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Environmental flow assessment for intermittent rivers supporting the most poleward mangroves

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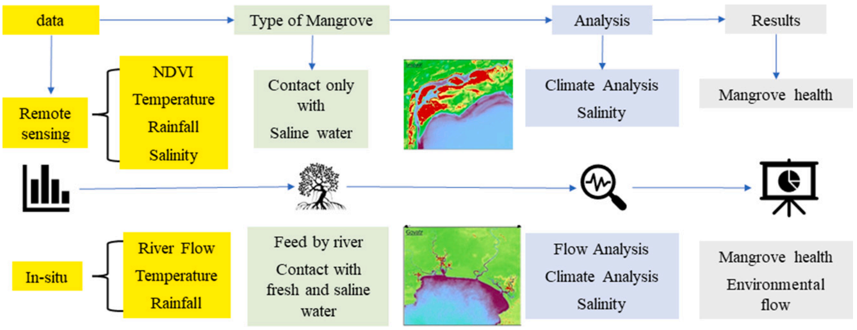
HIGHLIGHTS

- Our method is applicable to any coastal or estuarine ecosystem impact assessment.
- Setting Environmental Flow for ephemeral rivers to enhance restoration of mangroves
- Response of mangroves near the environmental tolerance threshold to physical stressors
- Peculiarities of ecosystem health assessment of the estuarine and sea-side mangroves

GRAPHICAL ABSTRACT



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ABSTRACT

The most vulnerable and dynamic ecosystems in terms of response to climate change and fluctuations in hydrological conditions are mangroves, particularly those located on the edge of their latitudinal range limits. The four primary Iranian mangrove forest sites: Nayband, Qeshm, Gabrik, and Govatr, located in the northern part of the Persian Gulf and the Gulf of Oman already exist near the limit of their tolerance to extreme temperature, precipitation, and salinity. Due to extreme climate conditions at these locations, the mangrove trees are usually smaller and less dense as compared with mangroves closer to the equator complicating their monitoring and mapping efforts. Despite the growing attention to the ecological benefits of mangrove forests and their importance in climate change mitigation, there are still a few studies on these marginal mangroves. Therefore, we investigated whether the variation in mangrove ecosystem health is related to the changes in physical parameters and differs between estuarine and sea-side locations. We developed a comprehensive database on NDVI values, associated rainfall, temperature, and river flow based on in-situ and remote sensing measurements. By understanding the normal hydrologic patterns that control the distribution and growth of mangroves in arid and semi-arid regions, we are questioning the need for environmental flow allocation to restore mangrove ecosystem health. This brings us to the second gap in the literature and the need for further studies on Environmental Flow assessment for intermittent and ephemeral rivers. Alike other mangroves studied, forests showed greenness seasonality, positively correlated with rainfall, and negatively correlated with temperature. As there was no clear difference between estuarine and marine sites, freshwater influence in the form of river flow, unlike temperature,

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cannot be considered a major limiting factor. Nevertheless, during prolonged droughts mangroves could benefit from the recommended allocation of Environmental Flow during the cold period (November–March).

1. Introduction

Mangroves are a globally distributed ecosystem in coastal areas across South and Southeast Asia, Africa, South America and the Caribbean, and Oceania, covering an area of approximately 150,000 km^2 (Duke et al., 2002; Giri, 2011). During the last three decades, the area of mangroves decreased by 1.04 million ha (FAO, 2020). The UN Decade on Ecosystem Restoration (2021–2030) calls for extensive ecosystem restoration actions to prevent, halt, and reverse the degradation of ecosystems, including mangroves, 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). Although relatively small in size (about 93,37 km^2 in 2002 (Zahed et al., 2010) and 111.77 km^2 in 2020 (The Global Mangrove Watch, 2023)), Iranian mangroves are ecologically and economically valuable, providing habitat for marine species, contributing to carbon sequestration and climate change mitigation, and supporting local livelihoods through fisheries and ecotourism (Ghasemi et al., 2010; Barbier et al., 2011). 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 anomalously low and high sea level events and increasing temperatures (Etemadi et al., 2016; Etemadi et al., 2018; Sharifinia et al., 2019; Duke et al., 2022; Chung et al., 2023). According to Blankespoor et al. (2014), a 1 m sea level rise might result in the loss of 96 % of coastal wetlands in the Middle East, including mangroves. Increased temperatures would also increase evaporation rates, increasing salinity stress (Clough and Rews, 1982). Furthermore, some areas of Iranian mangroves are experiencing declining freshwater input in addition to the abovementioned challenges (Mafi-Gholami et al., 2015). Since the 1990s efforts to protect mangroves have risen in Iran, however alongside protection, there is an imperative need for restoration, backed by science (Spalding and Leal, 2021; Su et al., 2022).

Mangroves are typically found in the intertidal zones of estuaries and coastal wetlands, where they are exposed to brackish water (a mix of saltwater and freshwater) (Kathiresan and Bingham, 2001; Saintilan et al., 2014). This water mix is crucial for the survival of mangrove trees, which have adapted to tolerate saltwater but require freshwater to survive. Freshwater inflow helps to flush out excess salt from the soil and provides the mangrove trees with the freshwater they need for growth and survival (Komiyama et al., 2019; Peters et al., 2020). It also helps maintain the ecosystem's balance by controlling the salinity levels in the soil and water. There is a clear correlation between hydrological stress and changes in the extent of mangroves in different parts of the world, indicating the negative impact of reduced freshwater flows on coastal ecosystems, fish assemblage, and the consequent decline of mangroves (Marins, 2002; Faunce et al., 2004). Several studies worldwide have shown the correlation between declining rainfall and surface water flow and the density and extent of mangroves due to increased salinity and reduced nutrient and sediment inputs (Selvam, 2003; Ewe et al., 2007; Godoy et al., 2018; Ezcurra et al., 2019; Ahmed et al., 2022).

Water resources development and dam construction have altered the natural flow of rivers worldwide raising strong debates around the complex issue of economic tradeoffs between hydropower generation and the associated environmental costs (Jager and Smith, 2008; Ezcurra et al., 2019). However, a changing climate combined with projected increases in population and water demands increasingly call for engineering solutions such as the construction of dams, while at the same time, the removal of old dams has become a common and widespread practice (Zarfl et al., 2015; Ho et al., 2017; Grill et al., 2019; Duda & Bellmore, 2021; Torabi Haghighi et al., 2023). Riverine and estuarine ecosystems have the same rights to water as those who depend on water resources in the area, but in practice, priority is given to agriculture and domestic water supply. One of the core ideas of Integrated Water Resource Management is the sustainable management of water resources to balance socioeconomic and ecosystem needs, including mangroves, which has led to the development of the environmental flow (EF) concept (Dyson et al., 2003; Kiwango et al., 2015).

Following the alteration of flow regimes resulting from water diversion for various purposes, releasing Environmental Flow will be recommended to diminish the negative consequence of water resource development. Although studies on EF implementation gained traction in recent years the actual EF implementation is still relatively limited despite the abundance of theories and concepts (Owusu et al., 2022; Dourado et al., 2023). The term environmental flow is widely used for permanent rivers, lakes, and wetlands, however, to our knowledge, it has not been considered for intermittent or ephemeral rivers and streams. Wineland et al. (2022) highlight a need to better understand the challenges facing water-limited systems due to extreme spatio-temporal hydrologic variability and uncertainty about future hydrological conditions due to climate change. Furthermore, studies into EF implementation within mangrove forests are very scarce as previous studies mainly have focused on flow patterns of tidal rivers in and near mangroves (Horstman et al., 2013; Kiwango et al., 2015; Pérez-Ceballos et al., 2020). This paper will assess the possibility of environmental flow allocation for the mangroves in arid and semi-arid regions like Iran. Despite their precarious existence, mangroves within the Middle East have received insufficient attention in global assessments, and there are significant knowledge gaps regarding the impact of climate change on them (Zahed et al., 2010; Ward et al., 2016; Etemadi et al., 2021). For this purpose, we studied four primary Iranian mangrove forest sites: Nayband, Qeshm, Gabrik, and Govatr considering the Normalized Difference Vegetation Index (NDVI) as a mangrove health indicator. Then we analyzed how different environmental variables, such as temperature, rainfall, river flow, and salinity, interact and impact the health and sustainability of mangrove ecosystems in the northern Persian Gulf, and Gulf of Oman. Finally, our study focuses on how this understanding can inform the development of optimal environmental flow strategies for mangrove restoration.

2. Material and methods

2.1. Study area and data

Iranian mangroves are one of the most poleward forests located between longitude 25° 19′ and 27° 84′, in the northern part of the Persian Gulf and Gulf of Oman (Zahed et al., 2010; Ximenes et al., 2023), mainly distributed in 3 coastal provinces including Bushehr, Sistan va Baluchestan, and Hormozgan. *Avicenna marina* is the dominant specie in Iranian mangrove forests due to its high tolerance for temperature and salinity changes which are categorized as non-industrial and conservation tree communities used for harvesting branches, beekeeping, aquaculture, recreational, and medicinal use (Milani, 2018; Ghayoumi et al., 2022). For this study, we selected four main Iranian Mangrove Forests sites, including a) Nayband, b) Qeshm, c) Gabrik, and d) Govatr (Fig. 1). Bidkhoon and Basatin are mangrove areas within Nayband Marine-Coastal National Park (Etemadi et al., 2021). Significantly dense mangroves are observed in Hormozgan Province Qeshm Island which is part of Hara Biosphere Reserve one of 13 UNESCO biosphere reserves of Iran. It is a key biodiversity site because of the largest *Avicennia* mangrove ecosystem along the Persian Gulf shoreline. While in the Hara-e Gabrik Protected area of the same province, mangroves are less dense.

