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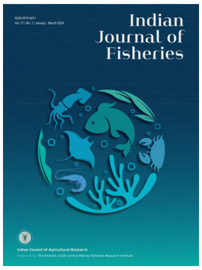
Ecological sustainability assessment of the Netravathi-Gurupur estuarine ecosystem in south-west India: Implications for fisheries management

Preetha Panikkar[1], M. Feroz Khan[1], S. Sibina Mol[1], M. E. Vijaykumar[1], Sonalika Sahoo[1], Ajoy Saha[2], S. K. Samanta[2*] and B. K. Das[2]

[1]Regional Centre of ICAR-Central Inland Fisheries Research Institute, Hessaraghatta, Bangalore-560 089, Karnataka, India
[2]ICAR-Central Inland Fisheries Research Institute, Barrackpore-700 120, Kolkata, India

Abstract

Tropical estuaries are dynamic, productive ecosystems with rich biodiversity, typically influenced by anthropogenic activities. The ecological integrity of the Netravathi Gurupur estuarine ecosystem in the south-western coast of India is is under increasing pressure from habitat degradation and pollution. Given the estuary's significant economic importance coupled with scarce information regarding its ecological status and trophic interactions, an assessment of the ecological sustainability focusing on fish production was conducted using the Ecopath modeling approach. The model comprised 28 functional groups spanning primary producers (trophic level, TL 1.0) to top predators (TL 3.9), depicting a trophic structure predominantly regulated by bottom-up control. Most fish groups exhibited relatively low ecotrophic efficiencies (EE), suggesting limited exploitation pressure and substantial energy dissipation within the system. In contrast, crustaceans emerged as the most intensively exploited groups, with crabs (EE=0.952), shrimps and prawns (EE=0.819) approaching full utilisation, indicating strong fishing pressure at lower trophic levels. System-level indices indicated high total system throughput (22,655.12 t km^{-2} yr^{1}), reflecting high ecosystem productivity, but low ascendancy (38.33%), consistent with a developing ecosystem that retains resilience but remains sensitive to continued anthropogenic disturbances. These metrics provide a quantitative basis for evaluating ecological sustainability by identifying both vulnerable functional groups and critical trophic pathways requiring management attention. The findings facilitate ecosystem-based management recommendations, such as regulating crustacean harvests, protecting nursery habitats, and regulating pollutant inputs, thereby promoting sustainable resource use while maintaining ecosystem structure and services that support local fisheries and livelihoods.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*Correspondence e-mail:
samantacifri@gmail.com

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Introduction

Estuaries are among the most productive and ecologically significant aquatic ecosystems. Their unique properties and biological composition support a diverse array of organisms. However, estuaries are reportedly the most degraded ecosystems (Chilton *et al.*, 2021) and are highly vulnerable to human-induced pressures. Because regions near estuaries are preferred locations for human settlements, increasing anthropogenic impacts intensify environmental risks to these ecosystems (Valiela *et al.*, 2001). Furthermore, rising sea levels and shifting precipitation patterns alter the volume and seasonality of freshwater flowing into estuaries, which can affect water circulation and fisheries (Worm, 2006).

A recent review of the estuarine fisheries in India (Swetha *et al.*, 2024) reveals that, although numerous studies have documented the composition and community structure of the estuarine fish fauna, research on ecosystem structure and trophic interactions remains scarce in this area. A proper understanding of ecosystem structure and the ecological interactions between functional groups is necessary to estimate anthropogenic and environmental impacts on the ecosystem and to formulate management protocols (Han *et al.,* 2016). One of the most effective approaches for assessing ecosystem health is ecological modeling (Abobi, 2024), which can be done effectively using Ecopath (Christensen and Pauly, 1993; Christensen *et al.,* 2005). Ecopath is a modeling application that characterises the transfer of biomass and energy within different components of the ecosystem. The resulting ecological indices provide quantitative measures of the health of the ecosystem and evaluate the effects of human impacts on fishery resources and biodiversity (Christensen *et al.* 2005; Watson *et al.,* 2020). Fish diversity and community structure in estuaries are shaped by geographic location, prevailing ecological conditions, ecosystem health, and sustainability. Therefore, understanding fish community structure and trophic functioning is essential for evaluating the ecological status and biological features of estuarine ecosystems.

In India, estuarine fishing is a vital subsistence activity that contributes significantly to the rural economy. The Netravathi–Gurupur (NG) Estuary, located in Karnataka along the south-west coast of India, is a biologically productive system that supports an active estuarine fishery, providing livelihood and nutritional security to local communities. Multiple studies have documented the estuary's ecological and fishery resources, including finfish and shellfish diversity highlighting its role as a nursery and recruitment ground for both crustaceans and finfish (Joseph *et al.* 1987; Deepashree *et al.,* 2017), plankton distribution (Gowda *et al.,* 2002; Ratheesh *et al*., 2020), shoreline changes (Bhat, 1995) , microbiological characteristics (Kadmane *et al*., 2018; Nasnodkar and Nayak, 2019) as well as water and sediment quality parameters such as trace metals and pesticide pollution (Saha *et al.,* 2023, 2024; Sahoo *et al.,* 2024). Despite this extensive body of work, a comprehensive ecosystem-based assessment integrating fisheries data with ecological network analysis has been lacking. To address this gap, the present investigation was undertaken in the NG Estuary. The specific objectives of the study were to: define the trophic interactions among the functional groups; evaluate ecosystem resilience and sustainability under prevailing anthropogenic pressures, while identifying critical trophic pathways that may constrain future productivity; provide ecosystem-based management insights to support sustainable fisheries and long-term livelihood security of dependent communities. The findings are expected to provide a scientific basis for ecosystem-based management strategies, thereby supporting sustainable resource use and safeguarding the livelihoods of dependent rural fishing communities.

