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Aziza Baubekova

CATCHMENT-ESTUARY-COASTAL SYSTEMS UNDER CLIMATE CHANGE AND ANTHROPOGENIC PRESSURE

*UNIVERSITY OF OULU GRADUATE SCHOOL;
UNIVERSITY OF OULU,
FACULTY OF TECHNOLOGY*

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AZIZA BAUBEKOVA

CATCHMENT-ESTUARY-COASTAL SYSTEMS UNDER CLIMATE CHANGE AND ANTHROPOGENIC PRESSURE

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Supervised by
Doctor Ali Torabi Haghighi
Professor Bjørn Kløve
Doctor Stefanos Xenarios

Reviewed by
Professor Paul Gremillion
Doctor Mohammad Reza Nikoo

Opponent
Doctor Najmeh Mahjouri

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Abstract

The UN Decade on Ecosystem Restoration (2021–2030) calls for extensive action to prevent and reverse ecosystem degradation. Thus, the main objective of this thesis is to assess the effects of climate change and hydrological alterations on coastal ecosystems in the most water-stressed regions, Central Asia and the Middle East. As a result, a thorough understanding of Catchment-Estuary-Coastal systems is needed to enable the development of effective management and restoration strategies.

A starting assumption for the thesis was that coastal zones are susceptible to both the decline and rise in water level. The first study site is the world's largest endorheic lake, the Caspian Sea, which faces continuous water decline. The second study site is a vulnerable coastal ecosystem in the Persian Gulf experiencing sea level rise. For both sites, the freshwater input from river discharge and precipitation has been decreasing. It can also be assumed that the causes of water level changes are both natural and anthropogenic. Therefore, this work attempts to separate and quantify the impact of anthropogenic activities and climate change on river flow alteration, lakes, and coastal systems.

In Publication I, we addressed the effect of change in water balance parameters on the desiccation of different areas of the Caspian Sea. Publication III took the first step in quantifying and decoupling the effect of anthropogenic activities and climate change effect on river flow alteration impacting the water level in the southern Caspian Sea. Results suggested the major role played by anthropogenic activities in the fluctuation of the Caspian Sea level. To assess the direct impact of climate change on lake conditions, we determined the changes in the ice regime and their socio-ecological implications in Publication V.

The high complexity of the catchment-estuary-coastal system was examined in Publication II, showing the necessity of a basin-level perspective and the integration of the entire hydrological continuum, including upstream river regulation, land use changes, and coastal studies. By considering the interconnection between temperature, rain, flow, and salinity in Publication IV, we addressed the cumulative impacts of these variables on mangrove health. Understanding the hydrological requirements of mangroves enables policymakers to justify environmental flow strategies for mangrove restoration.

Keywords: climate change, coastal ecosystems, dams, environmental flow, estuary, flow alteration, ice, lake, river, upstream-downstream

Baubekova, Aziza, Valuma-suisto-rannikkojärjestelmät ilmastonmuutoksen ja ihmisen aiheuttaman paineen alaisena.
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Oulun yliopisto, PL 8000, 90014 Oulun yliopisto

Tiivistelmä

YK:n ekosysteemien ennallistamisen vuosikymmen (2021–2030) vaatii laajoja toimia ekosysteemien tilan parantamiseksi. Tämän tutkimuksen päätavoitteena oli arvioida ilmastonmuutosten ja hydrologisten muutosten vaikutuksia rannikon ja suistoalueiden ekosysteemeihin alueilla, jossa veden niukkuus uhkaa ekosysteemejä Keski-Aasiassa ja Lähi-idässä. Tavoitteena oli lisätä ymmärrystä erityisesti valuma-alueen ja suisto-rannikkojärjestelmien ymmärtämiseksi tehokkaampien maankäyttö ja vesien ennallistamisstrategioiden kehittämiseksi.

Väitöstyön lähtökohtana oli, että rannikkoalueet ovat alttiita sekä vedenpinnan laskulle että nousulle. Ensimmäinen tutkimuskohde oli maailman suurin sisävesimuodostuma eli Kaspianmeri, jonka vedenpinta on pitkään ollut laskeva. Toisena tutkimuskohteena olivat Persianlahden haavoittuvat rannikkoekosysteemit, joissa merenpinta on nouseva. Molemmissa tapauksissa makean veden määrä on vähentynyt sateiden ja jokien virtaamien vähentyessä. Työn oletuksena oli, että vedenpinnan muutosten syyt olivat sekä luonnollisia että ihmisperäisiä. Tämän vuoksi työ pyrki erottelemaan ja kvantifioimaan ihmisperäisen toiminnan ja ilmastonmuutoksen vaikutukset jokien virtauksen muutoksiin, järvien vedenkorkeuteen ja rannikkojärjestelmiin.

Artikkelissa I käsiteltiin vesitaseen muutoksien vaikutuksia Kaspianmeren eri alueiden kuivumiseen. Artikkeli III otti ensimmäisen askeleen kvantifioidakseen ja erottaakseen toisistaan ihmisen toiminnan ja ilmastonmuutoksen vaikutukset Kaspianmeren vedenkorkeuteen vaikuttavien jokien virtaamien muutoksiin. Julkaisun perusteella ihmisperäisillä valuma-alueiden toimilla on hallitseva rooli Kaspianmeren tulovirtaaman vaihteluissa. Koska Kaspianmeri on talvella osittain jään peittämä, työssä tutkittiin myös merijään muutoksia ja arvioitiin tarkemmin näiden muutosten vaikutuksia Kaspianmeren taloudellisiin ja ekologisiin olosuhteisiin.

Valuma-alue sekä suisto- ja rannikkojärjestelmän monimutkaisuutta ja vuorovaikutuksia tarkasteltiin artikkelissa II. Tutkimus osoitti valuma-aluetason näkökulman ja koko hydrologisen jatkumon integroinnin tarpeellisuuden, mukaan lukien latvavesien ja niiden jokien sääntelyn, maankäytön muutoksien tarkastelun ja rannikon tutkimukset. Lämpötilan, sademäärän, virtauksen ja suolaisuuden välisiä yhteyksiä ja kumulatiivisia vaikutuksia mangroven tilaan käsiteltiin artikkelissa IV.

Asiasanat: ilmastonmuutos, joki, järvi, jää, padot, rannikkoekosysteemit, suisto, virtauksen muutos, ylä- ja alavirta, ympäristövirtaus

In loving memory of my grandmother, whose waiting and endless belief in my achievements will always be missed.

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My heartfelt appreciation goes to my parents Meiram and Maryam, who, despite the geographical distance from Kazakhstan, have been unwavering pillars of support, providing me with the strength to overcome challenges and persevere.

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I would like to thank my husband Dias and our kids Arlen and Dariya, who bravely embarked on this adventure with me, moving to Finland, your unwavering love and support have been my anchor. The imminent arrival of our baby girl, just after the defense, has added a layer of motivation to complete this journey promptly, and I'm grateful for the joy she has already brought to our lives.

List of abbreviations and symbols

AMF	Annual Mean Flow
CEC	Catchment-Estuary-Coastal
CVA	Covered potential Vulnerable Area
EF	Environmental Flow
EFCs	Environmental Flow Components
GDP	Gross Domestic Product
HA	Hydrological Alteration
IHA	Indicators of Hydrologic Alteration
IRIMO	Iran Meteorological Organization
ITA	Innovative Trend Analysis
IWRM	Integrated Water Resource Management
IWRMC	Iran Water Resources Management Company
LST	Land Surface Temperature
MCM	Million Cubic Meters
MIF	Magnitude Impact Factor
MK	Mann-Kendall
MK3	Modified Mann-Kendall method
MPA	Mond Protected Area
NCS	Northeastern Caspian Sea
NDVI	Normalized Difference Vegetation Index
NDWI	Normalized Difference Water Index
NIR	Near Infrared
PET	Potential Evapotranspiration
RI method	River Impact method
RivDIS	Global Monthly River Discharge Data Set
RRI	River Regime Index
SCS	Southern Caspian Sea
SDGs	Sustainable Development Goals
SF	Salman Farsi dam
SPEI	Standardized Precipitation-Evapotranspiration Index
SPI	Standardized Precipitation Index
SWIR	Shortwave Infrared
SWL	Sea Water Level
Ta	Tangab dam
TIF	Timing Impact Factor

UN	United Nations
VIF	Variation Impact Factor
VKC	Volga-Kama Cascade
WEFN	Water-Energy-Food Nexus

List of original publications

This thesis is based on the following publications, which are referred to throughout the text by their Roman numerals:

I Akbari, M., Baubekova, A., Roozbahani, A., Gafurov, A., Shiklomanov, A., Rasouli, K., Ivkina, N., Kløve, B., & Haghighi, A. T. (2020). Vulnerability of the Caspian Sea shoreline to changes in hydrology and climate. *Environmental Research Letters*, *15*, 115002. https://doi.org/10.1088/1748-9326/abaad8

II Baubekova, A., Akbari, M., Etemadi, H., Ashraf, F. B., Hekmatzadeh, A., & Haghighi, A. T. (2023). Causes & effects of upstream-downstream flow regime alteration over Catchment-Estuary-Coastal systems. *Science of The Total Environment*, *858*, 160045. https://doi.org/10.1016/j.scitotenv.2022.160045

III Sharifi, A., Baubekova, A., Patro, E.R., Kløve, B., & Haghighi, A.T. (Manuscript). The impact of anthropogenic activities and climate change on river flow alteration.

IV Baubekova, A., Ahrari, A., Etemadi, H., Kløve, B., & Haghighi, A. T. (Manuscript). Environmental Flow Assessment for intermittent rivers supporting the most poleward mangroves.

V Naurozbayeva, Z., Baubekova, A., Kvasha, A., Lobanov, V., Kløve, B., & Haghighi, A. T. (2023). Determining factors for changes in the ice regime of the Caspian Sea. *International Journal of Water Resources Development*. https://doi.org/10.1080/07900627.2023.2231099

The author's contribution to Publications I–V was as follows:

I Baubekova A. contributed to the interpretation of the results, and the writing of the article itself.

II Baubekova A. contributed to the selection of the subject matter, the research questions, the research design and methods, data collection, analyses, the interpretation of the results, and the writing of the article itself.

III Baubekova A. contributed to the interpretation of the results, and the writing of the article itself.

IV Baubekova A. contributed to the selection of the subject matter, the research questions, the research design and methods, data collection, analyses, the interpretation of the results, and the writing of the article itself.

V Baubekova A. contributed to the analyses, the interpretation of the results, and the writing of the article itself.

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1 Introduction

The growing need for water resources and an increase in water stress, especially in arid regions, has become a critical global concern. North Africa, the Middle East, and Central Asia are projected to face either "extremely high" or "high" water-stress levels by 2040 (Figure 1). Arid regions, characterized by low precipitation and high evaporation rates, face significant challenges in meeting the water demands of their populations, agriculture, industry, and ecosystems. Population growth, urbanization, unsustainable irrigation practices, and growing energy demand exacerbate the scarcity of water resources in these regions. Climate change poses an additional challenge to water resources in the arid areas of Central Asia and the Middle East, where over 70 percent of the global net permanent water loss has already occurred (Pekel et al., 2016). Rising temperatures, the significant retreat of glaciers in mountainous areas, and changing precipitation patterns alter the hydrological cycle, reducing water availability (Yu et al., 2019). Increased evaporation rates and prolonged droughts intensify water stress in these already water-scarce areas. Approximately 60% of the water bodies in arid regions have seen significant water losses because of a drying climate and unsustainable human water consumption, as can be seen in the Caspian Sea, the Aral Sea, Lake Bakhtegan, and Lake Urmia (Yao et al., 2023). The severe consequences of poor water resource management, which overlooked the importance of water allocation for ecosystems, and a rise in temperature in these regions which is twice the global average prompted the thesis's primary focus, which aimed to assess the impact of river flow alteration on lakes, estuaries, and coastal zones, and to improve existing methods for environmental flow assessment for vulnerable coastal ecosystems.

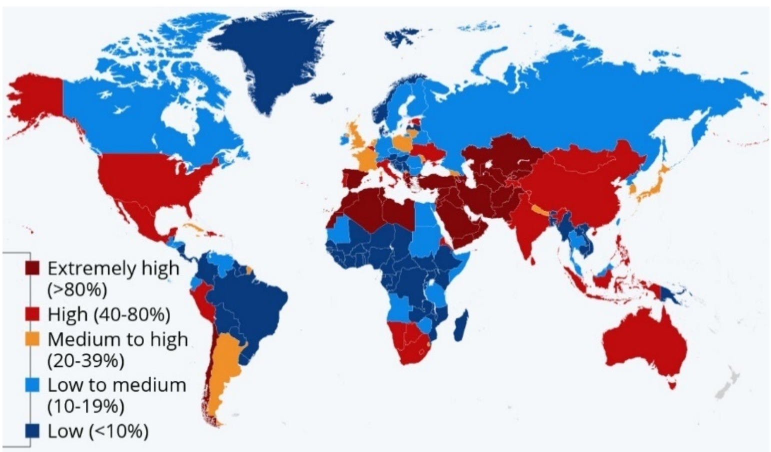

Fig. 1. The projected ratio of water withdrawals to water supply (water stress level) in 2040 (World Resources Institute via the Economist Intelligence Unit, 2023).

1.1 Background

Dramatic population growth, industrialization, and urbanization are estimated to increase demand for water by 40%, energy by 50%, and food by 35% by 2030. Agricultural production, including crops and livestock, may increase by about 70% in the next twenty years (National Intelligence Council, 2012; Zarei et al., 2021). This is particularly concerning in arid and semi-arid regions where freshwater resources are already scarce and demand for food and energy constantly increases. Considering the interlinkages of the water, energy, and food sectors, any strategy that focuses on one component and ignores its relationship with others creates a serious risk of overlooking these key interactions and may cause multiple problems (Bizikova et al., 2013). Our comprehensive study of the implementation of water-related Sustainable Development Goals (SDGs) in the basin, one of the most well-known environmental disaster areas, showed limited water availability, poor water quality, and an overall uneven achievement of SDG 6 in five Central Asian states (Baubekova & Kvasha, 2019). The freshwater and groundwater sources in the Aral Sea Basin mainly serve the agricultural sector with low irrigation efficiency (35-40%) due to high evaporation rates, leakages, and outdated infrastructure inherited from the Soviet era (Xenarios et al., 2023). Implementing the Water-Energy-Food nexus (WEFN) concept and promoting water-efficient practices and cost-effective technologies would ease pressure on natural resources (Baubekova & Kvasha, 2019). Our recent publication with Hasanzadeh Saray et al. (2022) optimizes the holistic WEFN model, which accounts for the three sectors and their interlinkages while minimizing carbon emissions. The analysis of the evolution of agricultural sector development in Kazakhstan and an overview of recent trends in the context of climate change mitigation and river basin management shows that the nation put a great deal of effort towards sustainability and Integrated Water Resource Management (IWRM) (Baubekova et al., 2021; Xenarios et al., 2023).

1.2 Changes in endorheic and exorheic systems

The global water cycle is experiencing high spatial and temporal variability due to climate and land use change, and the development of water resources (Yang et al., 2021). As lakes, rivers, deltas, coastal zones, and seas are connected, change in one system induces change in others. In the context of global warming and human water security challenges, there is a growing need for interdisciplinary studies to develop methods and datasets to better address the interconnections in the water cycle and water resource management.

The levels and areas of lakes, notably closed lakes (endorheic), are sensitive to changes in climate, and are thus important indicators of climatic changes (Mason et al., 1994, Publication V). Globally endorheic basins cover one-fifth of the Earth's land surface, and nearly half of this is comprised of water-stressed arid and semi-arid regions (Yao et al., 2023). These basins, which lack connection with the ocean, retain low inventories of surface water within their boundaries due to topographic barriers and the balance between precipitation, evaporation, and groundwater exchanges. In these basins, the stored water in lakes, reservoirs, and aquifers becomes crucial to ecological and social needs (Bai et al., 2011). However, the delicate balance of water storage in endorheic systems is disrupted by climate change and human activities such as water withdrawals, diversions, and damming. This disruption causes a decline in water storage, evidenced by shrinking lakes, retreating glaciers, and depleting aquifers. This ultimately reduces the total terrestrial water storage within the global endorheic system (Wang et al., 2018). In particular, the world's largest lake, the Caspian Sea, accounts for 49% of the total decline and 71% of the net decrease in natural lake volume (Yao et al., 2023). Rodell et al. (2018) explain how 60% of the variance in the annual mean level of the Caspian Sea can be attributed to the reduction of the annual discharge from the Volga River due to diversions and direct withdrawals of water from the river. This is compared with 18% of the variance being caused by evaporation from the sea.

