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RESEARCH ARTICLE

Ecosystem health status and trophic modeling of an anthropogenically impacted small tropical estuary along India's west coast

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Abstract

The tropical estuaries are characterized with high biological production and also impacted by anthropogenic activities. Describing these estuaries in terms of ecological data and trophic dynamics to reveal the ecological impacts is gaining attention recently. In this study, the ecological structure is analyzed for a heavily impacted small macrotidal tropical estuary, Ulhas river estuary (URE), situated near Mumbai megacity in the western coast of India, to delineate the impact of anthropogenic stressors on the ecosystem functioning. The URE is being exploited for sand and fisheries resources, and also faces risks from anthropogenic activities. The ecological data of URE were compiled for 2017-18 together with the most relevant literature estimates to construct an ecosystem model. A trophic organization in 20 functional groups was identified for URE using Ecopath modeling approach. The functional groups identified in the food web ranged from detritus and primary producers (trophic level (TL) = 1) to large pelagics (TL = 4.14). Detritivory: herbivory ratio (1.35) indicated that the detritus chain is dominant over the primary producer's chain. The total system throughput (TST) was estimated as 16 736.2 t km^{-2}year^{-1}. The indices such as net system production (NSP = 1 398.781 t km^{-2} year^{-1}), total primary production/total biomass (TPP/TB = 25.17), biomass/total system throughput (TB/TST = 0.01), recycling index (Finn's Cycling Index = 13.94%), system omnivory index (0.3), relative ascendency (25.6%), and system overhead (74.4%) classified URE as an immature system. The eco-exergy index (30748.54 gm detritus equivalent m^{-2}) showed that the ecosystem is a moderately stable and relatively less organized network. The estuarine fish community index (EFCI) yielded a value of 38 indicating the poor health status of the fish community in URE. The study delivers a comprehensive understanding of the ecosystem setting in URE and characterizes the prevailing condition. The ecological indicators analyzed here point towards a medium to a high level of impact in URE due to anthropogenic activities.

Keywords Trophic model · Small tropical estuary · Mumbai Megacity · Anthropogenic activities · Ecological indicators · Estuarine fish community index

Introduction

Estuaries have been considered as the interface ecosystems, more productive than both the rivers and the ocean that influence from either side (Pritchard 1967). They are vital habitats for several marine species and called the "nurseries of the sea" because the protected environment supported by the mangroves, and organic-rich mudflats provide an ideal habitat condition for most of the commercially important fish and shellfish species (Beck et al. 2001; Elliot and Hemingway 2002). Various aquatic species visit the estuarine waters for feeding and breeding activities in addition to the resident species and contribute to the overall biodiversity of an estuary (Beck et al. 2001). Apart from the enumerable ecosystem

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services, estuaries provide livelihood to fishers from marine and inland sectors and are considered as ideal sites for human settlement and industrial units (Costanza et al. 1997). Hence, these ecosystems are subjected to a higher degree of anthropogenic impacts (Post and Lundin 1996). The level of anthropogenic stressors on these interface systems should be quantified in the current context due to the increase in the population density and associated needs for basic amenities on one side and the depleting aquatic resources and ecosystem integrity on the other side (Elliott and Quintino 2007; Diaz and Rosenberg 2008).

Ecosystem Approach to Fisheries (EAF) is a strategic framework that considers both structural and functional components of an ecosystem for managing fisheries (FAO 2003). EAF considers habitat features and multiple functional groups in the ecosystem and, thus, characterizes the ecological processes efficiently (Christensen and Pauly 2004). The major goal of EAF is to rebuild and sustain habitats and biological communities to maintain the ecological services provided by the ecosystem to the human population (Christensen and Pauly 2004). Rational management of sensitive ecosystems such as estuaries requires a coherent understanding of the effect of anthropogenic stress on the functioning of ecosystems measured along the structure and features of the biological communities (Patrıcio et al. 2004; De Jonge et al. 2006).

The structure of a community of co-existing species can be described by the trophic positions of these species along different resource dimensions in an ecological space (Ross 1986; Persson 1990). The estimation of energy and biomass flows through diverse compartments in an ecosystem as well the assimilation, transfer, and dissipation pattern of energy would help to portray the structure and function of the ecosystem over time (Baird and Ulanowicz 1993; Polis and Strong 1996; Fath 2015). The thermodynamic and network-oriented tools are powerful in analyzing the ecosystem properties by integrating a multitude of relevant data sources concerning an ecosystem and enabling the assessment of ecosystem health and maturity with precision (Vassallo et al. 2006; Selleslagh et al. 2012).

Generally, the energy balance models have been used worldwide as tools: (1) to characterize the structure of an ecosystem, (2) to analyze the trophic organization of the food web within the ecosystem, (3) to estimate the energy fluxes between functional groups, and (4) to assess the maturity and stability of the system (Colléter et al. 2015). Among these models, *Ecopath*, which uses ecological network analysis, is an efficient tool for modeling the ecosystem features and to correlate the indices with the anthropogenic impacts in the system (Christian et al. 2005). The Ecopath model is a steady-state trophic model that characterizes the transfer of material or energy within different components of an ecosystem (Christensen and Pauly 1992; Christensen et al. 2005). Recently, ecosystem models have also proved to be useful in measuring the energy balance, eco-exergy, robustness, and the overall health of an ecosystem (Fath 2015; Mukherjee et al. 2019). The Ecopath approach and the indices based on ENA reveal links in the food web and identify reference indicators for monitoring its health (Fath 2015). Studies have also documented that the recycling and ascendancy are the relevant indicators of anthropogenic impacts on ecosystem functioning (Patrıcio et al. 2004; Christian et al. 2005; Selleslagh et al. 2009). In the past two decades, several successful attempts have been made to depict the ecosystem structure through Ecopath model from Indian's western and eastern coasts (Vivekanandan et al. 2003; Mohamed et al. 2008; Dutta et al. 2017; Das et al. 2018; Mukherjee et al. 2019; Sreekanth et al. 2020).

The studies on the structure and functioning of biological communities of tropical estuaries under anthropogenic impacts can yield baseline information in estimating impacts of human-mediated stressors on food web functioning (Blaber et al. 1996; Garrison and Link 2000; Hajisamae et al. 2003; Carrassón and Cartes 2002; Elliott et al. 2007). The Ulhas river estuary (URE) is a small tropical estuary located along the western coast of India, experiencing declined water quality, and miserable ecological conditions due to heavy discharge of industrial and urban effluents (Nikam et al. 2008; Rathod and Patil 2009; Rathod 2012). There are several industries situated along either bank of the river, adding their effluents at various localities and ultimately concentrating the estuarine part with pollutants (Mohapatra and Rengarajan 2000; Mishra 2002; Zingde 2002; Lad and Patil 2016). A considerable load of sewage from Thane city is also being added, which affects the aquatic life and ecosystem health (Lala 2004; Athalye et al. 2003). Extensive destruction of mangrove cover along the banks has also been identified as a major anthropogenic stressor (Jagtap et al. 1994; Kantharajan et al. 2018). Apart from that, the fishery in the estuary has declined due to the enormous by-catch and discards landed in the indiscriminate fishing operations prevailing in the region (Kumawat 2014). A holistic, ecosystem-based assessment including all ecological groups and trophic interactions has not been carried out for the URE so far. On the other hand, the ecological structure and ENA indices are attracting increasing interest from ecosystem managers and conservationists, and such strategic investigations are the need of the hour. Hence, it was against this background that we applied the Ecopath model, and ENA indices to quantify the attributes, trophic organization, maturity, stability, and health of the URE. The trophic mass-balanced model for URE was developed to address the specific objectives: (1) to construct a mass-balance model of the URE to understand the trophic interactions among functional groups within this ecosystem through ENA; (2) to measure the level of ecosystem maturity, stability, and trophic functioning; (3) to evaluate the health of the URE ecosystem; and (4) to compare the ecological indices of the URE with those of other estuarine systems. This model is expected to strengthen the information on ecosystem processes and current status to suggest appropriate management strategies for this small tropical estuary, subjected to anthropogenic impacts.

Material and methods

Study area

The URE is a small macrotidal tropical estuary situated along the banks of Mumbai megacity, western coast of India that connects the Ulhas river to the Arabian Sea through Vasai creek (Fig. 1). The Ulhas River originates in the Western Ghats (Lat. 18° 45″ to 19° 00 N; Long. 72° 45″ to 73° 20″ E) and characterized a large catchment area and its confluence with a large number of tributaries and appears to be one of the major source of sediments for the beach deposits of western Indian coast (Chandramohan et al. 2001; Rathod et al. 2003). The estuarine part of the river extends to 40 km upstream up to where the tidal influence is experienced. The area belongs to the tropical region, sultry and humid, with mild winters and warm summers (Singare et al. 2012). The onset of monsoon starts in June and extends until the end of September and the average annual rainfall is in the range of about 1500-2000 mm (Singare et al. 2012). URE is a macrotidal and well-mixed estuary, characterized by semi-diurnal tides and rich mangrove vegetation along the banks (Rathod and Patil 2009). The estuary remains saline and dry (no freshwater flow) for eight months (postmonsoon and premonsoon) annually after the monsoon season (June-September). During the dry period, the average salinity of the URE is 25.3 psu (minimum 7.8 and maximum 34.1) and marine conditions persist. The estuary has been exploited since long for its sand resources and fisheries resources (Rathod et al. 2003). The present study considered the downstream part of the URE, covering an area of 13.55 km^2 at the Vasai—Naigaon region of the Mumbai coast.

