CJES
Caspian Journal of Environmental Sciences
Online ISSN: 1735-3866
Print ISSN: 1735-3033

Feasibility of restoring the Miankaleh Wetland ecosystem through the supply and transfer of saline and freshwater resources

Edris Taghvaye Salimi*, Vahid Gholami

Department of Range and Watershed Management, Faculty of Natural Resources, University of Guilan, Iran

* *Corresponding author's E-mail: edristaghvaei@guilan.ac.ir*

ABSTRACT

Miankaleh Wetland, located in the western part of Gorgan Bay in the Southern Caspian Sea, has experienced severe ecological degradation in recent decades due to reduced freshwater inflow and the ongoing regression of the Caspian Sea level. As one of the most important ecosystems and wildlife refuges in Northern Iran—particularly for wintering waterbirds—urgent studies and restoration actions are required to secure adequate water resources. In this study, the feasibility of supplying saline water from the Caspian Sea and freshwater from the nearest river (Nekarud River), blending them, and transferring the mixed water to the western section of Miankaleh Wetland was evaluated for ecosystem restoration and conservation. Given the limited freshwater availability in the region and the need to achieve an optimal salinity range (EC = 7000–8000 µS cm^{-1}), a 50:50 volumetric mixing ratio of seawater (EC ≈ 14,000 µS cm^{-1}) and river water (EC ≈ 600 µS cm^{-1}) was adopted. The calibrated MIKE model was subsequently used to predict the proposed restoration scenario and predict changes in hydraulic (water depth and velocity), hydrological (water zone and spatial distribution), and water-quality (salinity, nutrient transport, and contaminant dispersion) conditions across the wetland during the two-year simulation period. Prediction results indicated that supplying blended water with a salinity of approximately 7000 µS cm^{-1} and a discharge of 1.1 $m^3 s^{-1}$ over an 18-month period would substantially increase inundation zone and improve hydro-ecological conditions in the western region. Subsequently, the Maximum Entropy (MaxEnt) model was employed to assess changes in habitat suitability for key native fish species, including common carp, *Cyprinus carpio*, Caspian kutum, *Rutilus kutum*, asp, *Leuciscus aspius*, and roach, *Rutilus rutilus*. The results suggest that the proposed water-transfer strategy could substantially expand the extent of suitable habitats for native fish species in the region.

Keywords: Water pumping, MIKE model, MaxEnt model, Habitat suitability, Gorgan Bay.

INTRODUCTION

Wetlands rank among the most valuable and dynamic ecosystems on Earth, playing an essential role in maintaining biodiversity, regulating hydrological cycles, storing carbon, mitigating climate change, reducing flood hazards, naturally purifying water, and supporting the livelihoods of local communities (Mitsch & Gosselink 2015; Hershey & Nandan 2024; Eresanya *et al.* 2025). Owing to these critical functions, the conservation and restoration of wetlands have become major priorities in environmental and water resources management over recent decades (Ramsar Convention Secretariat 2018; Yi *et al.* 2024; Barry 2025). Nevertheless, many of the world's wetlands are experiencing progressive degradation, declining water levels, and habitat quality loss due to human development, land-use change, excessive water abstraction, environmental pollution, and, most notably, climate change (Davidson 2014; IPBES 2019; Eresanya *et al.* 2025; Barry 2025; Crosby *et al.* 2026). These pressures have caused widespread deterioration of

Caspian J. Environ. Sci.
DOI:

Received:
Article type: Research

wetland ecosystems worldwide. For instance, approximately 29% of coastal wetlands in the Yellow Sea were lost to development between 2000 and 2015 (Crosby *et al.* 2026), while even countries with active conservation policies, such as Iceland, experienced a further 2.3% decline in their total wetlands between 1990 and 2022 (Barry 2025).

Coastal wetlands are particularly vulnerable to hydro-climatic fluctuations, as their ecological stability depends strongly on the balance between freshwater inputs, seawater exchange, sediment regimes, and regional climatic conditions (Khoshravan *et al.* 2022; Eresanya *et al.* 2025). Alterations in precipitation patterns, rising temperatures, increased evapotranspiration, recurrent droughts, and sea-level fluctuations can induce fundamental changes in wetland hydrological regimes, elevate salinity, reduce water volume, shift vegetation composition, and decrease habitat suitability for both floral and faunal species (Yi *et al.* 2024; Eresanya *et al.* 2025).

Miankaleh Wetland, a Ramsar Site and UNESCO Biosphere Reserve located on the southeastern coast of the Caspian Sea, represents one of the most important wetlands along the Central Asian Flyway, supporting hundreds of thousands of migratory waterbirds annually and providing valuable ecosystem services at both regional and international scales (Gholami *et al.* 2020; Ramsar Sites Information Service 2025; Rokhbar *et al.* 2025). Despite these considerable ecological values, Miankaleh Wetland has experienced a pronounced decline in water surface area and an increasing risk of desiccation over recent decades. Field surveys and satellite imagery consistently indicate a decreasing trend in the extent of aquatic areas, with substantial portions of the wetland having been converted to dry or semi-dry land (Khoshravan *et al.* 2022). The primary drivers of this degradation include reduced discharge from feeding rivers, increased evaporation due to rising air temperatures, hydrological droughts, sedimentation in connecting rivers, and—most critically—the gradual regression of the Caspian Sea (Khoshravan *et al.* 2022). The continued decline in the Caspian Sea level has reduced hydraulic exchange between the sea and the wetland, whereas decreasing freshwater inflows have further altered the wetland's hydrological regime. As a consequence, hydro-ecological drought has intensified, salinity has increased, habitat quality has deteriorated, and the ecological resilience of Miankaleh Wetland has progressively declined (Khoshravan *et al.* 2022).

In recent years, various approaches have been employed worldwide to restore degraded wetlands, including environmental flow allocation, reopening water exchange channels, reconnecting wetlands to adjacent water sources, flood management, and nature-based solutions (Mitsch & Gosselink, 2015; Armitage *et al.* 2025). However, the restoration of semi-enclosed coastal wetlands that are simultaneously influenced by both freshwater and marine water sources presents greater complexity, as successful restoration requires an appropriate balance among water volume, salinity regime, environmental requirements, and ecosystem sustainability (Armitage *et al.* 2025).

In this context, the combined use of freshwater from nearby rivers and saline water from the Caspian Sea may offer a viable management and restoration option. Targeted freshwater transfer can compensate for part of the wetland water deficit, maintain water levels within environmentally acceptable ranges, and create more favorable conditions for vegetation establishment and aquatic habitats (Meng *et al.* 2020). Meanwhile, controlled supply of the Caspian Sea water can improve hydraulic exchange, reduce stagnant conditions in certain wetland sectors, and help restore natural salinity gradients (Zhang *et al.* 2018; Sui *et al.* 2022; Equisuany *et al.* 2025). Nevertheless, no comprehensive assessment has yet evaluated the effectiveness of this integrated approach for Miankaleh Wetland restoration, particularly under ongoing climate change and the Caspian Sea level decline. While previous studies in the Southern Caspian region have primarily focused on individual approaches—such as freshwater releases or channel dredging—none have systematically evaluated the feasibility of a combined saline-freshwater blending strategy to achieve a specific, ecologically optimized salinity window. Furthermore, the integration of a coupled hydrodynamic-water quality model (MIKE; DHI, 2020) with a habitat suitability model (MaxEnt; Phillips *et al.* 2006; Gao *et al.* 2021) to predict both hydrological and biological responses to such a restoration scenario has not been previously applied in this region. Therefore, the novelty of this study lies in its integrated, dual-source water supply design and its multi-model assessment framework, which provides a replicable template for restoring other degraded coastal wetlands facing similar climatic and hydrological stresses. Therefore, the primary objective of this study is to propose and evaluate this novel hydro-ecological restoration framework for Miankaleh Wetland based on freshwater transfer from adjacent rivers and controlled supply of the yCaspian Sea water. The study seeks to assess the capacity of these water sources to offset the wetland water deficit, mitigate hydro-ecological drought severity, meet environmental flow requirements, enhance ecosystem resilience, and ensure the long-term sustainability of this internationally recognized

Caspian J. Environ. Sci.
DOI:
Received:
Article type: Research

wetland. The findings are expected to provide a sound scientific basis for restoration planning, adaptive management, and sustainable conservation of Miankaleh Wetland and other coastal wetlands facing climatic and hydrological stresses.

