Water and Soil Management and Modeling

Online ISSN: 2783 - 2546

University of Mohaghegh Ardabili

Assessment of climate change and its impact on the hydrological regime of Gorgan Bay Wetland

Behzad Rayegani [1]*, Susan Barati [2], Mona Izadian[3], Farhad Hosseini Tayefeh [3], Seid Ghasem Ghorbanzadeh Zaferani [1], Siavash Shamsipour[4]

[1] Research Group of Environmental Assessment and Risk, Research Center for Environment and Sustainable Development (RCESD), Department of Environment, Tehran, Iran

[2] Soil Conservation and Watershed Management Research Institute (SCWMRI), Agricultural Research, Education and Extension Organization (AREEO), Tehran, Iran

[3] Research Group of Biodiversity and Biosafety, Research Center for Environment and Sustainable Development (RCESD), Department of Environment, Tehran, Iran

[4] Department of Environment, Tehran, Iran

Abstract

Wetlands offer critical ecosystem services, yet they are increasingly threatened by climate change. This study investigates the historical and projected hydrological dynamics of the Gorgan Bay Wetland, located in northern Iran along the Caspian Sea, which is highly sensitive to climate variability and upstream water management. Landsat imagery from 1984 to 2022, combined with field surveys and bathymetric modeling, was used to estimate changes in surface area and water volume. Spectral indices (NDWI, MNDWI) facilitated wetland delineation, while field-measured water depths informed volumetric analyses using TIN modeling. Climate variables, including temperature, precipitation, and snow-water equivalent, were obtained from the TerraClimate database. Pearson correlation and regression analyses assessed the impact of climatic factors, revealing a strong negative relationship between maximum temperature and both wetland area ($r = -0.496$) and volume ($r = -0.479$), and a positive correlation with snow water equivalent ($r = 0.400$). Results indicate a 24% reduction in surface area and a 47% decline in volume from 2015 to 2022. Scenario-based projections using IPCC AR6 (SSP2-4.5) suggest a 1.3–1.8°C rise in temperature by 2040, potentially reducing wetland area by approximately 4,494 hectares. Under higher-emission scenarios, losses could be more severe. These findings highlight the vulnerability of the wetland to ongoing warming and stress the need for adaptive water management strategies. Recommendations include increased environmental water allocations and modernized upstream irrigation. This study offers a robust, integrative framework for assessing climate-driven wetland change and supports policy efforts aimed at sustainable ecosystem management.

Keywords: Water depth, Storage volume, Landsat, Time series analysis, Wetland area

Article Type: Research Article

Academic Editor: Zainab Hazbavi

*Corresponding Author, E-mail: bhz.ray@gmail.com

Citation: Rayegani, B., Barati, S., Izadian, M., Hosseini Tayefeh, F., Ghorbanzadeh Zaferani, S. G. and Shamsipour, S. (2025). Assessment of Climate Change Transformations and Their Impact on the Hydrological Regime of Gorgan Bay Wetland. Water and Soil Management and Modelling, 5(Special Issue: Climate Change and Effects on Water and Soil), 1-17.
doi: 10.22098/mmws.2025.17004.1568
Received: 16 March 2025, Received in revised form: 3 May 2025, Accepted: 1 June 2025., Published online: 22 June 2025
Water and Soil Management and Modeling, Year 2025, Vol. 5, Special Issue, pp. 1-17

Publisher: University of Mohaghegh Ardabili

1. Introduction

Wetlands, as multifunctional ecosystems, provide valuable services such as flood regulation, water purification, carbon storage, and biodiversity conservation. Additionally, they play a crucial role in mitigating climate change impacts, reducing erosion, enhancing water resources, and creating diverse habitats for various species. In many regions, the economic value of regulatory services provided by wetlands, such as runoff control and pollutant filtration, is also highly significant, as these functions are key to environmental sustainability and the well-being of local communities (Nyandwi & Ndikubwimana, 2024).

However, multiple lines of evidence indicate that many wetlands worldwide have experienced shrinkage or reductions in water volume in recent decades due to climate change-related factors, including rising temperatures, altered precipitation patterns, and intensified extreme events. Case studies have shown that, in certain wetlands, increasing temperatures and declining precipitation may lead to seasonal drying by mid-century and a permanent reduction in water levels by the end of the century. Hydrological modeling in certain wetland basins has demonstrated that, under current climate change trends, wetlands may gradually transition into seasonal water bodies, posing a serious threat to the sustainability of their dependent ecosystems (Mahdian et al., 2024). The decline in wetland water levels and surface area not only limits habitats for plant and animal species but also weakens key ecosystem functions such as flood control and livelihood support for local communities. Research has shown that the shrinkage of wetlands due to climate change and human exploitation has led to declining water quality, losses of natural habitat, and reduced ecosystem service values (Das et al., 2021).

This trend not only affects biodiversity and hydrological functions but also has profound socio-economic implications for communities dependent on these ecosystems, particularly in sectors such as agriculture, fisheries, and water supply. Studies indicate that the reduction in wetland area leads to decreased water storage capacity and lower income for local populations reliant on natural resources. Wetland water loss, coupled with changes in hydrological patterns, has resulted in declining agricultural productivity, declining fish stocks, and heightened food security risks in many regions. This challenge is particularly significant in countries where the livelihoods of many residents are directly tied to wetland resources (Baguma & Barakagira, 2023). Coastal wetlands, in particular, face heightened vulnerability due to the combined effects of sea level fluctuations, upstream river inflows, and anthropogenic pressures. Studies have shown that sea level changes, coupled with declining sediment inputs from rivers and increased human exploitation, can accelerate the degradation of these ecosystems. Specifically, the phenomenon known as "coastal squeeze" and intensified erosion in coastal wetlands reduce their long-term stability and, in some areas, have led to the widespread loss of these ecosystems (Wen & Hughes, 2022).

A comprehensive understanding of wetland hydrological dynamics over time requires continuous monitoring of both water surface extent and depth. While field measurements of discharge or depth provide high accuracy, they often lack sufficient spatial coverage and offer only a partial representation of a wetland's actual behavior. In this regard, the integration of remote sensing technologies and numerical modeling can provide a more comprehensive depiction of water level variations and wetland hydrology. Studies have shown that combining satellite imagery with hydrological models not only enables the reconstruction of historical wetland water level trends but also facilitates precise monitoring of water fluctuations in data-scarce regions (Chen et al., 2021). Remote sensing with satellite imagery—particularly the Landsat mission, which has provided a continuous dataset since the 1980s—allows for the systematic extraction of shorelines and water boundaries on a regional scale. The analysis of spectral indices such as NDWI and MNDWI, or the use of pixel classification methods, are common approaches for detecting water surfaces and their seasonal or annual variations. Research has demonstrated that automated methods based on spectral indices and satellite image processing algorithms, especially those utilizing Landsat data, offer high accuracy in distinguishing water bodies from other land cover types (Rajeswari & Rathika, 2024).

However, relying solely on two-dimensional (surface-based) data without considering actual depth and wetland water volume may limit our understanding of wetland vulnerability to climate change. Therefore, integrating remote sensing data (for delineating water boundaries) with field depth measurements and bathymetric mapping provides a more holistic approach to wetland hydrological studies. Research has shown that merging satellite imagery with field observations not only improves the accuracy of wetland water level estimations but also enhances our ability to analyze wetland hydrological responses to climate change and inform water resource management strategies (Trabelsi & Abida, 2024). Furthermore, investigating the linkage between climate change and changes in wetland volume or surface area requires access to long-term climatic datasets. Databases such as TerraClimate have provided essential information on temperature, precipitation, evapotranspiration, and drought indices in recent decades, enabling the assessment of long-term trends and correlation analyses between these climatic parameters and wetland hydrological behavior. Studies have utilized data from this database to analyze changes in temperature and precipitation, as well as to examine their effects on hydrological variables such as runoff, actual evapotranspiration (AET), and climatic water deficit (DEF). The use of TerraClimate data in long-term analyses has allowed researchers to better identify climate change trends and evaluate their impacts on sensitive ecosystems such as wetlands (Singha et al., 2023).

