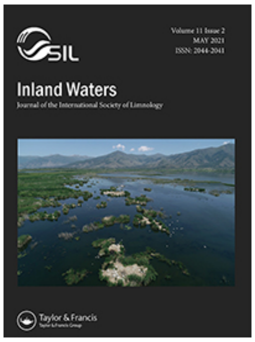

Inland Waters

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/tinw20

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To cite this article: Gültekin Yılmaz, Mehmet Arda Çolak, İbrahim Kaan Özgencil, Melisa Metin, Mustafa Korkmaz, Serhat Ertuğrul, Melisa Soyluer, Tuba Bucak, Ü Nihan Tavşanoğlu, Korhan Özkan, Zuhal Akyürek, Meryem Beklioğlu & Erik Jeppesen (2021): 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, Inland Waters, DOI: 10.1080/20442041.2021.1924034

To link to this article: https://doi.org/10.1080/20442041.2021.1924034

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INLAND WATERS
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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.

ARTICLE HISTORY
Received 14 November 2020
Accepted 26 April 2021

KEYWORDS
fish; habitat loss; irrigation; land-use change; salinisation; waterbird

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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Supplemental data for this article can be accessed here: https://doi.org/10.1080/20442041.2021.1924034.
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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 – paleo-environmental 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

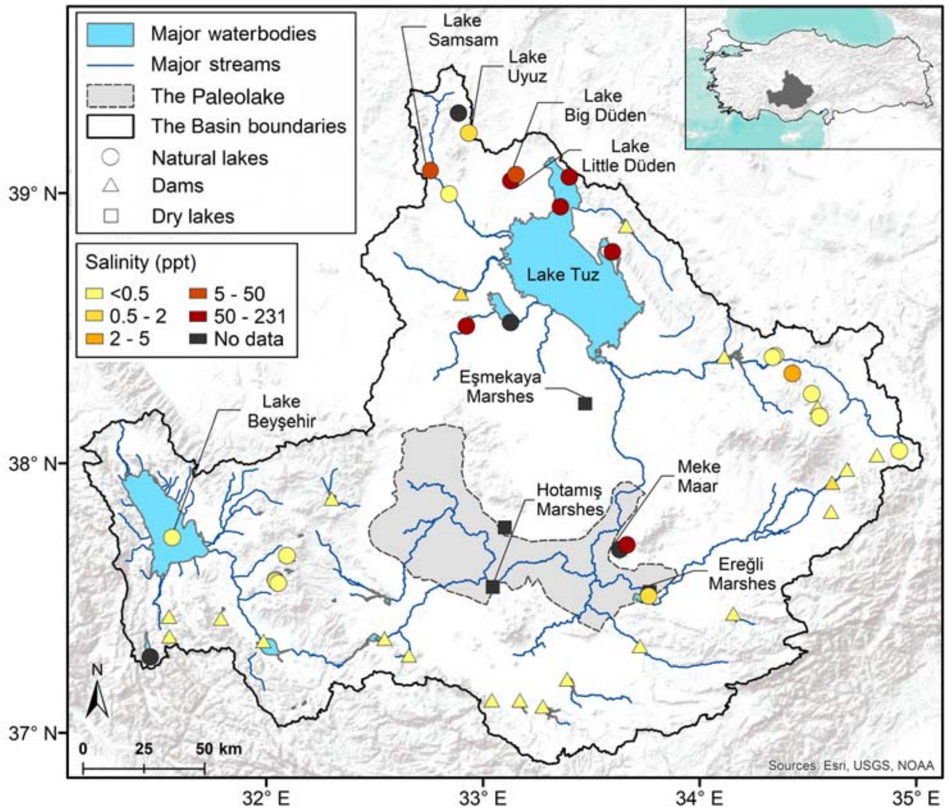

Figure 1. Konya Closed Basin (KCB) showing the location of KBC in Turkey (inset), its boundaries, its major watebodies; salinity (ppt) of its lakes and reservoirs based on YSI ProDSS multiprobe measurements taken in June 2020, and the greatest extent of the Paleolake Konya during the last glacial maximum.

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 $>22 \times 10^6$ 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, $>3 \times 10^3$ 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.