Materials and methods

Description of the estuary

The Netravathi-Gurupur (NG) estuarine system (Fig. 1) is a coastal plain estuary located in Karnataka, south-western India. This drowned river valley estuary was formed by the confluence of the Netravathi River (148 km long) and the Gurupur River (87 km long), both of which originate in the Sahyadri Hills of the Western Ghats (Ratheesh *et al.,* 2020). The Netravathi River flows almost directly west into the Arabian Sea, while the Gurupur River runs parallel to the coast, joining the Netravathi from the north shortly before they meet the sea.

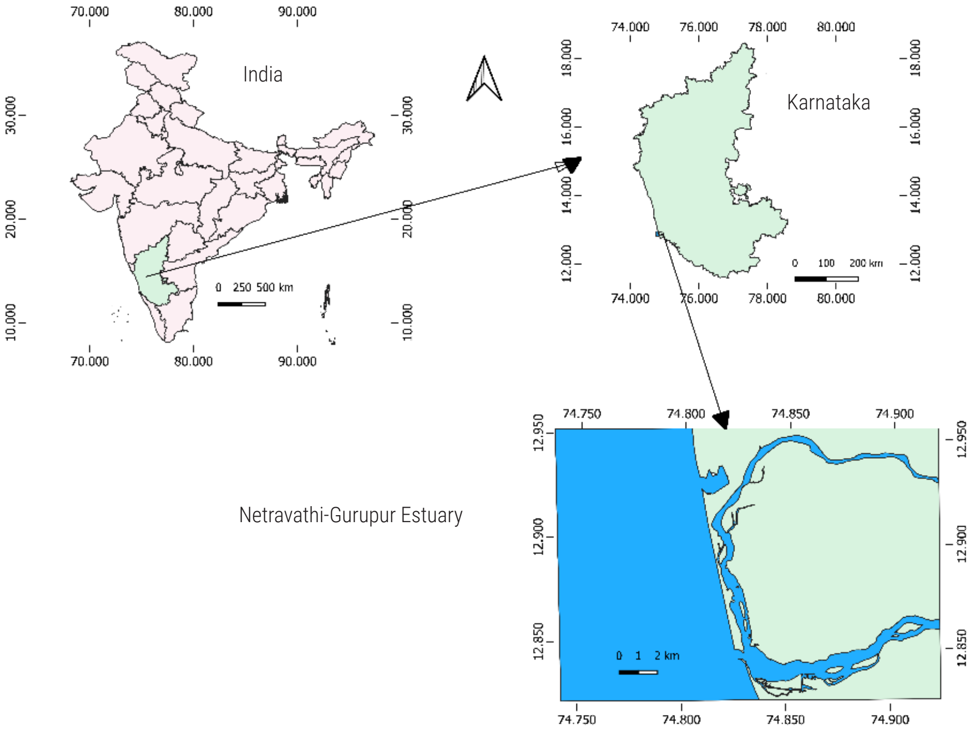

Fig. 1. The map of Netravathi-Gurupur Estuary, Mangalore, Karnataka, India

Model input parameters

For the biomass estimation of fish groups, monthly sampling at the fish landing centres around NG Estuary was carried out during 2021-22. The data on fish catch, length and weight of fish were recorded from the landings to ensure the representation of all the species caught within the estuary. The length frequency data for various fish species were used to estimate the mortality rates. The total mortality (Z=P/B) was estimated using the Pauly's empirical equation available in FiSAT II software. The fish catch and mortality rates were used to estimate the biomass for each functional group.

Phytoplankton and zooplankton samples were collected by filtering 100 l of water through a No. 25 bolting silk plankton net. The collection was done in the early hours of the day between 7.00 hrs and 9.00 hrs to minimise the influence of diurnal variation on the plankton composition. Samples were preserved in 4% v/v formalin solution in airtight containers and subsequently identified following Needham and Needham (1962). Phytoplankton biomass was calculated using the chlorophyll method (Abdul and Adekoya, 2016) and converted to mg m^{-2} by multiplying the chlorophyll value by the euphotic depth (m). Zooplankton biomass was estimated by the volumetric method (Goswami, 2004). The biomass of benthos in the estuary was determined from the data collected using Ekman grab sampling and the biomass of aquatic insects was estimated by the method outlined by Cressa (1999). Macrophyte standing biomass for the study period was obtained through direct harvest using quadrants, following Downing and Anderson (1985) and detritus biomass was estimated using an empirical equation, based on primary production and euphotic depth (Christensen and Pauly, 1993). The biomass estimates of aquatic birds was derived from reports on ecologically similar estuarine ecosystems (Sreekanth *et al.*, 2020; Kiranya *et al.*, 2024). Production to biomass ratios (P/B) of phytoplankton and benthos were collected from published studies conducted in other similar habitats (Mohamed *et al.*, 2008; Sreekanth *et al.*, 2020, Kiranya *et al.*, 2024) and also calculated using the regression models in the EwE software. The consumption to biomass (Q/B) ratio for fish was estimated using the empirical equation provided by Palomares and Pauly (1998). The diet matrix was developed from the gut content analyses of fish groups using standard protocols (Chipps and Garvey, 2007), using data generated from our field study and supplemented with data from FishBase (Froese and Pauly, 2026).

Ecological grouping

The ecological groups within the NG estuarine ecosystem were identified and categorised to represent the food-web structure, as presented in Table 1. Based on the criteria established by Christensen *et al.* (2005), these groups can be comprised of either a single species or multiple species that share similar life history characteristics, dietary habits, and taxonomic or ecological relationships. The living resources of the ecosystem were categorised into 27 distinct ecological groups which encompass, aquatic birds functioning as the top predator, 18 fish groups, five invertebrates, zoobenthos, zooplankton, phytoplankton and one non-living group (detritus).

