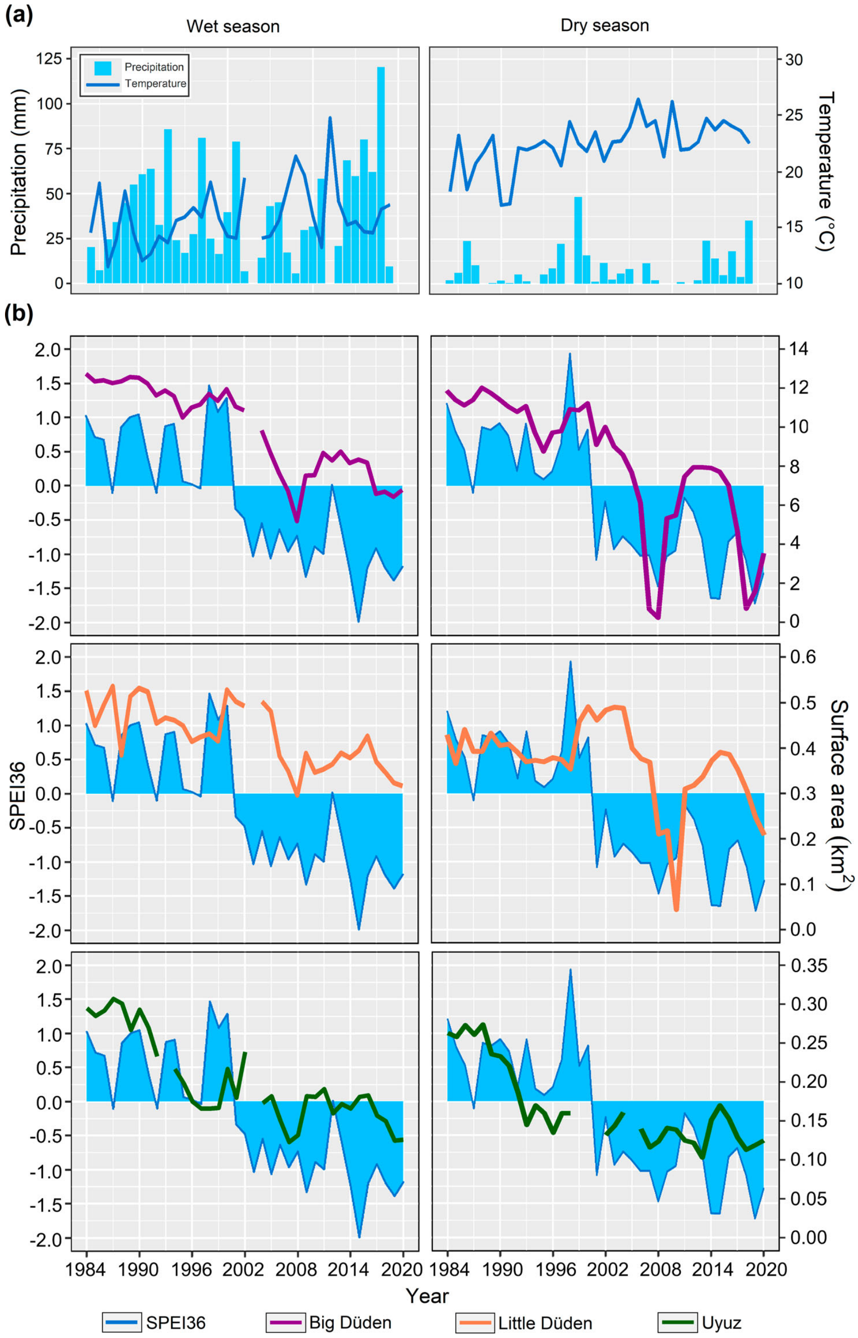

Figure 5. (a) Monthly total precipitation and average temperature and (b) long-term (1985–2020) changes in the 36-month Standardized Precipitation Evapotranspiration index (SPEI) for KCB for the wet season (May each year; left column) and the dry season (August each year, right column). The superimposed coloured lines show the surface area of Lakes Big Düden, Little Düden, and Uyuz, as retrieved from satellite images.

surface area of the 3 lakes studied was lost during this 35-year period (Fig. 5b), the decrease being most prominent in the dry season for Lake Düden.

Among the calculated Standardised Precipitation Evapotranspiration Indices (SPEI), we determined a 36-month period (SPEI 36) to be optimal. A water deficit was seen after 2000 in Lake Düden, accompanied by a decrease in lake surface area (Fig. 6). The groundwater level increased after 2008 in the well in the vicinity of Düden Lakes (Fig. 4), followed by an

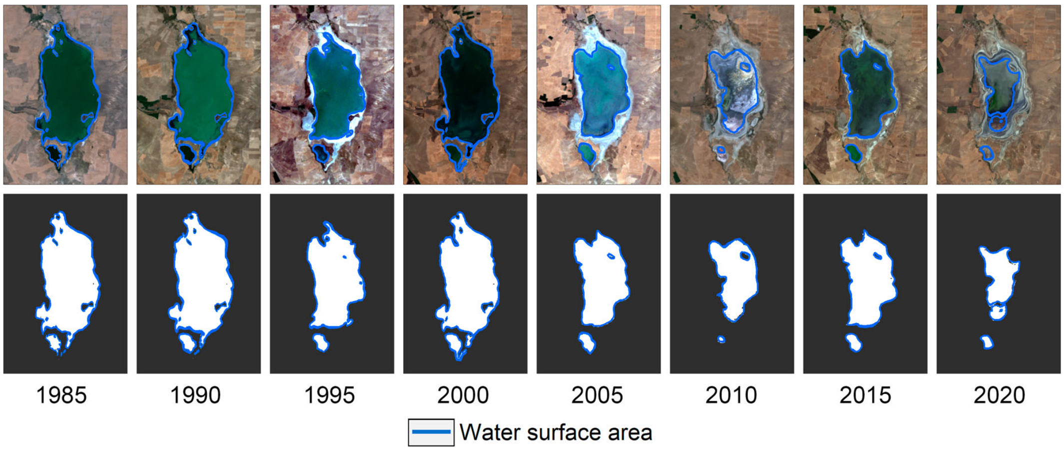

Figure 6. Landsat true colour RGB images (upper panels) and black and white images marking the surface area (lower panels) of Lakes Big Düden and Little Düden at 5-year intervals from 1985 to 2020.

increase in lake area, emphasising the importance of groundwater input (Fig. 5b and 6). Also, in Lake Uyuz water deficit effects led to surface area changes, although an increase was observed in the wet season in 2002 and in the dry season in 2004 and 2015 (Fig. 5b), suggesting a lower dependency of groundwater input in Lake Uyuz than in the other 2 lakes, which can mainly be attributed to the differences in aquifer systems.

The remote sensing-based salinity index calibrated on ground truth data revealed a correlation coefficient of 0.92. We used salinity index as a proxy for salinity for Lakes Uyuz and Düden for 1985–2020. In the observed period, the salinity of the 3 lakes showed no clear trend in the wet season while both Düden lakes became increasingly more saline in the dry periods, as indicated by a more negative index value (Fig. 7). Lake Uyuz showed no such trend of salinisation, which can be attributed to difference in hydrology of this lake with less dependency on surface inputs.

Populations of globally threatened waterbird species

The changes in lake area and salinity in the KCB were associated with major changes in the waterbird communities. Common pochard had a small population of breeding birds but large migrating and wintering populations in the KCB (Supplemental Fig. S1). During the 1990s and early 2000s, its breeding population in the basin peaked with >120 pairs occurring at several sites across the KCB, but in 2019 the breeding population had declined by 95% to only 6 pairs. The highest number of common pochard recorded during migration was 45 000 individuals at Lake Düden in 1970, counted on a single day. During the last 20 years, only 200 migrating/molting individuals have been observed in the basin, a >99% decline. The wintering population of the species exceeded 45 000 individuals at Lakes Düden and Beyşehir in the 1980s and 1990s, but during the last few years the wintering populations have been confined to Lake Beyşehir, counting only 2000–3000 individuals, a 94–96% decline.

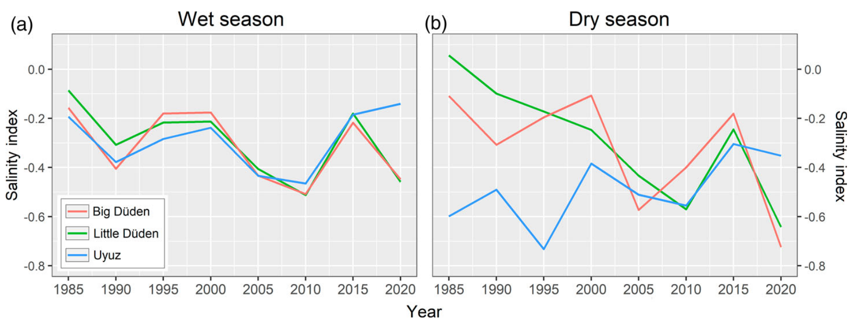

Figure 7. Changes in the salinity index for Lakes Düden, Little Düden, and Uyuz from 1985 to 2020 at 5-year intervals in (a) the wet season and (b) the dry season.

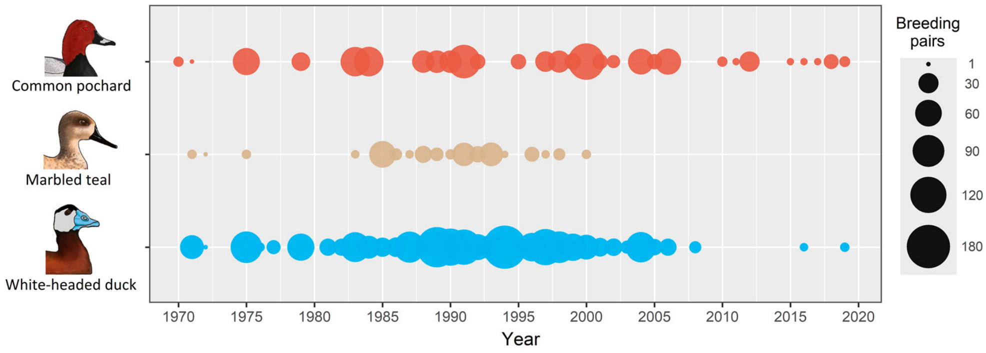

Figure 8. Changes in the sizes of the breeding populations of the 3 globally threatened waterbird species: common pochard, marbled teal, and white-headed duck from 1970 to 2020 in the KCB.

Marbled teal used to breed at several localities in the basin, all of which have either been totally lost or severely degraded, such as Ereğli and Hotamış marshes (see Case 1). The highest recorded breeding population in the basin was 60 pairs in 1985 (Fig. 8). Migrating individuals have only been observed in the Ereğli Marshes and Lakes Düden, Samsam, and Beyşehir, and since 1994 no migrating marbled teal have been sighted in the KCB (Supplemental Fig. S1). The species has not been observed in the KCB since 2000 and not in Turkey since 2015.

White-headed duck populations in the KCB have suffered major losses over the last few decades (Fig. 8, Supplemental Fig. S1). The size of the breeding population peaked in the late 1980s, with at least 152 breeding pairs distributed over several wetlands, but the most recent fieldwork and sightings reported no breeding pairs in the basin in 2019 and only a single pair in 2020 (Özgencil 2019; Ogün Aydın pers. comm.). More than 1500 molting/migrating individuals were observed across the KCB in the 1980s, but in 2019 only 3 individuals were sighted at a single locality, suggesting a 99% decline in migrating populations. The wintering population of the species in the basin was >500 individuals in the late 1990s. Only a single individual has been sighted wintering in the region since 2005.

Both slender-billed curlew and red-breasted goose were rare visitors in the basin with fewer than 4 records during 1980–2000. All sightings of the 2 species were in wetlands that are currently either totally drained or severely degraded. The 2 species have not been observed in the basin recently, and the slender-billed curlew is thought to be globally extinct (Buchanan et al. 2018).

Changes in breeding waterbird communities between 1998 and 2018

Our comparison of the 2 bird atlases indicated a widespread decline in the species richness of breeding waterbirds in the whole basin, with a loss of 18 species over the last 20 years (Fig. 9). Total breeding waterbird richness has declined by 23% (from 62 to 48 species), and 76% of the species that no longer breed in the KCB were Red-Listed at the national scale in the 2004 assessment (Kılıç and Eken 2004). Among the lost species were the iconic common crane (*Grus grus*), which used to breed around the former Eşmekaya Marshes, and the Dalmatian pelican (*Pelecanus crispus*), which used to breed in the former Ereğli Marshes, and some rare breeders such as the Caspian tern (*Hydroprogne caspia*), which has confirmed breeding at only 2 localities in the whole of Turkey. During this 20-year period, only 4 new species have (re)colonised the basin: cattle egret (*Bubulcus ibis*), great cormorant (*Phalacrocorax carbo*), white-tailed lapwing (*Vanellus leucurus*), and yellow-legged gull (*Larus michahellis*).

Compared with 20 years ago, of the thirty-four 50 km × 50 km grid squares, 62% had a lower species richness (mean change: −7.53), 29% exhibited zero net change, and only 9% had a higher breeding waterbird species richness (Fig. 9). The biggest losses of breeding waterbird richness have occurred in the squares corresponding to Ereğli, Hotamış, and Eşmekaya Marshes with a loss of >40 species in each (see Case 1).

Threats to fish species

The KCB hosts 38 fish species, 74% of which are endemic. This extreme endemism ratio is 1.6 times higher than the average ratio for Turkey, which is already a biodiversity hotspot for fishes (384 species, 47.4% endemic; Çiçek et al. 2020). Of the endemic species in the KCB, 61% are considered threatened or near threatened by IUCN (Supplemental Material 3), and the Beyşehir bleak (*Alburnus akili*), endemic to Lake Beyşehir and its tributaries, is now extinct (Küçük 2012). Endemic fish populations in the KCB have exhibited major reductions

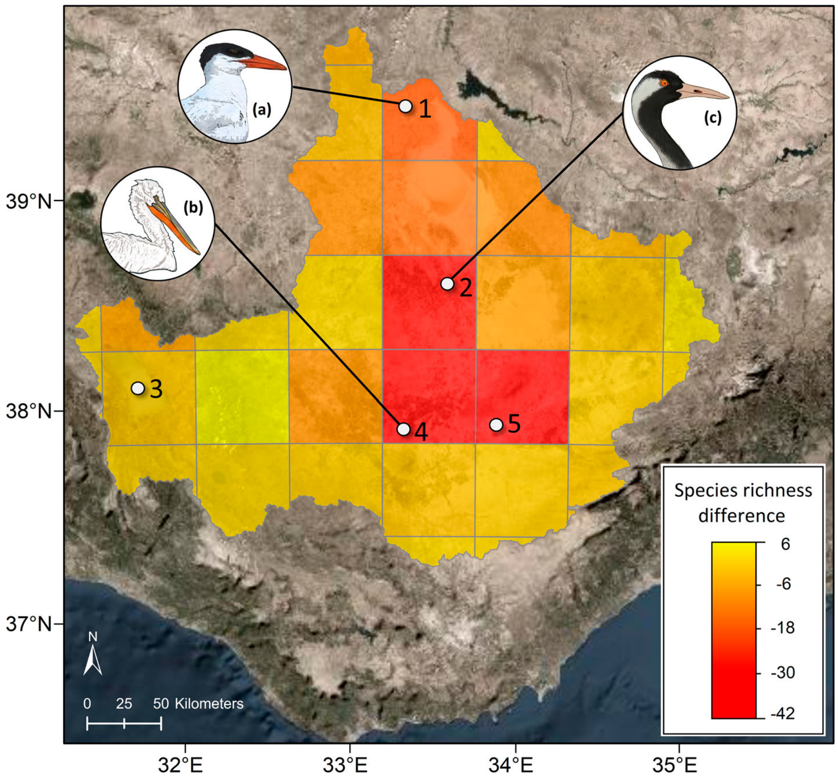

Figure 9. Species richness loss of breeding waterbirds in Konya Closed Basin over the last 20 years. Some species that no longer breed in the basin are (a) Caspian tern, (b) Dalmatian pelican, (c) and common crane. 1: Lake Düden, 2: Former Eşmekaya Marshes, 3: Lake Beyşehir, 4: Former Hotamış Marshes, 5: Former Ereğli Marshes. Satellite imagery source: Esri, DigitalGlobe, GeoEye, Earthstar, Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community.

over the last few decades (Meke et al. 2012, Yeğen et al. 2015, Küçük et al. 2016), coinciding with habitat loss, and most of the once widespread endemic fish species are now restricted to small refuges (Freyhof et al. 2020). The distribution range contraction of the declining endemic fish populations is indicative of an ongoing extinction process (Pimm et al. 2014, Ceballos et al. 2015).

The already stressed native and mostly endemic fish fauna of the KCB (Supplemental Material 3, Table S1) is further threatened by non-native invasive species introductions that include pikeperch (*Sander lucioperca*), tench (*Tinca tinca*), and Prussian carp (*Carassius gibelio*) (İnnal and Erk'akan 2006, Tarkan et al. 2015). The big-scale sand smelt (*Atherina boyeri*) was illegally dispersed by fishermen in the early 2000s for commercial reasons (Gençoğlu and Ekmekçi 2016). In addition, the exotic eastern mosquitofish (*Gambusia holbrooki*), rainbow trout (*Oncorhynchus mykiss*), and stone moroko (*Pseudorasbora parva*) were introduced, and the sakarya bleak (*Alburnus escherichii*), common carp (*Cyprinus carpio*), and Caucasian dwarf goby (*Knipowitschia caucasica*) were translocated to the KCB (Tarkan et al. 2015). Anatolian killifish (*Anatolichthys anatoliae*) in the Central Anatolia region, Konya killifish (*A. iconii*) in Lake Beyşehir, and pearl-spotted killifish (*Paraphanius similis*) in Lake Akgöl have been affected by the exotic mosquitofish (Yeğen et al. 2006, Kurtul and Sarı 2019).

Case studies

To illustrate the severity of the changes that the KCB lakes and wetlands have faced/undergone and will expectedly face in the future, we present case stories on the iconic marshes and Lake Beyşehir.

Case 1: the iconic marshes

The KCB once had several large marshes of exceptional biological value that contributed to biodiversity, fisheries, reed-cutting, and the maintenance of a local mild climate (Fig. 1). Among these were the iconic

Hotamış, Ereğli, and Eşmekaya Marshes, which have almost or totally disappeared over the last 4 decades.

The Hotamış Marshes covered ~174 km^2 (33.050E, 37.550 N) in the mid-1980s, and at its deepest point the water depth was 3 m (Ertan et al. 1989, Magnin and Yarar 1997). The size of the marshland decreased over time, mainly due to diversion of its major inflows through construction of drainage channels and groundwater extraction and, to a lesser extent, reduced rainfall (10% between 1965 and 1994) in the catchment (Magnin and Yarar 1997). Before then, the marshes supported breeding populations of >50 species of waterbirds along with regionally important breeding and nonbreeding populations of the globally threatened white-headed duck and marbled teal, making it an IBA; Eken and Magnin 2000, Kılıç and Eken 2004). Before the drainage in the 1990s, the marshes accommodated as many as 110 000 wintering waterbirds, whose number fell to a few thousands afterward (DKMP 2019).