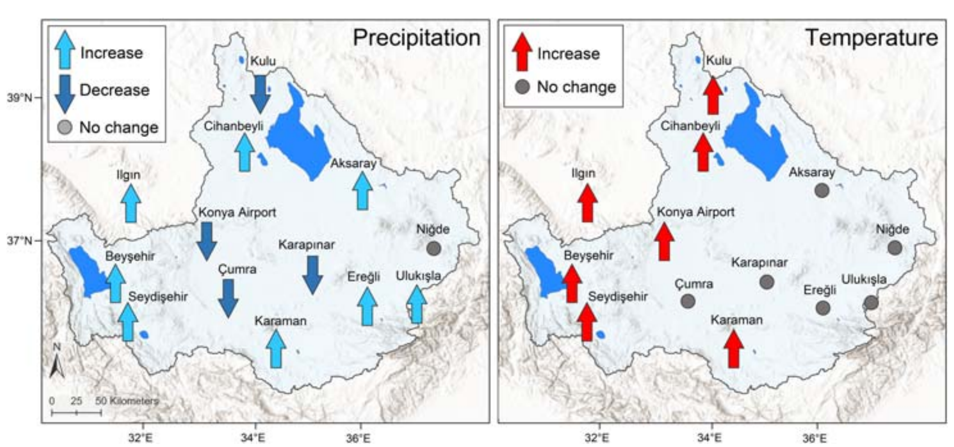

Figure 2. Trend analysis of annual precipitation and mean annual air temperature for selected meteorological stations for the period 1970–2020 in Konya Closed Basin based on data from the Turkish State Meteorological Service.

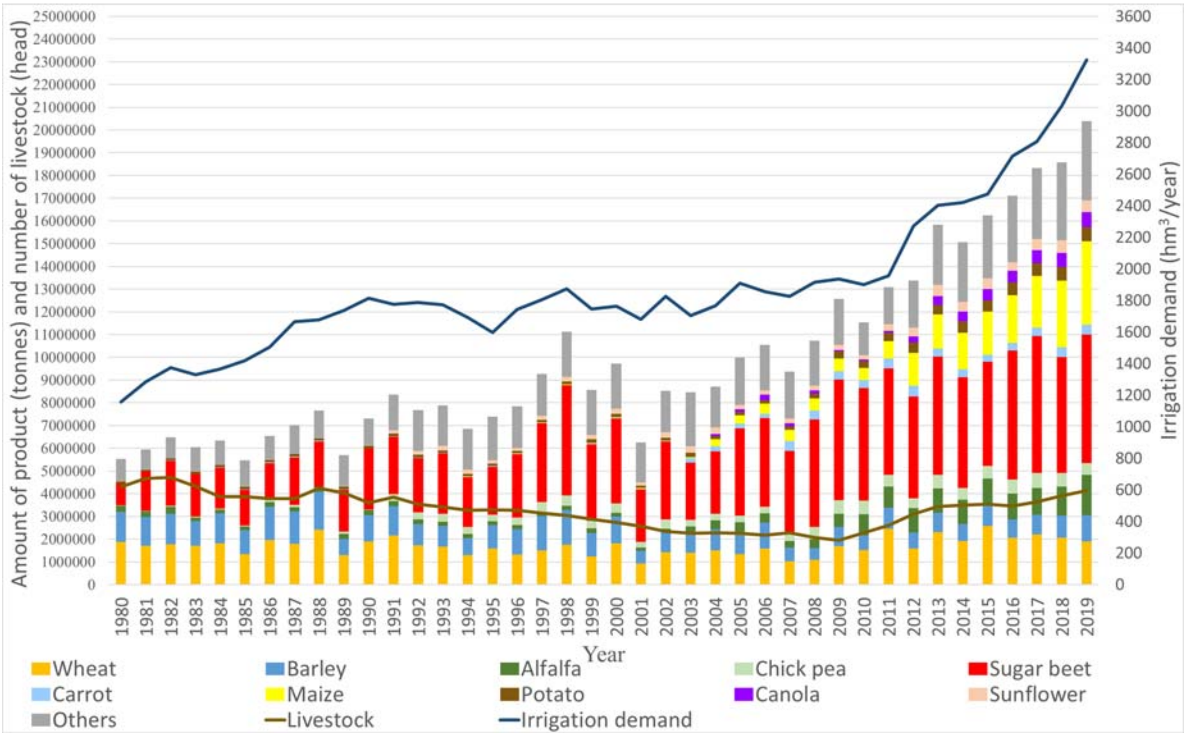

Figure 3. Total agricultural products, number of livestock, and estimated irrigation amount in the Konya and Karaman provinces between 1980 and 2019 (data taken from TUIK 2020). Net amount of irrigation water for crops largely cultivated in the Konya Closed Basin (upper left) (Berke et al. 2014) and 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

