

## Supplementary file

### **Biogeochemical controls on nutrient fluxes in small tropical mountainous river basins: Mechanisms for P-limitation and Si-rich conditions**

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This supplementary material

Fig. S1

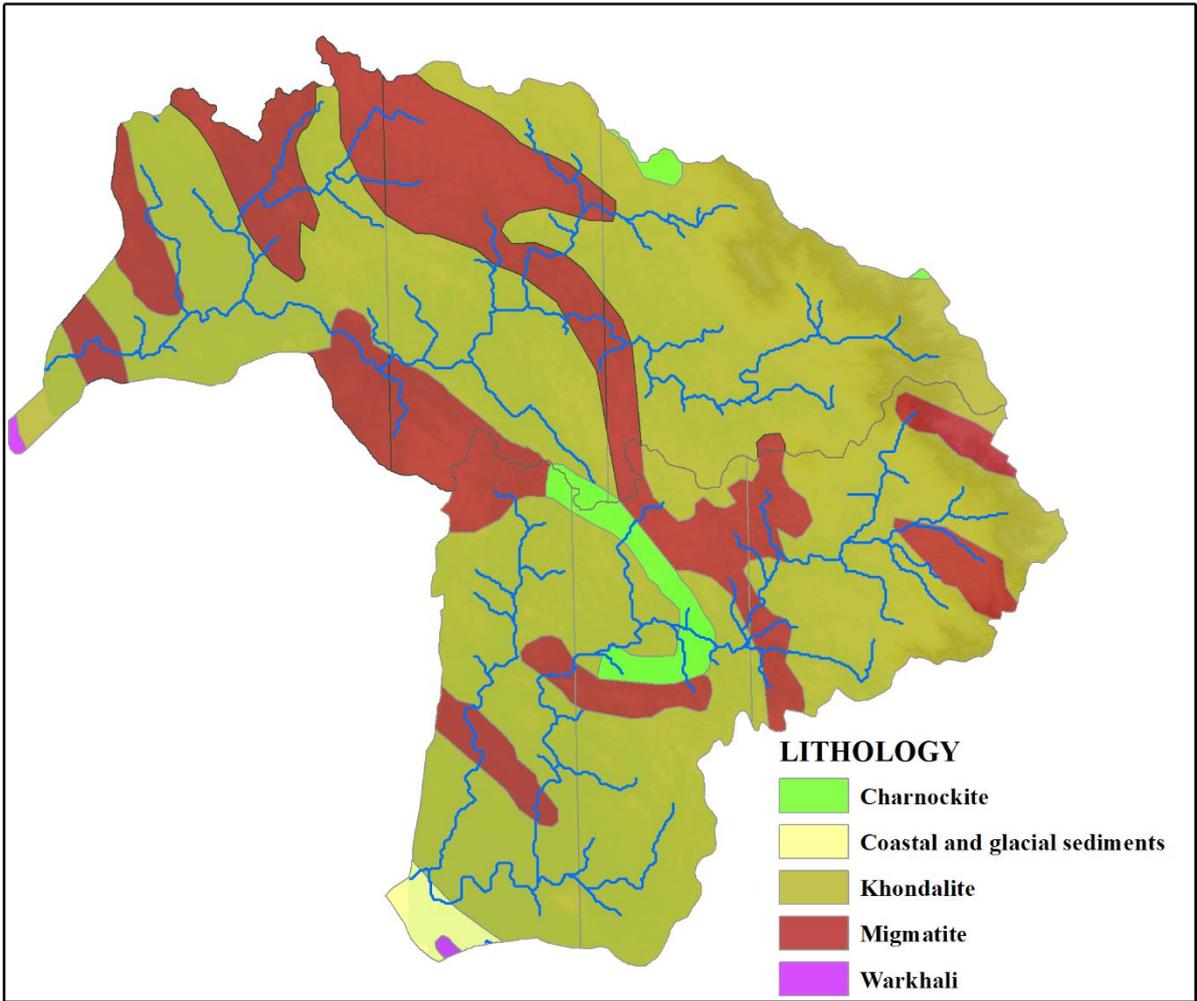
Fig. S2

Fig. S3

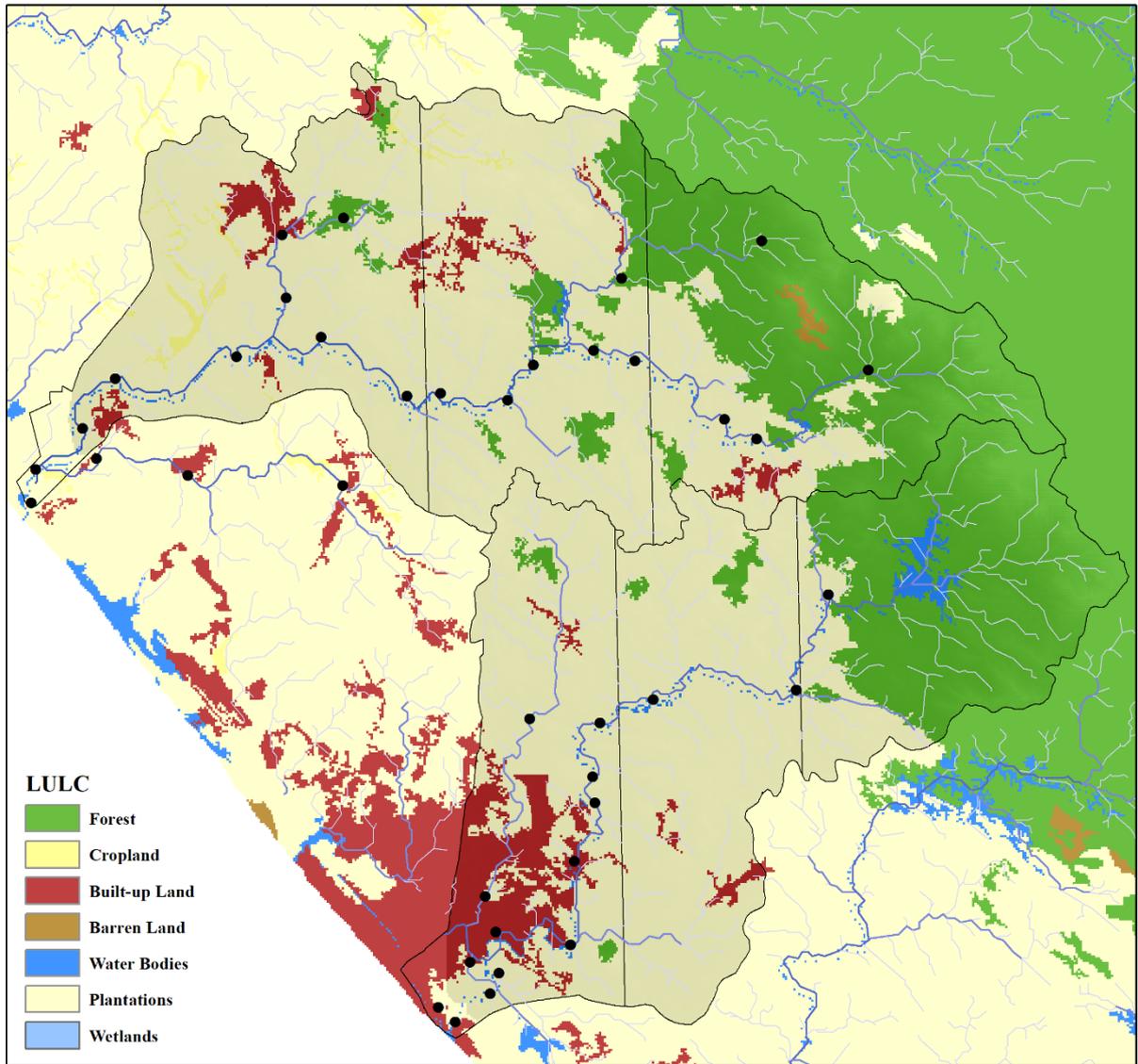
Fig. S4

Fig. S5

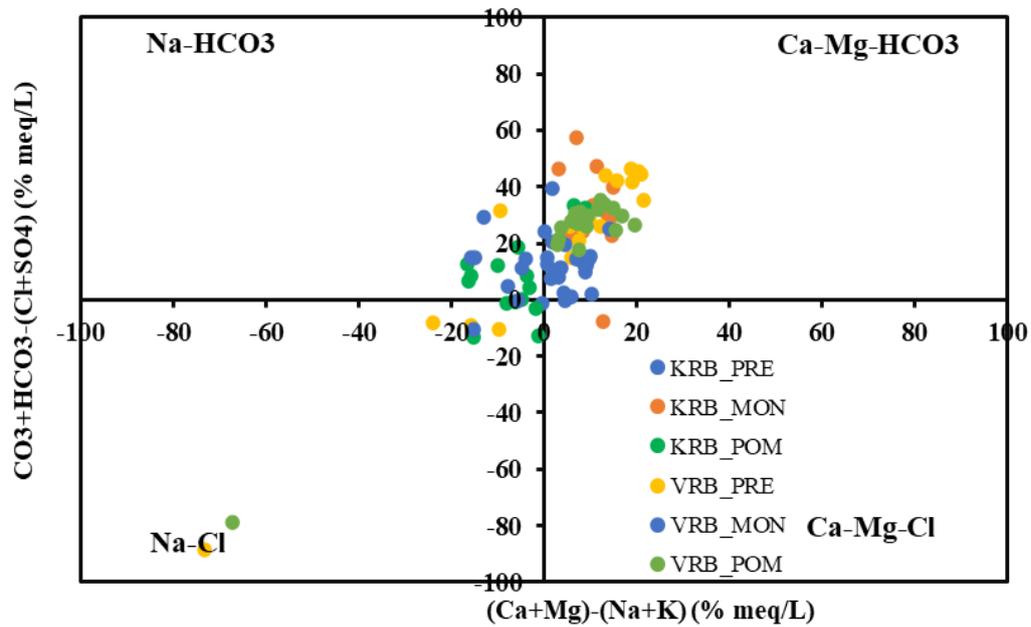