The Ecopath model

We used mass-balanced modeling with Ecopath as the tool to understand the food web of the URE, taking important

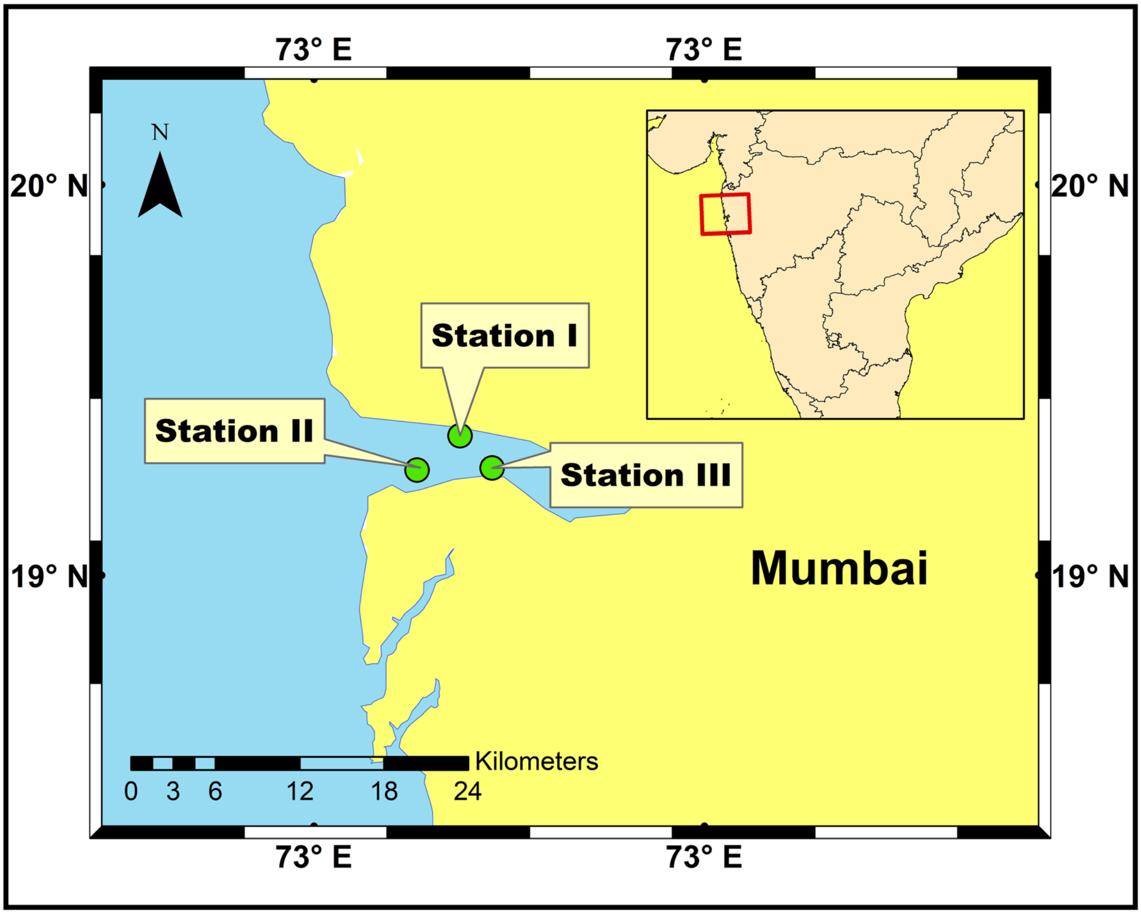

Fig. 1 Map showing the study area and sampling stations. Inset a shows Mumbai city of Maharashtra State-India. Each dot indicates the sampling stations in URE

functional groups from each trophic position. Ecopath model uses a set of linear equations to estimate the values of all flows in an ecosystem, which can then be analyzed with indices derived from ENA. Ecopath, with the Ecosim (EwE) software package (EwE version 6.6.1), was used here to fit the model (Christensen et al. 2005). The model is based on the parameterization of two master equations:

(1)Production = yield + predation + net migration + biomass accumulation + other mortality

(2)Consumption = production + respiration + unassimilated food.

The model is also represented by the following formula:

$$B_i.(P/B)_i.EE_i - \sum_{j=1}^{n} B_j.(Q/B)_j.DC_{ji} - EX_i = 0$$

Where B_i is the biomass of group (i); P/B_i is the production/biomass ratio of (i), which is equal to total mortality coefficient (Z) or natural mortality (M) (Allen 1971); EE_i is the ecotrophic efficiency of (i), which represents the part of the production of the group that is transferred to higher trophic levels or utilized within the system, which varies from 0 to 1; B_j is the biomass of the predators (j); Q/B_j is the food consumption per unit of the biomass of the predators (j); DC_{ji} is the fraction (%) of (i) in the diet of (j); and EX_i is the export of (i) and refers to the biomass that is caught by fishing and/or migrates to other environments. In this case, as for other Ecopath models (Coll et al. 2006; Patrício and Marques 2006; Han et al. 2016), we considered migration to be equal to immigration, given the difficulty of estimating the movements of individuals.

For n groups (compartments), the Ecopath model solves a system of n linear equations. At least three out of four of the input parameters B_i, PB_i, QB_i, and EE_i must be fixed to parameterize the model. By connecting the production of one group with the consumption of the others, the missing parameter can be estimated based on the assumption that the production of one group is utilized by another group inside the system (Christensen et al. 2005). The biomasses and flows were expressed in t km^{-2} year^{-1}.

Functional groups

The ecological groups were defined based on similarity in size, population parameters, and diet contents, considering that, larger, detailed fish catch dataset "group" approach is more suitable (Pauly et al. 2000; Christensen et al. 2005). In this study, 20 functional groups were defined to construct the mass balanced model such as birds (BS), large pelagics (LP), bombay duck (BD), cephalopods (CP), benthopelagics (BP), large benthic carnivores (LBC), croakers (CR), medium benthic carnivores (MBC), small benthic carnivores (SBC), mackerel (ML), clupeids and anchovies (CA), crabs (CB), acetes (AC), shrimps (SR), benthic omnivores (BO), heterotrophic benthos (HB), sessile benthos (SB), zooplankton (ZP), phytoplankton (PP), and detritus (DT) (Table 1). A few functional groups were retained as individual species compartments (BD and AC) due to their disproportionately higher abundance in the samples. The functional grouping is mainly based on diet composition, size, common predators, ecological niche, and commercial landing patterns (Vivekanandan et al. 2003; Mohamed et al. 2008; Sreekanth et al. 2020).

Data collection

Fish

Experimental fishing was conducted at three stations in the true estuarine zone (Fig. 1) between September 2017 and August 2018. Monthly sampling was carried out for an entire year to ensure representation of resident and the seasonal migrant species in the URE. Single-day Dol net (bag net) of cod-end mesh size 10 mm was used throughout the sampling, which was performed during the day time for 3-4 hours. Total weight of the catch during each haul was measured while landing. Unsorted subsamples of fish catch (with the catch to subsample ratio-5:1) were brought to the laboratory and care was taken to include all the fish species caught, to be well represented in the subsamples. In the laboratory, finfishes and shellfishes were identified up to species level based on the relevant taxonomic keys (Fischer and Bianchi 1984; Bianchi 1985). The length was recorded to the nearest millimeter (0.1 mm) and weight in gram (0.01 g accuracy), using a digital scale and a weighing balance. The biomass for the fish compartments was estimated as the sum of the individual weights of each group (weight in the subsample, raised for the weight of catch in each haul) divided by the total dragged area, expressed in t km^{-2} year $^{-1}$. To minimize the underestimation of biomass due to gear selectivity, a catchability model (Lauretta et al. 2013) was applied to each functional group:

$$P = q.E.A^{-1}$$

$$N = C.P^{-1}$$

Where P is the mean proportion of the population captured, q is the catchability coefficient, E is the fishing effort (total area sampled in km^2), A is the model area (13.55 km^2), C is the catch of the experimental samples (t km^{-2} year $^{-1}$), and N is the standardized biomass with the catchability model (t km^{-2} year $^{-1}$). The total area sampled is calculated using the swept area method (Gulland 1969), considering the mouth opening area of the gear, the tidal current velocity at each sampling, and the duration of the fishing operation.