As water is conserved within the hydrosphere, a deficit in endorheic water storage leads to a surplus of water in the exorheic system. Although the redistribution of water mass between two systems is not immediately obvious as there is no direct discharge of surface water or glacial meltwater that originates from endorheic basins to the ocean, it may happen through vapor transfer (Sahagian, 2000; Brun et al., 2017; Wang et al., 2018). Therefore, the changes in land water storage can significantly impact global sea level variations (Wada et al., 2017). Over the second half of the 20th Century, sea level rise has averaged around 1.9 mm per year, increasing to approximately 3.4 mm per year in the current millennium (Church & White, 2011). Ocean thermal expansion and ice-sheet mass loss in Greenland and Antarctica have been the primary contributors to recent sea level rise, accounting for 70–80% of the increase (Wang et al., 2018). The remaining 20–30% is attributed to various factors, such as mountain glacier and ice cap loss, groundwater depletion, reservoir impoundment, and global endorheic surface water loss (Dieng et al., 2017).

1.3 River flow alteration

Over the past 100 years, hydraulic engineering modified 80 percent of continental runoff to some degree, with 30 percent of that runoff being highly altered (Nilsson et al., 2005). At least 3700 large dams, either planned or under construction, will further reduce the number of free-flowing large rivers remaining by 21% (Zarfl et al., 2015). Large reservoirs, interbasin transfers, and water consumption practices like irrigation and hydropower generation can significantly alter the natural flow of rivers. Dry-region reservoirs lose substantial amounts of water to evaporation and seepage. These changes can affect long-term net runoff and the timing and intensity of peak and low flows downstream (Haghighi & Kløve, 2015). Compared to natural lakes, artificial reservoirs experience high evaporation rates, reducing the overall amount of water available in the basin (Zhao et al., 2023). Additionally, large reservoirs modify the natural patterns of river discharge, affecting riverine habitats (Zhang et al., 2018). These alterations in hydrographs result in decreased maximum-to-minimum discharge ratios and shifts in the timing of high and low flows. Estuarine wetlands are particularly affected as they rely on periodic inundation and the associated sediment and nutrient inputs (Day et al., 2012).

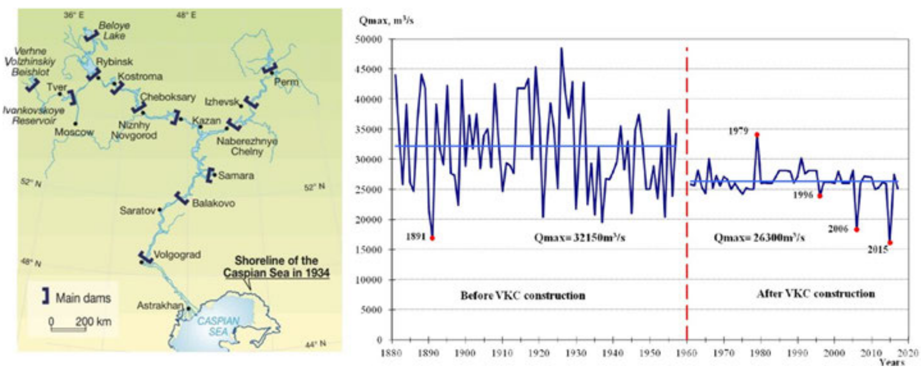

Fig. 2. Fragmentation of the Volga River by the Volga-Kama Cascade (VKC) (Adapted after Rekacewicz et al., 2023) and a change in the maximum Volga River discharge at Volgograd station from 1881-2017 (Adapted after Gorelits & Zemlyanov, 2017).

The construction of dams for energy production and irrigation purposes in arid regions results in less water flow into terminal lakes and has led to a decline in water levels in major lakes such as the Aral Sea and the Caspian Sea in Central Asia; lakes Urmia, Hamoun and Bakhtegan in the Middle East; and The Salton Sea, Walker Lake and Great Salt Lake in the US (Erdinger et al., 2011; Barnum, et al., 2017; Torabi & Kløve, 2017; Wurtsbaugh et al., 2017; Modares, 2018; Akbari et al., 2020; Akbari et al., 2022). The Volga-Kama Cascade (VKC), which produced 25% of Russia's hydroelectricity, has considerably changed the inflow to the Caspian Sea and has led to an alarming decline in water level (Figure 2). Reservoirs are mainly used for energy production and the control of seasonal discharge, so significant changes in the total annual release were mostly observed during the construction and initial filling of reservoirs between 1930–1970s and later primarily changes in the interannual hydrograph are apparent (Leummens, 2016). Furthermore, these human interventions in river regime and catchment hydrology have adverse environmental effects on the lakes' shores and coastal wetlands, including habitat loss, the disruption of migration patterns, the reduction of floodplains, and impacts on estuarine ecosystems (Revenga et al., 2005).

1.4 Coastal ecosystem vulnerability

Despite occupying only 5% of the global landmass, the coastal zone contributes to human sustenance, culture and economics, being home to three-quarters of the worldwide population and with more than half of the worldwide GDP being generated within it (Creel, 2003; Vörösmarty et al., 2009). Coastal ecosystems are among the world's most productive, yet threatened, ecosystems; they include a narrower band of terrestrial areas dominated by the influence of tides, areas where freshwater and saltwater mix (UNEP, 2006). The climate creates both direct and indirect impacts, putting the lives of humans living near the coast in danger (Blum & Roberts, 2009; Syvitski et al., 2009; Vörösmarty et al., 2009). Coastal ecosystems are so specialized that any minor variation in their hydrological or temperature regimes has a noticeable death toll, making them good indicators of climate change (Blasco et al., 1996). Climate-related drivers (sea level rise, increasing temperatures, changes in precipitation, larger storm surges, and increased ocean acidity) and human-induced drivers (rapid urbanization in coastal areas, overexploited fisheries, pollution, and river flow alteration) have continued to increase their pressure on the coasts, leading to consequences for coastal resources (Wong et al., 2014). Coastal ecosystems are disappearing at a rapid rate and on an alarming scale; 50% of salt marshes, 35% of mangroves, 30% of coral reefs and 29% of seagrasses worldwide have been lost or degraded over several decades (Barbier, 2017). Furthermore, the extensive growth in population, urbanization, and economic development is leading to increased interest in expanding hydropower infrastructure and the diversion of most coastal rivers towards potable water and irrigation (Zarfl et al., 2015; Tessler et al., 2015). The expansion of hydropower infrastructure will reduce the river discharge rate that is essential for nourishing estuaries. It will disturb the sediment supply to beaches, leading to further erosion and habitat loss, and may compromise the integrity of coastal food webs in the sediment-starved coastal zones (Kondolf, 1997; Vörösmarty et al., 2000; Vörösmarty et al., 2003).

The most sensitive coastal ecosystems to hydrological alterations are estuarine ecosystems located in arid regions (Schile et al., 2016). Due to their unique geographic position between the mainland and the sea, these complex, dynamic, and biotically rich environments are dominated by physical forces and are impacted by human activity, leading to their rapid response to the river regulation and shifts in environmental variables caused by climate change (Day et al., 2012; Adame et al., 2021). The quantity of freshwater input, the amount of associated dissolved and suspended materials, and the input of organic and inorganic nutrients is important for ecosystem mixing, salinity, and stability of a biota that depends on such material (Day et al., 2012). Thus, agricultural intensification and development of extensive irrigation systems in dry regions accompanied by pollution and groundwater depletion have been linked to the reduction of wetland areas, exemplified through adverse climatic effects (Hollis, 1990).

2 Research objectives and motivation for this study

This research will make a theoretical contribution through the empirical investigation of the sustainability of coastal ecosystems. The main objective of the thesis is to examine the possible effects of different environmental variables on coastal and estuarine habitats, focusing on the impacts of climate change and river flow alteration caused by damming and agricultural intensification in two different settings: inland water body (lake shore) and the marine coastal environment. A combination of in-situ hydrological and meteorological data and remote sensing monitoring of land use and vegetation cover offers excellent potential for spatial and temporal monitoring in data-scarce or difficult-to-access areas, such as mangrove ecosystems (Figure 3). The systemic approach and quantitative assessment tools applied to the Caspian Sea, northern Persian Gulf, and Gulf of Oman are both scalable and transferrable to a wide range of watersheds and aquatic ecosystems. Together, these approaches provide actionable tools on which more sophisticated strategies of integrated water resources and ecosystem management can be developed.

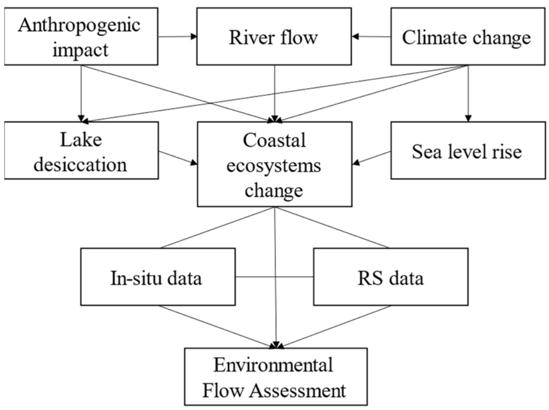

Fig. 3. Schematic diagram summarizing the work performed in this thesis.

In this research, three pivotal questions were formulated to investigate the effects of climate change and hydrological alterations on coastal ecosystems in water-stressed regions in Central Asia and the Middle East. These questions address the drivers of changes in estuarine wetlands, inland lake coastal areas, and mangrove habitats; they explore the interactions between environmental variables impacting these ecosystems, and propose scalable strategies for integrated water resources and ecosystem management with implications for the UN Decade on Ecosystem Restoration:

> ***Research question 1:*** *What are the primary drivers of changes in coastal ecosystems in the most water-stressed regions of Central Asia and the Middle East?*
>
> ***Research question 2:*** *How do different environmental variables, such as temperature, rainfall, river flow, and salinity, interact and impact the health and sustainability of coastal ecosystems in the Caspian Sea, northern Persian Gulf, and Gulf of Oman?*
>
> ***Research question 3:*** *How can this understanding inform the development of optimal environmental flow strategies for mangrove restoration?*

To address the research questions outlined above, the research objectives have been formulated to study the interaction between terrestrial and coastal processes, and comprehensively investigate the drivers of coastal ecosystem changes. These objectives are:

- To investigate the cause of estuarine wetland changes: climate change or/and anthropogenic activities.
- To study the response of inland lake coastal areas to changes in climate and alteration of inflow.
- To design the optimum environmental flow release strategy to maintain coastal habitats.

2.1 Motivation for this study

The focus of this thesis is on the hydrological and environmental assessment of the causes and effects of river regime change in the associated vulnerable estuarine ecosystems and coastal zones. A starting assumption for the thesis was that the coastal zones are susceptible to both a decline and rise in water level. Thus, as a case study, we have chosen the largest inland water body, the Caspian Sea, which faces continuous desiccation, and vulnerable coastal areas of the Persian Gulf and Gulf of Oman, which experience sea level rise. In both cases, the freshwater input from both river discharge and direct precipitation is decreasing. It was also assumed that the causes of water level changes are both natural and anthropogenic. Therefore, the work attempts to separate and quantify the impact of anthropogenic activities and climate change on river flow alteration (Publications II, III), lake water level (Publication I), and coastal systems (Publications I, II, IV). The Caspian Sea also shows a direct response to climatological changes through ice-regime change. It experiences significantly faster warming than ice-free lakes (Publication V). The main target of this thesis was to find a solution for the conservation of coastal ecosystems and the development of environmental flow assessment for intermittent rivers supporting fragile mangroves located on the edge of this ecosystem tolerance limit. This thesis is based on three peer-reviewed original scientific publications (Publications I, II and V) and two submitted manuscripts that are currently under review (Publications III, IV). A further breakdown of the reasons justifying the need for each of these studies is presented here.

2.1.1 Climate change and changing demands: Addressing emerging needs (Publications I, IV)

Climate change, such as increases in air temperature and fluctuations in precipitation, and new engineering water management projects have destabilized hydrological systems in fragile drylands. In response to climate change and damming, rivers have seen significant alterations in their natural flow regimes, reducing the inflow to many terminal lakes and leading to desiccation and degradation of water quality. Water levels in inland lakes worldwide have fallen dramatically in the 21st century, jeopardizing the further existence of coastal ecosystems. The biggest lakes in the world, the Caspian Sea, the Aral Sea, and Lake Balkhash, are currently in devastating condition and their ecosystems are in danger. The impact of large dams on coastlines, estuaries, deltas, and lagoons is often under-reported in environmental studies of hydropower projects.

2.1.2 Bridging Coastal and River Basin studies: Connecting for comprehensive understanding (Publication II)

Despite extensive existing research on river flow alteration and its impact on riverine ecosystems, the effect of dam operation on downstream estuarine wetlands has yet to be addressed (Yang et al., 2019; Zheng et al., 2019; da Silva et al., 2020). This is partly due to the fragmentation of water management and the lack of attention paid to IWRM and the basin approach to water resources management.

Furthermore, IWRM challenges are intensified in situations of transboundary catchments. The tension between upstream and downstream water users, typically represented by upstream farmers and downstream protected areas, is a common problem in developing regions with arid climates. Unfortunately, the conservation of ecosystem services, which are difficult to value, is a concession to the agricultural sector, which is a major source of income and food. The literature extensively covers the relationship of estuarine wetland dynamics with sea-level rise, but there is a lack of understanding of the dominance of climate change and hydrological alterations caused by dam operations (Lotze et al., 2006; Chi et al., 2018; Adame et al., 2021; Baubekova et al., 2023). Therefore, these dynamic transition zones are better assessed by considering the entirety of the Catchment-Estuary-Coastal (CEC) systems (Bamunawala et al., 2020, 2021).

2.1.3 Coastal systems vulnerability: Identifying critical requirements (Publications I, II, IV)

Climate change affects marine and inland waters differently, but in both cases, coastal ecosystems will take the first hit. Estuaries and coastal zones are dynamic environments that are constantly undergoing change. Being ecotones between water and land, they are vulnerable to change, in terms of either rising or falling water levels. To conserve coastal habitats, it is important to understand existing processes and recognize potential pressures/threats. The comprehensive assessment of climate variables and key hydrological processes is critical to determining background processes, possible tolerance thresholds, and limits to resilience. As such, due to the unique geographic position and because mangroves in arid climates depend on a single or a few foundation species, the health and expansion of these biodiversity hot spots rapidly respond to fluctuations in the environmental variables caused by climate change or increased human activities on the mainland and in the sea (Publication IV).

2.1.4 Unlocking the potential: Harnessing ecosystem services and nature-based solutions (Publications I, II, III, V)

The study of coastal ecosystems is crucial due to the importance of ecosystem services and the potential of nature-based solutions that can help mitigate and adapt to the impacts of climate change (Spalding et al., 2014). Coastal ecosystems, such as estuarine wetlands, mangroves, and salt marshes, provide a wide range of valuable services that benefit human populations and the environment (Duart et al., 2013). These services include coastal protection against storms and erosion, carbon sequestration, water filtration, habitat provision for numerous species, and support for fisheries and tourism industries (Gedan et al., 2011; Temmerman et al., 2023). Understanding the functioning and resilience of these ecosystems is essential for sustainable coastal management and planning.

2.1.5 Rethinking allocation: Towards a novel methodology for EF assessment (Publication IV)

Commitments to ecosystem restoration of marine and coastal areas are needed to deliver nature-based solutions for food insecurity, climate change mitigation and adaptation, and biodiversity loss (UNEP, 2021). Unfortunately, nearly half of the efforts to restore mangroves globally fail or underperform (Su et al., 2022). Although it is almost impossible to completely restore coastal habitats after a significant sea level rise or fall, it is possible to reduce the extent of environmental damage through restoration actions. Gaining a comprehensive understanding of spatial and temporal variations in key abiotic parameters within an ecosystem across the full range of actual or projected hydrological change is critical in determining how ecosystems respond to hydrological alterations (Petts, 2009). Therefore, we propose designing an environmental flow regime for intermittent rivers to support mangroves in arid regions which considers the assessment of hydrological and climatic parameters that affect the ecosystem health while recognising the needs of upstream water users.

3 Brief overview of the study area

To test the assumption that coastal zones are susceptible to both a decline and rise in water level, two main study sites have been chosen: the Caspian Sea (Publications I, III, V) and the North coast of the Persian Gulf (Publications II and IV). Publication I covered the entire Caspian Sea basin, Publication III focused on river inflow from the South Caspian Sea basin, and Publication V covered ice regime change and its socio-economic and biodiversity implications in the Northern Caspian Sea (Figures 2 and 4). To assess the interaction between sea level rise and the catchment level assessment in Publication II, changes to the estuary of the Mond River were investigated. In Publication IV, two coastal and two estuarine mangrove sites in the northern part of the Persian Gulf and Gulf of Oman were studied.

