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Aquatic health indicators: holistic evaluation tools for sustainable management of a tropical oxbow lake ecosystem

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ABSTRACT

Quantitative relationship of primary productivity and fish productivity and estimating aquatic health indices in tropical oxbow lake ecosystems remains to be addressed as predictors of fisheries yield in sustainable management. The aquatic health indicators and aquatic health status assessed with biological properties of phytoplankton, zooplankton, macroinvertebrates, macrophytes and fish in a semi-closed tropical oxbow lake ecosystem in the eastern India were studied along with socio-ecological and socio-economical aspects. Five ecological classes namely phytoplankton, zooplankton, macroinvertebrate, macrophyte and fish have been championed as effective biological indicators supported by physicochemical attributes. The established aquatic health indices registered the health status as moderate to poor. Organic loading and consequent nutrient enrichment and water quality deterioration during monsoon led to more homogeneous benthic biotic assemblage. With observed diverse nature of each trophic level of the ecosystem, there occurred a downstream 'spillover' of diversity along the food chain. The 'structure affecting structure' argument goes in tune with the theory of consumers controlling species diversity. Total 38 fish productivity regression equation models explained clearly that fish abundance and productivity were declining due to high anthropogenic activities of jute retting and indiscriminate uses of fishing gears of various mesh sizes during monsoon and thereafter, which need to be regulated.

Keywords: Aquatic health, Fish productivity, Jute retting, Oxbow lake

Introduction

A central principle of an ecosystem-based approach to fisheries management is the recognition that fisheries yield is mainly limited by primary production. To predict future fishery yield, environmental mechanisms have received a great deal of attention. Though the "bottom up" model to describe the productivity of fishery resources has been tested in a variety of ways and across a range of ecosystem types including coastal lagoons, estuaries, open marine systems and freshwater environments, much ambiguity remains regarding the predictive value of metrics of primary productivity to estimate fishery production. Anthropogenic impacts such as increased loadings of phosphorus in freshwater ecosystems are associated with increased phytoplankton biomass and subsequent fish yields in many lake ecosystems which necessitate verifying the quantitative relationships between primary production and fish productivity. Some works on oxbow lake management are widely and dispersedly available although the oxbow lakes are often described as "kidneys of the landscape" (Mitsch and Gosselink, 1986). Several workers have attempted to study the hydro-biological profile of varied water bodies with intent of assessing the quality of water. Wetlands represent a transitional zone between terrestrial uplands and aquatic bodies and are characterised by a large number of ecological niches which establish huge biological diversity. The wetlands of West Bengal were studied by several authors in the past (Mukherjee and Palit, 2001; Mandal *et al*., 2003; Chakraborty *et al*., 2004; Biswas *et al*., 2005; Palit *et al*., 2006; Biswas *et al*., 2007; Mandal and Mukherjee, 2007; Palit and Mukherjee, 2007; Bala and Mukherjee, 2011; Biswasroy *et al*., 2011)

Varied correlation studies on primary and secondary productivity (fish productivity) of different ecosystems have been conducted in the past (Srinivasan, 1972; Melack, 1976; Noreiga-Curtis, 1979; Olah *et al*., 1986; Iverson, 1990; Ware, 2000; Ware and Thomson, 2005; Chassot *et al*., 2007; Hayat and Javed, 2008; Friedland *et al*., 2012) where the ineffectiveness of primary production as an indicator of fisheries yield at a global scale was consistent with theoretical arguments supporting a more nuanced and complex relationship between the two quantities. However, information available on quantitative relationship of primary and fish productivity or estimating aquatic health indices in a tropical oxbow ecosystem in Ganga River basin in Nadia District in particular is lacking, which remain to be addressed as predictors of fisheries yields for adopting sustainable management measures.