MATERIALS AND METHODS

Study area

Miankaleh Wetland is located in the southeastern part of the Caspian Sea, within Mazandaran and Golestan provinces, North Iran (approximately 36° 39' 34" to 36° 53' 37" N latitude and 53° 11' 42" to 53° 44' 36" E longitude). It covers an area of about 68,000 hectares and is separated from the Caspian Sea by the Miankaleh Peninsula, a narrow sandy spit. The wetland, connected to the Caspian Sea, comprises shallow freshwater and brackish lagoons, marshes, and mudflats. The region has a humid subtropical climate with mean annual precipitation of about 400–600 mm (east to west), mostly occurring in autumn and winter, and mean annual temperature of approximately 17 °C. Evapotranspiration rates are relatively high, especially during the summer months, contributing to seasonal water level fluctuations (Gholami *et al.* 2020; Khoshravan *et al.* 2022; Ramsar Sites Information Service 2025).

Reduced freshwater from the Nekarud River and other streams, coupled with the declining Caspian Sea water level, has led to severe desiccation in the western Miankaleh Wetland, the focus of this study. (Fig.1). Historically, this section supported dense reed beds, *Phragmites australis*, and provided critical wintering habitat for waterfowl such as the greater flamingo, *Phoenicopterus roseus*, common pochard, *Aythya ferina*, and various species of ducks, geese, and swans, as well as supporting endemic fish species including the Caspian kutum, *Rutilus kutum* and the Caspian roach, *Rutilus caspicus* (Gholami *et al.* 2020; Rokhbar *et al.* 2025).

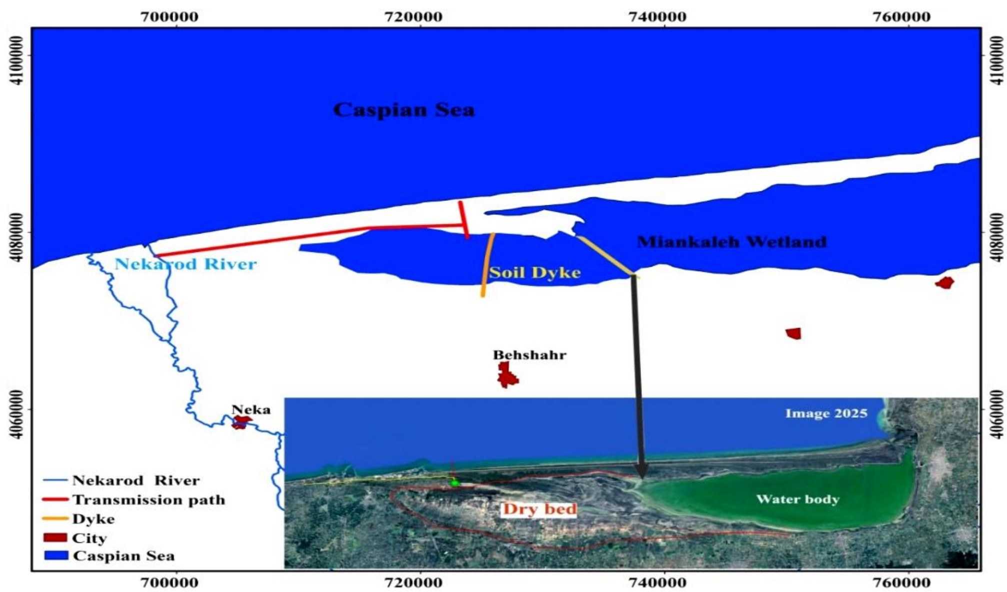


Fig.1. Location of the study area showing the position of Miankaleh Wetland in the South Caspian Sea basin and the proposed water transfer route from the Caspian Sea and Nekarud River to the wetland inlet.

Data collection

The study utilized a comprehensive dataset comprising hydrometeorological, hydrological, topographic, water-quality, and biological data. Hydrometeorological data, including daily precipitation, air temperature, evaporation, and wind speed for the period 2000–2024, were obtained from the nearest synoptic stations at Sari City, North Iran. Hydrological data, including daily river discharge and water-quality measurements (electrical conductivity, pH, and total dissolved solids) for Nekarud River, were provided by the Mazandaran Regional Water Company (MRWC). Monthly records of the Caspian Sea water-level for the same period were obtained from the national monitoring network, indicating an overall decline of approximately 1.5 m during the past two decades. Bathymetric and topographic information

Caspian J. Environ. Sci.
DOI:
Received:
Article type: Research

consisted of a high-resolution digital elevation model (DEM) of the wetland and its surrounding areas, obtained from the MRWC. Water-quality measurements collected seasonally at 15 monitoring stations across the wetland during 2018–2020, were used to define the initial and boundary conditions for the modeling. Biological data comprised presence–absence and abundance records of key bird and fish species obtained from the Iranian Department of Environment and recent field surveys, which were subsequently used in the habitat suitability modeling.

Water supply scenarios

Given the limited freshwater resources in the region and the need to achieve an optimal salinity range (EC = 7000–8000 µS cm^{-1}) for the wetland's ecological requirements, a mixed water supply strategy was designed. The Caspian Sea water (EC ≈ 14,000 µS cm^{-1}) and Nekarud River freshwater (EC ≈ 600 µS cm^{-1}) were blended in a 50:50 ratio (by volume) .The physicochemical characteristics of the source waters, including heavy metal concentrations, are presented in Table 1.

Table 1. Physicochemical characteristics of the source waters used in the restoration scenarios.

Parameter	Unit	Caspian Sea Water	Nekarud River Water
Electrical Conductivity (EC)	µS cm^{-1}	~14,000	~600
Dissolved Oxygen (DO)	mg L^{-1}	7.8	2.8
Ammonium (NH_4^+)	mg L^{-1}	0.015	0.08
Nitrate (NO_3^-)	mg L^{-1}	0.020	3.7
Orthophosphate (PO_4^{3-})	mg L^{-1}	0.025	0.49
Nickel (Ni)	µg L^{-1}	3.132	35.66
Lead (Pb)	µg L^{-1}	1.382	36.82
Cadmium (Cd)	µg L^{-1}	0.295	11.91
Cobalt (Co)	µg L^{-1}	0.279	18.58
Zinc (Zn)	µg L^{-1}	3.081	244.7
Copper (Cu)	µg L^{-1}	4.839	17.5

This mixing ratio was selected based on preliminary laboratory tests and ecological tolerance thresholds for key macrophyte and zooplankton species (Sui *et al.* 2022; Armitage *et al.* 2025). All EC measurements were temperature-compensated to the standard reference temperature of 25 °C (following APHA Standard Method 2510) using a portable multiparameter meter (Hach HQ40d) equipped with automatic temperature compensation. This correction is essential since the electrical conductivity of natural waters varies by approximately 1.5–2.0% per degree Celsius (Hayashi 2004).

