CHAPTER 7

CONCLUSION, RECOMMENDATIONS AND FUTURE SCOPES

7.1 CONCLUSION AND RECOMMENDATIONS

This study examined the interplay between water quality parameters, sediment heavy metal concentrations, macrophyte richness, and their collective influence on sediment carbon sequestration across multiple aquatic ecosystems. Each chapter addressed a distinct component ranging from abiotic water chemistry to biotic diversity, and together they provided a comprehensive framework to understand the drivers of carbon storage in sediments.

To integrate these findings, a combined statistical analysis was conducted to assess the relative contributions of each factor to sediment carbon sequestration using correlation matrix and multiple modelling approaches such as Multiple Linear Regression (MLR), LASSO (Least Absolute Shrinkage and Selection Operator) or Ridge Regression, and Random Forest Regression. All the statistical analyses were performed using R-software (Version 4.4.3). The modelling approach involved the following steps:

1. Data Preprocessing: All predictor variables were standardized (z-score normalization) to ensure comparability and reduce scale-related bias.

2. Correlation Analysis: Pearson's correlation coefficients were computed to identify potential multicollinearity and preliminary relationships.

3. Model Development:

    - Multiple Linear Regression (MLR) was initially applied as a baseline model.

    - LASSO Regression was employed to perform variable selection and mitigate multicollinearity by penalizing less informative variables.

- Random Forest Regression was used to capture complex, non-linear relationships and interaction effects.

4. Model Evaluation: Models were compared based on RMSE, residual analysis, and predictive accuracy to determine robustness.

The heatmap illustrates Pearson's correlation coefficients among all measured variables, including water quality parameters, sediment heavy metals, and macrophyte richness (figure 7.1). Sediment carbon sequestration exhibits weak to moderate positive correlations with variables such as macrophyte richness, turbidity, salinity, and total hardness (TH). Notably, macrophyte richness shows moderate positive associations with turbidity and TH, suggesting that ecosystems with greater plant diversity may influence, or be influenced by, underlying physico-chemical conditions. Several heavy metals, including chromium (Cr), copper (Cu), and manganese (Mn), display strong inter-correlations, indicating potential co-mobility or a shared geochemical source within the sediment matrix. The overall correlation structure is characterized by predominantly weak to moderate relationships, highlighting the absence of any single dominant driver of sediment carbon sequestration.

This pattern supports the interpretation that carbon sequestration is likely governed by complex multivariate interactions, rather than simple univariate effects. Consequently, advanced modelling approaches, such as Random Forests or LASSO regression, are needed to capture the combined and potentially non-linear influences of biological, chemical, and physical variables on sediment carbon dynamics.

