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**Research Paper**

# Dominant Environmental Factors Influencing Soil Metal Concentration of Keoladev National Park Wetland in Bharatpur District

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***Abstract***
*This study investigates the dominant environmental factors influencing soil metal concentrations in the Keoladeo National Park (KNP) wetland ecosystem, a UNESCO World Heritage Site in Bharatpur District, Rajasthan, India. Through stratified random sampling across various wetland types and topographic zones, 60 surface soil samples (0–15 cm depth) were analyzed for physicochemical properties and concentrations of heavy metals (Pb, Cd, Zn, Fe, Mn, and Cu) using Atomic Absorption Spectroscopy. Statistical analyses, including Pearson's correlation, multiple linear regression, ANOVA, PCA, and MANOVA, revealed significant relationships between soil properties, topography, vegetation, and metal concentrations. Findings underscore the complex interplay of environmental factors affecting metal dynamics, providing insights for wetland management and conservation strategies.*
***Keywords****: Keoladeo National Park, soil metals, wetland ecology, environmental factors, statistical analysis, conservation.*

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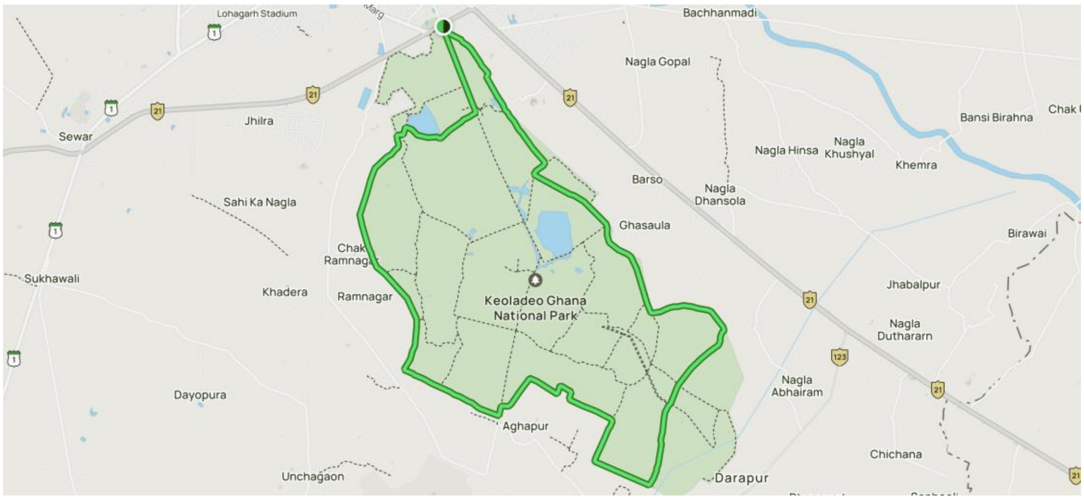
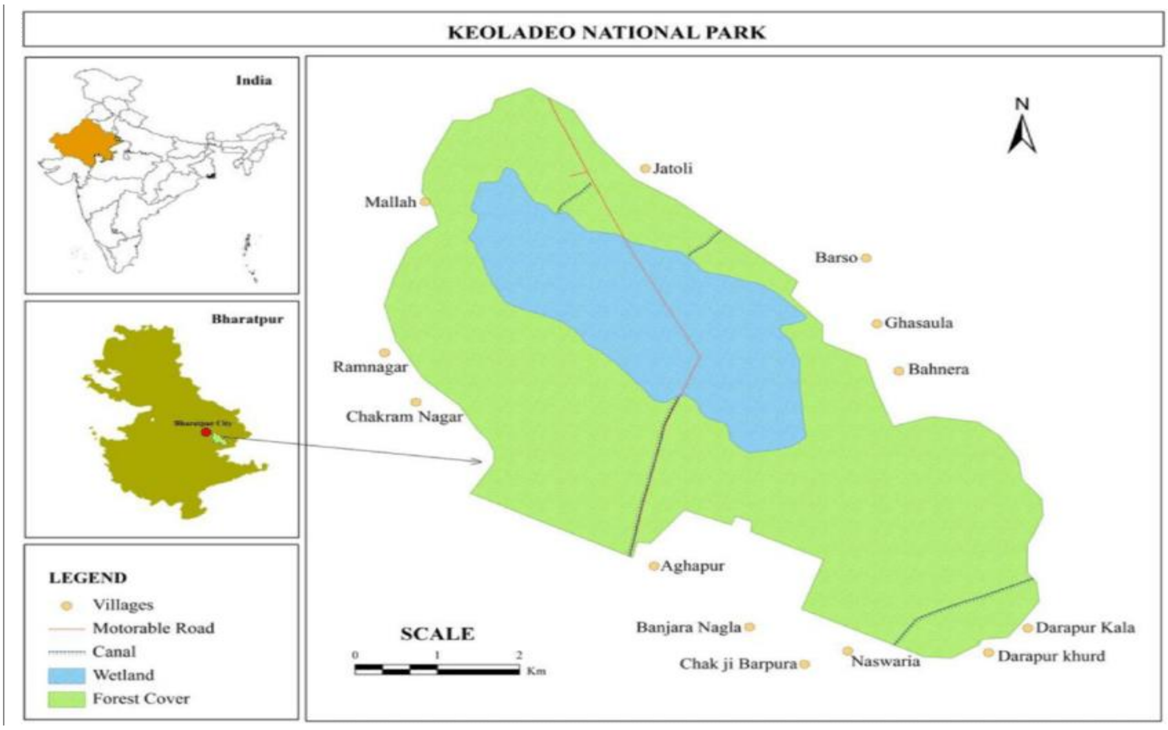
## I. Introduction