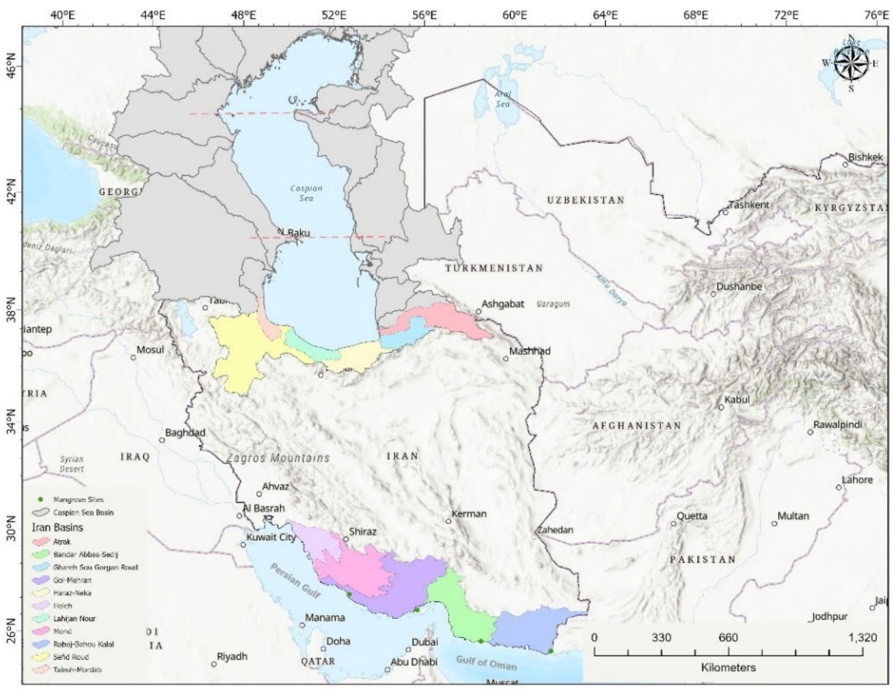

Fig. 4. Study site map.

3.1 Caspian Sea

The Caspian Sea, located in Eurasia, is the largest continental water body in the world with no outlets; it spans Iran, Russia, Kazakhstan, Turkmenistan, and Azerbaijan. It covers an area of approximately 390000 km^2 and has a water volume of around 78000 km^3 (Publication III). The sea is divided into three regions: Northern, Middle, and Southern Caspian, each with varying depths, ranging from 5–6 meters in the north to over 1000 meters in the south (Amirahmadi, 2000; Aladin & Plotnikov, 2004; Ibrayev et al., 2010). The N–S elongated Caspian Sea region is climatically diverse, with annual precipitation ranging from 130 mm in the vast semi-arid and temperate arid deserts of northern Kazakhstan and Turkmenistan to 1900 mm in the temperate humid Caucasus and Elburz mountains in the south and south-west (Leroy et al., 2022; Publication I).

The area of the watershed of the Caspian Sea covers around 3300000 km^2, whereas the area of the lake itself makes up only 12% of the total area of the watershed (Aladin & Plotnikov, 2004). River runoff dominates the water budget, with more than 130 rivers flowing into the Caspian. Their total runoff into the sea ranges from 205–215 to 450–460 km^3/year, with an average of about 300 km^3/year (Skolskiy et al., 2018). Of this volume, 80% is runoff from the Volga River, and 5% is from the Zhaiyk River (Ural) (Aladin & Plotnikov, 2004). About 10% of the runoff is provided by the rivers of the western coast: Terek, Sulak, Samur, Kura, and other small rivers, and the remaining 5% is provided by the rivers of the Iranian coast (Skolskiy et al., 2018). The Caspian Sea is partially covered with ice every year. Stable ice phenomena have been observed in the northern Caspian, with the highest ice thickness in the North-East, while the southern part of the lake is never covered with ice. The formation of ice is influenced by Siberian anticyclones and east winds from Kazakhstan's rapidly cooling semi-deserts and steppes.

3.2 Mond River basin

The Mond River basin (47654 km^2) is a sub-basin of the Persian Gulf that consists of the fifth longest river in Iran, the Mond River, and several tributaries, Qare-aqaj, Simakaan, Shoor Jahrom, Shoor Firouzabad, and Baqan (Torabi Haghighi et al., 2020). The Mond River is a leading source of surface water for agricultural activities in Fars and Bushehr provinces of Iran. The rapidly growing population and farm areas are increasing pressure on groundwater and surface water resources. Since early historical times, more than 1700 years ago, the Band Bahman dam has diverted the Qare-aqaj River flow for irrigation purposes (Torabi Haghighi et al., 2020). Due to the basin's high-water demand, two storage dams were constructed in 2006: the Salman Farsi (SF) dam (1.4 km^3) on the Qare-agaj River and the Tangab (Ta) dam on the Shoor Firouzabad River (0.2 km^3). Before emptying into the Persian Gulf, the Mond River supports the national park known as the Mond protected area (MPA), located in the lower part of the basin. The national park consists of three significant habitats: the coastal, riverine, and inland zones provide more than 50000 ha of valuable habitat for migratory birds, wildlife, and aquatic organisms (mostly fish) (Mehrabian et al., 2009; Pouladi et al., 2017).

3.3 Persian Gulf and Gulf of Oman mangroves

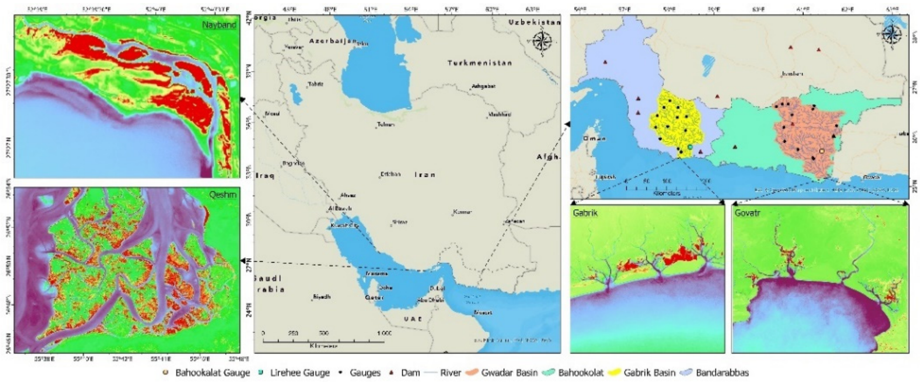

Fig. 5. Study site map of mangrove forests in Iran.

Mangroves are a globally distributed ecosystem in the tropical and subtropical coastal areas between latitude 25°N and 25°S, covering an area of approximately 150000 km^2 (Spalding et al., 2010). One of the most poleward mangroves is in Iran, between latitude 25° 19′ and 27° 84′, in the northern part of the Persian Gulf and Gulf of Oman; it is mainly distributed in 3 coastal provinces, Bushehr, Sistan & Baluchestan, and Hormozgan (Zahed et al., 2010; Ximenes et al., 2023). Mangroves covered a relatively small area of about 111.77 km^2 in 2020, with the most extensive and densest mangrove forest in the Hara Protected Area near Qeshm Island in the Hormozgan Province (The Global Mangrove Watch, 2023). Iran’s mangroves consist mainly of a pure stand of *Avicennia marina* due to its high tolerance for temperature and salinity changes (Milani, 2018; Erfanifard et al., 2022). For Publication IV, we selected two main Iranian Mangrove Forests sites, Nayband and Qeshm, and two estuarine mangroves, Gabrk, and Govatr (Figure 5). The primary water source for these mangrove forests is seawater, but freshwater supports Gabrik and Govatr. Nayband Marine-Coastal National Park mangroves exist under an arid climate with hypersaline conditions (37.9–41.3 ppt) and without direct riverine input (Moaddab et al., 2017). The Govatr mangrove site within the delta of the BahooKalat River is a part of the Gandoo Protected Area and Bahoo wetland (Khosravi 1992). The Gabrik mangrove is in the estuary of the Gabrik River (Zahed et al., 2010). The climate in this region is classified as hot desert, with an average annual precipitation of 146.58 mm (Publication IV).

4 Methodology

To assess the spatio-temporal alterations in daily, monthly, and annual flow from upstream to downstream, two sets of indices were used, River Impact (RI) method (Publication II) and Indicators of hydrologic alteration (IHA) (Publications II, IV). We used the abrupt change detection technique based on the Pettitt test to identify the significant breakpoint in the rivers flow time series in Publications II and III (Pettitt, 1979). To assess the extent of anthropogenic activities and climate change contributions to river flow alteration, elasticity-based methods and Budyko hypotheses were applied in Publication III. To evaluate spatio-temporal change in inflow, precipitation, and potential evapotranspiration (PET), two non-parametric methods were used, the Mann-Kendall method (Publications II and III) and Innovative Trend Analysis (ITA) (Publication III). A number of remote sensing-derived indexes were used, including the Normalized Difference Water Index (NDWI) to produce the Caspian Sea water body maps (Publication I) and Normalized Difference Vegetation Index (NDVI) for land use change monitoring (Publication II), as well as the mangrove health assessment (Publication IV) and meteorological indexes: PET in Publications II, III, IV. the Standardized Precipitation Index (SPI) and the Standardized Precipitation-Evapotranspiration Index (SPEI) for the drought analysis (Publication II) were also used in this study. In situ river discharge data was used in Publications I, II, III, and IV, along with climatological data from the local meteorological stations in Publications III, IV, and V. Furthermore, ice regime related long-term series of observations from hydrological and meteorological stations in Kazakhstan and Russia were used in Publication V.

4.1 Flow regime alteration: Indicators of hydrologic alteration and monthly flow regime index

Several methods have been developed to assess the degree of hydrological alteration caused by climate change and various forms of river regulation, especially dam construction (Gao et al., 2009). One of the most widely used in environmental flow studies is Indicators of Hydrologic Alteration (IHA) (Yan et al., 2021). The IHA method developed by Richter et al. (1996) for the US Nature Conservancy involves analysing a set of hydrological indicators derived from daily streamflow data. The IHA contains 33 hydrologic parameters that capture various aspects of intra- and inter-annual variation in the hydrological regime, including the magnitude of monthly stream flows, the magnitude and duration of annual extreme flows, the timing of annual extreme flows, the frequency and duration of high and low pulses, the rate and frequency of flow changes, and 34 "environmental flow components" (EFCs) parameters that characterize the hydrograph in a manner that is representative of key flow-ecology relationships (Richter et al., 1998; Mathews and Richter, 2007). Olden and Poff (2003) evaluated statistical variation patterns among all to-date published hydrologic indicators and concluded that the 33 IHAs capture most variation and can thus be used to represent the major aspects of the flow regime. Similarly, Yang et al. (2008) discovered a small subset of hydrologic indicators that best represented ecological flow regimes, resulting in the selection of six IHA parameters as the most ecologically relevant hydrologic indicators; these were: date of minimum, rise rate, number of reversals, 3-day maximum, 7-day minimum, and May flow. As the Mond River system experienced an abrupt change due to dam construction, two period analysis was used in Publication I. The change point was detected using the Pettitt test described later in this section. Whereas in Publication IV, the studied intermittent rivers had no significant change point and were mainly impacted by climate change variability and change; thus, one-period analysis was used. The IHA was used to examine standard hydrological patterns of intermittent rivers in order to understand the impact of climate change and anthropogenic activities on river flow alteration and to develop environmental flow recommendations.

In the lack of daily flow data, the rate of change in the natural flow regime as the result of dam operation can be seen on monthly hydrographs, which give the impacts on river flow magnitude, timing, and intra-annual flow variability (Haghighi & Kløve, 2013). Such changes were quantified by the River Impact (RI) index developed by Torabi Haghighi et al. (2014), who considered three main impact factors: MIF (magnitude impact factor), TIF (timing impact factor), and VIF (variation impact factor). The RI method was applied to assess the cause and effects of upstream-downstream river regulation across the Mond basin in Publication II using the data from 1987 to 2017 from 12 gauges. Dam construction can change one or more of these factors, depending on their size, purposes (water supply, hydropower generation or flood control) and distance from the gauge. Therefore, river flow data was divided into two categories, pre-impact, and post-impact flows. The combined RI factor considers all three major impacts:

$$RI = MIF \times (TIF + VIF), \tag{1}$$

where MIF is of equal importance to the sum of TIF and VIF because flow magnitude is the controlling factor; if there is no flow (MIF is 0) there is no river and RI will show a completely changed river flow (Haghighi et al., 2014). The value of RI can range between 1 (the pre-impact period or the natural river flow regime) and 0 (the post-impact or completely changed river flow regime). The RI index range is defined by five different impact classes: 'low' impact (<20% alteration in flow regime characteristics), with a 0.8–1.0 RI value; 'incipient' impact, with a 0.6–0.8 RI value; 'moderate' impact, with a 0.4–0.6 RI value; 'severe' impact, with a 0.2–0.4 RI value; and 'drastic' impact (>80% alteration in river flow regime), with a 0.0–0.2 RI value (Publication II).

The magnitude impact factor is calculated as:

$$\mathrm{MIF} = \mathrm{AF}_{\mathrm{Post}} / \mathrm{AF}_{\mathrm{Pre}}, \quad (2)$$

where AF_{Pre} and AF_{Post} are mean annual flow in the pre-impact and post-impact periods, respectively for a specific gauging station.

Variation impact factor quantifies the variation in the hydrograph as:

$$VIF = \frac{50-0.5*I_{RR}}{100} \quad (3)$$

and

$$I_{RR} = \frac{|RRI_{Pre}-RRI_{Pos}|}{RRI_{Pre}} * 100, \quad (4)$$

where RRI_{Pre} and RRI_{Pos} are the River Regime Index (RRI) in the pre-impact and post-impact periods, respectively (details of RRI calculation can be found in Haghighi and Kløve (2013)).

Timing impact factor considers shifts in maximum, minimum, and 50% of discharge cumulative density function (CDF) (Torabi Haghighi et al., 2014):

$$TIF = \frac{50-0.247*TF}{100} \quad (5)$$

and

$$TF = \frac{|DT_{Max}|+|DT_{Min}|+|DT_{Median}|}{3}, \quad (6)$$

where DTMax, DTMin, and DTMedian are the time shifts in monthly maximum discharge, monthly minimum discharge, monthly median discharge and CDF50 timing value.

4.2 Statistical analysis

The Pettitt test, as a non-parametric test, based on the Mann-Whitney two-sample test, was used to highlight the causes of river flow changes and detect abrupt changes in the discharge data in Publications II and III (Pettitt, 1979). The Pettitt test calculates a test statistic based on the maximum absolute difference between two parts of the dataset divided by the total number of observations. By comparing this test statistic to critical values from a pre-determined significance level, the Pettitt test helps determine if there is evidence of a significant change point in the time series. It is commonly employed in hydrology, climatology, and environmental sciences to identify abrupt changes in variables like streamflow, precipitation, temperature, or pollutant levels over time (Liu et al., 2010; Rougé et al., 2013; Xie et al., 2014).

In Publication II, we applied the nonparametric Mann-Kendall (MK) (Kendall, 1948; Mann, 1945) test to evaluate trends in inflow, precipitation, and potential evapotranspiration. In Publication III, to evaluate spatial/temporal change in temperature, precipitation, PET, and rivers flow across the South Caspian Sea region, two non-parametric methods, including the modified Mann-Kendall method (MK3) (Hamed and Rao, 1998) and Innovative Trend Analysis (ITA) (Şen, 2012), were used. Hamed and Rao (1998) modified the MK test to remove all significant autocorrelations in the time series data.

In this new approach, a modified variance of S (V(S)*) computes as follows (Hamed and Rao, 1998):

$$V(S)^* = V(S)\frac{n}{n^*}, \tag{7}$$

where n* is the effective sample size.

The $\frac{n}{n^*}$ ratio can be calculated as (Hamed and Rao, 1998):

$$\frac{n}{n^*} = 1 + \frac{2}{n(n-1)(n-2)}\sum_{i=1}^{n-1}(n-i)(n-i-1)(n-i-2)\,r_i, \tag{8}$$

where r_i denotes the lag-i significant autocorrelation coefficient of rank i of time series.

Then the standardized statistic of the *S* statistic, i.e., *Z* can be computed as:

$$Z = \begin{cases} \frac{S-1}{\sqrt{V(S)^*}} & S > \circ \\ \circ & S = \circ \\ \frac{S+1}{\sqrt{V(S)^*}} & S < \circ. \end{cases} \tag{9}$$

There is no trend in the time series at the significance level of α if $Z_{1\text{-}\alpha/2} < Z > -Z_{1-\alpha/2}$. The positive and negative Z values indicate increasing and decreasing trends, respectively.

Innovative trend analysis, proposed by Şen (2012), allows graphical evaluation of trends without any assumptions on the time series data. It was widely applied for detecting trends in hydro-meteorological variables (Singh et al., 2021). ITA methodology is based on the 1∶1 (45°) line comparison of the scatter points on a Cartesian coordinate system (Şen, 2014). The plots are a result of available time series first-half values versus second half after sorting in ascending order. Data collected on the 1:1 ideal line (45° line), means no trend in the time series; data accumulated on the upper triangular area of the 1:1 line shows an increasing trend; and data in the lower triangular area represents a decreasing trend in the time series (Şen 2012; Şen, 2014; Caloiero, 2020).