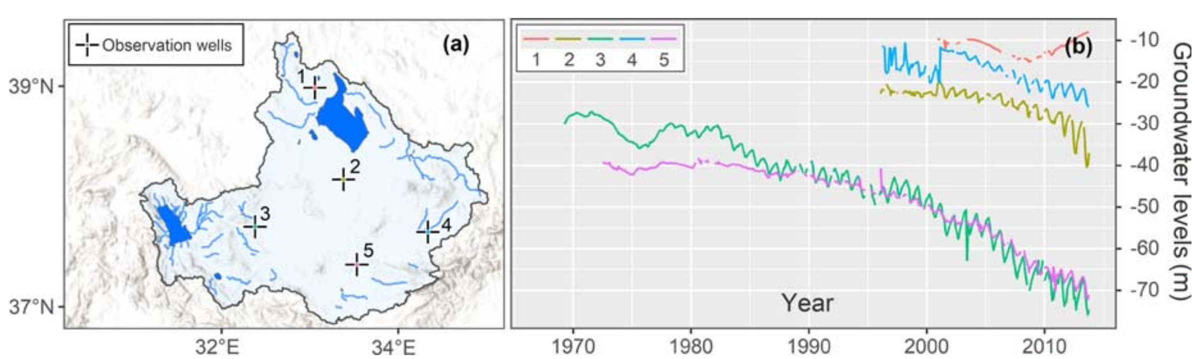

Figure 4. (a) The 5 selected observational wells numbered from 1 to 5 and (b) long-term changes in the groundwater levels of the 5 selected wells in the Konya Closed Basin.