Mangroves of BahooKalat protected area in Govatr Bay in the southeast part of Iran in Sistan and Baluchestan province consist of pure communities of *Avicennia marina* with a mean density of about 1623 trees per hectare.

The primary water source for these mangrove forests is seawater, but freshwater supports Gabrik and Govatr. Govatr mangrove site is situated in the southeastern of Sistan va Baluchestan, within the delta of the BahooKalat River as a part of the Gandoo Protected Area and Bahoo wetland (Danehkar, 2001; Khosravi, 1992). The Gabrik region, covering an area of 28,812 ha and is located 85 km east of the Jask port in the Hormozgan province of Iran. The climate in this region is classified as hot desert, with an average annual precipitation of 146.58 mm. The main rivers in this region are Jegin and Gabrik. River regulation affects both sites, though to varying degrees. The most crucial in-operation dams are Jegin and Pishin, which are placed upstream of Gabrik and Govatr, respectively. In contrast, Nayband and Qeshm sites are mainly fed by seawater. These two sites are chosen as reference sites to compare with the mangroves fed by the freshwater.

The analysis combines in-situ and remotely sensed data. We used monthly precipitation, temperature, and flow data from Pirsohrab and Lireeay, nearby Govatr and Gabrik sites. Regarding mangrove analysis, remote sensing data have been used to assess vegetation health, evapotranspiration, and sea surface salinity at different time scales including monthly and annually from 2001 to 2020. NDVI calculated by Landsat series (Landsat 5–8) Collection 2 Level 2, images with MODIS potential evapotranspiration (PET) (MOD16A2) and HYCOM salinity product extracted from Google Earth Engine platform (Table 1).

2.2. Methods

The approach for responding to research questions consists of four main parts. Given the limited availability of in-situ data for monitoring and assessing mangrove ecosystems, remote sensing studies were conducted as a first step. Hydrological studies and river regime alteration were carried out in the second phase. The third phase will investigate the interactions between river regimes and other factors, (e.i., rainfall and temperature) and their impact on mangrove health (NDVI). Finally, recommendations will be made regarding environmental flows based on the results of the previous stages (Fig. 2).

2.2.1. Mangroves health index

NDVI is the most widely applied index in mangroves, used in 82 % of the studies (Tran et al., 2022). NDVI is a remote sensing index that measures the amount of green vegetation in an area and is often used to assess the health and productivity of vegetation in terrestrial ecosystems (Ruan et al., 2022). NDVI is determined by the degree of absorption by chlorophyll in the red wavelengths and the reflectance of near-infrared radiation, which is proportional to leaf chlorophyll density, and green leaf density (Chellamani et al., 2014). NDVI values are sensitive to the green leaf area or green leaf biomass, thus higher NDVI values indicate denser, healthier vegetation (Tucker, 1979). In order to evaluate the health status of mangrove trees of four study sites, NDVI was calculated using Landsat and MODIS for the period 2000–2020 provided by the Google Earth Engine.

Table 1
Remote sensing data.

Product name	Spatial resolution	Temporal resolution
Landsat 5–8 Collection 2 Level 2	30 m	16 days
MODIS PET (MOD16A2)	500 m	8 days
HYCOM Salinity	9000 m	Daily

2.2.2. Flow regime alteration analysis

Indicators of Hydrologic Alteration (IHA) is a software program developed by The Nature Conservancy that assesses 67 ecologically-relevant statistics derived from daily hydrologic data, including “environmental flow components” (Mathews and Richter, 2007; The Nature Conservancy, 2009). This methodology is widely used by water resources managers and researchers to understand the extent of the impact of dam constructions and climate change on river flow or for the development of environmental flow recommendations (Richter et al., 1996; Richter et al., 1997; Ashraf et al., 2016; Yan et al., 2021; Baubekova et al., 2023). One of the hydrological criteria for determining the Environmental flow is the allocation of water based on the river's base flow. The IHA Group 2 statistics include the base flow index, defined as a 7-day minimum flow/mean flow for the year and a number of almost zero flow days (The Nature Conservancy, 2009). In this study, a single period IHA analysis using non-parametric statistics was applied, because of the skewed nature of hydrologic datasets due to the intermittent nature of the studied rivers. The two-period analysis was not chosen as there is no clear change point in the hydrological data. The dams constructed on the tributaries of the studied rivers in the upstream part of the basins are either too far from the estuary or a large midstream part of the basin relieves the impact.

2.2.3. Hydro/climate interaction with mangrove health

To assess the possible impact of river flow, rainfall, and temperature

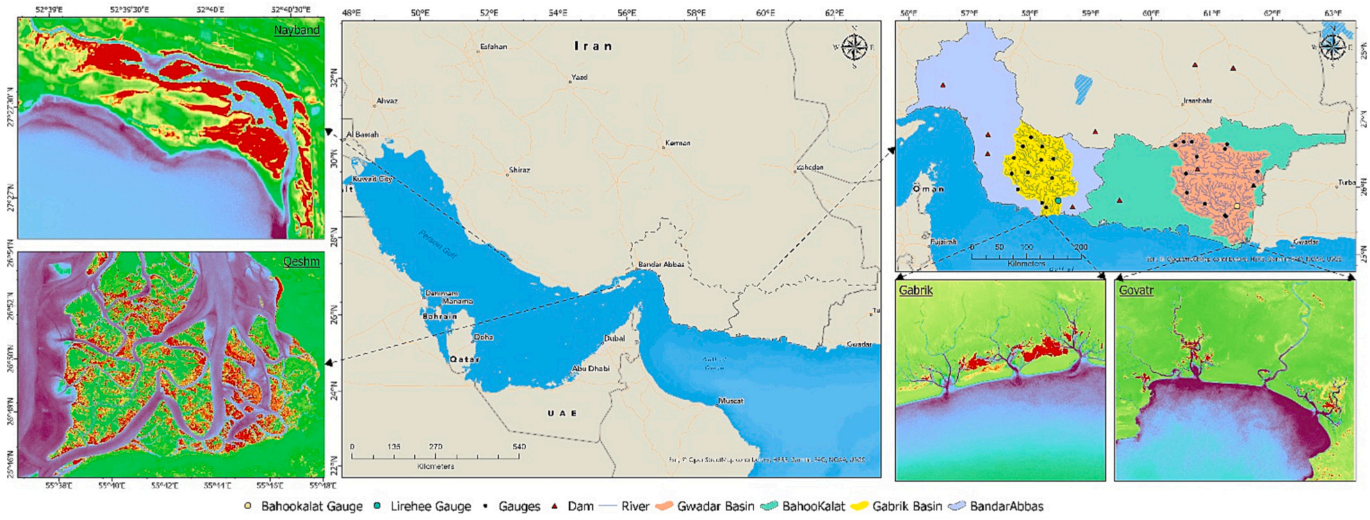


Fig. 1. Study site map.

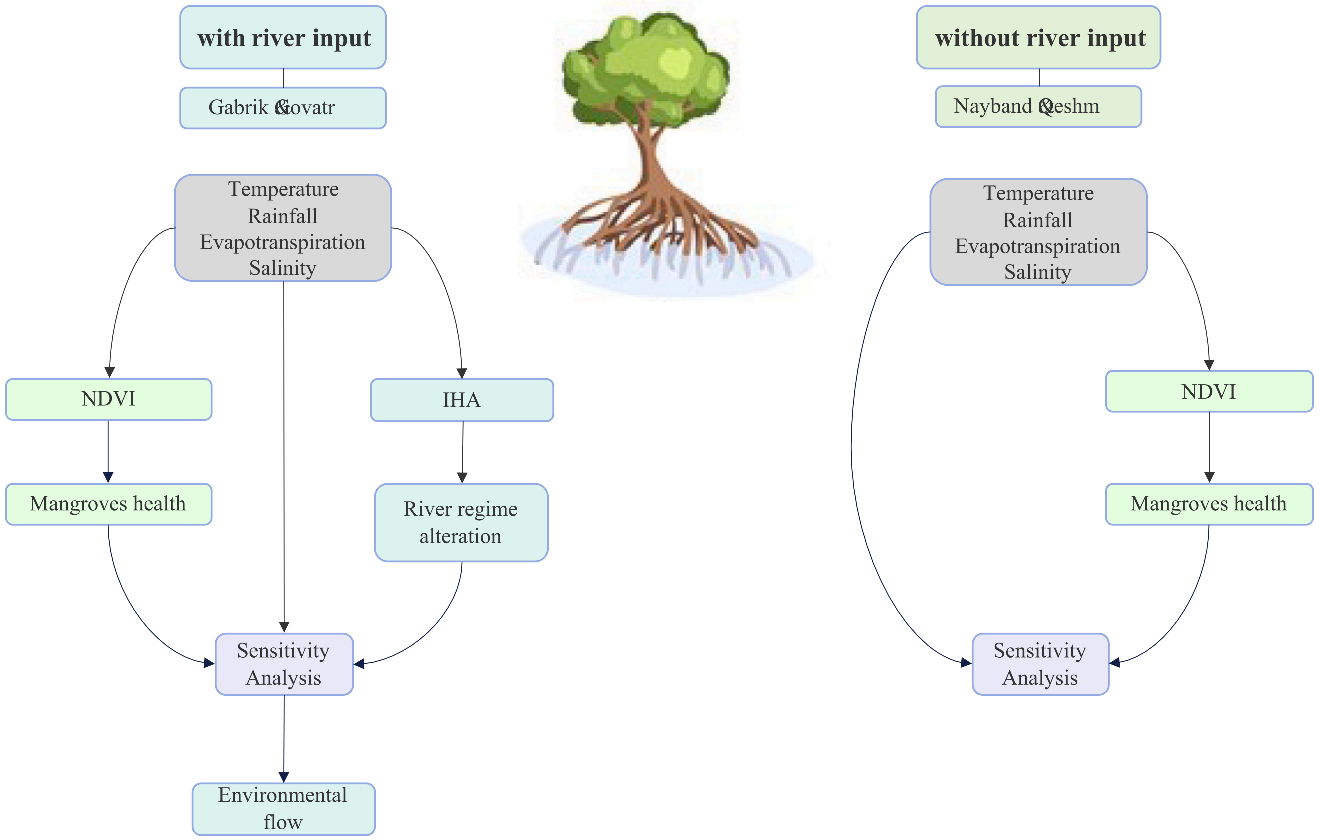


Fig. 2. Proposed method for EF analyses for mangrove forest.

