University of Tehran Press

Online ISSN: 2345-475X

DESERT

Home page: https://jdesert.ut.ac.ir/

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Integrated Rehabilitation of Maharloo Wetland: Source Control and Ecological Water Allocation Based on Spatio-Temporal Evidence

Bahareh Samadi Kuchaksaraei[1], Kamran Rezaei Tavabe[1*], Elnaz Namdari Ghareghani[2], Hamid Zohrabi[3], Mohammad Javad Sayahpour[4], Yalda Movasaghi[5]

[1] Department of Fisheries, Faculty of Natural resources, University of Tehran, Karaj, Alborz, Iran. Email: krtavabe@ut.ac.ir

[2] Department of Reclamation of Arid & Muntainous Regions, Faculty of Natural Resources, University of Tehran, Karaj, Alborz, Iran

[3] Department of Environment, Faculty of Natural Resources, University of Tehran, Karaj, Alborz, Iran

[4] Department of Agricultural Extension and Education, School of Agriculture, Shiraz University, Shiraz, Iran

[5] Department of Natural Resources and Environmental Engineering, School of Agriculture, Shiraz University, Shiraz, Iran

Article Info.

Article type:
Research Article

Article history:
Received: 28 Jan. 2026
Received in revised from: 04 Mar. 2026
Accepted: 12 Mar. 2026
Published online: 27 Mar. 2026

Keywords:
Maharloo Wetland,
Water Quality Index,
Pollution hotspot,
Ecological water right,
Rehabilitation strategy.

ABSTRACT

Maharloo Wetland, a vital yet degraded ecosystem in Iran, faces a dual crisis of severe water scarcity and intense pollution. This study aimed to diagnose the wetland's water quality status to inform a targeted rehabilitation strategy. Seasonal sampling was conducted at 8 stations from autumn 2023 to summer 2024, analyzing physicochemical and microbial parameters and synthesizing data using the Iranian Surface Water Quality Index (IRWQISC). Results revealed a pervasive and critical condition, with IRWQIsc scores (5.2–11.4) categorizing all stations as "very bad" year-round. Spatial analysis identified two consistent pollution hotspots (Stations 7 and 8), located at the inlets of the Soltan-abad and Khoshk rivers respectively. these hotspots exhibited significantly elevated levels of organic matter (BOD up to 450.6 mg/L), nutrients (NO_3^- up to 212 mg/L), and fecal coliforms. These hotspots indicate persistent anthropogenic inputs, likely from agricultural drainage and wastewater. The remaining stations showed relatively better but still poor quality. It is argued that successful rehabilitation requires an integrated two-pillar approach: (1) Immediate, targeted pollution source control at identified hotspots through agricultural best management practices and wastewater regulation, and (2) Scientifically determined ecological water allocation to address the hydrological deficit, informed by methods like flagship species assessment. Allocating water without first mitigating pollution loads would be ecologically inefficient. This spatio-temporal evidence provides a clear roadmap for prioritizing interventions, emphasizing that controlling contamination is the essential prerequisite for any effective hydrological restoration of Maharloo Wetland.

Cite this article: Samadi Kuchaksaraei, B., Rezaei Tavabe, K., Namdari Ghareghani, E., Zohrabi, H., Sayahpour, M.J., Movasaghi, Y. (2026). Integrated Rehabilitation of Maharloo Wetland: Source Control and Ecological Water Allocation Based on Spatio-Temporal Evidence. DESERT, 31 (1), DOI: 10.22059/jdesert.2026.107545

DOI: 10.22059/jdesert.2026.107545

Publisher: University of Tehran Press

1. Introduction

Maharloo Wetland, a critical aquatic ecosystem located southeast of Shiraz in Fars Province, Iran, represents a stark example of the global crisis facing inland wetlands. With an average area of 4100 km² and a remarkably shallow average depth of 55 cm, its ecological balance is highly vulnerable to hydrological and anthropogenic changes (Zamanpoore *et al*., 2023). Historically, this wetland has played a vital role in biodiversity support, flood regulation, and local climate moderation. However, in recent decades, it has faced severe degradation, primarily driven by prolonged drought and unsustainable water abstraction for intensive agriculture in its basin (Fars Department of Environment, 2018; Danehkar & Samadi Kuchaksaraei, 2021). This has led to frequent episodes of complete drying, fundamentally disrupting ecosystem services and threatening dependent species (Fars Department of Environment, 2018; Zamanpoore *et al*., 2023).

The degradation of Maharloo is multifaceted. Studies indicate a drastic reduction in surface water extent linked to expanded vegetation cover and subsequent groundwater extraction (Shafiei *et al*., 2017; Jafari *et al*., 2021). Concurrently, the wetland is subjected to significant pollution loads. Research has identified the presence of heavy metals like chromium, lead, mercury, and arsenic in its waters, with concentrations peaking in summer due to reduced dilution, posing serious risks to aquatic life and human health (Fars Department of Environment, 2020). Furthermore, nutrient enrichment from agricultural return flows is a latent threat, potentially driving eutrophication under specific conditions (Du *et al*., 2019; Samadi Kuchaksaraei *et al*., 2024a; Zamani-Ahmadmahmoodi *et al*., 2025). These compounded pressures—hydrological deficit and pollution—demand an integrated rehabilitation strategy that moves beyond simplistic water allocation to include stringent pollution control.

The quest for effective wetland restoration strategies is ongoing in the region. Lessons from adjacent systems highlight the importance of a multi-pronged approach. For instance, ecological water right assessments using flagship species have been advocated for Parishan Wetland, emphasizing the need to define minimum and optimal water volumes for ecological integrity (University of Tehran, 2021; Rezaei Tavabe & Samadi Kuchaksaraei, 2021a; Rezaei Tavabe *et al.*, 2021; Rezaei Tavabe *et al.*, 2022). Moreover, comparative evaluations of management options, such as agricultural management versus inter-basin water transfer (Wang *et al*., 2018), consistently identify the optimization of agricultural water use and cropping patterns as the foremost priority, followed by engineered water transfers as a supplementary measure (Afshrtabar *et al*., 2023; Samadi Kuchaksaraei *et al*., 2024b). Any intervention, however, must be preceded by a rigorous, spatio-temporally explicit diagnosis of the system's ailments to avoid unintended consequences, such as salinity rise or invasive species introduction, which have been carefully modeled for other basins (Rezaei Tavabe & Samadi Kuchaksaraei, 2021b; Samadi Kuchaksaraei *et al*., 2024b).

