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Seasonal and spatial dynamics of physico-chemical water quality in Khairi Dam: Implications for *Labeo catla* (Hamilton, 1822) aquaculture

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Abstract
This study evaluates the seasonal and spatial dynamics of physico-chemical water quality in Khairi Dam and interprets their implications for *Labeo catla* (Hamilton, 1822) aquaculture. Monthly surface samples were collected at five fixed sites (North, Central, South, East, West) from September 2023 to August 2024 (n = 5 replicates per site per month) for twelve parameters: temperature, pH, dissolved oxygen (DO), nitrate, phosphate, turbidity, total hardness, total dissolved solids (TDS), biological oxygen demand (BOD), chloride, alkalinity, and dissolved CO_2. Data were summarized as mean ± SD and analyzed using two-way ANOVA with factors Site and Season (Post-monsoon: Oct–Jan; Pre-monsoon: Feb–May; Monsoon: Jun–Sep). Temperature (24.6–31.0 °C) and pH (7.30–7.75) remained within culture-suitable ranges, whereas DO showed pronounced seasonality, with pre-monsoon minima (~5.0–5.8 mg L^{-1}) and monsoon/post-monsoon maxima (~7.3–7.8 mg L^{-1}). Monsoon pulses increased nitrate (0.1–0.7 mg L^{-1}), phosphate (0.06–0.21 mg L^{-1}), turbidity (15–50 NTU), and BOD (1.5–3.4 mg L^{-1}), particularly at the North inflow, while conservative ions and alkalinity concentrated pre-monsoon and diluted during monsoon (hardness 132–172 mg L^{-1}; TDS 285–405 mg L^{-1}; chloride 25–45 mg L^{-1}; alkalinity 118–160 mg L^{-1}; dissolved CO_2 3.2–7.5 mg L^{-1}). Season was a significant driver ($p < 0.001$) for most parameters; site effects were present for nutrients, turbidity, and select ions, with generally non-significant Site×Season interactions, indicating parallel seasonal trajectories across sites. Benchmarking against aquaculture guidelines shows overall suitability for L. catla, with two management priorities: mitigating pre-monsoon DO dips (aeration, feeding/biomass control) and managing monsoon nutrient–turbidity surges near the inflow (site selection, solids shielding, prudent feeding). Findings provide an operational, season-aware template for reservoir-based carp culture under monsoon variability.

Keywords: Khairi Dam, seasonal water quality, Labeo catla, aquaculture, monsoon hydrology, dissolved oxygen

Introduction

Reservoirs that support inland fisheries and aquaculture operate under strong seasonal hydro-climatic controls that modulate nutrient delivery, dissolved oxygen dynamics, and optical properties of the water column. In monsoon-influenced basins, storm pulses alternately dilute and enrich receiving waters, altering trophic status and habitability for cultured carps within weeks (Kim & Kim, 2021) [5]. Globally, aquaculture's rising share of aquatic production intensifies the need for water-quality risk management: in 2022, total aquatic production reached 223.2 million t, of which aquaculture produced 130.9 million t (including 37.8 million t of algae), underscoring sectoral dependence on stable water quality (FAO, 2024) [3]. In temperate and tropical reservoirs alike, studies consistently report meso- to eutrophic conditions with seasonal deviations tied to rainfall intensity and internal loading, with implications for phytoplankton composition and oxygen budgets that directly affect carp performance (Kim & Kim, 2021; Varol, 2020) [5, 7]. In Asian monsoon systems, summer rainfall often reorganizes spatial patterns within large impoundments by advecting suspended sediments and nutrients along inflow–center–outflow transects. Multiyear assessments in Korean reservoirs show that monsoon seasons can shift trophic metrics from oligotrophic/mesotrophic towards eutrophic states; for example, one five-year analysis found 46% of eutrophic occurrences clustered in the monsoon quarter (July–September) (Cho *et al*., 2023) [2]. Such reorganization affects light climate, chlorophyll-a, and downstream dissolved oxygen (DO), all of which are critical for pond-reared and cage-reared Indian major carps (Kim & Kim, 2021; Cho *et al*., 2023) [2, 5].

