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RESEARCH ARTICLE

Socio-Ecological Resilience and Geomorphic Decay: A Study of Riparian Biodiversity and Anthropogenic Stress in the Pampa River Basin, Kerala, India

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Abstract

The Pampa River, a vital hydrological artery of Kerala, is currently undergoing a transition from a stable fluvial system to a degraded "green desert." This study evaluates three critical sites in the Elanthoor Block Panchayat of Pathanamthitta district in Keralam, India—Cherukolpuzha, Keezhukara, and Maramon—to assess the interrelatedness between geomorphic instability, sand mining, and invasive proliferation. Using transect sampling and community interviews, the research identifies twelve dominant plant species, none of which possess the structural root architecture required to mitigate bank failure. The study argues that climate-induced extremes, exacerbated by unregulated extraction, have created a crisis of climate injustice for riparian communities. Recommendations center on Nature-Based Solutions (NBS), specifically integrated bioengineering and a total extraction ban, to restore the river’s hydrological and social sovereignty.

1. INTRODUCTION

The Pampa River, draining 2,235 km^2 of Kerala’s landscape, serves as the ecological backbone for the Kuttanad lowlands, a Ramsar wetland of global significance. However, the reach flowing through the Elanthoor Block Panchayat represents a fragile “mid-reach” ecosystem where the balance between sediment deposition and transport is increasingly volatile.

In the paradigm of Climate Justice, a river is not merely a resource but a cultural heritage that provides ecosystem services—flood regulation, groundwater recharge, and habitats that support biodiversity. When these services fail, the burden falls disproportionately on local agrarian and riparian communities.

The degradation of the Pampa is driven by two interlocking forces:

1. Unregulated Anthropogenic Intervention (UAI): Specifically, instream sand mining. This activity triggers a “knickpoint” effect, causing channel bed incision of 5-10 cm annually.
2. Hydro-climatological Extremes: The 2018 Kerala floods acted as a “systemic shock,” revealing the vulnerability of riverbanks stripped of their natural defences.

When mining removes the protective coarse sediment layer, the river’s equilibrium profile is shattered. This leads to Lateral Channel Migration, where the river “eats” into the banks, destroying the riparian and ecotonal assemblages—the vital transition zone between water and land.

2. STUDY AREA AND METHODOLOGY

Selection of Vulnerability Zones

Three sites within the Elanthoor Block were selected based on their unique hydrogeomorphic regimes (Figs. 1-3):

- Cherukolpuzha (C): A depositional area focused on Sediment Accretion Dynamics. (Lat: 9^0 19’20’’ N; Long: 76^0 40’ 50’’ E).
- Keezhukara (K): A historical hotspot of Intense Substrate Removal. (Lat: 9^0 20’ 52’’ N; Long: 76^0 46’ 45’’ E).

- Maramon (M): An area characterized by Intense Bank Scour and Slumping. (Lat: 9^0 20'25''N; Long: 76^0 41' 35'' E).

Figures 1-3: Photographs showing study sites

Fig.1: Cherukole

Fig.2: Keezhukara

Fig.3: Maramon

Sampling and data collection

A comparative geo-ecological design was employed. Transect Methods were used to quantify plant dominance across the riparian gradient. The study sites were monitored for indicators of degradation, including lateral bank erosion, sediment aggradation, and the anthropogenic pressures of livestock grazing and invasive species proliferation, which collectively compromise the river's structural integrity. Field observations were supplemented by interviews with members of the Biodiversity Management Committees (BMCs) and local elders to reconstruct a topographic history of the river, comparing past stability to current decay. The sites were observed for threats such as loss of river bank, deposition of silt or clay, over grazing and occurrence of invasive plants. Plant species were identified with the help of standard flora and taxonomists.

3. RESULTS AND DISCUSSION

The study observed that the Pampa River reach within the Elanthoor Block functioned as a high-energy fluvial system that struggled with severe geomorphic instability. The field survey documented twelve primary plant species. Out of the twelve plant species documented, ten plants were of invasive category. Plants with their ecological impact is summarized in Table 1.

The investigation revealed a critical functional mismatch between extant riparian vegetation and the hydraulic demands of the Pampa River. While native taxa such as *Alternanthera sessilis* (L.) DC and *Eclipta alba* (L.) Hassk provide localized, surface-level soil cohesion, their shallow root systems lack the tensile strength and vertical depth required to mitigate mass bank failure or arrest lateral channel migration during hydro-climatological extremes, such as the catastrophic 2018 Kerala floods (Sreeja *et al.*, 2016). The study further elucidates the direct correlation between unregulated anthropogenic interventions and the acceleration of ecological decline. As established by Padmalal and Maya (2014), pervasive instream sand mining across Kerala's coarse-bed rivers has systematically stripped the "armour layer"—the protective coarse sediment matrix that maintains the vertical stability of the riverbed.