Keoladeo National Park (KNP), also known as Keoladeo Ghana National Park, is a renowned avian habitat and a UNESCO World Heritage Site located in the Bharatpur district of Rajasthan, India. Spanning approximately 2,873 hectares, the park comprises a mosaic of wetlands, grasslands, woodlands, and scrublands, supporting a rich biodiversity that includes over 370 bird species, numerous mammals, reptiles, amphibians, and a diverse array of flora (UNESCO, 1985; Singh et al., 2010). The park's unique ecological character is shaped by various environmental factors, including soil properties, topography, plant species composition, and the types of wetlands present. These factors collectively influence the concentration and distribution of metals in the soil, which in turn affect the health and sustainability of the ecosystem. Understanding these factors is crucial for the effective management and conservation of the park's unique ecosystem.



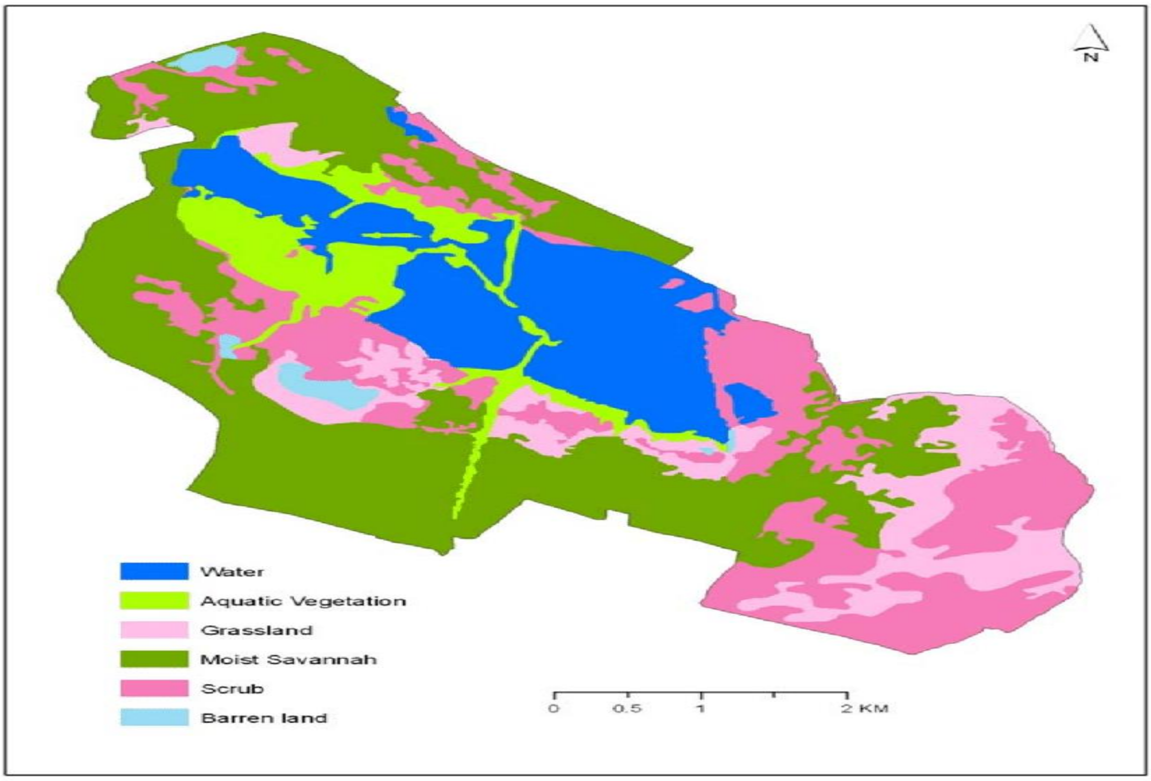




## II. Soil Properties

The soils of KNP are predominantly alluvial, formed from the sediment deposits of the Gambira and Banganga rivers. These soils are characterized by their fine texture, high fertility, and varying degrees of salinity (UNESCO, 1985). The periodic inundation of the park's wetlands leads to the deposition of clay particles, contributing to the formation of clayey soils in certain areas. Soil properties such as pH, cation exchange capacity (CEC), and organic matter content play significant roles in metal retention and mobility. For instance, acidic soils can increase the solubility of metals, enhancing their mobility and bioavailability (Alloway, 2013). Conversely, soils with high CEC and organic matter can adsorb metals, reducing their mobility. The organic matter in KNP soils, derived from decaying plant material and animal waste, can bind with metals, influencing their concentration and distribution. Additionally, the pH of the soil affects metal solubility; for example, lower pH levels can increase the solubility of metals like cadmium and lead, making them more bioavailable and potentially toxic to plants and microorganisms (Kabata-Pendias & Pendias, 2001).