Table 1 Functional groups defined for Ulhas river estuary

Sl. no	Group	Code	Species/subgroups
1	Birds	BS	Fish consuming birds
2	Large pelagics	LP	Barracudas, seerfishes
3	Bombay duck	BD	*Harpadon nehereus*
4	Cephalopods	CP	Squids, cuttlefishes, and octopus
5	Benthopelagics	BP	Horse mackerel, carangids, and ribbonfishes
6	large benthic carnivores	LBC	Snappers, threadfins
7	Croakers	CR	*Johnius* spp., *Johnieops* spp., *Otolithus* spp, *Protonebea* spp and *Otolithides* spp
8	Medium benthic carnivores	MBC	Pomfret, sand whitling, catfishes, flatheads, rabbitfishes, eels and scat
9	Small benthic carnivores	SBC	Glassy perchlets, false trevally, pufferfish, tiger perches, silverbellies, and silverbiddies
10	Mackerel	ML	Indian mackerel
11	Clupeids and Anchovies	CA	Oilsardine, white sardine, lesser sardines, mustached anchovies, bony breams, tardoore, shads, whitebaits, and golden anchovy
12	Crab	CB	swimming crabs, mud crab, and spider crab
13	Acetes	AC	*Acetes indicus*
14	Shrimps	SR	Penaeids, nonpenaeids, fresh water prawns, and stomatopods
15	Benthic omnivores	BO	Mullets, soles, tongue soles and gobies
16	Heterotrophic benthos	HB	Gastropods and bivalves
17	Sessile benthos	SB	Polychaete and hydrozoans
18	Zooplankton	ZP	Copepods, ostracods, bivalve larvae, cladocerans, mysids, euphausids, amphipods, chaetognathans, and fish larvae
19	Phytoplankton	PP	Diatoms, dinoflagellates, and blue green algae
20	Detritus	DT	

The tidal current velocity is simulated in the study area for the period between 2017 September and 2018 September with The SWAN + ADCIRC (Simulating WAves Nearshore + ADvanced CIRCulation) shallow-water circulation model (Dietrich et al. 2011), which is proven to be useful for tide-surge and wave simulation in coastal and gulf areas (Xie et al. 2016). ADCIRC is a two-dimensional, depth-integrated, barotropic time-dependent long-wave, hydrodynamic circulation model. Whereas, SWAN is a third-generation wave model, that computes random, short-crested wind-generated waves in coastal regions and inland waters.

The catchability coefficients (q) of Lauretta et al. (2013) were used, taking into account the genus, the body shape, and/or the fin profile of our species (Supplementary table S1).

Both (P/B) and (Q/B) ratios of the different fish species were taken from available literature and reports (Vivekanandan et al. 2003: Mohamed et al. 2008) and fish survey data published by Central Marine Fisheries Research Institute (Srinath et al. 2006). P/B was calculated using the standard empirical relationship (Beverton and Holt 1957; Pauly 1980). The formula to calculate fish biomass and P/B is given in Supplementary table S3: equation 1. The Q/B for fish groups has originally been calculated using the standard empirical formula (Supplementary table S3: equation 2) given by Palomares and Pauly (1998). Q/B ratios for crustaceans (shrimps and crabs) and cephalopods were calculated on the basis of the modified empirical formula (Supplementary table S3: equation 3) suggested by Palomares and Pauly (1998).

Other compartments

Birds

For birds, each input parameter values were collected and modified from similar and adjacent ecosystems (Mohamed et al. 2008; Sreekanth et al. 2020).

Detritus

The biomass of detritus was calculated using the empirical equation from the primary production and euphotic depth suggested by Christensen and Pauly (1993):

$$\text{Log D} = 0.954\log\text{PP} + 0.863\log\text{E} - 2.41$$

where "D" is the detrital biomass in (g C m^{-2}), PP is the average primary production in (g C m^{-2}), and E is the euphotic depth in meters. The depth of the euphotic zone was calculated as follows: $E = 2.5 \times SD$ (Secchi depth in meters).

Phytoplankton

The phytoplankton biomass was calculated from the average net primary productivity estimated for the URE using a conversion factor of 0.06 g C = 1 g wet weight of algae (Walsh et al. 1981). Gross primary productivity (GPP) and net primary productivity was estimated using the Light and Dark bottle method (APHA 2005). *P/B* value of phytoplankton and benthic producers was collected and modified from other published sources (Mohamed et al. 2008; Sreekanth et al. 2020).

Zooplankton and benthos

Zooplankton was collected at high tide ± 2 h using a standard 200 µ net by sub-surface (1 m depth) horizontal hauls. The filtered water volume by the net in 0.5 hr was calculated using the speed of the haul and the net volume. The samples were fixed using 4% formaldehyde solution. The density of this group was recorded as the number of individuals per meter cube. From the count data, the biomass was estimated based on the average individual weight of major subgroups (Copepods, ostracods, cladocerans, mysids, chaetognaths, and fish larvae). The biomass values were presented in t km^{-2}. *P/B* was calculated from the empirical formula given by Banse and Mosher (1980) using the weighted average individual body weight (W) of the subgroups as follows:

$$\frac{P}{B} = 0.6457 \times W^{-0.37}$$

The Q/B of zooplankton was collected and modified from other published sources (Shetye et al. 2007; Mohamed et al. 2008; Sreekanth et al. 2020).

Benthos was considered as two subgroups, such as heterotrophic benthos and sessile benthos. Heterotrophic benthos includes gastropods and bivalves, and sessile benthos includes polychaetes and hydrozoans. The biomass, P/B, and Q/B of benthos were collected and modified from secondary sources of information (Mohamed et al. 2008; Sreekanth et al. 2020).

Diet composition

The diet matrix is an essential input that characterizes the prey-predator interactions between functional groups. A diet matrix for various functional groups (Supplementary table S4) has been prepared based on the gut content analysis for all the possible species (for 32 species where the number of samples was more than 60) and also from secondary sources of information available such as Mohamed et al. (2008) and Fish Base (Froese and Pauly 2016). For the functional groups such as BS, LP, BD, CP, BP, LBC, and CR, the import was also considered as a part of the diet matrix, assuming frequent movements for these groups outside the estuary (Supplementary table S4). After compiling the diet composition data on various species, they were pooled for functional groups based on relative biomass for each species within a functional group.

Fishery landings

Although direct estimates of catch from the landing centers near the study area were available, they were not considered for the present study because a major share of these catches was contributed by multiday Dol netters, which are operating beyond the estuarine mouth towards the sea (Kumawat 2014). The fishery within the estuary was solely contributed by single day Dolnets, locally known as the *Bokshi jal*. Presently around 7-10 of them are operating round the year in the study area and the average fishing days are 15-25 per month (Kumawat 2014). Hence, the fishery landings were calculated using the sampling data from the present study scaled for the total fleet size and days of operation validated with primary field data obtained from ICAR-Central Marine Fisheries Research Institute, Regional Centre, Mumbai.

Ecopath pedigree and measure of fit

The pedigree algorithm of Ecopath was run to confirm the validity of the input parameters used in the model (Funtowicz and Ravetz 1990). The pedigree routine describes the data origin as a coded statement categorizing the origin of a given input and assigns confidence interval to the data based on its origin (Pauly et al. 2000). The index specifies the likely uncertainty associated with the input that allows the user to mark the data origin using a pre-defined table for each type of input parameters. The routine yields a pedigree index, “*P*,” which is calculated as the product of all the individual pedigree parameter indices (Supplementary table S3: Equation 4). The “P” scales between 0 and 1 and the maximum values indicate that the model relay mostly towards the primary sourced data of local origin. Since “P” is more or less a function of the number of groups in the system, we have also used a measure of fit, “t” to confirm the validity of the index (Supplementary table S3: Equation 5).

Balancing the model

In general, manual amendments are required to be performed on the input data, since the Ecopath principle relies upon the ecosystem’s mass balance. While balancing the model, the Ecopath parameterization routine was used to check whether the model was “mass balanced” with the criterion that, EE value of any group cannot be greater than 1 since any group cannot be consumed more compared to its production. For the URE Ecopath model, 6 out of the 20 groups such as AC, SR, CA, SBC, ML, and BO showed an Ecotrophic efficiency value of more than 1 in the initial run. Adjustments were made in their biomasses (supplementary Table S1), *Q/B* values, and diet matrix until a mass balanced model was achieved.

Ecosystem performance indicators

The performance of the ecosystem functioning was measured using the Ecopath indices such as total system throughput (TST), the sum of all production (TP), mean trophic level of the catch (TLC), gross efficiency (GE)(catch/NPP), net system production (NSP), and total net primary production (NPP). The food web structure and ecosystem maturity were analyzed with the indices such as total primary production/total respiration (TPP/TR), total primary production/total biomass (TPP/TB), total biomass/total throughput (TB/TST), connectance Index (CI), system omnivory Index (SOI), Finn's cycling index (FCI), Finn's mean path length (FML), ascendancy (AS), and system overhead (SO). Different performance indicators and their description are provided in Supplementary Table S5. A single trophic flow diagram was generated from the mass balanced modeling approach, representing all flows and biomasses in the ecosystem. The "Lindeman spine" flow chart was used to estimate the transfer efficiencies and flows to detritus between the trophic levels (Lindeman 1942). The mixed trophic impacts (MTI) routine of Ecopath is employed to describe the impact of one functional group on the other groups (both predatory and competitive interactions) (Ulanowicz and Puccia 1990). The presence and dynamics of some groups are crucial in maintaining the integrity and complexity of the ecosystem, and these groups are called keystone species (Christensen et al. 2005). In Ecopath, a routine assigns Keystoneness index (KS_i) values to every functional group in the trophic network (Libralato et al. 2006). The KS_i and relative total impacts are measured for each functional group and, thus, the keystone species/groups are identified.

Eco-exergy index

The ecosystem's health status has also been measured with "Eco-exergy," an index on the stored workable energy of an ecosystem when the system reaches a thermodynamic equilibrium with its environment (Jørgensen 2007). The eco-exergy value of an organism is basically a function of the genetic complexity; the more the complexity, the higher the exergy value of that individual (Jørgensen 1992, 2007; Mukherjee et al. 2019). The eco-exergy index for an ecosystem is considered to be the summation of the usable portion of energy from different functional groups towards ecosystem functioning. The index serves as an efficient indicator for the stability and health status of an ecosystem (Jørgensen 2007).