Modelling approach

The NG model was constructed employing Ecopath with Ecosim software (ver. 6.6) which delineates the flux of biomass and energy

Table 1. Ecological groups defined for Netravathi-Gurupur Estuary

Sl No.	Ecological group	Abbreviation	Group description
1	Aquatic birds	AB	*Alcedo atthis, Halcyon smyrnensis, Ardeola striata, Casmerodius albus, Phalacrocorax niger*
2	Catfishes	CF	*Arius arius, A. jella, Horabagrus brachysoma*
3	Eels	EL	*Muraenesox* sp.
4	Belonids	BL	*Strongylura strongylura, S. leiura, Tylosurus crocodilus*
5	Silver bellies	SB	*Leiognathus equulus*
6	Breams	BR	*Acanthopagrus berda, A. latus,*
7	Glassy perchlets	GP	*Ambassis sp*
8	Carangids	CG	*Alepes djedaba, caranx ignobilis, C. sexfasciatus, Trachinotus baillonii, Parastromateus niger*
9	Clupeids	CL	*Nematolosa nasus, Opisthopterus tardoore, Sardinella fimbriata, Escualosa thoracata*
10	*Sillago sihama*	SS	Silver whiting
11	Anchovies	AC	*Stolephorus commersonii*
12	Lethrinids	LT	*Lethrinus nebulosus*
13	Flat fishes and flatheads	FF	*Bothus myriaster, Cynoglossus arel, C. puncticeps, Euryglossa orientalis, Synaptura commersonni, Paralichthodes algoensis, Platycephalus indicus*
14	Scombrids	SR	*Rastrelliger kanagurta, Scomberomorus commerson*
15	Snappers	SN	*Lutjanus argentimaculatus, L. russelli*
16	Mullets	ML	*Mugil cephalus*, *Planiliza parsia*
17	Gerridae	GR	*Gerres erythromus, G. filamentosus*
18	Carps and barbs	CB	*Hypselobarbus kolus, Puntius sarana*
19	Cichlids	CC	*Etroplus suratensis*
20	Crabs	CR	*Charybdis lucifera, Portunus pelagicus, P. sanguinolentus,*
21	Mud crabs	MC	*Scylla serrata*
22	Shrimps and prawns	SP	*Penaeus indicus, P. monodon, Metapenaeus monoceros, Macrobrachium rosenbergii*
23	Molluscs	MO	*Meretrix meretrix, M. casta*
24	Aquatic insects	AI	*Halobates* sp. *Micronecta* sp., *Sigara* sp., *Diplonychus* sp.
25	Zoobenthos	ZB	Chironomid larvae, Oligochaetes. Gastropods, Bivalves
26	Zooplankton	ZP	*Calanus* spp., *Oithona* spp, *crustacean* larvae
27	Phytoplankton	PP	*Oscillatoria* spp., *Skeletonema* spp., *Chaetoceros* spp., *Melosira* spp., *Protococcus* spp.
28	Detritus	DT	

through the ecological groups of the estuary. The inherent Ecopath methodology yields a static mass balanced representation of the ecosystem's resources and their interactions (Christensen and Walters, 2004; Heymans *et al*., 2016). The model was successfully balanced to represent the 2021–2022 period and incorporated 28 discrete ecological groups (Table 1). Parametrisation of the model was achieved using input data for biomass (B), production to biomass ratio (P/B), and consumption to biomass ratio (Q/B), with ecotrophic efficiency (EE) derived internally by the model (Table 2).

A comprehensive network flow diagram representing all energy flows and biomass estimates was generated. The transfer efficiency and flow to detritus among various trophic levels were estimated from the Lindemann spine flow chart (Lindeman, 1942). Niche overlap among various functional groups was quantified using the modified Pianka's overlap index (Pianka, 1973), a function available in the EwE module (Christensen *et al.,* 2008). Finally, the mixed trophic impact routine in the Ecopath was used to characterise the competitive and predatory dynamics between the defined ecological groups (Ulanowicz and Puccia, 1990, Christensen *et al.,* 2008).

To assess the resilience of the NG ecosystem to anthropogenic impacts, several key ecological indices were applied, including the omnivory index (OI), cycling index (CI), and connectance index (Panikkar and Khan, 2008; Xu *et al*., 2011; Selleslagh *et al.,* 2012). These metrics were selected as reliable indicators of aquatic ecosystem health (000) because they effectively integrate the effects of biomass and energy changes across diverse environmental parameters. Additional indices used were ascendancy and overhead, which quantify the ecosystem's reserve energy and the extent of internal interactions.

Ecosystem stability and maturity were evaluated using various system metrics and network indices based on the framework proposed by Odum (1969). The system's total production is the sum of its primary and secondary production. The primary production to respiration ratio (PP/R) serves as a maturity indicator a value of 1 suggests a mature system, while a value above 1.0 indicates lower resilience to perturbations. Total system throughput (TST) is defined as the sum of total consumption (TC), total exports (TE), flows to detritus (SD), and total respiration (RF). The ratio of total biomass to total system throughput (TB/TST) represents the amount of reserve energy relative to biomass; with higher values signifying mature ecosystems (Christensen et al., 2000).

Results and discussion

Model quality and reliability

A mass-balanced Ecopath model systematically describes complex interactions within an ecosystem. The associated tools provide insights into the system's health, trophic relationships, and energy flows. The model developed for the NG Estuary successfully balanced all 28 functional groups, reflecting internal consistency in production, consumption, and transfer flows. Model was assessed using the pedigree index, which evaluates input data quality and parameter uncertainty (Heymans *et al*., 2016). The NG model yielded a pedigree index of 0.51, exceeding the reported global average of 0.41 for Ecopath-based ecosystem models (Mohamed *et al*., 2008; Heymans *et al.,* 2016; Sandra *et al.,* 2023). This comparatively higher value indicates moderate-to-high confidence in the input data and parameterisation, suggesting that the model outputs are robust and suitable for ecological interpretation and management applications. The model's measure of fit (ε=2.95) further confirms satisfactory convergence during balancing, indicating minimal residual inconsistencies among biomass, production (P/B), and consumption (Q/B) parameters. Together, these diagnostics demonstrate that the NG model provides a reliable representation of ecosystem structure and trophic dynamics.