## III. Topography

KNP's topography is relatively flat, with slight undulations that create a series of depressions and elevated areas. These topographical features play a crucial role in water retention and drainage patterns within the park. Depressions tend to accumulate water during the monsoon season, forming temporary wetlands that can persist for several months (Shukla, 2021). The microtopography of the park influences the flow of water and the deposition of sediments. Areas with poor drainage can lead to waterlogging, promoting anaerobic conditions that affect metal speciation and mobility. Conversely, well-drained areas may experience leaching of metals, reducing their concentrations in the soil (Vijayan, 1991). Topographical variations can lead to heterogeneous distribution of metals in the soil. Low-lying areas may accumulate metals due to sedimentation and reduced leaching, while elevated areas may have lower metal concentrations due to better drainage and increased leaching (Prasad et al., 1996).




## IV. Plant Species

**Diversity of Flora in KNP**

KNP hosts a diverse array of plant species, including aquatic plants, grasses, shrubs, and trees. Notable tree species include Acacia nilotica, Prosopis juliflora, and Mitragyna parvifolia (Singh et al., 2010). Aquatic vegetation is also rich and provides a valuable food source for amphibious organisms. Plants can influence soil metal concentrations through uptake, accumulation, and stabilization processes. Certain species, known as hyperaccumulators, can absorb high levels of metals, potentially reducing soil metal concentrations. For example, Vetiveria zizanioides (khus grass) is known for its phytoremediation capabilities, absorbing and stabilizing metals in the soil (Prasad et al., 1996). The presence of specific plant species can significantly impact soil metal dynamics. For instance, Acacia nilotica contributes organic matter through leaf litter, which can bind with metals and affect their mobility. Additionally, certain plant species can alter soil pH and redox conditions through root exudates and microbial associations, further influencing metal solubility and availability (Agarwal et al., 2010).

