Contents lists available at NCBI

The American Journal of Science and Medical Research

Journal homepage: https://ajsmrjournal.com/

Research Article

Hydrological Parameter Dynamics of Chippaleru Mangroves, Andhra Pradesh, India: A Cluster Analysis Approach

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https://dx.doi.org/10.5281/zenodo.21305982

Received: 29 April 2026
Revised: 22 June 2026
Published: 29 June 2026

ISSN: 2377-6196
Published by AIRA

Keywords: *mangroves, hydrology, cluster analysis, estuarine dynamics, Andhra Pradesh, water quality*

ABSTRACT

This study investigated the hydrological dynamics of the Chippaleru mangrove estuary in Andhra Pradesh, India, through analysis of physico-chemical parameters across three monitoring stations. Nine key parameters were measured: water temperature, air temperature, dissolved oxygen (DO), nitrates (NO_3-N), turbidity, phosphates (PO_4-P), salinity, transparency, and pH. Cluster analysis revealed consistent grouping patterns across all three stations, with parameters organizing into three distinct clusters. Cluster 1 consistently grouped water and air temperature, demonstrating strong thermal correlation. Clusters 2, the largest cluster, contained DO NO_3-N, PO_4-P, and turbidity, representing interconnected biogeochemical processes. Cluster 3 grouped salinity, transparency, and pH, reflecting water clarity and ionic composition relationships. The similarity was there in clustering patterns across all stations (80% similarity).

1. Introduction

Mangrove ecosystems represent one of the most productive and ecologically important coastal habitats, serving as critical nursery grounds for marine species and providing essential ecosystem services. The Chippaleru mangrove swamp, located in Andhra Pradesh, India, constitutes a low-lying deltaic swamp characterized by a network of small creeks that form the main watercourse during tidal ebb and flow. Understanding the hydrological dynamics of such systems is essential for ecosystem management and conservation efforts.

Hydrological studies are fundamental to understanding the relationship between different trophic levels and food web structures in mangrove ecosystems. The life-sustaining properties of water make hydrological investigations crucial for ecosystem assessment and management. In the Chippaleru system, these creeks are sometimes eroded by tidal action to form saucer-shaped depressions that may retain standing water during low tide periods. The seasonal hydrology of the Chippaleru region is characterized by a distinct dry period, where for approximately eight months of the year (November to June), potential evaporation exceeds precipitation. This hydrological pattern significantly influences the physico-chemical parameters of the estuarine waters and affects the overall ecosystem dynamics.

Tidal flow serves as the primary source for sustaining estuarine communities, and any restriction of this water flow can alter physico-chemical parameters as well as vegetative, macro-invertebrate, and fish community structures (Romen et al., 1984; Warren et al., 2002). The inundation and discharge of tidal water are considered critical factors for mangrove growth and nutrient dynamics, as tidal variations are directly related to the exchange and addition of nutrients and sediments (Alongi, 2018 & Li et al., 2024)

These hydrological changes are particularly important because estuaries and mangroves function as critical nursery habitats for juvenile reef species and support the sustainability of offshore fisheries (Stoner, 2003). The abundance of fish larvae, juveniles, and adult fish can be significantly influenced by physico-chemical conditions including salinity, temperature, pH, and turbidity, all of which vary temporally due to seasonal variations in freshwater input. Elevated salinity levels can profoundly impact various aquatic organisms including zooplankton, fungi, benthic forms, fish, shrimp, and crabs. Understanding these parameter interactions through statistical methods such as cluster analysis provides insights into the underlying processes governing estuarine water quality and ecosystem health.

This study aims to characterize the hydrological parameter dynamics of the Chippaleru mangrove system through comprehensive analysis of physico-chemical parameters across multiple monitoring stations, with particular emphasis on identifying parameter relationships through cluster analysis.

2. Materials and Methods

2.1 Study Area

The Chippaleru mangrove estuary is located in Andhra Pradesh, India, and represents a typical low-lying deltaic swamp system. The study area is characterized by a network of small creeks that constitute the main watercourse during tidal cycles. The region experiences a tropical climate with distinct wet and dry seasons, where potential evaporation exceeds precipitation for approximately eight months annually (November to June).

2.2 Sampling Stations

Three monitoring stations were established within the Chippaleru estuary to capture spatial variations in hydrological parameters. The stations were selected to represent different zones of the estuarine system and account for variations in tidal influence and freshwater input. The close proximity of the stations within the study area allowed for comparative analysis of parameter relationships across the system.