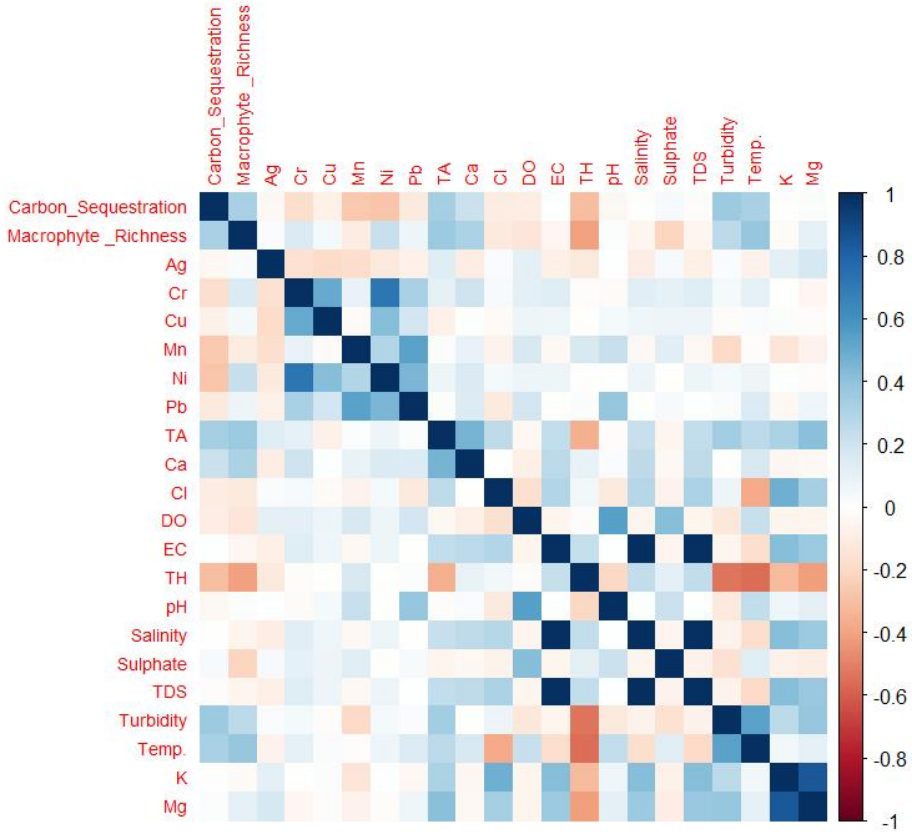

Figure 7.1: Pearson's correlation coefficients between all measured variables.

The LASSO regression model identified a streamlined set of key predictors of sediment carbon sequestration, effectively balancing model simplicity with explanatory power. Macrophyte Richness emerged as the most influential variable (β = 4.77), highlighting the pivotal role of aquatic plant diversity in promoting carbon storage, likely through organic matter input and habitat structuring (table 7.1). Other strong positive predictors included Calcium (β = 3.64), Turbidity (β = 2.97), and Temperature (β = 1.92), suggesting that mineral availability, particulate load, and thermal conditions enhance sediment accumulation and biological activity conducive to carbon burial. In contrast, Nickel (β = –0.82), Manganese (β = –0.085), and Chromium (β = –0.015) showed negative associations, possibly due to their inhibitory effects on microbial or plant-mediated stabilization of organic carbon. Total Alkalinity (β = 0.36) had a modest positive effect, potentially linked to its role in maintaining pH stability and supporting ecosystem productivity.

The scatter plot of observed versus predicted sediment carbon sequestration values using the LASSO model (Figure 7.2) demonstrates that the close clustering of points around the line suggests good model performance and predictive accuracy. The scatter plot shows a reasonable alignment of predicted values with observed ones, though slight dispersion exists, especially for higher carbon values—reflecting model limitations in capturing extreme sequestration levels.

Table 7.1: LASSO-selected variables for predicting sediment carbon sequestration

Variable	Macrophyte _Richness	Cr	Mn	Ni	TA	Ca	Turbidity	Temp.
Co-efficient	4.77	-0.02	-0.09	-0.82	0.36	3.64	2.97	1.92