Pampa riverbed at Keezhukara serves as a primary example of "Extractive Injustice." The removal of coarse sand has left behind a fine, clay-heavy slurry. Activities like dredging, sand mining, or increased water flow scour the channel bed. This lowers the river or stream bottom over time. As the channel bed deepens, it acts as a deep drain. The local groundwater (the unconfined aquifer) flows toward and into this lowered channel to reach hydraulic equilibrium. This effectively acts like pulling a plug, draining shallow aquifers and lowering the regional water table (Chambers *et al.*, 2021; Reynolds & Cooper, 2011). The lowered water table and constant drainage expose new, dry substrate that was historically saturated. This altered substrate has facilitated the proliferation of Bull Grasses (*Muhlenbergia richardsonis* (Trin.) Rydb.). These aggressive, mat-forming perennial grasses thrive in these newly dried, disturbed soils. The physical structure of the dense grass blades increases roughness, slows down water velocity, and forces suspended sediments to drop out of suspension. While sediment accumulation can sometimes naturally restore or aggrade an incised bed over decades, in severe cases—or if combined with continuous human disturbance—it results in a highly altered, choked, and stagnated waterway that permanently compromises local water security by disrupting the natural aquifer recharge-discharge cycles (Tague *et al.*, 2008). Empirical studies on river sand mining across India confirm that such channel incision leads to lowered groundwater tables, reduced well yields, and hydrological disconnection between rivers and floodplains (Kondolf, 1997; Padmalal & Maya, 2014; Rentier & Cammeraat, 2022). Therefore, the visible drop in groundwater levels at Keezhukara is a predictable hydrogeological response to sediment extraction, posing a significant threat to local water security and reinforcing the characterization of the site as an instance of extractive environmental injustice.

At Maramon region, the study recorded complete absence of deep-rooted riparian trees. Instead, the banks are covered in a dense carpet of shallow-rooted plants. The deep-rooted trees were reported to develop a strong taproot system with deep vertical penetration along with extensive lateral roots, which enables firm anchorage in riverbanks and high resistance to erosion and flood scouring. Classical Indian silvicultural literature explicitly describes *Terminalia arjuna* (Roxb.Ex DC.) Wright & Arn. (Maruthu in Malayalam) as a riverine species adapted to alluvial banks with deep, binding roots suited for bank stabilization (Troup, 1921). The tree was also reported to grow in some parts of Pampa river bank (Kerala State Biodiversity Board, 2018). Its ecological role in riparian zones has also been supported by broader riparian research, where deep-rooted trees contribute to long-term bank strength and resistance to hydraulic shear stress (Naiman & Décamps, 1997). Although several other riparian species in Kerala, such as *Ficus* *racemosa* L., *Ochreinauclea missionis* (Wall. Ex G.Don) Ridsd., and *Neolamarckia cadamba* (Roxb.) Bosser are important for bank protection, they primarily rely on lateral or buttressed root systems rather than deep taproots (Mohanan & Sivadasan, 2002; Mani, 2018). Without deep tree roots to act as "living nails," the bank's internal friction is too low to withstand the weight of saturated soil during monsoons. The lack of bioengineering in this ceremonial and culturally significant area represents a failure to protect biocultural heritage.