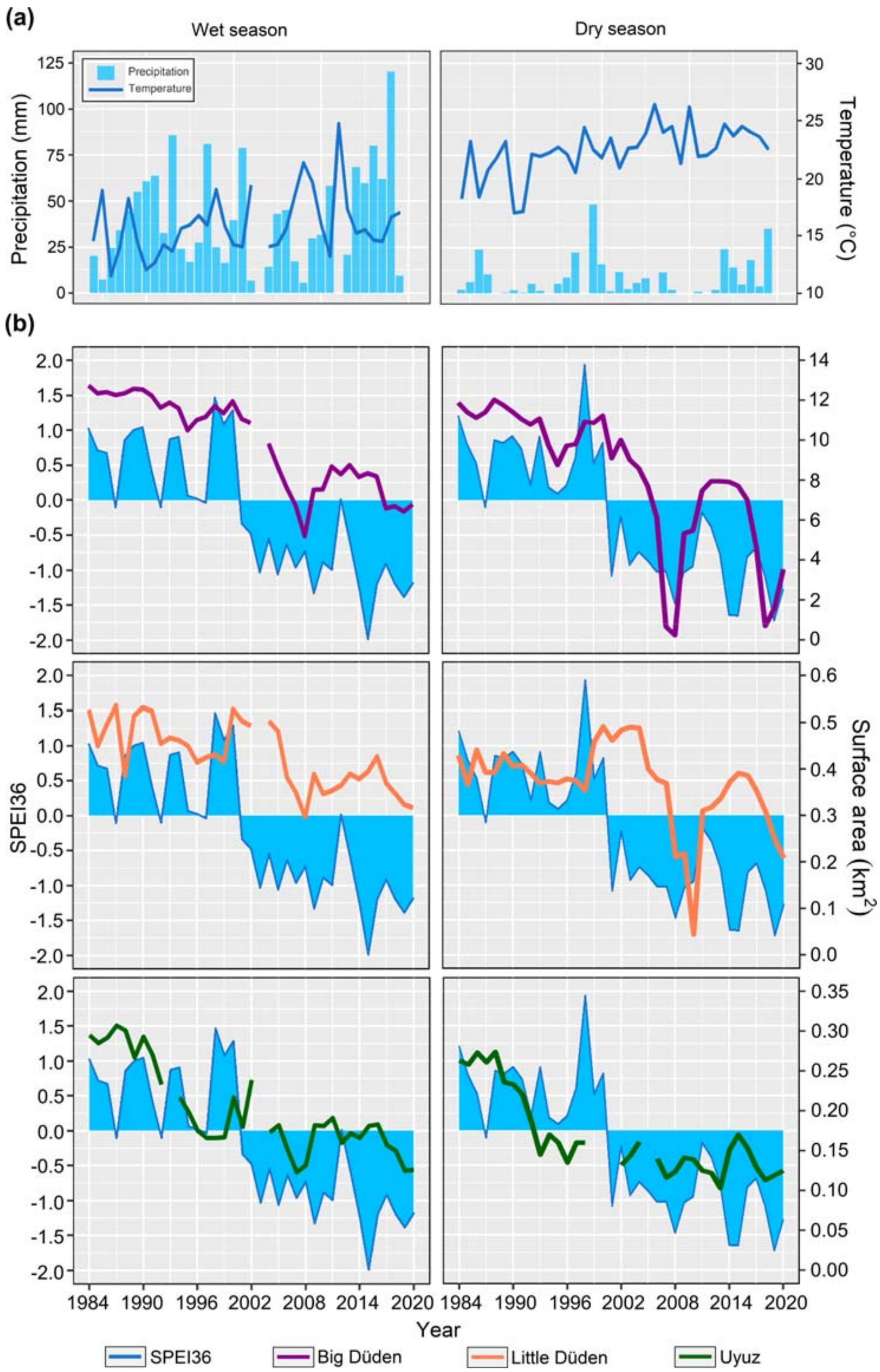

Figure 5. (a) Monthly total precipitation and average temperature and (b) long-term (1985–2020) changes in the 36-month Standardized Precipitation Evapotranspiration index (SPEI) for KCB for the wet season (May each year; left column) and the dry season (August each year, right column). The superimposed 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

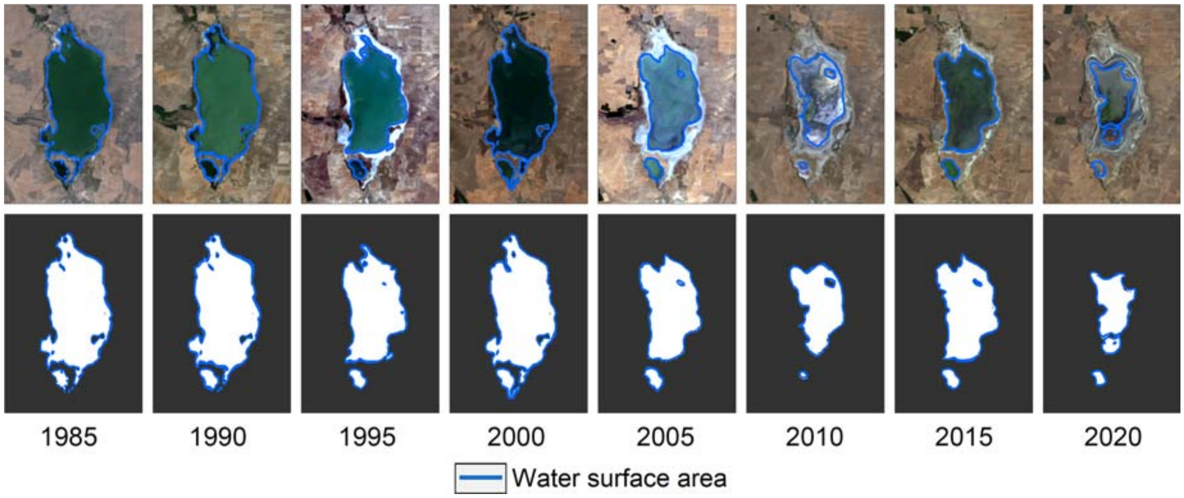

Figure 6. Landsat true colour RGB images (upper panels) and black and white images marking the surface area (lower panels) of Lakes Big Düden and Little Düden at 5-year intervals from 1985 to 2020.

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.