The eco-exergy of URE has been estimated using the standard formula,

$$Ex = \sum_{i-1}^{n} \beta_i C_i$$

Where β_i stands for the weighting factor of the ith component in the system and C_i is the corresponding biomass for the ith group (tonnes km^{-2}). Also, i = 1 represents detritus. Hence, eco-exergy can be expressed as a detritus exergy equivalent (mg L^{-1}, $\beta_i = 1$ for detritus). The relative "β" for different components are obtained from earlier reports (Jørgensen 1992) such as the following: Birds: 940, Fishes: 499, Mollusc: 310; Crustaceans: 232; Sessile benthos: 133, Zooplankton: 33; Phytoplankton 20; and Detritus: 1. The specific eco-exergy was calculated by dividing the total exergy by the total biomass.

Indicators of ecosystem health and estuarine fish community index (EFCI)

The ecological network analysis (ENA) indices like FCI and SOI were also applied here to determine the magnitude of anthropogenic interventions in the URE according to Baird and Ulanowicz (1993) and Selleslagh et al. (2012). Biotic indicators are considered as reliable pointers of aquatic ecosystem health since they can integrate the effect of changes across a wide array of environmental factors (Karr 1986; Harris and Silveira 1999; Simon 2000). A matric is a measurable factor representing some aspect of biological assemblage structure, function, or other community components (USEPA 2000). Here, we used a multi-metric index, the estuarine fish community Index (EFCI), developed by Harrison and Whitfield (2004) to evaluate URE's ecosystem status as a response to anthropogenic pressure. The estuarine fish community index (EFCI) is an already established index for the transitional ecosystems (Harrison and Whitfield 2004, 2006; Harrison and Kelly 2013), and it is successfully applied for tropical estuaries that are impacted due to anthropogenic pressures (For examples, the Sezela Estuary situated on the East Coast of South Africa of nearly similar characteristics that of our study area (Harrison and Whitfield 2004). Being an estuary of predominantly open type, 14 community metrics were considered to develop the EFCI following the guidelines of Harrison and Whitfield (2004) (Table 2). Since any index is devised to integrate information from various measures of biological attributes, and the attributes themselves will vary in their measures like numbers, percentages, or descriptive terms, the matrices have been parameterized into standard comparable scores (Harrison and Whitfield 2004). Scores of 5, 3, and 1 were allocated to each metric for URE, depending on the extent of deviation from the reference condition. The final EFCI was calculated by summing the scores defined for each metric. Based on the 14 metrics, the EFCI will range from 16 to

Table 2 EFCI matric for subtropical predominantly open estuaries (Harrison and Whitfield 2004)

Score	5	3	1	Score obtained for URE
Species diversity and composition				
Total number of taxa	≥37	<37and ≥21	<21	5
Rare or threatened species	Present	Absent		3
Exotic or introduced specie		Absent	Present	3
Species composition (%similarity to reference)	≥80%	<80% and ≥50%	<50%	3
Species abundance				
Species relative abundance (% similarity to reference)	≥60%	<60% and ≥40%	<40%	1
Number of species that make up 90% of the abundance	>13	<13 and ≥ 8	<8	1
Nursery function				
Number of estuarine resident taxa	≥7	<7 and ≥ 4	<7	1
Number of estuarine-dependent marine taxa	≥23	<23 and ≥14	<14	3
Relative abundance of estuarine resident taxa	25-27%	≥10% and <25% or >75% and ≤90%	<10% or >90%	1
Relative abundance of estuarine-dependent marine taxa	25-27%	≥10% and <25% or >75% and ≤90%	<10% or >90%	3
Trophic integrity				
Number of benthic invertebrate feeding taxa	≥13	<13 and ≥ 7	<7	5
Number of piscivorous taxa	≥6	<6 and ≥ 4	<4	3
Relative abundance of benthic invertebrate feeding taxa	≥25%	< 25and ≥10%	<10%	3
Relative abundance of piscivorous taxa	≥2%	<2 and ≥1%	<1%	3
Total				38

68, with the rating criteria of ecosystem integrity such as Critical (0-16), Very poor (16-20), Poor (22-38), Moderate (40-44), Good (46-62), and Very good (64-68).

Definition of the reference ecosystem

Reference sites are required to be selected based on the physical or chemical variables such as those that are substantially free of contaminants, with little or no industrial point of discharge, a system with little or no urban runoff, and with no agriculture or nonpoint sources of pollution (USEPA 2000). The biological attributes of these least impacted sites are then used to generate reference conditions. In case if the prior definition of least disturbed sites is not available because every site is considered impaired and no reference site exists, alternate methods can be used to establish reference conditions. In such situations, reference conditions can be derived from the distribution of calculated metrics without an independent preselection of any reference site. Using the biological data set, the "best" values of candidate metrics can be used to establish the biological reference condition (Harris and Silveira 1999; USEPA 2000). For this study, the reference conditions are derived from the detailed literature surveys concerning the estuarine ecosystems of the Indian coast (Suresh and Shetye 2007; Murugan et al. 2012; Rakshit et al. 2017; Dutta et al. 2017; Das et al. 2018; Sreekanth et al. 2019; Kiranya et al. 2018).

Results

Model validation and basic estimates

The quality of the input data was analyzed using the Ecopath pedigree index. The current model had a pedigree index of 0.60 and the measure of fit was 3.11; these values indicate that the model is reliable with a high level of confidence. Based on the criteria and assumptions used in evaluating, the ratios of production to consumption, respiration to assimilation, and respiration to biomass were within acceptable limits (Table 4). The criteria for balancing the model were satisfied in the final mass-balanced model, in which the *EE* values for all the functional groups were less than 1 (Table 4). Similarly, the *P/Q* ratio (0.05 to 0.3), another pre-balance diagnostic measure of the mass-balanced model, was also within the acceptable range for most of the functional groups. The highest EE values were recorded for CA (0.95), AC (0.92), SR (0.90), and SBC (0.95) because of the high rates of predation by their predators LP, BD, and CR (Table 3). Therefore, the biomass of these groups was underestimated initially and later increased to meet the model's requirement.

Food web structure and trophic levels

The trophic levels (TLs) in the URE ranged from the assigned value of 1 for DT and PP to 4.14 for LP. The majority of the groups belonged to TL 2, including ZP, SB, HB, BO, SR, AC,

Table 3 Basic parameters of the mass balanced trophic model for URE. TL: trophic level, B: biomass (t km^{-2} year^{-1}), P/B: production/biomass (year^{-1}), Q/B: consumption/biomass (year^{-1}), EE: ecotrophic efficiency, P/Q: production/consumption or gross efficiency of food conversion (year^{-1}). The parameters estimated by the model are shown in italics and earlier estimates for input variables are in parentheses

	Group name	Trophic level	Biomass	P/B	Q/B	EE	P/Q
1	BS	4.06	0.25	0.35	65.00	0.000	0.005
2	LP	4.14	0.004	1.35	8.20	0.405	0.165
3	BD	3.53	11.53	1.44	7.60	0.771	0.189
4	CP	3.69	0.69	5.41	36.50	0.582	0.148
5	BP	3.74	1.84	6.55	18.80	0.341	0.348
6	LBC	3.42	0.41	2.74	12.20	0.074	0.225
7	CR	3.14	4.45	6.89	24.70	0.455	0.279
8	MBC	3.06	5.38	3.51	10.80	0.684	0.325
9	SBC	3.04	6.57	6.27	24.70	0.957	0.254
10	ML	2.65	0.62	6.24	20.20	0.960	0.309
11	CA	2.70	7.82	8.51	26.30	0.952	0.324
12	CB	2.93	2.53	7.415	20.50	0.673	0.362
13	AC	2.32	9.58	9.62	26.00	0.918	0.370
14	SR	2.31	8.64	8.56	26.00	0.897	0.329
15	BO	2.76	3.24	6.74	22.85	0.932	0.295
16	HB	2.44	26.00	3.40	16.70	0.747	0.204
17	SB	2.27	18.20	9.80	45.00	0.835	0.218
18	ZP	2.00	18.40	40.00	300.00	0.816	0.133
19	PP	1.00	70.84	70.00		0.945	
20	DT	1.00	92.90			0.614	