While numerous studies have mapped trophic state and water-quality indices (WQI) in reservoirs using in-situ and remote sensing data, many emphasize system-level eutrophication diagnostics rather than aquaculture-oriented operational thresholds for Indian major carps. Remote sensing work in India's Mettur Reservoir has demonstrated spatial heterogeneity in chlorophyll-a and trophic status across the basin, yet translation of these gradients into stock-management guidance for carps remains sparse (Saha *et al*., 2021) [6]. Recent integrative analyses in Indian reservoirs combine WQI, Carlson-type indices, and multivariate statistics to parse runoff-driven versus internal-loading signals; however, explicit cross-walks to fish-culture thresholds (e.g., DO minima, carbonate buffering bands, nutrient ceilings) are often only briefly treated (Gogoi *et al*., 2025; Varol, 2020) [4, 7]. Moreover, comparatively few reservoir studies report fully replicated, site-resolved monthly means for a broad panel of 10–12 physico-chemical parameters over a complete monsoon cycle—a data structure necessary to inform stocking, feeding, and aeration decisions for *Labeo catla* (Bhatnagar & Devi, 2013; Saha *et al*., 2021) [1, 6].

For monsoon-fed reservoirs used for carp aquaculture, managers lack site- and season-specific evidence linking routine physico-chemical fluctuations to established culture ranges for *Labeo catla* (Hamilton, 1822). Specifically, there is limited guidance on how inflow-centric nutrient and turbidity pulses, pre-monsoon DO troughs, and carbonate system stability vary across reservoir sub-basins within a year—and how these spatio-temporal patterns align with recommended aquaculture thresholds for temperature, DO, pH–alkalinity, hardness/TDS, and inorganic nutrients (Bhatnagar & Devi, 2013; Kim & Kim, 2021) [1, 5]. This study addresses that gap by quantifying the seasonal and spatial dynamics of twelve physico-chemical parameters in Khairi Dam over an annual cycle and interpreting them against carp-culture thresholds relevant to *L. catla*. The objectives are to: (i) characterize monthly means (±SD) at fixed North, Central, South, East, and West sites; (ii) test for main effects of Site, Season, and their interaction using two-way ANOVA on replicated observations; and (iii) benchmark observed ranges against aquaculture-recommended bands for temperature (22–32 °C), DO (>5 mg L^{-1}; optimal ~6–8 mg L^{-1}), pH (6.5–8.5), alkalinity (50–200 mg L^{-1} as $CaCO_3$), hardness (50–300 mg L^{-1} as $CaCO_3$), nutrients (preferably phosphate <0.1–0.2 mg L^{-1}; nitrate <1.0 mg L^{-1}), and BOD (≤3 mg L^{-1}) (Bhatnagar & Devi, 2013) [1]. Framing the analysis within monsoon-season hydrology and reservoir trophic responses allows us to disentangle rainfall-driven external loading from internal processes affecting DO and algal biomass (Kim & Kim, 2021; Cho *et al*., 2023) [2, 5].

By aligning replicated, site-resolved reservoir observations with aquaculture thresholds, this study offers an operational template for decision-making in carp culture under monsoon variability. Findings contribute to (a) risk anticipation for pre-monsoon DO dips and monsoon turbidity/nutrient surges; (b) spatial targeting of aeration, feeding adjustments, and biomass management where inflow arms exhibit recurrent stressors; and (c) harmonization of limnological diagnostics (WQI, TSIs, PCA) with farm-scale actions (Bhatnagar & Devi, 2013; Varol, 2020) [1, 7]. For India's reservoir-based aquaculture, such translation from seasonal limnology to site-specific husbandry is critical as aquaculture expands within multiuse water bodies and as climatic variability amplifies the frequency of extreme monsoon seasons (Saha *et al*., 2021; Gogoi *et al*., 2025) [4, 6]. By situating Khairi Dam within this broader evidence base, the paper speaks to both water-resources managers and aquaculture practitioners seeking robust, seasonally tuned operating envelopes for *L. catla* culture (Kim & Kim, 2021; Cho *et al*., 2023) [2, 5].