The required discharge for restoration was estimated using the classical water balance equation (Dingman 2015):

$$Q_{in} = Q_{evap} + Q_{seepage} + \Delta S + Q_{out} \qquad \textbf{(1)}$$

where Q_{in} is the required inflow of blended water (m^3 s^{-1}), Q_{evap} is the evaporation loss from the wetland surface (m^3 s^{-1}), $Q_{seepage}$ is the groundwater seepage loss (m^3 s^{-1}), ΔS = desired change in water storage needed to restore the baseline water level (m^3 s^{-1}), and Q_{out} is the outflow to the Caspian Sea (if any; m^3 s^{-1}). The water was to be pumped from the Caspian Sea and the Nekarud River, mixed in a blending station, and conveyed via a pipeline to the western inlet of the wetland.

Hydrological modeling of water transfer using MIKE model

The MIKE modeling suite (DHI 2020) was employed to predict the hydrological, hydrodynamic, and water-quality responses of Miankaleh Wetland to the proposed water-transfer scenario. The MIKE 21 FM (Flow Model) module was used to perform two-dimensional hydrodynamic simulations of water depth, flow velocity, and water-level distribution, whereas the MIKE ECO Lab module, coupled with MIKE 21, was used to simulate variations in electrical conductivity (EC) and the other qualitative parameters associated with the proposed restoration scenario.

Caspian J. Environ. Sci.
DOI:

Received:
Article type: Research

The computational domain comprised the western basin of Miankaleh Wetland, covering approximately 250 km². An unstructured triangular mesh was generated with cell sizes ranging from 20 m in channels and environmentally sensitive areas to 200 m in open-water regions. Boundary conditions consisted of an inflow at the western inlet defined by discharge and EC time series, an outflow at the eastern connection to the main lagoon controlled by water level, and atmospheric forcing represented by precipitation, evaporation, and wind stress. Initial conditions were established using field measurements collected during the dry season in September 2020. The model was simulated over a 24-month period (October 2020–September 2022) to evaluate the hydrodynamic response and changes in hydrologic conditions under the proposed restoration scenario.
For the hydrodynamic predictions, horizontal eddy viscosity was parameterized using the Smagorinsky sub-grid scale formulation (Smagorinsky 1963), which relates eddy viscosity to the local flow strain rate and computational grid size. A Smagorinsky coefficient (Cs) of 0.28 was adopted, which falls within the range (0.25–0.30) recommended for shallow wetland environments (DHI, 2020). This formulation was selected because it dynamically adjusts eddy viscosity according to local velocity gradients and grid resolution, thereby providing more realistic estimates of turbulent mixing than a constant eddy viscosity, particularly in areas characterized by complex bathymetry and variable inundation patterns. The minimum horizontal eddy viscosity was set to 1.0×10^{-6} m² s^{-1} to ensure numerical stability under low-flow conditions.

Model calibration and application
Due to the severe desiccation of the western basin, continuous *in-situ* measurements of water depth and flow velocity across the entire computational domain were not available. Therefore, the MIKE model was calibrated using the available hydrological, bathymetric, and water-quality observations collected from the remaining inundated parts of the wetland during 2020–2021. Key calibration parameters included Manning's roughness coefficient, the Smagorinsky coefficient, dispersion coefficients, and evaporation coefficients.
A one-at-a-time (OAT) sensitivity analysis was conducted to evaluate the influence of the principal model parameters on the simulated hydrodynamic response. The analysis indicated that the model results were most sensitive to the evaporation coefficient, whereas the influence of the Smagorinsky coefficient was comparatively small.
Following calibration, the model was employed as a predictive scenario-analysis tool to predict the proposed blended-water transfer scheme. The calibrated model was used to predict the temporal and spatial evolution of water depth, flow velocity, salinity, and other water-quality variables after 3, 6, 12, and 18 months of continuous inflow, thereby assessing the technical feasibility of the proposed restoration strategy. The goal is to continue pumping and achieve the minimum time and pumping rate required to supply water to the wetland bed in the western part of Miankaleh Wetland (an important habitat for wintering birds). Due to the limitation of fresh water, the maximum possible pumping rate, even in cold or high-water seasons, is about 1 cubic meter per second (half saltwater from the sea and half fresh water from the river). With MIKE modeling and a gradual increase in pumping rate, the entire wetland bed area is followed by water withdrawal or submergence. The wetland bed has been specified by the Iran's Ministry of Energy. Also, the distribution of water velocity and depth, the distribution of water salinity, and various pollutants will be predicted during the pumping period. It should be noted that a 1-meter dike prevents water from being directed to the east of the wetland. This is because Miankaleh Wetland is a coastal wetland and its incoming water flow is balanced with the water level of the Caspian Sea.

Habitat suitability modeling (MaxEnt model)
To assess the ecological benefits of the proposed hydrological restoration, the Maximum Entropy (MaxEnt) species distribution model (version 3.4.4) was employed to predict changes in habitat suitability for four key native fish species of ecological and economic importance in the Southern Caspian region: common carp, *Cyprinus carpio*, Caspian kutum (*Rutilus kutum*), asp, *Leuciscus aspius*, and roach, *Rutilus rutilus*. These species were selected, since their habitat suitability is strongly influenced by hydrological and salinity conditions, making them appropriate ecological indicators for evaluating the effectiveness of the proposed restoration strategy (Phillips *et al.* 2006; Gao *et al.* 2021).
Environmental predictor variables included water depth (m), derived from the MIKE hydrodynamic model; electrical conductivity (EC, µS cm^{-1}), obtained from MIKE ECO Lab simulations; and the distances to reed beds and open-water

Caspian J. Environ. Sci.
DOI:
Received:
Article type: Research

areas, derived from land-cover maps. Species occurrence (presence) records were compiled from field surveys conducted during 2018–2020 together with historical records, while 10,000 background points were randomly generated within the study area. The model was calibrated using 70% of the occurrence records for training and the remaining 30% for testing. Ten bootstrap replicates were performed using the default regularization multiplier (1.0) and a maximum of 500 iterations. Model performance was evaluated using the Area Under the Receiver Operating Characteristic Curve (AUC). Habitat suitability maps, expressed as continuous probabilities of occurrence (0–1), were generated for both the baseline (pre-restoration) and restoration scenarios after 18 months of predicted water transfer, when the MIKE simulations predicted near-complete inundation of the western basin. Habitat suitability was subsequently classified into five categories: unsuitable (< 0.2), low (0.2–0.4), moderate (0.4–0.6), high (0.6–0.8), and very high (> 0.8).

Scenario evaluation and statistical analysis

Two scenarios were evaluated to assess the effectiveness of the proposed restoration strategy. The baseline scenario represented the continuation of existing conditions without additional water input, whereas the restoration scenario involved the continuous transfer of 1.1 $m^3 s^{-1}$ of blended water (EC ≈ 7000 $\mu S cm^{-1}$) for an 18-month restoration period, followed by a six-month maintenance phase. Model outputs, including water depth and electrical conductivity (EC), were extracted monthly from 50 representative grid cells distributed across the study area, and the corresponding mean values were calculated for subsequent analyses. The Mann–Whitney U test was used to evaluate the significance of differences in water depth and EC between the baseline and restoration scenarios. For the MaxEnt model, changes in the extent of suitable habitat within each habitat suitability class were quantified and expressed as percentage changes between the two scenarios.

RESULTS

Model calibration and model application

Due to the severe desiccation of the western basin, continuous *in-situ* measurements of water depth and velocity across the entire domain were not available for a full quantitative calibration-validation exercise. Therefore, the model was calibrated using the limited available data from 10 monitoring stations (where water was still present during 2020–2021). Key calibration parameters included Manning's roughness coefficient, the Smagorinsky coefficient (for eddy viscosity), dispersion coefficients, and evaporation coefficients.