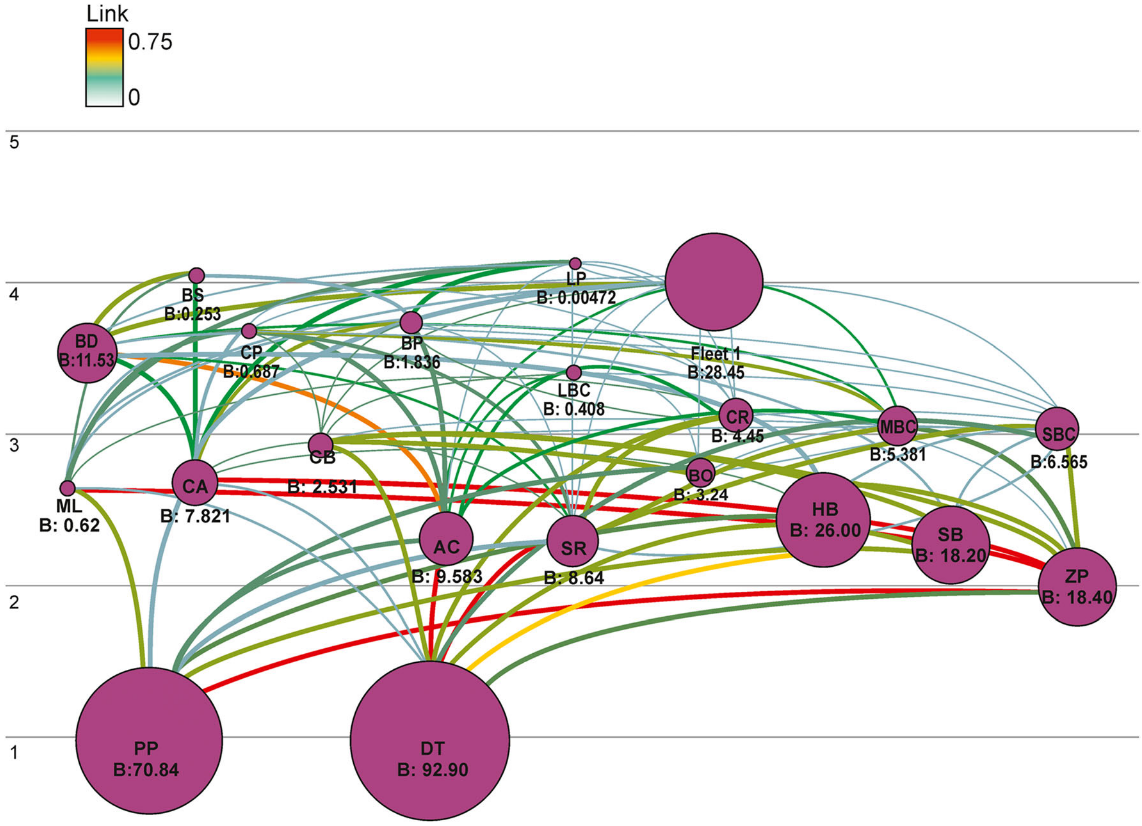

Fig. 2 Food web structure of Ulhas River Estuary depicting the trophic structure of the system, size of the nodes and the thickness of the arches are according to their biomass and quantity of material flow respectively. Trophic levels are denoted in the left side

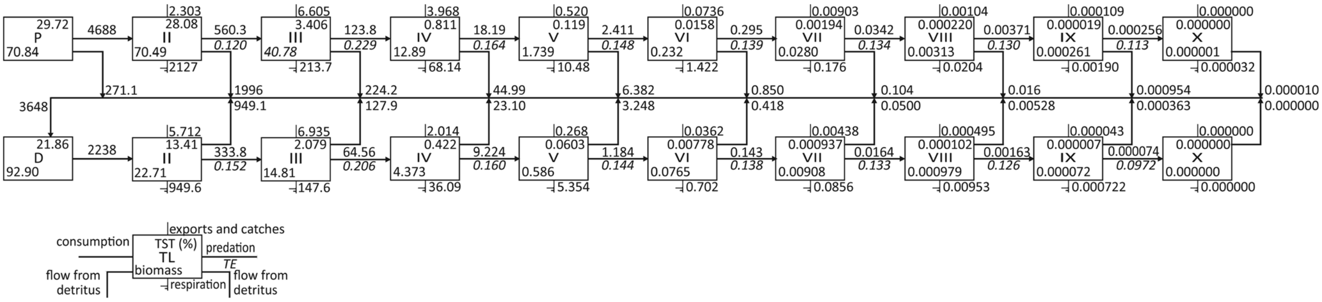

Fig. 3 Transfer efficiency of material from lower to higher trophic levels in the Ulhas River Estuary. Amount of material flows along the grazing and detritus food chain are also represented

CB, CA, ML, and SBC. Trophic level 3 consisted of MBC, LBC, CR, BP, CP, and BD. The prey-predator interactions are shown in Fig. 2 using the Ecopath flow diagram.

Transfer efficiencies

A detritus-based food chain and a grazing food chain with ten discrete TLs (1 to 10) were identified from the Lindeman's spine constructed for the URE (Fig. 3). Annual material flows from primary producers and detritus components to higher TLs were 4688 t km^{-2} and 2238 t km^{-2}, respectively, and the sum of annual flows to detritus was 2544 t km^{-2}. The transfer efficiency (TE) from the primary producers was 16.5% and that from the detritus was 17.1% (Table 4). The mean TE of the food web was 16.7%, and the proportion of flows originating from the detritus to the total flows was 40%. Approximately 41.5% of the total system throughput (TST) was concentrated in TL 1, and TE was the highest between TL 3 and TL 4 and decreased gradually as the TL went up.

Mixed trophic impacts and keystoneness

The mixed tropic impacts (MTI) routine is a tool for evaluating the possible impact of direct and indirect interactions (including competition) on an ecosystem. In the present study, MTI indicated both positive and negative impacts between functional groups of the ecosystem (Fig. 4). The groups with the most positive impact on most of the other groups were detritus and primary producers. The interaction between fishing effort and LP (−0.9) and that between BP and CP (−0.63) showed the highest negative impacts. These interactions essentially comprise prey-predator interactions, competition between groups feeding on similar food types, and cascading effects on the system. At the same time, the largest positive impacts were those of DT on AC (0.35) and on SR (0.32) and those of PP on ZP (0.33). Similarly, BD had a negative impact on most of its prey, including AC, CA, and CR, and SBC, MBC, and CR also had a negative impact on the other groups. Most of the groups had a negative impact on themselves, probably because of competition for resources and cannibalism (Christensen et al. 2005). The maximum value of the relative total impact of keystoneness index was recorded for CP (1.00), followed by BP (0.997) (Supplementary Table S6). Based on the RTI and MTI indices, CP and BP were the most important keystone species in the URE ecosystem, even with their comparatively low biomass.

Electivity

The electivity indices show that the groups ML CA, AC, SR, and ZP are the most preferred prey of predators in the URE (Supplementary Table S7): AC is highly preferred by BD, CP, and CR, as indicated by the high electivity indices. Similarly, CP seems to be a major predator of several mid-TL groups (MBC, ML, CA, AC, and SR) and itself serves as the preferred prey for the higher TLs (LP, BP, and LBC). The most abundant group in terms of biomass, BD preferred AC followed by CA and CR whereas ZP was the favorite prey group of AC, SR, and CA.

Table 4 Transfer efficiencies between trophic levels in Ulhas river estuary

Source\trophic level	II	III	IV	V	VI	VII	VIII	IX	X
Producer	12.01	22.94	16.38	14.81	13.95	13.36	12.95	11.34	
Detritus	15.17	20.61	15.96	14.45	13.77	13.3	12.56	9.72	
All flows	13.03	22.06	16.23	14.69	13.89	13.34	12.83	10.9	0.288

From primary producers: 16.52%
From detritus: 17.09%
Total: 16.71%

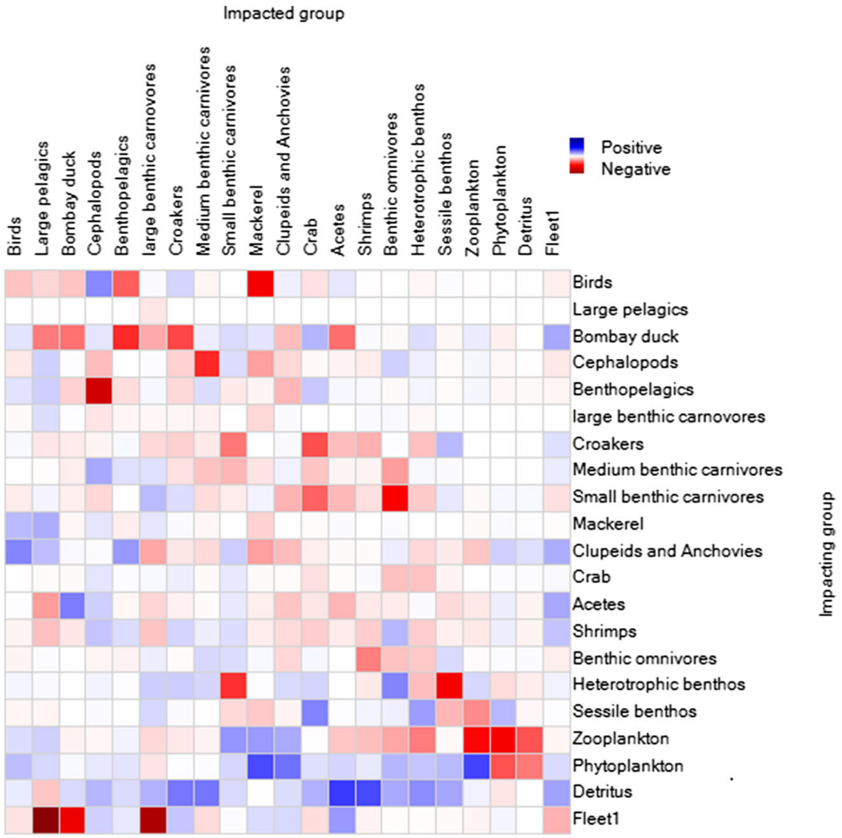

Fig. 4 Mixed trophic impact plot of Ulhas River Estuary indicating the positive and negative interactions among the functional groups

Ecosystem properties and indicators

The ecosystem parameters and flow indices for the URE are described in Table 5. The annual total system throughput of the system was 16 736.2 t km^{-2}, of which 48.3% was derived from consumption, 21.2% from respiration, 8.5 % from exports, and 21.8% eventually flowed into detritus. The ratios of TPP to TB and TPP to TR were 25.17 and 1.39, respectively. The annual NSP was 1398.8 t km^{-2} and the mean TL of catches was 3.01. The indicators of system maturity, such as CI and SOI, were 0.36 and 0.32, respectively. The estimated value of Finn's cycling index (FCI) and Finn's mean path length were 13.94% and 3.9, respectively. The indicators of ecosystem stability, such as ascendancy (AS) and system overhead (SO), were 25.6% and 74.4%, respectively.