Materials and Methods

1. Study site and sampling design

Khairi Dam was sampled monthly from September 2023 to August 2024 at five fixed surface stations: North (inflow), Central, South (outflow), East, West. At each station and date, five independent surface grab replicates (0–0.5 m; ~5–10 m apart within a 20–30 m transect) were collected in pre-rinsed HDPE bottles. Sampling months were grouped a priori into Post-monsoon (Oct–Jan), Pre-monsoon/Late dry (Feb–May), and Monsoon (Jun–Sep) to capture hydrologic forcing. In situ measurements (temperature, pH, DO, turbidity, conductivity/TDS) were taken immediately after stabilization at each replicate location; discrete samples for nutrients and alkalinity/chloride/hardness/BOD were transported on ice to the laboratory and processed the same day unless otherwise specified.

2. Field measurements and sample processing

- **Temperature (°C), pH, DO (mg L^{-1}), TDS (mg L^{-1}), Turbidity (NTU):** measured in situ using a calibrated multiparameter sonde (glass pH electrode; optical LDO sensor for DO; conductivity-based TDS; nephelometric turbidity at 860 nm). Instruments were two-point calibrated at the start of each field day (pH 4.00/7.00/10.00 buffers; 0%/100% air saturation for DO; 84/1,413 µS cm^{-1} conductivity standards; for turbidity, 0/20/100 NTU for check).

- **Nutrients:** water was filtered (0.45 µm) into acid-washed HDPE, stored dark at 4 °C, and analyzed within 24 h. Nitrate (mg L^{-1} as NO_3^-) was determined colorimetrically (cadmium reduction–diazotization) by UV–Vis spectrophotometry; phosphate (mg L^{-1} as PO_4^{3-}) by the ascorbic acid molybdenum blue method (λ ≈ 880 nm).

- **Titrimetric ions and BOD:** Total hardness (as CaCO) by EDTA versenate titration with Eriochrome Black T; alkalinity (as $CaCO_3$) by gran/electrometric titration to pH 4.5; chloride by argentometric Mohr titration; BOD_5 by 5-day incubation at 20 °C (dilution water saturated with air and seeded as required; initial and final DO by Winkler/optical).

- **Dissolved CO_2 (mg L^{-1}):** computed from measured pH, alkalinity, and temperature using carbonate equilibrium relationships at in situ temperature.

3. Data reduction and statistical analysis

All monthly site values are reported as Mean ± SD computed from n = 5 replicate observations per site per month. Seasonal means (Table 3.2) are simple averages of monthly means within each season.

To test spatiotemporal drivers, a two-way fixed-effects ANOVA was performed for each parameter with factors Site (5 levels), Season (3 levels), and their interaction (Site × Season), using the model:

$$Response \sim Site + Season + Site \times Season$$

Prior to analysis, distributions were inspected (Q–Q plots) and variance homogeneity was checked (Levene's test). Where needed, log10 or Box–Cox transformations were considered; results are presented on the original scale for interpretability. Statistical significance was evaluated at α = 0.05 with Type-III sums of squares; for significant main effects, Tukey HSD post hoc comparisons were examined. Analyses were conducted in a standard statistical environment (e.g., R with stats, car, emmeans), and F- and p-values are summarized in Table 3.3.

4. Quality assurance/quality control (QA/QC)

Field and laboratory QA/QC measures included: (i) field blanks and lab reagent blanks per batch; (ii) calibration verification every 10–15 samples (acceptance ±5% or re-calibration); (iii) matrix spikes/duplicates (≥10% of samples) for colorimetric assays (acceptance 80–120% recovery; RPD ≤10–15%); (iv) standard reference checks for titrations; and (v) data screening for outliers (values >3 SD from monthly site mean flagged and re-checked against field notes/instrument logs). No censored values were encountered within reporting limits; where replicate anomalies were traced to instrument instability, those readings were excluded a priori and the replicate replaced in the field.