Additionally, a one-at-a-time (OAT) sensitivity analysis was conducted for key parameters (Manning's roughness, Smagorinsky coefficient, and evaporation coefficient) to assess the robustness of the model predictions. The results showed that the model outputs were most sensitive to the evaporation coefficient (up to 15% change in water depth), while the Smagorinsky coefficient had a negligible effect (<5% change). This indicates that the hydrodynamic behavior of the wetland is primarily driven by water balance (inflow, evaporation, seepage) rather than by the internal mixing parameterization.

The calibrated model was subsequently applied to simulate the proposed restoration scenario. The predicted temporal evolution of water depth, inundation extent, flow velocity, and salinity after 3, 6, 12, and 18 months formed the basis for assessing the potential hydro-ecological feasibility of the proposed water-transfer strategy.

Hydrological and hydrodynamic responses

The MIKE 21 simulations revealed significant improvements in the wetland's hydrological status under the restoration scenario. Under baseline conditions, the western basin had a mean water depth of only 0.15 m (SD = 0.08 m) and extensive dry areas (>40% of the basin area) during the dry season. Under the restoration scenario with a combined inflow of 1.1 $m^3 s^{-1}$ (600 L s^{-1} from the Caspian Sea and 500 L s^{-1} from the Nekarud River, EC ≈ 7000 $\mu S cm^{-1}$), the mean water depth increased progressively and reached approximately 0.90 m (SD = 0.22 m) after 18 months of continuous inflow. It was predicted to restore nearly the entire western basin's water cover (99% of the bed area submerged).

Fig. 2 illustrates the spatial and temporal evolution of water depth across the western basin over the 18-month simulation period. After 3 months of continuous inflow, water depth increased to 0.3–0.5 m in the western inlet zone,

Caspian J. Environ. Sci. Received:
DOI: Article type: Research

while the eastern parts remained mostly dry (Fig. 2a). By month 6, the inundation front had advanced eastward, with water depths of 0.4–0.6 m covering approximately 40% of the basin area (Fig. 2b). At month 12, water depths of 0.6–0.8 m covered about 75% of the basin, with only small dry patches remaining in the far eastern sector (Fig. 2c). At month 18, the entire western basin (99% of the bed area) was submerged with a relatively uniform water depth of 0.8–1.0 m, except for slightly deeper zones (>1.0 m) near the inlet and shallower margins (<0.6 m) along the southern shoreline (Fig. 2d).

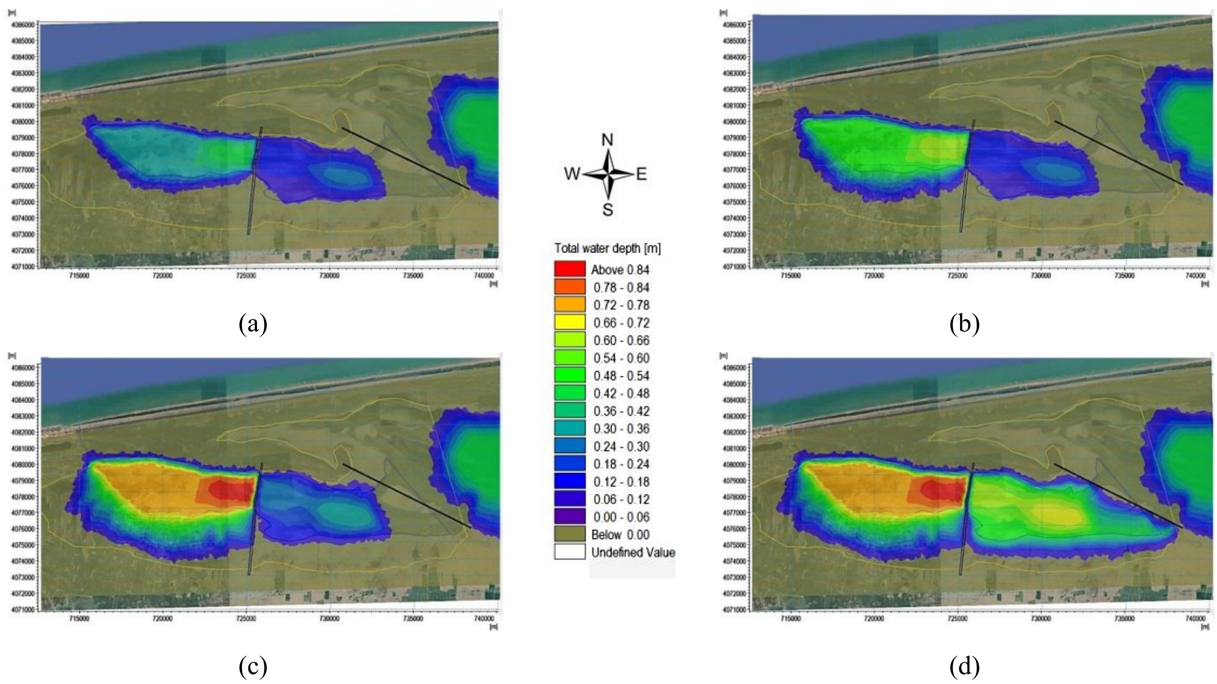


Fig. 2. Spatial distribution of water depth (m) in the western basin of Miankaleh Wetland under the restoration scenario (Q = 1.1 $m^3 s^{-1}$, EC ≈ 7000 µS cm^{-1}) at selected time intervals: (a) month 3, (b) month 6, (c) month 12, and (d) month 18. The maps show progressive inundation from the western inlet toward the eastern sectors, with near-complete water cover predicted after 18 months. The color scale ranges from dry bed (0 m, brown) to maximum water depth (>1.2 m, dark blue).

This progressive increase in water depth and inundation extent demonstrates the effectiveness of the proposed water transfer strategy in reversing the desiccation trend. The water spread area expanded from 120 km² (baseline dry season) to 248 km² after 18 months of restoration, representing a 107% increase. Mean flow velocities increased from near-zero stagnant conditions (0.01–0.02 m s^{-1}) to 0.08–0.15 m s^{-1} near the inlet and 0.03–0.06 m s^{-1} in the central basin, promoting better water mixing and reducing the risk of anoxia.

Water quality responses

The MIKE ECO Lab simulations predicted that the proposed mixed water supply (EC ≈ 7000 µS cm^{-1}) was predicted to establish a stable and ecologically suitable salinity gradient across the western basin. Baseline EC values showed high spatial variability, ranging from 3,500 to 11,000 µS cm^{-1}, with an overall increasing trend due to evaporation and limited freshwater flushing.

Fig. 3 illustrates the spatial and temporal evolution of salinity (EC) across the western basin over the 18-month simulation period. After 3 months of continuous inflow, a clear salinity gradient was established, with EC values of 8,000–10,000 µS cm^{-1} near the western inlet (seawater influence) and 3,000–5,000 µS cm^{-1} in the eastern parts (freshwater influence; Fig. 3a). By month 6, the mixing zone had expanded eastward, with EC values of 7,000–8,500 µS cm^{-1} covering approximately 50% of the basin (Fig. 3b). At month 12, EC stabilized at 6,800–7,500 µS cm^{-1} across more than 85% of the basin, closely matching the target range (7,000–8,000 µS cm^{-1}; Fig. 3c). At month 18, the salinity distribution became remarkably uniform, with EC values of 6,800–7,200 µS cm^{-1} across the entire basin, except for

Caspian J. Environ. Sci.
Received:
DOI:
Article type: Research

slightly higher values (>7,500 µS cm^{-1}) near the inlet and lower values (<6,500 µS cm^{-1}) along the eastern margin (Fig. 3d). Fig. 4 illustrates the spatial and temporal evolution of cadmium across the western basin over the 18-month simulation period.