on the mangrove forests, the frequency of occurrence of each was analyzed across different groups of monthly NDVI indices. For this purpose, based on the dates of the available NDVI index, the associated river flow, rainfall, and temperature were identified. Based on the variation NDVI, the database was divided into 5 groups of NDVI (G1-G5); the resulting database includes the year, month, NDVI, and one of the three parameters (river flow, rainfall, or temperature). We assume a higher value of NDVI indicates better health conditions for mangroves. Usually, previous months' hydroclimate conditions can also influence mangrove health; therefore, the value of NDVI was compared with river flow, rainfall, or temperature of the prior month, 2, 3, 6, and 12 months. This approach will be valuable in identifying potential drivers of mangrove ecosystem changes and developing effective management strategies for preserving and restoring these critical habitats. In this part we used recorded in-situ data for the climatic variables.

2.2.4. *Environmental flow (EF) assessment*

Determining the EF for mangroves is a complex process that requires a thorough understanding of the ecosystem and the hydrological and climatic conditions that affect it. More than 200 environmental flow assessment methodologies can be grouped into four categories: hydrological, hydraulic rating, habitat simulation, and holistic methodologies (Tharme, 2003). Although few studies focus on EF allocation for mangroves (Sathyanathan et al., 2009; Kiwango et al., 2015). In order to allocate EF for the mangrove forests, two key characteristics need to be defined: the magnitude and timing of water release. The interaction of hydrological and climatic parameters, as discussed in the previous section, will be used to determine the best time for water release. The magnitude of EF can be estimated based on the PET during the recommended months. PET is the amount of water that plants could evaporate and transpire if sufficient water was available. PET was retrieved from a MODIS product named MOD16A2 at 8-day intervals using Google Earth Engine. The PET values for recent years can be used to estimate the average amount of water needed for the healthy growth of mangroves in the study sites. This information can then be used to determine the magnitude of EF required to maintain the health of mangroves.

3. Results

3.1. *Remotely sensed analysis of mangrove health*

Based on previous literature, NDVI was selected as the main remote sensing index to assess mangrove health conditions. The NDVI values for the two-decade period were calculated using Landsat and MODIS products, and the results were compared. Table 2 demonstrated a greater than 0.74 correlation between annual NDVI values acquired from Landsat and MODIS data. Although there were significant differences in the NDVI values obtained from Landsat and MODIS images over several years across all study sites, the overall trend suggested an increase in the health index of mangroves. Due to missing data and a lack of temporal continuity in Landsat images prior to the launch of Landsat 8 in 2013 and considering the high temporal frequency and connectivity of MODIS products, the latter was chosen for further analysis (Table SM 1). The upward trend observed in NDVI, which was used as an indicator of mangrove health, suggests an improvement in the health condition of the mangrove forests in recent years (Fig. 3). Higher NDVI shows denser and healthier vegetation, and forests in Gabrik show higher initial NDVI and almost doubled increase compared to the mangroves in Govatr, which showed a slower increase rate.

The monthly correlation was used to find the relationship between Land Surface Temperature (LST)/precipitation/salinity and NDVI for each site. Correlations of NDVI with monthly climatic variables were stronger for both temperature and precipitation in comparison to the salinity (Table 2). However, LST and NDVI show more statistically

Table 2
Results of monthly correlation analysis between the NDVI and temperature/precipitation/salinity for the 2001–2020 period.

Sites	NDVI and LST correlation	NDVI and precipitation correlation	NDVI and salinity correlation
Nayband	−0.36	0.27	0.2
Qeshm	−0.64	0.35	0.09
Gabrik	−0.43	0.34	−0.26
Govatr	−0.57	0.19	−0.07

significant results with a strong negative correlation for all study sites. There is a significant inverse relationship between temperature and vegetation index for the Qeshm and Govatr sites with 0.64 and 0.57 respectively. Precipitation is occurring mainly in the cold season, and the NDVI is highest in this period. The correlation between monthly precipitation variations and NDVI over the last 20 years showed a lower correlation for Nayband 0.27 and Govatr 0.19 (Table 2). We assume that the reason for this is the presence of noises in the remote-sensing images. Although Gabrik and Qeshm mangroves are located closer to each other and have similar patterns of response to the changes in precipitation

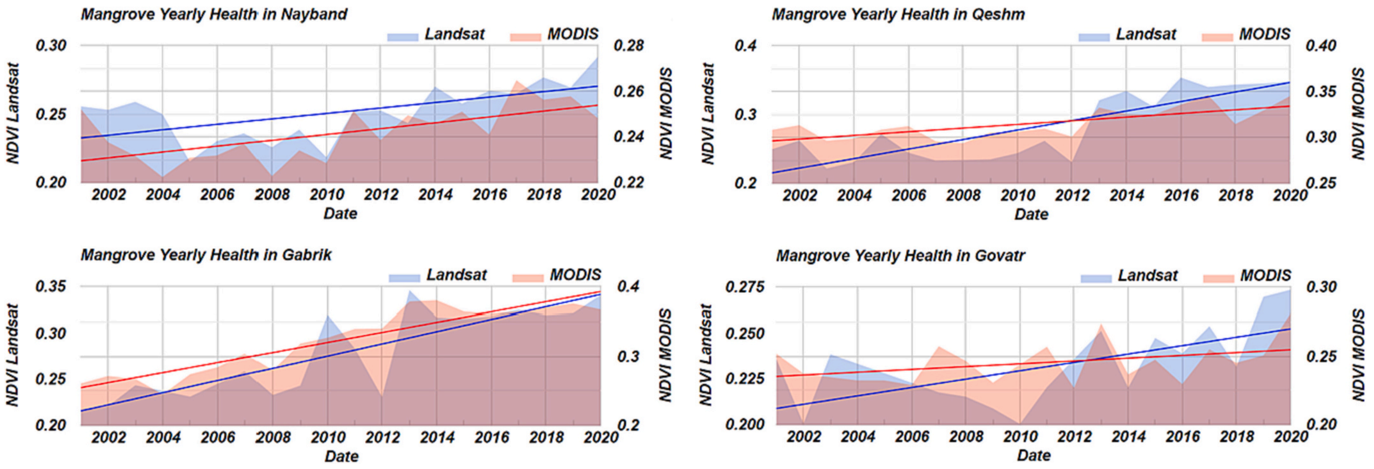


Fig. 3. Annual variation of NDVI, based on the Landsat and MODIS data.