Results

1. Annual and seasonal patterns

Across the annual cycle (Sept 2023–Aug 2024), temperature (24.6–31.0 °C) and pH (7.30–7.75) were stable and aquaculture-suitable across sites, while dissolved oxygen (DO) exhibited marked seasonal structure with pre-monsoon lows (~5.0–5.8 mg L^{-1}) and monsoon highs (~7.3–7.8 mg L^{-1}). Nutrient concentrations (nitrate, phosphate) and turbidity peaked during the monsoon, most prominently at the North sector, consistent with runoff influence. Carbonate system indicators (alkalinity, dissolved CO_2) and conservative ions (hardness, TDS, chloride) showed pre-monsoon concentration followed by monsoon dilution. Annual summaries and seasonal means for stressor parameters are provided in Tables 1 and 2.

Table 1: Annual summary by site—Mean ± SD [min–max] (Sept 2023–Aug 2024)

Parameter	North	Central	South	East	West
Temperature (°C)	27.6 ± 1.9 [24.9–30.8]	27.6 ± 1.8 [24.7–30.5]	27.4 ± 1.8 [24.6–30.4]	27.8 ± 1.9 [24.8–30.6]	27.6 ± 1.8 [24.7–30.5]
pH	7.53 ± 0.11 [7.30–7.75]	7.49 ± 0.05 [7.42–7.56]	7.52 ± 0.09 [7.42–7.64]	7.50 ± 0.05 [7.44–7.60]	7.49 ± 0.04 [7.43–7.55]
DO (mg/L)	6.6 ± 0.9 [5.0–7.8]	6.5 ± 0.8 [5.4–7.6]	6.6 ± 0.8 [5.3–7.6]	6.6 ± 0.8 [5.3–7.5]	6.6 ± 0.8 [5.3–7.6]
Nitrate (mg/L)	0.4 ± 0.2 [0.2–0.7]	0.3 ± 0.1 [0.2–0.5]	0.3 ± 0.1 [0.1–0.5]	0.4 ± 0.2 [0.2–0.6]	0.3 ± 0.1 [0.2–0.6]
Phosphate (mg/L)	0.1 ± 0.0 [0.1–0.2]	0.1 ± 0.0 [0.1–0.2]	0.1 ± 0.0 [0.1–0.2]	0.1 ± 0.0 [0.1–0.2]	0.1 ± 0.0 [0.1–0.2]
Turbidity (NTU)	30.8 ± 10.1 [20.0–50.0]	24.5 ± 8.4 [16.0–40.0]	23.2 ± 7.5 [15.0–36.0]	27.3 ± 9.0 [17.0–43.0]	26.5 ± 8.6 [16.0–41.0]
Total Hardness (mg/L as $CaCO_3$)	154.1 ± 11.0 [138.0–172.0]	147.8 ± 11.1 [135.0–165.0]	144.3 ± 10.5 [132.0–160.0]	151.3 ± 11.0 [136.0–168.0]	148.2 ± 10.2 [134.0–163.0]
TDS (mg/L)	352.9 ± 34.9 [305.0–405.0]	334.8 ± 34.2 [290.0–385.0]	327.0 ± 34.1 [285.0–375.0]	341.5 ± 33.5 [295.0–392.0]	335.1 ± 32.4 [288.0–380.0]
BOD (mg/L)	2.3 ± 0.6 [1.6–3.4]	2.0 ± 0.4 [1.5–2.7]	1.9 ± 0.4 [1.5–2.4]	2.1 ± 0.5 [1.5–2.9]	2.1 ± 0.4 [1.5–2.7]
Chloride (mg/L)	34.8 ± 5.3 [28.0–45.0]	31.5 ± 4.6 [26.0–41.0]	30.6 ± 4.5 [25.0–39.0]	33.1 ± 5.1 [27.0–43.0]	32.4 ± 4.7 [26.0–40.0]
Alkalinity (mg/L as $CaCO_3$)	141.6 ± 12.3 [122.0–160.0]	133.3 ± 12.1 [120.0–153.0]	130.3 ± 11.9 [118.0–148.0]	137.3 ± 12.0 [121.0–156.0]	134.5 ± 11.3 [119.0–150.0]
Dissolved CO_2 (mg/L)	5.4 ± 1.3 [3.6–7.5]	4.7 ± 0.9 [3.4–6.0]	4.6 ± 0.8 [3.2–5.6]	4.9 ± 1.0 [3.5–6.3]	4.9 ± 0.8 [3.4–5.9]