Eco-exergy index and estuarine fish community index

To calculate the eco-exergy of the system, the relative β values for different organisms were collected and modified for the ecological components of the URE (Jørgensen 2007). Using the β values and the value of biomass (t km^{-2}), we obtained the eco-exergy (expressed as grams of detritus equivalent per square meter) of each compartment in the system. The total eco-exergy of the system was 30 748.54 g m^{-2} and specific exergy was 29.86 g m^{-2} (both values as detritus equivalent). The scores of EFCI matrix for the URE are given in Table 2. Based on the scoring criteria, such as species diversity and composition, species abundance, nursery function, and trophic integrity, the total EFCI score for the URE was 38.

Discussion

Estuarine food webs are more complex and dynamic than those in other aquatic ecosystems, primarily because of high intra-annual fluctuations in fish diversity due to marine and freshwater emigrants and the resultant changes in the community (Amara et al. 2000; Maes et al. 2004; Selleslagh et al. 2012; Sreekanth et al. 2018). Mass-balance modeling using Ecopath provides insights into the maturity, stability, health, trophic organization, and energy transfer in an ecosystem. The static modeling approach using Ecopath can bring together and synchronize all the available data on the basic ecosystem components and portray the complex ecosystem interactions within it, thereby answering ecosystem-wide questions reasonably and precisely.

Ecopath model for Ulhas river estuary

The model developed in the present study was based on data obtained from direct field observations, relevant secondary

Table 5 System attributes and important ratios obtained for Ulhas river estuary

Parameter	Value	
Ecosystem properties		
Sum of all consumption (TC)	8090.13	t.km^{-2}.year^{-1}
Sum of all exports (TE)	1438.29	t.km^{-2}.year^{-1}
Sum of all respiratory flows (TR)	3560.02	t.km^{-2}.year^{-1}
Sum of all flows into detritus (TD)	3647.75	t.km^{-2}.year^{-1}
Total system throughput (TST)	16736.20	t.km^{-2}.year^{-1}
Sum of all production (TP)	6363.04	t.km^{-2}.year^{-1}
Mean trophic level of the catch (TLc)	3.01	
Gross efficiency (catch/net p.p.)	0.01	
Total net primary production (TNP)	4958.80	t.km^{-2}.year^{-1}
Net system production (NSP)	1398.78	t.km^{-2}.year^{-1}
Total biomass (excluding detritus)	196.99	t.km^{-2}
Total catch	28.45	t.km^{-2}.year^{-1}
Ecosystem maturity		
Total primary production/total respiration (TPP/TR)	1.39	-
Total primary production/total biomass (TPP/TB)	25.17	-
Total biomass/total throughput (TB/TST)	0.01	year^{-1}
Eco-exergy index	38748.54	g detritus equivalent m−2
Specific exergy	29.86	g detritus equivalent m^{-2}
Food web structure		
Connectance Index (CI)	0.36	-
System Omnivory Index (SOI)	0.32	-
Finn's Cycling index (FCI)	13.94	%TST
Finn's mean path length (FML)	3.39	-
Ascendancy (AS)	25.58	%
System Overhead (SO)	74.42	%
Model reliability		
Ecopath pedigree	0.60	
Measure of fit (t *)	3.11	

sources, and other nearby estuaries and coastal ecosystems that comprised similar functional groups (Vivekanandan et al. 2003; Mohamed et al. 2008; Selleslagh et al. 2012; Sreekanth et al. 2020). Here, a "catchability" model was used for minimizing bias in gear selection in estimating biomass. The catchability coefficient q is considered for species with similar fin shapes. The modeled area of 13.55 km^2 comprises the lower reach of the URE where true estuarine conditions prevail and fishing is the predominant activity. The movement of organisms from the adjacent marine as well as the freshwater areas, or "the immigration/emigration," was not included because the required data were not available and the accumulation of biomass was not considered in the study (Coll et al. 2006; Patrício and Marques 2006; Lira et al. 2018). Well-established empirical equations were used for calculating the basic input data on ecological groups. Moreover, uncertainty in the data for the model was assessed using a pedigree index and the associated "t" statistic. The value of the index was found acceptable when compared to the pedigree indices for other Ecopath models.

The highest EE values were recorded for CA, AC, SR, and SBC, which indicate severe predation pressure by the higher TL groups. A more or less similar trend in fishing mortality was observed for most of the exploited resources in the system, except BD (M = 0.65) and CR (M = 0.608). These trends indicate a non-selective fishing fleet operating in the estuary, particularly a bag net with a codend of 10 mm mesh, which captures all trophic components irrespective of size. A high degree of grazing pressure on PP and ZP by the planktivorous species is reflected in the system, as indicated by EE values of 0.95 and 0.82, respectively. These observations were consistent with the reports from other coastal ecosystems in Indian waters such as one-off Karnataka coast (PP, 0.84; ZP, 0.98) (Mohamed et al. 2008) and the Hooghly-Matlah estuary (PP, 0.75; ZP, 0.95). Along the south-western coast of India, EE values of PP and ZP were 0.75 and 0.19, respectively

(Vivekanandan et al. 2003). For the Zuari estuary, the EE values were 0.15 (PP) and 0.76 (ZP) (Sreekanth et al. 2020). The pattern of EE in the URE indicates an abundance of planktivorous fish in the coastal and estuarine ecosystems of India. However, the abundance and the diet preferences over these primary and secondary producer groups are highly ecosystem specific.

For the detritus groups in the URE, the EE was 0.61. Among the ecosystems along India's west coast, the EE values were 0.37 for the south-western coast (Vivekanandan et al. 2003), 0.55 for the Arabian Sea off Karnataka (Mohamed et al. 2008), and 0.12 for the Zuari estuary (Sreekanth et al. 2020). However, higher values of detrital EE were reported from India's east coast: 0.63 for the Sunderban estuary (Dutta et al. 2017), 0.77 for northern Bay of Bengal (Das et al. 2018), and 0.79 for the Hooghly-Matlah estuary (Mukherjee et al. 2019). The higher detrital EE for the URE suggests greater use of detritus as a resource in the north-western and eastern coastal ecosystems than in the south-western ecosystems. The Ulhas river estuary is characterized by extensive stretches of mangroves along its banks (Rathod et al. 2003). Also, the Mumbai coast alone harbors 66 km^2 of mangroves, which account for 21.7 % of the mangrove cover of the state of Maharashtra (Kantharajan et al. 2018). The similarity in the use of detritus may be due to the extensive mangrove cover in the study area, which greatly supports high detritus load in the ecosystem.

Ecosystem flow indices

Total system throughput (TST) is the sum of all flows representing the size of the entire system in terms of its flows (Ulanowicz 1986). The annual TST (16736.20 t km^{-2}) of the URE is marginally higher than that of other tropical estuaries and coastal systems in India—south-western coast, 14 083.4 t km^{-2}; Arabian Sea off Karnataka, 11 522 t km^{-2}; and Sundarbans, 5220.6 t km^{-2}—but lower than that of the Zuari estuary (23 333.9 t km^{-2}) and the Hooghly-Matlah estuary (22 976.03 t km^{-2}). The Ulhas river estuary is characterized by its shallow depth (3–4 m on average), run-off from the catchment area carrying enormous quantities of sediment, and human habitation (Rathod and Patil 2009). Besides, considerable loads of municipal sewage (approximately 64 million liters a day discharged directly from the nearby Bhayandar Municipal Corporation and several times that from other places along the course of the estuary) also result in high levels of organic matter in the URE (Nikam et al. 2008; Patil and Ingle 2016; Nikam 2019), which, in turn, leads to fairly high TST.

The annual flow towards detritus was quite high (2544 t km^{-2}) compared to that in the Sundarbans mangrove estuarine ecosystem in northern Bay of Bengal (1128.85 km^{-2}) (Dutta et al. 2017), one of the largest detritus-based ecosystems in the world (Ray 2008). The present study was in an area in which most of the fishing was concentrated: 71 units of bag nets (*bokshi jal* or *dol*) and 12 of barrier nets had been operational in the early years of the century (2000–2005) (Rathod et al. 2003). Over the latter half of the last decade, the age-old practice of sand extraction had metamorphosed into a commercial activity, causing a great deal of damage to the floor channel as well as to the mangroves (Rathod et al. 2003). As a result, fishing has decreased markedly; at present, it is confined only to 7–10 *dol* net units operated from a few motorized vessels, particularly in the Naigaon-Vasai area (Kumawat 2014). Although fishing mortality reported in the present study is lower (Supplementary Table S8), year-round fishing with nets of smaller mesh is harmful to the ecosystem. Because estuaries are generally considered nurseries for commercially important groups (Cardoso et al. 2004; Elliott and Quintino 2007), the juveniles captured in huge quantities annually from the ecosystem are simply discarded, which transformed into organic matter, which serves as the nutrient base for benthic groups (Abdul and Adekoya 2016). This process results in greater flows of organic matter towards detritus, which eventually increases the TST. Larger detritus biomass and flows towards detritus, together with high EE, emphasize the relevance of the detrital food chain to the ecosystem.