Parameter Measurement: Nine key physico-chemical parameters were measured at each station: Measured by standard methods prescribed by APHA etc.,

2.3 Statistical Analysis

2.3.1 Correlation Analysis

Pearson correlation coefficients were calculated between all parameter pairs to identify relationships between variables. Correlation matrices were generated for each station to assess the strength and direction of parameter associations.

2.3.2 Cluster Analysis

Hierarchical cluster analysis was performed using complete linkage method to group parameters based on their similarity patterns. The analysis was conducted separately for each station to identify consistent grouping patterns across the study area. Dendrograms were generated to visualize the clustering results, with rescaled distances used to determine cluster formation.

2.3.3 Data Processing

Statistical analyses were performed to identify patterns in parameter relationships and to group variables based on their interactions within the estuarine system. The clustering approach allowed for identification of parameters that respond similarly to environmental drivers within the mangrove ecosystem.

3 Results and Discussion

3.1.1 Strong Positive Correlations

Water temperature and air temperature showed strong positive correlation across all stations.

NO_3-N and PO_4-P demonstrated positive correlation, indicating linked nutrient dynamics.

Turbidity showed positive correlations with nutrient parameters (NO_3-N and PO_4-P).

Strong Negative Correlations:

Dissolved oxygen showed negative correlations with nutrient parameters (NO_3-N, PO_4-P). Dissolved oxygen was negatively correlated with turbidity. Temperature parameters showed negative correlations with dissolved oxygen.

Station-Specific Correlation Patterns:

At all three stations, the correlation structure revealed consistent patterns, with correlation coefficients demonstrating the interconnected nature of biogeochemical processes in the estuarine environment.

3.1.2 Cluster Analysis Results

The hierarchical cluster analysis produced consistent grouping patterns across all three monitoring stations, revealing three distinct clusters with 80% similarity in parameter relationships. Station 1 Cluster Results: The cluster analysis at Station 1 produced three distinct clusters:

Cluster 1 (Smallest): Water Temperature and Air Temperature These parameters showed the highest proximity and correlation Represents thermal processes and heat exchange dynamics

Cluster 2 (Largest): Dissolved Oxygen, NO_3-N, PO_4-P, and Turbidity Contains four interconnected water chemistry variables Represents biogeochemical and nutrient cycling processes

Cluster 3 (Medium): Salinity, Transparency, and pH. Transparency and pH showed closer proximity within this cluster Represents water clarity and chemical composition relationships

Station 2 Cluster Results: Station 2 demonstrated similar clustering patterns to Station 1:

Cluster 1: Water Temperature and Air Temperature. A Consistent thermal parameter grouping observed across stations

Cluster 2: Dissolved Oxygen, NO_3-N, PO_4-P, and Turbidity: The same biogeochemical parameter grouping as Station 1. It maintained negative correlation between DO and the other three parameters

Cluster 3: Salinity, Transparency, and pH: At this station, salinity and transparency showed closer proximity than transparency and pH. This indicates spatial variation in ionic composition effects on water clarity

Station 3 Cluster Results: Station 3 exhibited clustering patterns consistent with Station 2

Cluster 1: Water Temperature and Air Temperature: Smallest cluster with consistent thermal parameter association