Trophic structure and functional organisation

The input and output parameters of the mass balanced ecological model of NG Estuary are presented in Table 2, along with the estimated trophic levels (TL) for each functional group. The TL values for the various ecological groups exhibit a range from 1.0, encompassing primary producers such as phytoplankton and detritus, up to 3.902 for aquatic birds indicating a typical food chain of tropical estuarine ecosystem. Among finfish groups, Gerridae exhibited the highest trophic level followed by breams, reflecting their carnivorous feeding habits and reliance on invertebrate prey. In contrast, comparatively lower TLs were recorded for eels, lethrinids, belonids, silver bellies, and clupeids consistent with omnivorous or planktivorous feeding strategies. Most ecological groups were concentrated around TL3, with TL2 comprising primarily invertebrates and lower level consumers, forming the second largest category. This clustering around intermediate trophic levels suggests a food web dominated by mid-level consumers and supports the inference of bottom-up regulation, where energy availability from primary producers and detrital pathways governs higher trophic levels. The dominance of

Table 2. Basic estimates of ecological parameters of Netravathi-Gurupur Estuary

Ecological group	Trophic level	Biomass (t km^{-2})	Production / Biomass (yr^{-1})	Ecotrophic efficiency
AB	3.90	0.002	0.153	0
CF	3.32	11.300	2.000	0.160
EL	2.18	2.000	3.800	0.500
BL	2.38	5.598	3.000	0.149
SB	2.39	2.705	4.055	0.050
BR	3.50	0.779	3.000	0.813
GP	3.02	2.507	4.000	0.170
CG	3.01	3.746	0.900	0.608
CL	2.48	17.64	1.800	0.173
SS	2.93	6.780	2.624	0.467
AC	3.09	16.13	3.756	0.088
LT	2.37	0.379	1.700	0.256
FF	3.13	2.900	3.918	0.286
SR	3.31	6.000	2.400	0.344
SN	2.98	0.273	1.400	0.209
ML	3.02	12.000	3.600	0.196
GR	3.83	1.283	2.932	0.771
CB	3.02	4.000	1.500	0.797
CC	2.52	6.536	1.315	0.298
CR	3.16	5.227	7.500	0.952
MC	3.08	15.21	3.700	0.263
SP	2.01	11.47	19.900	0.819
MO	3.00	6.000	15.140	0.278
AI	2.22	26.19	21.860	0.683
ZB	2.00	13.310	19.130	0.724
ZP	2.00	29.49	34.780	0.730
PP	1.00	72.380	117.700	0.996
DT	1.00	300.000	-	0.307

TL 3 groups in the NG Estuary also indicates a substantial trophic redundancy which may enhance system stability by distributing energy across multiple consumer pathways. Such structural characteristics are typical of productive estuarine ecosystems, where detritus-based energy flows and plankton productivity serve as primary drivers of secondary production. Comparable patterns have been reported in other Indian estuarine and coastal systems. In the Zuari Estuary, most fish and invertebrate groups clustered at TL 2 and 3, reflecting moderate exploitation of higher TLs and strong dependency on basal production (Sreekanth *et al.,* 2020). Similarly, the Ulhas River Estuary exhibited a trophic distribution dominated by mid-level carnivores, with apex predators contributing relatively less to total biomass (Lal *et al*., 2021). Similar trophic patterns have been reported in other productive tropical estuarine systems, such as Lake Kivu (Villanueva *et al.*, 2008) and the Gulf of California (Pauly *et al.,* 1998), where functional groups were predominantly concentrated at TL 2 and 3, reflecting high detrital input and primary productivity. Collectively, these findings corroborate the bottom-up control mechanism, highlighting that energy availability from primary producers and detritus largely governs the structure and stability of estuarine food webs. The trophic structure reflects efficient energy transfer but also suggests potential vulnerability if lower TLs are disrupted by stressors such as pollution, eutrophication or overexploitation. The strong representation of intermediate trophic groups indicates active secondary production, supporting the estuary's fishery potential.

Ecological pathway and system implications

Ecotrophic efficiency (EE) values for all ecological groups were below unity, consistent with the fundamental ecological principle that only a fraction of production at one trophic level is transferred to higher levels. The remaining production is exported, respired, or incorporated into detrital pools. Aquatic birds, which function as apex predators within the estuarine ecosystem, exhibited an EE of zero because no direct predation pressure was observed on this group. Among the invertebrates, crabs recorded the highest EE value (0.952), followed by shrimps and prawns (0.819), indicating intense exploitation and high predation pressure. These elevated EE values suggest that crustaceans represent critical trophic nodes subjected to strong fishery-driven removal. A significant grazing pressure by planktivores on phytoplankton (EE=0.996) highlighting the abundance and ecological dominance of planktivorous groups within the estuarine food web. Similar exploitation and grazing patterns have been documented from south-west Indian coastal ecosystems (Vivekanandan *et al*., 2003; Mohamed *et al.,* 2008) and the Ulhas River Estuary (Lal *et al*., 2021). This finding suggests comparable trophic structuring across western Indian coastal systems where strong phytoplankton–planktivore coupling reflects high productivity and rapid energy turnover. Within the finfish assemblage, breams, carps, barbs, and silver biddies were identified as highly exploited groups. In contrast, silver bellies, anchovies, belonids, catfishes and glassy perchlets exhibited lower exploitation intensity indicating substantial biomass reserves within the ecosystem (Table 2). The trophic flow structure (Fig. 2) further illustrates the predominance of mid-trophic-level energy transfer, reinforcing the bottom-up regulatory pattern inferred from trophic level distribution.