The mean TL of the catch, which was 3.01, indicates a fishery exploiting groups at the lower to middle TLs. These results are consistent with recent records from the estuarine and coastal systems of India, the values being 2.72 for Sundarbans, 3.12 for the Bay of Bengal (Das et al. 2018), 2.34 for the Hooghly-Matlah estuary (Mukherjee et al. 2019), and 2.91 for the Zuari estuary (Sreekanth et al. 2020). Globally, the TLs of landings have been declining at a rate of 0.1 per decade (Pauly et al. 1998a). The present trend, if it continues unabated, will lead to widespread collapse of fisheries due to a decrease in the top-down control (Power 1992). Pauly et al. (1998b) also proposed that the mean TL of fish landings can be used as a tool for assessing ecosystem status so long as the series extends into the past to cover major changes in the relative biomass of key ecosystem components. Although the *dol* net with such a fine-mesh codend (10 mm) is said to be targeting *Acetes* spp., it is evident that the gear itself is non-selective, catching ecosystem components regardless of the size or species. Therefore, the underlying mechanism for the lower TL of the catch can be considered the result of non-selective fishing along with the nursery function and the restricted area of the estuarine ecosystem (Rathod and Patil 2009; Kumawat 2014). The lowest abundance of top predatory species resulting from the protective nature of the environment can also be a potential reason for the reduction in the mean TL of the catch (Elliott and Quintino 2007).

The mixed trophic impact routine is considered to be a tool to assess the possible impacts of trophic interactions on a steady-state system (Ulanowicz and Puccia 1990). The positive impact of detritus and producers on most of the other groups can be considered a bottom-up effect in the system. In contrast, the zooplankton being the major prey for most of the middle TLs shows the negative impact on itself and on other groups as well. Hence, the indirect effect of ZP on other groups is evident, as has been documented in some earlier studies too (Scharler and Fath 2009; Mukherjee et al. 2019). The general consensus is that in estuarine ecosystems, larger fish, mostly pre-adult and adults, are considered top predators (Kroetz et al. 2017; Matich et al. 2017), which exert predation pressure on forage species through top-down control in the food web (Wasserman et al. 2013; Du et al. 2015). Although Bombay duck has direct negative impacts on its prey populations, fishing is the sole component impacting the species negatively. Therefore, relatively strong negative impacts of the fleet on Bombay duck and large pelagics populations would augment the biomass of groups at lower TLs, especially that of CR, AC, and CA, through a trophic cascading effect.

Keystone species or groups have strong impacts on trophic organization and on the abundance of other groups—impacts that are disproportionate to their abundance (Power et al. 1996; Libralato et al. 2006). Keystone species are relatively low-biomass species that have a significant structuring effect on the food web. In general, top-down control of food webs has been observed in estuaries along India's east coast, with top predators as keystone species (Rakshit et al. 2017; Dutta et al. 2017). A similar trend was observed in the present study, with cephalopods being the keystone species in the system, followed by benthopelagics. Das et al. (2018) have also reported cephalopods as keystone species in the northern Bay of Bengal. Cephalopods comprise a carnivorous group targeting small and medium benthic and pelagic fishes and crustaceans as well. The prey groups of cephalopods are also targeted by the top predators and those at other higher TLs. Cephalopods have both top-down and bottom-up effects on the ecosystem, as reported by Gasalla and Rossi-Wongtschowski (2004). Hence, the abundance of cephalopods regulates the abundance of their prey groups, which, in turn, controls the biomass of top predators in the ecosystem.

Transfer efficiencies between TLs were higher and consistent in the URE ecosystem than the values reported for other tropical coastal systems; in those systems, a steep declining trend was observed beyond TL 2 or TL 3 (Mohamed et al. 2008; Murugan et al. 2012; Abdul and Adekoya 2016; Rakshit et al. 2017; Das et al. 2018). The gradual reduction can be correlated to the increased prey overlap between the higher TL groups in the estuary. As the TL increases, energy transfer based on the theoretical energy transfer decreases gradually (Odum 1971). This pattern of transfer efficiency has been observed in many estuaries from the tropics and subtropics (Lira et al. 2018). The mean TE for the URE ecosystem was 16.7%, which stands well above the standard estimate of 10% proposed by Lindeman (1942) and lies within the range of TE values calculated for global estuaries (Lira et al. 2018).

Indicators of ecosystem maturity, stability, and complexity

The food chain tends to change from a linear to a web-like structure as the system matures (Odum 1969). The complexity and maturity of the system can be indicated by SOI and CI, with higher values of these indices indicating a more complex food chain and hence a more mature ecosystem. The diversity of functional groups along with their feeding links affects both CI and SOI strongly, as can be seen from their values in different tropical and subtropical estuaries (Lira et al. 2018). These indices showed higher values for tropical and subtropical estuaries than for temperate estuaries. In the present study, the values of SOI and CI were 0.32 and 0.36, respectively. Comparatively high values of these indices suggest a moderately complex structure of the food web and diversity in terms of diet composition (Abdul and Adekoya 2016). The system omnivory index of 0.32 is comparable to that reported in other models for the tropics (Mohamed et al. 2008; Murugan et al. 2012; Lercari et al. 2015; Abdul and Adekoya 2016; Rakshit et al. 2017; Sreekanth et al. 2020). The higher biodiversity of tropical estuarine ecosystems is attributed to fish species being more generalized or opportunist feeders (Pereira et al. 2012; Pereira et al. 2017). This could be a possible explanation for the high SOI observed for such ecosystems.

Both TST and AS are associated with the maturity of the system and ecosystem stress (Odum 1969; Patrıcio et al. 2004). Ascendancy (AS) measures the average mutual information in a system (Ulanowlcz and Norden 1990): ecosystems with high values of AS reflect high levels of efficiency. The value of AS for the URE (17 471 flowbits) was higher than that for the Arabian Sea off Karnataka coast (14 482 flowbits) and lower than that for the Hooghly-Matlah estuary (25 799 flowbits). Therefore, the value of AS for the URE indicates that the system had a lower efficiency of ecosystem functioning. The upper limit of AS is referred to as the development capacity, and the difference between the capacity and AS is the system overhead. Therefore, the SO indicates the extent to which AS can increase and meet unexpected perturbations by virtue of its reserves of strength and the number of parallel pathways among its compartments (Ulanowicz 1986). For the URE, the SO was 74.42%, which was well within the range recorded from most of the Ecopath models of Indian coastal waters: 67% (Mohamed et al. 2008), 70% (Rakshit et al. 2017), 60.1% (Sreekanth et al. 2020), 80.4% (Das et al. 2018), and 70.4% (Mukherjee et al. 2019). The lower relative AS (25.6%) recorded for the URE indicates that the system is less organized and is affected by anthropogenic activity. However, a high SO indicates a system strong enough to resist perturbations and with the capacity to revert to the original state despite them. These results are consistent with the values for such anthropogenically impacted systems as Hooghly-Matlah and Canche estuaries (Selleslagh et al. 2012; Mukherjee et al. 2019).

The indicators of ecosystem structure showed the consumption to be greater than exports and the flows to detritus and are in agreement with the indicators reported for other trophic models (Vivekanandan et al. 2003; Mohamed et al. 2008; Murugan et al. 2012; Dutta et al. 2017; Mukherjee et al. 2019). The ratio of TPP to TR is important for describing the maturity of an ecosystem (Odum 1971). In the early stages of development of a system, production is expected to exceed respiration, leading to a ratio greater than 1; in the URE, the ratio was 1.39, indicating that the system is in the developing stage (the ratio being greater than 1). Similarly, a moderate value of the NSP (1398.78 t km^{-2} per year), a high ratio of TPP to TB (25.17), and a low ratio of TB to TST (0.01) indicated the immature status of the ecosystem. The value of NSP for the URE was quite small compared to that for other tropical coastal ecosystems such as the Ogun estuary in Nigeria (Abdul and Adekoya 2016) and the Zuari estuary (Sreekanth et al. 2020) and the Hooghly-Matlah estuary (Rakshit et al. 2017; Mukherjee et al. 2019), both in India, and much closer to that of the Sirinhaém river estuary in northern Brazil (NSP = 1286.61 t km^{-2} per year), a small-sized ecosystem in the tropical realm with ecological conditions similar to those of the URE and also highly impacted by anthropogenic activity (Lira et al. 2018). Given their high dynamics, as in the case of other coastal ecosystems such as bays, reefs, lagoons, and shelves, estuaries, in general, are considered immature or developing systems (John and Lawson 1990) that require particular strategies such as ecosystem-based management to maintain equilibrium. The values of the indicators of ecosystem structure obtained in the present study strongly indicate the need for proper management strategies for the URE considering its developing stage, which is highly likely to ensure managerial success (Flores et al. 2017).