The area of the Ereğli Marshes was even larger than that of the Hotamış Marshes (estimated total area: 215 km^2) and included Lake Akgöl with a surface area of 192 km^2 when its water level was highest in the early 20th century (Akkuş 1991, Magnin and Yarar 1997). The main inflow of the marshes was the İvriz stream (providing 0.23×10^3 hm^3/yr) until 1984 when it was diverted to the İvriz reservoir for irrigation (Fig. 10). Thereafter, the derivative channel Karaman Deliçay and sewage effluent from the nearest town, Ereğli, became the main inflow, lowering the water input. In 1988, the Karaman Deliçay was also diverted to Gödet reservoir, leaving the treated sewage effluent from Ereğli as the main inflow to the marshes. At one point, the Ereğli Marshes hosted 5 endemic fish species, including Anatolian gudgeon (*Gobio hettitorum*), Anatolian loach (*Oxynoemacheilus eregliensis*), Anatolian minnow (*Pseudophoxinus anatolicus*), Ereğli minnow (*Garra kemali*), and killifish (*Paraphanius similis*), but they have all disappeared. The marshes, a designated IBA (Ertan et al. 1989), were also home to a high variety of breeding, migrating, and wintering waterbirds occurring in the tens of thousands before the lake dried out in the 1990s (Fig. 10; DKMP 2019), including the globally endangered white-headed duck and marbled teal as well as nationally rare breeders like white pelican (*Pelecanus onocrotalus*), Dalmatian pelican, and white-tailed lapwing (Magnin and Yarar 1997).

The Eşmekaya Marshes were the smallest of the 3 with a maximum surface area of 112.5 km^2 in the 1980s before the construction of a diversion channel drained most of the area (Magnin and Yarar 1997). The marshes were home to important populations of 2 endemic freshwater fish species: spring minnow (*Pseudophoxinus iconii*) and killifish (*A. anatoliae*; Eken et al. 2006, Küçük et al. 2016). The marshes also accommodated rich bird communities making it an IBA (Magnin and Yarar 1997) where nationally rare breeders such as pallid harrier (*Circus macrourus*) and short-eared owl

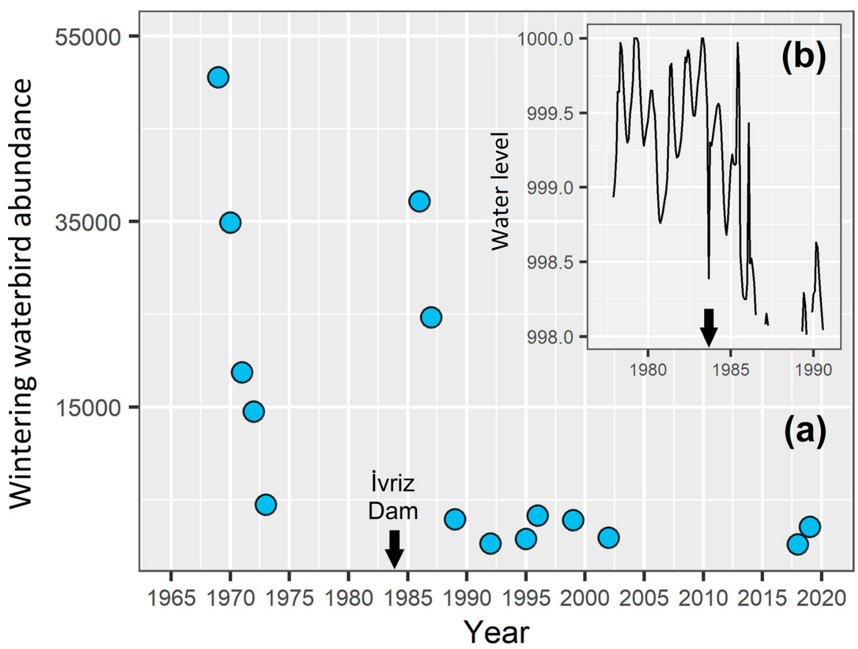

Figure 10. Changes in (a) wintering waterbird abundances and (b) water level (m a.s.l) of Lake Akgöl in the Ereğli Marshes.

(*Asio flammeus*) were found (Eken and Magnin 2000, Eken et al. 2006).

Case 2: Lake Beyşehir

Lake Beyşehir, positioned in the upstream part of the KCB with a surface area of 650 km^2 and a catchment area of 4704 km^2, is the largest freshwater lake in Turkey and in the whole Mediterranean basin. More than 40% of the catchment is covered by range-brush and >25% agricultural land, while forested areas (evergreen and deciduous forests) constitute >11% (Bucak et al. 2017). The lake shows inter- and intra-annual water level fluctuations (Fig. 11) and has a maximum depth of 8–9 m depending on the season. The lake is primarily fed by streams from the Sultan and Anamas mountains as well as by springs from Mesozoic calcareous cracks and one outflow. The lake is oligotrophic to mesotrophic, with low phytoplankton biomass (mean chlorophyll *a* ~3 µg/L) and nutrient concentrations (mean total phosphorus ~23 µg/L; Bucak et al. 2018).

The first study of fish in the lake revealed 6 species, none of which were predators (Numan 1958). A number of species have since been introduced, including pikeperch in 1978, tench in the early 1990s, Prussian carp in the late 1990s, big-scale sand smelt in the early 2000s, topmouth gudgeon (*Pseudorasbora parva*) in the early 2010s, with rapidly increasing populations (Balık 1997, Yeğen et al. 2006, Meke et al. 2012, Bayçelebi et al. 2020), which likely caused the observed decline of the endemic fish species and extinction of the Beyşehir bleak (Küçük 2012). Today, 15 fish species native to the lake are threatened with extinction, 7 of which are assessed as endangered and 1 as vulnerable according to IUCN (Supplemental Material 3, Table S1). The introductions also affected the waterbird communities. The islands in the lake used to accommodate big colonies of wading, diving, and scooping piscivorous birds such as black-crowned night heron (*Nycticorax nycticorax*), great cormorants, and Dalmatian pelicans, but these have either disappeared or declined in numbers following the stocking of non-native fish (Ertan et al. 1989, Magnin and Yarar 1997, Bucak et al. 2018).

Historical and paleolimnological studies of Lake Beyşehir have shown that water level fluctuations are critical for its ecosystem structure and functioning (Beklioglu et al. 2006, Levi et al. 2016), as seen elsewhere (Zohary

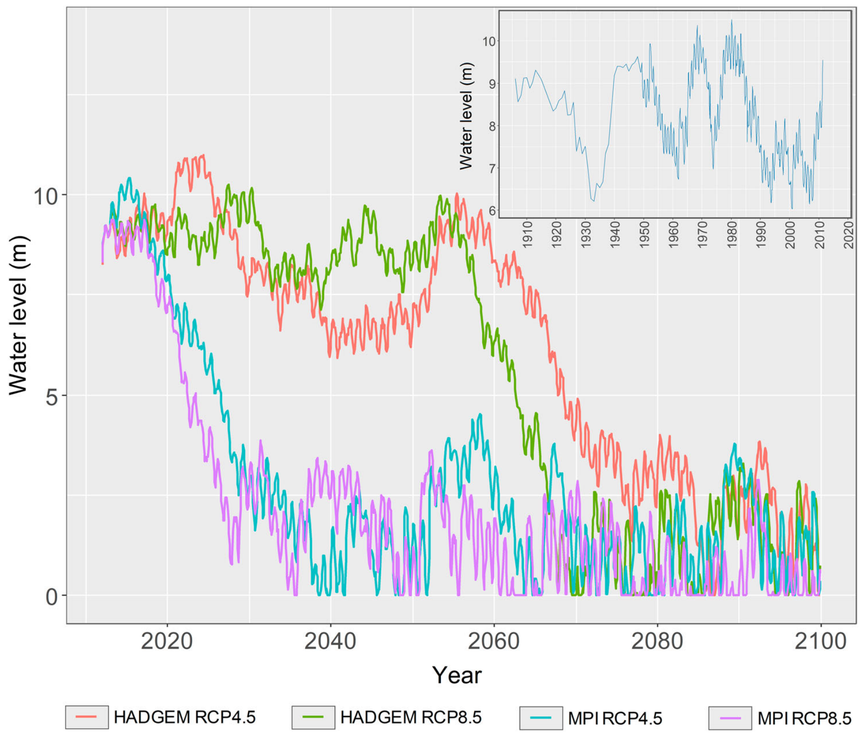

Figure 11. Changes in the actual water level of Lake Beyşehir from 1910 to 2010 and under different climate change scenarios. RCP4.5 assumes that greenhouse gas emission will peak around 2040, followed by a decline, while RCP8.5 assumes that emissions will increase throughout the 21st century (IPCC 2014) (reproduced from Bucak et al. 2017).

and Ostrovsky 2011). During 1960–2012, the monthly average water input to the lake (including precipitation, inflows, and groundwater) was $0.09 \pm 0.07 \times 10^3$ hm^3, and surface evaporation was $0.08 \pm 0.04 \times 10^3$ hm^3. However, the average monthly water abstraction for irrigation of the downstream basin was as high as $0.02 \pm 0.03 \times 10^3$ hm^3 (Bucak et al. 2017). The future water level state of the lake looks gloomy. Bucak et al. (2017) conducted a simulation of the future water level changes relative to different land uses and climate change scenarios using the watershed model Soil and Water Assessment Tool (SWAT; Arnold et al. 1998) with ε-SVR (Support Vector Regression model ; Vapnik 1995, Raghavendra and Deka 2014). In this water level study, outputs of 2 general circulation models (GCM), HadGEM2-ES (Hadley Centre Global Environmental Model) and an MPI-ESM-MR (Max Planck Institute Earth System Model) were used with 2 Representative Concentration Pathways (RCP4.5 and RCP8.5). RCP 4.5 assumes that greenhouse gas emission will peak around 2040, followed by a decline, while RCP8.5 assumes that emissions will increase throughout the 21st century (IPCC 2014). The climate models were dynamically downscaled by Demir et al. (2013) for the period 2013–2099 at a 20 km resolution using the RegCM 4.3.4 Regional Climate Model. In all scenarios, the results revealed a major water level reduction, and the most pessimistic climate and land use scenario predicts a potential dry out by the 2030s at the current outflow regime (Bucak et al. 2017). Outflow management scenarios run to determine the reduction of water abstraction needed to maintain the water level of the lake showed that a 20–60% reduction of the outflow is required to save the lake from complete disappearance (Bucak et al. 2017). Therefore, urgent and strict water resource planning and outflow management are clearly vital to sustain the lake ecosystem and its many services (Bucak et al. 2017).

Discussion

The past

Judged from the examples presented, a drastic loss of lake surface area and salinisation have occurred during the past 40 years in the KCB, not least during the last 2 decades, in part due to changes in climate but largely a result of water abstraction and landscape regulation conducted to support an increasing agricultural production. The changes have had significant effects on the lakes, waterbirds, and fish, as clearly illustrated by the 2 case studies.

While increased evaporation has contributed to further deterioration of the already damaged water balance, water withdrawal for agriculture is by far the key factor behind the substantial changes observed in the groundwater table (overall 1 m/yr rate of decrease since 1980s) and the major reduction of lake and marsh surface areas in the KCB. A major increase in crop production and a shift to water intensive crops have transformed the land use to intensively irrigated crop farming at the expense of the animal farming and herding that historically characterised the farming in the region (England et al. 2008). Especially after 2000, crop production has increased 2-fold (Fig. 3), in part due to the establishment and privatisation of sugar factories, which is clearly mirrored by the major drop in the groundwater tables (Fig. 4). A yearly water deficit of almost 350 hm^3 owing to irrigation has led to water import from neighbouring catchments (e.g., the Blue Tunnel Project involving transfer of water from the Göksu catchment to Konya Plain). Such compensatory import is well known from other arid regions (e.g., Zadereev et al. 2020) but has negative consequences for the lakes in the exporting catchments, a notable example being the iconic Aral Sea (Aladin et al. 2018). Moreover, reservoirs have been constructed, mainly in the southern KCB, in some cases at the expense of natural lakes and marshes by diverting their major inflows (Republic of Turkey Ministry of Agriculture and Forestry 2018b). Reservoir construction is a common practice in semiarid and arid areas worldwide but has led to redistribution of water and water loss with devastating effects on downstream aquatic ecosystems (Albert et al. 2020, Zadereev et al. 2020). That changes in land use and irrigation rather than in climate have had the most devastating effects in semiarid and arid areas worldwide in recent decades is well established (Wurtsbaugh et al. 2017, Zadereev 2018, Albert et al. 2020, Zadereev et al. 2020).

In the KCB, the surface areas of lakes have decreased markedly (e.g., Lake Düden) and several have even dried out (see Case Study 1). Moreover, many lakes have become more saline, such as Lake Düden (Fig. 7). Increasing salinity may lead to reduced biodiversity and an expected loss of ecosystem functioning (Williams et al. 1990, Schallenberg et al. 2003, Flöder and Burns 2004, Kipriyanova et al. 2007, Jeppesen et al. 2015, Anufriieva and Shadrin 2018, Golubkov et al. 2018). Often, pronounced effects are seen when specific salinity thresholds are surpassed, such as a complete loss of fish at high salinities (Lin et al. 2017, Vidal et al. 2021). In addition, widespread drainage of the wetlands and deterioration of the lake ecosystems in the KCB in the last 60 years have resulted in major declines in the populations of threatened waterbirds and species richness in the region (Fig. 9 and 10).

The fish fauna of the KCB, which includes a large component of endemic species, is subject to a serious threat of extinction (Çiçek et al. 2018). Abstraction and diversion of freshwater to reservoirs cause habitat fragmentation and alteration of natural seasonal patterns (Korkmaz et al. 2015, Albert et al. 2020) and have forced the native fish fauna to find refuge in restricted spring-fed tributaries, making these species even more vulnerable to hydrological alterations (İnnal and Erk'akan 2006). Even relatively low environmental stress on these small populations of native fish can lead to local extinction; 61% of the endemic species are threatened. Moreover, invasive species now comprise 20% of the fish fauna, thus adding additional pressure on the native fish fauna, which has already led to the extinction of the Beyşehir bleak (Küçük 2012), with potential cascading effects on waterbird populations (see Case Study 2). For example, carp can compete with diving omnivorous ducks for benthic macroinvertebrate food sources and thereby cause eutrophication, both of which are factors that may disturb the habitats of diving omnivorous waterbirds (Maceda-Veiga et al. 2017, Özgencil et al. 2020).

The future

The trend analysis suggests that the water loss from the basin will increase due to enhanced evaporation and transpiration, clearly evidenced by the observed negative SPEI values (Fig. 5b) that indicate a water deficit after 2000. Increased evapotranspiration was historically critical for either the shrinkage or complete loss of lakes in the basin (e.g., Paleolake Konya), and now it seems that history is unfortunately repeating itself. We used the global circulation models MPI-ESM-MR, HadGEM2-ES, and GFDL-ESM2M, together with the regional climate models RCP4.5 and RCP8.5 (Dolsar 2015), to analyse the water balance in the KCB until 2050 and predict a decrease in water resources. Moreover, with the current agricultural policies, the agricultural production in the KCB will likely continue to increase to satisfy the demand of an increasing human population. Left uncontrolled, the production of crops with a high irrigation requirement such as sugar beets will increase, and so will the extent of irrigated areas and the amount of water used (Republic of Turkey Ministry of Environment and Urbanisation 2020). To ensure effective use of the basin, a switch to water-saving irrigation methods and planting of crops suitable for the climate and water potential of the area are needed through strict regional level actions (Albert et al. 2020). If the demand for water remains at the current level or increases to meet irrigation needs, the groundwater table will expectedly drop further, which may be compensated for by a radical change in water allocation inside the basin or additional inter-basin water transfer, with all the negative consequences this may have.

The major changes in climate and continued water abstraction are also expected to create future environmental changes in lakes, clearly illustrated by the simulation of the future water level changes in the largest freshwater lake in Turkey, Lake Beyşehir (Case Study 2). The simulation showed that, under the current outflow regime, the lake might suffer from frequent episodes of dry out as soon the 2030s–2050s (Bucak et al. 2017). Reduced water input to the lake will result in a lower nutrient loading from the catchment to the lake, which, as judged from modelling results, will only insignificantly affect the biomass of algae in this nutrient-poor lake (Bucak et al. 2018). More eutrophic lakes in semiarid climates may be more substantially affected by the climate change (Zohary and Ostrovsky 2011). A mass balance and modelling study of Lakes Mogan and Eymir (outside the KCB) revealed that, during dry periods, low inflow rates and high evaporation produced increased in-lake nutrient concentrations due to both the concentration of nutrients in less water and increased internal loading (Coppens et al. 2016, 2020). The algal biomass and the abundance of cyanobacteria were also much higher in the drier and warmer scenarios. Overall, the results show that lower hydraulic loads and reduced flushing rates as a result of drier and warmer conditions lead to lower water levels and higher in-lake nutrient concentrations. Such changes are also accompanied by salinisation, a state where even a few years with a prolonged hydraulic residence time can shift a lake to briny conditions (Beklioğlu et al. 2018). Apart from eutrophication, the expected salinity changes will severely affect the biodiversity and trophic dynamics of the KCB lakes (Brucet et al. 2012, Lin et al. 2017, Jeppesen et al. 2020, Zadereev et al. 2020, Vidal et al. 2021), and major shifts may occur when certain salinity thresholds are surpassed (Jeppesen et al. 2007, Lin et al. 2017). To reverse the ecosystem degradation or even preserve the current status, a framework policy is needed that aims to restrict the exploitation of water resources within sustainable limits in the KCB while simultaneously promoting conservation efforts. This action seems achievable only if the basin-wide legal regulation of water abstraction is combined with economic incentives of transition to climatically appropriate crop farming.