Additionally, to understand the future trajectory of wetlands under various temperature rise and precipitation change scenarios, outputs from General Circulation Models (GCMs) in the latest IPCC AR6 reports can be employed. By applying downscaling techniques or climate change factors, the impacts of different greenhouse gas emission scenarios on wetland behavior can be modeled. Research has shown that downscaling techniques, such as statistical and dynamic models, enhance the spatial and temporal resolution of GCM data, making climate simulations more precise for regional and local applications (Gergel et al., 2024).

Along the southern Caspian Sea coast, the Gorgan Bay Wetland serves as a prime example of a climate-vulnerable ecosystem due to its coastal location and dependence on freshwater inflows from upstream rivers. Studies have shown that fluctuations in the Caspian Sea level, combined with reduced river inflows and intensified sedimentation and coastal erosion processes, have significantly contributed to the reduction of this wetland's surface area. Satellite imagery and field data analyses indicate that, in recent decades, large sections of this wetland have dried up due to water level declines and the closure of water exchange pathways with the Caspian Sea (Khoshravan et al., 2021). Therefore, assessing the climatic and hydrological conditions of this wetland is essential for safeguarding its ecosystem functions.

Previous research has primarily focused on shoreline changes or the drying trends of water bodies, with limited efforts to simultaneously estimate both wetland surface area and volume while directly analyzing climate parameters. Therefore, the present study aims to integrate Landsat data, in situ depth measurements, bathymetric mapping, and TerraClimate datasets to investigate the historical and future hydrological regime of the Gorgan Bay Wetland. The findings are expected to reveal the significant role of climate factors (such as temperature rise and drought) on wetland expansion or contraction and provide evidence-based management strategies aligned with different greenhouse gas emission scenarios to preserve the ecological and economic functions of this wetland.

The study specifically addresses the following questions:

- How have climate variations influenced wetland surface area and volume over recent decades?
- What are the projected hydrological changes in the wetland under different emission scenarios?
- How can satellite data and field observations be integrated to support wetland management?

2. Material and Method

2.1. Study Area:

The Gorgan Bay Wetland is located along the southeastern coast of the Caspian Sea, with its hydrodynamics largely influenced by water exchange with the sea and freshwater inflows from upstream rivers (Khoshravan et al., 2021). The regional climate is shaped by the humid air masses from the Caspian Sea and the dry air masses of Central Asia, leading to significant seasonal variations in temperature and precipitation. Studies indicate that fluctuations in the Caspian Sea level, along with human activities in upstream watersheds, have played a crucial role in the wetland's expansion and contraction trends.

2.2. Methodology:

To evaluate climate variability and its impact on the hydrological regime of the wetland, this study utilized remote sensing data, field measurements, and regional climate information (Figure 4).

2-2-1- Remote Sensing Data and Wetland Boundary Extraction:

Monitoring changes in wetland surface area using Landsat satellite data and remote sensing techniques is a key approach for assessing hydrological dynamics in such ecosystems. Research has demonstrated that processing Landsat imagery and utilizing time series datasets from TM, ETM+, and OLI sensors can provide high accuracy in assessing wetland area fluctuations. These methods also allow for the evaluation of hydrological variables and land-use changes affecting wetlands (Berhanu et al., 2021; Ehsani & Shakeryari, 2021).

For this study, Landsat Level-2 surface reflectance images were employed, which include radiometric and atmospheric corrections (Meghrajk et al., 2023). These Level-2 products, particularly those atmospherically corrected, have been widely used for analyzing surface changes and aquatic ecosystems. Recent studies have confirmed the accuracy of Landsat 8 and 9 Level-2 products using field-based validation methods, demonstrating their high precision in estimating surface reflectance (Mann et al., 2024).

To delineate water bodies, spectral indices such as NDWI (Normalized Difference Water Index) and MNDWI (Modified Normalized Difference Water Index) were utilized (Rajeswari & Rathika, 2024). Additionally, regions with potential pixel mixing at water/land boundaries were refined using supervised classification and visual inspection. Studies indicate that MNDWI outperforms NDWI in accurately detecting water boundaries, particularly in coastal areas, rivers, and small water bodies, as it effectively minimizes background noise and interference from other land cover types, thereby improving classification accuracy (Kumari et al., 2024).

Finally, for each target year/period, the wetland shoreline was extracted and stored as a GIS shapefile for further spatial analysis.

The NDWI and MNDWI indices were calculated using the following formulas:

$$\mathrm{NDWI} = \frac{\mathrm{G} - \mathrm{NIR}}{\mathrm{G} + \mathrm{NIR}} \quad (1)$$

$$\mathrm{MNDWI} = \frac{\mathrm{G} - \mathrm{SWIR1}}{\mathrm{G} + \mathrm{SWIR1}} \quad (2)$$

Where: G = Green band reflectance, NIR = Near-infrared band reflectance, SWIR1 = Shortwave infrared band 1 reflectance. A threshold close to zero was applied to classify water pixels, and the results were validated using field-based ground control points.

2.2.2. Field-Based Depth Measurements and Bathymetric Mapping

To develop a bathymetric map of the wetland, a field survey was conducted during the reference year on October 4–5, 2022. In this operation, a GPS-equipped boat with a differential GPS receiver and a digital depth sounder (Figure 1) was used to record numerous sampling points across the wetland. For each point, geographical coordinates (X, Y) and water depth (Z) were collected (Figure 2).

Research has demonstrated that sonar-based depth measurement technologies combined with GPS offer reliable accuracy for monitoring underwater topographic changes and analyzing sedimentation and erosion processes. These methods provide rapid and extensive measurement coverage while maintaining high precision, especially in shallow water environments (Bradbury et al., 2023).

Simultaneously, topographic surveys along cross-shore transects were conducted to determine bed slope variations in nearshore areas (Figure 3). This step was particularly important in regions where the wetland shoreline had advanced or retreated between consecutive years, requiring continuous depth assessments along the shoreline profile.

At the water-land boundary, determined from Landsat imagery, additional zero-depth points were recorded to improve interpolation accuracy and ensure a stable shoreline reference.

Figure 1: Depth measurement operation in the Gorgan Bay Wetland and Miankaleh.

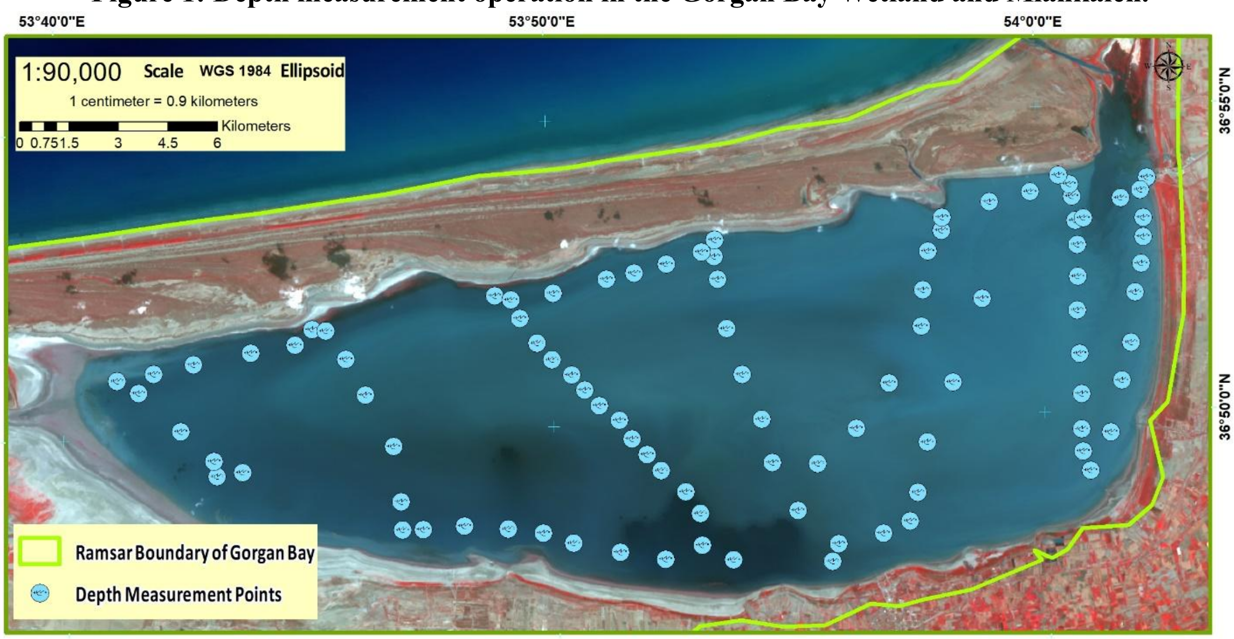

Figure 2: Depth sampling points in the Gorgan Bay Wetland and Miankaleh.