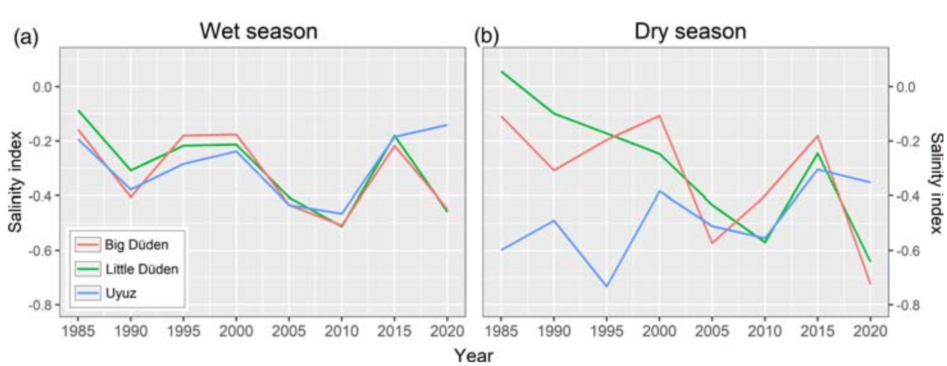

Figure 7. Changes in the salinity index for Lakes Düden, Little Düden, and Uyuz from 1985 to 2020 at 5-year intervals in (a) the wet season and (b) the dry season.

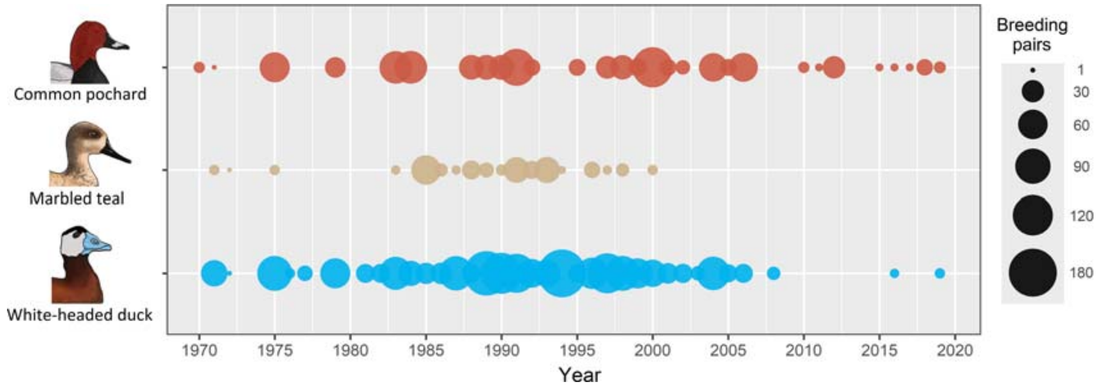

Figure 8. Changes in the sizes of the breeding populations of the 3 globally threatened waterbird species: common pochard, marbled teal, and white-headed duck from 1970 to 2020 in the KCB.