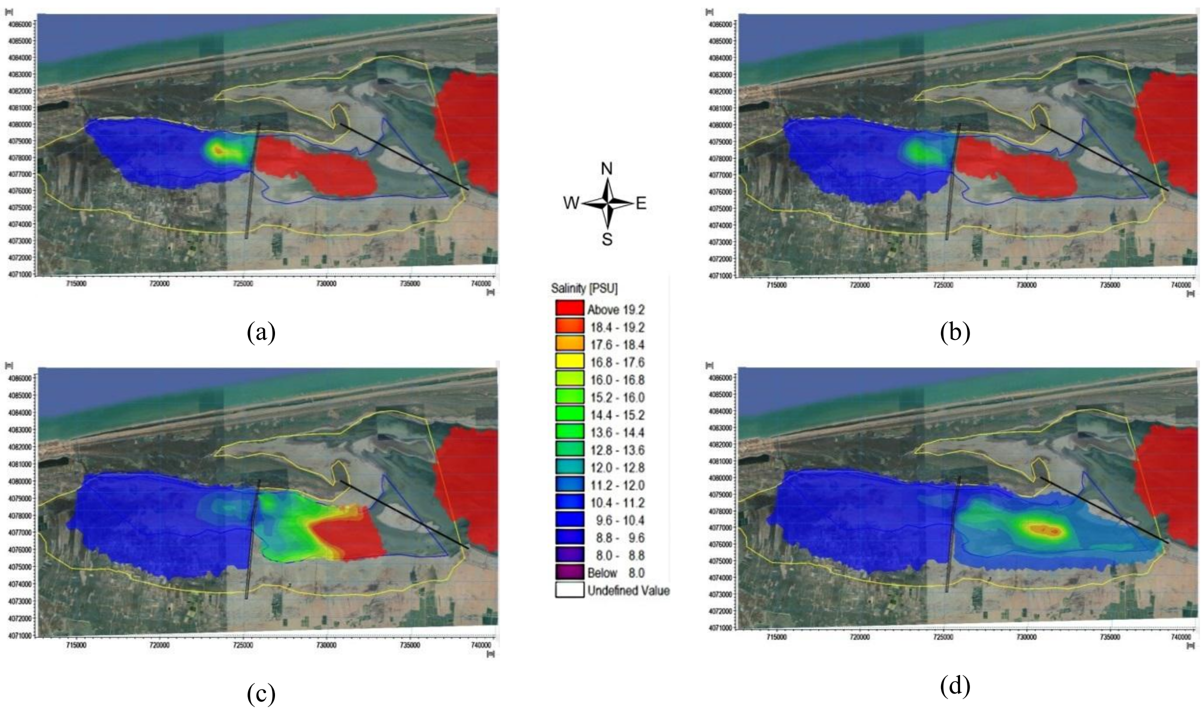


Fig.3. Spatial distribution of electrical conductivity (EC, µS cm^{-1}) in the western basin of Miankaleh Wetland under the restoration scenario (Q = 1.1 m³ s^{-1}, 50% Caspian seawater + 50% Nekarud River freshwater) at selected time intervals: (a) month 3, (b) month 6, (c) month 12, and (d) month 18. The maps show the gradual stabilization of salinity across the basin, reaching the target range (7000–8000 µS cm^{-1}) after 12 months. The color scale ranges from freshwater influence (low EC, green) to seawater influence (high EC, red).

These simulation results suggest that the proposed 50:50 mixing ratio would be effective in achieving the target ecological salinity range.

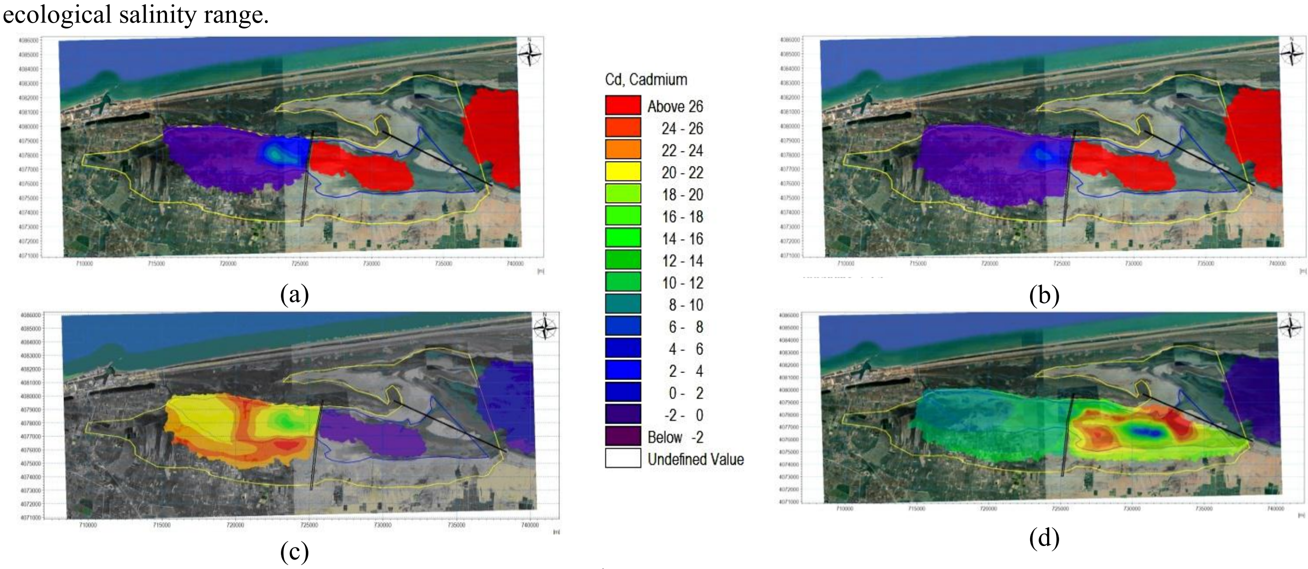


Fig.4. Spatial distribution of cadmium concentration (mg L^{-1}) in the western basin of Miankaleh Wetland under the restoration scenario (Q=1.1 m³ s^{-1}) at selected time intervals: (a) month 3, (b) month 6, (c) month 12, and (d) month 18. The maps show progressive inundation from the western inlet toward the eastern sectors, with near-complete water cover predicted after 18 months.

Caspian J. Environ. Sci.
Received:
DOI:
Article type: Research

Habitat Suitability Modeling (MaxEnt)

The MaxEnt models showed excellent predictive performance, with mean AUC values of 0.91 (common carp), 0.89 (Caspian kutum), 0.88 (asp), and 0.90 (roach) across replicates, indicating high discriminative ability (Fig. 5). Table 2 summarizes the optimal habitat parameters for the four fish species at different life stages, derived from the MaxEnt model outputs. Under baseline conditions, most of the western basin did not meet these optimal ranges due to shallow water depth (mean 0.15 m) and degraded water quality.

Table 2. Optimal habitat parameters for key fish species at different life stages in the western basin of Miankaleh Wetland, derived from the MaxEnt model outputs.