Despite this context, a critical gap remains: a comprehensive, fine-scale spatio-temporal assessment of water quality across Maharloo Wetland that can directly link pollution hotspots to potential sources and inform targeted source control within a broader rehabilitation framework. Current studies often focus on singular aspects—hydrology, heavy metals, or habitat classification—lacking an integrated analysis of conventional physicochemical and microbial parameters across seasons. Therefore, this study was designed to generate the necessary evidence base for integrated management.

The primary objectives of this research are: (1) To evaluate the spatio-temporal variability of key physicochemical and microbial water quality parameters across eight stations in Maharloo Wetland over four consecutive seasons; (2) To employ the Iranian Surface Water

Quality Index (IRWQISC) to synthesize the overall pollution status and identify critical degradation hotspots; and (3) To synthesize these findings with existing hydrological and ecological evidence to propose a coherent rehabilitation strategy that synergistically combines targeted pollution source control with ecological water allocation. The outcomes aim to provide actionable insights for policymakers to implement precise, evidence-based interventions for the restoration of Maharloo Wetland.

The success of any rehabilitation plan ultimately depends on socio-economic feasibility and stakeholder acceptance. Studies in similar basins have shown that while agricultural water conservation is the most effective long-term strategy, it faces significant implementation barriers due to potential reductions in farmers' income and livelihood security (Afshrtabar *et al*., 2023; Samadi Kuchaksaraei *et al*., 2024b). This underscores the necessity of complementing technical water quality and allocation plans with economic incentive mechanisms and participatory approaches to ensure sustainability. Thus, a holistic strategy for Maharloo must bridge the gap between ecological requirements and socio-economic realities on the ground.

2. Materials and methods

2.1. Study area

The study area encompasses Maharloo wetland, located in the Maharloo basin in Fars province, southeast of Shiraz, Iran (Coordinates: 29°31'26"N, 52°43'26"E). the wetland's altitude ranges from 1461 to 1465 meters above sea level (Zamanpoore *et al*., 2023), while the broader basin has an average elevation of 1775 meters (Fars Department of Environment, 2019). The wetland is characterized by an average area of 4100 km^2, an average depth of 55 cm (maximum 3 m), a length of 31 km, a maximum width of 11 km, and an estimated average water volume of 130 million cubic meters (MCM) (Zamanpoore *et al*., 2023). The surrounding Maharloo sub-basin covers an area of 4274 km^2, consisting 2056 km^2 of plains with the remainder as highlands (Vazirzadeh, 2018). And has an average slope of 9.3% (Fars Department of Environment, 2019). The wetland is hydrologically bounded by the Bakhtegan wetland basin to the north and a portion of the Qara-Aj river basin (part of the Mond basin) to the south (Fars Department of Environment, 2018). Aligned with the Zagros mountains, the basin extends from the northwest to the southeast, spanning approximately 160 km in length and 43 km in width across the Sarvestan Plain and Maharloo wetland (Fars Department of Environment, 2018). During low-rainfall periods, such as the past decade, the wetland experiences severe water depletion and frequent drying episodes (Zamanpoore *et al*., 2023).

2.2. Field visits and measure water quality parameters

Field visits and water sampling were carried out at 8 stations within the Maharloo wetland area across 4 seasons, from autumn 2023 to summer 2024 (Figure 1). The geographical coordinates of the sampling stations are provided in
Table 1.

Sampling procedure: At each station, sampling was performed in triplicate using standard methods (APHA, 2017). Prior to sampling each 250 mL polyethylene sampling can was thoroughly cleaned with 10% nitric acid, followed by rinsing three times with distilled water and finally with the ambient water from the sampling site. Water samples were collected from a depth of 20-30 cm below the water surface to avoid surface film and bottom sediments. For each replicate, the can was filled completely to eliminate air bubbles, sealed immediately, and labeled with station code, date and replicate number.

Sample preservation and transport: for physicochemical parameters (pH, EC, DO, temperature), measurments were performed *in situ* immediately after collection using field-calibrated portable meters to prevent changes due to temperature and pressure variations during transport. For laboratory analyses, smples were placed in insulated coolers containing ice packs to maintain a constant temperature of 4°C ±1°C during transport. Specifically:

- Smaples for BOD and COD analysis were kept in amber glass bottles to prevent photochemical degradation and transported at 4°C.

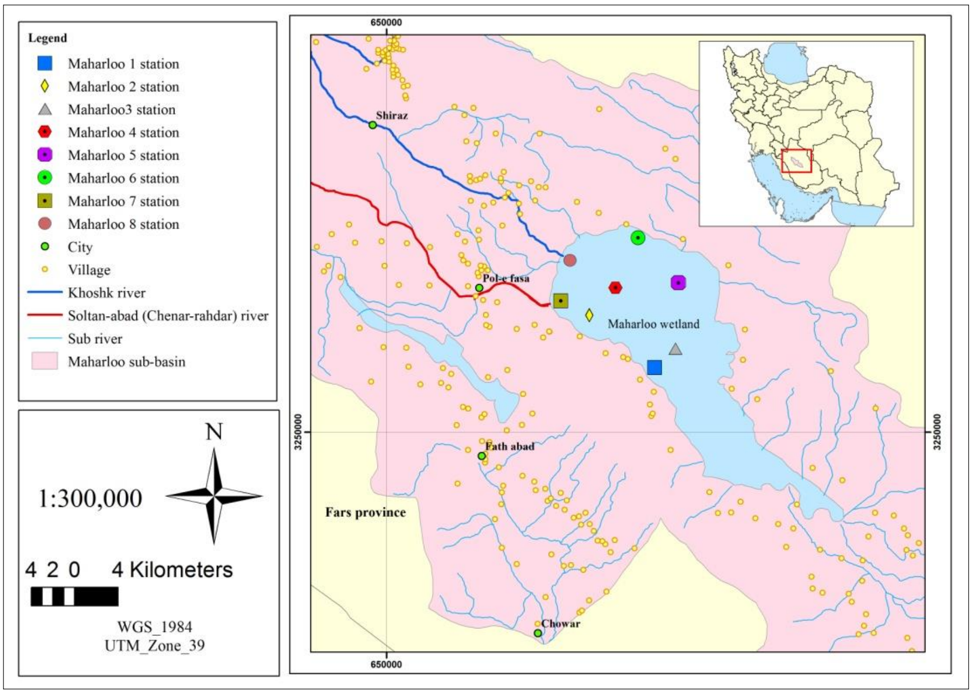

Figure 1. Sampling stations in Maharloo wetland

Table 1. Geographical coordinates of sampling stations for analysis of physicochemical parameters of water