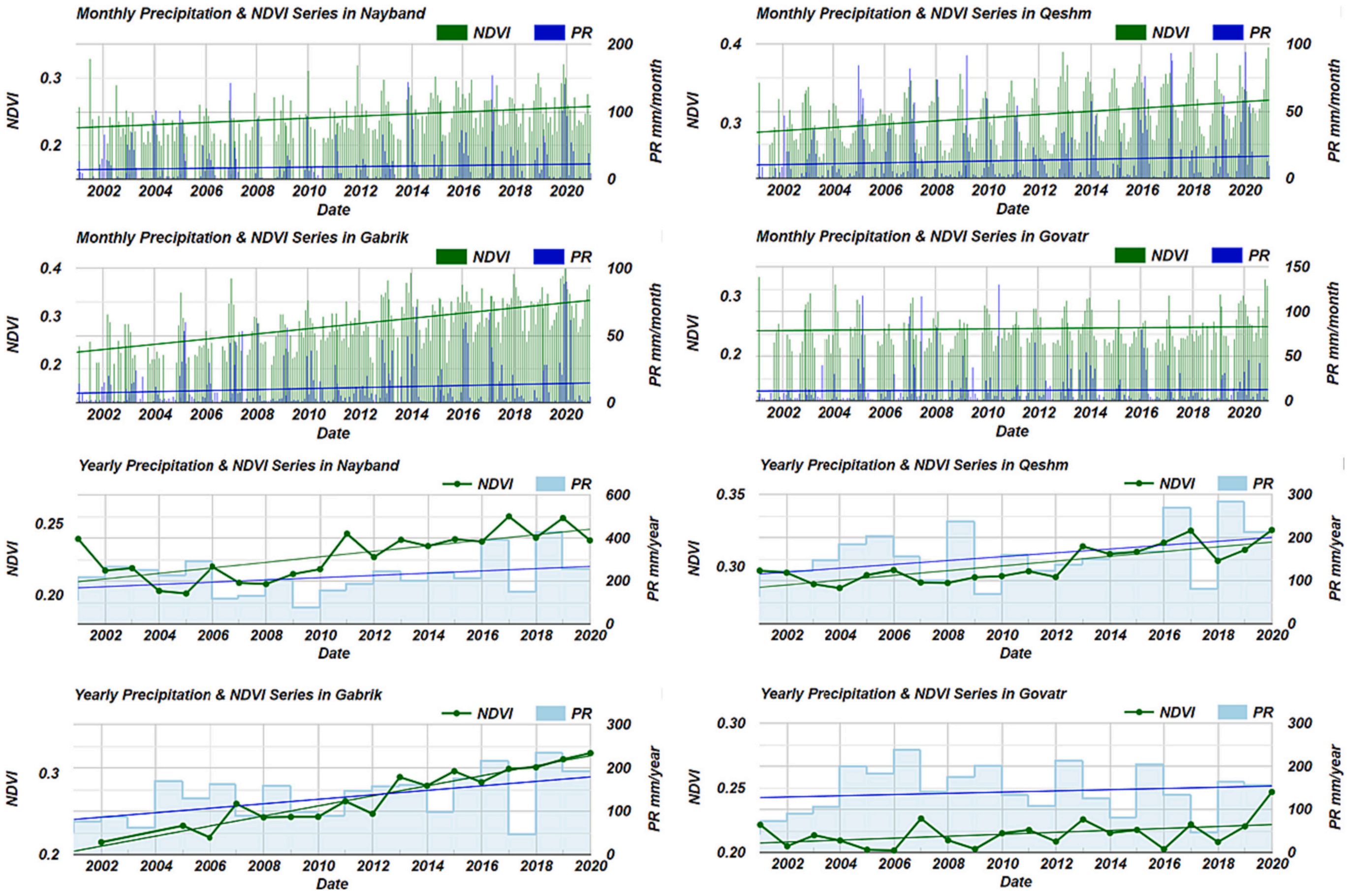


Fig. 4. Monthly and annual changes in Precipitation and NDVI.

showing 0.34 and 0.35 correlation.

A correlation analysis was conducted between the NDVI and the temperature and rainfall on a monthly and annual scale to investigate the relationships between the mangrove forest health and climatic drivers (Figs. 4 and SM1). On a monthly scale, both sea-side and estuarine sites showed that the NDVI is highest when the precipitation is high (Fig. 4). On the annual scale, time series analysis for monitoring mangrove health shows a clear increasing trend for all sites in the south of Iran except Govatr along with the increase in precipitation over the last two decades. In contrast to precipitation, LST over vegetation cover shows a decreasing trend on the yearly scale and is stable on the monthly scale on all the stations (Fig. SM 1).

To assess the influence of salinity on mangrove health we analyzed the relationships between precipitation and salinity and vegetation cover and salinity on monthly and yearly scales. Neither of these showed a strong correlation. The amount of rainfall is insufficient to influence the salinity therefore there is a weak correlation between salinity and rainfall both on a monthly and yearly scale. Although the long-term monthly analysis shows inverse trends over the last 20 years with a drop in salinity and an increase in precipitation during the last decade on three studied sites except for Govatr, where the precipitation trend was constant. Similarly, there were reverse trends for NDVI and salinity, showing the negative impact of increased salinity on the mangroves' health. True mangroves tolerate salinity changes however, chronic high salinity and hypersalinity are beyond mangroves' physiological limits to their capacity to withstand inundation (Patel et al., 2010; Naidoo, 2006). Although yearly analysis shows that both salinity and NDVI in Govatr have increased over the studied period, a closer look at the last decade shows that mangrove health and salinity levels are negatively correlated, as was observed on other sites (Fig. 5).

3.2. Hydrological regime of the rivers feeding the studied mangroves

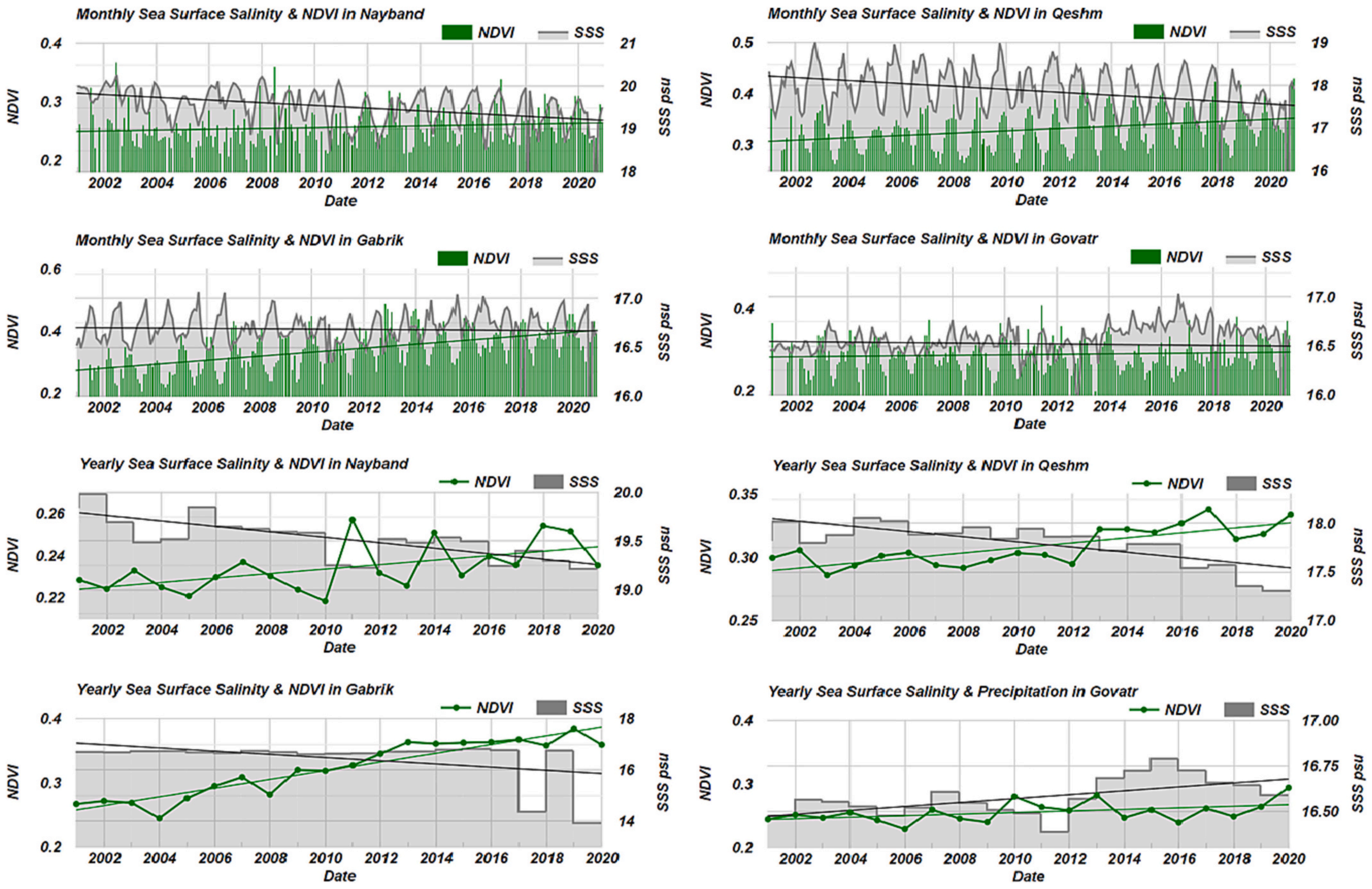
As mentioned, we selected two rivers for hydrological analysis: BahooKalat at Pirsorab and Gabrik at Lireaee from Govater and Gabrik mangroves, respectively. Both rivers have a similar flow regime due to their almost identical climate. Therefore, in this section, we only provide the analysis of the flow regime of BahooKalat (1972–2017). The results of Gabrik will be presented in the Supplementary Materials (Fig. SM 3–5).

The BahooKalat has a seasonal regime, and the main part of the flow (more than 68 %) runs from Jan. to Apr. (Fig. 6 a2) and almost follows the precipitation pattern (Fig. 6 b2). The mean annual flow is about 7 m^3s^{-1} and varies from 0.01 m^3s^{-1} (2015) to 59 m^3s^{-1} (1998).

This considerable variability underscores the unstable hydrological conditions in the region, as confirmed by the results of the IHA analysis. In the entire duration of the study, only in 2009 was a minimum flow (more than zero) recorded for seven consecutive days (Fig. 7). However, this flow discontinuity was also identified in more extended periods, such as 30 and 90 days, indicating the persistent hydrological inconsistency in the river. The frequent occurrence of zero flow days, except for 2009 and 2007, provides further evidence of the unstable hydrological regime in the river. These findings highlight the vulnerability of the river ecosystem to altered hydrological patterns, emphasizing the need for effective monitoring and management measures to ensure its sustainability.

3.3. Hydro/climate interaction with mangrove health

To evaluate the possible impact of fresh water, rainfall, and temperature on the health of mangroves, we employed a methodology that involved classifying the NDVI time series into five groups. For instance,



Monthly Sea Surface Salinity & NDVI in Nayband

Monthly Sea Surface Salinity & NDVI in Qeshm

Monthly Sea Surface Salinity & NDVI in Gabrik

Monthly Sea Surface Salinity & NDVI in Govatr

Yearly Sea Surface Salinity & NDVI in Nayband

Yearly Sea Surface Salinity & NDVI in Qeshm

Yearly Sea Surface Salinity & NDVI in Gabrik

Yearly Sea Surface Salinity & Precipitation in Govatr

Fig. 5. Monthly and annual changes in Sea Surface Salinity and NDVI.