4.3 Quantifying the impact of anthropogenic activities and climate change on river flow alteration

Studies aiming to separate and quantify the relative contribution of human activities and climate change on the changes in surface runoff typically use empirical methods, elasticity-based methods, or hydrological modelling approaches (Liu et al., 2010; Gao et al., 2011; Zeng et al., 2015; Zhao et al., 2015; Wu et al., 2017; Bao et al., 2019), either on their own or in combination. Empirical methods, such as simple linear regression and double mass curve, are commonly employed as the most straightforward approach. However, they have three limitations: i) requiring long term hydrological and precipitation data; ii) ignoring other important variables, such as temperature and evapotranspiration; and iii) neglecting the physical mechanisms of runoff generation (Publication III). In contrast, hydrological models have a more realistic physical basis, but their high complexity requires a considerable amount of time and data (Sharifi et al., 2021). Elasticity-based methods, which include nonparametric and analytical methods based on the Budyko hypothesis, are also commonly used, as they are the fastest and most intuitive method.

Publication III, using elasticity-based methods and the Budyko hypothesis, investigated 40 rivers' hydrological response to climate change and human activities based on the data from the closest gauges to the Southern Caspian Sea in Iran.

According to Wu et al. (2017), runoff (Q) in a basin can be expressed as the following function:

$$Q = f\left(P.ET_p.V\right), \tag{10}$$

where P is precipitation, ET_p is PET, and V is the characteristics of the basin. Changes in runoff (ΔQ) can be expressed as follows:

$$\Delta Q = \frac{\partial Q}{\partial P}\Delta P + \frac{\partial Q}{\partial ET_p}\Delta ET_p + \frac{\partial Q}{\partial V}\Delta V, \tag{11}$$

where ΔP and ΔET_p, are the changes in mean annual precipitation and PET, respectively, and ΔV is the change in basin characteristics.

The contribution of climate change to runoff change can be defined as the impact of climate change on precipitation and PET:

$$\Delta \overline{Q}_{cc} = \frac{\partial Q}{\partial P}\Delta P + \frac{\partial Q}{\partial ET_p}\Delta ET_p. \tag{12}$$

According to Schaake (1990), by replacing the climate elasticities to runoff with precipitation ($\varepsilon_p = \frac{\partial Q/Q}{\partial P/P}$) and PET ($\varepsilon_{ET_p} = \frac{\partial Q/Q}{\partial ETp/ETp}$) in Eq. (12), the contribution of climate change in runoff can be expressed as:

$$\Delta \overline{Q}_{cc} = \left(\frac{\varepsilon_P \Delta P}{P} + \frac{\varepsilon_{ET_p} \Delta ET_p}{ET_p}\right) Q, \tag{13}$$

where ε_P and ε_{ET_p} are the climate elasticities of runoff to precipitation and PET, respectively. According to the long-term water balance, runoff can be expressed as follows:

$$Q = P - ET_a - \Delta S, \tag{14}$$

where, ET_a is the actual evapotranspiration, and ΔS is the change in water storage, which can be assumed to be zero on a multi-year scale.

Budyko (1974) defined aridity and evaporative indexes and the relationship between them, known as Budyko curve (Dey & Mishra, 2017). The aridity index (φ) is the ratio of the PET to the precipitation:

$$\varphi = ET_p/P. \tag{15}$$

The evaporative index (F(φ)) is the ratio of the actual evapotranspiration to the precipitation:

$$ET_a = PF(\varphi). \tag{16}$$

A combination of the climate elasticity of runoff with Eq. (14), the precipitation elasticity coefficient, and the PET elasticity coefficient for runoff can be derived as:

$$\varepsilon_P = 1 + \frac{\varphi F'(\varphi)}{1-F(\varphi)}, \qquad \varepsilon_P + \varepsilon_{ET_p} = 1, \tag{17}$$

where F′(φ) represents the derived function of F(φ) (For more information about the derivation of ε_P please refer to Sharifi et al. (2021)).

4.4 Remote sensing and meteorological indexes

Table 1. Major remote sensing and meteorological indexes used in the study.

Index	Full Name	Formula	Reference
NDVI	Normalized Difference Vegetation Index	(NIR - Red) / (NIR + Red)	Rouse et al. (1974)
NDWI	Normalized Difference Water Index	(NIR - SWIR) / (NIR + SWIR)	Gao (1996)
NDWI	Normalized Difference Water Index	(Green - NIR) / (Green + NIR)	McFeeters (1996)
SPI	Standardized Precipitation Index	(P - μ) / σ	McKee et al. (1993)
SPEI	Standardized Precipitation Evapotranspiration Index	(P - PET - μ) / σ	Vicente-Serrano et al. (2010)
PET	Potential Evapotranspiration	$ET_p = 0.0023R_a(T_{ave} + 17.8)(T_{max} - T_{min})^{0.5}$	Hargreaves and Allen (2003)

Landsat satellite images from 1990 to 2020 were used to calculate NDVI for a land cover change analysis of the Mond Protected Area in Publication II. MODIS Land Cover Type (MCD12Q1) Version 6 (Friedl & Sulla-Menashe, 2019) was used to produce the land cover map of the Mond River Basin, including barren, cropland, grassland, shrubland, urban, and water. In Publication IV, NDVI was used as a mangrove health index as it is widely applied for this purpose. NDVI was calculated using Landsat and MODIS satellite images for the period 2000–2020 using Google Earth Engine.

Landsat 30-meter spatial resolution images with cloud cover <20% from 1977–2018 were used to produce water body maps of the Caspian Sea in Publication I, using the Google Earth Engine (Gorelick et al., 2017) JavaScript Application Program Interface. Summer images of each year, when cloud cover is less than in other seasons, were used to produce annual maps of NDWI, where NDWI values greater than zero were considered to be water (Gao, 1996; McFeeters, 1996). Images for 1978–1986 are low quality and thus could not be used for analysis. We calculated NDWI for the period 1987–2018 using the Gao (1996) equation (Table 1), based on the spectral resolution of recent Landsat sensors (ETM, ETM + and OLI), which cover NIR and SWIR bands. NDWI for the year 1977 was calculated using a McFeeters (1996) equation (Table 1) due to there being limited bands in the Landsat MSS collection spectral resolution. NDWI maps were later used for the vulnerability assessment of the shorelines concerning the impacts of the SWL. The vulnerability ratio (vi) is a representative index for comparing the vulnerability of countries as the coastline of the Caspian Sea is not equally distributed:

$$vi = \frac{Ai}{Li}, \tag{18}$$

where Ai is a potentially vulnerable area in each country, determined by comparing the NDWI maps of the sea in 1995 and 1977, when the sea was at its highest and lowest respectively. Li is the length of the coastline in each surrounding country. SWL raise and covered potential vulnerable area (CVA) (SWL–CVA) relationships were developed for the Caspian Sea, Northern/Middle/Southern Caspian, and surrounding countries using 33 NDWI maps from 1977 to 2018.

We used the Standardized Precipitation Index (SPI) and Standardized Precipitation-Evapotranspiration Index (SPEI) for drought analysis in Publication II. We used a Mann–Kendall trend test to quantify the significance of drought characteristic trends at different time and space scales. The SPI developed by McKee et al. (1993), based on a precipitation probabilistic approach, is recommended for use by the World Meteorological Organization for detecting and characterizing meteorological droughts (European Drought Observatory, 2020). The SPI measures drought intensity by comparing observed total precipitation amounts for an accumulation period of interest with the long-term historical rainfall record for that period (Edwards & McKee, 1997). The new SPEI is simple to calculate based on the SPI calculation but also considers the effect of PET on drought severity, capturing the major impact of increased temperatures on water demand (Vicente-Serrano et al., 2010; Liu et al., 2021). Positive SPI or SPEI values show wet conditions, and negative values indicate meteorological droughts (Mckee et al., 1993; Paulo et al., 2012).

In Publication III, PET was calculated using the modified Hargreaves model (Hargreaves & Allen, 2003) based on the work of Hargreaves & Samani (1985) (Table 1). In the proposed formula, ET_p is PET (mm day^{-1}), R_a is the water equivalent of extraterrestrial radiation (mm day^{-1}), T_{ave}, T_{max}, and T_{min} are the mean, maximum, and minimum air temperature (°C), respectively. For Publication II we retrieved PET and precipitation data in the sub-basins of the Mond River basin from an ECMWF Re-Analysis (ERA) product available from 1980 onwards (Hersbach et al., 2020). In Publication IV, we used a ready MODIS product MOD16A2 with 8-day intervals.

4.5 Environmental flow allocation

Determining the Environmental Flow (EF) for mangroves is a complex process which should be tailored to the specific characteristics of the study area, considering factors such as regional climate, hydrological patterns, and the unique requirements of mangrove species. A global review of the present status of environmental flow methodologies revealed more than 200 environmental flow assessment methodologies that can be grouped into four categories: hydrological, hydraulic rating, habitat simulation, and holistic methodologies (Tharme, 2003).

1. Hydrological methods focus on quantifying the water requirements of ecosystems based on hydrological parameters such as streamflow, rainfall, and groundwater levels.
2. Hydraulic rating methods assess the flow requirements of ecosystems by considering hydraulic characteristics such as water depth, velocity, and sediment transport.
3. Habitat simulation methods reproduce the physical habitat conditions required by ecosystems, considering factors such as water depth, salinity, temperature, and nutrient availability. These methods provide insights into the optimal habitat conditions for supporting ecosystems by integrating these variables.
4. Holistic methods consider multiple ecological, social, and economic factors to develop comprehensive EF allocation strategies. They involve stakeholder engagement, considering the perspectives and needs of various users and the

beneficiaries of water resources to strike a balance between human needs and the preservation of ecosystems.

Despite many studies of environmental flow assessment and allocation, only a few focus on EF allocation for mangroves (Sathyanathan et al., 2009; Sun et al., 2013; Kiwango et al., 2015). To allocate the EF for the mangrove forests, two fundamental characteristics must be defined, the magnitude and timing of water release. More details on the methodology used to determine the best time for water release can be found in Publication IV, which discusses the estimation of hydrological and climatic parameters that affect the health of the mangrove. The magnitude of EF needed for the healthy growth of mangroves in the study sites was estimated based on the PET during the recommended months in recent years. PET was retrieved from a MODIS product named MOD16A2 at 8-day intervals.

5 Results

5.1 Response to lake to river flow alteration and climate change

5.1.1 Changes in total inflow to the Caspian Sea

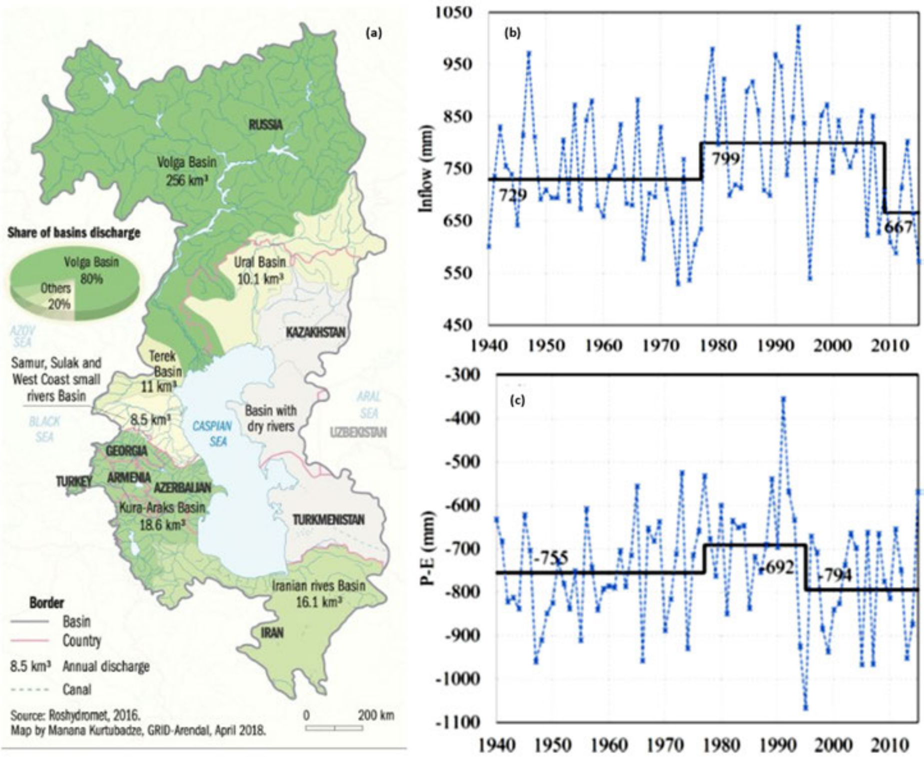

Fig. 6. (a) River basin discharge into the Caspian Sea (Adapted from Kurtubadze, 2020), (b) total inflow to the Caspian Sea (mm), estimated considering 0.86 as Volga inflow contribution to total inflow which is then divided by the area of the sea and (c) net precipitation (precipitation minus evaporation) over the Caspian Sea (mm), estimated from the difference between annual SWL change and total flow (Adapted under CC BY 4.0 license from Publication I @ 2020 Authors).

To estimate the total inflow to the Caspian Sea shown in Figure 6, we used monthly averaged discharge measurements from downstream river gauges on the Volga River from the Global Monthly River Discharge Data Set (RivDIS). Total inflow to the Caspian Sea was estimated based on the observed discharge at

Vernelebyazhye from 1940 to 2015. The Volga River contributes over 80% of the total inflow to the sea with a mean annual flow of about 250 km^3 (Figure 6) (Arpe et al., 2000; Chen et al., 2017). For the SWL simulation and sensitivity analysis in Publication I, we considered the Volga contribution to be equal to 0.86 to estimate the total sea inflow from all rivers. This approach was adopted due to the need for more available inflow data from other rivers and a considerable number of missing values after 1983, except for from the Volga River at the Vernelebyazhye gauge.

Climate change directly affects Caspian Sea level variations through open-water evaporation and precipitation and indirectly through river runoff changes caused by increased or decreased precipitation over the whole basin. A significant difference was observed in the trend of net precipitation (P-E) in 1977, 1995, and 2008 (Figure 6(c)). Mean net precipitation increased from -755 to -692 mm, corresponding with an SWL rise between 1977 and 1995. After that, in the second period, net precipitation decreased, so SWL started to decline even further to -794. After 2008, mean annual inflow has also fallen, in parallel with continuing decreases in net precipitation, meaning SWL decline has increased in speed. In 2010–2015, the total inflow was about 260 km^3/year, and the average net precipitation was -786 mm. In current conditions, to recover all vulnerable areas of Kazakhstan, there is a need to increase the total inflow from 260 to more than 300 km^3/year as it is not possible to control the net precipitation, which would require an increase from -786 to -680 mm.

5.1.2 River flow alteration in the Southern Caspian Sea

Six sub-basins, including Atrak, Gorgan-Rud, Haraz-Neka, Lahijan-Noor, Sefid-Rud, and Talesh, on the Southern coast of the Caspian Sea supply about 15 km^3 of freshwater inflow to the sea annually. However, an increasing rate of migration and subsequent rapid urbanization and land use change from forests to agricultural, urban, and industrial lands has resulted in increased water supply needs and water withdrawal. To fulfill the needs of the growing population, about 117 dams have been constructed on rivers across the southern Caspian Sea (SCS) sub-basins (Publication III). Sefidrud Dam, which was commissioned in 1962, is the largest of them (Smith, 1984).

In Publication III, in-situ monthly discharge data from 40 gauges closest to the sea, obtained from the Iran Water Resources Management Company (IWRMC), and meteorological data from 36 weather stations, collected from the Iran

Meteorological Organization (IRIMO), were used to assess the causes and extent of freshwater inflow alteration to the SCS area.

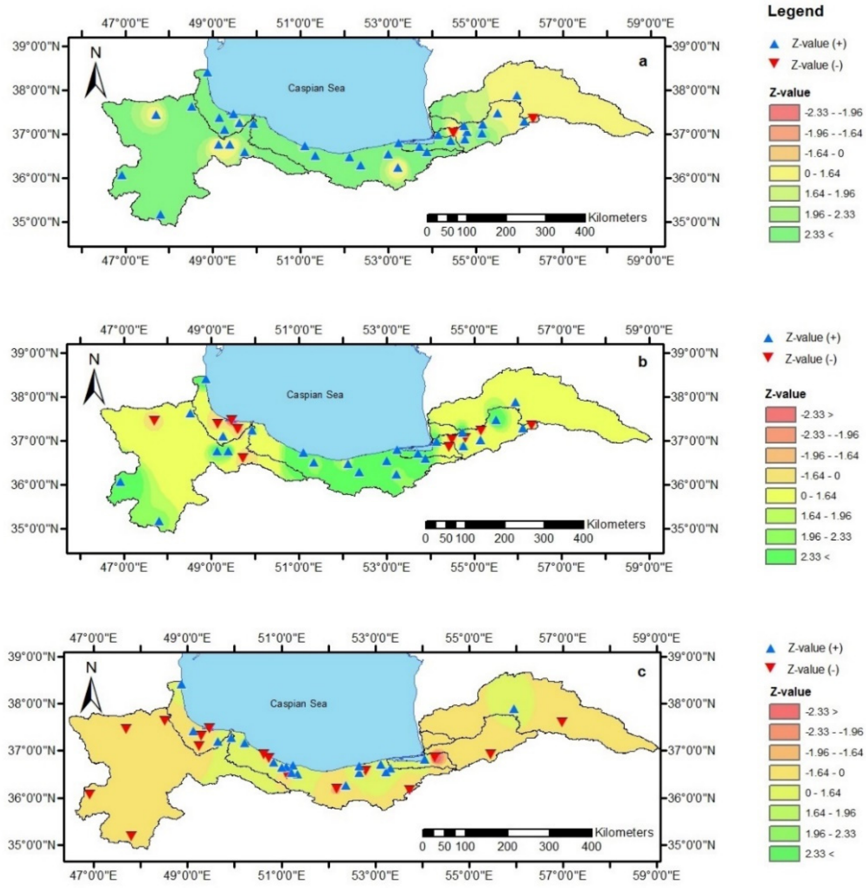

Fig. 7. Z-value and its spatial distribution obtained from MK3 for temperature (a), evapotranspiration (b), and precipitation (c).