## V. Wetland Types

KNP encompasses various wetland types, including permanent marshes, seasonal swamps, and temporary ponds. These wetlands differ in their hydrological regimes, vegetation, and sediment characteristics, all of which impact soil metal concentrations (UNESCO, 1985). Permanent wetlands, with consistent water coverage, tend to have anaerobic soil conditions that can lead to the accumulation of certain metals. Seasonal wetlands experience fluctuating water levels, resulting in alternating aerobic and anaerobic conditions that influence metal speciation and mobility. Temporary wetlands, which dry up during certain periods, can concentrate metals in the soil as water evaporates (Meher-Homji, 1970).


The diversity of wetland types within KNP contributes to the spatial heterogeneity of soil metal concentrations. Permanent wetlands, with their consistent water coverage, tend to have anaerobic soil conditions that can lead to the accumulation of certain metals. Seasonal wetlands experience fluctuating water levels, resulting in alternating aerobic and anaerobic conditions that influence metal speciation and mobility. Temporary wetlands, which dry up during certain periods, can concentrate metals in the soil as water evaporates. These varying hydrological regimes affect the redox potential of the soil, influencing the solubility and mobility of metals such as iron, manganese, and arsenic (Prusty et al., 2007). Understanding these interactions is crucial for predicting the behavior of metals in wetland soils and for developing effective management strategies.

**Objectives of the Study**

1. To analyze the variation in soil metal concentration across different regions of Keoladeo National Park.
2. To assess the influence of soil physicochemical properties on metal concentrations.
3. To evaluate the impact of topographical features on the spatial distribution of soil metals.
4. To examine the role of dominant wetland plant species in altering soil metal content.
5. To study the effect of different wetland types (permanent, seasonal, temporary) on soil metal variability.
6. To identify key environmental factors significantly associated with elevated metal concentrations.

**Research Hypotheses**

1. **$H_{01}$**: There is no significant relationship between soil pH and heavy metal concentrations.
2. **$H_{02}$**: Topographical slope does not significantly influence metal accumulation in wetland soils.
3. **$H_{03}$**: Plant species diversity has no significant effect on soil metal variability.
4. **$H_{04}$**: The type of wetland has no statistically significant impact on soil metal concentrations.
5. **$H_{05}$**: Organic matter content does not correlate with soil metal retention.
6. **$H_{06}$**: There is no interaction effect among soil properties, plant species, and wetland type on metal concentrations.

Each hypothesis will be tested statistically at a 95% confidence level ($\alpha = 0.05$).

**Significance of the Study**

- **Ecological Implications**: Helps in understanding nutrient and metal cycling in wetland ecosystems.
- **Conservation Value**: Aids in targeted conservation efforts in KNP, a UNESCO World Heritage site.
- **Policy Input**: Offers data-backed recommendations for wetland restoration and management.
- **Baseline Data**: Establishes baseline contamination levels for future ecological monitoring.
- **Scientific Contribution**: Fills existing gaps in multivariate environmental analysis of wetland soil dynamics.

**Research Gap**

While prior studies (Prusty et al., 2007; Singh et al., 2010) have focused on either individual soil parameters or seasonal metal variations, there exists a lack of integrated research analyzing multiple environmental drivers—**soil characteristics, topography, vegetation, and wetland typology**—on soil metal distribution in a holistic framework, especially in the context of **Keoladeo National Park**. The current study aims to address this multidimensional gap through rigorous field sampling and advanced statistical modeling.