No.	Station name	latitude	Longitude
1	Maharloo 1	29°25'10.30"N	52°48'2.44"E
2	Maharloo 2	29°27'54.33"N	52°44'24.49"E
3	Maharloo 3	29°26'10.42"N	52°49'17.08"E
4	Maharloo 4	29°29'15.33"N	52°45'55.29"E
5	Maharloo 5	29°29'27.94"N	52°49'29.98"E
6	Maharloo 6	29°31'44.10"N	52°47'14.67"E
7	Maharloo 7	29°28'38.47"N	52°42'46.86"E
8	Maharloo 8	29°30'39.29"N	52°43'20.22"E

- Samples for nitrate and phosphate analysis were filtered through 0.45 µm membrane filters *in situ* to prevent mictobial activity from altering nutrient concentrations.
- Smaples for fecal coliform analysis were collected in sterile glass bottles trasported at 4°C and processed within 6 hours of collection.
- Samples for total hardness and ammonium analysis were acidified to pH<2 using

concentrated sulfuric acid (H_2SO_4) when preservation beyond 24 hours was required.

All samples were transferred wihthin 4-6 hours of collection to the Aquatic Ecology Laboratory and the General L Ecology Laboratory and the General Laboratory of the Natural Resources Faculty at the University of Tehran, where they were stored in 4°C until analysis, which was completed within 48 hours of collection.

Analytical methods: The samples were subsequently analyzed for a comprehensive suite of physicochemical parameters and microbial quality indicators.

To synthesize the water quality and pollution status across the stations, the Iranian Surface Water Quality Index (IRWQISC) was employed. This index is a composite tool, optimized for Iran's surface waters, which integrates the National Sanitation Foundation Water Quality Index (NSFWQI) and the British Columbia Water Quality Index (BCWQI). It calculates a single quantitative score by weighting 11 key water quality parameters: biochemical oxygen demand (BOD), chemical oxygen demand (COD), pH, nitrate, phosphate, dissolved oxygen (DO), total dissolved solids (TDS), electrical conductivity (EC), ammonium, turbidity, total hardness, and fecal coliform density. The resulting index value ranges from 0 to 100, providing a clear representation of overall water quality (Table 2).

Table 2. Qualitative classification of surface water resources based on the IRWQIsc index number

Numerical value of the index	<15	15-29.9	30-44.9	45-55	55.1-70	70.1-85	85<
Descriptive-qualitative equivalent	Very bad	Bad	Relatively bad	Medium	Relatively good	Good	Very good

pH was measured with a HACH device, dissolved oxygen saturation, biological oxygen demand (BOD) with an oxygen meter and digital BOD meter from Hanna, model F0021256, made in Romania, chemical oxygen demand (COD) with an open reverse distillation method, phosphate (PO_4) under acidic conditions by reaction with ammonium heptamolybdate, nitrate (NO_3) by reduction with cadmium and then reaction with sulfanilic acid (Eaton *et al.*, 2005). Analysis of electrical conductivity (EC) were performed with a Hanna, model DS-5467, digital multimeter, made in Romania. Measurement and evaluation of fecal coliform counts were analyzed and counted using tubular dilution and EC culture medium in the general microbiology laboratory, and the total hardness factor (TH) was also measured and evaluated using titration with EDTA in the general laboratory.

The Iranian Surface Water Quality Index (IRWQIsc) was calculated based on the 11 factors presented below. Unlike simple additive indices where all parameters have equal weight, the IRWQIsc employs a weighted aggregation approach. Each of the 11 parameters is assigned a specific weight coefficient (w_i) based on its relative importance for assessing water quality in Iranian surface water bodies, particularly for drinking and aquatic life protection purposes. These weights were determined through expert judgment and calibration using historical water quality data from Iran's water resources (Department of Environment, 2015). The index is calculated using the following formula:

$$IRWQIsc = \Sigma (q_i \times w_i) / \Sigma w_i$$

Where:

q_i = quality score for parameter i (ranging from 0 to 100), derived from a sub-function that transforms the measured concentration into a score based on standard curves defined in Iranian environmental regulations.

w_i = weight coefficient for parameter i.
Weight coefficients (w_i) for the 11 parameters are as follows:
Dissolved Oxygen saturation % :0.097
Biochemical Oxygen Demand (BOD), mg/L: 0.117
Chemical Oxygen Demand (COD), mg/L: 0.093
Fecal Coliforms, No./100ml: 0.140
Electrical Conductivity (EC), µS/cm: 0.096
pH: 0.051
Nitrate (NO_3^-), mg/L: 0.108
Phosphate (PO_4^{3-}), mg/L: 0.087
Total hardness: 0.059
Ammonium (NH_4^+), mg/L: 0.09
Turbidity, NTU: 0.062
Total: 1.00
the IRWQIsc index was calculated and the results were analyzed accordingly. The resulting graphs were plotted (Samadi Kuchaksaraei & Rezaei Tavabe, 2023; Rezamohammadi *et al*., 2024; Mazandarani *et al*., 2024; Samadi Kuchaksaraei *et al*., 2024b).

2.3. Statistical Analysis
Statistical analysis of the data was performed using IBM SPSS Statistics Software (Verson 22), considering the number of stations and 3 replications. Data were presented as mean ±standard deviation. To compare the mean values of water quality parameters among the 8 sampling stations within each season, a one-way analysis of variance (one-way ANOVA) was performed. When a significant overall difference was detected ($p<0.05$), post-hoc test was applied for detailed pairwise comparisons between stations. The results of these comparisons are denoted by letters (a, b, c,…) in the tables, where stations sharing at least one common letter, are not statistically significantly different from each other. For water quality index (IRWQIsc), graphs were drawn using Excel software.