An evaluation of the spatial/temporal changes in temperature across the region in Figure 7a shows an increase in almost all stations. In the central part of the study area, the increase was more significant and showed an increase in PET and precipitation. However, PET and precipitation declined in the southwest and southeast of the study site, although the precipitation trend was insignificant (Figures 7 b & c).

Both the modified Mann-Kendall method (Figure 8a) and the ITA method results indicated a decline in the annual mean flow in more than half of the gauges (28/40 and 23/40 gauges, respectively) (Table 2). As can be seen in Figure 8b, the annual mean flow has declined in 9 (of 11) rivers, after the significant abrupt change point that caused a decrease of inflow to the Caspian Sea by about 3580 MCM, annually. While the remaining two rivers have increased inflow to the sea by about 40 MCM, annually. The significant decline in AMF by about 88.9 m^3/s on average occurred at the Astaneh gauge in the Sefid-Rud River after the abrupt change in 1996 (Table 3).

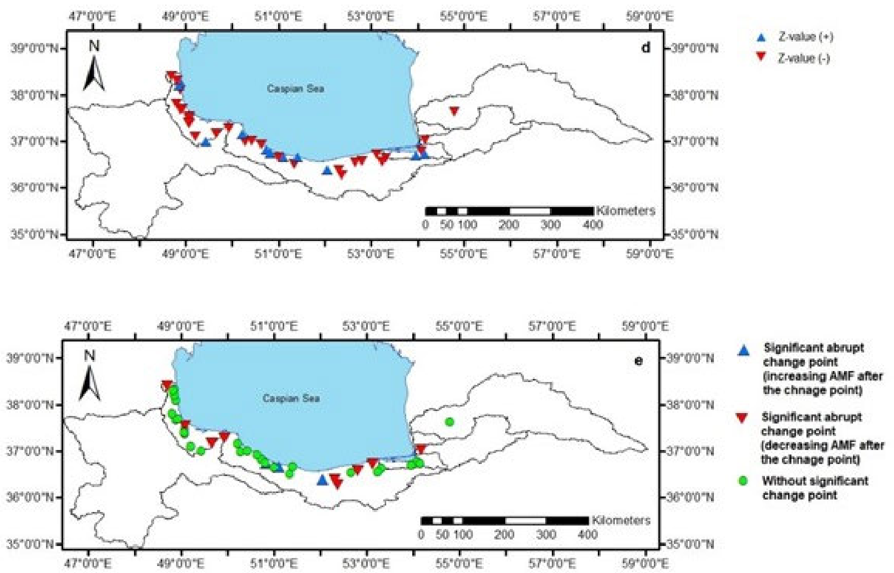

Fig. 8. (a) The Z-value of the annual mean flow at the gauges. (b) The gauges in which a significant abrupt change point has been found in the time series using the Pettitt test.

Table 2. Results of MK3& ITA methods analysis of annual flow .

River name (Guage name)	Trend (+ or -)	Z Value	ITA method
Atrak (Dashli borun)	Yes (-)	-0.15	Nonmonotonic (-)
Gorgan-Rud (Basir Abad)	Yes (-)	**-3.58****	Nonmonotonic (-)
Kordkuy (Pole Jadeh)	Yes (-)	-0.72	Nonmonotonic (-)
Baghoo (Baghoo)	Yes (+)	0.23	Nonmonotonic (+)
Gaz (Vatana)	Yes (+)	0.72	Nonmonotonic (+)
Neka-Rud (Abloo)	Yes (-)	**-1.85**	Nonmonotonic (-)
Darabkola (Darabkola)	Yes (-)	-0.26	Nonmonotonic (-)
Tajan (Kord Khail)	Yes (-)	**-2.23***	Nonmonotonic (-)
Talar (Kiakola)	Yes (-)	**-2.70****	Nonmonotonic (-)
Babol-Rud (Babol)	Yes (-)	-1.18	Nonmonotonic (+)
Haraz (Karehsang)	Yes (-)	**-2.45****	Nonmonotonic (-)
Lavij (Tangeh Lavij)	Yes (+)	1.16	Nonmonotonic (+)
Chaloos (Pole Zoghal)	Yes (-)	-0.01	Nonmonotonic (+)
Sardab-Rud (Sardab-Rud)	Yes (+)	1.11	Nonmonotonic (+)
Palang-ab-Rud (Kelar Abad)	Yes (-)	0.00	Nonmonotonic (+)
Kazem-Rud (Mashaallah Abad)	Yes (+)	**2.26***	Nonmonotonic (+)
Cheshmeh kileh (Haratbar)	Yes (+)	0.49	Nonmonotonic (-)
Chalek-Rud (Kangsar)	Yes (+)	0.15	Nonmonotonic (+)
Safa-Rud (Ramsar)	Yes (-)	-0.80	Nonmonotonic (-)
Pol-Rud (Derazlat)	Yes (-)	-0.93	Nonmonotonic (+)
Shalamn-Rud (Shalman)	Yes (+)	0.13	Nonmonotonic (+)
Azad-Rud (Dinar Sara)	Yes (-)	-0.23	Nonmonotonic (-)
Khoshk-Rud (Bajigooabr)	Yes (-)	-1.51	Nonmonotonic (-)
Alish-Rud (Oskoo Mahleh)	Yes (-)	**-2.10***	Nonmonotonic (+)
Tirom (Rezapet)	Yes (+)	**2.12***	Nonmonotonic (-)
Sefid-Rud (Astaneh)	Yes (-)	**-3.25****	Nonmonotonic (-)
Siah-Rud (Behdan)	Yes (-)	**-1.95**	Nonmonotonic (-)
Chaf-Rud (Roodbar Sara)	Yes (-)	-1.40	Nonmonotonic (-)
Shafa-Rud (Poonel)	Yes (-)	**-2.21***	Nonmonotonic (-)
Nav-Rud (Kharjegil)	Yes (-)	-1.36	Nonmonotonic (-)
Kargan-Rud (Mashin Khaneh)	Yes (-)	-1.10	Nonmonotonic (-)
Shirabad (Shir Abad Bala)	Yes (-)	-1.29	Nonmonotonic (+)
Choobar (Choobar)	Yes (+)	0.79	Nonmonotonic (+)
Landvil (Bash Mahaleh)	Yes (+)	0.68	Nonmonotonic (+)
Ghasht-Rud (Pirsara)	Yes (-)	-0.05	Nonmonotonic (-)
Khalkaee (Tasko)	Yes (-)	**-2.18***	Nonmonotonic (+)
Morghak (Emamzade Shafy)	Yes (-)	-0.71	Nonmonotonic (-)
Chelvand (Khan Hayati)	Yes (-)	-0.79	Nonmonotonic (+)
Khaleh sara (Kaleh sara)	Yes (-)	-0.30	Nonmonotonic (-)
Emamzade Ebrahim (Keshm)	Yes (+)	0.26	Nonmonotonic (-)
Baharestan (Baharestan)	Yes (-)	**-1.89**	Nonmonotonic (-)

To quantify the impact of anthropogenic activities and climate change on river flow regimes, elasticity-based methods and the Budyko hypothesis were used. The results of the elasticity-based methods in 10 of the 11 rivers indicate that anthropogenic activities played a dominant role in river flow alteration in the region, with only the Alish-Rud River being mostly impacted by climate change. The relative contribution of anthropogenic activities to river flow alteration ranges from about 45.1% (in the Alish-Rud River) to around 100% in four rivers. In contrast, the average relative contribution of climate change was about 8.3% (Table 3). Approximately 89.8% of the decline in inflow (equivalent to 3216 MCM per year) to the Caspian Sea is attributed to anthropogenic activities. About 10.2% is attributed to climate change (364 MCM per year).

Table 3. The relative contribution of human activities and climate change on runoff change in the rivers and the change point.

River name	Sub-basin	Changepoint	Discharge change (m^3/s)	Climate change (%)	Anthropogenic activities (%)
Gorgan-Rud	Gorgan-Rud	1995	-7.79	9.5	90.5
Tajan	Haraz-Neka	1988	-5.42	0.0	100
Talar	Haraz-Neka	1998	-3.10	0.0	100
Haraz	Haraz-Neka	1979	-5.73	4.9	95.1
Lavij	Lahijan-Noor	1987	0.26	0.0	100
Kazem-Rud	Lahijan-Noor	2001	0.98	0.0	100
Alish-Rud	Lahijan-Noor	1998	-0.28	54.9	45.1
Siah-Rud	Talesh	2003	-0.60	3.4	96.6
Shafa-Rud	Talesh	1994	-1.27	0.4	99.6
Baharestan	Talesh	2005	-0.45	9.7	90.3
Sefid-Rud	Sefid-Rud	1996	-88.86	8.9	91.1

Since 1962, dam construction in the SCS has been focused on meeting water demand, with a significant increase in the number of dams observed from 1993 to 2007, which correlated with an increase in change points in the rivers (Table 3). By 2007, 95 dams regulated about 4.5 km^3 annually, affecting Caspian Sea inflow, particularly in the early 21st century. Post-2007, newer dams were smaller and had no significant impact on river flow, as evidenced by the absence of abrupt change points (Table 3).

5.1.3 Vulnerability of the coastal lake area

Publication I simulated SWL using total inflow from rivers and net precipitation over the sea to assess the vulnerability of the Caspian Sea shoreline to hydrological and climatic changes. NDWI maps with a minimum annual water body in 1977 (355000 km^2) and maximum water body in 1995 (380000 km^2) were compared to determine the vulnerable areas of the sea over the past 80 years when satellite observations were available (Figure 9a). As a result, the area identified as being potentially vulnerable to level drop was estimated to be 25000 km^2. The study also identifies desiccated areas in different regions of the Caspian Sea and affected states, based on a combination of SWL-CVA regression and SWL simulation model.

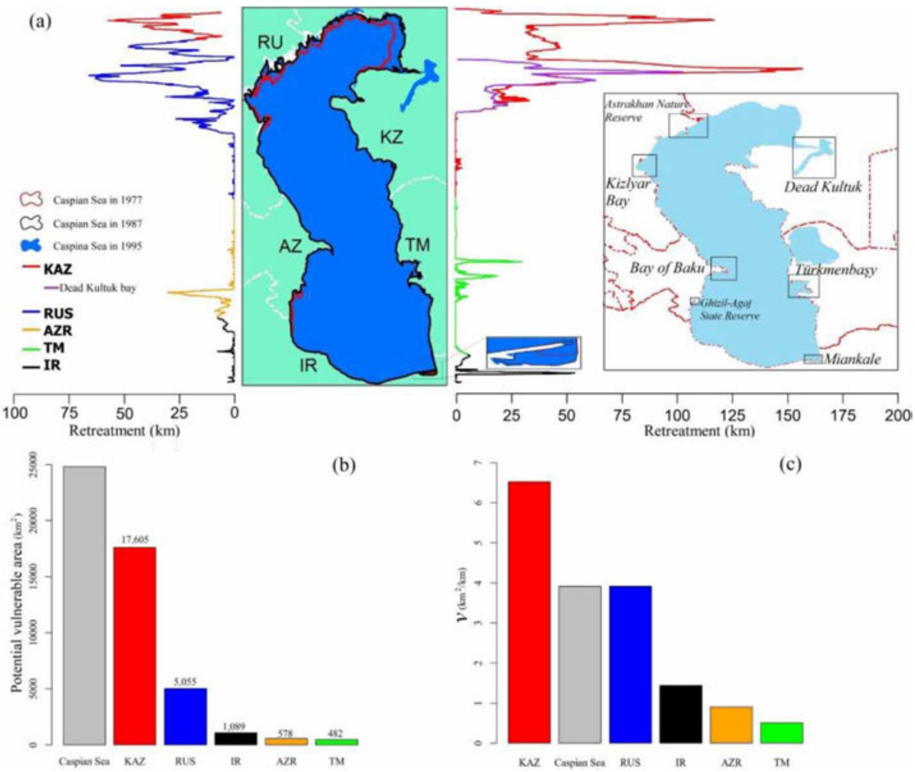

Fig. 9. Spatial vulnerability of coastal areas of the Caspian Sea to SWL fluctuation: (a) coastline retreat in the west and east of the Caspian Sea and maps showing the location of essential gulfs in the sea, (b) potential vulnerable area of the Caspian Sea and surrounding countries and c) vulnerability ratio for the Caspian Sea and all surrounding countries) (Adapted under CC BY 4.0 license from Publication I @ 2020 Authors).

The results showed that Kazakhstan will be affected the most by the desiccation of the Caspian Sea, as 70% of the potentially vulnerable area is located there (Figure 9b). The shallow northern Caspian including ecologically important bay Dead Kultuk, shown by the purple curve in Figure 9a, are the areas most vulnerable to fluctuation in SWL. Therefore, Kazakhstan and Russia will face severe issues of coastline retreat, as 90% of the potentially vulnerable area is on the northern Caspian coastline shared by these two states (Figure 9c). The socio-economic implications of the lake desiccation on the southern Caspian coast are even more significant due to the high population density in Iran and Azerbaijan (Modabberi et al., 2019). The calculation of SWL-CVA linear regression for 1977 to 2018 indicates that with a one-meter SWL rise, 7700 km^2 of the vulnerable area would be covered. The sensitivity analysis highlighted the importance of evaporation in the SWL simulation model, followed by total inflow and precipitation. Although the inflow relationship with the SWL simulation model is non-linear, it is essential as it interacts with other variables.

5.1.4 Climate change effect on the northern Caspian Sea

The background analysis of climatic changes in air temperatures during the cold season was conducted using data from 28 meteorological stations near the Caspian Sea. The earlier study by Panin et al. (2014) of seasonal variations of air temperature over 1946–2010 revealed that the significant variations took place in winter, as the relative variations of the temperature in winter are almost one and a half times greater than annual variations. The formation of the maximum ice thickness was mostly dependent on the sum of negative temperatures for the cold period (Bukharitsin, 1986). As shown in Figure 10, the sum of negative temperatures decreased at different intensities, by an average of -200 °C, mostly due to warming in March. According to the spatial distribution, the northeast and east parts of the study area showed the most significant change in average long-term temperatures in March (ΔT = 3–4 °C), followed by the northwest part and the south and southwest parts, with a 3 °C and lowest 2 °C increase, respectively. This decrease in temperature norms is associated with the features of atmospheric circulation over each area, with the western part being influenced by air masses from the Atlantic Ocean and the eastern part affected by Asian continental air masses. While wind is not the main factor in ice formation, it can influence the transfer of heat or cold in winter and affect the destruction or formation of ice cover. Analysis of wind characteristics from four meteorological stations revealed a decline in the maximum wind speed, while winds over 20 m/s are practically unobserved. Study of the wind recurrence showed a 1.5-fold increase in the frequency of southwestern winds, especially in November and March. Winds from the west and south increased, bringing warm air masses from the Black Sea and the southern part of the Caspian Sea. This led to a shift in the appearance of the first ice phenomena in November and a faster clearing of ice from the sea in March. Along with thermal conditions, winds, and SWL fluctuation are essential factors affecting the sea freeze-up scenarios of the NCS (Ivkina et al., 2017). With the projected desiccation of the NCS, ice conditions will be jeopardized regardless of the changes in the regional climate.

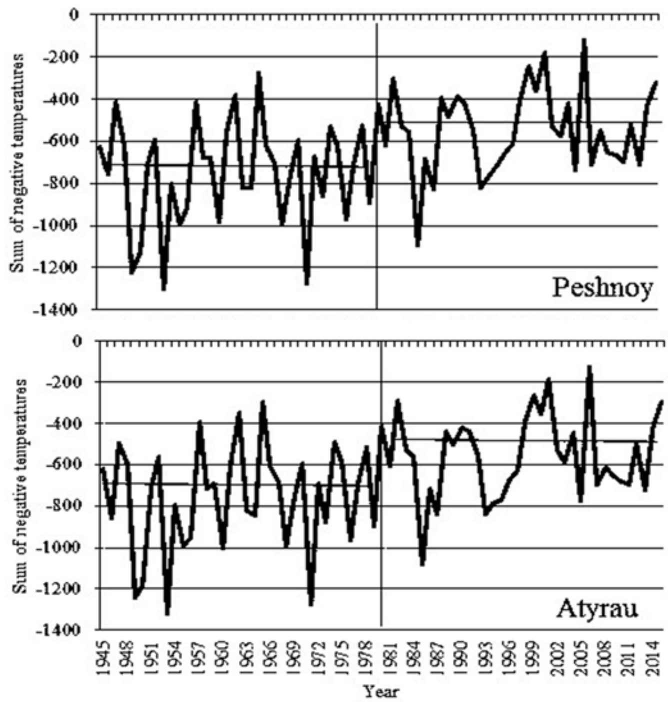

Fig. 10. Long-term time series of sums of negative temperatures for the winter period at Peshnoy and Atyrau meteorological stations (Adapted, with permission, from Publication V @ 2023 Informa UK Limited).