Table 1: Dominant Riparian Flora, Ecological Function and Threat

Sl. No.	Species Name & Family	Soil Stability & Ecological Functions	Impacts/Threats to Riverbanks
1	*Melochia corchorifolia* L. (Malvaceae)	Fibrous roots bind topsoil; pioneers on disturbed ground.	Ruderal; dominates exposed margins after disturbance
2	*Talinum fruticosum* (L.) Juss (Talinaceae)	Succulent habit improves moisture; prevents surface erosion.	Non-native species, can be invasive
3	*Asystasia gangetica* (L.) T. Anderson (Acanthaceae)	Creeping stems bind loose soil; aids slope stability.	Invasive risk; suppresses native riparian vegetation
4	*Passiflora foetida* L. (Passifloraceae)	Extensive climber network reduces direct soil exposure.	Highly invasive; smothers shrubs and alters bank structure
5	*Alternanthera sessilis* (L.) DC (Amaranthaceae)	Excellent binder in wetlands; reduces seasonal flood erosion.	Excessive growth may clog narrow drainage waterways, Invasive Alien Species
6	*Combretum indicum* (L.) De Filipps (Combretaceae)	Woody climber; roots stabilize semi-riparian zones.	Minimal; primarily an ornamental escapee, popularly grown as Rangoon creeper
7	*Ageratum conyzoides* L. (Asteraceae)	Rapidly covers bare soil; provides short-term erosion control.	Highly invasive; alters soil chemistry and native flora
8	*Eclipta alba* (L.) Hassk (Asteraceae)	Dense mat formation stabilizes moist riverbank soils.	No serious issues; ecologically beneficial stabilizer, medicinal plant
9	*Mimosa diplotricha* C. Wright (Fabaceae)	Nitrogen fixation improves nutrient-depleted soil.	Severely invasive; thorny thickets obstruct flow and access.
10	*Cleome rutidosperma* DC. (Cleomaceae)	Light root system; provides minor surface erosion control.	Common in disturbed riparian substrates
11	*Amaranthus spinosus* L. (Amaranthaceae)	Rapid growth covers exposed soil following disturbances.	Aggressive growth nature, competes with native riparian species
12	*Cleome viscosa* L. (Cleomaceae)	Pioneer species; provides temporary/seasonal soil cover.	Negligible geomorphological impact

CRITICAL THREATS AND ECO-GEOMORPHIC CONCERNS

The Pampa River is currently locked in a degenerative cycle of geomorphic decay and ecological homogenization. The study identifies three primary pillars of concern that threaten the long-term viability of the riverine corridor:

1. Structural Vulnerability and Bank Instability

The most immediate threat found in the study area is the systemic failure of the riverbank's mechanical integrity. The study found a total absence of deep-rooted riparian tree species such as *T. arjuna*, *F. racemosa*, *O. missionis*, and *N. cadamba*, which historically served as the primary anchor for the soil matrix. Current vegetation is dominated by shallow-rooted herbaceous plants that provide only superficial ground cover. During high-magnitude flood events, these plants offer zero resistance to mass soil movement. This leads to severe bank scour and slumping, resulting in irreversible land loss and the widening of the river channel at the expense of terrestrial biodiversity.

2. Anthropogenic Extractive Violence: Sand Mining

Instream sand mining is the fundamental driver of ecological collapse at the Keezhukara and Maramon sites. The Physical Shift: Unselective extraction removes the coarse, protective "armour layer" of the riverbed. As noted by Paul and George (2010), this lowering of the riverbed forces a corresponding drop in the local groundwater table, weakening the banks and threatening the water security of the Elanthoor community.

3. Invasive Dominance

Sedges and grasses are fundamental structural components of the Pamba riparian ecosystem, particularly abundant during the post-monsoon drawdown phase when the sandy riverbed is exposed (Thomas & Raju Thomas, 2023). Species such as *Cyperus rotundus, Torenia bicolor, Ludwigia octovalvis, and Hypolytrum nemorum* are the common herbs reported from Pampa riverbed (Thomas & Raju, 2023). The present study could not find any of these plants. Physical disturbances have created vacant, unstable niches that are now occupied by aggressive invasive species. Species like *Mimosa diplotricha*, *Passiflora foetida*, and *Asystasia gangetica* have achieved high abundance, suppressing the recruitment of native plants. According to Bhatt *et al*. (2012), these invaders are highly adaptive to disturbed environments but lack the soil-binding capacity of native flora. They "halt" natural ecological succession, leaving the ecosystem brittle and unable to recover from climate-induced stress.

As highlighted by the Kerala State Biodiversity Board (2013), the transition from a tree-anchored riparian zone to a herb-dominated margin is a "tipping point." The loss of biodiversity is not just a loss of species; it is the loss of the river's physical defence system. Without immediate intervention to halt mining and implement bioengineering, the Pampa River will continue its shift toward an unstable, functionally deficient system that can no longer support the local socio-ecological framework.

THE CLIMATE JUSTICE FRAMEWORK FOR RESTORATION

Climate Justice demands that we restore the Pampa not through concrete walls (hard engineering), which often shift erosion downstream, but through Nature-Based Solutions (NBS) that empower the ecosystem and the community.