Table 2: Seasonal mean ± SD for key stressors by site

Parameter	Season	North	Central	South	East	West
DO (mg/L)	Post-monsoon	6.6 ± 0.3	6.3 ± 0.3	6.7 ± 0.2	6.6 ± 0.0	6.6 ± 0.0
DO (mg/L)	Pre-monsoon	5.4 ± 0.3	5.5 ± 0.2	5.5 ± 0.2	5.5 ± 0.2	5.4 ± 0.2
DO (mg/L)	Monsoon	7.3 ± 0.2	7.1 ± 0.1	7.3 ± 0.1	7.2 ± 0.1	7.2 ± 0.1
Nitrate (mg/L)	Post-monsoon	0.38 ± 0.04	0.29 ± 0.02	0.29 ± 0.03	0.31 ± 0.02	0.28 ± 0.02
Nitrate (mg/L)	Pre-monsoon	0.24 ± 0.03	0.20 ± 0.02	0.18 ± 0.02	0.22 ± 0.02	0.20 ± 0.02
Nitrate (mg/L)	Monsoon	0.62 ± 0.06	0.50 ± 0.01	0.48 ± 0.04	0.54 ± 0.04	0.52 ± 0.03
Phosphate (mg/L)	Post-monsoon	0.11 ± 0.01	0.10 ± 0.01	0.10 ± 0.00	0.11 ± 0.01	0.10 ± 0.01
Phosphate (mg/L)	Pre-monsoon	0.10 ± 0.02	0.08 ± 0.01	0.09 ± 0.02	0.09 ± 0.01	0.08 ± 0.01
Phosphate (mg/L)	Monsoon	0.17 ± 0.02	0.16 ± 0.02	0.14 ± 0.02	0.16 ± 0.01	0.15 ± 0.01
Turbidity (NTU)	Post-monsoon	23.3 ± 2.5	20.0 ± 2.0	18.5 ± 1.7	20.5 ± 1.9	19.5 ± 1.7
Turbidity (NTU)	Pre-monsoon	23.0 ± 2.1	20.0 ± 2.1	18.0 ± 1.8	21.0 ± 2.2	20.0 ± 2.1
Turbidity (NTU)	Monsoon	43.8 ± 4.9	35.5 ± 2.1	33.3 ± 1.7	39.8 ± 3.0	37.8 ± 2.9

2. ANOVA Summary

Two-way ANOVA (Site, Season, Site×Season) confirmed strong seasonal effects for most parameters, with additional but comparatively modest spatial variation (Table 3). Interactions were non-significant, indicating broadly parallel seasonal trajectories across sites.

Table 3: Two-way ANOVA for seasonal and spatial effects (F-values with p).

Parameter	Site effect F (p)	Season effect F (p)	Site×Season F (p)
Temperature	2.1 (p=0.08)	165.4 (p<0.001)	0.42 (ns)
pH	1.3 (ns)	1.1 (ns)	0.51 (ns)
DO (mg/L)	3.0 (p=0.02)	152.7 (p<0.001)	0.37 (ns)
Nitrate (mg/L)	12.6 (p<0.001)	204.8 (p<0.001)	0.07 (ns)
Phosphate (mg/L)	9.1 (p<0.001)	182.3 (p<0.001)	0.11 (ns)
Turbidity (NTU)	10.4 (p<0.001)	190.1 (p<0.001)	0.06 (ns)
Total Hardness (mg/L as $CaCO_3$)	4.7 (p=0.001)	88.5 (p<0.001)	0.14 (ns)
TDS (mg/L)	5.2 (p<0.001)	96.2 (p<0.001)	0.18 (ns)
BOD (mg/L)	8.6 (p<0.001)	120.7 (p<0.001)	0.09 (ns)
Chloride (mg/L)	3.9 (p=0.004)	40.3 (p<0.001)	0.22 (ns)
Alkalinity (mg/L as $CaCO_3$)	4.4 (p=0.002)	76.9 (p<0.001)	0.17 (ns)
Dissolved CO_2 (mg/L)	9.9 (p<0.001)	135.6 (p<0.001)	0.10 (ns)

3. Comparison with aquaculture guidelines

Observed ranges across the full dataset remained within recommended limits for Indian major carp culture for most parameters, with borderline pre-monsoon DO dips (~5.0 mg L^{-1}) and phosphate monsoon peaks up to 0.21 mg L^{-1} flagged for management attention (Table 4).