The recurrence of mild and moderate winters, according to the accepted classification of winters, is increasing, and there were no severe or very severe winters after 1971 (Figure 11). The ice period decreased in both sectors of the Caspian Sea, by 18 days on average in the north (Peshnoy station), and by 27 days in the middle of the Caspian Sea (Kulaly Island). It is worth noting that the frequency of winters without stable ice in the middle of the Caspian has increased from 28% to 48% of the total number of winters. As for the dates of the first ice appearance, they have shifted by four days at Peshnoy station and by 24 days at Kulaly Island, with the dates of the maximum ice thickness in the NCS shifting by 13 days to the beginning of the year.

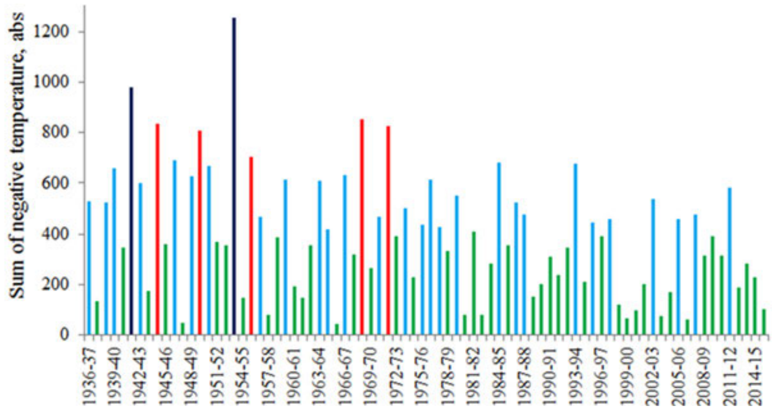

Fig. 11. Winter classes in Astrakhan station from 1936–2018 (dark purple - very severe, red - harsh, blue - moderate, green - mild winters (Adapted, with permission, from Publication V @ 2023 Informa UK Limited).

Remote sensing data for specific months of the cold season in the 2007–2019 period was used to calculate the dynamics of the changes in the ice cover for the NCS. Analysis of ice coverage variations over the last 13 years has shown a decrease in ice cover by about 30% in January and by almost 70% in March, when the sea's surface is already free of ice (Figure 12). With the absence of severe winters in recent years, stable ice has not been observed in the central part of the Caspian Sea; thus, the ice edge moved northward.

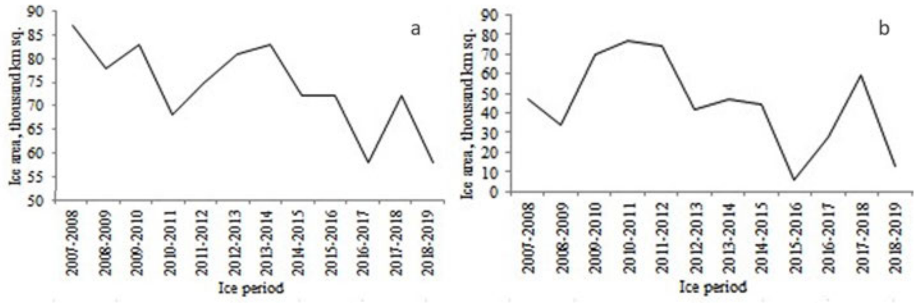

Fig. 12. Dynamics of ice coverage changes in a) January and b) March on the Caspian Sea for 2007–2019 (Adapted, with permission, from Publication V @ 2023 Informa UK Limited).

The thickest ice (80–120 cm) was observed in the NCS, where winters are cooler, followed by the western part of the Sea (60–80 cm) (Bukharitsin, 2011). It was observed that the long-term average in the maximum ice thickness had mostly decreased in the north-east by 20–28 cm, bringing it to 32–41 cm, while in the north-west of the northern Caspian the decrease was only 5–11 cm, which is lower than natural variability, and in the middle of the Caspian this was 13–17 cm, indicating an increase in the probability of the complete absence of ice in some years. Ice thickness in the middle of the Caspian has already reached critical values, with the years of ice-free winters becoming more frequent.

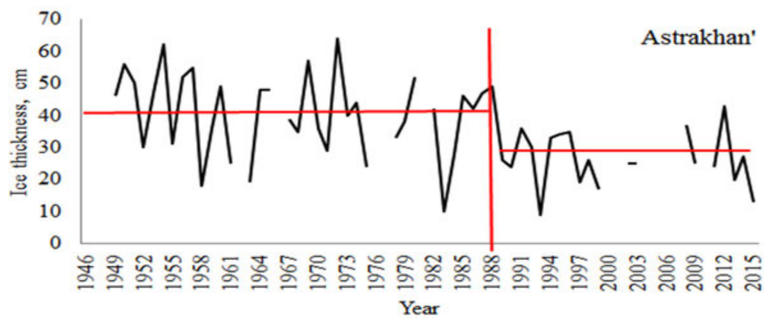

Fig. 13. Long-term time series of maximum ice thicknesses in the North Caspian Sea (Adapted, with permission, from Publication V @ 2023 Informa UK Limited).

5.2 Impact of hydrological and meteorological drivers on the coastal ecosystems

5.2.1 Spatio-temporal change in the Catchment-Estuary-Coastal system in the Mond River Basin

Generally, the impact of dam construction and the water intake for irrigation upstream is expected to have a cumulative effect along the river and thus have a more significant influence on the lower area of the basin (Ashraf et al., 2016; Fazel et al., 2017; Xu et al., 2021; Torabi Haghighi et al., 2021). There are many studies on the impact of large dams and river flow alteration on terminal lakes in Central Asia and the Middle East (Micklin, 2007; Crétaux et al., 2013; Torabi & Kløve, 2017; Nourani et al., 2019). Although, in the case of smaller dams, the impact is not that obvious and is highly dependent on the distances and the size of the catchment between the dam and the estuary, land use in the midbasin, and many other factors that should be analysed. Moreover, due to the unique geographic position between land and sea, estuarine wetlands, particularly those in arid regions, will be highly influenced by the SWL rise. Thus, the assessment of estuarine wetland dynamics should be performed taking the entirety of the CEC systems into consideration (Bamunawala et al., 2020, 2021).

Publication II focused on dam impact on the Mond River's downstream flow and the MPA. Therefore, all data for the IHA and RI analyses was divided into a pre-impact (before 2006) and post-impact (after 2006) period, based on the abrupt change year for the stations below the SF dam, the largest reservoir in the Mond, calculated using the Pettitt test (Figure 14). Assessment of the spatio-temporal change in the river flow using the IHA method showed moderate to high HA levels of monthly flow alterations across all studied gauging stations for the Mond River and its tributaries as the river regime changed from the pre-impact to post-impact period in all parts of the basin except the ephemeral Shoor Jahrom stream at Baba Arab, which experienced the lowest level of alteration (Figure 15).

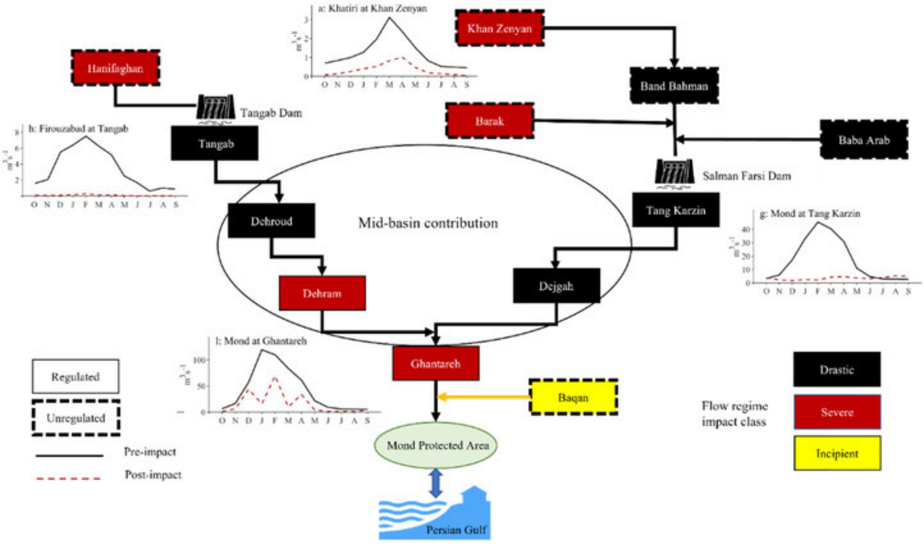

Fig. 14. River network of Mond River sub-basins with the examples of monthly flow for pre (1985–2005) and post-impact (2006–2015) periods from upstream, below dams, and downstream gauges and the results of the RI approach, showing "drastic" impact levels in black, "severe" impact levels in red and "incipient" impact levels in yellow (Adapted under CC BY 4.0 license from Publication II @ 2022 Authors).

The mean annual daily flow has reduced significantly by 72% in the post-impact period across four stations upstream from the main dams. However, we cannot solely attribute these changes to climate change. Evaluating natural variability, even on unregulated gauges, is challenging because most irrigated agricultural lands are located in this part of the basin, leading to overexploitation of groundwater and surface water. Nevertheless, the hydrological regime in upstream gauges still reflects the meteorological variability, as we observed high flow pulses, and small and large floods during the wet periods in 1994–1996 and 2004–2005, and an overall decrease in water flow after 2006 during the dry years. Also, a high flow rate in the upstream stations was observed during November–April, when more than 95% of precipitation falls.

The most remarkable changes were observed on the stations immediately downstream from the SF and Ta dams. The Ta dam has almost completely stopped the river flow (a 90% flow reduction), with an increased number of zero-flow days from 19.21 in the pre-impact period to 307.9 in the post-impact period. The operation of the SF dam in the Mond River causes homogenization of river dynamics, with minimum and maximum flow values being considerably reduced and the magnitude of high flow being decreased; however, river discharge during the growing period (July-October) increased. This is the opposite of the natural response of the river to the basin's climate pattern and confirms the main purpose of the SF dam being to store water during the wet season and release it in the dry season for agricultural needs.

There is a large midstream basin between the SF and Ta dams and MPA; therefore, we observed the recovery of the river flow on downstream stations as the IHA showed a similar extent of alteration for upstream, unregulated and downstream gauges. Low-flow events at two downstream gauges (Baqan and Ghantareh) showed significant alteration, reflecting the climate and land-use changes rather than the impact of river regulation, as the high-flow was unaffected.

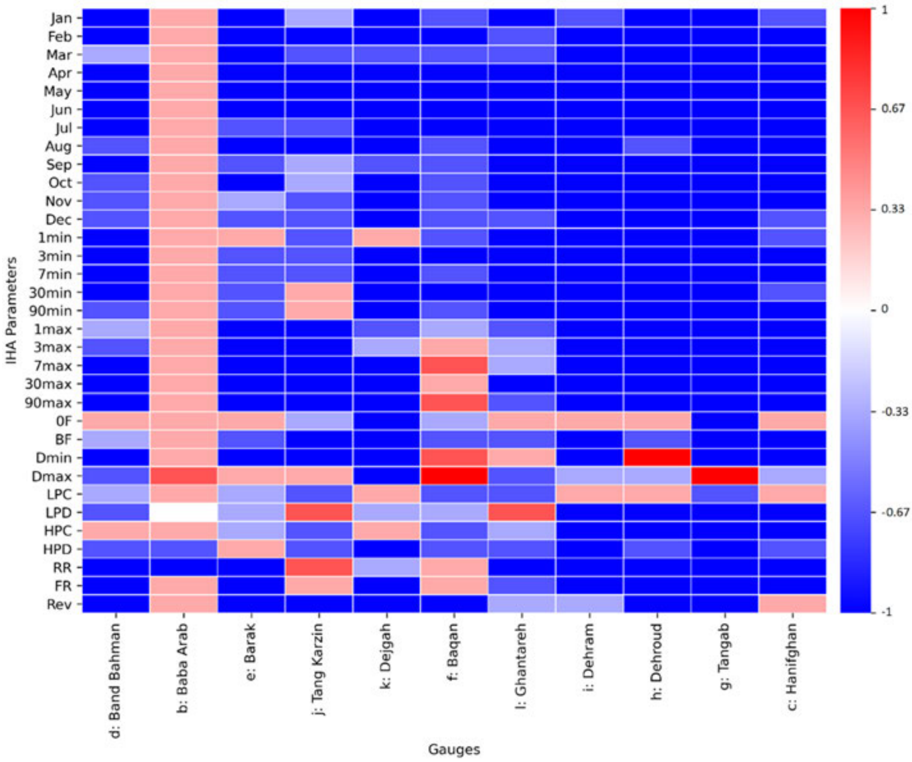

Fig. 15. Heat map of Indicators of hydrological alteration IHA for different Mond Sub-basins (Reprinted under CC BY 4.0 license from Publication II @ 2022 Authors).

The RI approach confirms the results of the IHA analysis showing the highest impact on the flow regime at the Tangab (RI index 0.02) and Tang Karzin (RI index 0.09) gauges located downstream of the Ta and SF Dams, with the two gauges below these stations (Dejgah and Dehroud) showing a 'drastic impact' level (Figure 16). This shows the effect of the dams and insufficient additional flow in the midstream between Tang Karzin, Dejgah, and Tangab and Dehroud. In contrast, the RI index at the most downstream gauge of the Mond River basin showed a moderated to severe impact level as the two most upstream gauges on the headwater. The lowest 'Incipient impact' impact level was observed at Baqan station on the Baqan River (RI=0.61), the last lowland tributary of the Mond River before it joins the Persian Gulf.

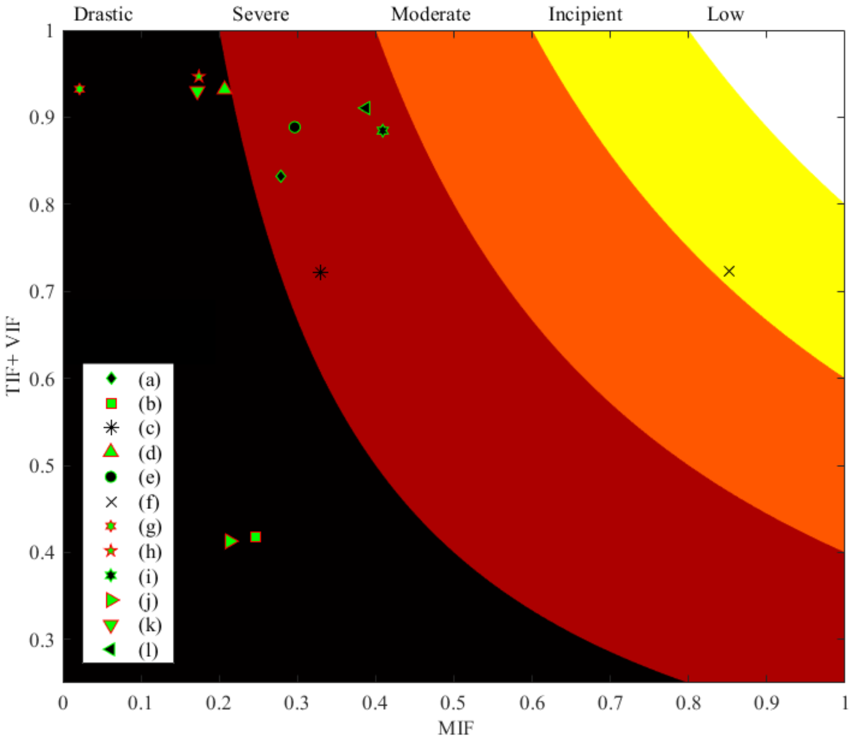

Fig. 16. Flow regime impact across the Mond basin a: Khan Zanyan, b: Band Bahman, c: Hanifghan, d: Baba Arab, e: Barak, f: Baqan, g: Tang Karzin, h: Tangab, i: Dehram, j: Dehroud, k: Dejgah and l: Ghantareh (Reprinted under CC BY 4.0 license from Publication II @ 2022 Authors).