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

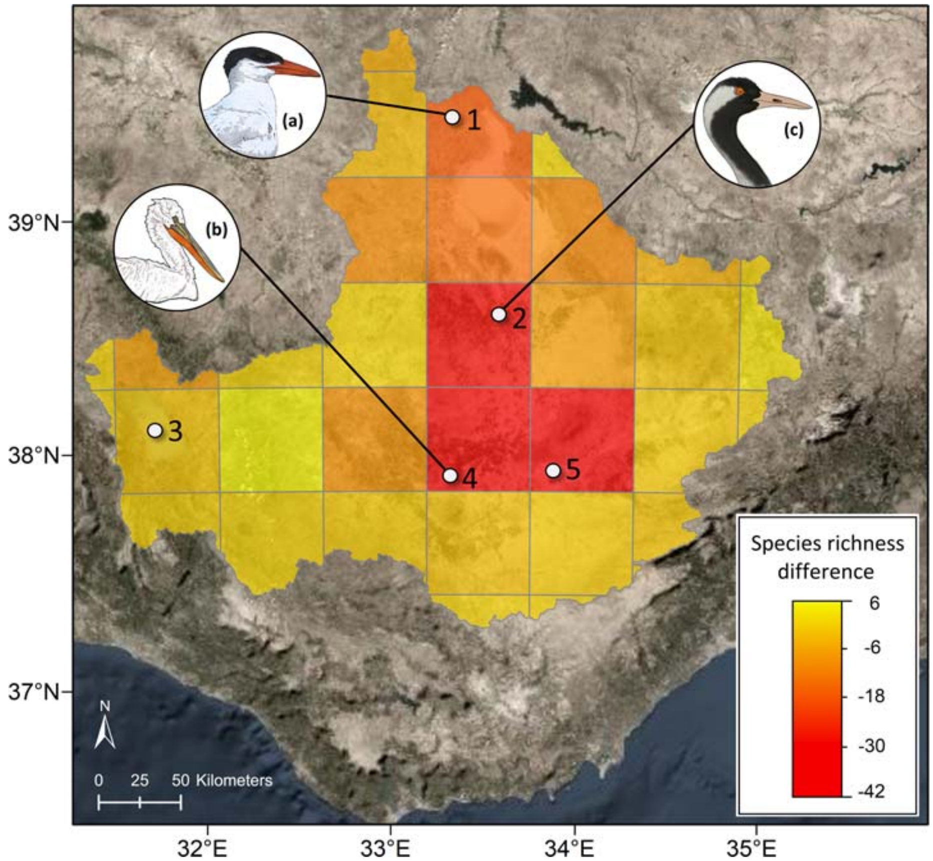

Figure 9. Species richness loss of breeding waterbirds in Konya Closed Basin over the last 20 years. Some species that no longer breed in the basin are (a) Caspian tern, (b) Dalmatian pelican, (c) and common crane. 1: Lake Düden, 2: Former Eşmekaya Marshes, 3: Lake Beyşehir, 4: Former Hotamış Marshes, 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

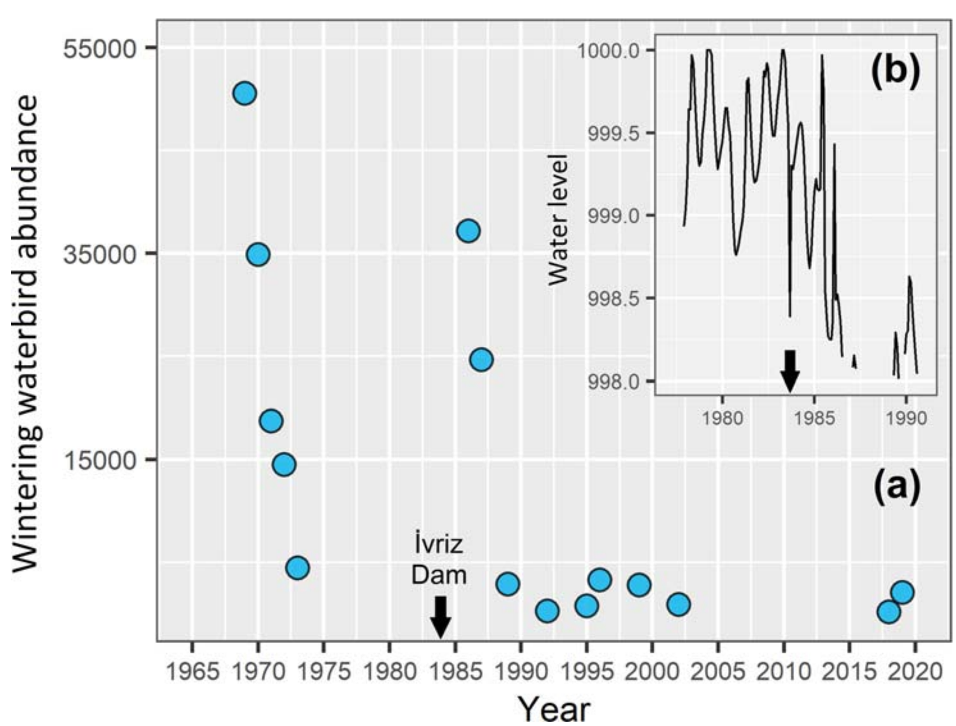

Figure 10. Changes in (a) wintering waterbird abundances and (b) water level (m a.s.l) of Lake Akgöl in the Ereğli Marshes.