Text S1



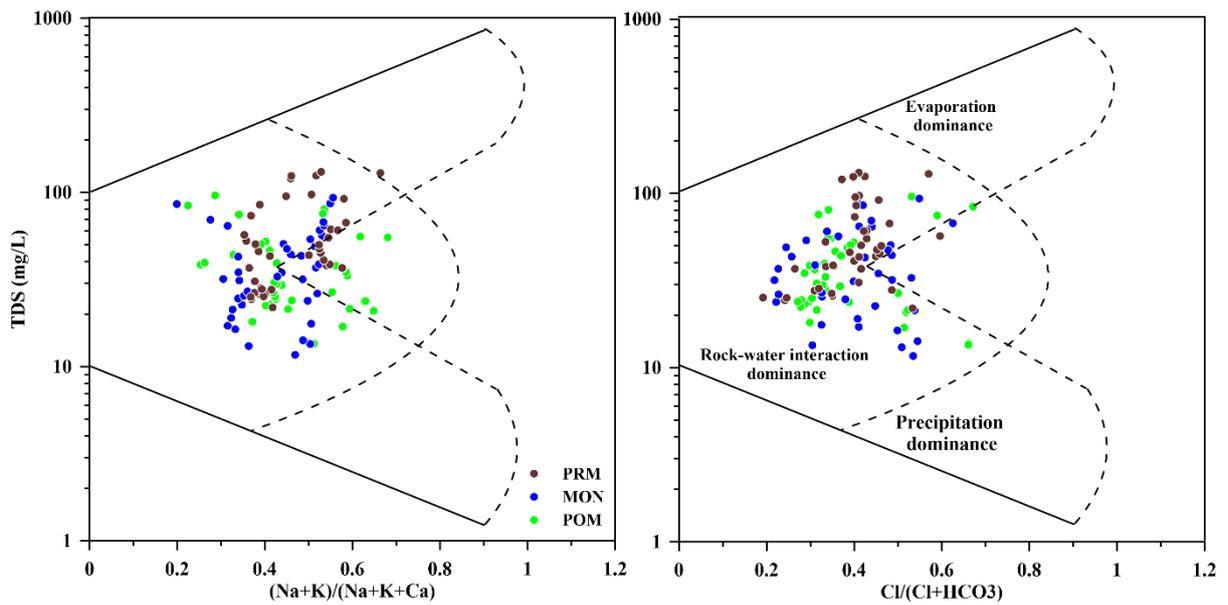
**Fig. S1:** Geology (major lithology) of the study basins (Data is derived from GSI interactive portal: <https://bhukosh.gsi.gov.in/Bhukosh/MapView.aspx>).