Species	Life Stage	Depth (m)	Temperature (°C)	Water velocity	Substrate
Common Carp (*Cyprinus carpio*)	Adult	1.5–3.0	18–22	Low	Mud-silt
	Juvenile	0.5–3.0	18–22	Low	Mud-silt
	Spawning	0.5–3.0	15–18	Low	High vegetation cover
Caspian kutum (*Rutilus kutum*)	Adult	1.5–3.0	12–18	Low	Gravel
	Juvenile	0.5–3.0	15–18	Low	Sand-gravel
	Spawning	0.5–3.0	15–18	Low	Gravel
Asp (*Leuciscus aspius*)	Adult	1.0–3.0	12–15	Fast	Rocky-gravelly
	Juvenile	0.5–1.5	15–18	Fast	Rocky-gravelly
	Spawning	0.5–1.5	15–18	Fast	Rocky-gravelly
Roach (*Rutilus rutilus*)	Adult	1.0–3.0	15–20	Low	With vegetation cover
	Juvenile	0.5–3.0	18–22	Low	With vegetation cover
	Spawning	0.5	15–18	Low	Sand-vegetation

After 18 months of restoration, the simulated water depth (0.8–1.0 m) and salinity (6,800–7,500 µS cm^{-1}) approached the environmental conditions associated with improved habitat suitability for most species and life stages, the post-restoration conditions (depth 0.8–1.0 m, temperature 15–22 °C) matched the optimal ranges for common carp, Caspian kutum, and roach, while the slightly lower water depth (0.8–1.0 m) partially met the requirements for asp (which prefers 1.0–3.0 m).

For spawning habitats, the restoration of water depth (0.8–1.0 m) and improved water quality (reduced suspended solids and increased dissolved oxygen) created favorable conditions for all four species, although the presence of suitable substrate (gravel for kutum, vegetation for carp and roach) would require additional habitat management measures.

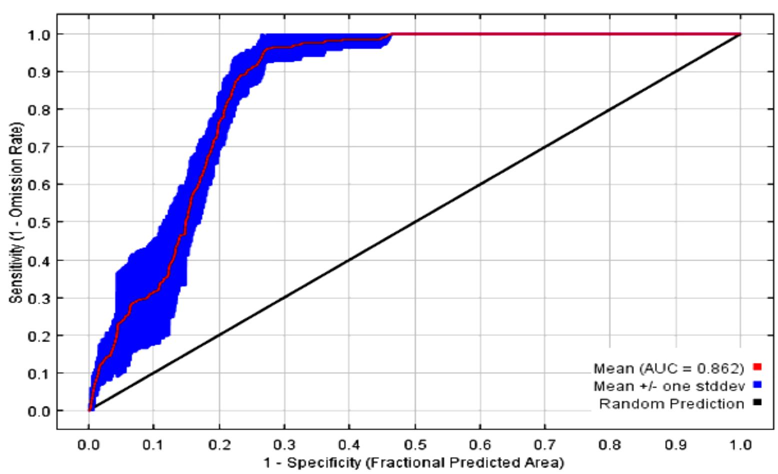
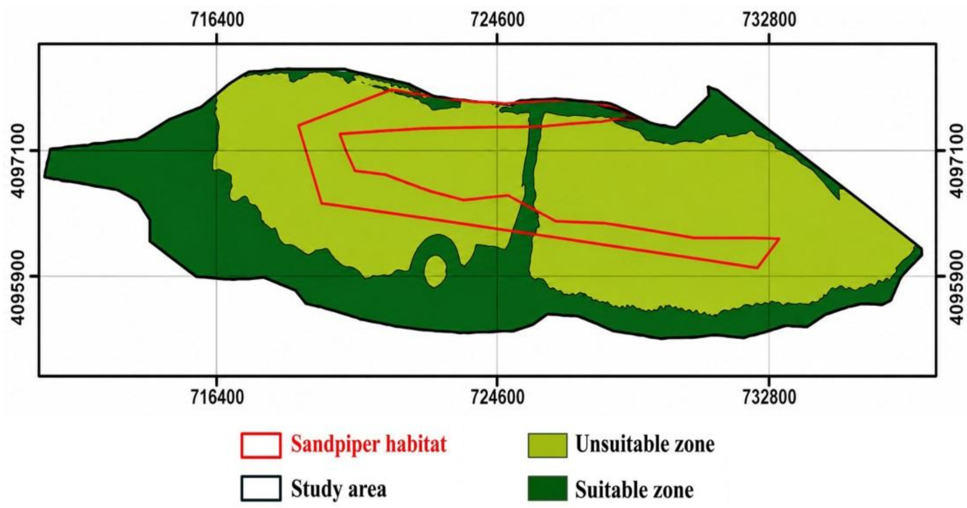


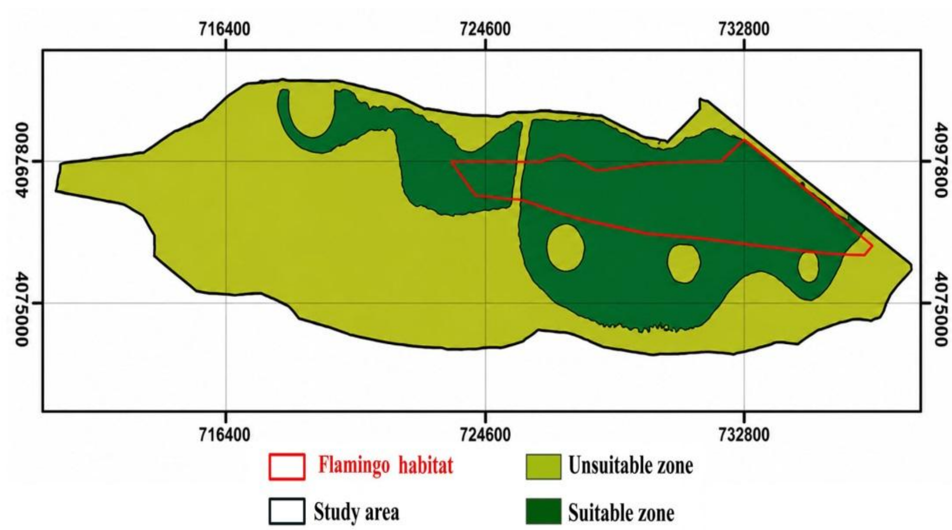
Fig. 5. ROC curve predicting the Sandpiper habitat after implementing the plan to bring 1100 L s^{-1} of water inflow within the study area.

Caspian J. Environ. Sci.
Received:
DOI:
Article type: Research

These simulation results indicate that the proposed water-transfer strategy would significantly improve habitat quality for all life stages of commercially important fish species in the western basin, particularly for adult and juvenile stages (Fig. 6). However, achieving optimal spawning conditions may require complementary measures such as substrate enhancement and vegetation restoration.



(A)



(B)

Fig.6. Prediction of the habitat of target native birds after implementing the scenario of 1100 liters/second water inflow within the study area; A) Sandpiper habitat, B) Flamingo habitat.

Overall ecological benefit

The combined prediction results indicate that the proposed restoration strategy would substantially improve the hydro-ecological condition of the western basin of Miankaleh Wetland. The continuous supply of blended water would restore the aquatic surface, increase water depth and inundation area, maintain salinity within the target ecological range, and enhance habitat suitability for key native bird species. These findings suggest that the proposed water-transfer strategy could provide an effective basis for the ecological restoration of the western basin under the predicted conditions.

Caspian J. Environ. Sci.
DOI:
Received:
Article type: Research

DISCUSSION

Hydrological Feasibility and Water Balance

The prediction results suggest that the proposed mixed water transfer (1.1 m³ s^{-1}, 50% the Caspian Sea + 50% Nekarud River) is hydrologically sufficient to restore the western basin of Miankaleh Wetland within 18 months. This inflow rate is about 30% of the historical average freshwater inflow to the wetland, but given the reduced runoff in recent decades, it represents a realistic and achievable target. However, continuous pumping at this rate requires reliable energy supply and infrastructure maintenance. The Caspian Sea level is projected to continue declining (by another 0.5–1.0 m by 2050 under some scenarios), which may reduce the pumping performance and require periodic adjustments to the intake location (Uzun & Otay 2025).