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A.2 Paper B

water

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Article

Increased Water Abstraction and Climate Change Have Substantial Effect on Morphometry, Salinity, and Biotic Communities in Lakes: Examples from the Semi-Arid Burdur Basin (Turkey)

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Abstract: Global warming and altered precipitation patterns are predicted to intensify the water loss in semi-arid and arid regions, and such regions in Turkey will be particularly affected. Moreover, water abstraction, not least for irrigation purposes, is expected to increase markedly, posing major threats to the water balance of the lakes and thus their biodiversity. Among the closed basins in Turkey, the Burdur Closed Basin (BCB), located in the southwest of Turkey, is expected to be most affected. The BCB includes several types of aquatic ecosystems which support high biodiversity, including one Ramsar site, six Important Bird Areas, and a considerable richness of native and endemic fish species. Therefore, it is essential to analyze the potential environmental impacts of climate change and increased water abstraction on BCB lakes and their biotic communities. Here, we combined historical data on ecosystems as well as meteorological, remote sensing, and ground-truth data to analyze the changes in the temperature and precipitation of the BCB, water surface areas, and land use, as well as the potential effects on waterbird and fish communities. We calculated the water budget to elucidate water availability in the basin over the last few decades and predicted future conditions based on rainfall and temperature forecasts using climate models. The Standardized Precipitation–Evapotranspiration Index (SPEI) was used to relate the water surface area to precipitation and temperature change in the basin. Crop-farming irrigation in the BCB has increased notably since 2004, leading to intensive water abstraction from the lakes and their inflows, as well as from ground water, to meet the increased demand for irrigation. The water abstraction from the lakes, inflows to the lakes, and the groundwater in the basin has increased the water loss in the catchment substantially. Remotely sensed data on lake surface areas showed a major shrinkage of shallow lakes in the last 40 years. Moreover, the largest lake in the basin, Lake Burdur, lost nearly half of its surface area, which is worrisome since the shallower areas are the most suitable for supporting high biodiversity. Climate models (CNRM-ESM2-1GCM for temperature and GFDL-ESM4-GCM for precipitation) suggest that from 2070, the BCB will face long-term, moderate-to-severe dry periods. This, and the increased demand for water for irrigation, along with climate change, may accelerate the drying of these lakes in the near future with devastating effects on the lake ecosystems and their biodiversity.

Keywords: saline lakes; salinization; land-use change; habitat loss; fish biodiversity; waterbird

1. Introduction

Global warming and altered precipitation patterns are predicted to intensify water loss in semi-arid and arid regions [1,2]. Among the eastern Mediterranean countries, Turkey will likely experience major increases in summer drought [3]. A recent study, based on global circulation models (GCMs) [4], showed that there will be at least a 2 °C increase in spring and summer mean temperatures and a 10% decrease in annual total precipitation in Turkey by 2100. Moreover, water abstraction, not least for irrigation purposes, is expected to increase markedly [5,6]. These changes are major threats to the water balance of many lakes that may dry out temporarily or permanently, with the shallower areas being particularly vulnerable. This may increase the salinity of the remaining lakes, leading to a loss of biodiversity, and subsequently leading to changes in ecosystem functions and services [7–11].

A recent paper on the semi-arid Konya Closed Basin (KCB), Turkey, analyzed the changes in water balance and crop patterns and showed that water-thirsty crops and their demand for water have intensified over the past few decades [12] This, combined with climate warming, has led to a substantial reduction of the groundwater level (>1 m/year) and a major decline in the surface area of lakes and wetlands, followed by an increase in salinization and a pronounced decrease of waterbird and fish populations, of which many are endemic [12]. A recent study, describing the predicted changes in the hydrogeological reserve of the basins in Turkey, reveals that the Burdur Closed Basin (BCB) will be the most affected Anatolian basin [13]. Although the BCB is the smallest of the closed basins in Turkey, it is estimated that, at the end of the present century, due to the effects of climate change, the hydrogeological reserve of the basin will decrease by 14% and the possible reserve by 26% [13] compared with 3% and 6% in the KCB, which has already faced dramatic changes in recent decades [12]. In the BCB, there are extensive agricultural activities (as in the KCB) that depend heavily on surface water and groundwater abstraction, and the surface water has been controlled by constructing dams that provide water for irrigation. The BCB includes the second- and third-deepest lakes in Turkey, while the lakes in the KCB are mainly shallow. In both areas, the lakes host large and diverse waterbird and fish populations. Some of the shallow lakes in both basins have already dried out, and the deeper lakes in the BCB have shown signs of shrinkage due to increased evaporation and water abstraction [14]. Therefore, it is essential to analyze the potential environmental impacts of climate change and increased water abstraction on BCB lakes and their biotic communities.

In this study, we aim at elucidating the effect of increased water abstraction and climate change on the morphometry, salinity, and biotic communities in the BCB, which faces a severe water shortage. We combined remote sensing data, meteorological data, and water budget calculations to analyze the changes in the amount of water in the lakes in the basin and the consequent effects on waterbird and fish populations. Furthermore, climate models (CMIP6) were used to predict the potential changes in temperature and precipitation in the basin until the end of the century. The novelty of this study is that we relate the lake surface area as derived from satellite images to the SPEI, which is an index commonly used as an indicator of hydrological and meteorological droughts. With the help of climate model results, where the CMIP6 results are used for the first time for this basin, possible drought and wet periods can be predicted for the largest lake in the basin, and the effects on birds and fish are discussed. We took a close look at the basin in three case studies; we investigated the hydrological past and future of Lake Burdur in one of them; in the second one, we presented the bird and fish community changes in Lake Acıgöl, which is facing different pressures. Finally, we analyzed the current situation of the breeding avifauna, changes in the wintering waterbird populations, and the rapid decline of the most enigmatic bird in the basin, the White-headed Duck (*Oxyura leucocephala*), based on a review of bibliographic data.

2. Materials and Methods

2.1. Study Area

The mountainous Burdur Closed Basin (BCB, area 6296 km^2) is located in the southwest of Turkey, has a mean elevation of 1200 m, and contains deep lakes as a result of the Taurus graben formation in the Miocene and Pliocene periods [15]. The basin includes six large natural lakes: Lakes Acıgöl, Akgöl, Burdur, Salda, Yarışlı, and Karataş (Figure 1). Lake Akgöl has already dried out. Lakes Salda (max. depth: 184 m) and Burdur (max. depth: 110 m) are the second- and third-deepest lakes in Turkey, respectively. Moreover, there are six sub-basins, including the Burdur sub-basin, which is the largest. While the surface water flows into the lakes from the sub-basins Acıgöl, Akgöl, Salda, Yarışlı, and Burdur, in sub-basin Atabey, located in the north-eastern part of the BCB, surface water contributes only to the groundwater because of its karstic geology (Figure 1) [16].

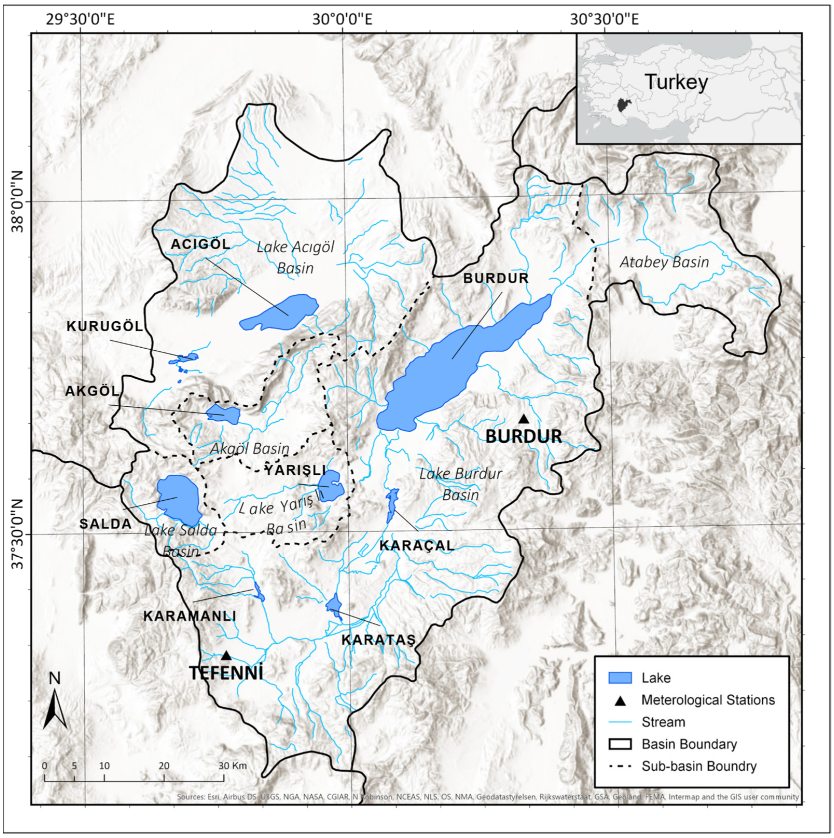

Figure 1. Burdur Closed Basin topography, sub-basins, lakes, and locations of meteorological stations.

Variation in climate in the Holocene altered the landscape and the water balance of the lakes. Sediment cores from Lake Burdur revealed that the lake level fluctuated between 10 and 13 m during the Holocene [17,18]. The lowest water level in the last millennia occurred around 300 BC (the same as today's level), while its highest level was in the humid Medieval Warm Period [18]. Consistently, a multiproxy study of Lake Salda sediment showed that, in the last two millennia before the modern period, the climate variability of the region was mainly influenced by solar forcing [19]. However, with the agricultural intensification in the modern era, human activity overruled the climatic variation in terms of lake levels and salinity [20].

2.2. Agriculture Data

Data on agricultural land area, crop patterns, and biomass production (i.e., crops, vegetables, and fruits) for the period 1980–2019 were obtained from the database of the Turkish Statistical Institute [21]. In addition, remotely sensed land-use data, from the Coordination of Information on the Environment Land Cover (CORINE) (2006 and 2018), were obtained from Copernicus Land Monitoring Service [22] to track land-use changes in the area.

2.3. Hydrometeorological Data and Climate Models

Data on monthly mean temperature and total precipitation were obtained from the Turkish State Meteorological Service [23] for the period 1970–2020. There are two meteorological stations in the BCB (Burdur and Tefenni, located 967 m and 1142 m above sea level, respectively; Figure 1). We only used the data from the Burdur meteorological station as it provides continuous data since 1970. The long-term monthly mean temperature of the basin is 13.2 °C, and the long-term total annual precipitation is 413 mm. After testing for normality and homogeneity of the temperature and precipitation data, a Mann–Kendal analysis and a Şen's trend analysis [24] were applied.

The water level and surface area of a lake are the key parameters in the Standardized Precipitation Evapotranspiration Index (SPEI) [25–27]. Thus, we chose to use the SPEI, a commonly used indicator of hydrological and meteorological droughts [28,29], in our study. We used time scales of 3, 9, 12, 24, 36, and 48 months to determine the interval that best describes the hydrological response of each of the waterbodies. We fitted the time series of the difference between precipitation and potential evaporation (PE) to a three-parameterized, log-logistic probability distribution to consider common negative values. The analyses were performed for wet (May) and dry (September) periods.

The surface water and groundwater levels and mean monthly discharge data in the basin were obtained from the State Hydraulic Works of Turkey (DSI).

We calculated the annual water storage of Lake Burdur since it is the largest lake in the basin and has the largest sub-basin area. We used a simple water balance approach (Equation (1)):

$$\mathrm{LWL(t)} = \mathrm{LWL(t-1)} + \mathrm{P(t)} - \mathrm{Q_{obs}(t)} - \mathrm{PE(t)} \quad (1)$$

where annual precipitation (P), observed discharge (Q_{obs}), and lake water level (LWL) data collected for this sub-basin and the PE were calculated using the Thornthwaite equation [30].

Information on the volume of annual surface water for the sub-basins between 1970 and 2020 was obtained from corresponding discharge observation stations. The surface water and the groundwater potentials of the basin are estimated to be 233 hm^3/year and 422 hm^3/year, respectively, while the total water needed for irrigation in the entire basin is 283 hm^3/year [31]. As of 2016, there were 15 dams and reservoirs operating in the basin, mostly for irrigation purposes [32]. The Karamanlı, Karataş, and Karaçal dams have the most significant water potential (Lake Karataş was a natural lake that was dammed in 1982 [33]), and their volumes were 24.8 hm^3, 65.3 hm^3, and 76 hm^3, respectively. These dams are located at the main inflow to Lake Burdur.

2.4. Satellite Data

We used long-life, operational Landsat Legacy satellite imagery data for the long-term monitoring and mapping of the lake surface area. Optical satellite images included 70 (two images for each year, representing dry (August–September) and wet (May–June) periods), non-cloudy Landsat Thematic Mapper (TM) (for 1984 to 2011), and Operational Land Imager (OLI) (for 2013 to 2020) images (30 m ground sample resolution), downloaded from the U.S. Geological Survey's (USGS) Earth Explorer (www.earthexplorer.usgs.gov, accessed on 20 November 2021). The Semi-Automatic Classification (SCA) plugin in QGIS [34] was used for the radiometric correction of satellite images.

2.4.1. Surface Water Detection

To assign the water pixels, we used the Modified Normalized Difference Water Index (MNDWI), typically used for inland waters as recommended by [35] (Equation (2)). Water class has positive values in MNDWI, unlike soil, vegetation, and built-up classes that have negative values since they reflect more shortwave infrared (SWIR) light than green light. Then, water pixels were digitized to calculate the surface areas of the lakes:

$$\text{MNDWI} = ((\text{Green} - \text{SWIR1})/(\text{Green} + \text{SWIR1})) \tag{2}$$

where Green and SWIR1 bands sense wavelengths 0.52–0.60 and 1.55–1.75 µm, respectively, for Landsat images.

2.4.2. Vegetation Change Detection

The Normalized Difference Vegetation Index (NDVI) (Equation (3)), which is commonly used to quickly identify vegetated areas and their condition [36], was used to detect live, green plant canopies in Landsat images:

$$\text{NDVI} = (\text{NIR} - \text{Red})/(\text{NIR} + \text{Red}) \tag{3}$$

2.5. Climate Models

A total of eight CMIP6 GCMs previously used for this area [4] were chosen as climate models (MRI-ESM2, MPI-ESM1-2-HR, CNRM-ESM2-1, NOR-ESM2-MM, HADGEM-GC-31-MM, ACESS CM-2, GFDL-ESM4, and CNRM-CM6-1-HR, see Appendix A Table A1). All of the CMIP6 outputs were downloaded using the Earth System Grid Federation (ESGF) LiU datanode (https://esg-dn1.nsc.liu.se/projects/esgf-liu/, accessed on 3 November 2021).

Daily temperature and precipitation data from the CMIP6 outputs were extracted for the Burdur meteorological station. The daily data were converted to monthly values, and the analysis was performed for three periods: the historical period (1970–2014), the validation period (2015–2020), and the future prediction period (2021–2100). For the validation and future predictions, we ran IPCC SSP242 and SSP585 simulations using centered root mean squared error (RMSE), correlation coefficient, and standard deviation, plotted in Taylor diagrams [37]. We corrected temperature data for bias using a simple seasonal bias correction method [38] (Equation (4)):

$$T_{\text{Bias Corrected (Model)}} = T_{\text{Model}} - \Delta T \tag{4}$$

where ΔT is the difference between the mean temperature of the climate model and the observations in the corresponding month. The difference between climate model results and observations (monthly data) was subtracted from the raw values of the model to get bias-adjusted temperature values for the historical, validation, and prediction periods.

Biases in the precipitation data were corrected by using the linear scaling method [39] (Equation (5)):

$$P_{\text{Bias-Corrected (Model)}} = P_{\text{Model}} * \left(\frac{\bar{P}_{\text{Observation}}}{\bar{P}_{\text{Model}}}\right) \tag{5}$$

where $P_{Bias\text{-}Corrected\ (Model)}$ is the bias-corrected monthly precipitation of the model prediction, P_{Model} is the monthly precipitation model value, and $\bar{P}_{Observation}$ is the means of the observation and model values for the corresponding month. The ratio between climate model results and observations was multiplied by the model's raw values to get bias-adjusted precipitation values for the historical, validation, and prediction periods.

2.6. Birds

We used *Turkish Breeding Bird Atlas* data [40], along with reviewed and confirmed eBird sighting records [41], to present an overview of the breeding avifauna in the basin. Details on the methodology used in the *Breeding Bird Atlas* are given in Section S1. We consulted the latest assessments of *The International Union for Conservation of Nature's Red List of Threatened Species* [42] to check if any breeding bird species were threatened globally. We used the mid-winter waterbird survey database [43], both to present the wintering waterbird community size changes between 1969 and 2020 in the basin and as the main data source for the White-headed Duck and Lake Acıgöl case studies. Section S2 gives a detailed description of the methodology used in the mid-winter waterbird surveys. For the White-headed Duck case study, we supplemented the mid-winter waterbird survey data with records (see Section S3 for a full list of the sources used) from the whole winter season. For the Lake Acıgöl case study, we used body mass, foraging stratum, foraging behavior, and diet functional traits to calculate functional evenness (FEve; [44], an indicator of how evenly the abundances are distributed within the niche space. (See Section S4 for more information on the traits chosen and the sources used to score them.) We then used generalized linear models (GLM; [45]) to check for temporal trends in FEve. Finally, we used BirdLife International's Important Bird Area (IBA) data zone [46] to review the states of the IBAs in the basin.

2.7. Fish

We collected information on fish species and their distribution and population status in the BCB from a wide range of literature [47–56]. The validity of the fish names was checked using FishBase [57] and the Catalog of Fishes [58]. The conservation statuses of the species were obtained from the IUCN's Red List [42].

3. Results

3.1. Changes in Land and Water Use

In 2019, 43.6% (1753 km^2) of the land in the BCB was cultivated [59]. As 956 km^2 (54.5%) of this cultivated land belongs to the Burdur sub-basin, we used the crop production in this sub-basin as an example of that of the whole basin (Figure 2). The main products in 2019 were maize, tomatoes, alfalfa, sugar beets, wheat, and barley, which constituted 34, 11.6, 9.4, 9, 8.3, and 7.2% of total production, respectively (Figure 2) [21]. While the production fluctuated between 7 and 10 $\times$ 10^5 tons per year from 1980 to 2007, it has increased since then to 15 $\times$ 10^5 tons in 2019. The establishment of a new fodder-crop factory and the distribution of government-supported maize-gathering machines led to an increase in maize and alfalfa production after 2004 ([60], Figure 2). The increase in the production of the water-thirsty maize, and also alfalfa, mainly served the purpose of feeding an increasing number of livestock. Accordingly, livestock increases largely followed the agriculture trends during the most recent 10-year period (Figure 2).

The CORINE land-use data indicated no major change in irrigated land for crop farming between 2006 and 2018, whereas the crop pattern has markedly changed. Thus, the CORINE maps revealed a 3% decrease in the wetlands and water bodies, an increase of 30% in urbanized areas and mineral extraction sites, and a decrease of 22% in shrub land from 2006 to 2018 (Figure 3a,b).