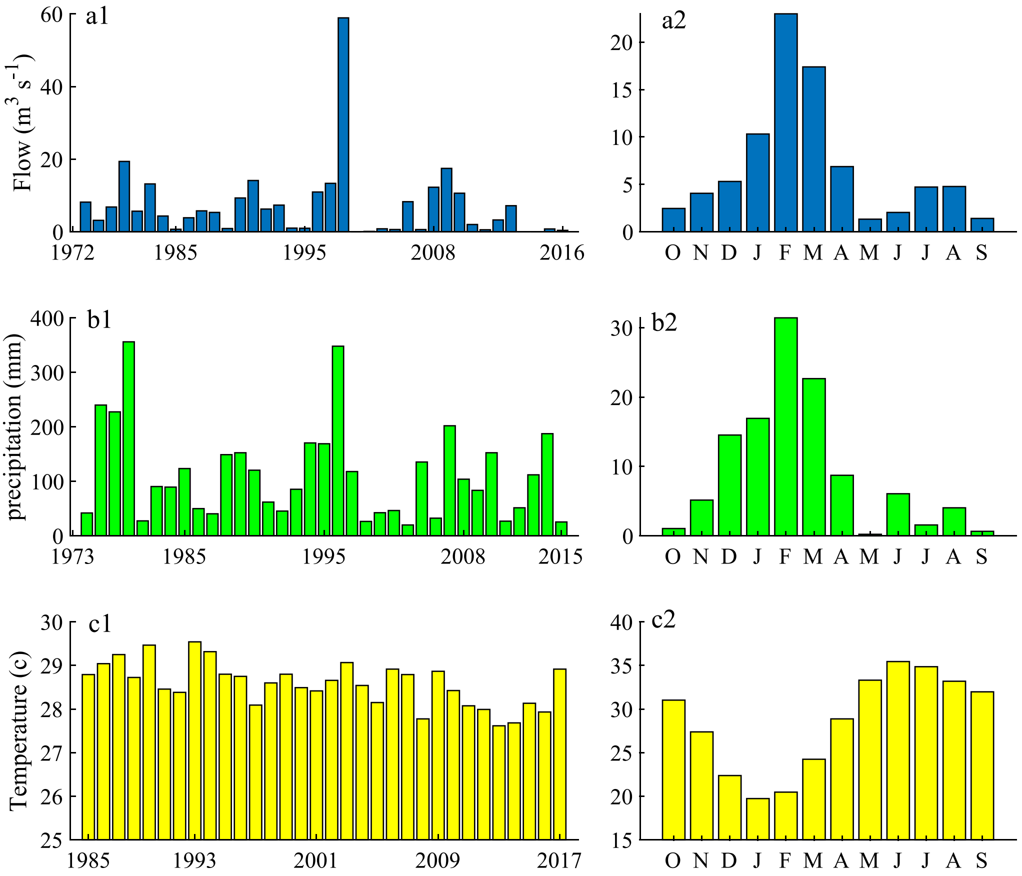


Fig. 6. Mean annual (1) and monthly (2) flow (a, at BahooKalat), precipitation (b, at Pirsohrab), and temperature (c, at Pirsohrab). O-S: October–September.

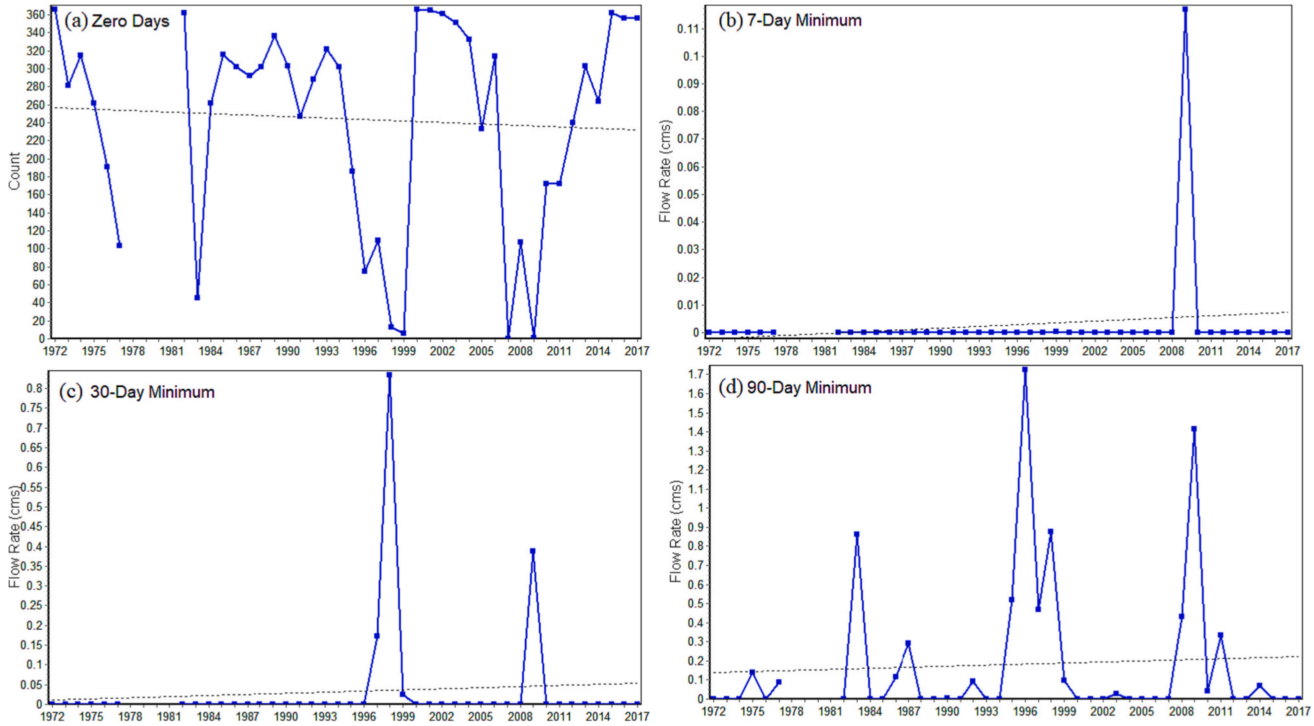


Fig. 7. Number of zero flow days (a) and recorded minimum flow for 7 (b), 30 (c), and 90 (d) consecutive days for BahooKalat River.

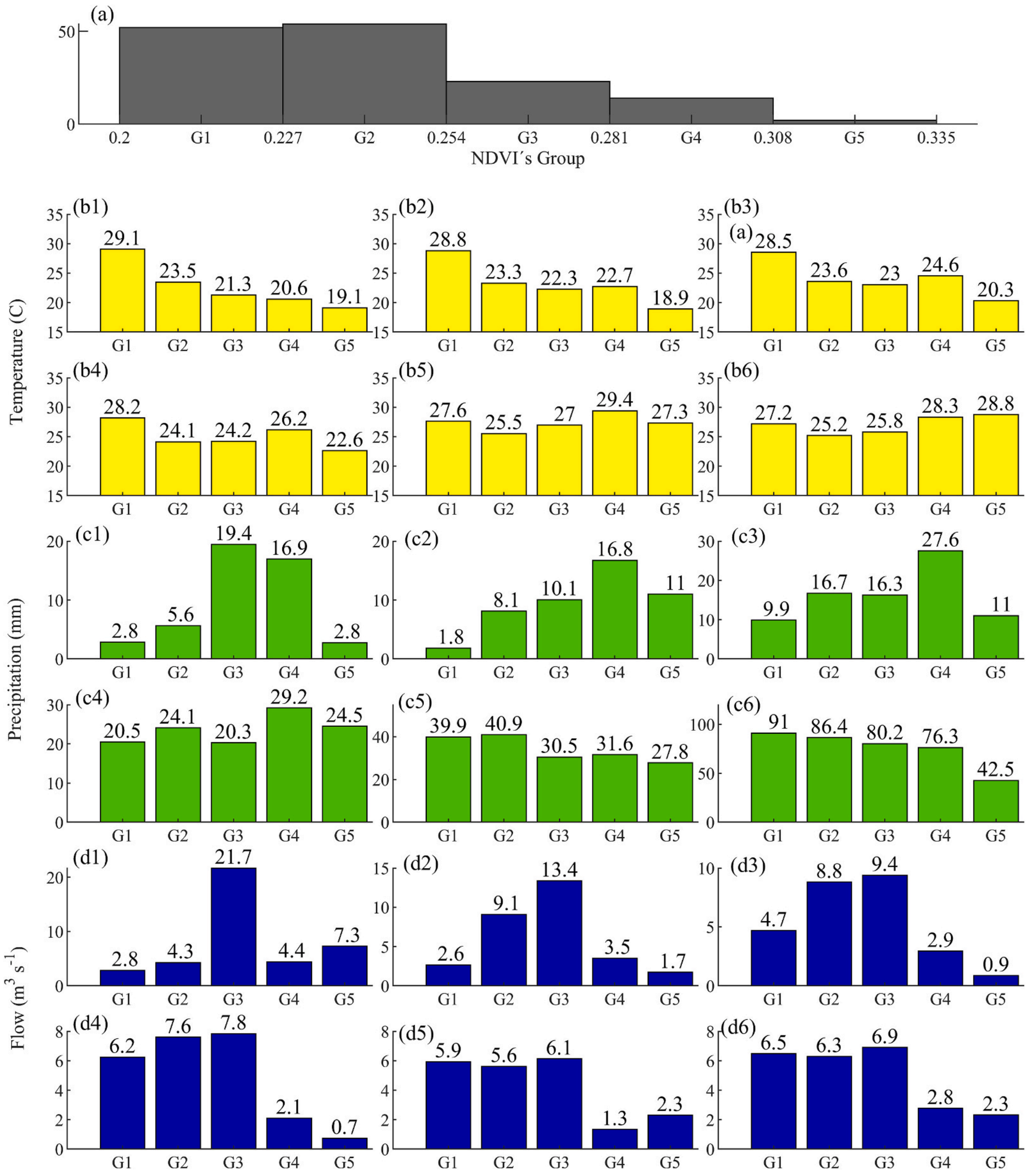


Fig. 8. The different temporal scales (1–12 months) of mean temperature (b1-6), accumulated rainfall (c1-6), and mean flow (d1-6) in Pirsohrab stations in different groups (a) of observed NDVI in Mangrove forest near Govatr. 1 indicates the same months, 2–6, for the last 1, 2, 3, 6, and 12 months.