The empirical evidence from this study underscores the pivotal role of Nature-Based Solutions in recovering ecological stability within the Elanthoor reach. At high-vulnerability sites such as Keezhukara and Maramon, the immediate implementation of stringent regulatory frameworks for sand mining is a prerequisite for restoration. Systematic unregulated extraction has precipitated the accumulation of fine-grained slurry sediments, which provide a fertile substrate for the explosive proliferation of aggressive ruderal species, notably Bull Grass (*Muhlenbergia richardsonis)*. This dense vegetative sprawl acts as a physical barrier within the active channel, obstructing natural discharge and significantly altering the river's hydrological dynamics.

This "slurry-invasive nexus" has fundamentally shifted the floristic composition toward opportunistic weeds, which outcompete and suppress native riparian stabilizers. The resulting degradation of the riverbank's structural integrity necessitates urgent bioengineering interventions. *Vetiveria zizanioides* (syn. *Chrysopogon zizanioides*) is globally recognized for its exceptionally deep, dense, and vertically oriented fibrous root system, which can penetrate several meters and substantially increase soil shear strength, thereby reducing erosion and shallow mass failure (Truong *et al.*, 2008). Bamboo (e.g., *Bambusa* spp.) and riparian reeds such as *Ochlandra*, although ecologically valuable, exhibit limitations under dynamic fluvial conditions. Bamboo typically develops shallow, laterally spreading rhizomes, which provide surface cohesion but limited deep anchorage. Field observations and biomechanical analyses show that, as bank toe erosion progresses and soils become saturated, bamboo clumps often tilt or bend toward the river channel, reflecting insufficient resistance to undercutting and increased bending stress (Donald and Sotir, 1996; Alexia *et al.*, 2014). Similarly, *Ochlandra* species form dense root mats that stabilize surface sediments but are generally less effective in preventing deep-seated bank failure. However, studies in fluvial geomorphology and eco-engineering demonstrate that multi-strata vegetation systems—combining grasses, shrubs, and trees—provide superior and more durable bank stabilization by integrating surface protection with deep mechanical reinforcement and hydraulic roughness (Abernethy and Rutherfurd, 2001; Pollen-Bankhead and Simon, 2010).

Current management strategies for riparian vegetation often lack the precision required for long-term ecological stability, necessitating a transition toward a structured, scientific framework. This approach prioritizes the targeted eradication of high-threat invasives, and simultaneous recruitment of native riparian trees to rebuild the vertical canopy and restore the deep-structural reinforcement vital for riverbank resilience. The most scientifically robust strategy for the Pampa basin is a hybrid bioengineering approach, where vetiver is deployed for rapid, deep-rooted stabilization of critically unstable banks, while native trees *Mitragyna parvifolia, Hydnocarpus* spp., and Willows (*Salix* spp.), along with endemic reed bamboos like *Ochlandra* are concurrently established to restore ecological integrity and ensure sustained resistance to fluvial stress under variable hydrological regimes (Donald and Sotir, 1996; Alexia *et al*., 2014).

4. CONCLUSION

The investigation of the Pampa Riverbed within the Elanthoor reach confirms a systemic collapse of traditional riparian defences. The current floristic landscape has transitioned into a functionally deficient state where shallow-rooted stabilizers and aggressive invasive taxa provide a deceptive "green cover" that lacks the biomechanical depth to resist mass-wasting. This study underscores that biodiversity loss in this corridor is not merely a biological concern but a structural one; the displacement of deep-rooted native timber has left the riverine socio-ecosystem defenceless against climate-induced hydrological extremes.

Restoring the Pampa's resilience necessitates a transition from reactive "counter-measures" to a proactive, dual-phased restoration framework. First, the geomorphic "extractive violence" of instream sand mining must be halted through stringent policy enforcement to allow for the recovery of the river's equilibrium profile. Second, the ecological "green desert" must be rehabilitated using science-backed Nature-Based Solutions (NBS). The strategic deployment of Vetiver bioengineering, combined with the selective eradication of high-threat invasives like *Mimosa diplotricha* and *Passiflora foetida*, offers a viable pathway for stabilizing bank architecture. By localizing successful restoration paradigms—such as the community-led models of Malappuram and Kottayam in Kerala—the Pampa River can be reclaimed as a stable, biodiverse, and climate-resilient fluvial commons.

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Conflict of Interest Statement

The authors declare no conflict of interest.

Author Contributions

Author 1: Conceptualisation, field study, data collection, analysis, manuscript preparation.

Author 2: Supervision, review, interpretation, and manuscript editing.

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