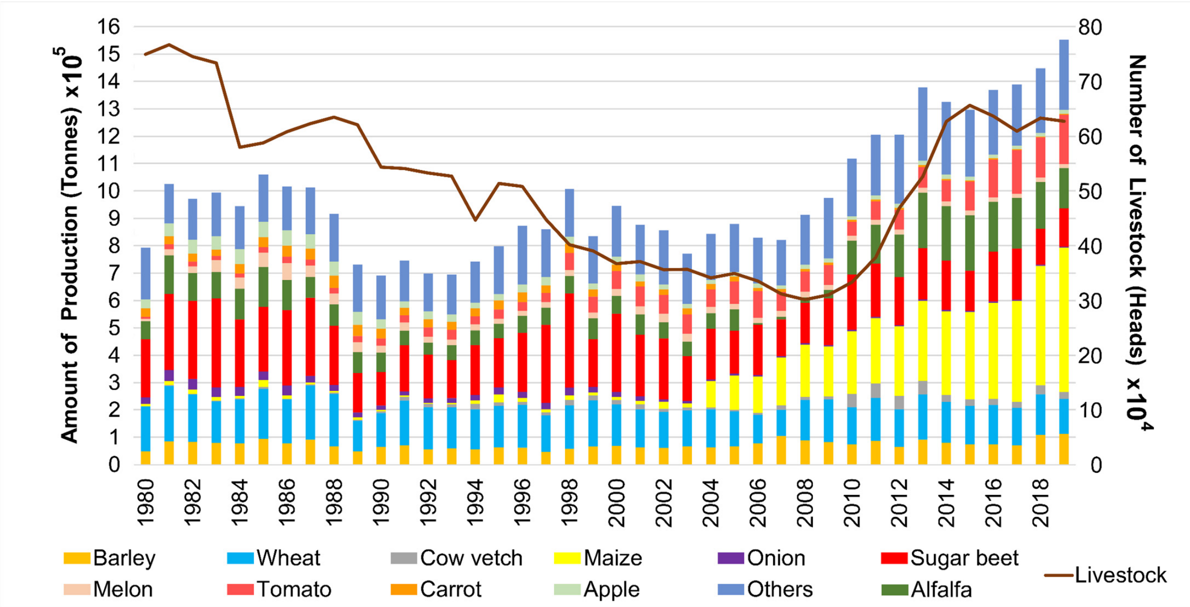

Figure 2. Total agricultural products (tons) and number of livestock (heads) in the Burdur sub-basin between 1980 and 2019 (from TÜİK 2020).

Crop farming in the BKB was intense, particularly southwest of Lake Karataş and northeast of Lake Burdur (Figure 3c,d). High NDVI values (red color in Figure 3c,d) indicated that the increase in irrigated areas corresponded to cultivated crops from 2006 to 2018 (Figure 3c,d).

3.2. Change in Surface-Water and Groundwater Resources

The water requirement for irrigation in the basin was estimated at 253 hm^3/year, 43% of which was obtained from surface water and the rest from groundwater in 2018 [31]. The use of groundwater for irrigation purposes differed in intensity among the sub-basins: 80% in the Yarışlı, Acıgöl, and Akgöl sub-basins, and less than 30% in the Burdur, Salda, and Atabey sub-basins. In the sub-basins having the least surface water, the use of groundwater became high, especially after 1992, and declines in the groundwater levels have been observed [31]. The amount of water needed for domestic supply and industrial use is comparatively small (24.5 hm^3/year and 4.9 hm^3/year, respectively) [31].

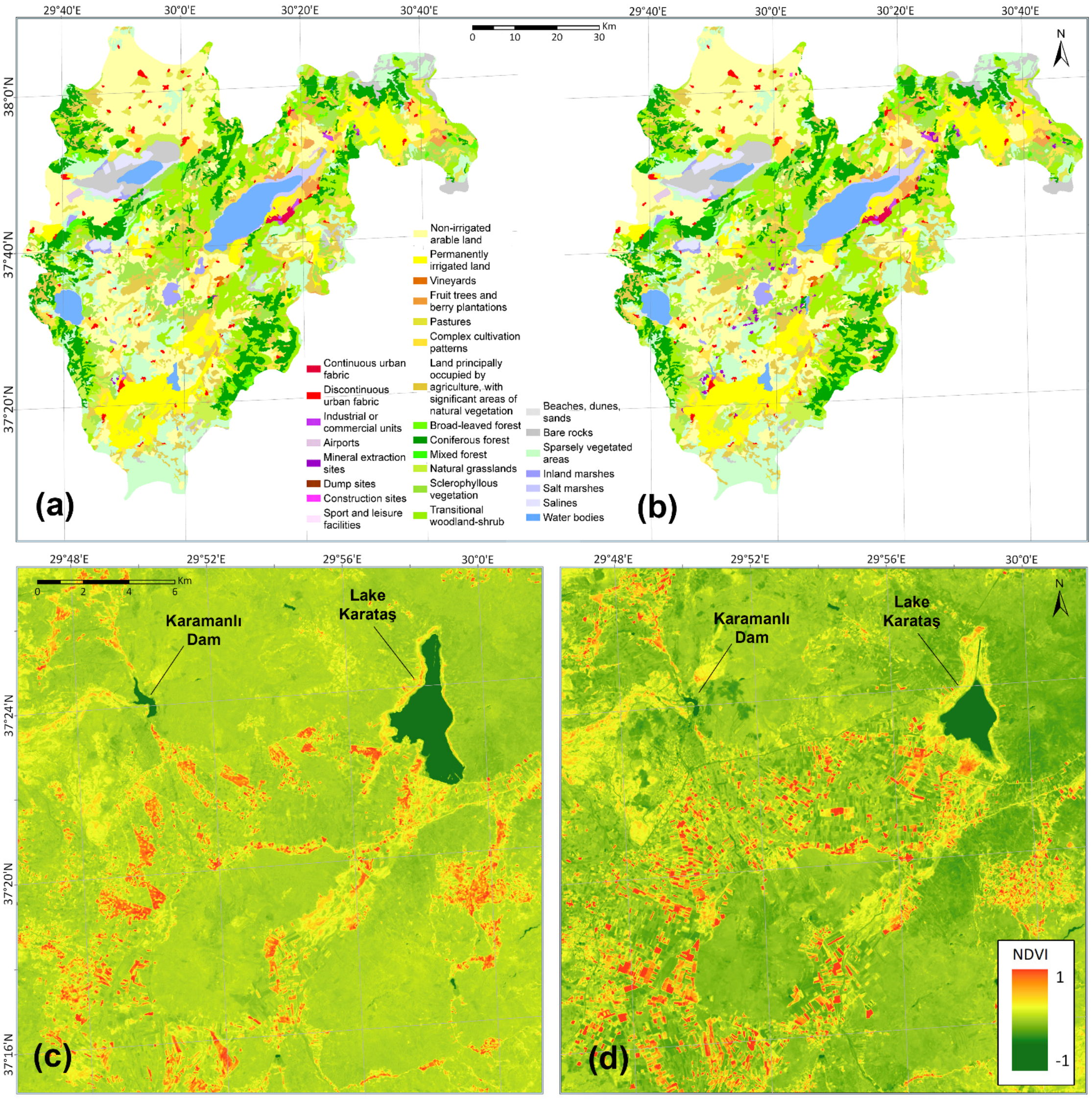

Figure 3. CORINE land-use map ((**a**,**b**), years 2006 and 2018, respectively) (red: irrigated areas; dark green: forest; light green: natural grassland and pasture; yellow: agricultural land without irrigation; purple: mineral extraction sites; gray: urban and salt marshes) and Landsat NDVI images (red: healthy vegetation) from 6 September 2006 to 23 September 2018 ((**c**,**d**), respectively) for the Lake Karataş region in c and d, respectively.

3.3. Change in Lake Surface Areas

The surface areas of Lakes Acıgöl, Akgöl, Burdur, Karataş, and Yarışlı decreased drastically, whereas this was not the case in deep Lake Salda (Figure 4). (In Figure 4e, the surface-area change of Lake Yarışlı is not easy to observe in True Color Images, but MNDWI results indicate a state of complete drought in Lake Yarışlı).

The SPEI for 12-month periods (SPEI-12) correlated best with the surface area of wet and dry seasons of Lake Acıgöl and the wet season of Lake Akgöl. SPEI-3 had the best correlation with the dry season of Lake Akgöl. For Lakes Burdur and Salda, SPEI-6 and SPEI-9 were best correlated with the surface area for the wet and dry seasons, respectively.

For Lakes Karataş and Yarışlı, SPEI-36 was best correlated with the wet season and SPEI-24 with the dry season (Figure 5).

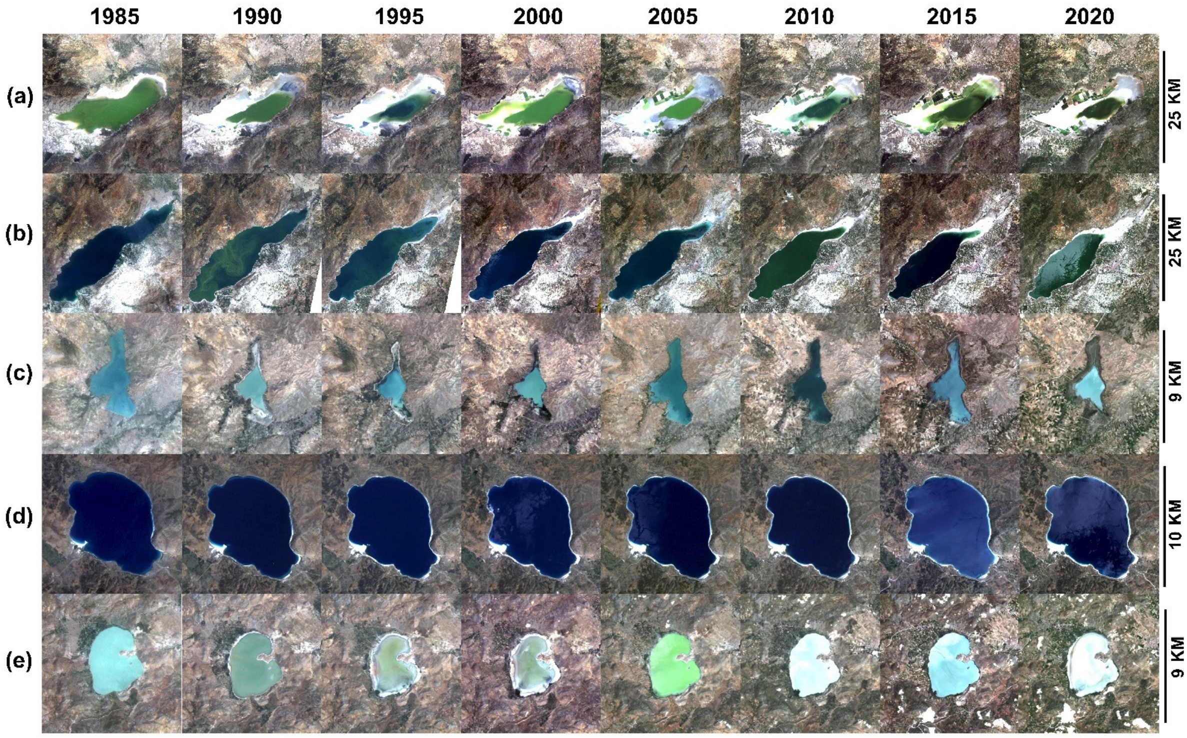

Figure 4. Change in the surface area of lakes: (**a**) Acıgöl, (**b**) Burdur, (**c**) Karataş, (**d**) Salda, and (**e**) Yarışlı for wet periods from 1985 to 2020.

A major decrease in the surface area of Lake Acıgöl occurred after 2005 in the wet season according to the SPEI changes (Figure 5a). Thus, the Acıgöl SPEI values for the 1986–2006 wet seasons corresponded to moderately wet conditions, followed by dry conditions from 2012 to 2020. For the dry season, the surface water of the lake started to decrease after 1984, and since then, it has ranged between 20 and 50 km^2.

Lake Akgöl was completely dry from 1988 to 2009 during the dry season, as indicated by the extremely low SPEI values. From 2010 to 2015, positive SPEI values indicated wet conditions, but apart from two peaks corresponding to extreme precipitation events, the lake was dry (Figure 5b).

The surface area of Lake Burdur has decreased during both the wet and dry seasons since 1984 (Şen's slope: −2.231, $p < 0.05$) (Figure 5c), and a similar decreasing trend was evidenced for Lake Salda (Figure 5d).

Lakes Karataş and Yarışlı showed similar changes in SPEI (Figure 5e,f), and in both cases the positive SPEI values are not related to an increase in the surface area of the lakes. Lake Yarışlı has dried out, or almost dried out, for a prolonged period during the dry season.

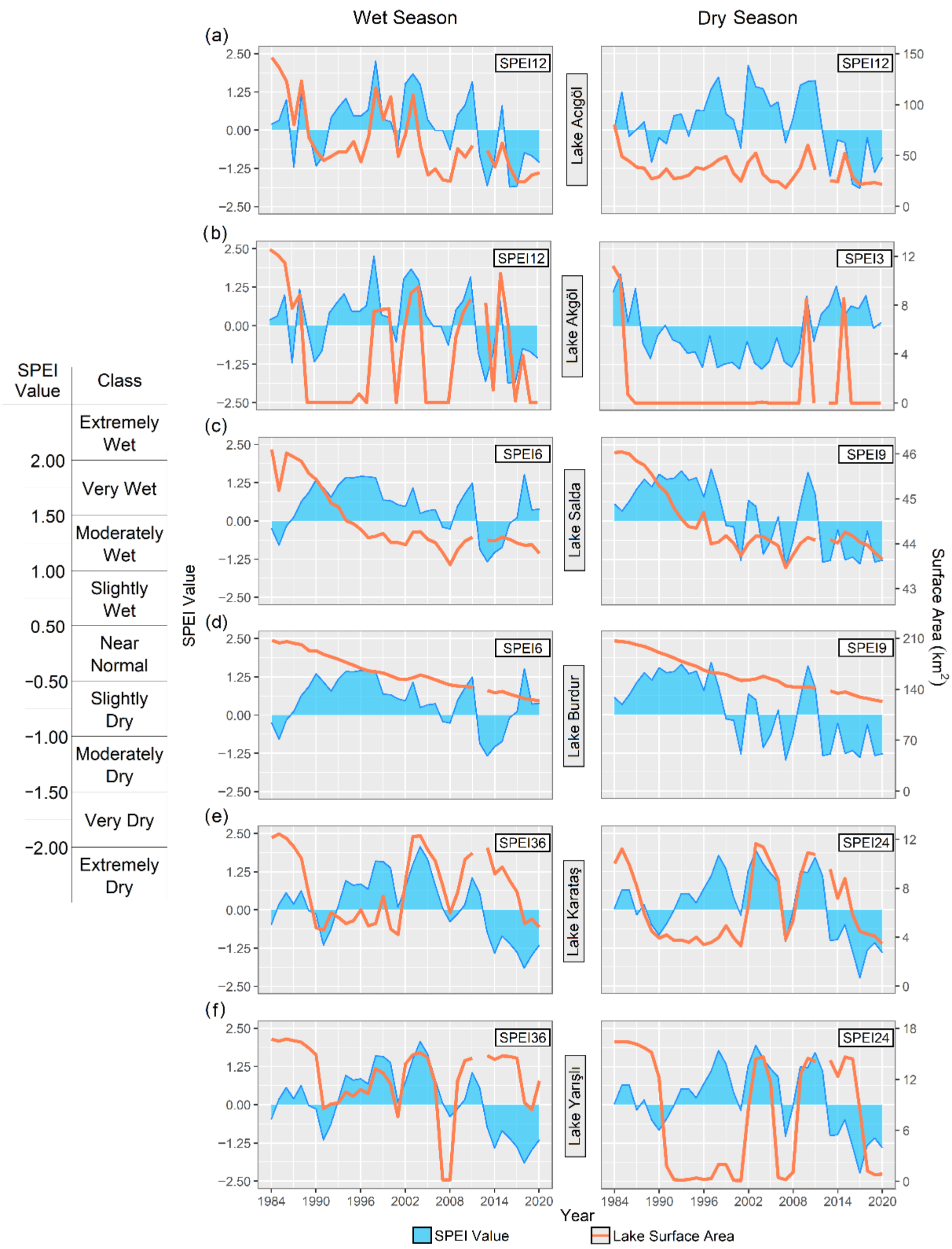

Figure 5. SPEI moisture categories (left) and SPEI and lake surface areas in wet and dry seasons for the period 1984–2020 for lakes (**a**) Acıgöl, (**b**) Akgöl, (**c**) Salda, (**d**) Burdur, (**e**) Karataş, and (**f**) Yarışlı.

3.4. Changes in the Bird and Fish Communities

The major changes in the lake area in the BCB have led to substantial changes in the biota, which we elucidated by focusing on the threats to waterbirds and fish.

3.4.1. Birds

The BCB is home to 106 bird species with either probable or confirmed breeding records and 55 more with possible breeding records. Of these, five species are included in the IUCN red-list as globally threatened [42]. The six IBAs in the BCB have had worsening scores and conditions, and half are listed among IBAs in danger, which are IBAs under intense pressure, requiring urgent action [61,62].

Over the last 50 years, the wintering waterbird population size has shown a significant negative trend (Figure 6; negative binomial GLM with log link; effect size estimate for year: −0.394, SE: 0.159, *p*-value: 0.013). The BCB harbored more than 360,000 waterbirds in the late 1960s, making it one of the most important waterbird wintering sites in Turkey, but for 2015–2020, the average declined to only 26,000 for the whole basin.

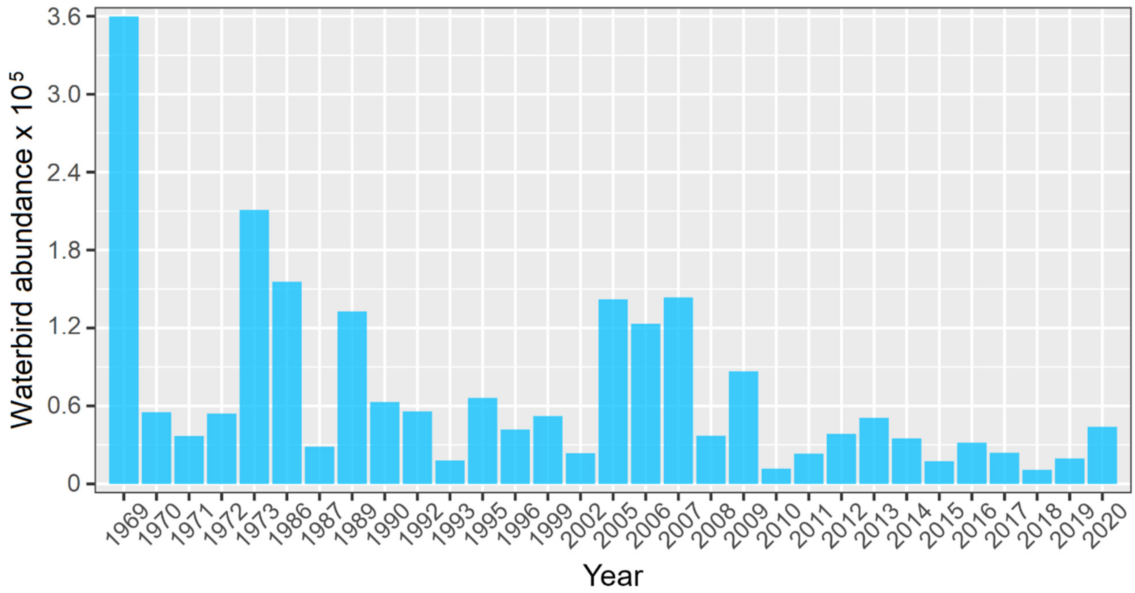

Figure 6. Total wintering waterbird abundance in the Burdur Basin between 1969 and 2019.