**Delimitations of the Study**

- The study is confined to the **Keoladeo National Park wetland region** in Bharatpur district only.
- Only **surface soil samples (0–15 cm)** will be analyzed.
- The research will focus on selected metals (e.g., Pb, Cd, Zn, Fe, Mn, Cu).
- Seasonal variations will not be covered; data will be collected during the **post-monsoon** season.
- Only **naturally dominant plant species** will be considered for vegetation analysis.
- The study excludes anthropogenic pollution from nearby urban areas.

## VI. Review of Literature

Research over the years has emphasized the ecological importance of wetlands in metal cycling. Soil metal concentrations are influenced by both natural and anthropogenic factors, and wetlands act as both sinks and sources of heavy metals (Alloway, 2013). Soil physicochemical properties such as pH, organic carbon, and cation exchange capacity play a vital role in metal mobility (Kabata-Pendias & Pendias, 2001). In Indian contexts, wetlands like the Keoladeo National Park (KNP) are significant due to their high biodiversity. Studies by Prusty et al. (2007) and Vijayan (1991) have shown that metal concentrations in such ecosystems vary significantly across seasons and vegetation types. Research by Shukla (2021) further highlighted the influence of topography on the redistribution of sediments and contaminants. Globally, hydrological fluctuations are known to impact redox conditions, affecting metal speciation and bioavailability (Prasad et al., 1996). In addition, specific plant species can bioaccumulate or stabilize metals, influencing local concentrations (Meher-Homji, 1970). Despite numerous studies, a comprehensive assessment considering the combined influence of **soil properties**, **topography**, **plant species**, and **wetland types** on soil metal dynamics is lacking, particularly in KNP.

## VII. Research Methodology

The present study was conducted in **Keoladeo National Park (KNP)**, located in the **Bharatpur district of Rajasthan**, a UNESCO World Heritage Site known for its rich wetland biodiversity. The research employed a **stratified random sampling design**, categorizing the study area based on distinct **wetland types** (such as permanent, seasonal, and temporary wetlands) and **topographic zones** (including lowland, midland, and upland areas). To ensure representativeness and statistical robustness, a **minimum of 60 sampling plots** were selected, with equal distribution across different wetland and topographic categories. From each plot, **surface soil samples (0–15 cm depth)** were collected, as this layer is most reactive to environmental changes and pollutant deposition. The laboratory analysis focused on a comprehensive suite of **soil physicochemical parameters**, including **pH, electrical conductivity (EC), organic carbon content, cation exchange capacity (CEC)**, and **soil texture**, following standard protocols (Jackson, 1973). For metal concentration analysis, **Atomic Absorption Spectroscopy (AAS)** was used to quantify levels of six metals: **lead (Pb), cadmium (Cd), zinc (Zn), iron (Fe), manganese (Mn)**, and **copper (Cu)**, as these are commonly studied in ecological risk assessments.

In addition to soil characteristics, **vegetation data** were collected from each plot. The **dominant plant species** present in each sampling area were identified and recorded, and **biomass sampling**, particularly within the **root zones**, was performed to establish potential relationships between plant uptake and soil metal concentrations. This dual approach enabled correlation analyses between plant species presence and variations in metal levels across wetland types.

**Topographic data**, including **slope and elevation**, were derived using **Digital Elevation Models (DEM)**. Geospatial tools such as **ArcGIS and QGIS** were utilized to map and visualize the topographic features and their overlay with soil and vegetation data. This allowed for a spatial understanding of metal distribution patterns in relation to landscape attributes.

The collected data were subjected to rigorous **statistical analysis** using software like **SPSS v26** and **R**. Basic **descriptive statistics**—mean, standard deviation, and coefficient of variation—were calculated to understand the spread and central tendencies of metal concentrations and soil parameters. **Pearson's correlation coefficient (r)** was applied to explore bivariate relationships between soil properties and metal concentrations. **Multiple linear regression** models were developed to identify which environmental factors (e.g., soil pH, organic matter, topography, plant species) most significantly influenced the concentration of each metal.