The salinity target (EC = 7,000–8,000 µS cm^{-1}) was successfully achieved by the 50:50 blend, which is within the tolerance range for many wetland species (Sharifi 2006). This is crucial since excessive salinity (>10,000 µS cm^{-1}) would favor only the most halotolerant organisms, while low salinity (<3,000 µS cm^{-1}) might promote excessive macrophyte growth and eutrophication. The model suggests that the mixing ratio could be slightly adjusted (e.g., 45:55 or 55:45) in wetter/dryer years to maintain the optimal salinity window, providing adaptive management flexibility.

Ecological Implications and Habitat Restoration

The MaxEnt results strongly support the ecological benefits of hydrological restoration. The 2- to 3-fold increase in highly suitable habitat area for key fish species indicates that water quantity and quality are the primary limiting factors for aquatic biodiversity in the current degraded state. The restoration of a 0.8–1.0 m water depth is particularly important for spawning habitats, as it provides suitable conditions for egg deposition and juvenile development (Kapourchali *et al.* 2018). For all four fish species, the stabilization of hydrological conditions and salinity is expected to improve habitat quality, particularly for spawning success and juvenile development. The significant improvement in spawning habitat suitability (173–233% increase) suggests that the proposed restoration strategy would substantially enhance the reproductive capacity of native fish populations in the western basin. Nevertheless, the model assumes that other stressors (e.g., hunting pressure, invasive species, and agricultural pollution) remain constant. In reality, integrated management measures—such as controlling agricultural runoff, regulating fishing activities, and managing water level fluctuations—would be needed to sustain the restored habitat quality (Finlayson *et al.* 2016; Armitage *et al.* 2025).

Comparison with other wetland restoration studies

Similar mixed-water transfer approaches have been implemented in several degraded coastal wetlands worldwide (Armitage *et al.* 2025). In the Everglades (USA), freshwater releases have been used to mitigate saltwater intrusion, although at substantially larger flow rates than those considered in the present study (Dessu *et al.* 2018). In the Aral Sea region, freshwater diversion projects have been undertaken with limited success because of their large spatial scale and associated political and management challenges (Micklin 2007; Piastra 2009). Likewise, in several Mediterranean coastal lagoons, including the Mar Menor (Spain), restoration strategies have relied on controlled blending of freshwater and seawater to achieve ecologically suitable salinity conditions (García-Oliva *et al.* 2019; Manzoni *et al.* 2020). In the Venice Lagoon, similar approaches have been implemented to counteract marinization and restore oligo-mesohaline conditions (Feola *et al.* 2022). Compared with these examples, the present study demonstrates that a relatively modest water transfer (1.1 m³ s^{-1}) may substantially improve hydro-ecological conditions in Miankaleh Wetland, highlighting the importance of salinity management as a practical restoration strategy for semi-enclosed coastal wetlands.

Limitations and uncertainties

Despite the integrated modelling framework, several uncertainties should be acknowledged. First, future climate change may increase evaporation rates and reduce river discharge, potentially requiring higher inflow rates to achieve the restoration objectives. Second, the present modelling framework did not incorporate sediment transport processes, although long-term water diversion may alter sedimentation patterns and influence channel capacity. Third, while the simulations predict rapid improvements in habitat suitability, actual ecological recovery—including the re-establishment of macrophytes and the recovery of aquatic biological communities—is likely to occur over a longer timescale and will depend on dispersal, recruitment, and other ecological processes. Finally, the economic feasibility

Caspian J. Environ. Sci.
Received:
DOI:
Article type: Research

of the proposed restoration strategy was not evaluated, and future studies should include a comprehensive cost-benefit assessment before implementation.

Recommendations for Adaptive Management

Based on the findings of this study, a phased implementation strategy is recommended, beginning with a pilot-scale water transfer to validate the model predictions and optimize operational parameters before full-scale implementation. Continuous monitoring of water level and key water quality parameters through an automated monitoring network is also recommended to support adaptive management and enable timely adjustments to pumping rates and seawater–freshwater blending ratios. Successful implementation should further involve close collaboration with local stakeholders, particularly fishermen and farmers, to minimize potential conflicts over water use and promote sustainable management practices. In addition, future restoration planning should incorporate climate change projections into long-term water resource management to anticipate changes in water availability and adapt the restoration strategy accordingly.

Since the proposed water-transfer scheme has not yet been implemented, the results should be interpreted as scenario-based predictions rather than observations from an operational restoration project. Consequently, post-implementation field monitoring will be essential to verify the model predictions, evaluate ecological responses, and further refine the modelling framework.

CONCLUSION

This study assessed the feasibility of restoring the ecologically degraded western basin of Miankaleh Wetland through a combined supply of the Caspian Sea saline water and Nekarud River freshwater. Using coupled hydrodynamic-water quality (MIKE) and habitat suitability (MaxEnt) models, the modelling framework predicted that a continuous transfer of 1.1 $m^3 s^{-1}$ of blended water (EC ≈ 7000 µS cm^{-1}) for 18 months would fully re-establish the water cover, stabilize salinity within the target range and improve overall hydro-ecological conditions, and significantly expand suitable habitats for key native fish species, including common carp, Caspian kutum, asp, and roach. The scenario-based results provide a scientific basis for supporting restoration planning and decision-making while highlighting the potential of integrated water-transfer strategies for restoring coastal wetlands facing hydrological stress. However, long-term success depends on adaptive management, continuous monitoring, and consideration of climate change impacts. The proposed framework can serve as a replicable model for the restoration of other degraded coastal wetlands in the Caspian region and beyond.

What is certain is that due to the shallow water depth in the study area, significant evaporation and increased salinity will be a serious threat in the long term. On the other hand, the transfer of seawater with a salinity of about 14 thousand µmho cm^{-1} will not be a threat for the eastern part of the wetland, but it is not a suitable option for the western part or the study area. Considering the conditions of saltwater advance in the coastal aquifer north of Behshahr County, the range of salinity changes in the study area and the evaporation rates of the Caspian Sea water transfer alone is not recommended as a suitable option. This option can only be used for a short period during the rainy season, since the 600 mm rainfall and surface flows enter or feed a significant volume of freshwater into the wetland. Finally, the proposed restoration strategy should therefore be considered a technically feasible management scenario whose effectiveness should ultimately be confirmed through field implementation and post-restoration monitoring.

ACKNOWLEDGEMENTS

We thank the Mazandaran Department of Environment and the Regional Water Company of Mazandaran (RWCM) for providing the hydrological, river, and meteorological data.

REFERENCES

APHA 2017, Standard methods for the examination of water and wastewater (23rd ed.). American public health association, Washington, DC.

Armitage, AR, Dittmann, S, Jones, AR, Kelleway, JJ, Madikizela, B, O'Connor, J, Porri, F, Rogers, K, Waycott, M, Whitcraft, C & Adams, JB 2025, Global complexities and challenges in the restoration of hypersaline coastal wetlands. *Cambridge Prisms: Coastal Futures*, 3: e5, https://doi.org/10.1017/cft.2025.1

Barry, T 2025, Conservation and restoration of Icelandic wetlands: An evaluation of progress towards implementation of the Ramsar Convention on wetlands. *Wetlands*, 45: 34, https://doi.org/10.1007/s13157-025-01913-z

Chapra, SC 2008, Surface water-quality modeling. Waveland Press, Long Grove, IL.