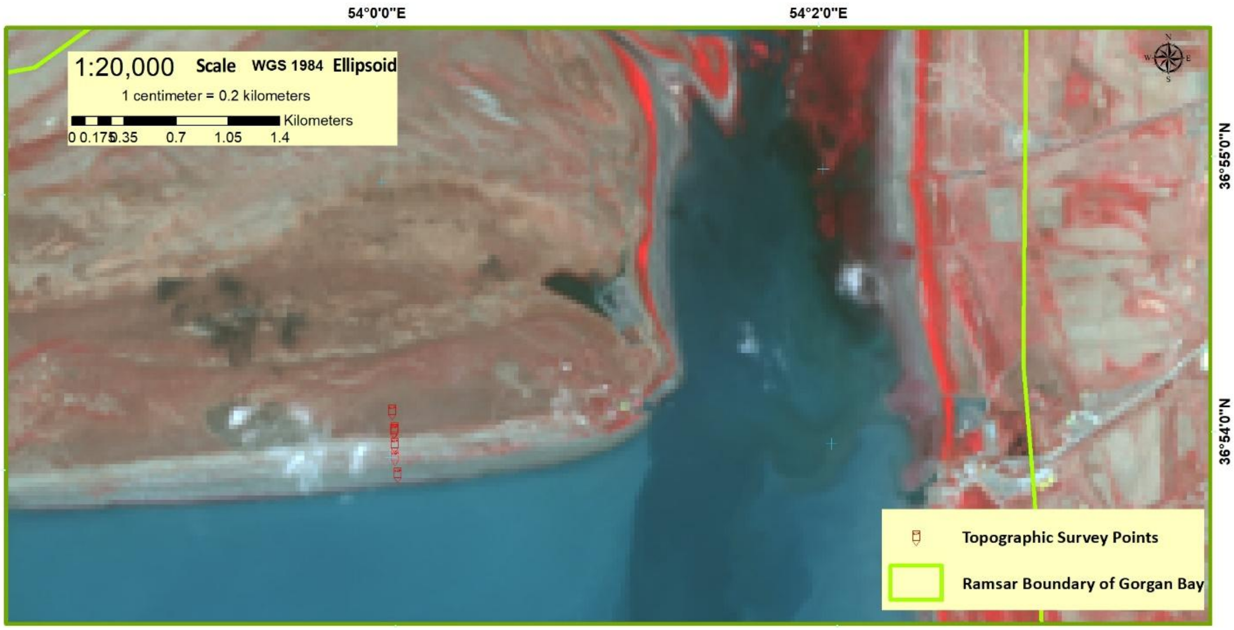

Figure 3: Field-based topographic survey points along the wetland shoreline.

2.2.3. Depth Map Interpolation for the Reference Year

To generate the depth map for the reference year, the Spline interpolation method was applied in a GIS environment. This method, based on actual depth measurements from field surveys and the assignment of zero-depth points at the wetland boundary, produces a continuous representation of the wetland bed elevation. Studies have shown that Spline interpolation, due to its minimal fluctuations in the resulting curves, provides greater accuracy compared to other interpolation methods when estimating depth in aquatic environments. By continuously distributing sampled depth data across the entire study area, this approach allows for a more precise estimation of wetland bathymetry (Hariski et al., 2024).

Spline interpolation is classified as an exact interpolation method, meaning that the interpolated surface passes precisely through the sampled data points without estimation errors at those locations. This characteristic enhances the accuracy of hydrological models, particularly in predicting water level and reservoir depth variations. Additionally, comparative analyses of different interpolation methods indicate that Spline interpolation often outperforms other approaches such as Inverse Distance Weighting (IDW) and Kriging, particularly in wetland studies (Igaz et al., 2021).

- Depth Map Adjustment for Other Years

In the next step, for past or future periods where field depth data were not available, a combination of the following procedures was applied:

1- Wetland boundaries for each year were extracted from Landsat imagery.

2- Depth adjustments were applied to points that either entered or exited the wetland area based on the bathymetric slope profiles obtained from localized topographic shoreline surveys (Figure 3).

3- Studies have shown that combining depth measurements with Spline interpolation significantly improves depth map accuracy, especially in shallow water zones (Dewi et al., 2022; Lawen et al., 2022).

Since the reference year represented the lowest wetland extent, in all other years, the water body covered a larger surface area, submerging portions of the surveyed shoreline. When water levels advanced toward the shore, newly inundated areas were detected using Landsat imagery. In such cases, the previous shoreline (reference year boundary) was assigned a non-zero depth based on slope equations derived from ground surveys. Similarly, depth values within

the wetland were adjusted for each year based on this methodology.
After revising depth values for boundary and in-wetland points, the Spline interpolation method was reapplied to generate a continuous depth map for each period. This resulted in a time series of depth maps, enabling the assessment of wetland hydrodynamic variations over time.

-Reservoir Volume Estimation
To estimate the wetland's reservoir volume, the final depth map for each year was converted into a Triangulated Irregular Network (TIN) model within the GIS environment. The volume calculation method, which integrates bathymetric topography with Landsat-derived wetland boundaries, was applied to calculate annual volume changes.
This approach has been proven to provide high accuracy in assessing reservoir volume variations over consecutive periods. Research indicates that the combination of TIN modeling and remote sensing data is highly effective in analyzing wetland volume change trends, making it a valuable tool for water resource management in vulnerable wetlands (Ahmed et al., 2021).
Finally, time-series datasets for both wetland surface area (derived from water boundaries) and reservoir volume were generated for consecutive periods, providing a comprehensive understanding of hydrological fluctuations.

2.2.4. Climate Data and Meteorological Analysis

To assess the impacts of climatic variations on wetland surface area and reservoir volume, monthly data from the TerraClimate database were utilized. This dataset provides a range of climatic variables, including minimum and maximum temperature, precipitation, potential evapotranspiration (PET), actual evapotranspiration (AET), climatic water deficit (DEF), and the Palmer Drought Severity Index (PDSI) over long-term periods (Abatzoglou et al., 2018; Singha et al., 2023). The accuracy of TerraClimate data in the study area was validated using observations from Gorgan, Tirtash, and Tahqiqat-e-Baykaleh stations for the period 2000–2022. Results showed high consistency, with correlation coefficients above 0.9 for temperature and over 0.7 for precipitation (see supporting study).
After extracting climatic data for the wetland's upstream watersheds, statistical tests—including Pearson correlation, Mann-Kendall trend analysis, and least squares regression—were employed to determine the extent to which each climatic parameter influenced wetland water level and volume variations. Studies have demonstrated that applying statistical models and regression techniques to analyze the effects of climate change on wetland water storage is a robust method for predicting long-term hydrological trends. Notably, multivariate regression models have revealed significant relationships between precipitation, temperature, and wetland water storage changes, highlighting their relevance for water management policies (Cui et al., 2021).

2.2.5. Modeling and Future Scenario Projections

To project the future state of the Gorgan Bay Wetland under various climate change scenarios, data from General Circulation Models (GCMs) included in the IPCC’s Sixth Assessment Report (AR6) were used. Specifically, ensemble median outputs from the CMIP6-based projections provided in the IPCC AR6 Interactive Atlas, for the baseline period 1995–2014 and projection period 2021–2040.
The study incorporated four major greenhouse gas emission scenarios:
-SSP1-2.6 (low-emission, sustainable development)
-SSP2-4.5 (moderate-emission, intermediate scenario)
-SSP3-7.0 (high-emission, regional rivalry)
-SSP5-8.5 (very high-emission, fossil-fuel dependent)
These scenarios were selected to capture a wide range of uncertainties in greenhouse gas emissions. Modeling results reveal that different climate scenarios can lead to significant changes in temperature and precipitation patterns. In coastal regions, rising temperatures, coupled with decreasing seasonal precipitation, may result in substantial alterations to wetland water levels (Toombs et al., 2023).
To improve model accuracy at the local scale, statistical downscaling techniques were applied.