for the Govatr area, the NDVI values ranged between 0.2 and 0.335 (based on minimum and maximum of observed NDVI values), which we then divided into five groups (G1 to G5) as illustrated in Fig. 8a. To accomplish this, we developed a comprehensive database containing information on the date, NDVI values, associated rainfall, temperature, and flow for the same months, with a 1, 2, 3, 6, and 12-month delay. The database allowed us to analyze how the past months' hydroclimate conditions impacted the mangroves' health. By utilizing this methodology, we could assess the potential effects of various factors on the mangrove ecosystem and gain insight into the interplay between hydroclimate variability and mangrove health. We analyzed observed in-situ data from the nearest station with trustworthy records. We obtained data from the Pirsohrab and Lireaee stations for the Govatr and Gabrik, respectively. After comparing the results from both stations, we found they were almost identical. Therefore, here we provide the results for the Pirsohrab station, representing the Govatr area (the results from the Lireaee stations in Gabrik are provided in the Supplementary materials, Fig. SM 4).

Comparing different groups of NDVI and temperature revealed that the high temperatures group (here 26.2) correlated with low NDVI (Fig. 8). The magnitude of NDVI can be increased (from G1 to G5) by decreasing the temperature of the same (Figs. 8b1 and SM 4 b1) and the previous month (Figs. 8b1 and SM 4 b1) of NDVI. As seen for groups G1-G5, the mean temperature of the same month is 29.1, 23.5, 21.3, 20.6, and 19.1, respectively (Figs. 8b1 and SM 4 b1). However, this decreasing pattern weakens when the NDVI value compares with a more extended period (i.e., three months, Figs. 8b4 and SM 4 b-4) and will be disappeared for 6 and 12 months (Figs. 8b5-6 and SM 4 b5-6). We can conclude that the NDVI value (mangrove health) mainly depends on the temperature of the same month or that of the preceding 1–3 months. However, based on our data set, precipitation in the preceding month can influence the NDVI value (Fig. 8c1-c6). No clear patterns are detected for the influence of flow magnitude on NDVI values (Fig. 8d1-d6). Therefore, we proposed another way (next Sections 3–4) to assess the influence of flow on the NDVI value and possible environmental flow assessment for this mangrove forest.

3.4. EF assessment

The NDVI value has been found to have an inverse correlation with

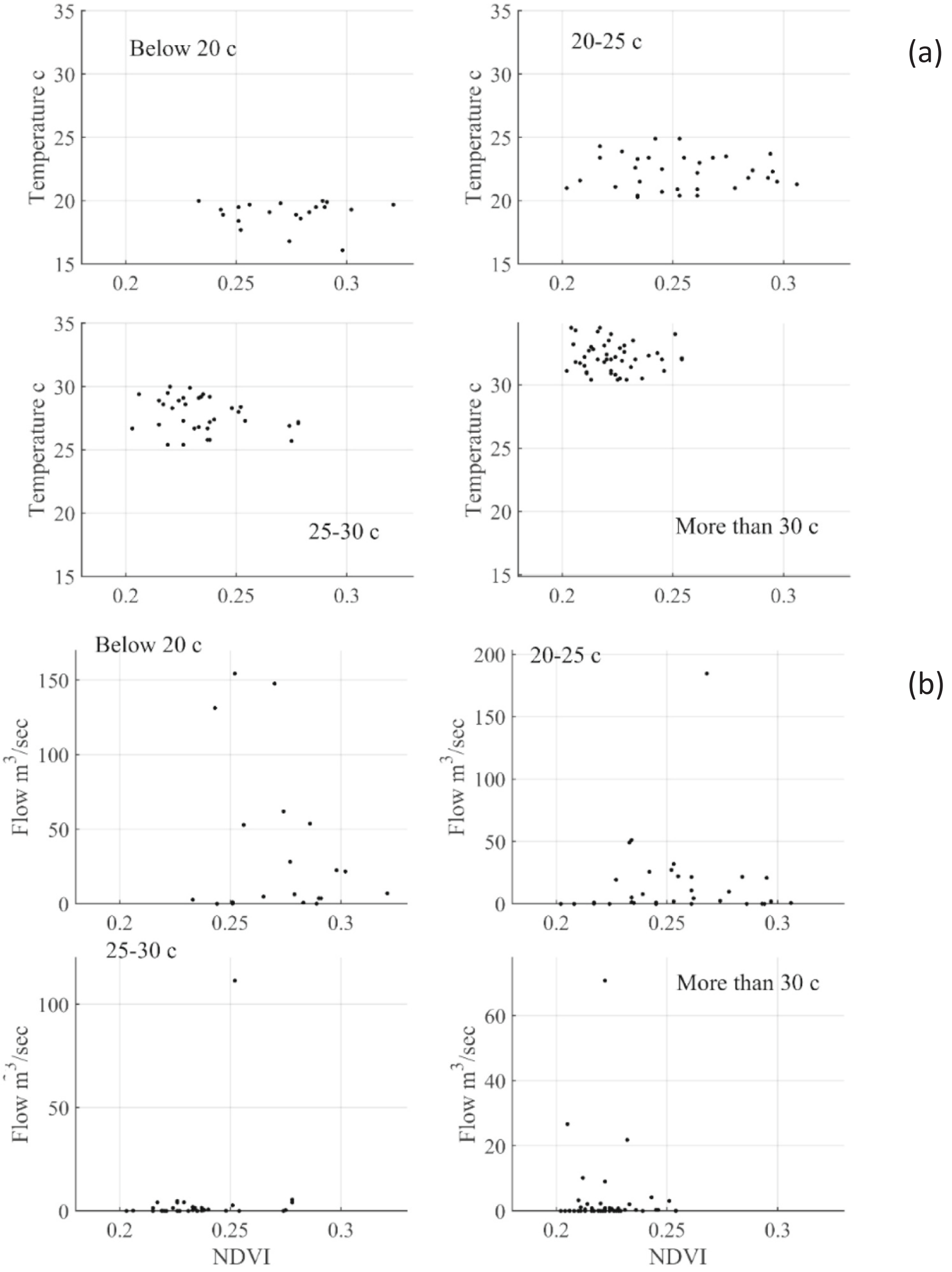


Fig. 9. Variation of NDVI value vs a) temperature and b) flow in different temperature groups in Govatr for the 2001–2017 period.

temperature. To estimate the best time for releasing EF, the temperature variation has been categorized into four groups (below 20 °C, 20–25 °C, 25–30 °C, and more than 30 °C). The NDVI variation is reduced by increasing temperature (Fig. 9a), while a considerable change in river flow can be seen in different temperature groups (Fig. 9b). Among the four temperature groups, only the first two groups (I and II) show a change in NDVI value with variations in river flow (Fig. 9b). In both groups (a and b), a lower value of NDVI is associated with lower river flow, while in Group IV, there is no apparent increase in NDVI with temperature (Fig. 9b).

Considering the lack of significant influence of flow on NDVI values in temperature groups III and IV, the EF released can be recommended during months related to groups I and II (Fig. 10). The frequency of temperature groups in Govatr (a) and Gabrik (b) are shown in Fig. 10. The recommended months for releasing environmental flow are indicated by different colors, with green representing high recommended months, blue representing recommended months, yellow representing low recommended months, and red indicating not recommended months. Therefore, the releasing EF can be recommended during December to March and November to March for Govatr and Gabrik, respectively.

As the mangrove's water demand is supported by seawater, the initial water for surviving mangroves will be available. The Released EF (freshwater) can help flush out excess salt from the soil, which can accumulate and become toxic to mangroves. The released EF can transfer sediments and organic matter, which are necessary for the growth and development of mangrove trees. Therefore, releasing EF can be recommended as much as possible; however, we recommend potential evapotranspiration as the minimum EF for releasing (Fig. 11).