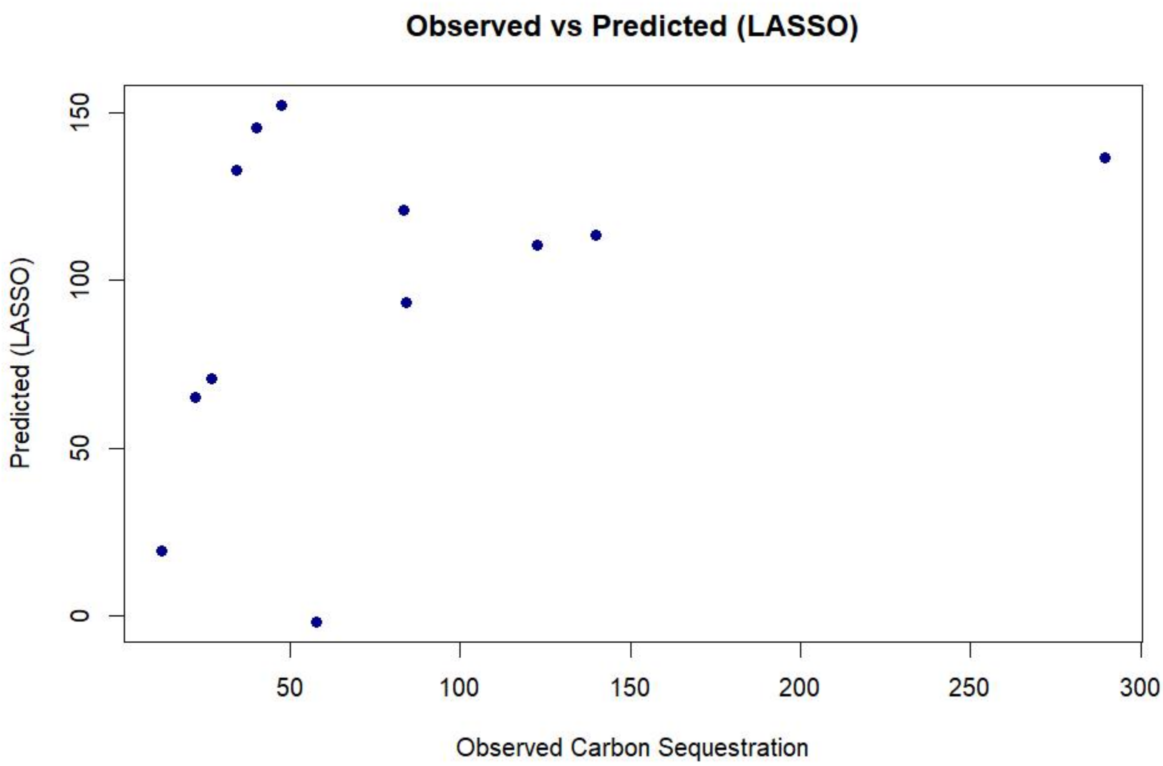

Figure 7.2: Observed versus predicted values of sediment carbon sequestration using the LASSO regression model.

LASSO's exclusion of non-contributory variables through coefficient shrinkage underscores its utility in managing multicollinearity and enhancing model interpretability. The results emphasize the importance of both biological structure and physicochemical conditions in regulating sediment carbon sequestration.

Random Forest analysis was used to identify the most important variables for predicting sediment carbon sequestration, based on two key metrics: %IncMSE (percentage increase in mean squared error), which quantifies the rise in prediction error when a variable is permuted, higher values indicate greater importance, and IncNodePurity, which reflects the total reduction in node impurity attributed to a variable, representing its effectiveness in data partitioning. Across both metrics (figure 7.3), Turbidity and Macrophyte Richness consistently emerged as the most influential predictors. Other notable contributors included Salinity, Total Hardness (TH), Temperature, and trace metals such as Nickel (Ni) and Manganese (Mn). In contrast, traditional water quality indicators such as pH, Dissolved Oxygen (DO), and Electrical Conductivity (EC) showed relatively lower importance.

These findings further highlight that biological structure (e.g., macrophyte richness) and physical parameters (e.g., turbidity, salinity, TH) are stronger predictors of sediment carbon sequestration than chemical characteristics alone. This underscores the critical role of integrated ecosystem functioning in governing carbon storage processes within aquatic sediments.