For temperature, a simple change factor (SCF) method based on additive anomalies was used. For precipitation, a multiplicative scaling method based on proportional change was applied. This method adjusts GCM outputs by computing the difference between historical observational data (e.g., TerraClimate) and GCM outputs for a baseline period, and then applying these differences to future projections to generate regionally adapted climate scenarios. Recent studies have shown that statistical downscaling methods offer greater reliability in maintaining climate change trends and aligning GCM outputs with local climatic conditions (Gergel et al., 2024).

Using the significant climatic parameters identified in the correlation and regression analyses, multivariate regression models and long-term scenario-based modeling were employed to simulate potential wetland area and volume changes for future periods. Given the inherent uncertainty of climate models, a combination of different scenario outputs was used, and median values were computed to reduce prediction errors. Recent studies suggest that CMIP6-based models (used in AR6) provide more accurate regional-scale climate change projections and outperform previous-generation models in predicting hydrological changes in wetlands (Kim & Villarini, 2024).

2.2.6. Final Analysis and Management Strategies

This study highlights the critical influence of climatic variability, particularly fluctuations in precipitation and surface temperature, on the hydrological stability of the Gorgan Bay Wetland. By comparing current wetland conditions with future projections under various climate scenarios, the research identifies areas most vulnerable to increased drought risk and temperature rise. These insights provide a scientific foundation for evidence-based decision-making in regional planning. Key management recommendations emerging from the findings include enhancing water resource governance, adjusting crop patterns based on hydrological forecasts, optimizing environmental water allocation, and strengthening conservation strategies to support wetland resilience. The integrated use of remote sensing, field-based depth measurements, and climate data supports the development of robust and adaptive management frameworks for sustainable wetland conservation under climate change.

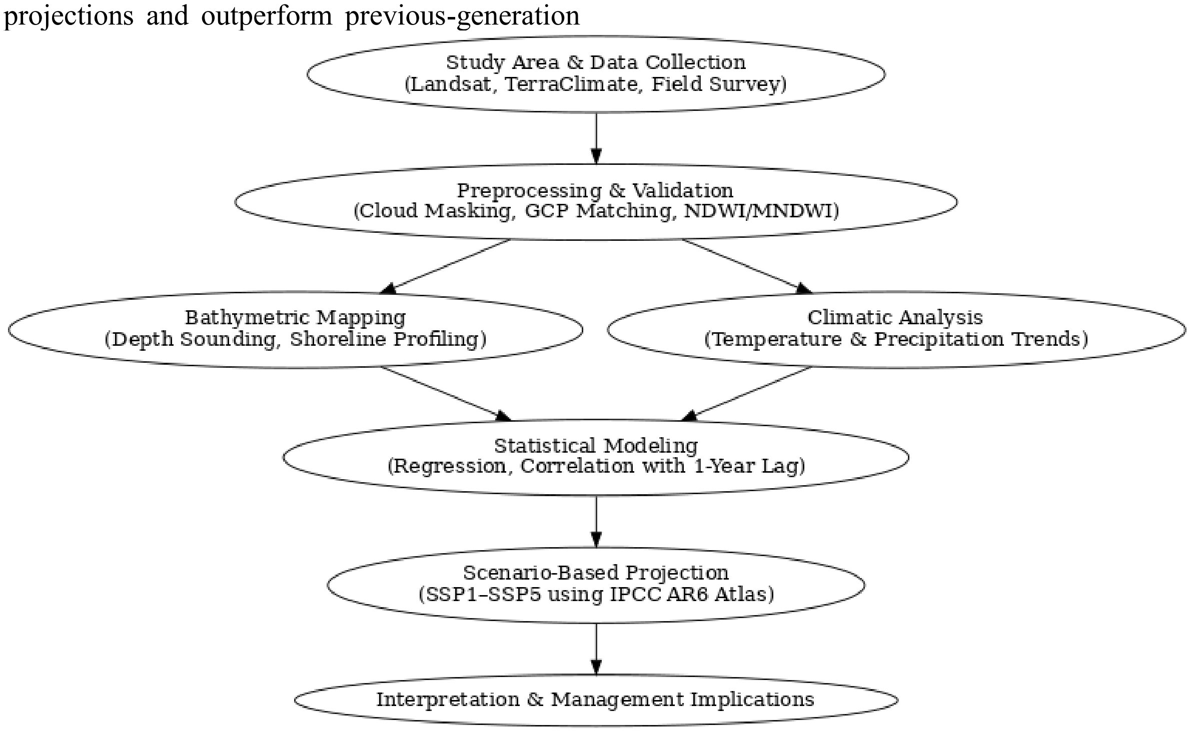

Figure 4: **Workflow of the study showing the key stages from data collection to scenario-based analysis and management implications.**

3. Results and Discussion

3.1. Data Validation and Initial Results

As a first step, TerraClimate data for temperature, precipitation, and related indices were extracted for the upstream watersheds of the Gorgan Bay Wetland. These data were compared with meteorological records from three local stations: Gorgan, Tirtash, and Tahqiqat-e-Baykaleh. Pearson correlation analysis and Root Mean Square Error (RMSE) assesments demonstrated strong agreement between satellite-derived and ground-based measurements, with correlation coefficients above 0.9 for temperature and above 0.7 for precipitation. Recent studies have also confirmed that TerraClimate data offer reliability in estimating climatic variables, especially in arid and semi-arid regions where ground stations are sparse (Bachidi et al., 2023).

As a result, the validated dataset and threshold calibration facilitated accurate delineation of wetland boundary, forming the foundation for volume calculations and historical trend analysis in subsequent research stages.

3.2. Historical Trends in Wetland Area and Volume

The time-series analysis of wetland surface area (extracted from Landsat imagery) revealed substantial fluctuations over the study period (Figure 5).

From 1984 to 1995, the wetland experienced a slight expansion in both surface area and volume. Since 2010, a sharp decline has been observed in both variables.

The most severe reduction occurred between 2015 and 2022, with wetland surface area shrinking from approximately 44,000 hectares in 2014 to less than 29,000 hectares in 2022—a more than 30% decrease compared to long-term averages.

Although some temporary recoveries were noted in 2012, 2013, 2016, 2017, and 2020, these were short-lived and seasonal, followed by continued wetland retreat due to prolonged droughts.

These findings align with recent research, which identifies global warming, reduced precipitation, and altered runoff patterns as key drivers of wetland shrinkage (Hemati et al., 2022).

Moreover, an analysis of depth and volume maps revealed that surface area reduction is not the sole factor contributing to wetland water storage loss; rather, the topographic structure of the wetland bed plays a significant role in determining the severity of these changes.

- In the western and southern sections of the wetland, where low-gradient terrain are observed (Figure 6), a decrease in water levels has led to a dramatic decline in reservoir volume (Figure 5).
- Correlation analysis between surface area and volume indicated that over 96% of wetland volume variations are directly linked to water surface changes, but the magnitude of change varies in certain periods.
- For example, from 2015 to 2022, the wetland area decreased by approximately 35%, yet reservoir volume declined by over 45%, underscoring the high sensitivity of shallow coastal wetlands to water loss.

3.3. Future Projections and Implications

Regression models indicate that if the current trend persists, a further decline in wetland area below 25,000 hectares could reduce reservoir volume to below 200 million cubic meters, representing a 75% decrease compared to previous decades. Similar studies in other wetlands (e.g., Leiva-Piedra et al., 2024) have projected severe volume loss under ongoing climate stress. Although these results are site-specific, they highlight the potential risks faced by coastal wetlands, including Gorgan Bay.