5.2.2 *Hydrological regime of the rivers feeding Gabrik and Govatr mangroves*

The primary water source for mangrove forests in Iran is seawater, but freshwater supports two sites: Gabrik and Govatr. The Govatr mangrove site is situated in the BahooKalat River delta, and the Gabrik site is in the estuary of the Gabrik River (Danehkar, 2001). Both rivers have a similar seasonal flow regime with most of the flow (more than 68%) occurring in winter from January to April. There is high variability in river flow due to climate variability and change. The mean annual flow of the BahooKalat River is about 7 m^3s^{-1}, but this can range from 0.01 m^3s^{-1} (in 2015) to 59 m^3s^{-1} (in 1998) (Figure 17). In Publication IV, the IHA analysis confirmed the unstable hydrological conditions in the region. The persistent hydrological inconsistency in the river could be seen in the minimum flow recorded for 7, 30, and 90 consecutive days and the occurrence of zero flow days, indicating flow discontinuity.

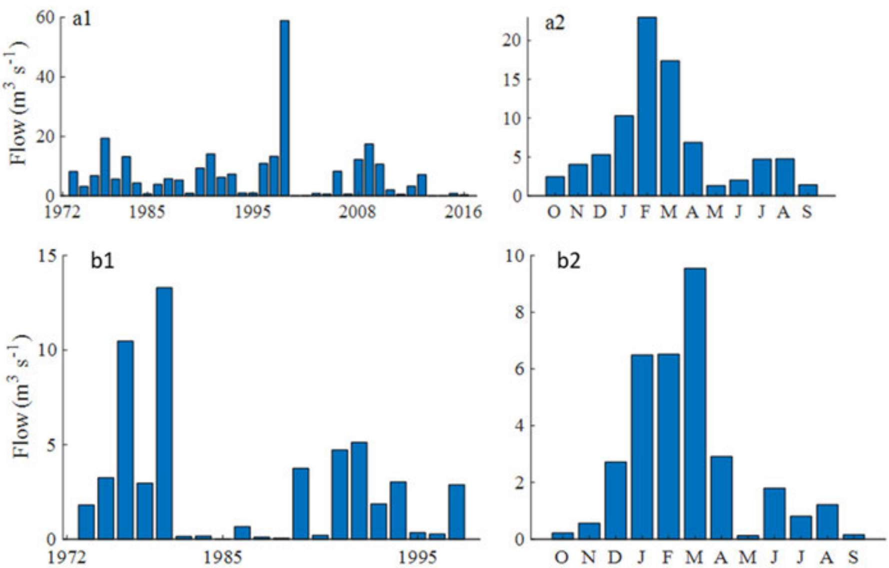

Fig. 17. Mean annual (1) and monthly (2) flow at BahooKalat (a) and at Gabrik-Lireaee (b).

5.2.3 Monitoring of coastal ecosystem change and health

NDVI was used to analyze vegetation cover changes in the protected area at the end of the Mond River basin in Publication II and as a health index for four mangrove forest sites on the Persian Gulf and Gulf of Oman coast in Publication IV. The annual NDVI values from Landsat and MODIS products were compared and found to demonstrate a significant correlation (0.74). Due to the high temporal frequency and connectivity of MODIS products, the latter was chosen for further analysis. Gabrik and Qeshm sites showed higher NDVI, indicating denser and healthier vegetation than the Nayband and Govatr mangroves. Among the two rivers-fed sites, Gabrik showed an almost double increase in the NDVI. In contrast, Govatr showed a considerably slower increase from the initially lower NDVI than the previous site (Figure 18).

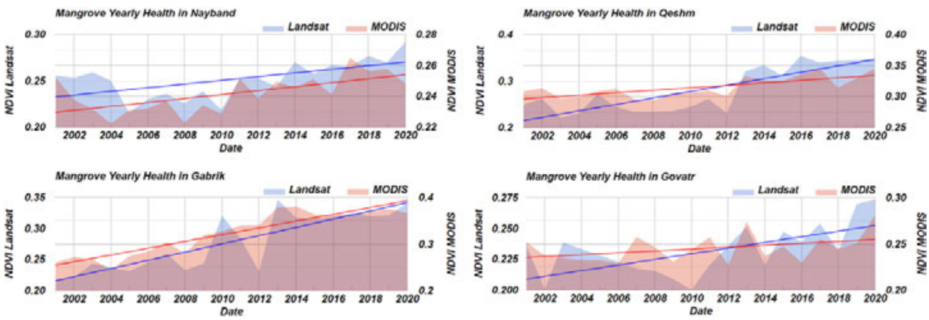

Fig. 18. Annual variation of NDVI, based on the Landsat and MODIS data.

A correlation analysis between the NDVI and the climatic variables showed a strong and significant negative correlation with Land Surface Temperature (LST) and a positive correlation with precipitation. Both sea-side and estuarine sites showed that the NDVI was highest when the precipitation was high. There was no strong correlation between precipitation and NDVI (around 0.29), or salinity and NDVI (around 0.15). However, the long-term monthly analysis showed a decreasing trend in salinity with an increase in precipitation and NDVI, indicating the negative impact of increased salinity on the mangroves' health.

In Publication II, changes in monthly NDVI in the estuary of the Mond River were calculated using Landsat satellite images for 1990–2020. NDVI values were found to be close to or less than zero, meaning the majority of the Mond protected area is covered by a negative NDVI value – water. Also, the temporal analysis of NDVI values in the protected area zone showed a shift after 2006 to more negative values because of sea-level rise; this has been discussed in the literature (Etemadi et al. 2020). The river buffer zone has a higher NDVI than the west and east of the Mond River because of the concentration of farmlands.

5.2.4 Environmental flow assessment for the mangrove forests

In Publication IV, we assess the potential effects of various abiotic factors on the mangrove health at Govatr and Gabrik sites by classifying NDVI time series into five groups (G1 to G5) and comparing them to associated rainfall, temperature, and river flow for the same months, with a 1, 2, 3, 6, and 12-month delay (Figure 19). This assessment revealed that the high temperature group correlated with low NDVI, meaning that decreasing the temperature of the current and previous months increases the magnitude of NDVI (from G1 to G5). So, the mangrove's health was mostly dependent on the temperature of the current month or that of the preceding 1-3 months and precipitation in the preceding month.

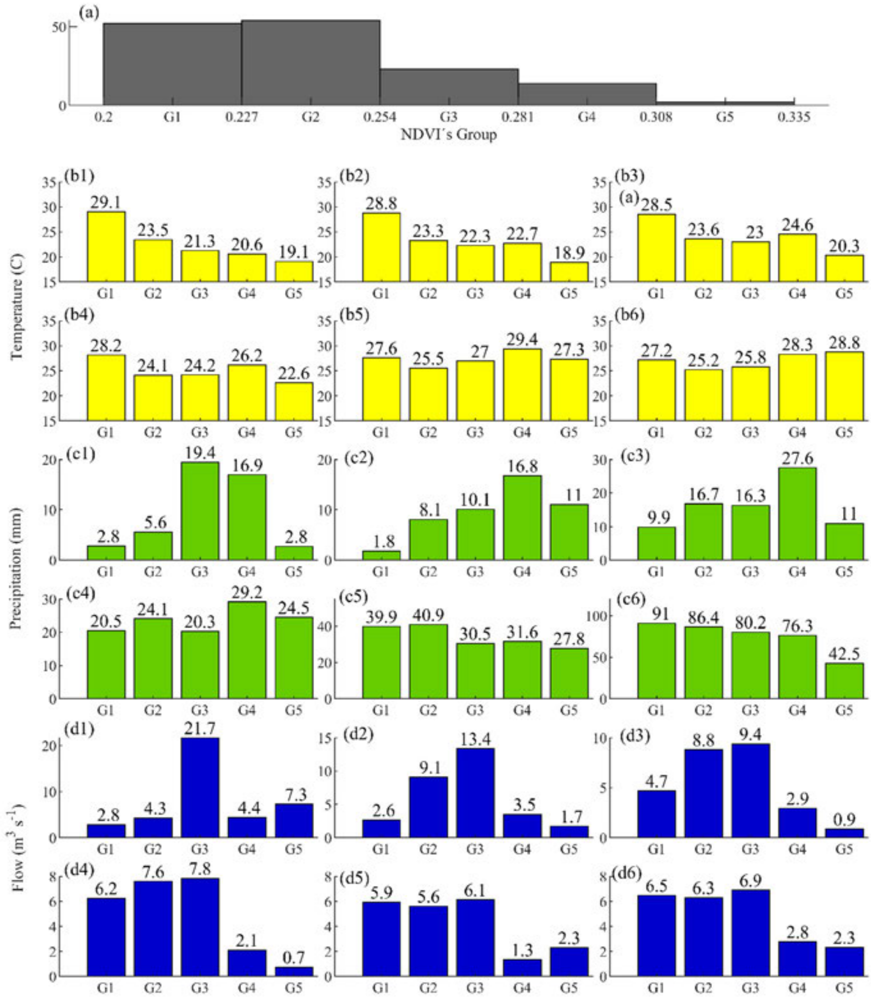

Fig. 19. The different temporal scales (1–12 months) of mean temperature (b1–6), accumulated rainfall (c1–6), and mean flow (d1–6) in Pirsohrab stations in different groups (a) of observed NDVI in the mangrove forest near Govatr. 1 indicates the same months, 2–6, for the last 1, 2, 3, 6, and 12 months.

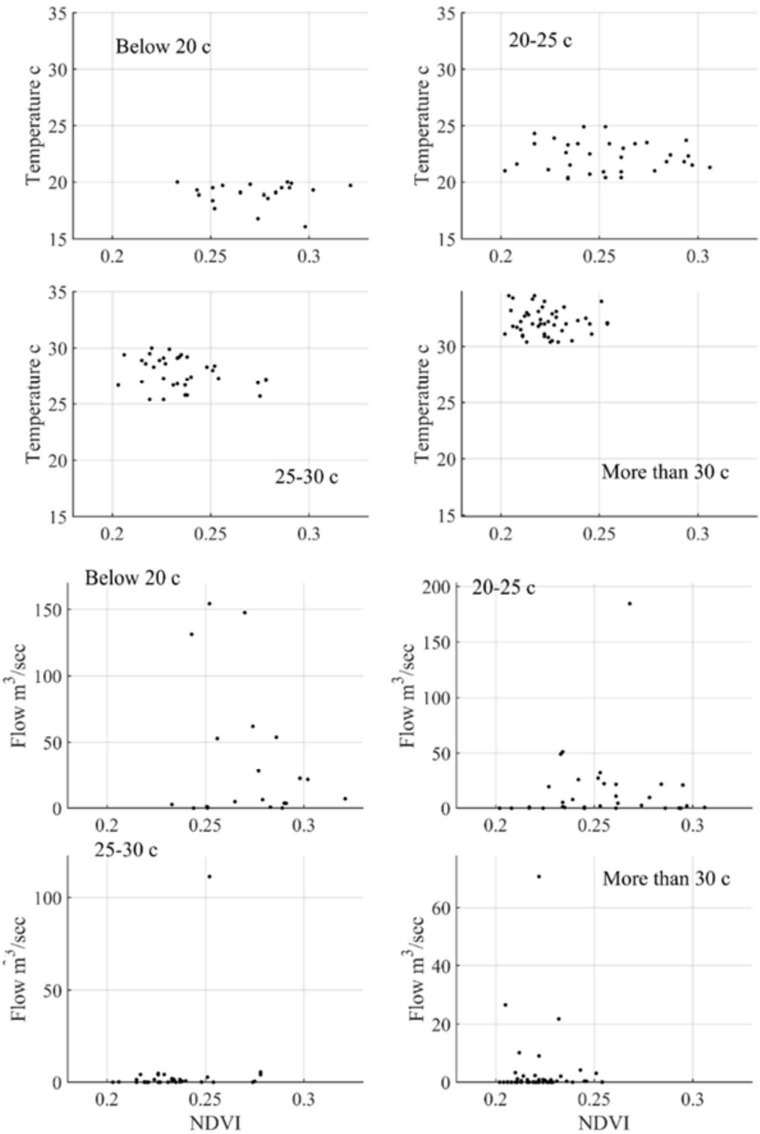

Fig. 20. Variations of NDVI value vs. a) temperature and b) flow in different temperature groups in Govatr.

To propose the best time for Environmental Flow allocation, the temperature variation has been categorized into four groups: below 20 °C, 20–25 °C, 25–30 °C, and over 30 °C. Only the first two groups (I and II) show a change in NDVI value with variations in river flow (Figure 20). The recommended months for releasing environmental flow are shown in Figure 21 and are indicated by different colors: green - highly recommended, blue - recommended, yellow - less recommended, and red - not recommended. Therefore, the EF released can be recommended during months related to these groups, from December to March for Govatr and November to March for Gabrik. As, naturally, the flow in the studied rivers is irregular, the altered hydrological conditions cannot be considered as potential adverse effects on the functioning and health of the mangrove ecosystem. However, in cases of EF release, we recommend potential evapotranspiration as the minimum EF.

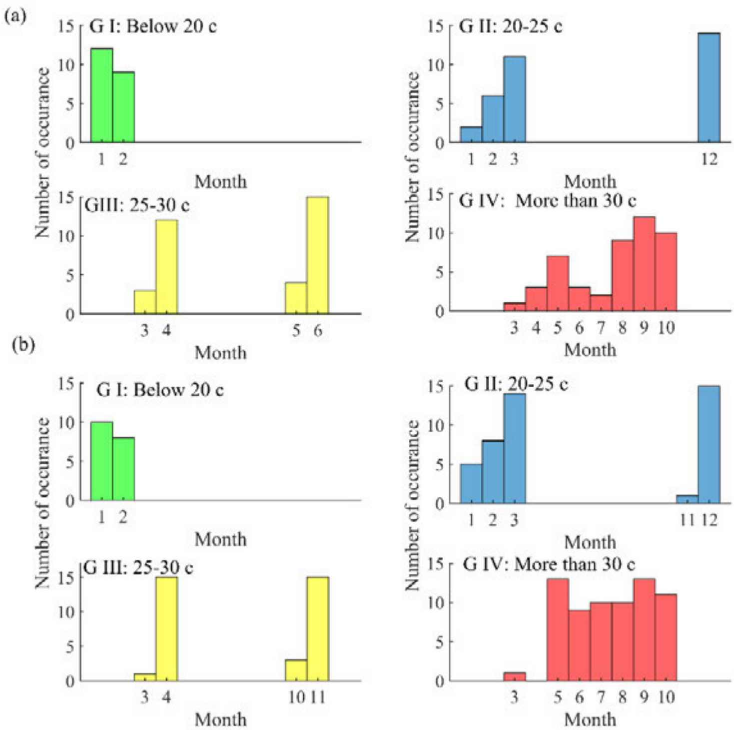

Fig. 21. Frequency of occurrence of different temperature groups in a) Govatr and b) Gabrik (numbers from 1 to 12 represent the months of the year).

6 Discussion

6.1 River flow alteration and climate change impact on the Caspian Sea

Climate change and human activities cause a decrease in the lake water level and inflow volume, leading to drastic changes in the lake area in the arid and semi-arid regions and at the end of rivers (Milly et al., 2005; Milano et al., 2015; Wang et al., 2021). Therefore, quantitative analysis and the degree of the relative influence of climate change and anthropogenic activities on the change in lake inflow is a problem that is gaining increasing attention (Gao et al., 2016; Wang et al., 2021). In recent years, many scholars have begun to analyze and explore the driving factors for the decreased water level and runoff in terminal lakes around the world, including Lake Daihai (Wang et al., 2021), Lake Urmia (Schulz et al., 2020), the Hamun Lake (Akbari et al., 2022), California’s Salton Sea (Barnum et al., 2017), the Aral Sea (Cretaux et al., 2013), and Lake Chad (Pham-Duc et al., 2020). The quantitative calculation of the driving factors affecting the inland lake water balance has always been a challenge in lake research; a low number of hydrometeorological gauge stations and the difficulty of obtaining data consistently and accurately from some regions further complicates the research, sometimes leading to misleading conclusions.

Several contentious studies have attempted to ascertain the primary driver behind the water level changes in the Caspian Sea, the world's largest landlocked water body: climate change or river flow modification (Prange et al., 2002; Wang et al., 2018; Akbari et al., 2020; Lahijani et al., 2023). The Caspian Sea is a vital geopolitical and environmental resource, providing a habitat for endemic and endangered species (Publication V). However, anthropogenic activities such as agriculture, industry, and urbanization have contributed to environmental degradation and water quality issues (Publication III). The sea level has experienced significant fluctuations, decreasing due to reduced inflow and increased evaporation (Publications I and III). Climate change projections suggest further sea level decline, which could exacerbate eutrophication and lead to socioeconomic and ecological challenges (Publication I).