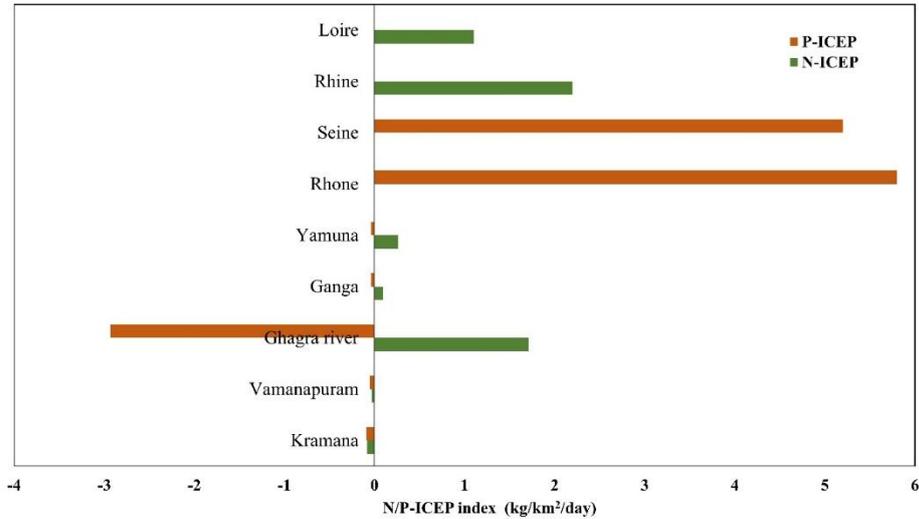
**Fig. S2:** Land use and land cover map of the study basins (Data is derived from Bhuvan portal: <https://bhuvan-app1.nrsc.gov.in/thematic/thematic/index.php>).



**Fig S3:** Chadha plot representing mixed type of water along with the post monsoon samples in Na-HCO<sub>3</sub> and downstream samples in Na-Cl zone for KRB and VRB.



**Fig. S4:** Gibbs plot showing the seasonal source mechanism of major ions in both the basins.



**Fig S5:** Calculated ICEP values for DIN and DIP and comparison with other large river systems.

### Text S1: Dissolved nutrient yield dynamics

In the KRB, significant spatial variability in nutrient dynamics was observed along the three longitudinal segments (Fig. 4 & 5), largely controlled by discharge, topography, and land-use conditions. The upstream region, dominated by dense forest cover with steep slopes and elevations >1000 m. Hence, minimal anthropogenic activity and strong nutrient retention in the soil-vegetation system result in the lowest nutrient load and yield across all parameters ( $\text{HCO}_3^-$ , DIN, DIP, and DSi). Midstream is a transitional zone with moderate slopes and elevations above 100 m, constituting extensive plantation areas, agricultural fields, and scattered rural settlements. This segment displayed the highest total nutrient load, indicating the influence of enhanced runoff and soil disturbance under mixed land use conditions. The high  $L_n$  is attributed to greater discharge volume from this midstream zone, which effectively mobilizes nutrients from agricultural and plantation areas. In contrast, downstream region, characterized by low