These results particular susceptibility of coastal wetlands with gentle bathymetric gradients, especially in arid and semi-arid regions, are highly vulnerable to climate change and human interventions. Studies have shown that water resource limitations and extreme climatic fluctuations have, in some cases, driven wetland area and volume changes beyond historical variability. Without effective conservation policies, these ecosystems may face severe environmental degradation and ecological instability in the near future (Fahrländer et al., 2024).

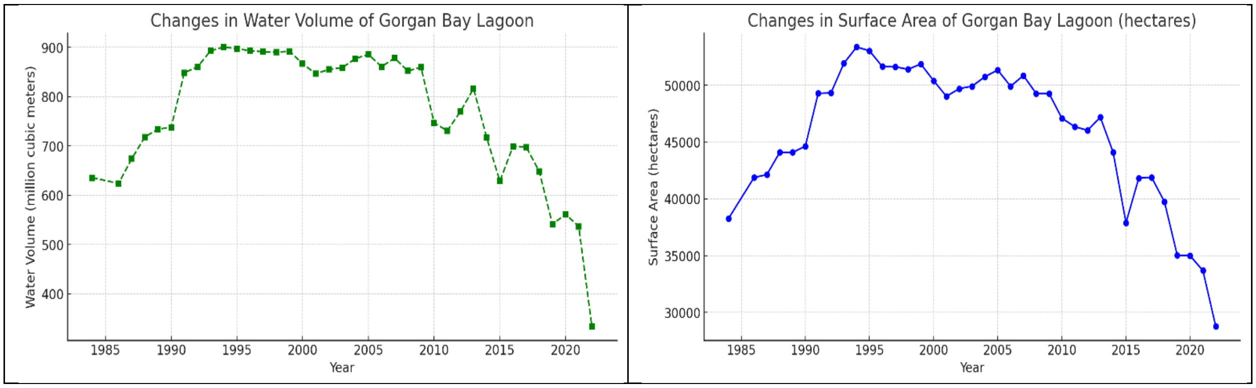

Figure 5. Changes in surface area (right) and volume (left) of the Gorgan Bay Wetland from 1984 to 2022.

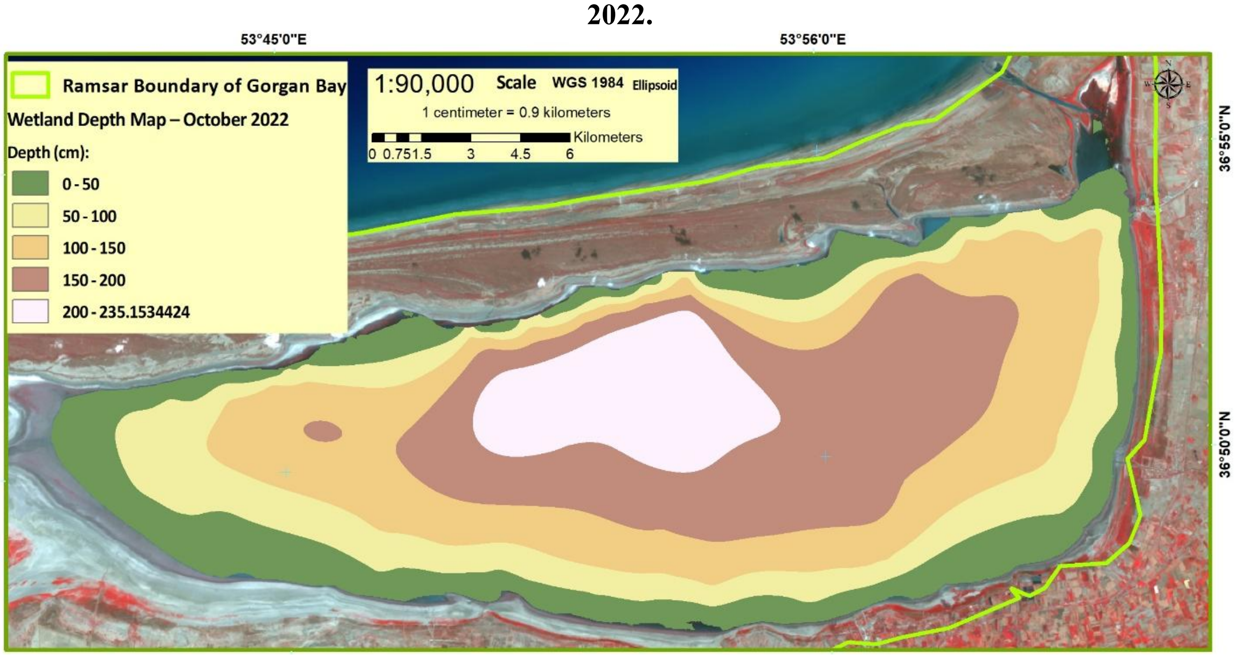

Figure 6. Estimated depth map derived from field sampling points in the Gorgan Bay Wetland using Spline interpolation (October 2022).

3.4. Relationship with Climatic Parameters

To identify the climatic factors influencing variations in the surface area and volume of the Gorgan Bay Wetland, Pearson correlation analysis was conducted between wetland extent, volume, and key climatic variables from TerraClimate, using a lag analysis of 1 to 3 years. The strongest and most statistically significant correlations were observed at a one-year lag (Lag 1), which was therefore used for the final interpretation (Table 1):

- Annual maximum temperature exhibited a significant negative correlation with both surface area ($r = -0.496$, $p < 0.01$) and wetland volume ($r = -0.479$, $p < 0.01$). This indicates that rising temperatures lead to increased evaporation and evapotranspiration, ultimately reducing both the surface area and the water volume. Recent studies confirm that global warming significantly reduces surface water resources in wetlands, particularly in arid and semi-arid regions, due to higher evaporation rates and decreased water inflows (Boldyrev et al., 2023).

- Annual mean temperature showed a similar pattern, with a negative correlation with surface area ($r = -0.476$, $p < 0.01$) and volume ($r = -0.482$, $p < 0.01$). This emphasizes that regional warming contributes to wetland shrinkage by intensifying evaporation intensity, reducing runoff, and altering hydrological cycles.

- Snow Water Equivalent (SWE) displayed a positive correlation with surface area ($r = 0.400$,

$p < 0.05$) and volume ($r = 0.410$, $p < 0.05$). This suggests that greater snow accumulation in upstream watersheds enhances wetland inflows, helping to maintain water storage. However, recent studies indicate that declining SWE trends in many regions have led to reduced surface runoff and decreased stream flow predictability and water resources, all of which severely impact wetland hydrology and ecological stability (Modi et al., 2022).

- Potential Evapotranspiration (PET) showed a negative correlation with surface area ($r = -0.374$, $p < 0.05$) and volume ($r = -0.358$, $p < 0.05$). This result aligns with expectations, as higher PET leads to greater water loss and wetland retreat. Recent studies indicate that increasing PET levels, particularly in arid and semi-arid regions where evaporation exceeds precipitation, play a major role in wetland depletion, imposing additional stress on water resources and aquatic ecosystem sustainability (Zheng et al., 2024).

- Climatic Water Deficit (DEF) exhibited a negative correlation with wetland surface area ($r = -0.335$, $p < 0.05$). This suggests that years with higher climatic water deficits correspond to greater wetland contraction. The results confirm that the Gorgan Bay Wetland is highly sensitive to climatic fluctuations and recurring droughts, during years of severe water deficit, the wetland experienced substantial shrinkage.

Palmer Drought Severity Index (PDSI) did not show a statistically significant correlation at the 0.05 level, but its correlation with surface area ($r = 0.303$, $p = 0.072$) and volume ($r = 0.285$, $p = 0.092$) suggests a general trend where wetland shrinkage corresponds to drier years. Since PDSI primarily reflects long-term drought trends, short-term fluctuations may not fully capture rapid wetland changes.

Overall, the findings indicate that rising temperatures, declining snow water equivalent, and increasing PET are the primary drivers of wetland surface and volume reduction in recent years. If global warming and water resource declines continue, wetland contraction is expected to intensify in the coming decades. Therefore, effective water resource management and reducing upstream runoff extractions are critical for maintaining wetland ecosystem stability.