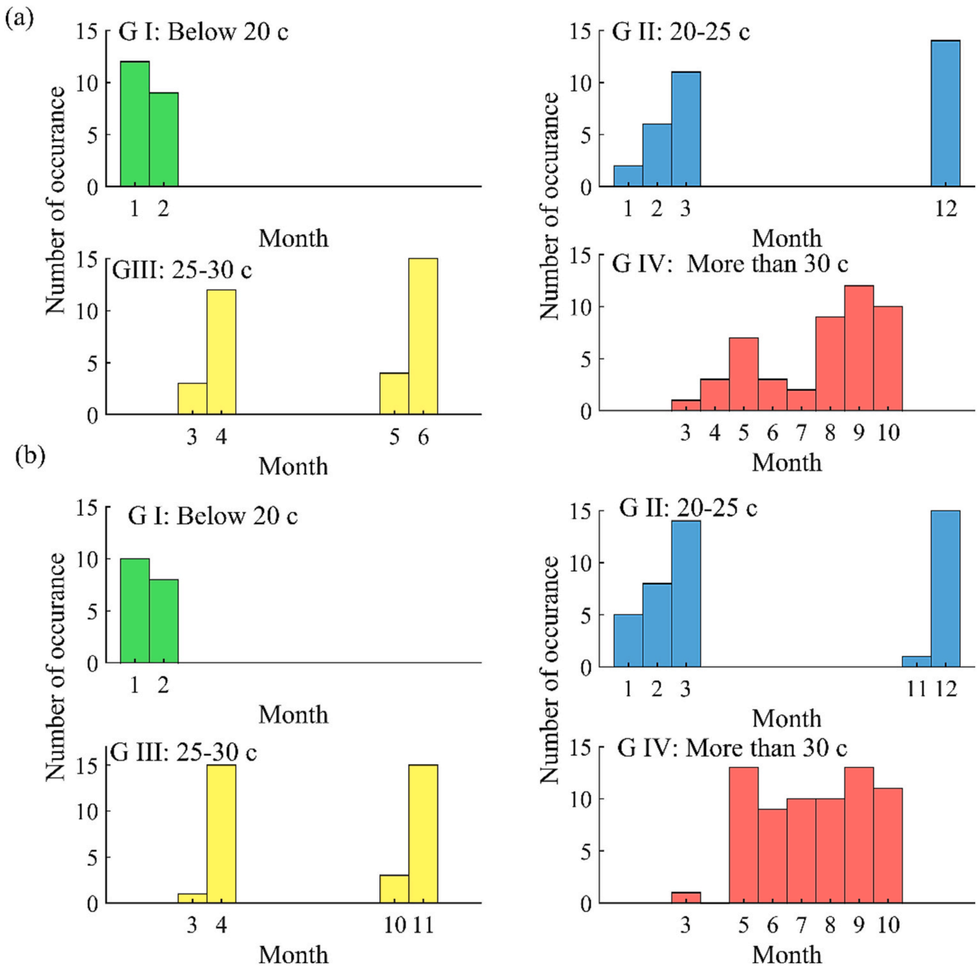


Fig. 10. Frequency of occurrence of different temperature groups in a) Govatr and b) Gabrik. (The numbers from 1 to 12 represent the months of the year). Green, yellow, and red indicate high recommended, recommended, low recommended, and not recommended months for releasing EF.

4. Discussion

4.1. Mangrove health

Healthy mangrove ecosystems are critical for building resilience to climate change, playing a key role in carbon storage and coastal protection (Leal and Spalding, 2022). Around 42 % of all remaining World's mangroves exist in designated protected areas and the goal is to double this number to reach the restoration goal of 4092 km^2 by 2030 (Leal and Spalding, 2022). The joint actions of government and local communities in restoration, afforestation, and reforestation of mangroves in Iran undertaken since the 1990s supported by the establishment of protected areas in almost all mangrove sites gave good results. The assessment showed an increase in NDVI for all study sites which was also observed by Milani (2018) in previous studies that attempted to assess the distribution and changes in the area of mangrove forests in the Persian Gulf and the Gulf of Oman. NDVI was widely used as a health index for mangrove forests in Iran (Milani, 2018; Etemadi et al., 2021; Erfanifard et al., 2022) and other parts of the world (Emch and Peterson, 2006; Giri et al., 2007; Lee and Yeh, 2009; Ruiz-Luna et al., 2010; Le et al., 2020; Blanco-Sacristán et al., 2022). NDVI can effectively delineate mangrove forests from the land cover classes and monitor canopy loss, degradation, and deforestation of mangroves (Shimu et al., 2019; Lovelock et al., 2017).

Mangroves located on the semi-desert coasts of the Persian Gulf and the Gulf of Oman of Iran face unique challenges due to their existence near the limit of tolerance to extreme environments, characterized by high temperatures, radiation, and hypersalinity, as well as low precipitation, making them vulnerable to additional stressors such as human activities and climate change (Etemadi et al., 2021; Mafi-Gholami et al., 2020; Baubekova et al., 2023). These mangroves located at their poleward range limits also have low primary productivity, species diversity, sediment deposition, and vertical accretion rates, making them distinct from other mangrove ecosystems (Duke et al., 1998; Ellison, 2002). The mangrove trees on the edge of the upper latitudinal range limits are usually smaller in structure, lower density, and smaller in extent as compared with their counterparts closer to the equator (Ximenes et al., 2023). It was also a limiting factor for using the Mangroves Index whereas even NDVI values for the studied sites are lower than average values for mangroves in other regions (Iran's Mangrove NDVI Average: 0.12, Global Mangrove NDVI Average: 0.57).

4.2. Physical conditions

Consistent with the other studies, the results showed that although mangroves are an evergreen species, the NDVI showed clear seasonality, negatively correlated with temperature, and positively correlated with rainfall (Pastor-Guzman et al., 2018). Temperature is a crucial environmental factor affecting mangrove trees' growth, distribution, and survival (Lovelock and Ellison, 2007). A study by Ghayoumi et al. (2022), that used a maximum entropy model to predict the potential decline of the mangrove forest area in Iran in the future, names temperature and precipitation as the most important determinants of the mangrove distribution. Furthermore, temperature affects the ability of

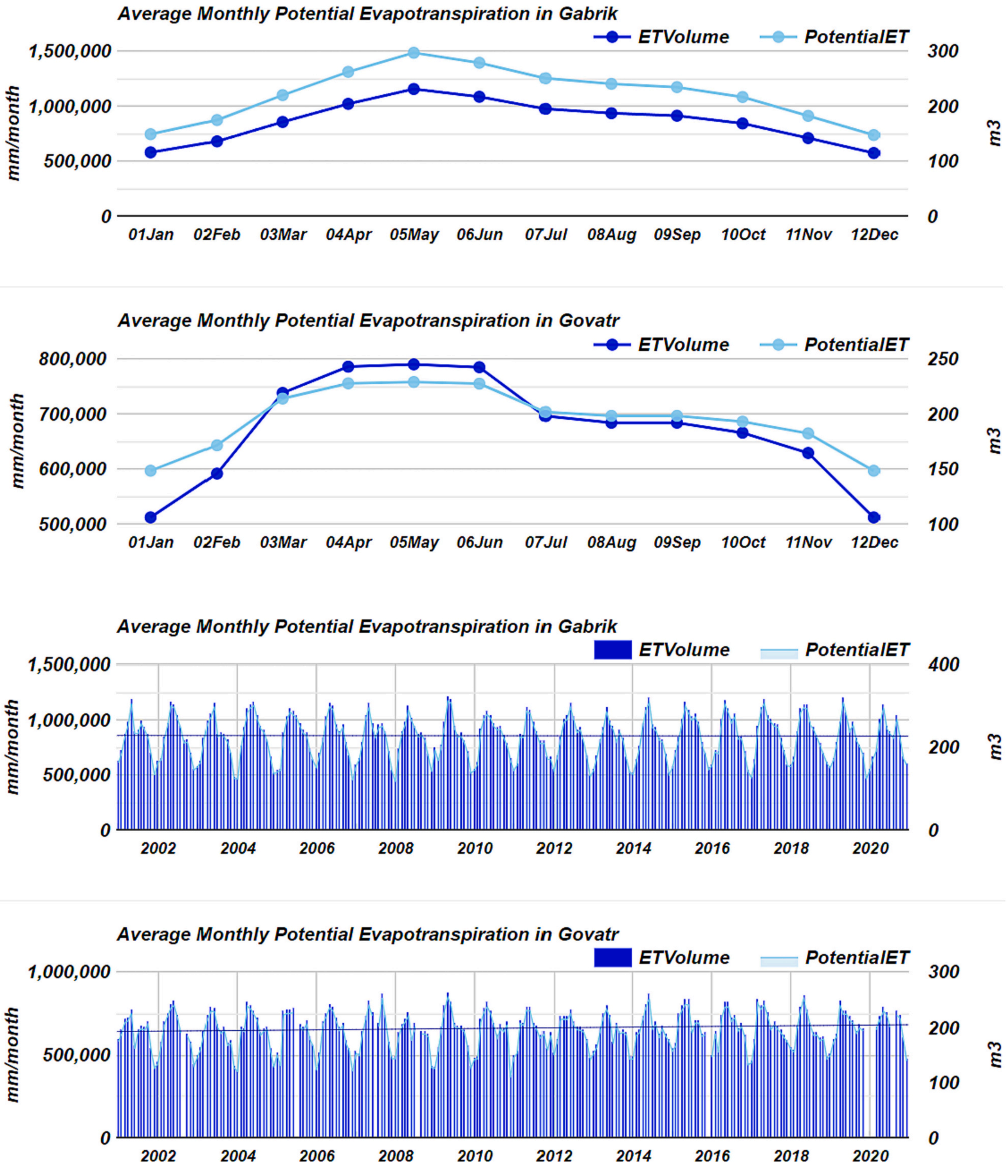


Fig. 11. The recommended minimum magnitude for the environmental flow of mangroves in Gabrik and Govatr, based on potential evapotranspiration.

mangroves to assimilate CO2 and store it in the form of biomass (Ball et al., 1988). Many mangroves are latitudinally restricted by a minimum air temperature of 16 °C, with leaf photosynthesis peaking at 28–32 °C; and productivity decreases up to 38–40 °C, when photosynthesis ceases (Clough and Rews, 1982; Saenger, 2002; Ball and Sobrado, 1999; Lovelock and Ellison, 2007; Ward et al., 2016). According to Wang and Gu (2021), global warming will provide favorable conditions for the introduction and expansion of mangrove species for lower to higher latitudes further which is consistent to findings of Ghayoumi et al. (2022) predicting biological range shifts of Iranian mangroves toward the Oman Sea.