Materials and methods

Study area

The Chhariganga Oxbow Lake, an abandoned, fractioned water body derived from the river Ganga located in Nakashipara Development Block of Nadia District, West Bengal, India (23.5800°N, 88.3500°E) was selected at random for the study. It is situated about 90 km away from the Kalyani University Campus, Nadia and nearly 40 km away from the line of Tropic of Cancer towards the north. It is a semi-closed type freshwater oxbow lake and receives water from the river Ganga during monsoon through a narrow channel at the north-east corner. The oxbow lake is spread over an area of 58.28 ha with an annual average depth of 2.6 m. It also stores rain water. The catchment area of the oxbow lake is nearly 600 ha (Fig. 1). The monsoon or rainy season from July to October, post-monsoon or winter from November to February and pre-monsoon or dry season from March to June are the distinct seasons of this region. There was an occasional inundation of surrounding banks during the monsoon. The oxbow lake is subjected to all forms of human activities including jute retting during monsoon, fishing in the oxbow lake and agriculture in the catchment areas. It is the only source of irrigation water to the adjacent agriculture communities. Summary of data collected on the Chhariganga Oxbow Lake and the summary of data on aquatic health indicators collected and analysed are given in Table 1 and 2.

Physicochemical, biological and socio-ecological/ economical analyses

The aquatic health indicators and aquatic health status of the Chhariganga Oxbow Lake Ecosystem (COLE) were assessed along with biological properties of phytoplankton, zooplankton, macroinvertebrate, macrophyte and fish. Physicochemical parameters were monitored as per Ghosh and Biswas (2017e; 2018). Biological parameters *viz*., phytoplankton (Ghosh and Biswas, 2015e), zooplankton (Ghosh and Biswas, 2014; 2015a), macroinvertebrates (Ghosh and Biswas, 2015b; 2017e), macrophytes (Ghosh and Biswas, 2015d), fishing gears and diversity (Ghosh and Biswas, 2017a; 2017c) were monitored. Fish sampling and assessment of productivity were carried out as per Ghosh and Biswas (2017b; 2017d). Socio-ecological and socio-economical studies were undertaken as described by Ghosh and Biswas (2016a, b).

From the above assessment of ecological, biological and socio-ecological/economical properties, the aquatic health indicators (as modified after Alberta Environment, 2007) and aquatic health status were evaluated for the Chhariganga Oxbow Lake during April, 2013 - March, 2014.

Statistical analyses

Statistical analyses including mean, standard deviation and the degree of relationships among different physicochemical factors of water and sediment were determined using linear regression with the help of MS-Excel and then presented in textual, tabular and graphical forms. The level of statistical significance was accepted at $p<0.05$.

Results and discussion

Aquatic health and productivity analyses

List of the aquatic health indices and pollution status of the Chhariganga Oxbow Lake Ecosystem (COLE) based on different aquatic health indicators is presented in

Fig. 1. Map showing study area (downloaded and modified on 26.06.2016 from https://www.google.co.in/maps/@23.5761796,88.229774,11837m/data=!3m1!1e3)

Table 1. Summary of data collected from Chhariganga Oxbow Lake

Assessment	Parameters
Ecological	For pre-monsoon, monsoon and post-monsoon (A) Physicochemical analyses ✓ Sediment (pH and organic carbon) ✓ Water Transparency, pH, Temperature, Dissolved oxygen (DO), Biochemical oxygen demand (BOD), Chemical oxygen demand COD, Ammonium nitrogen (NH_4-N), Nitrite nitrogen (NO_2-N), Nitrate nitrogen (NO_3-N), Orthophosphate, Total hardness, Total alkalinity, Gross primary productivity (GPP) and Net primary productivity (NPP) (B) Biological (Biodiversity analyses) ✓ Plankton (Phytoplankton and Zooplankton) ✓ Macroinvertebrate ✓ Macrophyte ✓ Fish
Economical	✓ Fish productivity, Demand and sale proceeds, Income, Employment ✓ Occupation and livelihoods generation, Dependency on fishing, Involvement of women in different econmic activities ✓ Income sources, House and land holdings pattern, Opportunities ✓ Fish consumption frequency, per *capita* consumption and sustenance need, Food sufficiency pattern ✓ Average price in changed climate, Adaptive measures, Constraints analyses on resource utilisation ✓ Cooperative management - economic, technical, marketing constraints, Finance capital for aquaculture ✓ Cooperative records on fish productivity, Income and profits ✓ Estimation of sustainable fish productivity
Social	✓ Educational, professional, legal and ethical aspects, Living standards ✓ Community needs and constraints, Priority problems, Encroachments and other activities of non fishers ✓ Households involvement in fishing and fishing frequency, Crafts and gears used in fishing, Days of operation ✓ Constraints analyses of cooperative management (social, technical and general) ✓ Opinion on ecological changes in last 30 years, Biodiversity for sustainable management ✓ Knowledge level on oxbow lake ecosystem management benefits and dangers ✓ Priority issues for sustainable management, Overall ranking of importance values of major issues ✓ Conducting seminars/meetings with all stakeholders