slopes (<50 m) and intense urbanization, showed the highest nutrient yield among the main-channel segments, with  $\text{HCO}_3^-$ : 107.16  $\text{kg ha}^{-1}\text{yr}^{-1}$ , DIN: 8.44  $\text{kg ha}^{-1}\text{yr}^{-1}$ , DIP: 0.09  $\text{kg ha}^{-1}\text{yr}^{-1}$ , and DSi: 143.37  $\text{kg ha}^{-1}\text{yr}^{-1}$ . Despite a smaller catchment area, the predominance of impervious surfaces and efficient waste water drainage networks enhances nutrient export per unit area. This indicates that urbanization intensifies runoff-driven nutrient transfer, producing high yield values even where total load remains lower than in midstream region. A tributary sub-basin, displayed the overall highest nutrient load and yield ( $\text{HCO}_3^-$ : 189.10  $\text{kg ha}^{-1}\text{yr}^{-1}$ ; DIN: 12.68  $\text{kg ha}^{-1}\text{yr}^{-1}$ ; DIP: 0.05  $\text{kg ha}^{-1}\text{yr}^{-1}$ ; DSi: 161.94  $\text{kg ha}^{-1}\text{yr}^{-1}$ ). The combination of semi-urban and agricultural land uses in this tributary catchment promotes cumulative nutrient inputs, contributing to elevated downstream fluxes.

Overall,  $\text{HCO}_3^-$  and DIN exhibit strong discharge- and runoff-driven transport intensified by urbanization, DIP shows anthropogenic influence with rapid flushing and low retention, and DSi reflects lithological and weathering control modulated by slope and sediment interaction. These results highlight that in short, steep, and urban-influenced WG River systems, the interplay of topography, land use, and hydrology governs spatial heterogeneity and enhances nutrient export efficiency toward the coastal zone. Similar to KRB, the spatial variation of nutrient load and yield in the VRB shows that both topography and land use play a crucial role in nutrient movement. The two tributaries located in the more or less near to upstream and downstream middle section of the basin are included under midstream, as they share similar land use features, although their topographic characteristic vary slightly.

Among all segments, the highest nutrient yield ( $Y_n$ ) was observed in upstream region ( $\text{HCO}_3^-$ : 81.75  $\text{kg ha}^{-1}\text{yr}^{-1}$ ; DIN: 14.78  $\text{kg ha}^{-1}\text{yr}^{-1}$ ; DIP: 0.19  $\text{kg ha}^{-1}\text{yr}^{-1}$ ; DSi: 77.90  $\text{kg ha}^{-1}\text{yr}^{-1}$ ), while the maximum nutrient load occurred in midstream region ( $\text{HCO}_3^-$ : 1116.14  $\text{kg ha}^{-1}\text{yr}^{-1}$ ; DIN: 442.84  $\text{kg ha}^{-1}\text{yr}^{-1}$ ; DIP: 4.09  $\text{kg ha}^{-1}\text{yr}^{-1}$ ; DSi: 2998.90  $\text{kg ha}^{-1}\text{yr}^{-1}$ ). This pattern indicates that variations in river discharge and terrain features strongly influence nutrient

transport within the basin. The high-slope upper region with an elevation above 1000 m, mainly covered by forest and plantations, functions as a nutrient retention zone with limited export. Midstream region, with moderate elevation (around 50-100 m) and mixed plantation-agricultural areas, shows higher nutrient loading due to runoff and soil erosion. The lower region, downstream region (<50 m), includes agricultural lands and small townships and records the highest nutrient yield, suggesting that gentle slopes and human activities increase nutrient movement toward the outlet.

In the KRB, the nutrient transport is mainly affected by urban development, where the steep forested upstream area acts as a nutrient sink, and the lowland urban zone shows the highest yield due to stormwater drainage and impervious surfaces. In contrast, the VRB is largely influenced by agricultural and plantation activities, where mid-basin runoff contributes to greater nutrient loads, and the downstream region shows high nutrient yield under slower flow conditions. Overall, the KRB reflects an urban-dominated nutrient system, while the VRB represents an agriculture and land use driven system. These findings highlight how differences in land use, discharge, and terrain conditions control nutrient behavior in small west-flowing rivers of the WG.