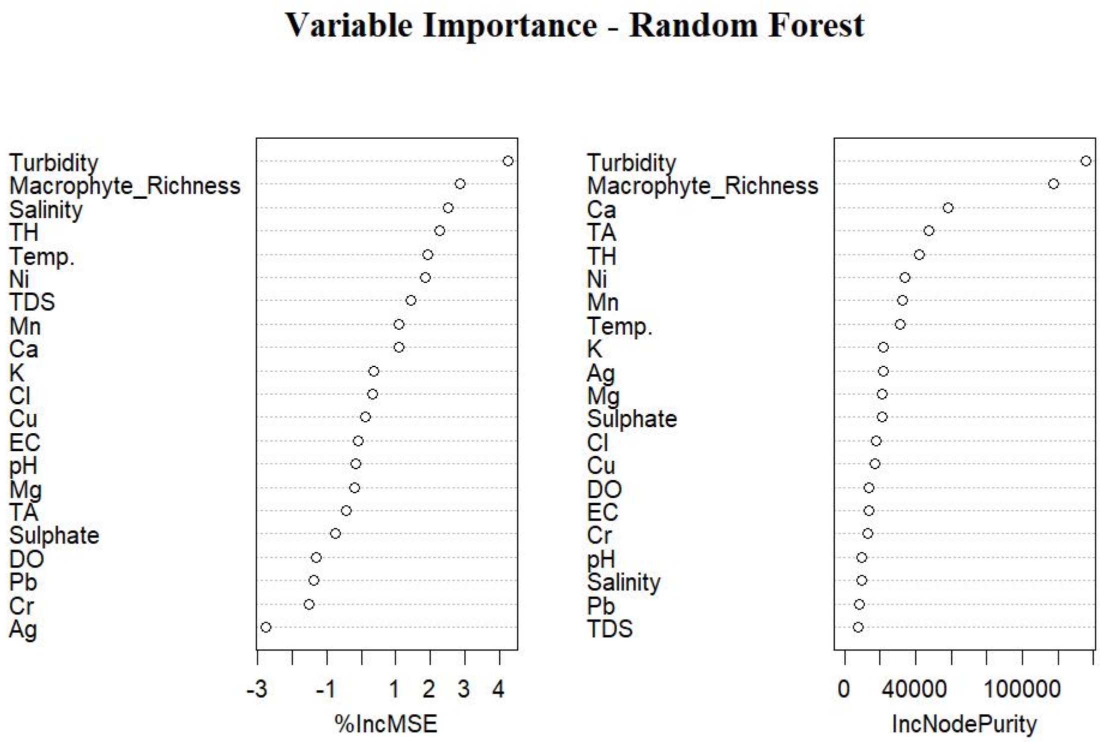

Figure 7.3: Variable importance (Random Forest) for different parameters of Loktak lake on carbon sequestration.

A comparison of RMSE values (Figure 7.4) across three models—LASSO, Random Forest, and MLR—revealed that LASSO regression achieved the lowest RMSE, indicating the highest predictive accuracy among the models evaluated. Random Forest exhibited a slightly higher RMSE but still outperformed Linear Regression, which showed the weakest performance overall. The relatively poor performance of Linear Regression likely stems from its strict assumption of linearity and its limited capacity to account for complex feature interactions and multicollinearity.

The superior performance of the LASSO model underscores the effectiveness of regularization techniques in managing noise and addressing multicollinearity within the dataset. Meanwhile, the competitive performance of Random Forest further supports the presence of non-linear relationships and interaction effects among the predictor variables influencing sediment carbon sequestration.

Figure 7.4: Comparison of RMSE values showing superior predictive accuracy of LASSO over other models.

The combined modelling approach identifies Macrophyte Richness, Turbidity, and Calcium concentration as strong positive predictors of sediment carbon sequestration, while trace metals like Nickel and Manganese exhibit a suppressive effect. The LASSO model provides a robust and interpretable framework with competitive performance compared to more complex models. This study highlights the intertwined effects of biological diversity and geochemical factors in governing sediment carbon storage and underscores the utility of regularized regression in ecological prediction modelling.

Overall conclusion

This study provides a holistic understanding of the ecological processes influencing carbon sequestration in Loktak Lake by integrating findings from water quality analysis, sediment heavy metal assessments, macrophyte species composition, land use and land cover (LULC) changes, and advanced modelling techniques.