Rainfall showed a positive correlation with NDVI playing a major role in the greenness phenology of mangroves. Cross-correlation analysis suggests that high rainfall affects NDVI, although we did not observe the lagging of the peak greenness occurring after high rainfall as it was reported in mangroves from other parts of the world (Prihantono et al., 2022). Rainfall is still a main source of freshwater for mangroves. The differences between estuarine and seaside sites are that the rainfall is distributed differently. As a primary water source for these seasonal rivers, rainfall reaches the mangroves through narrow river channels, creating a point source of freshwater. In contrast, in the seaside sites, rainfall is more evenly dispersed. During the rainy season, rainwater inundates the mangrove substrate, dilutes the salt, and decreases pore water salinity, thereby increasing water uptake and nutrient adsorption in the soil by mangroves (Prihantono et al., 2021).

Climate change with temperature and evaporation rise and lower precipitation rate lead to decreases in seedling survival, productivity, growth rates, species diversity, and resultant mangrove loss and conversion to hypersaline mudflats (Ball and Sobrado, 1999; Ward et al., 2016). Such in Senegal, a decade of low rainfall and high evaporation has caused salt flats growth that completely destroyed mangrove vegetation (Diop et al., 1997). Mangroves in Iran are naturally adapted to survive extreme drought and tolerate high salinity because there is no constant freshwater inflow to the system, unlike mangroves in the estuaries of large perennial rivers or mangroves in tropical regions where rainfall is evenly distributed throughout the year. Although, chronic high salinity, is detrimental to the mangroves as hypersalinity stunts tree growth in *A. marina* stands and seedlings of the red mangrove, *Rhizophora mangle*, require low salinity (Selvam et al., 1991; Smith et al., 1996; Patel et al., 2010). We observed mangrove decline and low NDVI in 2000 and 2008 when precipitation was extremely low. Long-term droughts and shortages of rainfall have increased mangroves' vulnerability and adversely affected the health and the spatial extent of mangroves on Iranian coasts (Mafi-Gholami et al., 2020). Thus, in dry years, it is advisable to release water during the cold season when it is not used by upstream farmers and EF could temporarily support the ecosystem in such cases. Furthermore, the future climate scenarios show that the area of mangrove forests in Iran will be declining due to the loss of suitable habitat area for *A. marina* caused by shortage of freshwater and frequent exposure to the critical temperature exceeding upper threshold leading to high evaporation, increasing salinity and aridity, that reduces tree growth and seedling survival making mangrove conservation implementation difficult in the future (Alongi, 2015; Ward et al., 2016; Servino et al., 2018; Ghayoumi et al., 2022).

4.3. Environmental flow

The first step for a successful restoration project is to get hydrology right by examining the normal hydrologic patterns that control the distribution and successful establishment and growth of targeted mangrove species (Lewis and Marshall, 1997; Lewis, 2005). BahooKalat and Gabrik are intermittent rainfed rivers with non-perennial flow regimes whose flows cease for varying periods with varying predictability following the precipitation pattern. There are more than 200 methods for determining EF, but a few of them are compatible with intermittent or ephemeral rivers (Magand et al., 2020). Each of the methods of EF assessment has its advantages and shortcomings and is highly case-specific, however, due to simplicity and easy application, hydrological methods are most often used to calculate EF (Torabi Haghighi and Kløve, 2017; Operacz et al., 2018). The assessment of the hydrological regime of a river is the first step in the design of EF for the intermittent river as it allows to assess the alteration of the current hydrological regime from its ‘natural’ conditions to find the ‘baseline’ or reference unimpacted regime characteristics for the studied river (Gallart et al., 2012; De Girolamo et al., 2015; Magand et al., 2020). At present, by far the more consolidated method for investigating the hydrological alteration of rivers is the Indicators of Hydrological Alteration (IHA) (Mathews and Richter, 2007). Among the IHAs that have been indicated for characterizing intermittency and flow alteration: zeroflow is considered to be the most relevant indicator regulating the ecosystem services in intermittent rivers (Magand et al., 2020). Also, IHAs describing the dry phase (i.e., the number of months with non-flow) and the magnitude of monthly flow and annual minimum flow (i.e. min flow on 30-day and 90-day duration) must be considered when setting an EF to define the low flow condition, the frequency and timing of the transition phases (Poff et al., 1997; Richter et al., 1996; Gallart et al., 2012; D'Ambrosio et al., 2017). In the present work, the substantial fluctuations observed in the hydrological regime may indicate the inconsistent freshwater supply to the mangrove forest. In line with IHA's guidance, it is recommended to establish an EF criterion that accounts for a minimum 7-day flow duration. However, the analysis conducted using the IHA approach shows that the minimum 7-day flow is absent and prolonged periods of 30 or 90 consecutive days with zero flow are evident. These results revealed that altered hydrological conditions cannot be considered as potential adverse effects on the functioning and health of the mangrove ecosystem. However, including EF in the conservation strategy during prolonged draughts could give an advantage for the estuarine mangroves as Alongi (2015) showed that mangrove forests that get more freshwater experience less stress, and less salinity, and their biomass and productivity are greater. Furthermore, previous studies showed that *A. marina*, while being a highly salt-tolerant species, has been shown to favor 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 and Reef, 2023). Therefore, the proposed allocation of environmental flow during extreme and prolonged draughts can prevent diebacks of mangrove forests and during normal and wet years can lead to mangrove expansion.

4.4. Uncertainty

Climate data (precipitation and temperature) has always been measured by meteorological stations, ground sensors, and remote sensing satellites. An increasing number of satellite measurements are provided by generally accessible data archives. Satellites provide spatial information with a high temporal frequency over wide areas, which makes remotely sensed data an attractive alternative to conventionally collected datasets. However, the uncertainty about the possible errors in remote sensing estimates has been an ongoing concern among users of these products (Karimi and Bastiaanssen, 2015. The quality of satellite data is typically degraded by atmospheric particles, gases clouds, topography, and other limitations imposed by satellite resolution. As opposed to the raw images, the use of pre-processed images published by leading organizations (i.e., NASA, ESA, etc.) reduces most of the atmospheric and topographic noise. Those atmospheric effects that are not removed by corrections (clouds and shadows) are justified by converting data into multi-temporal products (i.e., monthly and annually).

Due to the small size of the mangrove forest in southern Iran, utilizing high spatial resolution satellite images facilitate more accurate mapping. However, in contrast to the previous literature (Mafi-Gholami et al., 2019; Savari et al., 2022), we used MODIS NDVI (250 m) product to monitor the mangrove's health status. Compared to the Landsat Missions, MODIS data products provide a more accurate time series because they are available at frequent intervals. Landsat continuing time series is not possible due to the large existing gaps prior to the Landsat-8 launch date. Although coarse spatial resolution data may reduce the accuracy of estimations, MODIS has the highest spatial detail among high temporal resolution data.

5. Conclusion

Mangrove ecosystems occurring in extreme habitats at species' range edges being so close to their tolerance limits are particularly sensitive to minor variations in hydrological or meteorological regimes. There is an urgent need to develop restoration and management strategies based on a comprehensive understanding of the stress factors underlying mangrove ecosystem dynamics and their responses to environmental and anthropogenic factors. This study is the first attempt to allocate Environmental flow for the mangrove restoration in the estuary of the intermittent river. The results of the analysis of drivers behind mangrove ecosystem health changes using meteorological and water salinity data showed that although mangroves are an evergreen species, the NDVI showed clear seasonality, negatively correlated with temperature and positively correlated with rainfall. Temperature is a key environmental factor affecting the growth and survival of mangrove trees. Therefore, the recommended months for releasing environmental flow are December to March and November to March for Govatr and Gabrik, respectively. The cool season is when the most rainfall occurs in the region and releasing EF during this period means ensuring the flow regimes to which ecosystems have adapted naturally, additionally evaporation is lowest at that time. It is important as in terms of magnitude, releasing EF can be recommended as much as possible; however, we recommend potential evapotranspiration as the minimum EF for releasing. The comparison of alternations in riverside and sea-side cases showed minor differences due to the ephemeral nature of the studied rivers. The fact that they are rainfed makes the precipitation peak and availability of water flow in the river similar. Although the temporal distribution of runoff and river discharge coincide, the spatial distribution of freshwater over mangroves in riverside and sea-side cases varies. EF through the river is a point source of freshwater flow for the mangrove. In contrast, freshwater runoff on seaside locations is widely distributed over a larger area supporting Qeshm mangroves making it the largest mangrove ecosystem along the Persian Gulf shoreline. A thorough understanding of the hydrological requirements of mangroves and their ecosystem function enables policymakers to develop effective management and suggest optimal environmental flow strategies for mangrove restoration. The developed methodology can be used for environmental impact assessment for any coastal ecosystem fed by the intermittent river.

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CRediT authorship contribution statement

Aziza Baubekova: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft, Visualization, Project administration, Writing – review & editing. **Amirhossein Ahrari:** Investigation, Formal analysis, Data curation, Methodology, Writing – review & editing, Visualization. **Hana Etemadi:** Data curation, Writing – review & editing, Validation. **Björn Klöve:** Writing – review & editing, Validation. **Ali Torabi Haghighi:** Conceptualization, Methodology, Writing – original draft, Investigation, Formal analysis, Data curation, Supervision, Funding acquisition, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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