Table 1. Seasonal variations of physico-chemical parameters

Parameter	Station 1	Station 2	Station 3	Seasonal Trend
Salinity (ppt)	Winter: ~18–24 Summer: ~30–34 Monsoon: ~6–11 post-monsoon: ~12–17	Winter: ~7–12 Summer: ~26–31 Monsoon: ~2–5 post-monsoon: ~3–7	Winter: ~6–10 Summer: ~19–22 Monsoon: ~1–2 post-monsoon: ~2–6	High in summer, sharp decline during monsoon, gradual recovery post-monsoon
DO (mg/L)	Winter: ~4.0 Summer: ~3.0 Monsoon: ~4.3–4.6 post-monsoon: ~4.2–4.5	Winter: ~4.5 Summer: ~3.9–4.2 Monsoon: ~4.6–5.0 post-monsoon: ~4.6–5.0	Winter: ~4.7 Summer: ~4.1–4.3 Monsoon: ~5.1–5.6 post-monsoon: ~4.9–5.2	DO lowest in summer, peaks during monsoon due to mixing and freshwater inflow
Transparency (cm)	Winter: ~25–36 Summer: ~27–42 Monsoon: ~15–19 post-monsoon: ~14–16	Winter: ~20–32 Summer: ~26–36 Monsoon: ~15–17 post-monsoon: ~13–15	Winter: ~21–41 Summer: ~39–46 Monsoon: ~15–16 post-monsoon: ~12–16	Highest in summer, lowest in post-monsoon due to turbidity
Turbidity (NTU)	Winter: ~25–36 Summer: ~18–25 Monsoon: ~50–53 post-monsoon: ~41–53	Winter: ~26–34 Summer: ~20–32 Monsoon: ~52–56 post-monsoon: ~42–56	Winter: ~21–32 Summer: ~20–23 Monsoon: ~51–56 post-monsoon: ~42–54	Turbidity spikes during monsoon/post-monsoon due to runoff and resuspension
pH	Winter: ~8.2–8.4 Summer: ~8.6–8.7 Monsoon: ~8.1–8.3 post-monsoon: ~7.8–8.0	Winter: ~8.2–8.3 Summer: ~8.5–8.6 Monsoon: ~8.0–8.2 post-monsoon: ~7.5–8.0	Winter: ~8.2–8.4 Summer: ~8.5–8.6 Monsoon: ~8.2–8.3 post-monsoon: ~7.6–8.0	Slightly alkaline year-round, dips post-monsoon
Phosphates (µg/L)	Winter: ~26–37 Summer: ~6–9 Monsoon: ~55–86 post-monsoon: ~59–86	Winter: ~8–36 Summer: ~3–7 Monsoon: ~79–110 post-monsoon: ~95–110	Winter: ~59–79 Summer: ~9–12 Monsoon: ~79–105 post-monsoon: ~100–110	Nutrients surge during monsoon/post-monsoon due to sediment release
NO_3-N (µg/L)	Winter: ~15–20 Summer: ~3–5 Monsoon: ~58–90 post-monsoon: ~60–80	Winter: ~29–52 Summer: ~7–19 Monsoon: ~86–101 post-monsoon: ~74–93	Winter: ~37–62 Summer: ~6–11 Monsoon: ~86–102 post-monsoon: ~98–102	Nitrate peaks in monsoon/post-monsoon, lowest in summer

Cluster 2: Dissolved Oxygen, NO_3-N, PO_4-P, and Turbidity: Largest cluster containing four water chemistry variables. The DO showed negative correlation with NO_3-N, PO_4-P, and turbidity.

Cluster 3: Salinity, Transparency, and pH: Similar to Station 2, transparency and salinity showed closer grouping. This is a medium-sized cluster. Parameter Relationship Patterns Thermal Parameters (Cluster 1)

Water temperature and air temperature consistently formed the smallest cluster across all stations, demonstrating strong positive correlation. This relationship reflects the direct thermal exchange between atmospheric and aquatic environments in the shallow estuarine system.

Biogeochemical Parameters (Cluster 2)

The largest cluster consistently contained dissolved oxygen, nitrates, phosphates, and turbidity. These parameters exhibited strong interconnected relationships:

Nutrient Interactions: NO_3-N and PO_4-P showed positive correlation, indicating coupled nutrient cycling processes Oxygen-Nutrient Relationships: Dissolved oxygen was negatively correlated with nutrient parameters, reflecting consumption during decomposition and biological processes

Turbidity Associations: Turbidity correlated positively with nutrients and negatively with dissolved oxygen, indicating suspended matter influence on biogeochemical processes.

Water Quality Parameters (Cluster 3)

The medium-sized cluster contained salinity, transparency, and pH, with spatial variations in parameter proximity:
Station 1: Transparency and pH showed closer association
Stations 2 and 3: Salinity and transparency demonstrated stronger proximity

This variation reflects different environmental controls on water clarity and chemical composition across the estuarine gradient

3.1.3 Spatial Consistency

The remarkable consistency in cluster formation across all three stations (80% similarity) indicates uniform hydrological processes throughout the Chippaleru estuary study area. This consistency suggests that the relatively small spatial extent of the study area maintains similar environmental controls and parameter interactions.