The low EE value for detritus in the NG estuary indicates that only a small proportion of detrital biomass was utilised within the system, with a substantial fraction likely settling into the sediment. Such patterns are typical of tropical estuaries where organic matter accumulation exceeds consumer assimilation capacity. Similar

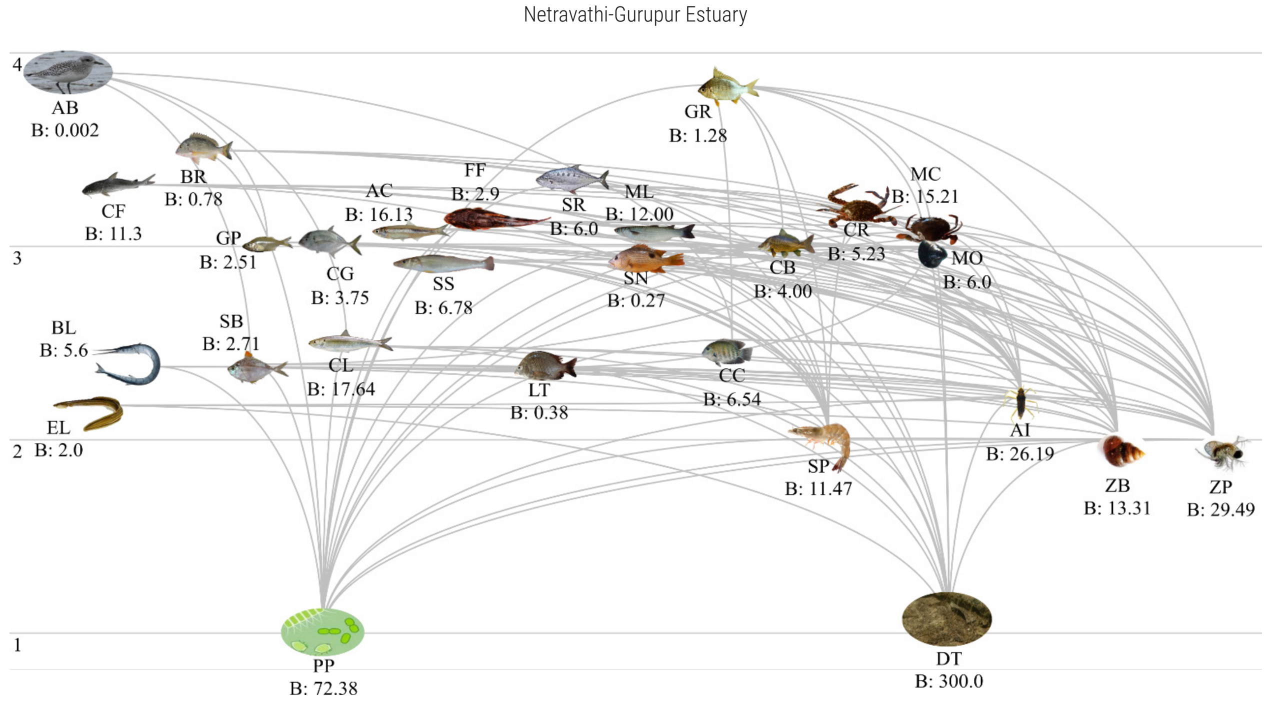

Fig. 2. Ecopath flow diagram depicting the trophic structure of the Netravathi-Gurupur Estuary

low detritus utilisation has been reported from the south-west coast of India (Vivekanandan *et al.,* 2003; Mohamed *et al*., 2008; Sreekanth *et al*., 2020; Sandra *et al*., 2023) when compared to the east coast of India (Dutta *et al*., 2017; Das *et al*., 2018; Mukherjee *et al.,* 2019). Comparable observations were made in Lake Kivu, where a very low detritus EE (0.079) indicated substantial organic matter sedimentation in deeper zones (Villanueva *et al.,* 2008). Low detrital utilisation may indicate accumulation of organic matter within sediments, which under sustained anthropogenic nutrient loading could enhance the risk of eutrophication and hypoxic events. From an environmental management perspective, monitoring detrital accumulation and nutrient inflows is essential to prevent deterioration of water quality and maintain ecological balance within the estuarine ecosystem.

Trophic interactions

The prey-predator niche overlap plot (Fig. 3) revealed pronounced resource competition between silverbellies and clupeids, which exhibited the highest overlap index. This indicates substantial dietary similarity and potential competitive interactions under conditions of resource limitation. Conversely, glassy perchlets and cichlids demonstrated the least overlap, indicating divergent food preferences and reduced inter-specific competition. Interestingly, although clupeids and cichlids differed in overall trophic positioning, they demonstrated a high prey overlap, suggesting convergence in dietary composition despite differences in predator assemblages. Such redundancy can enhance ecosystem stability by distributing grazing pressure across multiple taxa, buffering the food web against population fluctuations. Comparable patterns are reported in other estuarine systems. Studies from Zuari Estuary (Sreekanth *et al.,* 2020) and Ulhas River Estuary (Lal *et al*., 2021) documented similar dietary convergence among mid-trophic finfish, facilitating resource partitioning and reducing competitive exclusion. Globally, in Lake Kivu (Villanueva *et al.,* 2008) and the Gulf of California (Pauly *et al.,* 1998), mid-level planktivorous fishes exhibited partial dietary convergence, contributing to trophic redundancy and ecosystem stability under seasonal or nutrient-driven fluctuations. These findings collectively indicate that functional redundancy, prey overlap, and selective exploitation of lower and mid-level consumers are key stabilising features of the NG Estuary. Maintaining mid-level consumer populations and basal energy availability is crucial for sustaining ecosystem resilience and fishery productivity.