3. Results
3.1. Descriptive statistics of water quality parametes

Table 3 shows the mean and standard deviation of water quality parameters in different stations in Maharloo wetland in the autumn season. According to this table, at Maharloo 7 station, where oxygen has reached zero, the maximum BOD (450.6 mg/l) and COD (669.1 mg/l) were observed. Nitrate (212 mg/l) and phosphate (6.9 mg/l) also showed the maximum numerical value at this station. The turbidity of station 7 was also higher than the others (1856 NTU) and the lowest turbidity was calculated at Maharloo 4 (29 NTU). The highest amount of fecal coliform was also related to station 4 (8761 MPN/100 ml) and the lowest to station 3 (2535 MPN/100 ml). The lowest total hardness (384 mgCaCO3/l) was calculated at Maharloo 7 and the highest at Maharloo 6 (5921 mgCaCO3/l). The electrical conductivity has the lowest value at this station (µs/cm 2761) and the highest EC was related to Maharloo 6 (210433 µs/cm). Ammonia was also significantly higher at Maharloo 7 and Maharloo 8 than at other stations. pH was neutral at all stations and slightly acidic at Maharloo 5 (6.7). Statistical differences among stations for each season are indicated by letter (a, b, c, …) in the "sig group" row of Table 3 to Table 6. Stations that share a common letter (s), are not significantly different ($p<0.05$), according to post-hoc test.

Table 4 shows the mean and standard deviation of water quality parameters in Maharloo wetland in winter. According to this table, in this season, as in autumn, the lowest dissolved oxygen (1.9 mg/l), the highest BOD (226 mg/l), and the highest COD (447 mg/l) were calculated at Maharloo 7. Nitrate (153 mg/l) and phosphate (6 mg/l) also showed the maximum numerical value at this station. The turbidity of this station was also higher than other stations (871 NTU) and the lowest turbidity was calculated at Maharloo 5 (30 NTU). The highest amount of fecal coliform was also related to this station (6342 MPN/100 ml) and the lowest for Maharloo 6 (2593 MPN/100 ml). The lowest total hardness (318 mgCaCO3/l) was calculated at Maharloo 8 and the highest at Maharloo 3 (5589 mgCaCO3/l). The lowest electrical conductivity was at Maharloo7 (581µs/cm) and the highest at Maharloo 6 (262667 µs/cm). Ammonia was also significantly higher at Maharloo 7 than at other stations (21.9 mg/l). In gerneral, pH remained within the neutral range (7.3-8.6) across most stations; however, a slightly acidic condition (pH=6.7) was observed at Maharloo 5 (6.7).

Table 3. Mean and standard deviation of water quality parameters at Maharloo wetalnd stations in autumn

Parametrs	Stations	Maharloo 1	Maharloo 2	Maharloo 3	Maharloo 4	Maharloo 5	Maharloo 6	Maharloo 7	Maharloo 8
BOD (mg/l)	Mean	102.1	110.7	97.8	103.3	108.1	106.2	450.6	110.4
	std	6.5	3.4	12.5	7.2	6.6	1.8	6.6	7.8
	Sig group	a	a	a	a	a	a	b	a
COD (mg/l)	Mean	312.7	301.8	307.3	309.8	317.1	309.9	669.1	354.4
	std	7.5	12.8	15.8	12.3	13.1	7.1	14.1	7.7
	Sig group	a	a	a	a	a	a	b	b
DO (mg/l)	Mean	5.1	5.8	4.6	6.8	5.4	4.9	0.0	2.4
	std	0.1	0.1	0.1	0.4	0.1	0.1	0.0	0.1
	Sig group	a	b	a	c	d	a	e	f
DO%	Mean	77	86	108	107	86	27	0.0	34
EC (µs/cm)	Mean	174833.3	115066.7	133726.7	103243.3	135666.7	210433.3	2760.7	2817.0
	std	351.2	665.8	25.2	150.4	57.7	1900.9	62.1	11.3
	Sig group	a	b	c	d	e	f	g	g
Fecal coliform (MPN/100 ml)	Mean	3048.7	2806.0	2535.3	3320.0	2656.7	3128.0	8761.0	5745.3
	std	202.8	212.9	339.6	266.4	484.6	410.1	130.0	47.1
	Sig group	ab	a	b	a	a	a	c	c
NH_3 (mg/l)	Mean	2.2	2.5	2.6	2.5	2.5	2.5	24.1	14.9
	std	0.1	0.1	0.1	0.2	0.2	0.2	1.3	2.7
	Sig group	a	a	a	a	a	a	b	b
NO_3 (mg/l)	Mean	40.9	39.9	37.0	35.6	37.3	36.2	212.0	130.0
	std	0.4	0.4	3.7	2.2	5.7	0.5	8.5	5.7
	Sig group	a	a	a	a	a	a	b	b
PO_4 (mg/l)	Mean	1.4	1.3	1.2	1.2	1.3	1.2	6.9	3.5
	std	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
	Sig group	a	a	a	a	a	a	b	b
Total hardness ($mgCaCO_3/l$)	Mean	5081.3	5688.7	5616.7	5634.0	5697.0	5921.3	384.3	403.0
	std	639.1	248.5	251.0	303.6	313.0	187.2	9.0	9.0
	Sig group	a	b	b	b	b	b	c	c
Turbidity (NTU)	Mean	151.0	103.3	170.3	29.0	205.0	163.0	1855.7	1479.3
	std	1.0	11.1	0.6	1.0	3.0	32.5	101.2	55.6
	Sig group	a	a	a	c	a	a	b	b
pH	Mean	7.6	8.2	7.1	8.3	6.7	7.6	7.2	7.6
	std	0.1	0.0	0.1	0.1	0.1	0.1	0.0	0.1
	Sig group	a	b	c	b	d	a	c	a

Table 4. Mean and standard deviation of water quality parameters at Maharloo wetalnd stations in winter