Table 1. Pearson Correlation Between Annual Wetland Changes (Surface Area and Volume) and Climatic Parameters Across All Sub-Watersheds

Variable	Surface Area	Volume	Annual Max Temperature	Annual Mean Temperature	Snow Water Equivalent (SWE)	Potential Evapotranspiration (PET)	Palmer Drought Severity Index (PDSI)	Climatic Water Deficit (DEF)
Surface Area	1	.985**	-.496**	-.476**	.400*	-.374*	.303	-.335*
Volume	.985**	1	-.479**	-.482**	.410*	-.358*	.285	-.310
Sig. (2-tailed)		.000	.002	.003	.016	.024	.072	.046
N	37	37	36	36	36	36	36	36

Significance Levels: *$p < 0.05$, **$p < 0.01$, Note: Higher PET and temperature lead to wetland shrinkage, while greater SWE supports wetland water storage.

3.5. Future Projections Under Different Scenarios

Using stepwise regression, annual maximum temperature was identified as the best predictor of the Gorgan Bay Wetland surface area. Scenario-based projections of greenhouse gas emissions and their impact on annual maximum temperature indicate that, over the next 20 years, temperature increases are expected to range between 1.3°C and 1.8°C across most scenarios (Figure 7).

Based on the regression equation derived from historical wetland data, it was determined that for every 1°C increase in annual maximum temperature, the wetland loses approximately 3,280 hectares (Figure 8). Under the mean scenario (excluding SSP2 outliers), with a 1.37°C rise in maximum temperature, the wetland's surface area is projected to shrink by approximately 4,494 hectares. Given that the average wetland area over the past five years has been around 35,000 hectares, this decline would correspond to a 12.8% reduction in the current wetland extent. Although volume change was not directly modeled due to limited temporal depth observations, the strong correlation between wetland surface area and volume supports the use of surface trends as a reliable indicator of hydrological variation.

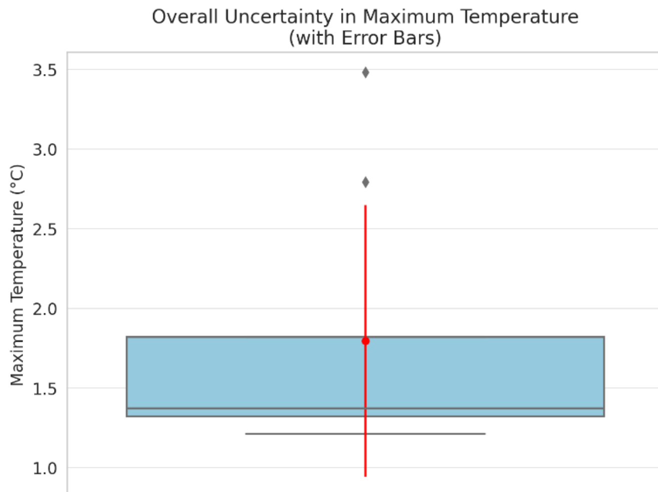

Figure 7: Cumulative Boxplot of Annual Maximum Temperature Changes Across Different Emission Scenarios (Next 20 Years)

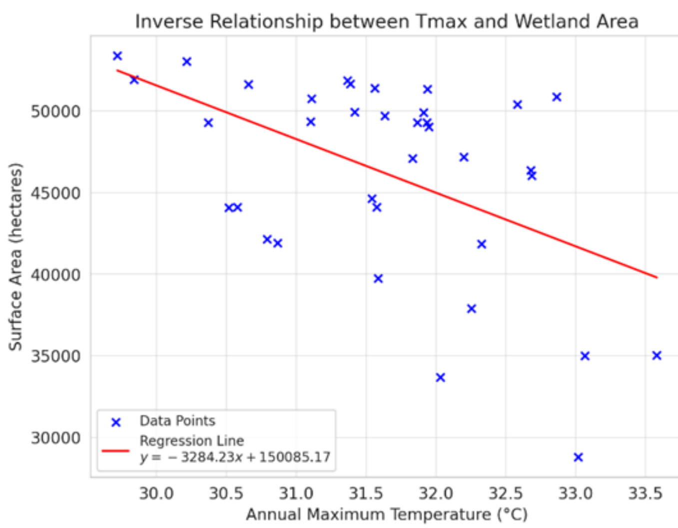

Figure 8: Relationship Between Wetland Surface Area and Maximum Temperature (Averaged Across All Sub-basins of the Gorgan Bay Wetland)

In high-emission scenarios such as SSP3-7.0 and SSP5-8.5, the increase in maximum temperature could exceed 1.8°C, leading to more severe wetland shrinkage (5,894 hectares, this corresponds to a projected decline of about 16.8%), accelerated evaporation rates, and exacerbated water resource shortages. Studies on other coastal wetlands indicate that rising temperatures, combined with reduced soil moisture and shifts in precipitation regimes, can intensify wetland retreat and place dependent habitats at severe risk (Chen et al., 2023).

Overall, these findings highlight that if climate warming trends continue, the Gorgan Bay

Wetland will experience significant surface loss in the coming decades. Such changes will not only alter the wetland's hydrodynamic balance but could also negatively impact water quality, salinity levels, sedimentation patterns, and regional ecological stability. Increased frequency and intensity of extreme events, such as droughts and floods, could make the wetland ecosystem even more vulnerable to future climate shifts.

Thus, sustainable water resource management and the development of climate adaptation policies will be essential to mitigate the environmental and ecological consequences of these trends (Shin et al., 2023).

3.6. Interpretation of Results and Management Strategies

A) Clear Link Between Climate Change and Wetland Storage Decline

A synthesis of historical data and future projections confirms that the Gorgan Bay Wetland is influenced not only by Caspian Sea level fluctuations but also by climate change, particularly rising temperatures and increasing drought severity, which play a major role in wetland volume and area loss. Recent studies highlight that reduced precipitation and increased evapotranspiration have significantly impacted similar water bodies, with seasonal water availability trends becoming increasingly climate-dependent (Rostami et al., 2024).

Therefore, integrated watershed management, along with optimization of agricultural and urban water use, is crucial to mitigating negative impacts and preparing for future climate scenarios.

B) The Need for Environmental Water Allocation

Correlation analysis between climatic water deficit (DEF) and wetland area/volume reveals that during drought years, even slight reductions in water inflows can result in significant wetland contraction. Reduced runoff and declining snow reserves in upstream watersheds, particularly in warmer seasons, limit minimum environmental flows, placing the wetland at risk of extensive desiccation.

Similar studies emphasize that sustaining minimum environmental flows in wetland-feeding rivers, especially during low-water periods, is critical. Under high-emission scenarios, implementing mandatory mechanisms for water use regulation and controlling illegal withdrawals will be key to ensuring wetland sustainability (Assani et al., 2022).

C) The Urgent Need for Agricultural Land-Use Reform

Rising temperatures, increased evapotranspiration, and climatic water deficits are likely to pose major challenges for traditional agriculture in upstream basins. Recent research suggests that higher temperatures and hydrological imbalances can increase crop water demands, jeopardizing agricultural system sustainability.

Reducing agricultural reliance on water-intensive irrigation, promoting drought-resistant crop varieties, and adopting modern irrigation management techniques—such as drip irrigation and smart irrigation systems—are effective strategies to reduce pressure on wetland water resources and enhance agricultural resilience to climate change (Moyers et al., 2024).

D) Research Outlook and Limitations

This study integrates remote sensing, field monitoring, and climatic analyses, providing a comprehensive assessment of wetland hydrological changes. However, several limitations influenced the findings, including:

- **Climate model uncertainties**
- **Land-use changes in upstream basins**
- **Caspian Sea level fluctuations**

Recent studies indicate that multi-algorithmic modeling in geohydrological and hydrodynamic systems can reduce structural uncertainties and provide more precise predictions of coastal wetland evolution. Future research should incorporate advanced dynamic-hydrological models that account for groundwater extraction and land-use changes (Tan et al., 2024).

The results of this study underscore the high vulnerability of the Gorgan Bay Wetland to global warming and climatic fluctuations. Integrating time-series monitoring of wetland area and volume with climate data and future scenario modeling can provide decision-makers and water resource managers with critical insights into future risks and help develop effective climate adaptation strategies.