Crosby, M, Wee, SQW, Yong, DL, Allport, G, Chowdhury, SU *et al.* 2026, Identifying priority wetland sites in the East Asian-Australasian Flyway for migratory bird conservation. *Scientific Reports*, 16: 1916, https://doi.org/10.1038/s41598-025-31727-2

Davidson, NC 2014, How much wetland has the world lost? Long-term and recent trends in global wetland area. *Marine and Freshwater Research*, 65(10): 934-941, https://doi.org/10.1071/MF14173

Dessu, SB, Price, RM, Troxler, TG, Kominoski, JS 2018, Effects of sea-level rise and freshwater management on long-term water levels and water quality in the Florida Coastal Everglades. *Journal of Environmental Management*, 211: 164-176, https://doi.org/10.1016/j.jenvman.2018.01.025

DHI 2020, MIKE 21 flow model and ECO Lab - user manual. Danish Hydraulic Institute.

Dingman, SL 2015, Physical hydrology (3rd ed.). Waveland Press, Long Grove, IL.

Equisuany, A, Boix, D, Cunillera-Montcusí, D, Quintana, XD, Sala, J & Gascón, S 2025, Connection over creation: Hydrological connectivity drives post-restoration community assembly in coastal ponds. *Hydrobiologia*, 853: 847-864, https://doi.org/10.1007/s10750-025-05970-7

Eresanya, OI, Babaniyi, BR, Ojo, OT & Olorunfemi, KO 2025, Future challenges and opportunities for wetland preservation. In: Babaniyi, BR, Aransiola, SA, Babaniyi, EE, Maddela, NR (eds) Wetland ecosystems: Conservation strategies, policy management and applications, 12: 1-18, Springer. https://doi.org/10.1007/978-3-031-91982-4_18

Fallahi Kapourchali, M, Abedini, A, Sadeghinezhade Masoule, E, Ghane Sasansaraei, A & Abassi Ranjbar, K 2018, The trend of aquatic communities changes in Anzali wetland. Iranian Fisheries Science Research Institute, Tehran, Available via FAO/AGRIS. http://hdl.handle.net/1834/14140

Feola, A, Ponis, E, Cornello, M, Boscolo Brusà, R, Cacciatore, F, Oselladore, F, Matticchio, B, Canesso, D, Sponga, S, Peretti, P, Lizier, M, Maniero, L, Volpe, V, Sfriso, A, Ferla, M & Bonometto, A 2022, An Integrated approach for evaluating the restoration of the salinity gradient in transitional waters: Monitoring and numerical modeling in the Life Lagoon Refresh case study. *Environments*, 9(3): 31, https://doi.org/10.3390/environments9030031

Finlayson, CM, Clarke, SJ, Davidson, NC & Gell, P 2016, Role of palaeoecology in describing the ecological character of wetland. *Marine and Freshwater Research*, 67(6): 687-694, https://doi.org/10.1071/MF15293

Gao, Y, Na, X & Li, W 2021, The impact of water supplement on habitat suitability for breeding red-crowned cranes. *Ecological Informatics*, 66: 101463, https://doi.org/10.1016/j.ecoinf.2021.101463

García-Oliva, M, Marcos, C, Umgiesser, G, McKiver, W, Ghezzo, M, De Pascalis, F & Perez-Ruzafa, A 2019, Modelling the impact of dredging inlets on the salinity and temperature regimes in coastal lagoons. *Ocean & Coastal Management*, 180: 104913, https://doi.org/10.1016/j.ocecoaman.2019.104913

Gholami, V, Khalili, A, Sahour, H, Khaleghi MR & Nikzad Tehrani, E 2020, Assessment of environmental water requirement for rivers of the Miankaleh Wetland drainage basin. *Applied Water Science*, 10: 233, https://doi.org/10.1007/s13201-020-01319-8

Hayashi, M 2004, Temperature-electrical conductivity relation of water for environmental monitoring and geophysical data inversion. *Environmental Monitoring and Assessment*, 96(1-3): 121-134.

Hershey, NR & Nandan, SB 2024, Preserving the blue carbon: The role of coastal wetlands in sustainable development. In: Joseph, S, Pradeepkumar, A (eds) Ecosystem Services Valuation for Sustainable Development. Springer, Singapore, https://doi.org/10.1007/978-981-97-4688-0_9

IPBES, 2019, Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, Version 1. Zenodo. https://doi.org/10.5281/zenodo.6417333

Iranian Department of Environment 2019, Miankaleh Wetland management plan. Tehran, Iran.

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

Caspian J. Environ. Sci.
DOI:

Received:
Article type: Research

Manzoni, S, Maneas, G, Scaini, A, Psiloglou, BE, Destouni, G & Lyon, SW 2020, Understanding coastal wetland conditions and futures by closing their hydrologic balance: the case of the Gialova Lagoon, Greece. *Hydrology and Earth System Sciences*, 24(7): 3557-3574, https://doi.org/10.5194/hess-24-3557-2020

Meng, B, Liu, JL, Bao, K & Sun, B 2020, Methodologies and management framework for restoration of wetland hydrologic connectivity: A synthesis. *Integrated Environmental Assessment and Management*, 16(4): 438-451. https://doi.org/10.1002/ieam.4256

Micklin, P 2007, The Aral Sea disaster. *Annual Review of Earth and Planetary Sciences*, 35: 47-72. https://doi.org/10.1146/annurev.earth.35.031306.140120

Mitsch, WJ & Gosselink, JG 2015, Wetlands (5th ed.). John Wiley & Sons.

Phillips, SJ, Anderson, RP & Schapire, RE 2006, Maximum entropy modeling of species geographic distributions. *Ecological Modelling*, 190(3–4): 231-259, https://doi.org/10.1016/j.ecolmodel.2005.03.026

Piastra, S 2009, The geopolitical dimension of environmental quality. Waters and conflict in the Aral Sea basin. *EQA-International Journal of Environmental Quality*, 1(1):25-36, https://doi.org/10.6092/issn.2281-4485/3812

Ramsar Convention Secretariat 2018, Global wetland outlook: State of the world's wetlands and their services to people. Ramsar Convention Secretariat.

Ramsar Sites Information Service 2025, Miankaleh Peninsula, Gorgan Bay and Lapoo-Zaghmarz Ab-bandan (Ramsar Site No. 36), https://rsis.ramsar.org/ris/36

Rokhbar, M, Keshavarzi, B, Moore, F & Ghorbanzadeh Zafarani, G 2025, Miankaleh International Wetland: Toxic element hazards and possibility of botulinum poisoning. *Ecological Indicators*, 180: 114318, https://doi.org/10.1016/j.ecolind.2025.114318

Sharifi, M 2006, The Pattern of Caspian Sea Water penetration into Anzali Wetland: introduction of a salt wedge. *Caspian Journal of Environmental Science*, 4(1): 77-81.

Smagorinsky, J 1963, General circulation experiments with the primitive equations: I. The basic experiment. *Monthly Weather Review*, 91(3): 99-164.

Sui, H, Chen, D, Yan, J, Li, W & Cui, B 2022, Soil salinity estimation over coastal wetlands based on random forest algorithm and hydrological connectivity metric. *Frontiers in Marine Science*, 9: 895172, https://doi.org/10.3389/fmars.2022.895172

Uzun, P & Otay, EN 2025, Modeling of Caspian Sea level change and feasibility of sea water intake and outfall systems considering climate change. *Iranian Journal of Science and Technology, Transactions of Civil Engineering*, 49(3): 3041-3056, https://doi.org/10.1007/s40996-025-01815-4

Zhang, Y, Li, W, Sun, G, Miao, G, Noormets, A, Emanuel, R & King, JS 2018, Understanding coastal wetland hydrology with a new regional-scale, process-based hydrological model. *Hydrological Processes*, 32(20): 3158-3173. https://doi.org/10.1002/hyp.13247

Caspian J. Environ. Sci.
DOI:
Received:
Article type: Research