The Caspian Sea level varied between -25.5 m in 1837 and -29 m in 1977, driven by hydroclimatic and geological processes. After a short-term increase up to -26.6 m in 1995, a new drop in the level began (Crétaux et al., 2011; Panin et al., 2014; Koriche et al., 2022). The Caspian Sea has experienced 100 times faster changes in SWL in comparison to the global average, with a substantial decline by about 2 m and a 15,000 km2 surface area loss since 1940 (Crétaux et al., 2011; Arpe et al., 2014). According to new projections, the Caspian Sea level may fall by 9–18 m in medium to high emission scenarios until the end of the 21st century (Nandini-Weiss et al., 2019; Prange et al., 2020). Many studies suggest that present-day SWL is mainly controlled by inflow from more than a hundred rivers, specifically the Volga River, which contributes more than 80% of the total inflow (Wang et al., 2018; Koriche et al., 2022; Yao et al., 2023)

The surface water inflow of more than 130 rivers in the Caspian Sea is distributed irregularly (Figure 6). The vast contribution of the Volga and Ural (also known as the Jaiyk River) discharge into the shallow Northern Caspian. About 10% comes from the rivers of the western coast, the Kura, Samur, Sulak, Terek, and the remaining 5% of the inflow goes to the southern Caspian from the rivers of the Iranian coast, mostly the Sefidrud. In contrast, on the eastern coast of the sea, there are no perennial rivers (Leroy et al., 2022). The total inflow into the Caspian Sea from 1880 to 2020 varied considerably (Figure 2). During the period from 1880 to 1930, there were considerable year-to-year variations in the inflow (Panin et al., 2014), but during the period from 1930 to 1980, there was a significant decline in the discharge to the Caspian Sea. These large changes occurred in the latter period of the Soviet era as a consequence of the engineering dominance of humans over nature, with dam construction on major rivers reaching the peak, 12 great water reservoirs and hydropower plants at the Volga-Kama cascade; Verkhneuralsk, Magnitogorsk, and Iriklinskoe reservoirs in the upper part of the Ural River; the commissioning of the Mingechaurskoe Reservoir on the Kura River in 1953; and the Sefidrud Dam in Iran in 1962 (Mikhailov et al., 2003; Hajiabadi & Zarghami, 2014; Sivokhip et al., 2017; Smith, 1984). Only two dams out of the eight found on the Volga River are equipped with fish passages, creating a burden for the critically endangered Caspian sturgeons, which produce the famous beluga caviar (Khodorevskaya et al., 2009). Although in terms of hydrology, the anthropogenic impact in the Caspian Sea was a total inflow decline, the rapidly warming climate in the region exacerbated these changes, which led to substantial changes in SWL and surface area (Publication I).

The fall in the Caspian SWL highly altered the shallow part of the sea, transforming the north-east coastal area, particularly the Dead Kultuk bay, from a permanent to a seasonal water body (Pekel et al., 2016). Although Kazakhstan is facing the highest extent of coastal area degradation, with 70% of the potentially vulnerable area located here, all other states will also be affected, as the drying bays in Russia, Azerbaijan, Turkmenistan, and Iran have high economic, social and ecological value (Publication I). The insurmountable pressure faced will be aggravated by the oil and gas industry, which is expected to develop more and more offshore production fields. In terms of impacted population, Azerbaijan and Iran are the most vulnerable, as due to favourable climate, the southern coast of the Caspian Sea is densely populated. Furthermore, recent ecological challenges in the capital region of Iran have triggered migration to the SCS region (Publication III). Farzanegan et al. (2023) examined the impact of air pollution on the domestic net outmigration ratio in Iran and suggest that higher levels of air pollution within provinces significantly increase the levels of net outmigration from the affected provinces. One of the ecologically important bays, Turkmenbasy, may experience the shoreline retreat of around 25 km. This bay, along with Miankale, Kizlyar and the above mentioned Dead Kultuk, are parts of nature reserves that are important stopover sites on one of the largest migratory routes for birds in Eurasia (UNESCO, 2017).

Although, in terms of hydrology, the anthropogenic impact was lately prevailing in the Caspian Sea, the direct effect of climate change can be seen in changes in the ice regime. The most significant increase in long-term average temperatures occurred in the winter months in the northeast and east parts of the Caspian Sea, reaching 3–4°C (Publication V). Accordingly, during the ice season, the sum of negative temperatures decreased by 30–50% in different parts of the Caspian Sea (Figure 10). The maximum ice thickness throughout the northern Caspian Sea has decreased, with the most significant decrease recorded in the northeast and the smallest in the northwest. The ice period has also reduced in the northeast and central parts. This reduction in ice coverage leads to the absence of stable ice throughout the winter, as confirmed by remote sensing data over the past 13 years.

The lack of stable ice can have severe consequences, particularly for seal pups. The seal is a flag species in the Caspian Sea, as it is its only marine mammal. Mild winters, resulting from climate change and reduced ice cover, pose a significant threat to the survival of these vulnerable young seals, forcing nursing seal pups into the water prematurely, before they have completed their lactation period. As a result, these young seals are unlikely to survive infections, as their immune system is not fully developed. This disruption in their natural life cycle can have a detrimental impact on the overall population.

6.2 Vulnerability of the Persian Gulf coastal ecosystems

Estuaries are dynamic transition zones where a river meets the sea forming one of the most productive ecosystems worldwide (Costanza et al., 1997; Day et al., 2012). Constant interactions between the sea and the mainland influence the estuarine wetland community's health and expansion. Over recent decades, more than 70% of riparian wetlands in the world have gradually been changed into other land use types (Zheng et al., 2019). However, these valuable ecosystems face a range of threats, including land-use change, deforestation, coastal pollution, invasive species, and the impacts of climate change, such as sea level rise and increasing temperatures (Sharifinia et al., 2019). Increased temperatures would also increase evaporation rates, increasing salinity stress (Clough, 2013). According to Blankespoor et al. (2014), sea level rise might result in the loss of 96% of coastal wetlands in the Middle East, including mangroves. Furthermore, the recovery rate of coastal communities such as mangroves is slow, and there is the risk of irreversible damage (Nairizi, 2017).

Iranian mangroves are ecologically and economically valuable, providing habitats for marine species, supporting local livelihoods through fisheries and ecotourism, and acting as effective nature-based solutions for coastal protection and climate change mitigation (Duarte & Cebrian, 1996; Alongi, 2008; Ghasemi et al., 2010; Barbier et al., 2011; Menéndez et al., 2020; Pennings et al., 2021). Mangroves store up to four times more carbon per unit area than tropical upland forests, and estuarine sites contain more carbon than oceanic sites (Kristensen et al., 2008; Donato et al., 2011; Alongi, 2012, 2014). Being the most productive woody ecosystem within arid regions, estuarine mangroves provide essential resources for local communities, including fuel, construction materials, and food, as well as supporting biodiversity and minimizing the rate of coastal erosion (Alongi, 2002; Vo et al., 2012; McIvor et al., 2012; Duarte et al., 2013; Duke et al., 2014; Costanza et al., 2021; Adame et al., 2021). They also support important commercial and subsistence fisheries (Faunce & Serafy, 2006; Igulu et al., 2014). These multiple valuable ecosystem services, as well as their great potential for climate change mitigation and adaptation, make mangrove preservation and restoration a crucial global challenge (Ball et al., 1988; Thura et al., 2023).

Because mangroves in dry climates depend on either a single or a small number of foundation species, the health and expansion of these biodiversity hot spots rapidly respond to the fluctuations in environmental variables caused by climate change or anthropogenic activities (Adame et al., 2021; Pouladi et al., 2017).

Mangroves in arid climates are generally tide-dominated as marine input prevails over the terrestrial runoff (Adame et al., 2021). Thus, climate change and sea-level rise are threatening many mangrove forests (Giri, 2021; Lovelock et al., 2015). The extent of mangrove degradation in arid zones is higher than deforestation; yet, this has not been adequately studied worldwide. Thus, in the long term, rapid sea-level rise as a climate-change consequence might be the most crucial thread to estuarine wetlands' spatial patterns and community structure (Gilman et al., 2006, Etemadi et al., 2021). Furthermore, some areas of Iranian mangroves are experiencing declining freshwater input in addition to the abovementioned challenges (Mafi-Gholami et al., 2015).

6.3 Environmental flow assessment for mangrove forest restoration

The UN Decade on Ecosystem Restoration (2021–2030) calls for extensive ecosystem restoration actions to prevent, halt, and reverse the degradation of ecosystems, which will help to achieve multiple global goals, including SDGs, the Paris Agreement, and the Post-2020 Global Biodiversity Framework (UNEP, 2021; Su et al., 2022). One of the world’s most ambitious ecosystem restoration efforts, the 10 Billion Tree Tsunami program, was initiated to expand and restore Pakistan’s mangroves and forests (Government of Pakistan, 2023). The rapid mangrove loss and fragmentation observed in past decades, and the coastal protection services that mangroves may provide during normal tidal conditions and extreme events, increased funding and focus for mangrove restoration actions. Unfortunately, nearly half of these efforts fail or underperform due to a lack of attention on the restoration site's short- and long-term physical setting (Spalding et al., 2014; Balke & Friess, 2016).

Damming and regulation of rivers cause direct or indirect impacts on river systems by altering the temporal patterns of water flow and restructuring natural habitats such as terminal lakes and wetlands (Sternberg, 2006). To ensure suitable environmental flow regimes and to overcome the management mismatch between energy, food, and ecosystem in regions with high seasonal agricultural demand, more knowledge is needed to develop an optimum environmental flow release strategy. More than 162 hydrological methods have been proposed for calculating EF, although these methods don’t have enough acceptability to be used in practical cases (Torabi Haghighi et al., 2010). Most hydrological processes lack some crucial information, such as basin physiography, climate, location of hydraulic structures, annual and monthly river flow regime, and purpose of hydraulic systems into consideration flows (Arthington et al., 2006). In many cases, decision-makers allocate EF based on an annual amount without considering the flow regime or using the two six-month release periods formulated by Tennant (1976), which also failed to show high efficiency (Acreman et al., 2014; Torabi Haghighi & Kløve, 2017).

Successful ecological mangrove forest rehabilitation requires careful analyses of the existing watershed needs and the changes to the coastal plain hydrology that may have impacted the mangroves (Wolanski et al., 2009; Lewis et al., 2019). In this regard, the first step for restoration activity includes examining the standard hydrologic patterns that control the distribution and successful establishment and growth of targeted mangrove species. Based on this, the establishment of environmental water rights and the allocation of part of the river flow for the needs of mangroves can be initiated (Lewis, 2005). Changes in hydrological conditions can result in two types of impact: Both direct effects on the state and the composition of habitats and indirect effects on the distribution of living organisms, and broader ecosystem-level consequences. Different species possess varying abilities to adapt to hydrological alteration, linked to the vulnerability of that species and associated habitats, irrespective of whether those changes are caused by climate change or human activities (van de Pol et al., 2010). Therefore, to satisfy both needs in the protection of natural ecosystems and human water needs, we propose designing the environmental flow release for intermittent rivers to support mangroves in arid regions that mimics the natural flow regime.

Similarly to the finding of Martínez-Díaz & Reef (2023), our study reveals that the mangrove's health mainly depends on temperature, while precipitation does not seem to have a direct effect on it. Our findings agree with previous studies that extreme temperatures determine the presence of mangroves (Cavanaugh et al., 2014, 2018). As Harris et al. (2017) reported the major dieback of the Gulf of Carpentaria mangrove near the end of 2015 caused by the coincidence of unusually hot and dry conditions with low sea levels, providing a cumulative stressful environment for the mangroves during most of 2015. Thus, multi-month extreme sea level anomalies and high evaporative stress associated with the maximum daily temperatures exceeding 40 °C may play an important role in overall mangrove health and causes severe stress for mangroves (Chung et al., 2023). Values above the mean annual temperatures of ~23 °C corresponded to a marked reduction in mangrove presence, and no mangroves are present above 37 °C (Martínez-Díaz & Reef, 2023). The physiological limits of mangroves prevent them from effectively photosynthesizing when surface temperatures exceed a ~35 °C threshold (Zheng & Takeuchi, 2022). Furthermore, previous studies showed that A. marina, while being a highly salt-tolerant species, has been shown to favour freshwater and is not found more than 8 km away from the river channel network in most regions of Australia, while an increase in freshwater availability can initiate gradual advance beyond usual limits (Eslami-Andargoli et al., 2009; Reef et al., 2015; Martínez-Díaz & Reef, 2023). Therefore, the proposed allocation of environmental flow during extreme and prolonged draughts can prevent the dieback of mangrove forests and, during normal and wet years, can lead to mangrove expansion.

6.4 Data uncertainty

There is always uncertainty in in-situ measurements; therefore, the accuracy of discharge and meteorological data provided by local hydro-meteorological agencies can be questioned. Also, as the study sites are in developing countries, there is a critical need for modernization efforts for hydro-meteorological services. There are gaps in the ice conditions-related data due to harsh weather conditions. Due to the inconsistency of data and shorter stream gauge record length, there may be uncertainties in implementing some approaches. For the IHA assessment, 20 years is considered a reasonable baseline requirement, as a shorter period can lead to skewed results due to climate variability and a few hydrologically extreme years. We omitted groundwater flow in Publications I and III because it is reported to be a minor part of the Caspian water balance, so this can be considered a source of uncertainty. Also, for more accurate environmental flow assessment in mangrove forests in Iran, future studies should include groundwater analysis.

The uncertainty in remote sensing data due to the possible errors caused by atmospheric particles, gases, clouds, topography, and other limitations imposed by satellite resolution has been widely discussed (Karimi & Bastiaanssen, 2015). Therefore, we used pre-processed products with applied atmospheric corrections. We also had to compromise between the spatial resolution and continuity of the time series, as Landsat data was available for extended periods. Still, we had coarse spatial details and bigger frequency intervals. In contrast, MODIS data products were more accurate in this sense but were only available from 2020.

7 Conclusion

Water levels in inland seas and lakes globally are likely to drop dramatically in the 21st century in response to climate change. Climate change directly affects lake-level variations through open-water evaporation and precipitation, and indirectly through river runoff changes caused by increased or decreased precipitation over the whole basin. Furthermore, river regulation has significantly changed the natural flow regime, reducing the inflow into many terminal lakes, such as the endorheic Caspian Sea. This sea has experienced substantial changes in SWL and surface area since 1940 with the construction of VKC on the Volga River. Today, a significant proportion of the northeast coastal area has changed from a permanent to a seasonal water body, affecting important marginal gulfs. The main novelty of this study was in the development of a framework for quantifying the influence of changes in water balance parameters in the Caspian Sea on the desiccation of those parts of the sea that are potentially vulnerable to SWL decline.

Quantifying the proportions of anthropogenic and climate change impacts on river flow alteration is crucial for addressing lake desiccation and making science-based recommendations for transboundary river management. Understanding the relative contributions of anthropogenic and climate change implications allows policymakers to implement targeted interventions, such as regulating water abstraction and negotiating river flow allocation for human and ecological needs in transboundary river systems. A developed framework combining statistical analysis, and modeling using in-situ and remote sensing data indicated the overall impact of anthropogenic activities (accounting for 91.7%) in river flow alteration, leading to about 3246 MCM decline in the annual inflow to the Caspian Sea. Decreasing inflow into the Caspian Sea can accelerate the lake's shrinking and alter socioeconomic and ecological conditions in the coastal areas.

The analysis of climatic changes in air temperatures indicates that the Caspian Sea is experiencing a more rapid warming trend than ice-free lakes. Furthermore, these changes predominantly occur during the cold season, highlighting the significance of understanding the changes in the ice regime. This study stands as the most comprehensive assessment conducted to date, examining the factors that drive long-term changes in the ice regime of the northern Caspian Sea. The study offers a solid understanding of the underlying drivers behind the observed alterations in ice characteristics by utilizing satellite and land observations. These insights hold significant implications for policy development and practical considerations, aiding in the formulation of strategies and measures to address the impacts of these changes on biodiversity, shipping, infrastructure development, and resource extraction in the region. The presence of solid ice in the Caspian Sea plays a crucial role in maintaining the ecological conditions necessary for the survival of the Caspian seal population. The Caspian seal is an endemic and critically important species in the region, playing a significant role in the Caspian Sea ecosystem. Its presence helps maintain the balance of the food web and contributes to the overall biodiversity of the area.

In contrast, climate change and the associated rise in sea levels significantly impact estuarine ecosystems in arid regions, such as the northern coast of the Persian Gulf and the Gulf of Oman. These ecosystems, characterized by irregular flow patterns of intermittent or seasonal rivers reliant on precipitation, exhibit heightened vulnerability to changes in hydrological regimes, changes which are mostly the result of climate change and less likely from human activities upstream. The rising sea levels exacerbate the situation by increasing saltwater intrusion into the estuaries and inundating coastal areas. Additionally, changes in precipitation patterns and temperature regimes can disrupt the delicate balance of these ecosystems, affecting the mangrove’s health and diminishing overall ecosystem productivity.

The high complexity and interplay within the catchment-estuary-coastal system emphasizes the necessity of a basin-level perspective and the integration of the entire hydrological continuum, including upstream river regulation, land use changes, and coastal studies. This comprehensive approach allows for a thorough understanding of the system dynamics and enables implementation of effective management and conservation strategies. Considering the interconnection between temperature, precipitation, flow, and salinity, we could address the cumulative impacts and interdependencies of these components on mangrove health. This approach enables policymakers to develop optimal environmental flow strategies for the preservation of vulnerable mangroves through an understanding of the hydrological requirements of mangroves and their ecosystem functions.

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884. Adediran, Adeolu Idowu (2023) Alkali activation of iron-rich fayalite slag : fresh, hardened and durability properties

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