Table 4: Aquaculture guidelines vs. observed ranges (overall)

Parameter	Recommended range	Observed (min–max)	Assessment	Note
Temperature (°C)	22–32	24.6–30.8	✓	
pH	6.5–8.5	7.30–7.75	✓	
DO (mg/L)	> 5	5.0–7.8	✓	
Nitrate (mg/L)	< 1.0 (preferably < 0.5)	0.1–0.7	✓	near upper preferred bound (0.5)
Phosphate (mg/L)	< 0.2 (preferably < 0.1)	0.1–0.2	✓	>0.2
Turbidity (NTU)	10–100	15.0–50.0	✓	
Total Hardness (mg/L as $CaCO_3$)	50–300 (100–200 ideal)	132.0–172.0	✓	
TDS (mg/L)	< 500	285.0–405.0	✓	
BOD (mg/L)	≤ 3 desirables	1.5–3.4	✓	
Chloride (mg/L)	< 250	25.0–45.0	✓	
Alkalinity (mg/L as $CaCO_3$)	50–200 (100–150 ideal)	118.0–160.0	✓	
Dissolved CO_2 (mg/L)	< 15 (preferably < 5–10)	3.2–7.5	✓	

Discussion & Conclusion

1. Synthesis of seasonal controls

Across a complete monsoon cycle, Khairi Dam exhibited a consistent hydro-seasonal signal that structured all measured physico-chemical parameters. Temperature tracked the regional climate, spanning 24.6–31.0 °C with winter minima (Dec–Jan) and pre-monsoon maxima (Apr–May). The pH remained narrowly neutral-alkaline (7.30–7.75), indicating stable carbonate buffering. In contrast, dissolved oxygen (DO) manifested the strongest seasonality: pre-monsoon troughs (~5.0–5.8 mg L^{-1}) coincided with higher temperatures and greater community respiration, whereas monsoon/post-monsoon plateaus (~7.3–7.8 mg L^{-1}) reflected enhanced mixing and photosynthetic production.

Nutrient and optical variables covaried with rainfall. Nitrate and phosphate attained monsoon peaks (site-wise maxima 0.70 and 0.21 mg L^{-1}, respectively), consistent with catchment runoff and near-surface transport. Turbidity rose sharply in the same period (up to 50 NTU at the inflow), mirroring suspended sediment loads. BOD co-increased during monsoon (to 3.4 mg L^{-1}), suggesting greater labile organic inputs. Conversely, conservative ions and alkalinity (TDS 285–405 mg L^{-1}; hardness 132–172 mg L^{-1}; alkalinity 118–160 mg L^{-1}; chloride 25–45 mg L^{-1}) concentrated in the late dry/pre-monsoon season and diluted during monsoon, a classic evapoconcentration–dilution cycle. Dissolved CO_2 inversely tracked DO, reaching 6–7.5 mg L^{-1} pre-monsoon and declining to ~3.2–3.9 mg L^{-1} in monsoon, reflecting seasonal shifts in metabolic balance and gas exchange.

The ANOVA results formally support this synthesis: Season was significant ($p < 0.001$) for the majority of parameters (e.g., Temperature, DO, Nitrate, Phosphate, Turbidity, TDS, Hardness, BOD, Alkalinity, Chloride, CO_2), while Site effects were present but weaker; Site×Season interactions were typically non-significant. Thus, although absolute levels differ among sectors, the temporal pattern is coherent across the reservoir.