Finn's cycling index is a measure that correlates to both ecosystem maturity and stability and to resource utilization within the system (Finn 1976); FCI is expected to increase as a system matures and becomes more stable (Odum 1971). The index is low if energy flow through the trophic links is rapid and the efficiency of utilization at each level is below par (significantly less than 10%). A low FCI indicates an unstable and vulnerable ecosystem, whereas the higher the FCI, the greater the ecosystem's ability to recover from perturbations. The index varied from 0.19% to 24.8% in estuarine and other coastal ecosystems (Mohamed et al. 2008; Lira et al. 2018). The cycling index is the fraction of the ecosystem's throughput that is recycled and strongly correlates to the ecosystem's maturity, resilience, stability, and recovery time. According to Odum (1969), mature and stable systems tend to have a high cycling index. For the URE, a moderate FCI of 13.94% on account of the detritus-based organization and higher transfer efficiency suggests that the ecosystem is neither highly immature nor fully mature. However, most of the maturity indicators point to an immature ecosystem. The higher values of FCI for the URE than those for other estuaries in the world (Lira et al. 2018) were unusual and may suggest a unique ecosystem, especially in terms of pollution stress (Baird and Ulanowicz 1993). The current value of FCI for the URE (13.94%)—lower than that in some estuaries, higher than that in some others, and similar to that in a few—shows that the URE is not susceptible to perturbations because the value lies within what is considered normal globally.

Ecosystem status and eco-exergy

Exergy, or "eco-exergy," is an indicator of the system's performance, especially of its stability and health. A relatively high exergy of an ecosystem is believed to indicate greater maturity, attributed to a relatively high concentration of higher-level organisms. The most noteworthy study of eco-exergy was that in which specific eco-exergies of 26 aquatic ecosystems were compared (Jørgensen 2007). In Indian waters, Mukherjee et al. (2019) studied the eco-exergy of the Hooghly-Matlah estuarine system in West Bengal. Compared to these reports, the eco-exergy for the URE, expressed as detritus equivalent, of 30 748.54 g m^2 was quite close to that for some of the tropical and subtropical bay ecosystems such as the Laguna de Bay, Philippines (44 700 g m^2) and Maputo Bay, Mozambique (33 767 g m^2) (Jørgensen 2007). The exergy storage for the URE was also much higher than that for most of the riverine and lake ecosystems as given in earlier reports but lower than that for the highly complex reef and shelf ecosystems (Jørgensen 2007). Compared to the values for ecosystems in Indian waters, for example, that for the Hooghly-Matlah estuarine system (Mukherjee et al. 2019) (20 192.16 g m^2), the exergy storage of the URE was higher. The specific exergy (29.86) was only marginally greater than that for benthic producers and phytoplankton (Jørgensen 2007). The abundance of detritus and of organisms that belonged to the lower level of organization, and their relatively higher proportion in the overall biomass in the estuary, may explain the lower specific exergy value. In short, the total exergy storage obtained for the URE also points towards its moderate level of maturity.

Estuarine fish community index and other indicators of anthropogenic impact

Many multi-metric indices based on biotic communities are used for assessing the ecological quality of aquatic systems (Harrison and Whitfield 2004, 2006; Breine et al. 2007; Coates et al. 2007; Delpech et al. 2010; Cabral et al. 2012; Harrison and Kelly 2013). These indices were developed to satisfy one of the core criteria, namely that the ideal index be sensitive to all human-generated stress exerted on biological communities but also with limited sensitivity to natural variations in physical and biological environments (Cardoso et al. 2011). In the present study, the EFCI (Harrison and Whitfield

2004) developed for subtropical and predominantly open estuaries was used for comparing fish communities and health status. The value of the index was 38 for the URE, which indicates its poor ecological quality in terms of the fish community. The index has been effectively employed for assessing the ecological health of estuaries in Portugal (Cardoso et al. 2011) and Matigulu/Nyoni and Umvoti estuaries in South Africa (O'Brien et al. 2009) that are subject to stress in the form of excessive soil erosion, destruction and removal of riparian vegetation, nutrient enrichment, and severely reduced flow (Malherbe et al. 2008). For the South African estuaries, the EFCI ranged from 14 to 42 during 2004–2008, indicating progressively higher ecological quality over time (O'Brien et al. 2009). However, the present study has not considered temporal variations in the system status because of the limited time-series data available on attributes of the fish communities of interest. We therefore recommend continued use and development of different attributes of fish communities in such stressed coastal ecosystems as the URE. Such a database, together with long-term monitoring, can be valuable in devising effective management strategies to improve the quality of this sensitive ecosystem.

Baird and Ulanowicz (1993) related ecosystem properties with the pollution status of those estuaries and contended that the FCI for polluted estuaries would be higher than that for the less stressed estuaries. Patrıcio et al. (2004) also suggested FCI as a better indicator of ecosystem stress. The comparatively high value of the FCI for the URE (13.94%) suggests high anthropogenic disturbance to the ecosystem based on this assumption. Finn’s cycling index for the URE was much higher than that for most of the other tropical coastal systems such as the Zuari estuary (2.78) (Sreekanth et al. 2020); Vellar estuary (2.88) (Murugan et al. 2012); Pearl River estuary, China (2.72) (Duan et al. 2009); Canche estuary, France (0.8) (Selleslagh et al. 2012); Ogun estuary, Nigeria (2.29) (Abdul and Adekoya 2016); Arabian Sea off Karnataka coast (5.76) (Mohamed et al. 2008); the south-western coast of India (6.03) (Vivekanandan et al. 2003); Bay of Bengal (11.9) (Das et al. 2018); and Hooghly-Matlah (12.99) (Mukherjee et al. 2019).

However, according to Selleslagh et al. (2012), out of the seven candidate Ecopath indices widely used for explaining ecosystem status and function, the SOI would best reflect anthropogenic disturbance. Accordingly, they recommended SOI as the most potential index to assess food web functioning and ecological quality in estuarine and coastal ecosystems. Similar results were reported by Patrício and Marques (2006), who found low, intermediate, and high values of the SOI associated with non-eutrophic, intermediate, and strongly eutrophic areas. The moderate value of the SOI for the URE indicates a medium-to-high level of impact on the estuary of anthropogenic activity. The theory of the estuarine quality paradox (Dauvin et al. 2007; Elliott and Quintino 2007) states that coastal biological communities are seldom well adapted to cope with environmental stress. The present health status of the URE, graded acceptable based on the indicators despite the high anthropogenic pressure, may be because of adaptation by the estuarine community—a level of adaptation that may be nearing the breaking point. Overall, although the URE is close to the margin of acceptable ecosystem health at present, the indicators are pointing that in near future, the trophic structure and integrity of the entire ecosystem may be irreversibly damaged.

Conclusions

The Ecopath model developed for the URE revealed the trophic interactions, trophic transfers, and energy flow among 20 ecological compartments or TLs. The significance of the detritus-based pathway and the role of TL 2 and TL 3, especially that of Acetes, shrimps, clupeids, and anchovies in the trophic functioning, were evident from the model of the URE ecosystem. All indicators of ecosystem functioning including TST, NSP, CI, SOI, and the ratios of TPP to TR, TPP to TB, and TB to TST, pointed to an immature and developing ecosystem, although the high SO and low AS indicated a high redundancy in the ecosystem to withstand stress in the form of natural and anthropogenic perturbation. The current study provides some crucial insights into the applicability of ENA indices to examine ecosystem health in the face of prevailing anthropogenic stress. Based on these indicators of ecological stress, a moderate to high anthropogenic impact is evident in the URE. Considering the persistent disturbances to the ecosystem in the form of pollution and habitat degradation due to the proximity to the megapolis of Mumbai, the present situation of ecosystem functioning is indeed alarming. However, the high degree of resilience despite the chronic disturbance may reflect the adaptive capacity of the estuarine community coupled with relief in the form of periodic flushing during the south-west monsoon. These two features may be responsible for the enormous capacity of the system to assimilate effluents and pollutants.

In a nutshell, the present model developed for the URE can act as a base for future simulations of the ecosystem. However, since there is no targeted fishery existing in the ecosystem, it is inappropriate to suggest management strategies specific for the various functional groups in the ecosystem. The present study suggests that rather than the fishing effort in terms of number of boats or the hours of *dol* net operation, it is the use of finer codend mesh is causing devastating effects on the fishery. Hence, a slight modification in gear specifications can lead to improved community structure of the URE in due course by ensuring the abundance of commercially valuable groups of fish in the system as well as in the adjacent marine coastal waters. This abundance, in turn, will benefit the fisherfolk by increasing their income as well as by reducing the quantum of discarded juveniles, which is alarmingly high at present.

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Authors' contributions Dhanya M. Lal: Collection of data, analysis and Preparation of MS

Sreekanth G. B: Data analysis and interpretation

Avadootha Shivakrishna: Field sampling and manuscript editing

Ratheesh Kumar R: Site selection and technical Guidance

Binaya Bhusan Nayak: Technical guidance

Zeba Jaffer Abidi*: Overall supervision, guidance and manuscript correction

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Data availability All of the data generated or analyzed during this study are included in this article [and its supplementary information files].

Declarations

Ethical approval The authors hereby declare that the research article entitled "*Ecosystem health status and trophic modeling of an anthropogenically impacted small macrotidal tropical estuary along India's west coast*" is based on the field sampling in participatory mode, onboard with the traditional fishermen in the study site and performed in accordance with the relevant ethical standards in field sampling and data collection.

Consent to participate NA

Consent to publish All the authors have consented for the communication and subsequent publication of the manuscript entitled "*Ecosystem health status and trophic modeling of an anthropogenically impacted small macrotidal tropical estuary along India's west coast*" in the Journal: Environmental Science and Pollution Research.

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