Parametrs	Stations	Maharloo1	Maharloo 2	Maharloo 3	Maharloo 4	Maharloo 5	Maharloo 6	Maharloo 7	Maharloo 8
BOD (mg/l)	Mean	68.67	60.53	65.40	63.80	66.50	65.30	225.77	70.33
	std	5.55	7.48	4.74	4.81	6.48	1.77	5.17	5.05
	Sig group	a	a	a	a	a	a	b	a
COD (mg/l)	Mean	119.03	135.13	122.80	128.77	130.77	128.27	447.13	188.47
	std	5.93	11.91	17.55	15.44	9.14	9.11	40.08	2.97
	Sig group	a	a	a	a	a	a	b	b
DO (mg/l)	Mean	5.60	5.37	6.00	7.57	7.47	6.03	1.90	11.20
	std	0.17	0.06	0.00	0.06	0.06	0.06	0.00	0.30
	Sig group	a	a	b	b	c	c	d	d
DO%	Mean	80.00	76.67	85.71	108.10	106.67	86.19	27.14	160.00
EC (μs/cm)	Mean	212000	216700	192000	147500	210100	262667	3596	581
	std	0	0	0	0	0	0	17.24	432.4
	Sig group	a	b	c	d	e	f	g	h
Fecal coliform (MPN/100 ml)	Mean	2620.67	2767.00	2602.33	2837.00	2606.67	2592.67	6342.00	4626.33
	std	212.22	331.46	34.50	441.47	207.69	81.82	179.77	272.54
	Sig group	a	a	a	a	a	a	b	b
NH_3 (mg/l)	Mean	1.67	1.63	1.47	1.62	55.75	1.69	21.86	4.77
	std	0.17	0.10	0.04	0.05	93.75	0.19	0.49	0.83
	Sig group	a	a	a	a	a	a	b	b
NO_3 (mg/l)	Mean	59.67	58.83	65.07	60.70	58.87	62.90	152.60	92.17
	std	3.07	4.60	9.64	6.15	6.41	6.91	4.12	3.95
	Sig group	a	a	a	a	a	a	b	b
PO_4 (mg/l)	Mean	1.36	1.52	1.35	1.38	1.32	1.44	5.85	2.10
	std	0.09	0.16	0.10	0.15	0.12	0.08	0.11	0.11
	Sig group	a	a	a	a	a	a	b	b
Total hardness ($mgCaCO_3/l$)	Mean	5550.67	5416.00	5589.00	5526.67	5413.00	5266.00	326.00	317.67
	std	217.22	261.02	255.98	265.06	479.50	320.16	13.00	6.03
	Sig group	a	a	a	a	a	a	b	b
Turbidity (NTU)	Mean	77.67	123.00	119.00	84.67	30.33	39.33	871.00	405.67
	std	0.58	1.73	1.73	0.58	0.58	0.58	110.22	42.67
	Sig group	a	ab	b	a	a	a	c	c
pH	Mean	7.87	8.10	7.97	8.60	6.70	7.37	7.50	8.10
	std	0.06	0.10	0.06	0.10	0.10	0.12	0.00	0.00
	Sig group	a	ab	b	d	e	c	c	a

Table 5 shows the mean and standard deviation of water quality parameters in Maharloo wetland in spring. According to this table, in this season, as in autumn and winter, the lowest dissolved oxygen (0 mg/l), the highest BOD (273 mg/l), and the highest COD (425 mg/l) were calculated at Maharloo 7 station. Nitrate (19 5mg/l) and phosphate (6 mg/l) also showed the maximum numerical value at this station. The turbidity of this station was also higher than others (1161 NTU) and the lowest turbidity was calculated at Maharloo 5 and Maharloo 6 (79 NTU). The highest amount of fecal coliform was also related to this station (6253 MPN/100 ml) and the lowest was related to Maharloo 1 (3163 MPN/100 ml). The lowest total hardness (318 mgCaCO3/l) was also calculated in Maharloo 7 and the highest in Maharloo 6 (5629 mgCaCO3/l). The lowest electrical conductivity was related to Maharloo 8 (1551 µs/cm) and the highest was related to Maharloo 5 (266667 µs/cm). Ammonia was also higher in Maharloo 7 than in other stations (25 mg/l). The pH was neutral in all stations.

Table 5. Mean and standard deviation of water quality parameters at Maharloo wetalnd stations in spring

Parametrs	Stations	Maharloo1	Maharloo 2	Maharloo 3	Maharloo 4	Maharloo 5	Maharloo 6	Maharloo 7	Maharloo 8
BOD (mg/l)	Mean	105.33	111.00	117.00	111.33	122.00	111.00	272.70	178.80
	std	4.93	8.72	4.00	14.84	6.24	4.58	7.57	9.86
	Sig group	a	a	a	a	a	a	b	b
COD (mg/l)	Mean	227.00	227.67	225.33	224.33	222.67	226.67	425.40	284.57
	std	2.65	3.51	1.53	7.51	3.21	3.06	15.01	15.19
	Sig group	a	a	a	a	a	a	b	b
DO (mg/l)	Mean	2.33	2.40	2.53	2.43	2.33	2.37	0.00	0.00
	std	0.15	0.10	0.06	0.06	0.15	0.06	0.00	0.00
	Sig group	a	a	b	ab	a	a	c	c
DO%	Mean	33.33	34.29	36.19	34.76	33.33	33.81	0.00	0.00
EC (µs/cm)	Mean	244667	255000	232333	196000	266667	262667	4676	1551
	std	21	577	2000	17039	1000	1528	66	99
	Sig group	a	ab	d	e	b	b	c	c
Fecal coliform (MPN/100 ml)	Mean	3163.67	3195.33	3248.33	3473.00	3385.00	3389.67	6253.33	5762.67
	std	45.63	19.22	13.58	201.22	244.55	199.93	641.25	133.00
	Sig group	a	a	a	a	a	a	b	b
NH_3 (mg/l)	Mean	1.70	1.73	1.60	1.60	1.67	1.80	25.35	18.96
	std	0.10	0.06	0.10	0.20	0.06	0.10	1.96	1.21
	Sig group	a	a	a	a	a	a	b	b
NO_3 (mg/l)	Mean	73.10	78.07	76.60	78.10	74.23	78.53	195.37	171.90
	std	3.08	1.05	3.35	3.64	2.67	3.96	9.62	3.99
	Sig group	a	a	a	a	a	a	b	b
PO_4 (mg/l)	Mean	1.60	1.67	1.70	1.60	1.70	1.67	6.04	5.66
	std	0.10	0.15	0.20	0.20	0.20	0.06	0.26	0.75
	Sig group	a	a	a	a	a	a	b	b
Total hardness ($mgCaCO_3/l$)	Mean	5567	5546	5610	5623	5550	5629	371	387
	std	126	71	170	100	128	78	52	18
	Sig group	a	a	a	a	a	a	b	b
Turbidity (NTU)	Mean	96.00	80.00	81.33	84.67	79.33	79.33	1161.67	1130.33
	std	1.00	4.58	4.73	8.50	4.16	11.02	149.37	97.65
	Sig group	a	a	a	a	a	a	b	b
pH	Mean	7.93	8.20	8.03	8.60	7.07	7.53	7.57	8.10
	std	0.12	0.20	0.15	0.10	0.12	0.06	0.12	0.00
	Sig group	a	ab	b	d	e	c	c	a