2. Spatial structure and hydraulics

Spatial contrasts were most pronounced at the North sector (inflow), where monsoon nutrient, turbidity, and BOD maxima recurred (e.g., NO_3^- up to 0.70 mg L^{-1}; PO_4^{3-} up to 0.21 mg L^{-1}; Turbidity up to 50 NTU; BOD up to 3.4 mg L^{-1}). The South and Central sectors generally expressed the lowest nutrient/optical values, consistent with downstream dilution and longer residence times that promote settling and assimilation. Temperature and pH showed minimal site-to-site spread (<~1 °C; ~0.1–0.2 pH), reflecting reservoir-scale mixing and carbonate equilibrium. Collectively, these spatial patterns align with an advective–dispersive inflow plume that weakens along the North→Center→South axis and is laterally moderated at the East/West margins.

3. Implications for *Labeo catla* aquaculture

When benchmarked to widely used culture ranges, most parameters remained well within operational limits year-round (Temperature 22–32 °C; pH 6.5–8.5; DO > 5 mg L^{-1}; Hardness 50–300 mg L^{-1} as $CaCO_3$; TDS < 500 mg L^{-1}; Chloride < 250 mg L^{-1}; Alkalinity 50–200 mg L^{-1}; CO_2 < 15 mg L^{-1}). Two recurring management flags emerge:

1. Pre-monsoon DO dips (~5.0–5.8 mg L^{-1})—particularly at dawn—can constrain feeding and growth. Actionable measures: targeted aeration (mobile or fixed) in high-biomass cages/ponds; dawn-time DO checks; feeding moderation or split rations during heat spikes; harvest thinning ahead of late-dry maxima; and macrophyte/organic load control in near-shore enclosures.
2. Monsoon nutrient–turbidity pulses (NO_3^- to 0.70 mg L^{-1}, PO_4^{3-} to 0.21 mg L^{-1}, Turbidity to 50 NTU; BOD to 3.4 mg L^{-1}) elevate eutrophication and disease risks near the inflow. Actionable measures: site selection/relocation of cages away from the North arm during peak runoff; suspended-solids shielding (e.g., baffles/silt curtains where feasible); feed management to avoid surplus; prophylactic health checks during high turbidity; and post-event flushing/monitoring before resuming high feeding rates.

Because interactions (Site×Season) were not significant, management rules can be season-generalized across sites while still prioritizing the North sector for enhanced vigilance in monsoon and the whole reservoir for DO management in pre-monsoon.

4. Strengths, limitations, and future work

A key strength is the replicated, site-resolved monthly design covering 12 parameters over a full hydrologic year, enabling robust seasonal/spatial inference and direct alignment with carp culture thresholds. The main limitations are: (i) reliance on surface (0–0.5 m) sampling, which may under-represent short-lived stratification events and night-time DO minima; (ii) absence of biological indicators (chlorophyll-a, phytoplankton composition, pathogen loads) that mediate fish health; and (iii) no explicit hydrometeorological covariates (wind, inflow discharge, rainfall intensity) to apportion external versus internal drivers.

Future work should incorporate vertical profiling (24-h DO, temperature, and CO_2), high-frequency sensors across inflow/central/outflow transects, and bio-optical assays (chlorophyll-a, Secchi depth) to couple metabolism and light climate. Integrating hydrodynamic–biogeochemical modeling with farm-scale trials (feeding regimes, stocking densities, aeration strategies) would convert reservoir limnology into operational playbooks for *L. catla* under variable monsoon intensities.

Conclusion

Khairi Dam presents a favourable water-quality envelope for *Labeo catla*, with temperature, pH, hardness, alkalinity, TDS, chloride, and dissolved CO_2 persistently within recommended aquaculture ranges. Season dominates variance, driving (a) pre-monsoon DO constraints and (b) monsoon-driven nutrient/turbidity/BOD surges centered at the North inflow. Despite modest spatial heterogeneity, the shape of seasonal trajectories is consistent across sites, enabling season-oriented management with targeted spatial caution. Practically, aeration and biomass/feeding control in the pre-monsoon, coupled with inflow-aware siting and turbidity management in monsoon, are likely to sustain growth performance and reduce risk. The compact tables provided translate these dynamics into operational thresholds and decision points for reservoir-based *L. catla* culture.

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