3.4.2. Fish

The BCB has the second-highest fish endemicity (54%) after the Konya Closed Basin (74%) [12], with 13 of the 24 fish species being endemic. In addition, the BCB has non-native fish species: four introduced (*Cyprinus carpio*, *Knipowitschia caucasica*, *Sander lucioperca*, and *Silurus glanis*) and seven invasive (*Carassius gibelio*, *Clarias gariepinus*, *Coptodon zillii*, *Gambusia holbrooki*, *Hemichromis letourneuxi*, *Oreochromis niloticus*, and *Pseudorasbora parva*). Of the 13 endemic fish species, 7 are categorized as threatened: 2 as critically endangered and 5 as endangered [63]. Endemic fish species populations in the BCB basin have declined in recent decades [48,49,53,64], mainly due to significant loss of lakes and streams, climate change, water pollution [47], and the invasion of non-native species [54].

The Anatolia region is a hotspot for the diversity of the killifish family (Aphaniidae), a euryhaline group that tolerates changes in salinity and can live in both fresh and brackish waters [65,66]. Many species of the *Anatolichthys* genus have a limited distribution in the BCB, with some species restricted to only a few springs or lakes, such as *Anatolichthys transgrediens*, which is only found in Lake Acıgöl during the spring [48], *Anatolichthys saldae*, which is only found in Lake Salda, and *Anatolichthys sureyanus*, which only occurs in Lake Burdur [51]. The endangered *A. sureyanus* has been highlighted as being under threat due to massive water abstraction and damming [48,63].

3.5. Future Predictions of Temperature and Precipitation

Mann–Kendal and Şen's trend analyses indicated an increase in annual mean air temperatures (0.012 °C/year) (Figure 7), but there was no significant trend in precipitation. Moreover, open surface evaporation showed an increasing trend of 6 mm/year for the basin [31].

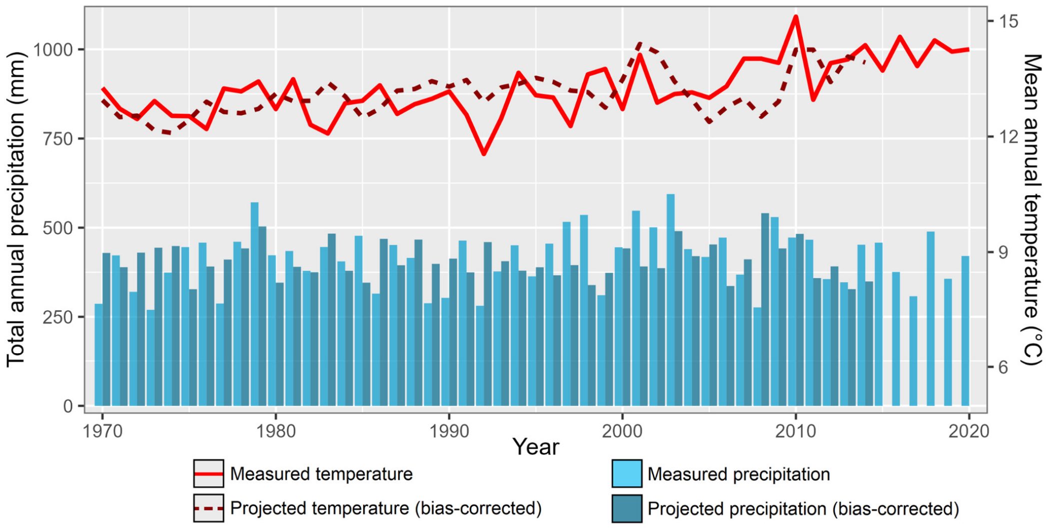

Figure 7. Annual mean air temperature and annual total precipitation for the period 1970–2014; projected (bias-corrected) air temperature and precipitation values for 1970–2020.

CNRM-ESM2-1 GCM data on temperature and GFDL-ESM4 GCM data on precipitation were selected for predictions as the model results fit best with the observations for the Lake Burdur sub-basin. Taylor diagrams showing the performance of the climate model results are given in Appendix A Figure A1. The annual mean temperature and precipitation data, before and after bias correction with the observations, are given in Figure 7.

The climate model (CNRM-ESM2-1 GCM) indicates that in 2100 the long-term average (1970–2100) annual mean temperature will be 14.38 °C. This is 1.18 °C warmer compared to the long-term average mean annual temperature for 1970–2020 of 13.2 °C. Total annual precipitation is predicted to increase by 2% in 2100 from 413 mm (1970–2020) to 422 mm (1970–2100). Long-term potential annual evaporation is estimated to increase to 1626 mm for 2100 as compared to 1432 mm for 2020 (Figure 8).

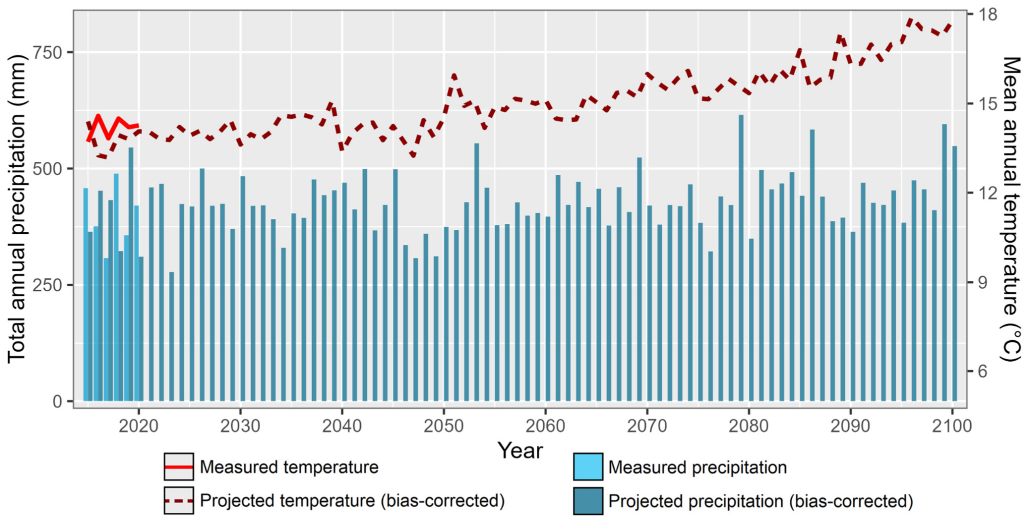

Figure 8. Annual mean air temperature and annual total precipitation values for validation (2015–2020) and future prediction (2021–2100) periods.

3.6. Case Studies

To illustrate the severity of the ecological changes that the BCB is facing, we provide three case stories on: (1) the hydrological change of Lake Burdur, (2) changes in bird and fish communities in Lake Acıgöl, and (3) the globally endangered White-headed Duck in the BCB.

3.6.1. Witnessing the Dry-Out of Lake Burdur

Lake Burdur has a basin area of approximately 3185 km^2, an average lake depth of 40 m, and a maximum depth ranging between 68 and 110 m. The maximum surface area of Lake Burdur was 206 km^2 in 1985 (Figure 9a). The lake receives water from seasonal and perennial streams, groundwater, and rainfall. The water balance of Lake Burdur based on water level recordings since 1970 showed good correspondence between the observed and modeled lake volumes (Figure 9c).

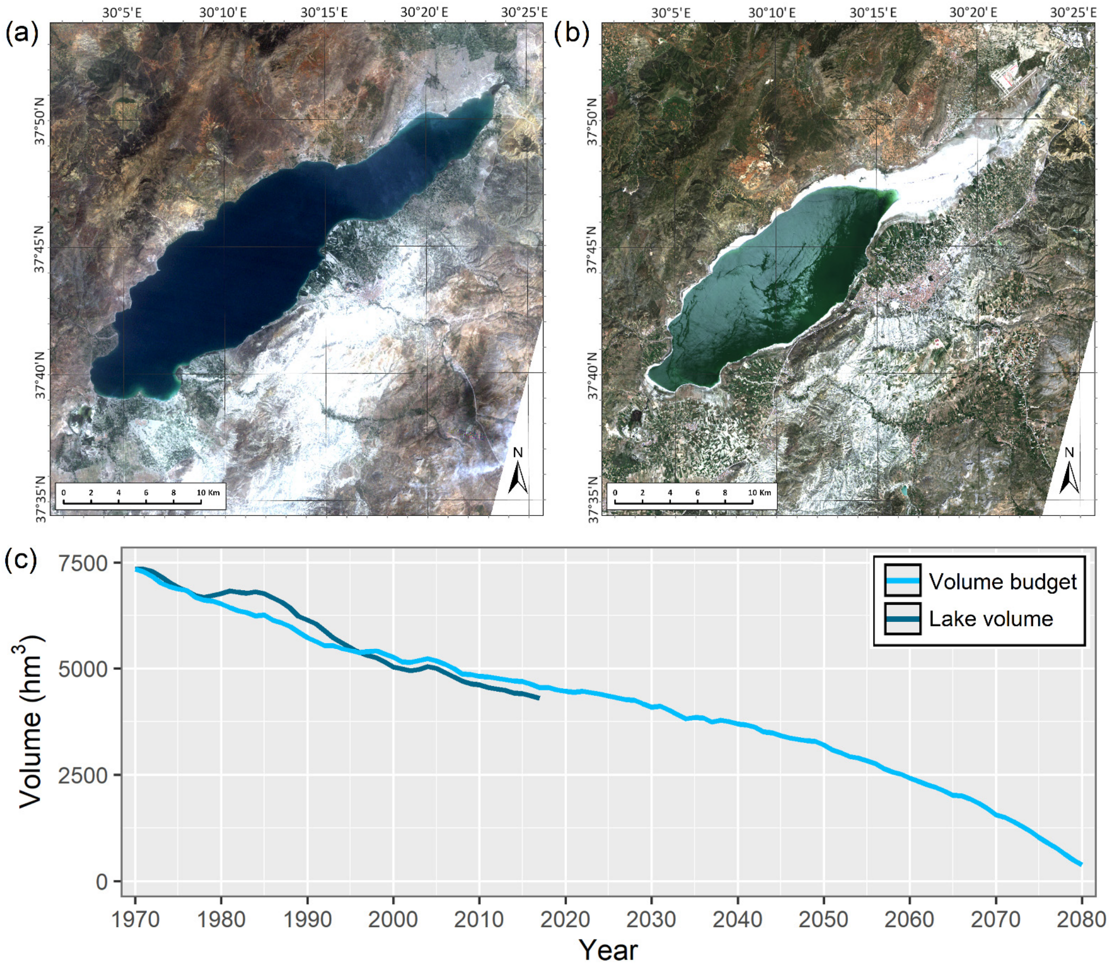

Figure 9. Lake Burdur in 1985 (**a**) and in 2020 (**b**) and the volume of water change in the lake from 1970 to 2080 (**c**).

Several dams had already been built before 1994 [67]. These dams collectively retained 31.17×10^6 m^3 water per year. The biggest dam built on the inflow is the Karaçal Dam. Between 2000 and 2010, small reservoirs were constructed on the rivers, also contributing to the lake's shrinkage.

The budget analysis for Lake Burdur revealed a decreasing trend in volume with time. The depth–volume curve indicates a depth of 841 m (mean sea level), corresponding to 4000 hm^3 volume by the end of 2045. Below 841 m, the side slopes of the lake are steep and without pronounced shallow areas. Since the mean annual temperature, and thus evaporation, is predicted to increase, the lake is predicted to dry out by the end of the century even if the water use in the lake basin remains the same (Figure 9c).

The SPEI values calculated from the temperature and precipitation data obtained from the climate models indicate slightly dry periods after 2050 and extremely dry periods after 2075 (Figure 10). The duration of negative SPEI values were more pronounced for the dry than the wet periods (Figure 10b), indicating that long-term droughts are likely to occur in Burdur Lake from 2090.

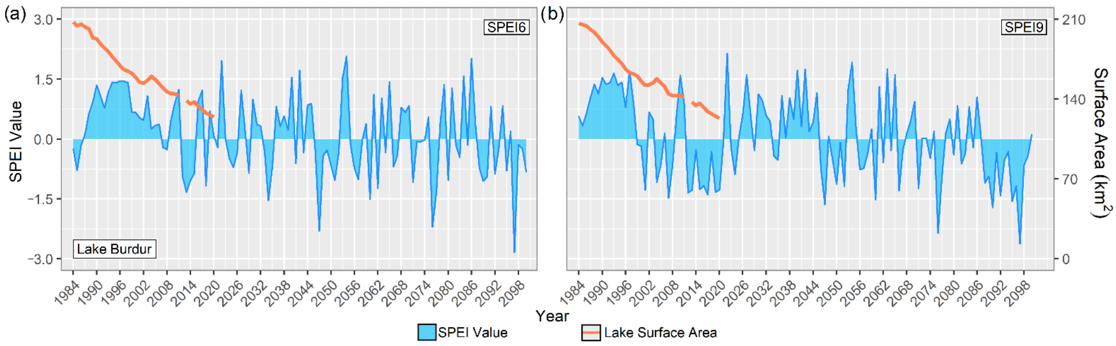

Figure 10. SPEI prediction for Lake Burdur for wet (**a**) and dry (**b**) periods based on SPEI-6 and SPEI-9, respectively.

Lake Burdur is an alkaline lake, with high salinity and high ion concentrations [68], reflecting the absence of outflows. The projected increased evaporation not compensated by precipitation, along with the expected increase in water use, will lead to an increase in the concentration of these salts and ions, and therefore an increase in salinity, with the consequent effects on ecosystem services and functions, including the support of biodiversity.

3.6.2. Lake Acıgöl

Lake Acıgöl is an endorheic, hypersaline soda lake situated in a tectonic depression. The lake receives spring water primarily characterized by high Na_2SO_4 and NaCl values, with a total flow of 1140 L/s [69] that enters the lake from a fault line on the southern side (Figure 11). Lake Acıgöl is the source of more than 85% of the anhydrous Na_2SO_4 production of Turkey (400,000 tons in the late 1990s) [70]. The lake had a surface area of 160 km^2 and a maximum depth of 8 m until the mid-1970s before the soda production operations started in the region [71]. Between the late 1970s and late 1980s, the lake surface area decreased by 75%, and the permanent water level has dropped more than 10 m since 1971 when the salt factories opened up [72,73]. Figure 11 shows the decrease in the lake's shoreline and the increase of the factories between 1984 and 2020. A major inlet to the lake was diverted for use in anhydrous Na_2SO_4 and Glauber salt extraction (60,000 tons/yearly). In addition, the major chemical factories around the lake used 25 million m^3 water per year for the extraction process [74]. Furthermore, the increased use of the southern springs for irrigation and domestic purposes, especially after the 2000s, contributed to the lake's shrinkage [69].

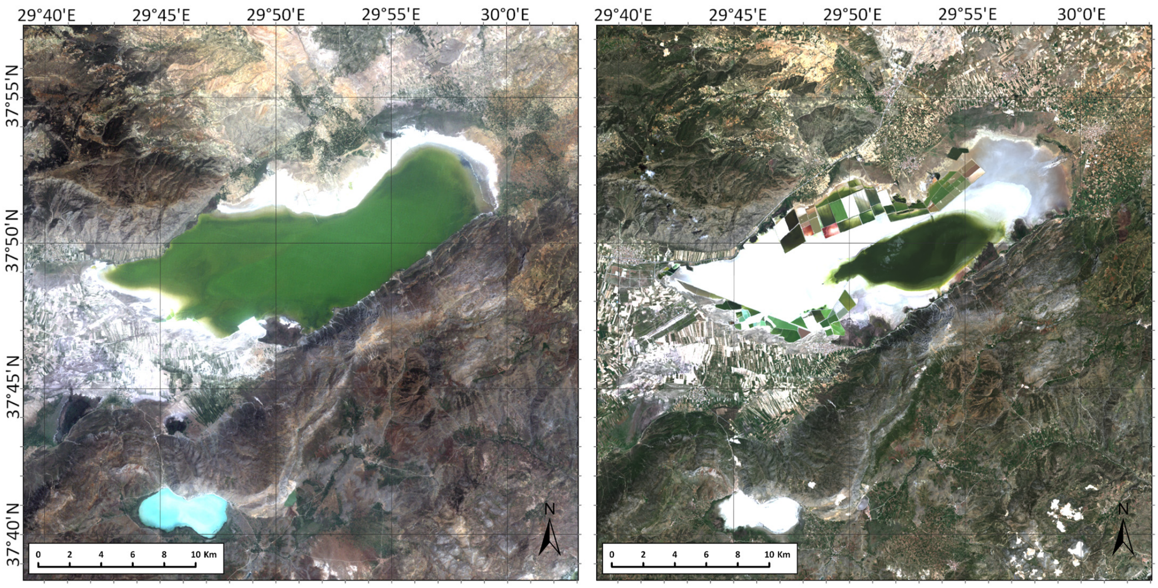

Figure 11. Lake Acıgöl in 1985 (**left**) and 2020 (**right**).

Lake Acıgöl is an important breeding, wintering, and stopover site for many bird species. Thus, regionally important numbers of Greater Flamingos (*Phoenicopterus roseus*) and the globally threatened Great Bustards (*Otis tarda*) inhabit the lake [67]. The analyses of mid-winter waterbird censuses did not reveal any significant trend in the species richness of the wintering bird population between the 1960s and 2019 although there was a slight negative effect of the year (negative binomial GLM with log link, effect size estimate: −0.365, SE: 0.199, p-value = 0.067). However, the abundance of the total wintering waterbird communities (−0.397, SE: 0.165, p-value = 0.016) and the functional evenness of the wintering waterbird communities have declined significantly over the last 51 years (gamma GLM with log link, effect size estimate: −0.272, SE: 0.060, p-value < 0.001).

The springs of Lake Acıgöl are also an important migration and wintering site for the endemic and threatened Acıgöl toothcarp *Anatolichthys transgrediens* [47,51]. During heavy rainfalls, when the salinity concentration is low, *A. transgrediens* can be found near the shores, especially in the southern part of the lake [47,66]. *A. transgrediens* populations have declined dramatically, and the species is currently listed as Critically Endangered [51,63]. The loss of habitat around the lake, as a result of reduced rainfall, water abstraction, and drying springs, has negatively impacted the species [75]. Furthermore, Mosquito fish (*Gambusia holbrooki*) were introduced by the end of the 1990s and had a significant impact on the native and endemic species, probably mainly due to resource competition and predation of the juveniles. Also, negative impacts on a variety of other animals, such as frogs and macroinvertebrates [66,76], were observed. It has been reported that this non-native species could affect the trophic levels of the ecosystem [77,78].