The Lindeman spine analysis (Fig. 4) revealed the presence of both a grazing food chain and a detrital food web, comprising six distinct trophic levels. The model estimated a transfer efficiency of 12.89% from primary producers and 14.41% from detritus resulting in a system wide mean transfer efficiency of 13.22% (Table 3). These values reflect the proportion of energy transferred between

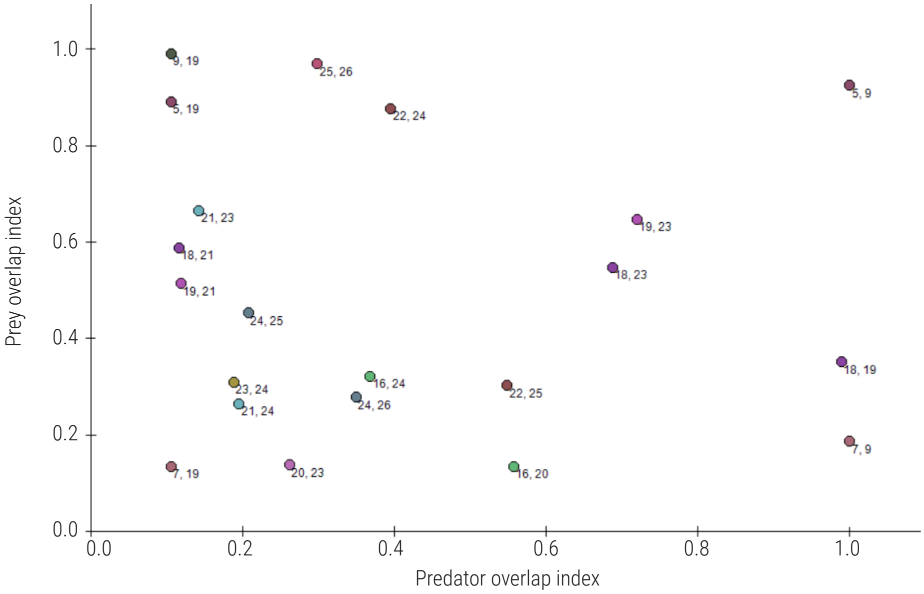

Fig. 3. Niche overlap among preys and predators in Netravathi-Gurupur Estuary

Table 3. Transfer efficiencies among various trophic levels in Netravathi-Gurupur Estuary

Source/Trophic level	II	III	IV	V	VI
Producer	11.860	15.870	11.390	6.182	5.321
Detritus	44.630	9.965	6.722	5.431	
All flows	15.190	14.120	10.760	6.170	5.321

From primary producers: 12.89%
From detritus: 14.41 %
Total: 13.22%

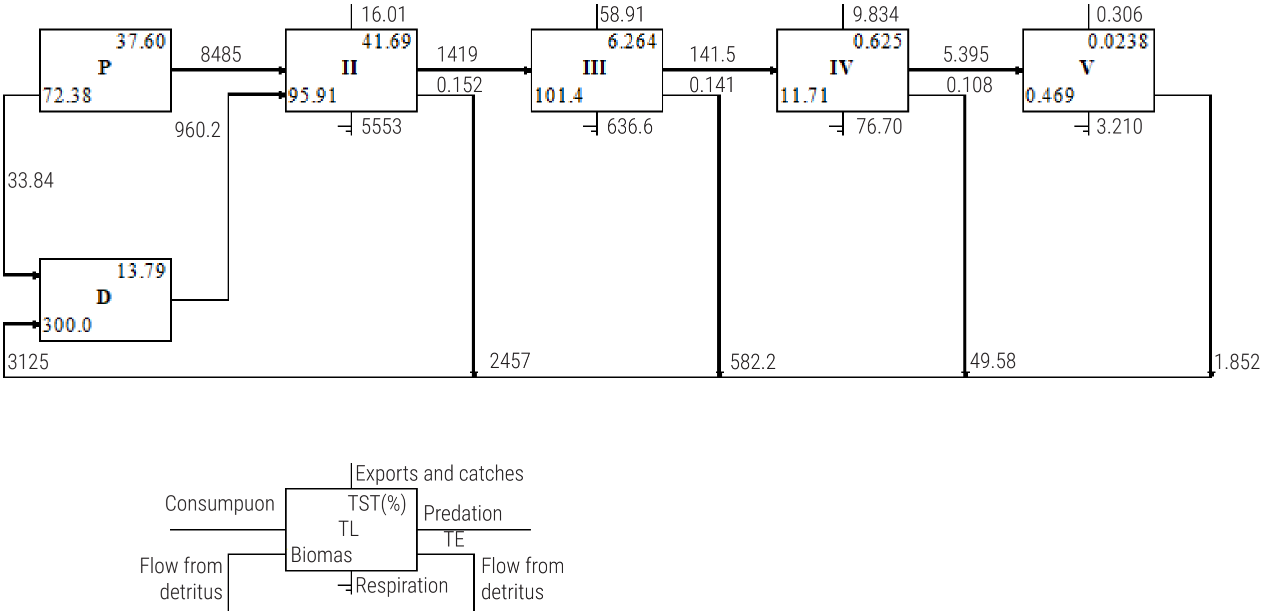

Fig. 4. Lindeman spine depicting trophic transfer efficiencies and energy flows in the Netravathi-Gurupur Estuary

successive trophic levels, a critical parameter for understanding ecosystem productivity and functioning. The slightly higher transfer efficiency from detritus (14.41%) compared to primary producers (12.89%) may indicate the significant role of detrital pathways in sustaining higher trophic levels in this estuary. Tropical estuarine and coastal ecosystems frequently show comparable trophic transfer dynamics, where detritus derived pathways contribute significantly to energy transfer. This pattern corroborates findings from Northern Bay of Bengal ecosystem (Dutta *et al.,* 2023) and Zuari Estuary (Sreekanth *et al.,* 2020) underscoring the role of detrital routes in supporting higher level consumers in tropical estuarine systems.