Water quality assessments revealed that although certain parameters were within acceptable limits (BIS, WHO), key concerns such as low Dissolved Oxygen and elevated potassium and magnesium levels highlight seasonal pollution and potential eutrophication. The accumulation of nutrients like nitrogen and calcium in water and sediment encourages the growth of invasive aquatic species, which further alters the lake's ecological balance.

The analysis of sediment heavy metals revealed medium to high toxic potential, with co-occurrence patterns suggesting shared geochemical sources. This reinforces the need for pollution source identification and sediment remediation to restore ecological health.

Macrophyte surveys showed dominance by invasive species such as *Hydrilla verticillata* and *Limnophila aquatica*, supported by nutrient enrichment and stagnant hydrology from the Loktak Multipurpose Project. These shifts in species composition reflect both ecological degradation and a decline in economically valuable native flora, affecting both biodiversity and the endangered Sangai deer population.

Carbon sequestration analysis demonstrated a strong link between organic matter input from macrophytes and sediment storage, especially in regions with dense vegetation and high sedimentation. The presence of sulfur in sediments likely plays a role in stabilizing organic carbon by preventing its dissolution.

Land use analysis highlighted significant alterations due to urbanization and infrastructure projects, disrupting the lake's hydrological regime, accelerating phumdi proliferation, and increasing the risk of carbon loss through greenhouse gas emissions.

Integrated modelling approaches confirmed the complex interplay of factors influencing carbon sequestration. Sediment carbon sequestration in Loktak Lake is governed by a synergy of biological richness, physico-chemical parameters, and anthropogenic impacts. The combined use of regularized regression and machine learning models underscores the importance of advanced modelling in ecological forecasting and reinforces the lake's role as a vital carbon sink in the Indo-Burma biodiversity hotspot.

These findings highlight that sediment carbon sequestration is a complex process influenced by living organisms, chemical properties, and human activities. Understanding these interactions is crucial for developing effective strategies to enhance carbon storage in sedimentary environments. Future research should focus on the specific roles of different organisms and how their activities can be optimized to improve sequestration rates. Loktak Lake, with its significant carbon storage potential, represents an important natural asset for climate mitigation, fulfilling the United Nations Sustainable Development Goal (SDG) of "Climate Action." It also emphasizes the need for comprehensive conservation strategies, effective land resource management, continuous monitoring, and community engagement to preserve various ecological processes of the Loktak Lake ecosystem.

To ensure the long-term health and ecological integrity of Loktak Lake, comprehensive conservation measures should be implemented. These measures include the regulation of human activities that contribute to encroachment and bioresource exploitation, management of invasive species, community engagement and awareness programs, and initiatives for wetland restoration. By adopting these strategies, stakeholders can aim to preserve the diverse flora and fauna of Loktak Lake, securing its status as a Ramsar site of international importance and a vital freshwater ecosystem.

7.2 FUTURE SCOPES OF THE STUDY

While this study presents an integrated understanding of the ecological factors influencing carbon sequestration in Loktak Lake, several critical aspects remain unexplored. Future research should aim to build on the current findings by focusing on the following key areas:

i. Microbial Community Dynamics:
Investigating the structure and function of microbial communities within lake sediments to better understand their role in organic matter decomposition, methane production, and long-term carbon stabilization. Molecular-level studies, including metagenomics or functional gene analysis, could provide insights into microbial-mediated carbon cycling.

ii. High-Productivity Macrophyte Species Identification:
Identification and evaluation of native and non-native macrophyte species with high biomass productivity and efficient organic matter contribution to sediments of macrophyte species with high biomass productivity enhancing significant storage of organic matter in wetlands.

iii. Long-Term Ecological Modelling:
Developing predictive models that incorporate climatic factors (e.g., precipitation, temperature), sedimentation rates, vegetation dynamics, and LULC changes to forecast future carbon sequestration scenarios.

iv. Greenhouse Gas Flux Measurement:
Quantification of fluxes of CO_2 and CH_4 from sediments under varying environmental and vegetation conditions to determine the net greenhouse gas balance of the lake.