3.6.3. The Fall of the Endangered White-Headed Duck in the Burdur Basin

The White-headed Duck (WHD) is a globally endangered, diving duck [79,80]. It is an iconic bird in the basin, and there used to be a bird festival in Burdur province until the mid-2000s [67] as Lake Burdur harbored the majority of the global population during the winters of the early 1990s [81,82]. Back then, several thousand WHDs regularly wintered in the lake, and the numbers reached a peak of 10,927 in 1991, corresponding to 58% of the global population ([81]; Figure 12). Other lakes in the basin, including Lakes Acıgöl, Akgöl, Karataş, Salda, and Yarışlı, supported a total of nearly 1500 wintering WHDs until the late 1990s [43]. A relatively small wetland southwest of Lake Burdur and Soğanlı Marshes had a breeding population of 2–3 pairs in the late 1990s [83]. Outside the breeding and wintering periods, in the migration and post-breeding periods, up to a few thousand WHDs could also be found in the basin, mainly in Lake Burdur [84].

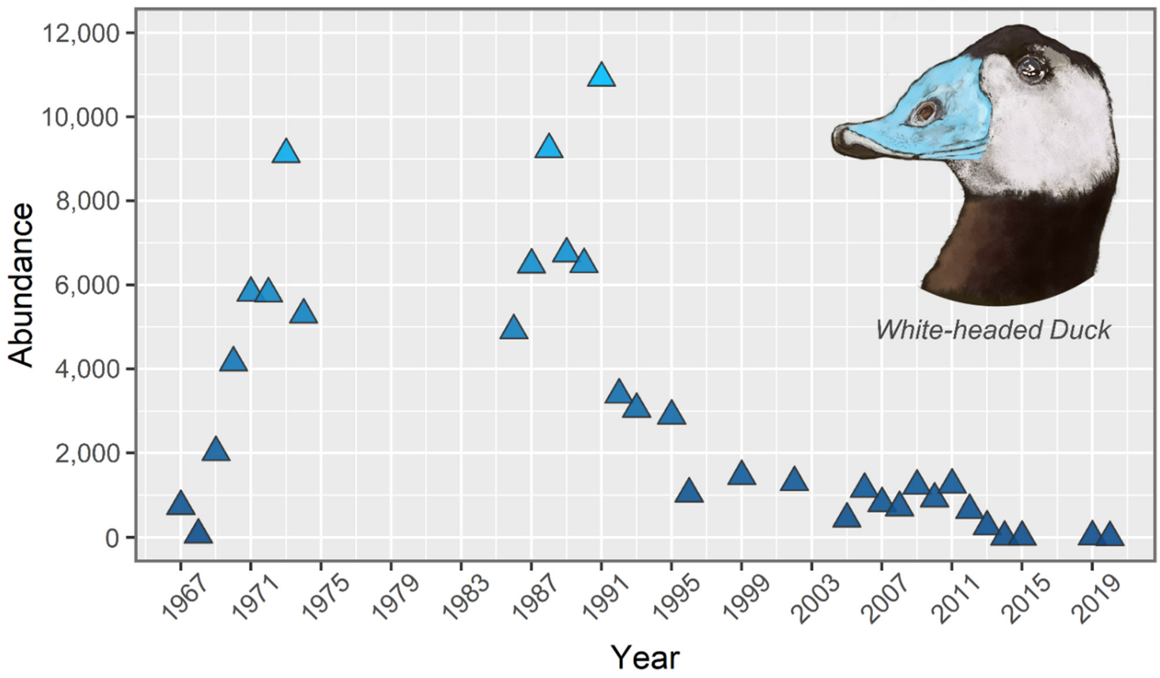

Figure 12. Wintering White-headed Duck abundance in the Burdur Basin from 1967 to 2020.

Following the water level decline in the lake, wintering WHD numbers in the basin started to decrease dramatically. In 2019, there were only 18 wintering WHDs left in the lake and its basin, and none in 2020 [43]. Multiple factors seem to have contributed to this decline. First, when the lake started to shrink, the northern and shallowest part of the lake dried out [14]. This part was particularly important for waterbirds, including the WHD [83]. The remaining southern parts of the lake have a steeper morphometry and offer limited amounts of shallow areas for waterbirds [14]. The loss of the shallow areas seems to have been the biggest contributor to the decline of the WHD population, considering that most WHDs were found there earlier [81]. Water level declines in the other lakes in the basin may also have contributed to the regional decline of the wintering population. Secondly, the loss of the shallow areas and increasing salinity may have decreased the capacity of the lake to support chironomids, which are the main food sources of WHDs [80]. Chironomid abundance in the lake was found to increase steadily up to and peak at around 10 m and decreased steeply at higher depths [85]. Studies have shown that high salinity levels can decrease the growth rate, survival, size, and emergence rate of some chironomid species [86,87] as well. Taxonomic studies have also confirmed an overall decrease in the diversity of benthic macroinvertebrates, including chironomids, between the late 1980s and mid-2000s [88]. Furthermore, the once-high hunting pressure in Lake Burdur may have contributed to the decline of the WHD population. Even when the lake was declared a no-hunting zone, around 4.5 WHDs per day were estimated to have been shot in only one-quarter of the lake, which was well over the sustainable limit [81]. In the winter of 1992–1993 alone, at least 1000 WHDs were estimated to have been shot [89]. Finally, declines in the regional and national breeding populations [82] likely also contributed to the decline, showing the effects of multiple stressors in addition to the water loss effects.

4. Discussion

4.1. Change in Lake Surface Area and Water Budget of the Largest Lake in the Basin

We used remote sensing and hydrometeorological data to understand the change in lake surface areas in the Burdur Basin and the water budget of the largest lake in the basin. Especially in closed basins, the expansion and reduction of lakes are important indicators of the regional climate conditions and the local hydrological cycle. We used Landsat images dating back to 1985 and the SPEI values calculated from meteorological data to describe the decadal changes in the surface area of the lakes in the BCB (Figure 4). The trend analyses of temperature and rainfall observations at the Burdur meteorological station from 1970 to 2020 revealed an increasing temperature in the basin, while precipitation has exhibited no significant trend. Accordingly, the water loss from the basin has increased due to enhanced evaporation and transpiration, as also evidenced by the observed negative SPEI values after 2000. Historical and current Landsat images showed a great shrinkage of almost all of the lakes in the basin, except for deep Lake Salda, from 1984 to 2020 (Figure 4). The relation between SPEI and surface areas showed a response time of 6–9 months for precipitation anomalies of the deep Lakes Burdur and Salda, indicating that the changes in mean surface area mostly depended on the meteorological events. The Lakes Acıgöl and Akgöl had a longer response time (12 months) and mostly interacted with groundwater and streamflow, while Lakes Yarışlı and Karataş had the highest response times (>24 months), which is generally the case for lakes used for irrigation purposes [14] (Figure 5).

As in the nearby, large Konya Closed Basin (KCB), a key factor driving the water loss in the lakes is the unsustainable use of water for agriculture. Crop production in the BCB increased from 7×10^5 tons per year during the 1980s to 10×10^5 tons per year in 2007, and later to 15×10^5 tons per year in 2019. The increase in crop production was especially caused by the production of water-thirsty crops, maize, soy, and alfalfa, which has increased since 2004 [60], thereby substantially augmenting the use of water in agriculture (Figure 2). In KCB, production has increased 2-fold since 2000, especially due to the enhanced production of maize and sugar beets, this increase being mirrored in the groundwater tables where major drops have been observed in most of the basin [12]. A yearly irrigation-induced water deficit of almost 350 hm^3 in the KCB has led to water importation from neighboring catchments (e.g., the Blue Tunnel Project involving the transfer of water from the Göksu catchment to the Konya Plain) [60]. Such compensatory importation is well-known from other arid regions (e.g., [10]) but has negative consequences for the lakes in the exporting catchments, an evident example of this being the iconic Aral Sea [90].

The climate projection models for the BCB furthermore predict an increase in annual mean temperature of up to 1.18 °C, an increase in annual precipitation of 10 mm per year, and an increase in the potential annual evaporation of 200 mm per year. The temperature increase concurs with previous climate change modeling results for the basin, mostly based on CMIP5. However, in contrast to the CMIP5 model results, CMIP6 predicts a slight increase in annual precipitation; however, this does not compensate for the expected increase in loss by evapotranspiration. We used the CMIP6 model as it was the best to describe the recent changes in Lake Burdur and predicted warmer annual temperatures than CMIP5, and our results suggest that, after 2070, the BCB will face long-term, moderate-to-severe dry periods. The budget analysis of the lake and the projected SPEI values show that there is a high risk that the lake may entirely disappear (the third-deepest lake in Turkey) in the medium 12 rm (2045–2070) due to excessive evaporation and water abstraction for irrigation (Figure 9). Also, Lake Acıgöl faces great shrinkage, in part because its water balance is highly controlled by the water use in the salt and sulfate factories around the lake. A simulation for Lake Beyşehir in KCB, Turkey's largest freshwater lake for which different climate models predicted a complete dry-out during the next 20–60 years if the current water use regimes continue, suggests that a reduction in water use of up to 60% is needed to avoid this [12,60]. Thus, a grim future is on the horizon for the lakes in the central plains of Turkey with a "business as usual" approach to irrigated crop farming.

4.2. Changes in Waterbird Communities and Aquatic Habitats in the Basin

Despite the drastic habitat loss and degradation that the BCB has been experiencing over the last several decades, it still exhibits an astounding bird diversity. All IBAs in the basin, which contain the majority of the populations of these globally threatened birds [67], have deteriorating conditions and declining populations. The dramatic wetland habitat losses and degradation have also resulted in a steep decline in waterbird numbers in the basin, including the enigmatic White-headed Duck. We anticipate that the contributions of the wintering range will shift due to global climate change [91,92], and the global and regional population declines that some of the waterbirds have experienced [93] are minor compared to the effects of water drainage and habitat degradation. Thus, the range shifts are not likely to have resulted in huge declines in total community size because waterbird species respond differently to climate change. Some species have shown no range shift at all [92], as indicated by the absence of steep declines in other long-term datasets in Turkey [94]. The decreased FEve of the wintering waterbird communities at Lake Acıgöl may have caused the deterioration of fundamental community functions [95]. A less-even distribution of abundance within the functional space implies that some parts of the niche space are under-utilized (although part of the niche space is occupied), which may decrease the overall stability and resilience due to less optimal resource use and weaker species complementarity [95,96].

Habitat degradation and loss driven by the water deficit of lakes in the BCB has led to a drastic impact on bird populations in recent decades, decreasing by 93% from the late 1960s to the period 2015–2020. In particular, the loss of the more sensitive shallower areas of these lakes threatens those species that depend on the habitat or food resources these areas provide, as in the case of the White-headed Duck. Furthermore, water loss increases the salinization, which impacts various communities, such as the macroinvertebrates and plants that serve as food for waterbirds. Even more dramatic changes have occurred in the KCB [12]. Here, a comparison of two bird atlases (from 1998 and 2018) indicated a widespread decline in the species richness of breeding waterbirds in the whole basin, with a loss of 18 species, and the total breeding waterbird richness has declined by 23% (from 62 to 48 species), and 76% of the species that no longer breed in the KCB were Red-Listed on the national scale in the 2004 assessment. In addition to preventing their hunting, specific measures to reduce the consumption of water from these lakes require urgent action to avoid the total collapse of waterbird populations in the BCB. In particular, in the face of climate change scenarios that can accentuate the effects of water abstraction, accelerating the water loss and salinization of these lakes.

Impacts related to water deficits and salinization have also been observed in fish in the BCB. Since endemic freshwater fish species are often distributed over small areas, they are the most vulnerable group of vertebrates to anthropogenic impacts [97,98]. Lakes and streams in the BCB are currently being affected by habitat loss and modification, as well as by the introduction of non-indigenous species [49,99]. Endemic BCB fish species, particularly *Anatolichthys* and *Pseudophoxinus* populations, are currently declining [48,49,52]. Concerning the native and endemic fish species in the BCB, it is notable that the reduction of native fish populations and the increase of threatened species place the native fish species in restricted areas with poor water quality. Here, the non-native species can persist, tolerate, and sometimes thrive under an exceptional range of environmental conditions, displaying a high reproductive potential and becoming predators of native species. Non-native invasive species have impacted the natural habitats of almost all endemic species in the BCB [53]. However, biological (reproductive and trophic aspects) and ecological (population and community aspects) information on the native and endemic species of the BCB, as well as on their interactions with non-native species, is still scarce, hampering the development of optimal conservation guidance for the species.

4.3. Management Perspectives

That changes in land use and irrigation rather than climate have had the most devastating effects in semiarid and arid areas worldwide in recent decades is well established (e.g., [10,100]) and clearly illustrated also when combing the results of the studies of the BCB and the KCB (in the present paper and [12]). The water deficit in the BCB and the KCB may be further affected by the intensification of agriculture. With the current agricultural policies, the crop production will likely continue to increase as in the past 20 years to satisfy the demand of an increasing human population. The war scenarios of the early 2020s in the region might further accentuate the needs for higher crop production, increasing even more the water abstraction and thus its environmental impacts. Left uncontrolled, the production of thirsty crops, especially that of fodder crops such as maize and alfalfa in the BCB, will likely increase, leading to higher demands for water [101]. To ensure effective use of the water in the basin, switching to water-saving irrigation methods and the planting of crops suitable for the climate and water potential of the area through regional-level action is highly needed [102]. If the demand for water remains at its current level or increases to meet irrigation needs, the groundwater table will drop further, and so will the lake levels, and therefore the potential of these lakes to support their functions and services, including irrigation. Given these and the projected increases in temperature and surface evaporation, the capacity of the basin to support waterbirds and endemic fish species might decline further in the future. The intense pressure on the BCB aquatic habitats has already resulted in a dramatic decline in the populations and range sizes of many waterbird and fish species [55,103]. Many endemic species have been restricted to isolated refuge habitats, such as springs and spring-fed streams, causing extreme limitation of dispersal. Therefore, immediate protection of these refuge areas, effective mitigation of current pressures, and restoration of native aquatic habitats in the BCB are critically important for the endemic fish fauna as well as for the iconic water birds (e.g., White-headed Duck, Flamingo) of the BCB. If these pressures remain at their current intensities, the local extinction of fish populations may be imminent. Restoring healthy and resilient ecosystems, with sustainable water use practices and strict control of invasive species, are a priority for maintaining the fish fauna of the BCB with its high endemism as well as habitat suitability for waterbird populations.

To reverse the ecosystem degradation or even preserve the current status, there is an urgent need for a policy framework that aims to restrict the exploitation of water resources within sustainable limits while simultaneously promoting conservation efforts. This seems achievable only if the basin-wide legal regulation of water abstraction is combined with economic incentives for the transition to climatically appropriate crop farming.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w14081241/s1, Section S1: Breeding Bird Atlas Methodology, Section S2: Additional Sources Used for the White-headed Duck Case Study, Section S3: Midwinter Waterbird Survey Methodology, and Section S4: Functional Diversity & Statistical Analyses. References [104–124] are cited in the supplementary materials.

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Appendix A

Table A1. Global circulation models.

Global Circulation Model	Ensemble	Historical Simulation	Future Simulation		Parameter
			SSP 245	SSP 858	
CNRM-ESM2-1	r1i1p1f2	+	+	+	Near-surface air temperature
MPI-ESM1-2-HR	r1i1p1f1	+	+	+	Near-surface air temperature
MRI-ESM2	r1i1p1f1	+	+	+	Near-surface air temperature
NOR-ESM2-MM	r1i1p1f1	+	+	+	Near-surface air temperature
ACCESS CM-2	r1i1p1f1	+	+	+	Precipitation
GFDL-ESM4	r1i1p1f1	+	+	+	Precipitation
CNRM-CM6-1-HR	r1i1p1f2	+	NA	+	Precipitation
HADGEM-GC-31-MM	r1i1p1f3	+	NA	+	Precipitation

(a)

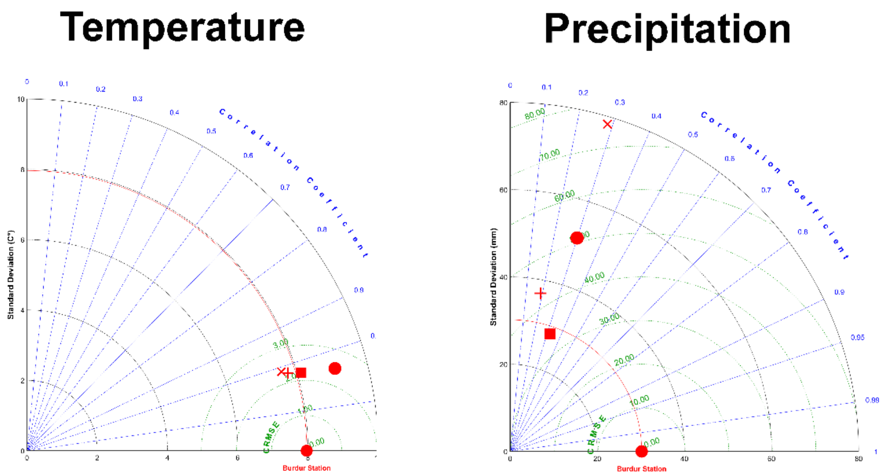

Figure A1. *Cont.*

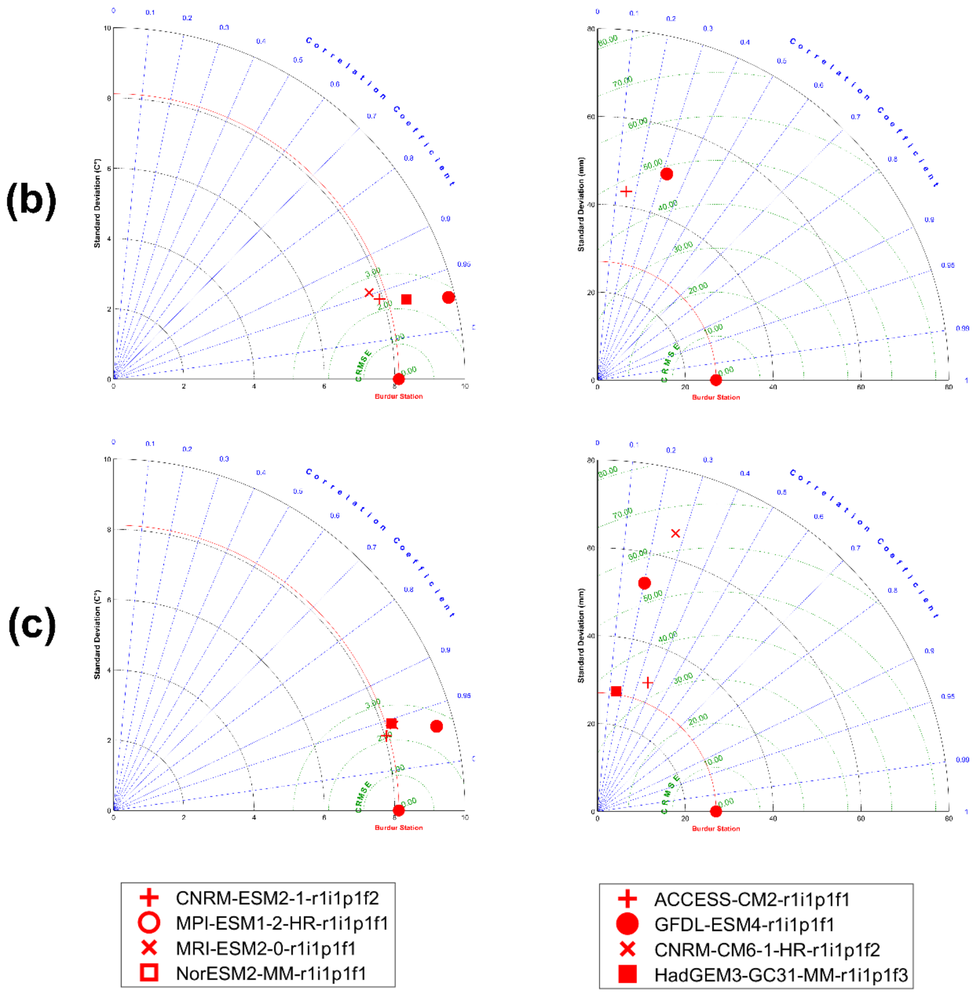

Figure A1. Taylor diagrams for temperature and precipitation comparison for the historical period (1970–2014) (**a**); the validation period (2015–2020) of R245 simulation (**b**); and the validation period (2015–2020) of R585 simulation (**c**).