Table 6 shows the mean and standard deviation of water quality parameters in Maharloo wetland in the summer season. According to this table, in this season, as in autumn and winter, the lowest dissolved oxygen (0 mg/l), the highest BOD (343 mg/l), and the highest COD (665 mg/l) were calculated at Maharloo 7. Nitrate (12 mg/l) and phosphate (7.8 mg/l) also showed the maximum numerical value at this station. The turbidity of this station was also higher than others (1725 NTU) and the lowest turbidity was calculated at Maharloo 5 and Maharloo 6 (79 NTU). The highest amount of fecal coliform was also related to this station (6253 MPN/100 ml) and the lowest was related to Maharloo 1 (6883 MPN/100 ml). The lowest total hardness (434 mgCaCO3/l) was calculated at Maharloo 7 and the highest at Maharloo 6 (5629 mgCaCO3/l). The lowest electrical conductivity was at Maharloo 8 (1795 µs/cm) and the highest at Maharloo 5 (266667 µs/cm). Ammonia was also higher at Maharloo 8 than at other stations (25 mg/l). The pH was neutral at all stations.

Table 6. Mean and standard deviation of water quality parameters at Maharloo wetalnd stations in summer

Parametrs	Stations	Maharloo1	Maharloo 2	Maharloo 3	Maharloo 4	Maharloo 5	Maharloo 6	Maharloo 7	Maharloo 8
BOD (mg/l)	Mean	105.33	111.00	117.00	111.33	122.00	111.00	342.67	310.67
	std	4.93	8.72	4.00	14.84	6.24	4.58	13.75	9.33
	Sig group	a	a	a	a	a	a	b	b
COD (mg/l)	Mean	227.00	227.67	225.33	224.33	222.67	226.67	665.33	640.97
	std	2.65	3.51	1.53	7.51	3.21	3.06	24.85	15.37
	Sig group	a	a	a	a	a	a	b	b
DO (mg/l)	Mean	2.33	2.40	2.53	2.43	2.33	2.37	0.00	0.00
	std	0.15	0.10	0.06	0.06	0.15	0.06	0.00	0.00
	Sig group	a	ab	b	ab	ab	ab	c	c
DO%	Mean	33.33	34.29	36.19	34.76	33.33	33.81	0.00	0.00
EC (µs/cm)	Mean	244666.67	255000.00	232333.33	196000.00	266666.67	262666.67	4676.00	1795.00
	std	577.35	2000.00	17039.17	1000.00	1527.53	1527.53	66.34	118.65
	Sig group	a	abc	e	f	bc	bc	d	d
Fecal coliform (MPN/100 ml)	Mean	3163.67	3195.33	3248.33	3473.00	3385.00	3389.67	6883.33	6338.67
	std	45.63	19.22	13.58	201.22	244.55	199.93	326.15	528.63
	Sig group	a	a	a	a	a	a	b	b
NH_3 (mg/l)	Mean	1.70	1.73	1.60	1.60	1.67	1.80	21.93	24.74
	std	0.10	0.06	0.10	0.20	0.06	0.10	2.10	1.39
	Sig group	a	a	a	a	a	a	b	b
NO_3 (mg/l)	Mean	73.10	78.07	76.60	78.10	74.23	78.53	244.27	262.87
	std	3.08	1.05	3.35	3.64	2.67	3.96	12.13	14.01
	Sig group	a	a	a	a	a	a	b	b
PO_4 (mg/l)	Mean	1.60	1.67	1.70	1.60	1.70	1.67	7.76	7.30
	std	0.10	0.15	0.20	0.20	0.20	0.06	0.51	0.20
	Sig group	a	a	a	a	a	a	b	b
Total hardness ($mgCaCO_3/l$)	Mean	5567.33	5546.00	5610.00	5622.67	5550.33	5629.33	433.67	449.67
	std	125.91	70.53	169.92	100.33	128.38	78.49	13.65	30.44
	Sig group	a	a	a	a	a	a	b	b
Turbidity (NTU)	Mean	96.00	80.00	81.33	84.67	79.33	79.33	1725.33	1573.33
	std	1.00	4.58	4.73	8.50	4.16	11.02	146.13	224.53
	Sig group	a	a	a	a	a	a	b	b
pH	Mean	8.07	8.27	8.07	8.37	7.07	7.83	8.07	8.13
	std	0.12	0.25	0.12	0.32	0.12	0.29	0.12	0.15
	Sig group	a	a	a	ab	c	b	a	a

Fig 1 shows the comparision of water quality index (IRWQIsc) in studied stations in different seasons. The calculated IRWQIsc values ranged from 5.2 to 11.4 across all stations and seasons, categorizing the water quality as 'very bad' according to the standard index (Table 2).