(*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 meso-trophic, 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 pike-perch 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

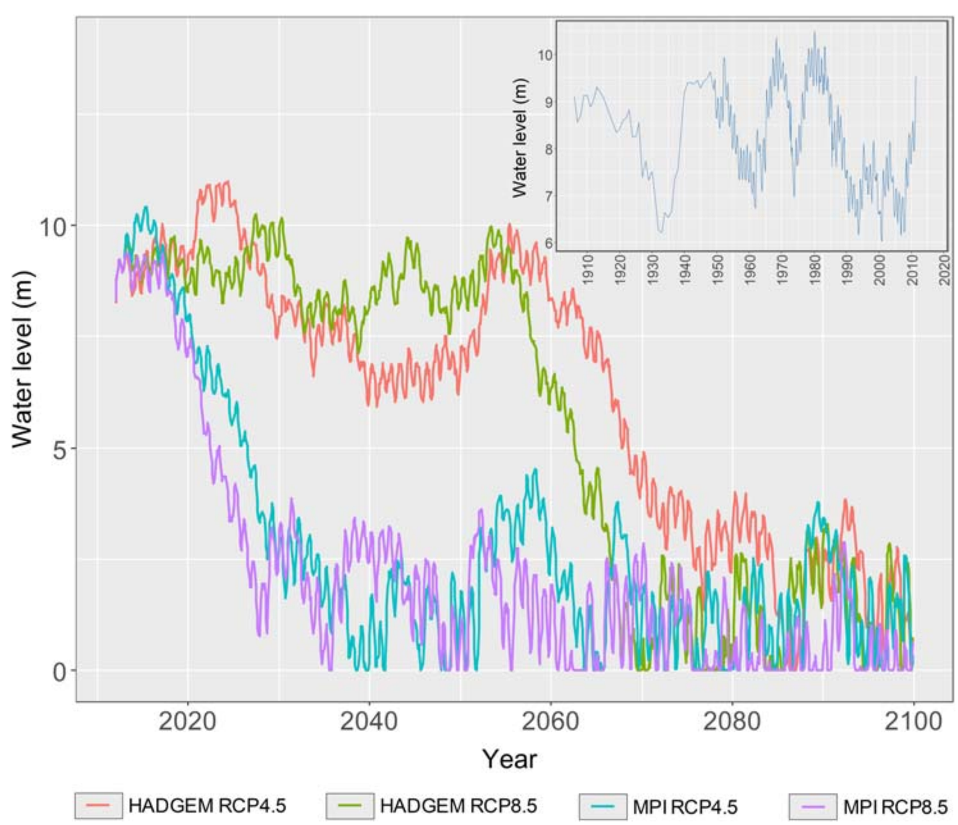

Figure 11. Changes in the actual water level of Lake Beyşehir from 1910 to 2010 and under different climate change scenarios. RCP4.5 assumes that greenhouse gas emission will peak around 2040, followed by a decline, while RCP8.5 assumes that emissions will increase throughout the 21st century (IPCC 2014)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

Acknowledgements

We thank Doğa Koruma ve Milli Parklar Genel Müdürlüğü for providing the mid-winter waterbird census data; Itri Levent Erkol for the IBA GIS layers; all the 2018 atlas volunteers;

Ece Işıl Eren, and Figen Kepenek for drawing the bird illustrations; Kiraz Erciyas Yavuz for the scans of the draft of the 1998 atlas; Aybüke Uysal and Alaz Uslu for help with data preparation, analyses and visualisation; Lider Sınav for the distribution maps of the 1998 breeding bird atlas; Cem Orkun Kıraç and Sühendan Karauz for sharing their articles; Ogün Aydın and Selami Oral for sighting reports; Doğa Derneği, OSME, and Mohamed bin Zayed Species Conservation Fund for funding the 2016 and 2019 White-headed Duck projects; and all the atlas volunteers for the data collection. We thank Anne Mette Poulsen for manuscript assistance.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

The project and EJ, KÖ, GY, MM, AÇ, SE, and MK were supported by TÜBITAK program BIDEB 2232 International Fellowship for Outstanding Researchers (project 118C250). MB and EJ were supported by EU-H2020, INFRAIA project AQUACOSM (Project no 731063), and AQUACOSM-Plus (no 871081); MB and ZA were supported by EU-H2020, PONDERFUL (No 869296); and KÖ was supported by TÜBA GEBİP programme; Turkish Academy of Sciences.

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