Fig 1. Cluster analysis at Station 1

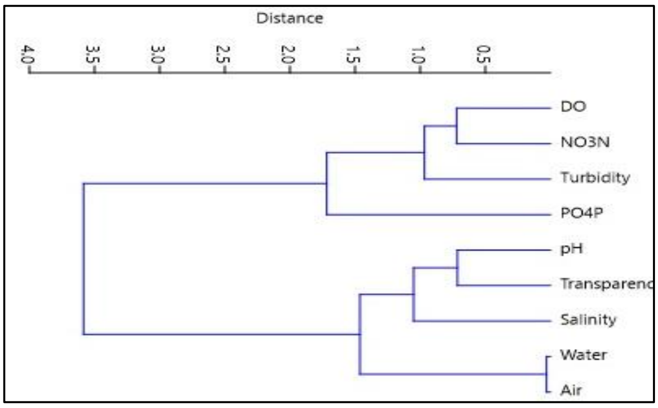


Fig 2. Cluster analysis at station 2

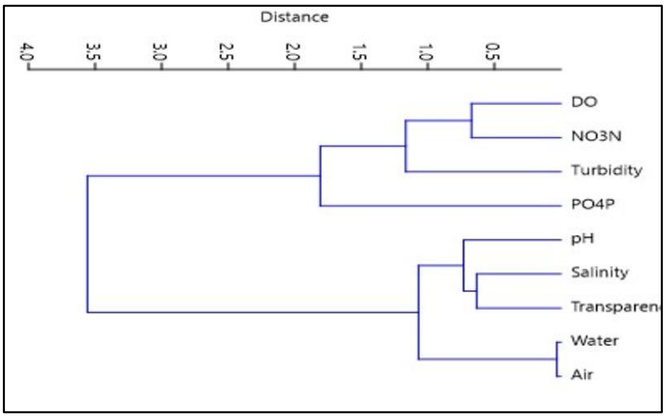
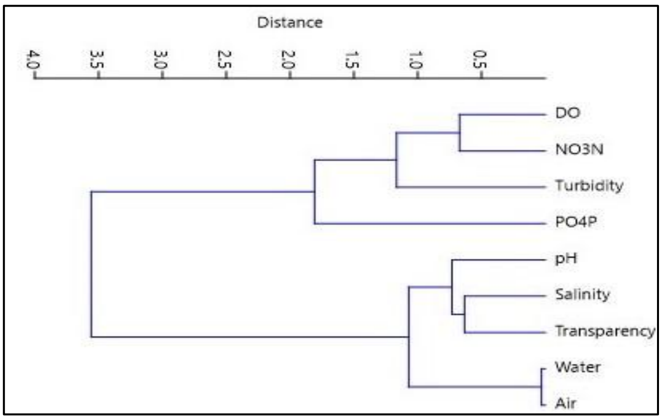


Fig 3. Cluster analysis at station 3



3.2.1 Hydrological Parameter Relationships

The cluster analysis results reveal fundamental relationships between physico-chemical parameters in the Chippaleru mangrove estuary that reflect underlying biogeochemical and physical processes. The consistent clustering patterns across all three stations demonstrate the coherent nature of estuarine processes within this system.

3.2.2 Thermal Dynamics

The strong clustering of water and air temperature across all stations reflects the shallow nature of the estuarine system and the direct thermal exchange between atmospheric and aquatic environments (Alongi, 2018). This relationship is particularly pronounced in mangrove ecosystems where shallow waters and extensive surface area promote rapid heat exchange. The consistent grouping of these parameters indicates that thermal processes are uniform across the study area, likely due to similar water depths and exposure conditions.

3.2.3 Biogeochemical Cycling

The largest cluster, containing dissolved oxygen, nitrates, phosphates, and turbidity, represents the core biogeochemical processes operating in the estuarine system. The negative correlation between dissolved oxygen and nutrient parameters (NO_3-N and PO_4-P) reflects fundamental biogeochemical processes:

Nutrient Utilization and Oxygen Consumption: The inverse relationship between DO and nutrients indicates active biological processes where microbial decomposition and respiration consume oxygen while releasing nutrients (Li et al., 2024). This pattern is characteristic of productive estuarine systems where organic matter decomposition drives nutrient cycling (Damotharan et al., 2010). The linkage between NO_3-N and PO_4-P reflects synchronized release from sediments and organic matter (Soundarapandian et al., 2009).

Turbidity-Nutrient Associations: The positive correlation between turbidity and nutrient parameters suggests that suspended particles may serve as sites for nutrient adsorption or that turbidity and nutrients share common sources, such as sediment resuspension during tidal mixing or terrestrial inputs during freshwater flow events.

Coupled Nutrient Cycling: The positive correlation between NO_3-N and PO_4-P indicates linked nitrogen and phosphorus cycling, likely reflecting common sources and synchronized release from sediments or organic matter decomposition.