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APPENDIX B

B.1 General Dataset

Table B.1: All-data flat file (B2, B3 etc. indicates Sentinel-2 Band2, Band3, etc.

FCODE	Name	Longitude	Latitude	Samp. Date	Sat. Img. Date	Date diff	EC	B2	B3	B4	B5	B6	B7	B8	B11	B12
FT1_01	Godet_Dam	33.27680	37.11320	21-06-20	22-06-20	1	357.50	910	806	762	718	764	795	745	281	488
FT1_02	Ibrala_Dam	33.39060	37.21420	21-06-20	22-06-20	1	293.60	1203	1153	830	814	853	908	796	441	557
FT1_03	Ayranci_Dam	33.73050	37.33670	21-06-20	22-06-20	1	306.00	1384	1567	1155	992	948	995	909	327	567
FT1_04	Ivriz_Dam	34.16600	37.45190	21-06-20	22-06-20	1	261.80	1123	1102	2157	2239	2640	2939	2731	322	2548
FT1_05	Akgol	33.77240	37.51950	21-06-20	22-06-20	1	3039.00	1055	1054	896	1178	1876	2206	1644	613	541
FT1_06	Yollarbasi_Dam	33.04050	37.13730	22-06-20	22-06-20	0	302.20	1146	1181	1542	1598	1783	2007	3109	480	1588
FT1_07	Delicay_Dam	33.17110	37.13630	22-06-20	22-06-20	0	383.10	1343	1477	1046	912	831	872	870	379	534
FT1_08	Aydogmus_Dam	32.65560	37.30320	22-06-20	22-06-20	0	386.30	1016	989	765	693	664	707	653	268	358
FT1_09	Apa_Dam	32.54250	37.36410	22-06-20	22-06-20	0	217.30	1099	1011	627	597	575	597	536	418	346
FT1_10	Sugla_Lake	31.97970	37.35220	22-06-20	25-06-20	3	231.30	1326	1286	649	695	680	662	527	813	430
FT1_11	Kovali_Lake	32.03250	37.57970	22-06-20	25-06-20	3	163.50	1208	1242	10251	9938	9904	9931	10837	1859	3806
FT1_12	Dipsiz_Lake	32.03400	37.57440	22-06-20	25-06-20	3	173.10	837	690	10418	10567	10647	10791	10669	177	4107
FT1_13	Suluklu_Lake	32.04550	37.56730	22-06-20	15-06-20	7	96.10	1055	1009	772	796	781	823	716	668	501
FT1_14	Gokcehuyuk_Dam	31.78090	37.43330	23-06-20	25-06-20	2	263.69	1132	1042	647	595	580	586	526	285	249
FT1_15	Gokcen_Dam	31.53910	37.43830	23-06-20	25-06-20	2	328.69	988	885	705	571	603	572	541	225	369
FT1_16	Derebucak_Dam	31.54200	37.36500	23-06-20	25-06-20	2	297.19	967	790	4221	4355	4876	5162	5011	312	4022
FT1_17	Cimen_Lake	32.08400	37.66950	23-06-20	25-06-20	2	64.79	2590	2500	7432	7521	7744	8013	7554	3370	3302
FT1_18	Inlice_Goleti	32.08790	37.67480	23-06-20	25-06-20	2	85.50	1602	1610	6035	6290	6555	6793	6217	1297	3853
FT1_19	Altinapa_Dam	32.29200	37.88320	23-06-20	25-06-20	2	387.89	1221	1141	7856	7927	7994	8200	8285	501	3901
FT1_20	Acigol	33.67320	37.71010	24-06-20	22-06-20	2	88438.00	1169	949	841	806	844	844	823	315	491

Table B.1 continued from previous page

FCODE	Name	Longitude	Latitude	Samp. Date	Sat. Img. Date	Date diff	EC	B2	B3	B4	B5	B6	B7	B8	B11	B12
FT1_21	Bahceli_Goleti	34.62850	37.82610	24-06-20	22-06-20	2	278.00	1222	1254	825	771	780	768	720	594	460
FT1_22	Akkaya_Dam	34.63500	37.93360	24-06-20	22-06-20	2	1084.00	880	796	594	759	796	847	726	389	299
FT1_23	Gumusler_Dam	34.70590	37.98110	25-06-20	22-06-20	3	254.09	1893	2056	2870	2899	3176	3540	3476	3101	2733
FT1_24	Uluagac_Goleti	34.84780	38.03240	25-06-20	22-06-20	3	261.50	937	887	652	610	613	668	595	396	341
FT1_25	Cayirli_Lake	34.95270	38.04580	25-06-20	22-06-20	3	533.00	801	716	650	655	753	745	710	367	374
FT1_26	Cinarli_Goleti	34.57340	38.21280	25-06-20	22-06-20	3	110.90	1252	1301	4518	4646	4850	5044	4824	1644	1592
FT1_27	Murtaza_Lake	34.58120	38.17690	25-06-20	22-06-20	3	112.40	766	595	1875	1928	2057	2093	2287	353	801
FT1_28	Golludag_Lake	34.54670	38.26090	25-06-20	22-06-20	3	197.30	833	683	6493	6744	7053	7369	6519	581	4526
FT1_29	Acigol_Narligol	34.45690	38.33760	25-06-20	22-06-20	3	3937.00	1052	1050	1289	1996	2088	2400	1412	1314	1484
FT1_30	Kayi_Lake	34.37740	38.40450	25-06-20	22-06-20	3	671.00	971	875	914	1178	1343	1479	996	597	879
FT1_31	Baki_Balikli_Lake	34.36430	38.39930	25-06-20	22-06-20	3	678.00	853	767	2803	3096	3605	3988	4055	385	2711
FT1_32	Mamasin_Dam	34.13650	38.40440	26-06-20	27-06-20	1	782.00	1136	1216	770	811	571	557	519	451	340
FT1_33	Tuz_Lake_1_Station	33.61300	38.79680	26-06-20	27-06-20	1	240000.00	1735	2143	2657	2534	1260	1325	1120	120	81
FT1_34	Pecenek_Dam	33.67910	38.89310	26-06-20	27-06-20	1	730.00	1165	1074	714	932	848	881	489	696	577
FT1_35	Tuz_Lake_2_Station	33.41010	39.07530	26-06-20	27-06-20	1	237000.00	3710	3990	4756	4961	4880	5090	4625	854	482
FT1_36	Duden_Small	33.13240	39.06250	26-06-20	27-06-20	1	91352.00	1660	1783	1478	1631	1088	1220	970	365	316
FT1_37	Duden_Big	33.15720	39.08460	26-06-20	27-06-20	1	70540.00	1675	1783	1523	1652	1381	1524	1340	381	186
FT1_38	Uyuz_Lake	32.93210	39.23940	27-06-20	25-06-20	2	2320.00	886	807	1292	1293	1127	1170	1117	181	600
FT1_39	Samsam_Lake	32.74800	39.09980	27-06-20	25-06-20	2	9664.00	2619	3073	4409	4585	4825	5162	4892	418	469
FT1_40	Kozanli_Gok_Gol	32.83860	39.01270	27-06-20	25-06-20	2	975.00	1111	1182	1924	1952	1508	1532	1419	86	795
FT1_41	Bolluk_Lake	32.92130	38.52280	27-06-20	27-06-20	0	83909.00	927	992	644	1114	1179	1418	1030	177	111

Table B.1 continued from previous page

FCODE	Name	Longitude	Latitude	Samp. Date	Sat. Img. Date	Date diff	EC	B2	B3	B4	B5	B6	B7	B8	B11	B12
FT1_42	Cihanbeyli_Dam	32.89660	38.64450	27-06-20	27-06-20	0	2907.00	1034	1040	780	1170	1250	1371	1007	589	342
FT1_43	Tuz_Lake_3_Station	33.36810	38.96490	27-06-20	27-06-20	0	240000.00	2698	2687	2873	2908	2891	2992	2789	366	230
FT2_01	Uyuz_Lake	32.92920	39.24060	05-07-21	15-07-21	10	2503.00	1015	989	1027	1010	690	737	670	331	237
FT2_02	Duden_Lake_Small	33.13240	39.06250	07-07-21	15-07-21	8	NA	2085	2020	2051	2056	2134	2193	2026	2403	1768
FT2_03	Tuz_Lake_1_Station	33.37100	38.96410	07-07-21	15-07-21	8	237300.00	3020	3195	3307	3191	2112	2188	1873	104	84
FT2_04	Kozanli_Gokgol	32.83910	39.01130	08-07-21	15-07-21	7	1586.00	985	948	728	1040	1092	1231	1050	248	188
FT2_05	Tuz_Lake_2_Station	33.61600	38.79930	10-07-21	12-07-21	2	237300.00	4072	4615	5817	5837	5206	5413	5365	612	330
FT2_06	Bolluk_Lake	32.91530	38.52140	11-07-21	12-07-21	1	115200.00	1158	1494	768	1320	759	839	648	374	275
FT2_07	Acigol_Narli	34.45410	38.33920	12-07-21	12-07-21	0	4168.00	834	818	417	362	256	333	336	232	175
FT2_08	Kaya_Lake	34.37580	38.40330	13-07-21	12-07-21	1	674.00	856	787	520	726	485	487	420	230	162
FT2_09	Baki_Lake_Balikli	34.36450	38.39707	14-07-21	12-07-21	2	650.00	790	695	422	387	451	320	391	273	144
FT2_10	Seker	35.41828	38.75668	16-07-21	17-07-21	1	398.00	1281	1359	1112	1302	1002	1218	799	583	440
FT2_11	Lake_Acigol_Konya	33.67320	37.71010	17-07-21	17-07-21	0	91650.00	1199	960	515	672	613	674	385	493	337
FT2_12	Lake_Akgol_Konya	33.77240	37.51950	18-07-21	17-07-21	1	5456.00	982	1059	597	1254	1312	1352	1053	343	222
FT2_13	Karatas_Lake	29.97330	37.39170	21-07-21	20-07-21	1	2006.00	1967	2053	1981	2072	2156	2273	2219	2015	1060
FT2_14	Burdur_Lake_Station_1	30.08770	37.70720	22-07-21	23-07-21	1	29830.00	1432	1387	1166	1153	1053	1141	954	862	716
FT2_15	Burdur_Lake_Station_2	30.19438	37.69884	23-07-21	23-07-21	0	29100.00	1217	1197	931	945	890	931	780	716	620
FT2_16	Lake_Acigol_Burdur	29.88499	37.82514	24-07-21	23-07-21	1	69520.00	1186	1082	1015	1107	717	691	564	198	110
FT2_17	Salda_Lake_Station_1	29.66059	37.52808	26-07-21	28-07-21	2	2003.00	1423	1302	1021	1115	930	897	654	741	501
FT2_18	Salda_Lake_Station_2	29.72067	37.52728	26-07-21	28-07-21	2	2035.00	1607	1366	1013	983	974	980	986	829	656
FT3_01	Little_Duden	39.06150	33.13557	18-05-22	18-05-22	0	72440.00	2420	2503	2209	2256	1858	1895	1757	1259	1213

Table B.1 continued from previous page

FCODE	Name	Longitude	Latitude	Samp. Date	Sat. Img. Date	Date diff	EC	B2	B3	B4	B5	B6	B7	B8	B11	B12
FT3_02	Tuz_1st	38.96454	33.38555	19-05-22	18-05-22	1	266900.00	3311	3937	4604	4800	3553	3629	3406	1203	1197
FT3_03	Small_Tuz	38.98956	33.32768	20-05-22	21-05-22	1	147400.00	2818	2947	3176	3132	3148	3317	3383	2140	1539
FT3_04	Acigol_Denizli	37.81824	29.88111	21-05-22	24-05-22	3	78950.00	2321	2814	2396	3009	2632	2727	2513	1218	1127
FS_06	Acigol_1	37.70896	33.66918	13-12-15	11-12-15	2	88650.00	1390	1160	1089	1204	1211	1304	1202	1262	877
FS_13	Acigol_1	37.70896	33.66918	17-01-16	30-01-16	13	88618.00	1492	1202	1190	1400	1562	1502	1096	872	618
FS_21	Acigol_1	37.70896	33.66918	21-02-16	19-02-16	2	87812.00	1197	1050	1020	1138	1212	1277	1049	1339	1027
FS_29	Acigol_1	37.70896	33.66918	13-03-16	10-03-16	3	85768.00	1507	1368	1434	1485	1647	1743	1621	1770	1336
FS_32	Acigol_1	37.70896	33.66918	13-04-16	09-04-16	4	86858.00	1438	1386	1364	1371	1639	1744	1636	1488	1099
FS_41	Acigol_1	37.70896	33.66918	21-05-16	09-05-16	12	87513.00	1548	1445	1528	1528	1750	1819	1784	1887	1424
FS_49	Acigol_1	37.70896	33.66918	19-06-16	18-06-16	1	93324.00	1570	1531	1578	1610	1734	1884	1707	1870	1407
FS_58	Acigol_1	37.70896	33.66918	19-07-16	18-07-16	1	94319.00	1328	1193	1038	1412	1573	1543	1092	1570	1204
FS_66	Acigol_1	37.70896	33.66918	22-08-16	17-08-16	5	95193.00	1296	1141	1031	1345	1465	1488	1032	1528	1140
FS_76	Acigol_1	37.70896	33.66918	21-09-16	16-09-16	5	95094.00	3881	3874	4253	4161	4290	4497	4347	4899	4028
FS_79	Acigol_1	37.70896	33.66918	15-10-16	16-10-16	1	94355.00	1133	923	812	1100	1149	1171	785	1158	946
FS_85	Acigol_1	37.70896	33.66918	12-11-16	15-11-16	3	89528.00	1229	1002	851	1113	1127	1168	741	1131	870
FS_91	Acigol_1	37.70896	33.66918	10-12-16	15-12-16	5	90059.00	1648	1243	1058	1967	2120	2059	982	627	486
FS_07	Acigol_2	37.71492	33.67147	13-12-15	11-12-15	2	88519.00	1310	1097	864	1001	1032	1142	770	917	596
FS_14	Acigol_2	37.71492	33.67147	17-01-16	30-01-16	13	88689.00	1181	932	700	871	838	843	591	800	470
FS_22	Acigol_2	37.71492	33.67147	21-02-16	19-02-16	2	87667.00	1043	934	701	863	871	900	602	932	639
FS_30	Acigol_2	37.71492	33.67147	13-03-16	10-03-16	3	87154.00	1572	1756	1711	1607	1541	1760	1661	1636	1424
FS_33	Acigol_2	37.71492	33.67147	13-04-16	30-03-16	14	85618.00	1118	968	716	873	882	892	660	831	637

Table B.1 continued from previous page

FCODE	Name	Longitude	Latitude	Samp. Date	Sat. Img. Date	Date diff	EC	B2	B3	B4	B5	B6	B7	B8	B11	B12
FS_42	Acigol_2	37.71492	33.67147	21-05-16	09-05-16	12	87089.00	1105	999	655	770	788	785	584	684	493
FS_50	Acigol_2	37.71492	33.67147	19-06-16	18-06-16	1	93739.00	1253	1097	797	887	942	1084	675	893	674
FS_59	Acigol_2	37.71492	33.67147	19-07-16	18-07-16	1	94417.00	1222	1047	728	902	980	1111	744	892	648
FS_67	Acigol_2	37.71492	33.67147	22-08-16	17-08-16	5	95028.00	1212	1059	787	970	1118	1211	865	1026	735
FS_80	Acigol_2	37.71492	33.67147	15-10-16	16-10-16	1	94197.00	1175	920	652	824	938	950	682	948	633
FS_86	Acigol_2	37.71492	33.67147	12-11-16	15-11-16	3	89523.00	1377	1200	979	1185	1220	1266	1007	1126	803
FS_92	Acigol_2	37.71492	33.67147	10-12-16	15-12-16	5	90087.00	1523	1246	1086	1387	1322	1353	984	726	497
FS_08	Acigol_3	37.71798	33.66489	13-12-15	11-12-15	2	88700.00	1343	1144	925	857	751	833	824	793	549
FS_15	Acigol_3	37.71798	33.66489	17-01-16	30-01-16	13	88638.00	1389	1095	939	797	792	749	787	702	522
FS_23	Acigol_3	37.71798	33.66489	21-02-16	19-02-16	2	87821.00	1152	1109	994	801	793	829	991	888	687
FS_31	Acigol_3	37.71798	33.66489	13-03-16	10-03-16	3	87419.00	3691	3825	4880	5026	4990	4743	4381	5521	3682
FS_34	Acigol_3	37.71798	33.66489	13-04-16	29-04-16	16	87177.00	951	890	596	583	545	606	572	651	526
FS_43	Acigol_3	37.71798	33.66489	21-05-16	09-05-16	12	87643.00	1034	937	659	594	644	546	472	612	485
FS_51	Acigol_3	37.71798	33.66489	19-06-16	18-06-16	1	93707.00	1229	1111	934	935	814	926	868	968	725
FS_60	Acigol_3	37.71798	33.66489	19-07-16	18-07-16	1	94550.00	1548	1464	1430	1289	1255	1328	1427	1394	1006
FS_68	Acigol_3	37.71798	33.66489	22-08-16	17-08-16	5	95255.00	1628	1500	1538	1166	1258	1156	1521	1331	991
FS_77	Acigol_3	37.71798	33.66489	21-09-16	16-09-16	5	95088.00	1354	1067	839	790	728	739	662	463	291
FS_81	Acigol_3	37.71798	33.66489	15-10-16	16-10-16	1	94319.00	1484	1390	1445	1114	1147	1157	1466	1293	1017
FS_87	Acigol_3	37.71798	33.66489	12-11-16	15-11-16	3	89798.00	1638	1540	1588	1314	1256	1328	1594	1438	1068
FS_93	Acigol_3	37.71798	33.66489	10-12-16	15-12-16	5	90319.00	2151	2013	2081	2055	1684	1817	2057	596	506
FS_01	Bolluk_1	38.55031	32.93266	12-12-15	11-12-15	1	162479.00	1499	1643	1586	2064	1595	1493	838	1149	737