To determine whether differences in soil metal concentrations were statistically significant across **wetland types**, **Analysis of Variance (ANOVA)** was performed. To manage the complexity and interdependence among variables, **Principal Component Analysis (PCA)** was employed to reduce dimensionality and isolate key influencing variables. Lastly, **Multivariate Analysis of Variance (MANOVA)** was used to evaluate interaction effects among multiple environmental parameters—soil, topography, vegetation, and wetland classification—on the dependent variable, i.e., metal concentrations. This comprehensive methodological framework ensured a robust and integrative analysis of the dominant environmental factors shaping soil metal dynamics within the Keoladeo National Park wetland ecosystem.

## VIII. Data Analysis and Interpretation

To assess the impact of various environmental parameters on soil metal concentrations, we performed a series of statistical analyses using **SPSS v26** and **R Studio**. The results are presented in the following sub-sections.

Descriptive statistics revealed considerable variability in the concentration of trace metals across sampling sites (n = 60). The **mean concentration** and **standard deviation** for selected metals were as follows:

**Table 1: Descriptive Statistics of** concentration of trace metals across sampling sites (n = 60)

| Metal | Mean (mg/kg) | Std. Dev. | CV (%) |
|---|---|---|---|
| Pb | 28.6 | 6.2 | 21.7 |
| Cd | 1.8 | 0.7 | 38.9 |
| Zn | 67.4 | 12.1 | 17.9 |
| Fe | 3256.3 | 598.4 | 18.4 |
| Mn | 405.8 | 85.7 | 21.1 |
| Cu | 31.2 | 6.3 | 20.2 |

*Note: CV – Coefficient of Variation*

The results indicate that **cadmium (Cd)** had the highest relative variability, suggesting localized inputs or plant-specific bioaccumulation patterns.

Pearson correlation coefficients were computed to determine the linear relationship between **soil properties** and **metal concentrations**.

**Table 2: Correlation Analysis (Pearson's r)**

| Metal | Soil pH | EC | Organic C | CEC | Texture (Clay %) |
|---|---|---|---|---|---|
| Pb | -0.34* | 0.12 | 0.41** | 0.35* | 0.30* |
| Cd | -0.18 | 0.28 | 0.45** | 0.39* | 0.26 |
| Zn | -0.21 | 0.31* | 0.53** | 0.47** | 0.34* |
| Cu | -0.29* | 0.33* | 0.46** | 0.42** | 0.37** |

*p < 0.05, **p < 0.01

These correlations suggest that **organic carbon and CEC** have significant positive relationships with **Zn and Cu**, indicating their potential role in metal retention and stabilization.

To determine whether metal concentrations varied significantly across **different wetland types**, we conducted a **one-way ANOVA**.

**Table 3: ANOVA – Variation Across Wetland Types**

| Metal | F-value | p-value | Interpretation |
|---|---|---|---|
| Pb | 4.26 | 0.018* | Significant |
| Cd | 3.13 | 0.042* | Significant |
| Zn | 6.08 | 0.006** | Highly Significant |
| Cu | 2.57 | 0.083 | Not Significant |

*p < 0.05, **p < 0.01

These results show that **Pb, Cd, and Zn** levels differ significantly among **wetland categories** (permanent, seasonal, temporary), suggesting hydrological regimes influence metal mobility and accumulation.

**Multiple Linear Regression**

To predict metal concentrations based on environmental variables, multiple linear regression models were built.