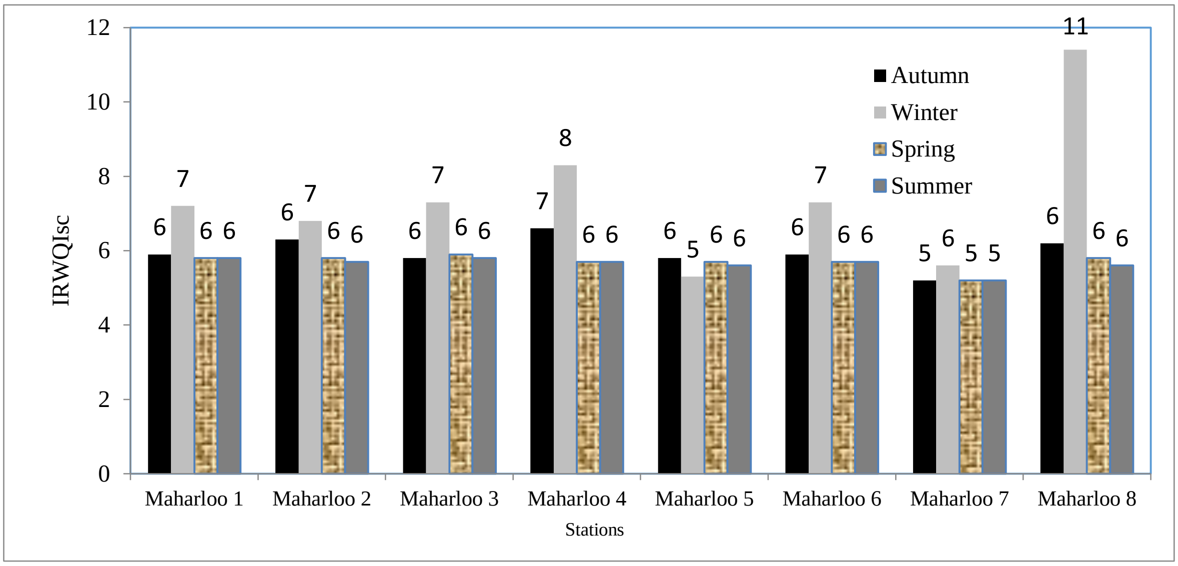

Figure 1. Comparison of water quality index ($IRWQI_{SC}$) in studied stations in different seasons

3.2. Synthesis of seasonal patterns

A consistent spatial pattern was observed across all four seasons for key pollution parameters (BOD, COD, nutrients). Stations Maharloo 7 and Maharloo 8 consistently formed a distinct statistical group (often denoted as 'b', showing significantly higher mean values compared to the cluster of Stations 1 through 6 (frequently grouped as 'a'). This indicates a persistent and pronounced difference in water quality between these two sites and the others.

4. Discussion

4.1. Spatio-Temporal Pollution Patterns and Source Attribution

The results delineate two dominant and spatially distinct pollution regimes in Maharloo Wetland, each indicative of different anthropogenic pressures and hydrological processes (Wu *et al*., 2021).

1. **Organic and Nutrient Enrichment at River Inlets:** Stations Maharloo 7 and Maharloo 8, situated at the confluences of Soltan-bad and Khoshk rivers, were identified as acute, year-round hotspots for organic and nutrient pollution. The persistently and significantly elevated levels of BOD, COD, ammonia, phosphate, turbidity, and fecal coliforms at these points are characteristic of untreated wastewater and agricultural return flow (Samadi Kuchaksaraei & Rezaei Tavabe, 2023; Fars Department of Environment, 2020). Phosphate is considered a production-limiting factor in freshwater ecosystems (Harper 1992; Sterner 2008), while nitrate is considered one in brackish and saline water sources (Howarth & Marino 2006; Mills *et al*. 2018).

This is consistent with broader findings in the basin that identify agricultural drainage as a major source of contaminants (Safavian *et al*., 2022; Jahanjirpour *et al*., 2015). The severe oxygen depletion (often anoxic) at Station Maharloo 7 is a direct ecological consequence of this organic overload, creating conditions toxic to most aquatic life and aligning with documented risks of pollutant accumulation in the wetland's biota (Fars Department of Environment, 2020).

2. Extreme Salinization in Evaporation-Dominated Zones: In stark contrast, the central and southern stations (notably Maharloo 3, Maharloo 5, and Maharloo 6) exhibited extreme salinity, with electrical conductivity (EC) consistently exceeding 200,000 µS/cm. This pattern reflects the terminal nature of the wetland, where insufficient freshwater inflow and intense evaporation concentrate salts in the water column (Ahmadianfar *et al*., 2020; Zamanpoore *et al*., 2023). This process of "salinization by concentration" is exacerbated by the widespread groundwater overdraft for agriculture in the surrounding plains, which reduces freshwater recharge to the wetland and can pull saline groundwater into the system (Jafari *et al*., 2021; Danehkar & Samadi Kuchaksaraei, 2021). The very high total hardness corroborates this, indicating dominance of calcium and magnesium salts. According to previous studies, the impact of salinity on the ecosystem is much greater than that of other physicochemical factors of water (Eriksson 1985; Worch 2015).

3. Implications of Decoupled Pollution Regimes: This spatial decoupling of primary pollutants—organic/nutrient loading at discrete surface water inlets versus generalized salt concentration from basin-scale hydrological imbalance—is a critical diagnostic finding. It demonstrates that Maharloo is subjected to multiple, compounding stressors. This complexity invalidates one-dimensional solutions. For instance, merely transferring freshwater to dilute salinity (as considered for Parishan Wetland by Isaei & Isaei, 2014; Isaei & Isaei, 2015; University of Tehran, 2021; Rezaei Tavabe & Samadi Kuchaksaraei, 2021b) without first intercepting the organic and nutrient loads at Stations Maharloo 7 and Maharloo 8 could fuel eutrophication and simply relocate the pollution problem downstream within the wetland (Bellemakers & Maessen, 1998; Ansari *et al*., 2010; Chislock *et al*., 2013). Conversely, only addressing the point-source pollution would leave the ecosystem crippled by hyper-salinity. Therefore, an effective rehabilitation strategy must be spatially explicit and multi-pronged, simultaneously targeting the specific surface water inputs and the broader hydrological deficit driving salinization.

4.2. Synthesis of Pollution Status and the IRWQIsc Index

The application of the IRWQISC index, which synthesizes eleven key parameters, provided a unequivocal and grim summary of the wetland's health. The index values ranging from 5.2 to 11.4 across all stations and seasons firmly place Maharloo's water quality in the "very bad" category. This objective classification transcends the variability of individual parameters and offers a powerful communication tool for managers and policymakers. It confirms that the pollution is not localized but a pervasive problem affecting the entire studied area of the wetland, with the identified hotspots representing the epicenters of degradation.