Table 2. Summary of data collected and analysed on aquatic health indicators

	Index	Phytoplankton			Zooplankton			Macroinvertebrates			Macrophytes			Fish		
S. No.	Season	PRM	MON	POM	PRM	MON	POM	PRM	MON	POM	PRM	MON	POM	PRM	MON	POM
1	Total abundance or density	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
2	Standing biomass	×	×	×	×	×	×	✓	✓	✓	✓	✓	✓	✓	✓	✓
3	Relative abundance and proportion	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
4	EPT index and % EPT	×	×	×	×	×	×	✓	✓	✓	×	×	×	×	×	×
5	Catch per unit effort (CPUE)	×	×	×	×	×	×	×	×	×	×	×	×	✓	✓	✓
6	Catch per gear effort (CPGE)	×	×	×	×	×	×	×	×	×	×	×	×	✓	✓	✓
7	Taxon richness	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
8	Shannon Wiener Index (SWI)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
9	Taxon evenness	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
10	Simpson's dominance Index	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
11	Simpson's diversity Index	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
12	Invasive species	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
13	Productivity	✓	✓	✓	×	×	×	×	×	×	×	×	×	✓	✓	✓
14	Trophic classification	✓	✓	✓	×	×	×	×	×	×	✓	✓	✓	✓	✓	✓
15	Aquatic health and pollution status	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Index S. No 6-7 for both in biomass and number but S. No 9-12 for number only, not for biomass of the aquatic health indicators,
✓refers to 'Yes to be done' and × refers to 'Not to be done'
PRM = Pre-monsoon, MON = Monsoon, POM = Post-monsoon

Table 3. The COLE looks polluted (bad to moderate) based on Shannon Wiener Index (SWI) of macroinvertebrate, phytoplankton, zooplankton, macrophytes and fish. Zooplankton SWI clearly indicated overall bad condition and macrophyte SWI showed overall moderate pollution throughout the year. The fish SWI revealed bad status except during monsoon when inflowing water from river helps in contributing slightly higher diversity and thus making moderate pollution status of the COLE during the monsoon when the macroinvertebrate and phytoplankton SWI diversity values pinpointed the bad ecological status of COLE. The overall pollution status of the Chhariganga Oxbow Lake based on both physicochemical and biological analyses is bad to moderate in all respects.

Physicochemical properties and biological abundance

In present study on oxbow lake, we found highly significant correlation between water nitrate nitrogen content and phytoplankton density; biochemical oxygen demand (BOD) and macroinvertebrate density; sediment organic content and macroinvertebrate standing biomass; water pH and macrophytes density as well as total alkalinity and effective water spread area (EWSA) fish productivity (g m^{-2} d^{-1}) (Table 4). Similarly highly positive correlations were also found between temperature/hardness/alkalinity and zooplankton density; BOD and macroinvertebrates biomass; macroinvertebrate biomass and fish catch per gear effort (CPGE) (n e^{-1}); ammonium nitrogen/nitrate nitrogen/DO and macrophytes biomass; orthophosphate/sediment organic content/BOD and macroinvertebrates density; zooplankton density and CPGE (g e^{-1}); recorded area (RAW) fish biomass and EWSA fish biomass (r=0.89); EWSA fish density and RAW fish density/biomass (r=0.95) as well as EWSA fish density and EWSA fish biomass. But present results also clearly demonstrated very strong negative correlation between phytoplankton density and zooplankton density; macrophytes density and orthophosphate content; macrophytes biomass and DO/water ammonium nitrogen/nitrate nitrogen; fish CPGE (g e^{-1}) and water ammonium nitrogen as well as fish CPGE

Table 3. Aquatic health indices ($p<0.05$) of the Chhariganga Oxbow Lake ecosystem