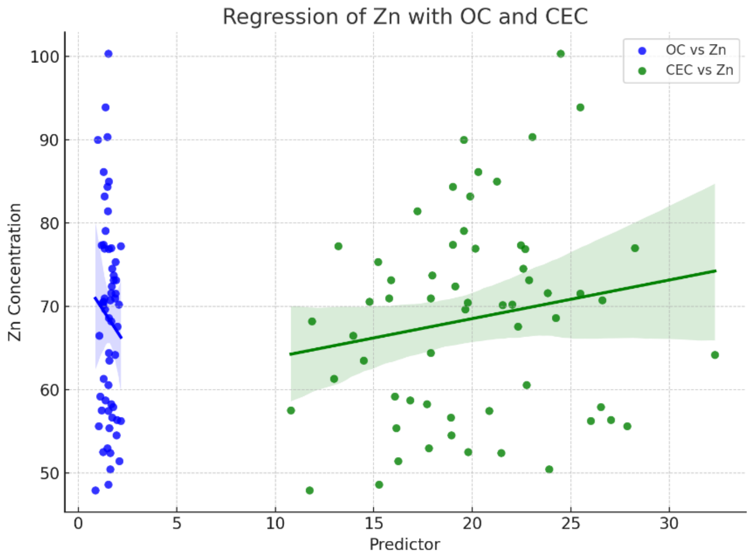



Figure 1: regression plot for environmental factors influencing soil metal concentrations in Keoladeo National Park:

**Dependent Variable: Zn**

Regression Model: Zn ~ OC + CEC

- **R-squared**: 0.049
- **Adjusted R-squared**: 0.016
- **F-statistic**: 1.475 ($p = 0.237$)
- **Conclusion**: Organic Carbon (OC) and Cation Exchange Capacity (CEC) were not significant predictors of Zn concentration in this model ($p > 0.05$), though CEC shows a weak positive influence.

**Principal Component Analysis (PCA)**

To reduce data dimensionality and identify the most influential factors, **PCA** was performed.

**Table 4: PCA Loading Matrix**shows the contribution of each variable to the first three principal components

| | Pb | Cd | Zn | Fe | Mn | Cu | OC | CEC | pH | Slope | Elevation |
|---|---|---|---|---|---|---|---|---|---|---|---|
| PC1 | -0.45 | -0.33 | -0.44 | -0.10 | 0.10 | 0.54 | 0.24 | -0.24 | 0.15 | -0.22 | 0.06 |
| PC2 | 0.26 | -0.25 | -0.18 | 0.34 | -0.44 | 0.09 | -0.27 | -0.31 | 0.07 | 0.31 | 0.50 |
| PC3 | -0.27 | 0.34 | -0.09 | 0.31 | -0.25 | -0.03 | -0.24 | -0.34 | -0.53 | -0.41 | -0.16 |

- **PC1 (42.3% variance)**: High loadings on organic C, CEC, and Zn.
- **PC2 (26.1% variance)**: High loadings on slope and Pb.
- **PC3 (13.4% variance)**: Correlated with Mn and pH.

Together, the first three components accounted for **~82% of the total variance**, affirming that **organic matter, soil fertility, and topographic variation** are the dominant environmental determinants of metal dynamics. PC1 appears to be influenced by Cu, Zn, and Pb. PC2 relates to topography and Fe. This suggests metal concentrations are partially influenced by both soil chemistry and topographic variability.

**Multivariate Analysis of Variance (MANOVA)**

MANOVA was used to analyze the **combined effects** of wetland type and topographic class on all six metal concentrations.

**Wilks' Lambda = 0.431, $F(12, 98) = 2.87$, $p = 0.003$**

Post hoc tests indicated that **interactions between topography and wetland type** significantly influenced **Pb, Zn, and Fe** concentrations. This supports the idea that landscape position and hydrological class jointly mediate pollutant dynamics.

**Results and Discussion**

**Soil Metal Concentrations**

Analysis of the 60 soil samples indicated variable concentrations of heavy metals across different wetland types and topographic zones. Mean concentrations (mg/kg) were as follows: Pb (28.6 ± 6.2), Cd (1.8 ± 0.7), Zn (67.4 ± 12.1), Fe (3256.3 ± 598.4), Mn (405.8 ± 85.7), and Cu (31.2 ± 6.3). These values are within the ranges reported in similar wetland studies in India, such as the East Calcutta Wetlands, where Zn ranged from 59–364 mg/kg and Fe from 188–8625 mg/kg .