Table B.1 continued from previous page

FCODE	Name	Longitude	Latitude	Samp. Date	Sat. Img. Date	Date diff	EC	B2	B3	B4	B5	B6	B7	B8	B11	B12
FS_35	Bolluk_1	38.55031	32.93266	13-04-16	12-04-16	1	116317.00	1298	1718	1341	2008	1459	1547	997	1111	718
FS_44	Bolluk_1	38.55031	32.93266	21-05-16	19-05-16	2	33414.00	1619	1863	1977	2760	2836	3073	2092	2577	1785
FS_52	Bolluk_1	38.55031	32.93266	19-06-16	18-06-16	1	137548.00	1142	1546	1137	2319	2137	2251	876	2070	1454
FS_61	Bolluk_1	38.55031	32.93266	19-07-16	18-07-16	1	157998.00	1148	1211	909	1923	1755	1858	822	1771	1257
FS_69	Bolluk_1	38.55031	32.93266	22-08-16	20-08-16	2	171453.00	955	1019	680	1778	1565	1625	707	1528	1015
FS_73	Bolluk_1	38.55031	32.93266	20-09-16	19-09-16	1	172367.00	1191	1448	1221	2242	2019	2158	1099	1830	1261
FS_82	Bolluk_1	38.55031	32.93266	15-10-16	16-10-16	1	170591.00	1341	1551	1428	2362	2023	2115	1162	1837	1306
FS_88	Bolluk_1	38.55031	32.93266	12-11-16	15-11-16	3	165104.00	1621	1743	1641	2229	1906	1955	1219	1483	986
FS_94	Bolluk_1	38.55031	32.93266	10-12-16	08-12-16	2	177791.00	1260	1417	1220	1750	1227	1164	621	807	515
FS_02	Bolluk_2	38.54878	32.93321	12-12-15	11-12-15	1	94920.00	2558	2522	2837	2879	2912	3156	3162	2430	1501
FS_09	Bolluk_2	38.54878	32.93321	16-01-16	10-01-16	6	104254.00	2312	2328	2524	2457	2576	2667	2414	1629	963
FS_16	Bolluk_2	38.54878	32.93321	20-02-16	19-02-16	1	82225.00	2150	2270	2105	2573	2710	2771	2393	2013	1316
FS_24	Bolluk_2	38.54878	32.93321	12-03-16	13-03-16	1	94587.00	2936	2979	3291	3134	3083	3507	3552	2780	2058
FS_36	Bolluk_2	38.54878	32.93321	13-04-16	12-04-16	1	103852.00	2427	2546	2753	2976	3147	3296	3163	2617	1684
FS_45	Bolluk_2	38.54878	32.93321	21-05-16	19-05-16	2	120549.00	2019	2164	1982	2572	2454	2585	1714	1443	828
FS_53	Bolluk_2	38.54878	32.93321	19-06-16	18-06-16	1	46775.00	2531	2651	2755	3298	3450	3382	2848	2629	1858
FS_62	Bolluk_2	38.54878	32.93321	19-07-16	18-07-16	1	24315.00	2465	2645	2733	3184	3354	3653	2862	2661	1920
FS_70	Bolluk_2	38.54878	32.93321	22-08-16	20-08-16	2	21741.00	2711	2834	3144	3141	3235	3614	3236	2805	2042
FS_74	Bolluk_2	38.54878	32.93321	20-09-16	19-09-16	1	22289.00	2271	2352	2590	2966	2956	3283	2420	2426	1626
FS_83	Bolluk_2	38.54878	32.93321	15-10-16	16-10-16	1	38391.00	2566	2691	2872	3137	3195	3402	2920	2688	2017
FS_89	Bolluk_2	38.54878	32.93321	12-11-16	15-11-16	3	26727.00	2399	2515	2621	2753	2763	3002	2617	2087	1485

Table B.1 continued from previous page

FCODE	Name	Longitude	Latitude	Samp. Date	Sat. Img. Date	Date diff	EC	B2	B3	B4	B5	B6	B7	B8	B11	B12
FS_95	Bolluk_2	38.54878	32.93321	10-12-16	08-12-16	2	9044.00	1522	1201	1021	984	972	931	898	454	265
FS_03	Tersakan_2	38.62993	33.04676	12-12-15	11-12-15	1	170976.00	2687	2573	2755	2838	2908	3031	2907	2121	1695
FS_17	Tersakan_2	38.62993	33.04676	20-02-16	19-02-16	1	196543.00	2004	2442	2034	2096	1188	1119	851	356	202
FS_25	Tersakan_2	38.62993	33.04676	12-03-16	13-03-16	1	124482.00	1579	2318	1575	1715	716	714	625	273	190
FS_37	Tersakan_2	38.62993	33.04676	13-04-16	12-04-16	1	115225.00	2001	2440	1718	1455	489	457	407	143	107
FS_46	Tersakan_2	38.62993	33.04676	21-05-16	19-05-16	2	114396.00	2014	2528	1712	1545	617	633	466	169	101
FS_57	Tersakan_2	38.62993	33.04676	23-06-16	18-06-16	5	148870.00	2478	3158	2670	2473	1492	1601	1324	1180	972
FS_63	Tersakan_2	38.62993	33.04676	19-07-16	18-07-16	1	137634.00	1490	1772	1215	993	412	423	358	194	150
FS_71	Tersakan_2	38.62993	33.04676	22-08-16	20-08-16	2	157895.00	1658	2269	2067	2391	1689	1816	1450	323	192
FS_75	Tersakan_2	38.62993	33.04676	20-09-16	19-09-16	1	163761.00	2604	2749	2924	3006	2891	3045	2821	1119	477
FS_84	Tersakan_2	38.62993	33.04676	15-10-16	16-10-16	1	163553.00	3064	3120	3533	3587	3564	3809	3606	1517	837
FS_90	Tersakan_2	38.62993	33.04676	12-11-16	15-11-16	3	162171.00	2381	2354	2432	2463	2210	2298	2009	771	479
FS_96	Tersakan_2	38.62993	33.04676	10-12-16	08-12-16	2	175603.00	1832	2093	1786	1757	846	761	600	148	69
FS_97	Tersakan_3	38.63142	33.06235	12-12-15	11-12-15	1	151299.00	3313	3327	3674	3653	3249	3150	3283	1499	1000
FS_98	Tersakan_3	38.63142	33.06235	12-03-16	13-03-16	1	203370.00	2892	3147	3285	3233	2243	2155	1933	199	130
FS_99	Tersakan_3	38.63142	33.06235	13-04-16	12-04-16	1	204969.00	3660	3960	4138	3961	2836	2723	2425	87	64
FS_100	Tersakan_3	38.63142	33.06235	21-05-16	09-05-16	12	205047.00	3246	3512	3769	3659	2807	2808	2540	86	53
FS_101	Tersakan_3	38.63142	33.06235	23-06-16	18-06-16	5	200641.00	3619	3976	4651	4684	4673	4837	4419	886	644
FS_04	Tuz_1	38.79528	33.61750	12-12-15	11-12-15	1	235552.00	1680	1515	1590	1601	1637	1695	1612	1629	933
FS_10	Tuz_1	38.79528	33.61750	16-01-16	10-01-16	6	234443.00	1562	1509	1575	1611	1652	1775	1722	1876	1097
FS_18	Tuz_1	38.79528	33.61750	20-02-16	19-02-16	1	235983.00	1520	1377	1207	1197	1043	1081	965	555	488

Table B.1 continued from previous page

FCODE	Name	Longitude	Latitude	Samp. Date	Sat. Img. Date	Date diff	EC	B2	B3	B4	B5	B6	B7	B8	B11	B12
FS_26	Tuz_1	38.79528	33.61750	12-03-16	13-03-16	1	239441.00	1433	1491	1480	1507	1389	1460	1352	725	418
FS_38	Tuz_1	38.79528	33.61750	13-04-16	22-04-16	9	226745.00	3494	3516	3888	4119	4136	4262	4145	1388	731
FS_47	Tuz_1	38.79528	33.61750	21-05-16	19-05-16	2	236889.00	3233	3278	3626	3484	3384	3540	3685	1053	540
FS_54	Tuz_1	38.79528	33.61750	19-06-16	18-06-16	1	251768.00	3581	3849	4483	4424	4440	4652	4491	1435	738
FS_64	Tuz_1	38.79528	33.61750	19-07-16	18-07-16	1	248465.00	3707	4081	4861	4942	4963	5212	5046	2570	1446
FS_72	Tuz_1	38.79528	33.61750	22-08-16	20-08-16	2	227958.00	3757	4141	5006	4999	5127	5374	5215	3607	2272
FS_05	Tuz_2	39.07178	33.41059	12-12-15	04-12-15	8	119597.00	2094	2136	2566	2492	2175	2191	2171	132	91
FS_11	Tuz_2	39.07178	33.41059	16-01-16	10-01-16	6	246856.00	1900	1975	2332	2241	1718	1724	1580	66	48
FS_19	Tuz_2	39.07178	33.41059	20-02-16	09-02-16	11	239154.00	2054	2055	2088	1978	978	932	784	65	56
FS_27	Tuz_2	39.07178	33.41059	12-03-16	13-03-16	1	238959.00	2083	2170	2062	1846	948	937	801	260	180
FS_39	Tuz_2	39.07178	33.41059	13-04-16	22-04-16	9	228864.00	3101	3292	3343	3151	1693	1666	1450	111	85
FS_48	Tuz_2	39.07178	33.41059	21-05-16	19-05-16	2	233335.00	2683	2999	3190	2923	1446	1478	1231	83	65
FS_55	Tuz_2	39.07178	33.41059	19-06-16	18-06-16	1	240561.00	3508	4038	5115	5096	4955	5143	4786	575	385
FS_65	Tuz_2	39.07178	33.41059	19-07-16	18-07-16	1	172076.00	4697	5049	5855	5911	5932	6212	5975	1714	891
FS_78	Tuz_2	39.07178	33.41059	21-09-16	19-09-16	2	226987.00	3160	3482	4261	4323	4390	4625	4402	1235	642
FS_12	Tuz_3	38.96131	33.42085	16-01-16	10-01-16	6	188451.00	1974	2124	2459	2336	2357	2518	2626	2138	1612
FS_20	Tuz_3	38.96131	33.42085	20-02-16	19-02-16	1	214953.00	1521	1454	1610	1686	1718	1769	1563	1388	1074
FS_28	Tuz_3	38.96131	33.42085	12-03-16	13-03-16	1	145652.00	1919	2157	2562	2340	2319	2635	2557	2297	1718
FS_40	Tuz_3	38.96131	33.42085	13-04-16	12-04-16	1	235581.00	2974	3069	3440	3296	3093	3304	3266	2144	1618
FS_56	Tuz_3	38.96131	33.42085	19-06-16	18-06-16	1	235474.00	2444	2797	3438	3470	3542	3735	3651	2957	2104

B.2 Case Study Dataset

Table B.2: Sentinel-2 Bands (B2, B3, etc.) and EC values of exact field points in the case study.

FCODE	EC	B2	B3	B4	B5	B6	B7	B8	B11	B12	Temp
P1	2121	1656	1344	708	645	623	636	549	452	375	25.34
P2	2206	1300	975	600	567	571	572	489	412	334	25.8
P3	2165	1266	814	499	462	459	461	393	290	241	25.38
P4	2174	1158	752	526	501	493	492	416	320	280	25.51
P5	2137	1138	742	526	491	491	496	427	332	279	24.66
P6	2193	1005	610	377	335	333	324	271	177	149	24.71
P7	2234	1040	642	418	396	380	388	319	228	196	25.2
P8	2244	1093	696	469	433	426	415	359	265	228	25.24
P9	2231	1116	732	513	484	464	463	404	314	267	24.7
P10	2234	1133	752	543	505	503	501	435	346	294	24.68
P11	2242	1137	771	580	552	536	538	472	389	334	24.75
P12	2243	1083	718	516	499	488	495	416	340	291	24.78
P13	2242	1031	662	457	430	419	421	349	268	238	24.76
P14	2240	1067	707	515	497	482	489	413	333	291	24.56
P15	2143	1056	697	505	475	463	464	394	313	276	24.83
P16	2202	1101	746	557	528	529	536	447	373	323	24.65
P17	2218	1126	773	586	555	547	556	482	395	343	24.53
P18	2225	1176	827	649	621	623	635	538	466	400	24.39
P19	2232	1118	773	579	556	541	558	474	390	336	24.43
P20	2233	1091	740	539	509	509	500	430	361	302	24.39
P21	2234	1068	705	502	465	464	460	398	321	269	24.36
P22	2233	1094	727	519	491	488	488	418	338	283	24.31
P23	2240	1081	719	512	479	473	475	411	332	275	24.38
P24	2235	1102	732	529	504	498	511	435	355	291	24.34
P25	2278	1186	829	646	616	603	629	546	468	386	25.23
P26	2281	2030	1748	1142	1041	797	877	823	759	571	25.28
P27	2280	2030	1748	1142	1041	797	877	823	759	571	25.02

Table B.3: Sentinel-2 Band and EC values of buffered field points in the case study.

FCODE	EC	B2	B3	B4	B5	B6	B7	B8	B11	B12	Temp
P1	2121	1593	1315	671	601.5	581	590.5	511.5	416.5	345	25.34
P2	2206	1300	975	600	567	571	572	489	412	334	25.80
P3	2165	1264	814	499	462	459	461	393	290	241	25.38
P4	2174	1158	752	526	501	493	492	416	320	280	25.51
P5	2137	1134	740	519	486	475	489	414	326	277	24.66
P6	2193	1013	610	377	335	333	324	271	177	149	24.71
P7	2234	1056	664	435	408	391	390	337	238	210	25.20
P8	2244	1093	703	483	451	437	434	364	281	236	25.24
P9	2231	1116	732	516	484	464	463	404	318	267	24.70
P10	2234	1134	759	548	513	510	509	442	357	303	24.68
P11	2242	1137	771	580	552	536	538	472	389	334	24.75
P12	2243	1083	718	516	499	488	495	416	340	291	24.78
P13	2242	1031	668	464	436	421	428	360	272	238	24.76
P14	2240	1067	707	515	497	482	489	413	333	291	24.56
P15	2143	1064	706	507	480	480	478	403	327	287	24.83
P16	2202	1101	746	557	528	529	536	447	373	323	24.65
P17	2218	1124	773	582	555	547	551	481	395	343	24.53
P18	2225	1137	786	606	571	573	576	489	420	352	24.39
P19	2232	1118	765	579	551	541	552	472	390	336	24.43
P20	2233	1091	740	539	509	509	500	430	361	302	24.39
P21	2234	1075	711	511	479	467	471	409	329	273	24.36
P22	2233	1093	726	519	486	488	487	418	338	283	24.31
P23	2240	1081	718	511	479	473	475	409	332	275	24.38
P24	2235	1094	727	521	496	491	493	425	342	283	24.34
P25	2278	1186	829	646	616	603	629	546	468	386	25.23
P26	2281	1566	1176	782	700	720	802	656	620	491	25.28
P27	2280	2030	1748	1142	1041	797	877	823	759	571	25.02

B.3 Periodically Measured Lakes

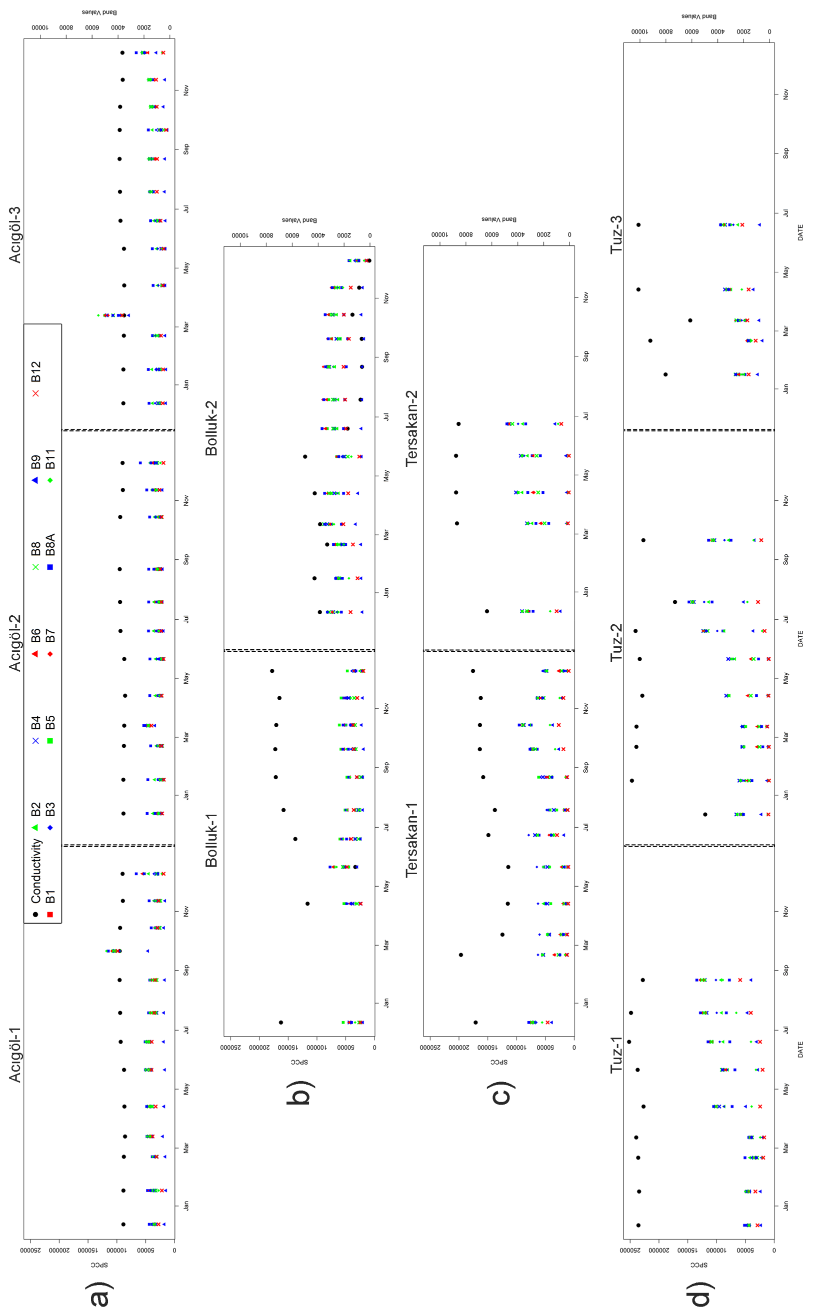

Figure B.1: Periodically sampled points. a) Acıgöl-1, Acıgöl-2, Acıgöl-3, b) Bolluk-1, Bolluk-2, c) Tersakan-1, Tersakan-2, d) Tuz-1, Tuz-2, Tuz-3