4. Conclusions

The findings of this study indicate that the Gorgan Bay Wetland has experienced a gradual decline in surface area and reservoir volume over recent decades, with this trend intensifying in recent years. Time-series analysis of surface area (based on remote sensing data) and reservoir volume (based on depth interpolation models) revealed that since 2010, the wetland area has decreased by more than 24%, while its water storage volume has declined by over 47% (regression-based estimates suggest area and volume losses of approximately19% and 23%).

The patterns of change indicate that periods of water level decline have primarily coincided with rising temperatures, reduced snow reserves in upstream watersheds, and increased evapotranspiration. Correlation analysis with climatic parameters confirmed that annual maximum and mean temperatures, declining snow water equivalent, and increasing climatic water deficit are the key drivers of wetland shrinkage. These findings are consistent with other coastal wetland studies, which suggest that wetlands in arid and semi-arid regions are highly sensitive to climate change and that rising temperatures and reduced runoff accelerate wetland retreat (Boldyrev et al., 2023).

Future scenario modeling based on greenhouse gas emission projections suggests that in the next 20 years, annual maximum temperatures will increase by 1.3°C to 1.8°C. Given the empirical relationship between temperature rise and wetland area, it is projected that the Gorgan Bay Wetland will lose approximately 4,494 hectares of its surface area during this period, equating to 12.8% of its five-year average extent. In high-emission scenarios (SSP3-7.0 and SSP5-8.5), this decline could be even more severe, with profound impacts on the wetland ecosystem, sedimentation dynamics, water salinity, and biological resources. Previous analyses have also demonstrated that wetland loss at this scale can lead to species composition shifts, increased desertification risk in surrounding areas, and significant reductions in the regulatory functions of wetlands.

4.1. Recommendations for Wetland Conservation

The results of this study underscore the necessity of sustainable water resource management and the reduction of upstream runoff extractions to preserve the wetland's ecological integrity. Based on the findings, the following recommendations are proposed for the conservation of the Gorgan Bay Wetland:

1- Environmental water allocation to maintain minimum water levels, especially during dry and low-precipitation years.

2- Regulated water withdrawals in upstream basins, focusing on reducing agricultural water consumption and improving irrigation efficiency.

3- Continuous monitoring of wetland surface area and volume using remote sensing data and field measurements to enable informed management decisions.

4- Agricultural land-use reform in surrounding areas to reduce dependency on water resources during drought periods.

5- Climate adaptation strategies at the regional level, incorporating policy measures to mitigate the impacts of rising temperatures and declining runoff.

4.2. Final Outlook

This study presents a comprehensive framework combining remote sensing, field observations, and climate models to assess wetland hydrological trends. However, for future studies, it is recommended to incorporate advanced hydrological models, particularly dynamic and agent-based models, to better simulate surface and volume changes under different climate and management scenarios.

The outcomes of this research can play a key role in future water resource planning, conservation strategies for the Gorgan Bay Wetland, and preventing further loss of this valuable ecosystem.

Author Contributions:

Behzad Rayegani: Modeling, performing software analysis, and writing the initial version of the article.

Susan Barti: Performing software analysis.

Mona Izadian: Cooperation in the preparation and Manuscript editing.

Farhad Hosseini Tayefeh: Preparation of data and information and field visits.

Seid Ghasem Ghorbanzadeh Zaferani: Cooperation in the preparation and discharge information and related information analysis.
Siavash Shamsipour: Controlling the results

Conflicts of interest
The authors of this article declared no conflict of interest regarding the authorship or publication of this article.

Data availability statement:
The datasets are available upon a reasonable request to the corresponding author.

References

A. Assani, A., Zeroual, A., Kinnard, C., & Roy, A. (2022). Spatial–temporal variability of seasonal daily minimum flows in southern Quebec: synthesis on the impacts of climate, agriculture and wetlands. Hydrology Research, 53(12), 1494-1509. doi: 10.2166/nh.2022.070

Abatzoglou, J. T., Dobrowski, S. Z., Parks, S. A., & Hegewisch, K. C. (2018). TerraClimate, a high-resolution global dataset of monthly climate and climatic water balance from 1958–2015. Scientific data, 5(1), 1-12. doi: 10.1038/sdata.2017.191

Ahmed, I. A., Shahfahad, S., Baig, M. R. I., Talukdar, S., Asgher, M. S., Usmani, T., Ahmed, S., & Rahman, A. (2021). Lake water volume calculation using time series LANDSAT satellite data: a geospatial analysis of Deepor Beel Lake, Guwahati. doi: 10.1108/FEBE-02-2021-0009

Baguma, C., & Barakagira, A. (2023). Effects of Wetland Degradation on Community Livelihoods: A Case of Mabengere Wetland in Kisiita Sub County, Kakumiro District, Uganda. Journal of Global Ecology and Environment. doi: 10.56557/jogee/2023/v19i18396

Berhanu, M., Suryabhagavan, K., & Korme, T. (2021). Wetland mapping and evaluating the impacts on hydrology, using geospatial techniques: a case of Geba Watershed, Southwest Ethiopia. Geology, Ecology, and Landscapes, 7, 293-310. doi: 10.1080/24749508.2021.1953744

Boldyrev, S., Levykh, A., & Zamyatin, D. (2023). Wetlands dynamics analysis: a case study of Keoladeo National Park (India), the wintering grounds of West Siberian white crane population. Samara Journal of Science. doi: 10.55355/snv2023123103

Bradbury, G., Puttock, A., Coxon, G., Clarke, S., & Brazier, R. E. (2023). Testing a novel sonar-based approach for measuring water depth and monitoring sediment storage in beaver ponds. River Research and Applications, 39(2), 266-273.

Chen, S., Johnson, F., & Glamore, W. (2021). Integrating Remote Sensing and Numerical Modeling to Quantify the Water Balance of Climate-Induced Intermittent Wetlands. Water Resources Research, 57. doi: 10.1029/2020WR029310

Chen, Y., Wang, L., Shi, X., Zeng, C., Wang, Y., Wang, G., Qiangba, C., Yue, C., Sun, Z., Renzeng, O., & Zhang, F. (2023). Impact of Climate Change on the Hydrological Regimes of the Midstream Section of the Yarlung Tsangpo River Basin Based on SWAT Model. Water. doi: 10.3390/w15040685

Cui, Q., Ammar, M., Iravani, M., Kariyeva, J., & Faramarzi, M. (2021). Regional wetland water storage changes: The influence of future climate on geographically isolated wetlands. Ecological Indicators, 120, 106941. doi: 10.1016/J.ECOLIND.2020.106941

Das, S., Bhunia, G. S., Bera, B., & Shit, P. K. (2021). Evaluation of wetland ecosystem health using geospatial technology: evidence from the lower Gangetic flood plain in India. Environmental Science and Pollution Research. doi: 10.1007/s11356-021-15674-9

Demarquet, Q., Rapinel, S., Arvor, D., Corgne, S., & Hubert-Moy, L. (2024). Satellite Long-Term Monitoring of Wetland Ecosystem Functioning in Ramsar Sites for Their Sustainable Management. Sustainability. doi: 10.3390/su16156301

Dewi, R., Sofian, I., & Suprajaka. (2022). The application of satellite derived bathymetry for coastline mapping. IOP Conference Series: Earth and Environmental Science, 950. doi: 10.1088/1755-1315/950/1/012088

Doughty, C. L., Gu, H., Ambrose, R. F., Stein, E. D., Sloane, E. B., Martinez, M., & Cavanaugh, K. C. (2024). Climate drivers and human impacts shape 35-year trends of coastal wetland health and composition in an urban region. Ecosphere, 15(4), e4832. doi: 10.1002/ecs2.4832

Eaton, M., Terando, A., & Collazo, J. (2024). Applying portfolio theory to benefit endangered amphibians in coastal wetlands threatened by climate change, high uncertainty, and significant investment risk. Frontiers in Conservation Science. doi: 10.3389/fcosc.2024.1444626

Ehsani, A., & Shakeryari, M. (2021). Monitoring of wetland changes affected by drought using four Landsat satellite data and Fuzzy ARTMAP classification method (case study Hamoun wetland, Iran). Arabian Journal of Geosciences, 14. doi: 10.1007/s12517-020-06320-8