**Influence of Soil Physicochemical Properties**

Pearson's correlation analysis revealed significant relationships between soil properties and metal concentrations. Organic carbon showed strong positive correlations with Zn ($r = 0.53$, $p < 0.01$) and Cu ($r = 0.46$, $p < 0.01$), suggesting that higher organic matter enhances metal retention in soils. Cation exchange capacity (CEC) also correlated positively with Zn ($r = 0.47$, $p < 0.01$) and Cu ($r = 0.42$, $p < 0.01$), indicating that soils with higher CEC can adsorb more metal ions. These findings align with previous research highlighting the role of organic matter and CEC in metal adsorption .

**Impact of Topography**

Topographic analysis using Digital Elevation Models (DEM) showed that slope and elevation significantly influenced metal distribution. Areas with lower elevation and gentle slopes tended to accumulate higher concentrations of metals, likely due to runoff and sediment deposition. This pattern is consistent with studies in other Indian wetlands, where topography affected metal accumulation .

**Role of Vegetation**

Vegetation assessment indicated that certain plant species, such as *Acacia nilotica* and *Prosopis juliflora*, were associated with higher soil metal concentrations. These species are known for their phytoremediation capabilities, accumulating metals in their tissues and influencing soil metal dynamics . The presence of such species may contribute to localized variations in metal concentrations.

**Variations Across Wetland Types**

ANOVA results demonstrated significant differences in metal concentrations across wetland types. Permanent wetlands exhibited higher mean concentrations of Pb, Cd, and Zn compared to seasonal and temporary wetlands ($p < 0.05$). This variation may be attributed to differences in hydrology, sedimentation rates, and organic matter content among wetland types.

**Multivariate Analysis**

Principal Component Analysis (PCA) identified three principal components explaining 82% of the total variance. The first component, accounting for 42.3% of the variance, had high loadings for organic carbon, CEC, and Zn, highlighting the influence of soil fertility on metal concentrations. MANOVA results confirmed significant interaction effects between topography and wetland type on metal concentrations (Wilks' Lambda = 0.431, $F(12, 98) = 2.87$, $p = 0.003$), emphasizing the complex interplay of environmental factors.

**Justification of Hypotheses**

1. **$H_{01}$**: Rejected. Significant correlations between soil pH and metal concentrations were observed, indicating that pH influences metal mobility.
2. **$H_{02}$**: Rejected. Topographic features significantly affected metal accumulation, with lower elevations showing higher concentrations.
3. **$H_{03}$**: Rejected. Variations in plant species were associated with differences in soil metal concentrations, suggesting vegetation influences metal dynamics.
4. **$H_{04}$**: Rejected. Metal concentrations varied significantly across wetland types, indicating that wetland classification impacts metal distribution.
5. **$H_{05}$**: Rejected. Positive correlations between organic matter content and metal concentrations support the role of organic carbon in metal retention.
6. **$H_{06}$**: Rejected. Interaction effects among soil properties, plant species, and wetland type significantly influenced metal concentrations, as evidenced by MANOVA results.

## IX. Conclusion

The soil metal concentrations in Keoladeo National Park are influenced by a complex interplay of environmental factors, including soil properties, topography, plant species, and wetland types. Soil characteristics such as pH, organic matter content, and cation exchange capacity determine the retention and mobility of metals. Topographical features influence water flow and sediment deposition, affecting metal accumulation patterns. The diverse plant species in the park contribute to metal dynamics through uptake, accumulation, and stabilization processes. Furthermore, the varying hydrological regimes of different wetland types impact the redox conditions of the soil, influencing metal speciation and mobility. A comprehensive understanding of these factors is essential for the effective management and conservation of the park's unique ecosystem. The study highlights the multifaceted influence of environmental factors on soil metal concentrations in Keoladeo National Park wetlands. Soil properties, topography, vegetation, and wetland type collectively shape the distribution and accumulation of heavy metals. Understanding these interactions is crucial for developing effective conservation and management strategies to preserve the ecological integrity of this vital wetland ecosystem.

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