3.2.4 Water Quality Indicators

The third cluster, containing salinity, transparency, and pH, represents water quality and ionic composition parameters. The spatial variation in parameter proximity within this cluster provides insights into estuarine mixing processes:

Salinity-Transparency Relationships: At Stations 2 and 3, the closer association between salinity and transparency suggests that dissolved salts have a more direct impact on water clarity in these locations. This relationship may reflect different mixing regimes or sediment dynamics between the stations.

pH-Transparency Interactions: At Station 1, the closer association between pH and transparency may indicate different biogeochemical controls, possibly related to photosynthetic activity or different buffering capacity of the waters (Kannan & Kannan, 1996).

3.2.5 Regional Context and Comparison

While specific comparative data for the Chippaleru system are not available in the regional literature, the observed parameter relationships align with documented patterns in southeast Indian mangrove systems. Regional studies emphasize tide-driven mixing and spatially variable seawater intrusion, which control salinity patterns and influence biogeochemical processes.

Tidal Mixing Control: The observed parameter clustering likely reflects tidal influence on mixing processes, where seawater intrusion during flood tides and freshwater/brackish water drainage during ebb tides create the dynamic conditions that drive parameter relationships (Sandilyan et al., 2010; Sasikumar et al., 1992).

Nutrient Enrichment Patterns: Regional mangrove studies report elevated NH_4^+, PO_4^{3-}, and SiO_2 in mangrove waters relative to overlying waters, reflecting sediment-porewater nutrient reservoirs and mangrove biogeochemical processing (Li et al., 2024; Al-Masri et al., 2024; Gujjeti et al., 2014; Gurrapu et al., 2017). The clustering of nutrient parameters in the Chippaleru system may reflect similar processes.

3.3 Ecological Implications

The identified parameter relationships have important implications for ecosystem functioning and management:

3.3.1 Nursery Habitat Quality

The negative correlation between dissolved oxygen and nutrients indicates potential water quality stress that could impact juvenile fish and invertebrates using mangrove creeks as nursery habitats (Boesch & Turner, 1984; Stoner, 1988). Understanding these relationships is crucial for predicting habitat suitability under varying environmental conditions.

3.3.2 Biogeochemical Processing

The clustering of biogeochemical parameters demonstrates the interconnected nature of nutrient cycling processes. This understanding is essential for predicting ecosystem responses to environmental changes, such as altered freshwater inputs or increased nutrient loading (Barletta et al., 2005).

3.3.3 Monitoring and Management

The consistent clustering patterns suggest that monitoring programs could potentially focus on representative parameters from each cluster to efficiently assess ecosystem health while reducing sampling effort and costs.

3.3.4 Methodological Insights

Cluster Analysis Utility: The cluster analysis approach proved effective for identifying parameter relationships and grouping variables based on their ecological interactions. The consistent patterns across stations validate the approach and suggest that similar methodologies could be applied to other mangrove systems for comparative analysis.

3.3.5 Spatial Scale Considerations

The similarity in clustering patterns across the three stations (80% similarity) reflects the relatively small spatial scale of the study area (Knox, 2001). This consistency suggests that local environmental controls are more important than spatial variation in driving parameter relationships within the Chippaleru system.

3.3.6 Limitations and Future Research

Temporal Considerations: This study represents a spatial analysis of parameter relationships, but temporal dynamics are also important for understanding estuarine processes. Future research should incorporate seasonal and tidal cycle variations to provide a more comprehensive understanding of system dynamics.

4. Conclusion

This study presents the first cluster analysis of hydrological parameters in the Chippaleru mangrove estuary, Andhra Pradesh. Nine physico-chemical parameters across three stations consistently grouped into three clusters with 80% similarity: (1) thermal (air and water temperature), (2) biogeochemical (dissolved oxygen, nitrates, phosphates, turbidity), and (3) water quality (salinity, transparency, pH). The largest cluster—biogeochemical parameters—emphasizes nutrient–oxygen interactions, where microbial activity consumes oxygen while releasing nutrients. Positive correlations among nutrients and turbidity suggest sediment–water coupling. Uniform clustering across stations indicates consistent hydrological processes due to the estuary's small spatial scale. These findings establish a baseline for water quality monitoring and conservation, highlighting the value of multivariate statistics in estuarine studies. Future work should explore temporal changes and additional parameters to deepen understanding and support ecosystem management.

These findings and cluster analysis demonstrate their usefulness for understanding estuarine parameter relationships. The results contribute to understanding nutrient dynamics and water quality patterns in Indian mangrove ecosystems, which are critical for conservation and management of these coastal habitats.

Competing interests:

The authors declare that they have no competing interests

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From National Conference on Advances in Life Sciences: Present & Future (NCALS–2026) | 24-25 March 2026 | Organized by: Department of Zoology, Kakatiya University, Warangal-506 009, Telangana State, India