The mixed trophic impact (MTI) analysis is a quantitative approach for evaluating the effects of trophic interactions within an ecosystem (Ulanowicz and Puccia, 1990). The MTI, a form of sensitivity analysis (Christensen and Walters, 2004) indicated a positive impact of lower-level groups on most other ecological groups in NG Estuary (Fig. 5). This observation is consistent with findings reported by Lal *et al.* (2021) in another anthropogenically impacted estuary in India. Lower TL groups exert predominantly positive influences on most other ecological compartments, emphasising their foundational role in sustaining the estuarine food web. The MTI results reveal clear trophic cascading effects, where higher TL groups impose direct negative impacts on their prey but indirect positive effects on the prey's predators. Impact of fishing gear was quantified, with notable effects on key species groups. Top predators, mainly carnivorous fishes, such as catfishes, exert significant predation pressure on lower trophic fishes (Du *et al.*, 2015; Matich *et al.*, 2017). While catfishes negatively impact various fish groups, they are themselves negatively affected by fishing gear, particularly hook and line and traps. This dual pressure suggests that fishing may indirectly increase the biomass of lower trophic level fishes through trophic cascades.

Gillnets demonstrated strong negative impact on a range of species, such as clupeids (-0.58), anchovies (-0.57), lethrinids (-0.57), flatfishes (-0.6), and scombrids (-0.55). This outcome is likely due to the deployment of set gillnets designed for pelagic species and sweeping gill nets utilised for bottom-dwelling species within the estuary. Conversely, gill nets exerted positive impact on crabs (0.24), molluscs (0.18), and aquatic insects (0.32) possibly due to reduced predation pressure from fish declines. Other fishing gear impacts included negative effects of traps on cichlids (-0.23), cast nets on silverbellies (-0.31) and cichlids (-0.24),as well as hook and line primarily on eels (-0.25). Within the trophic interactions, scombrids (-0.39) and catfishes (-0.29) negatively impacted crab population, whereas glassy perchlets had a notable positive impact on aquatic birds indicating complex predator-prey dynamics. Among dominant commercial fishes, *Sillago sihama* showed positive influences from shrimps and prawns (0.143) and zoobenthos (0.298), but was negatively impacted by zooplankton (-0.160), crabs (-0.0791), and aquatic insects (-0.0758). Similarly, *Rastrelliger kanagurta* was positively impacted by zooplankton (0.370), phytoplankton (0.213), and shrimps and prawns (0.075), whereas aquatic insects (-0.139) and molluscs (-0.110) exerted negative impacts. Both *S. sihama* and carangids were adversely affected by gill net fishing, with MTI values of -0.43 and -0.20, respectively

Ecological indices

The ecosystem properties and indicators outlined in Table 4 of the NG model provide a comprehensive measure of the system's total material and energy flows. Key system metrics include, total system

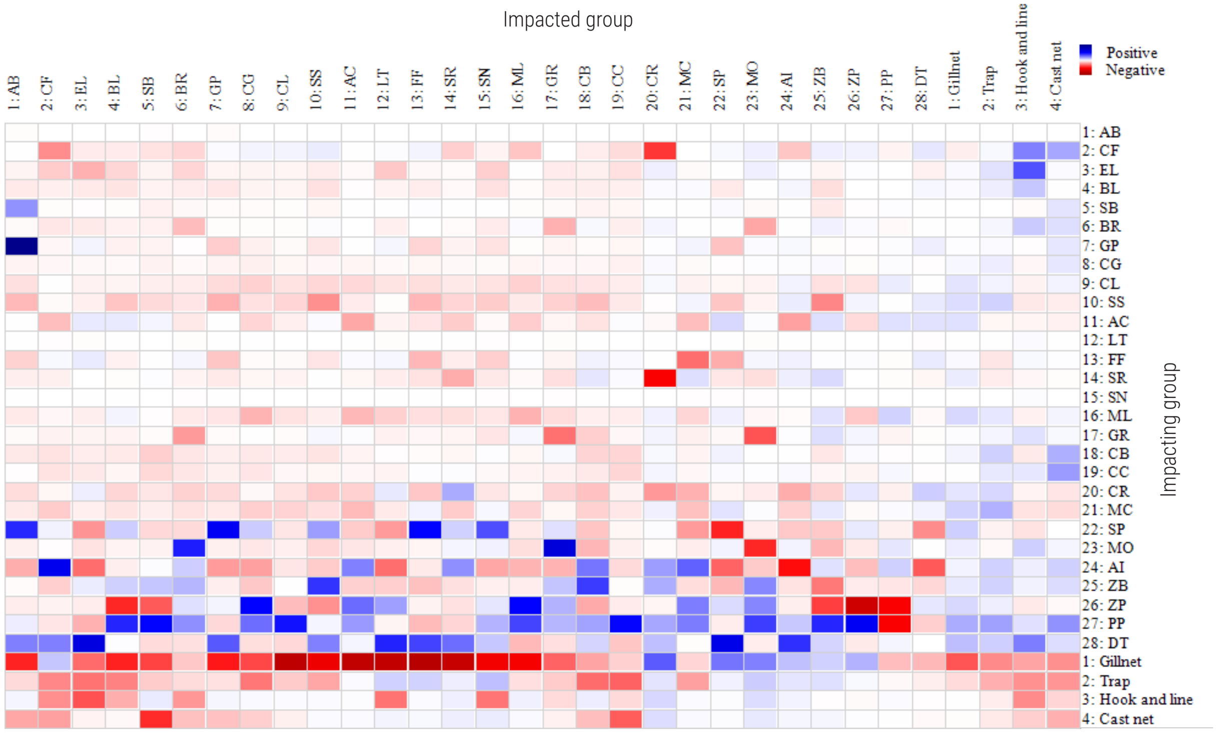

Fig. 5. Mixed trophic impact (MTI) plot of Netravathi-Gurupur Estuary depicting the interactions among various ecological groups