The seasonal variations, while present, did not alter the fundamental spatial pattern or the "very bad" classification. The slightly reduced pollutant concentrations in winter at some stations can be attributed to dilution from precipitation, a phenomenon also observed for heavy metals in the wetland (Fars Department of Environment, 2020). However, the persistence of high pollution levels even during rains indicates a continuous loading from sources that are not solely runoff-dependent, such as groundwater influx contaminated by agricultural return flows or persistent point sources.

4.3. Integrated Rehabilitation Strategy: Merging Source Control with Water Allocation

The mentioned findings, necessitate a shift from generic restoration talks to a targeted, two-pillar rehabilitation strategy: Pollution Source Control and Ecological Water Allocation.

1. Immediate Priority: Targeted Pollution Source Control

Before any significant water allocation can yield ecological benefits, the pollution influx must be curbed. Allocating clean water to a system receiving such high loads of organic matter and nutrients would be inefficient and could exacerbate downstream eutrophication. Actions must include:

* Source Identification and Regulation: A precise watershed-scale audit is needed to pinpoint the exact drains, industries, or settlements contributing to Stations Maharloo 7 and Maharloo 8. Enforcement of wastewater treatment standards is non-negotiable.

* Agricultural Best Management Practices (BMPs): Promoting drip irrigation, optimizing fertilizer use, and constructing vegetative buffer strips along drainage channels can drastically reduce nutrient and sediment runoff (Safavian *et al*., 2022; Jahanjirpour *et al*., 2015). This aligns with findings that agricultural management is the most critical intervention for wetland restoration in the region (Samadi Kuchaksaraei *et al*., 2024b; Afshrtabar *et al*., 2023).

2. Essential Foundation: Scientifically-Determined Ecological Water Right

Concurrently, the hydrological deficit must be addressed. Lessons from Parishan Wetland demonstrate the effectiveness of using flagship species to determine both minimum and optimal ecological water volumes (Rezaei Tavabe & Samadi Kuchaksaraei, 2021a; Rezaei Tavabe *et al*., 2021; Rezaei Tavabe *et al*., 2022). A similar study is urgently needed for Maharloo to define its non-negotiable water requirement. This "environmental flow" would help maintain a minimum aquatic habitat, dilute pollutants, and support basic ecosystem functions. Water can be secured through:

* Strict Management of Groundwater: Capping and metering illegal wells in the basin, as repeatedly recommended (Danehkar & Samadi Kuchaksaraei, 2021; Fars Department of Environment, 2018).

* Strategic Water Transfers: As a supplementary measure, and only after source control is initiated, controlled transfers from other sources could be considered. However, such projects require rigorous pre-assessment of water quality compatibility to avoid salinity increase or invasive species introduction, as meticulously modeled for the Nargesi-Parishan project (University of Tehran, 2021; Rezaei Tavabe & Samadi Kuchaksaraei, 2021b; Samadi Kuchaksaraei *et al*., 2024a).

4.4. Socio-Economic Considerations and the Path Forward

Implementing this strategy requires acknowledging socio-economic realities. Reducing agricultural water use will have economic impacts on farmers (Afshrtabar *et al*., 2023). Therefore, the strategy must be coupled with an incentive program, such as payments for ecosystem services, subsidized transition to low-water crops, and investments in modern irrigation infrastructure. Furthermore, as seen in Parishan wetland, community awareness and acceptance are crucial for long-term success (Samadi Kuchaksaraei *et al*., 2024b). Public education on the value of the wetland and participatory monitoring programs can foster local stewardship.

5. Conclusion

This study provided the first detailed spatio-temporal evidence of severe and chronic water quality degradation in Maharloo Wetland, systematically identifying two critical pollution hotspots and classifying the overall water quality as "very bad". The data reveal a system under immense stress from untreated organic and nutrient loads, superimposed on a well-documented hydrological crisis. It can be concluded that an effective rehabilitation strategy cannot rely on water allocation alone. It must be integrated, prioritizing immediate and targeted pollution source control at identified hotspots—particularly through agricultural BMPs and wastewater management—as a prerequisite for any meaningful ecological water allocation. The defined ecological water right, determined through methods like flagship species assessment, should then guide the re-allocation of water from regulated agricultural use. This dual approach, implemented with socio-economic sensitivity and robust monitoring, represents the most viable pathway to halt the degradation of Maharloo Wetland and steer it towards a state of recovered ecological function and resilience. Future research should focus on precise source tracking, detailed ecological flow assessment for Maharloo, and cost-benefit analysis of the proposed interventions.

Acknowledgment
The authors would like to thank Fars Province Department of Environment for their cooperation and administrative support in facilitating access to the study site.

Author Contributions
Conceptualization, Bahareh Samadi Kuchaksaraei and Kamran Rezaei Tavabe; methodology, Kamran Rezaei Tavabe; software, Bahareh Samadi Kuchaksaraei; validation, Kamran Rezaei Tavabe; formal analysis, Kamran Rezaei Tavabe; investigation, Bahareh Samadi Kuchaksaraei and Elnaz Namdari Ghareghani.; resources, Kamran Rezaei Tavabe; data curation, Bahareh Samadi Kuchaksaraei; writing—original draft preparation, Bahareh Samadi Kuchaksaraei; writing—review and editing, Bahareh Samadi Kuchaksaraei and Kamran Rezaei Tavabe; visualization, Bahareh Samadi Kuchaksaraei; supervision, Kamran Rezaei Tavabe; project administration, Kamran Rezaei Tavabe; funding acquisition, Kamran Rezaei Tavabe. Field sampling, Elnaz Namdari Ghareghani, Hamid Zohrabi, Mohammad Javad Sayahpour and Yalda Moassaghi .All authors have read and agreed to the published version of the manuscript.

Data Availability Statement
Data that support the results of this study are available from the corresponding author upon reasonable request.

Ethical considerations
Not applicable. This study did not involve human or animal subjects, and no ethical approval was required.

Funding
This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Conflict of interests
The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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