The comparison of nutrient fluxes of the KRB and VRB with other major Indian and global river systems is presented in Table S1. The comparison depicts that the DSi flux of KRB ( $127.25 \text{ kg ha}^{-1} \text{ yr}^{-1}$ ) is comparable to that of the world's largest rivers, the Amazon ( $108.6 \text{ kg ha}^{-1} \text{ yr}^{-1}$ ) and the Mississippi ( $118.21 \text{ kg ha}^{-1} \text{ yr}^{-1}$ ), despite their much greater drainage areas. This indicates that the KRB delivers a relatively high silica yield due to enhanced rock weathering intensity, dominant silicate lithology, and runoff characteristics within the basin. Moreover, the DIC flux ( $101.06 \text{ kg ha}^{-1} \text{ yr}^{-1}$ ) in KRB is much higher than those reported for several east-flowing Indian rivers such as the Vaigai ( $42 \text{ kg ha}^{-1} \text{ yr}^{-1}$ ), Penna ( $43 \text{ kg ha}^{-1} \text{ yr}^{-1}$ ), Krishna ( $9 \text{ kg ha}^{-1} \text{ yr}^{-1}$ ), Godavari ( $46 \text{ kg ha}^{-1} \text{ yr}^{-1}$ ), Cauvery ( $98 \text{ kg ha}^{-1} \text{ yr}^{-1}$ ), Mahanadi (63

kg ha<sup>-1</sup> yr<sup>-1</sup>), and Subarnarekha (58 kg ha<sup>-1</sup> yr<sup>-1</sup>). This similar pattern indicates that KRB exhibits significantly higher fluxes compared to most of the other Indian basins, emphasizing its strong geochemical weathering control on both carbon and silica mobilization. In contrast, the VRB also shows notably high DSi fluxes (71.49 kg ha<sup>-1</sup> yr<sup>-1</sup>), which exceed those of most east-flowing Indian rivers and are comparable to that of the Yangtze river (40.37 kg ha<sup>-1</sup> yr<sup>-1</sup>). However, the DSi flux in VRB remains lower than that of the Amazon and Mississippi, suggesting relatively moderate weathering intensity and sediment transport capacity compared to KRB. When considering DIN and DIP fluxes, KRB shows slightly lower values than VRB, particularly in the case of DIP (0.05 kg ha<sup>-1</sup> yr<sup>-1</sup>). In contrast, KRB exhibits higher DIC (101.06 kg ha<sup>-1</sup> yr<sup>-1</sup>) and DSi (131.28 kg ha<sup>-1</sup> yr<sup>-1</sup>) fluxes compared to VRB (40.93 kg ha<sup>-1</sup> yr<sup>-1</sup> and 71.49 kg ha<sup>-1</sup> yr<sup>-1</sup>, respectively), reflecting the influence of catchment lithology, slope, and hydrological regime, which enhance chemical weathering and solute generation in KRB.

Furthermore, the DIN flux of KRB is higher than that of most east- and west-flowing Indian rivers, except for the Yamuna (31.1 kg ha<sup>-1</sup> yr<sup>-1</sup>) and Mississippi (13.01 kg ha<sup>-1</sup> yr<sup>-1</sup>). Meanwhile, the DIP flux of VRB (1.45 kg ha<sup>-1</sup> yr<sup>-1</sup>) is remarkably higher than all other Indian rivers listed and is comparable to that of the Mississippi river (1.32 kg ha<sup>-1</sup> yr<sup>-1</sup>). The elevated DIP flux in VRB may be attributed to anthropogenic influences, particularly agricultural runoff and domestic effluent discharge, which contribute to phosphorus enrichment in the basin. Overall, this comparative analysis demonstrates that both KRB and VRB exhibit nutrient fluxes that are comparable to or higher than many large Indian and global river systems when normalized to drainage area. This unravels the significant biogeochemical role of these tropical small river basins in nutrient transport, highlighting their substantial contribution to regional and coastal nutrient budgets.