throughput (TST), flows to detritus, total consumption, respiratory flows, and total production. The TST for the ecosystem was calculated at 22655.12 t km^{-2} yr^{-1}. This throughput is apportioned as: consumption (48.61%), exports (9.93%), respiratory flows (27.67%) and flows to detritus (13.79%). This finding is comparable to that of the Zuari Estuary (23,333.9 t km^{-2}) on India's west coast (Sreekanth *et al.,* 2020). This high TST is likely due to the combined effects of freshwater inflow from the Netravathi and Gurupur rivers, along with nutrient inputs from domestic and industrial effluents and agricultural activities within the catchment area (Saha *et al.,* 2024). These findings align with observations in other coastal ecosystems (Abdul and Adekoya, 2016; Bella *et al.,* 2023), where elevated TST is similarly linked to nutrient loading from adjacent rivers. Water quality monitoring in the NG Estuary revealed elevated nutrient levels, with total phosphorus ranging from 0.09–0.18 ppm and phosphate 0.039–0.055 ppm, nitrate 0.046–0.065 ppm and silicate 6.2–11.0 ppm, respectively. Consequently, the estuary's trophic state index consistently indicated eutrophic conditions throughout the year, primarily driven by pollution from surrounding urban, industrial, and agricultural sources (Sahoo *et al.,* 2024).

Table 4. Ecological indices of Netravathi-Gurupur Estuary

Parameter	Value	Units
Sum of all consumption (TC)	11011.49	t km^{-2} yr^{-1}
Sum of all exports (TE)	2249.41	t km^{-2} yr^{-1}
Sum of all respiratory flows (RF)	6269.65	t km^{-2} yr^{-1}
Sum of all flows into detritus (SD)	3124.56	t km^{-2} yr^{-1}
Total system throughput (TST)	22655.12	t km^{-2} yr^{-1}
Sum of all production (TP)	11058.67	t km^{-2} yr^{-1}
Mean trophic level of the catch (MTL)	2.94	
Calculated total net primary production	8519.13	t km^{-2} yr^{-1}
Total primary production/Total respiration (TPP/TR)	1.36	
Net system production (NSP)	2249.47	t km^{-2} yr^{-1}
Total primary production/Total biomass (TPP/TB)	30.23	
Total biomass/Total throughput (TB/TST)	0.01	t km^{-2} yr^{-1}
Total biomass (excluding detritus)	281.83	t km^{-2}
Total catch	85.06	t km^{-2} yr^{-1}
Connectance index	0.17	
System omnivory index (SOI)	0.12	
Finn's cycling index (FCI)	2.79	% TST
Finn's mean path lengt (FML)	2.66	
Ecopath pedigree	0.51	
Measure of fit, t*	2.95	

The mean trophic level of fish landings from the NG Estuary was 2.93, indicating a fishery sustained by lower to middle trophic levels. This value aligns with regional findings, such as 2.72 reported in the Sunderbans (Das *et al*., 2018), 2.92 in the Zuari Estuary (Sreekanth *et al.,* 2020), and 3.01 in the Ulhas Estuary (Lal *et al.,* 2021). As noted by Pauly *et al*. (1998) a gradual decline in the TL of fish landings by 0.1% per decade underscores the utility of the mean TL as an indicator of ecosystem health and sustainability.

Indices denoting the ecosystem's maturity and structure yielded total primary production to total respiration (TPP/TR) and total primary production to total biomass (TPP/TB) ratios of 1.3588 and 30.2274, respectively. The connectance and system omnivory indices were 0.1674 and 0.1177, respectively. Analysis of the system's ascendancy (38.33%), which relates to maturity, system overhead (61.67%), and reserve energy (Ulanowicz, 1986) suggests low efficiency but strong resilience to environmental disturbances. These values are consistent with those reported from other anthropogenically stressed coastal ecosystems (Mohamed *et al*., 2008; Mukherjee *et al.*, 2019). The reduced efficiency of the NG Estuary can be attributed to stress from industrial effluents along its banks and agricultural runoff within the catchment. While the phosphorus pollution index in surface sediments confirm significant anthropogenic stress (Saha *et al.,* 2023), the overall water quality index suggests the aquatic system remains suitable for fisheries.

Management implications and recommendations

Based on the ecological assessment of the NG Estuary, the following management measures are suggested to enhance ecosystem health and ensure sustainable fisheries:

- Regulation of industrial discharges and sewage disposal into the estuary through strict monitoring and control to maintain water quality and to protect fish breeding and nursery grounds.
- Restoration and conservation of mangrove habitats by adopting best practice principles, which will help improve nursery habitats and enhance overall ecosystem resilience
- Implementation of clam ranching and stock enhancement programs in the estuary to restore depleted bivalve populations, thereby supporting ecosystem functioning while enchancing the livelihoods and nutritional security of dependent fishers.

Regular assessment and long term monitoring of ecosystem health are crucial for maintaining the quality of the estuarine system, thereby ensuring its continued capacity to support fish, fisheries, and the livelihoods of stakeholders. Findings of this study provide a scientific basis for evaluating habitat quality and can guide ecosystem based management and estuarine conservation strategies.

The present study reveals that the NG Estuary is under ecological stress as evidenced by nutrient enrichment, eutrophic conditions and moderate ecosystem maturity indices. Despite these pressures, the system sustains high system throughput and a mean trophic level of 2.93 indicating active energy flows and continued support of fisheries largely based on lower to mid-trophic level species. Seasonal monsoonal flushing and strong primary production appear to buffer the ecosystem against structural collapse, contributing to its current resilience. However, the relatively low ascendancy and signs of nutrient driven stress suggest that the estuary is functioning close to a stability threshold. Without effective management of pollutant inputs and habitat degradation, the long-term resilience of the estuary and the sustainability of its fisheries may be compromised. The trophic model developed in this study provides a robust baseline for future monitoring, dynamic simulations, and ecosystem-based fisheries management. Proactive, science-based interventions are essential to safeguard ecological integrity and ensure sustainable resource utilistion in the NG Estuary.

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