Fahrländer, S. F., Wang-Erlandsson, L., Pranindita, A., & Jaramillo, F. (2024). Hydroclimatic vulnerability of wetlands to upwind land use changes. Earth's Future, 12(3), e2023EF003837. doi: 10.1029/2023EF003837

Gergel, D., Malevich, S., McCusker, K., Tenezakis, E., Delgado, M., Fish, M., & Kopp, R. (2024). Global Downscaled Projections for Climate Impacts Research (GDPCIR): preserving quantile trends for modeling future climate impacts. Geoscientific Model Development. doi: 10.5194/gmd-17-191-2024

Hariski, M., Kusumastuti, N., & Yudhi, Y. (2024). Cubic spline interpolation to approximate sea depth between Teluk Suak and Lemukutan Island. Epsilon: Jurnal Matematika Murni dan Terapan (Epsilon: Journal of Pure and Applied Mathematics), 18(1). doi:10.20527/epsilon.v18i1.10813)

Hemati, M., Mahdianpari, M., Hasanlou, M., & Mohammadimanesh, F. (2022). Iranian Wetland Hydroperiod Change Detection Using an Unsupervised Method on 20 Years of Landsat Data Within the Google Earth Engine. IGARSS 2022 - 2022 IEEE International Geoscience and Remote Sensing Symposium, 6209-6212. doi: 10.1109/IGARSS46834.2022.9884716

Igaz, D., Šinka, K., Varga, P., Vrbičanová, G., Aydın, E., & Tárník, A. (2021). The evaluation of the accuracy of interpolation methods in crafting maps of physical and hydro-physical soil properties. Water, 13(2), 212. doi: 10.3390/w13020212

Khoshravan, H. , Alinejad-Tabrizi, T. and Naqinezhad, A. (2022). Hydromorphology and environmental restoration of Gorgan Bay, the Southeast Caspian Sea. Caspian Journal of Environmental Sciences, 20(1), 17-28. doi: 10.22124/cjes.2022.5388

Kim, T., & Villarini, G. (2024). Projected changes in daily precipitation, temperature and wet-bulb temperature across Arizona using statistically downscaled CMIP6 climate models. International Journal of Climatology, 44, 1994-2010. doi: 10.1002/joc.8436

Kumari, S., Wu, J., Ayala-Cabrera, D., & Dev, S. (2024). Effective Water Body Extraction from Hyperspectral Data: A Focus on Unsupervised Band Indices. 2024 IEEE 9th International Conference on Computational Intelligence and Applications (ICCIA), 251-255. doi: 10.1109/ICCIA62557.2024.10719176

Lawen, J., Lawen, K., Salman, G., & Schuster, A. (2022). Multi-Band Bathymetry Mapping with Spiking Neuron Anomaly Detection. Water. doi: 10.3390/w14050810

Leiva-Piedra, J. L., Ramírez-Juidias, E., & Amaro-Mellado, J.-L. (2024). Use of Geomatic Techniques to Determine the Influence of Climate Change on the Evolution of the Doñana Salt Marshes' Flooded Area between 2009 and 2020. Applied Sciences, 14(16), 6919. doi: 10.3390/app14166919

Mahdian, M., Noori, R., Salamattalab, M., Heggy, E., Bateni, S., Nohegar, A., Hosseinzadeh, M., Siadatmousavi, S., Fadaei, M., & Abolfathi, S. (2024). Anzali Wetland Crisis: Unraveling the Decline of Iran's Ecological Gem. Journal of Geophysical Research: Atmospheres, 129. doi: 10.1029/2023JD039538

Mann, J., Maddox, E., Shrestha, M., Irwin, J., Czapla-Myers, J., Gerace, A., Eon, R., Raqueno, N., Coburn, C., Byrne, G., Broomhall, M., & Walsh, A. (2024). Landsat 8 and 9 Underfly International Surface Reflectance Validation Collaboration. Remote. Sens., 16, 1492. doi: 10.3390/rs16091492

MeghrajK, C., Leigh, L., Pinto, C., & Kaewmanee, M. (2023). Method of Validating Satellite Surface Reflectance Product Using Empirical Line Method. Remote. Sens., 15, 2240. doi: 10.3390/rs15092240

Modi, P., Small, E., Kasprzyk, J., & Livneh, B. (2022). Investigating the role of snow water equivalent on streamflow predictability during drought. Journal of Hydrometeorology. doi: 10.1175/jhm-d-21-0229.1

Moyers, K., Abatzoglou, J., Escriva-Bou, A., Medellín-Azuara, J., & Viers, J. (2024). An invisible water surcharge: Climate warming increases crop water demand in the San Joaquin Valley's groundwater-dependent irrigated agriculture. PLOS Water. doi: 10.1371/journal.pwat.0000184

Nyandwi, O., & Ndikubwimana, I. (2024). The Effects of Wetland Degradation on Ecological Species. International Journal of Innovative Science and Research Technology (IJISRT). doi: 10.38124/ijisrt/ijisrt24apr1244

Rachidi, S., Mazoudi, E. E., Alami, J. E., Jadoud, M., & Er-Raki, S. (2023). Assessment and Comparison of Satellite-Based Rainfall Products: Validation by Hydrological Modeling Using ANN in a Semi-Arid Zone. Water. doi: 10.3390/w15111997

Rajeswari, S., & Rathika, P. (2024). Exploring Spectral Indices for Improved Water Body Classification in Landsat Imagery. 2024 Third International Conference on Intelligent Techniques in Control, Optimization and Signal Processing (INCOS), 1-5. doi: 10.1109/INCOS59338.2024.10527525

Rostami, E., Vahid, R., Zarei, A., & Amani, M. (2024). Dynamic Analysis of Water Surface Extent and Climate Change Parameters in Zarivar Lake, Iran. ECRS 2023. doi: 10.3390/ecrs2023-17345

Shin, S., Her, Y., & Khare, Y. (2023). Evaluation of impacts of climate change on natural and managed wetland basins. JAWRA Journal of the American Water Resources Association, 59, 1549-1568. doi: 10.1111/1752-1688.13140

Singha, C., Sahoo, S., Govind, A., Pradhan, B., Alrawashdeh, S., Aljohani, T. H., Almohamad, H., Islam, A. R. M. T., & Abdo, H. G. (2023). Impacts of hydroclimate change on climate-resilient agriculture at the river basin management. Journal of Water and Climate Change. doi: 10.2166/wcc.2023.656

Tan, Z., Leung, L., Liao, C., Carniello, L., Rodríguez, J., Saco, P., & Sandi, S. (2024). A multi-algorithm approach for modeling coastal wetland eco-geomorphology. Frontiers in Earth Science. doi: 10.3389/feart.2024.1421265

Ticehurst, C., Teng, J., & Sengupta, A. (2022). Development of a Multi-Index Method Based on Landsat Reflectance Data to Map Open Water in a Complex Environment. Remote. Sens., 14, 1158. doi: 10.3390/rs14051158

Toombs, N., Chapman, S., Trancoso, R., Zhang, H., Owens, D., & Syktus, J. (2023). A snapshot of climate change impacts for Queensland and regions using high-resolution downscaled CMIP6 projections. MODSIM2023, 25th International Congress on Modelling and Simulation. doi: 10.36334/modsim.2023.toombs

Trabelsi, R., & Abida, H. (2024). Wetland water balance estimation in an arid region using remote sensing technology and hydrological modelling. Hydrological Sciences Journal, 69, 905-922. doi: 10.1080/02626667.2024.2343353

Wen, L., & Hughes, M. (2022). Coastal Wetland Responses to Sea Level Rise: The Losers and Winners Based on Hydro-Geomorphological Settings. Remote. Sens., 14, 1888. doi: 10.3390/rs14081888

Zheng, Q., Huang, X., Zheng, T., He, J., Xiang, M., Qin, M., & Jin, K. (2024). The Abrupt Change in Potential Evapotranspiration and Its Climatic Attribution over the Past 50 Years in the Sichuan–Chongqing Region, China. Atmosphere. doi: 10.3390/atmos15070829