	Index	Phytoplankton			Zooplankton			Macroinvertebrate			Macrophyte			Fish		
S. No.	Season	PRM	MON	POM	PRM	MON	POM	PRM	MON	POM	PRM	MON	POM	PRM	MON	POM
1	RAW total abundance / density	3650	4680	8760	520	440	125	129	359	191	113.2	27.3	120.45	0.83	2.21	1.54
2	EWSA total abundance/ density	3650	4680	8760	520	440	125	129	359	191	113.2	27.3	120.45	2.43	2.58	2.99
3	RAW Standing biomass (g m^{-3})	×	×	×	×	×	×	95.64	286.65	178.56	424.49	281.78	1816.72	17.33	17.43	10.19
4	EWSA Standing biomass (g m^{-3})	×	×	×	×	×	×	95.64	286.65	178.56	424.49	281.78	1816.72	50.50	20.32	19.80
5	Relative abundance and proportion	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
6	% EPT	×	×	×	×	×	×	Nil	Nil	Nil	×	×	×	×	×	×
7	EPT index	×	×	×	×	×	×	Nil	Nil	Nil	×	×	×	×	×	×
8	CPUE (g h^{-1})	×	×	×	×	×	×	×	×	×	×	×	×	5.07	3.98	3.33
9	CPUE (n h^{-1})	×	×	×	×	×	×	×	×	×	×	×	×	0.24	0.5	0.5
10	CPGE (g e^{-1})	×	×	×	×	×	×	×	×	×	×	×	×	36.38	36.19	23.31
11	CPGE (n e^{-1})	×	×	×	×	×	×	×	×	×	×	×	×	1.75	4.59	3.52
12	Taxon richness	22	14	23	6	5	4	14	14	18	36	22	44	28	23	26
13	Shannon Wiener diversity Index	2.16	1.61	2.42	1.53	1.37	1.33	2.1	1.88	2.12	2.64	2.45	3.14	1.82	2.02	1.19
14	Taxon evenness	0.7	0.61	0.77	0.85	0.85	0.96	0.8	0.71	0.73	0.74	0.79	0.83	0.54	0.64	0.36
15	Simpson's dominance Index	0.19	0.32	0.14	0.28	0.3	0.27	0.15	0.22	0.2	0.12	0.13	0.06	0.28	0.21	0.51
16	Simpson's diversity Index	0.81	0.68	0.86	0.72	0.7	0.73	0.85	0.78	0.8	0.88	0.87	0.94	0.72	0.79	0.49
17	Invasive species	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	*Eichhornia, Wolffia*	Nil	Nil	Nil	Nil
18	Productivity	1.26	0.61	1.04	×	×	×	×	×	×	×	×	×	0.53	0.18	0.21
19	Trophic classification	Oligo to Mesotrophic			×	×	×	×	×	×	Oligotrophic			M	B	B
20	Aquatic health and pollution status	M	B	M	B	B	B	M	B	M	M	M	M	B	M	B

PRM=Pre-monsoon, MON=Monsoon, POM=Post-monsoon, RAW=Recorded area of water body, EWSA=Effective water spread area, Density of plankton (no. l^{-1}) and of others (n m^{-3}), M=Moderate, B=Bad; Index S. No 11-14 for number only, not for biomass of the aquatic health indicators, ✓refers to 'Yes done' (please refer to respective results sections of 4.2 & 4.7), × refers to 'Not done', phytoplankton productivity as NPP (gC m^{-3} d^{-1}) and average fish productivity of ESWA (g m^{-3} d^{-1})

Table 4. Correlation coefficients ($p<0.05$) of physicochemical and biological parameters in Chhariganga Oxbow Lake

Parameter	PD	ZD	MD	MB	MPD	MPB	CPGE^g	CPGE^n	CPUE^g	CPUE^n	RFD	RFB	RFP	EFD	EFB	EFP^2	EFP^3
SpH	0.79	-0.79	0.56	0.70	-0.26	0.59	-0.66	0.84	-0.98	0.98	0.24	-0.15	-0.07	0.06	-0.53	-1.00	-0.95
SOC	0.07	-0.07	0.99	1.00	-0.89	-0.20	0.11	0.96	-0.53	0.80	0.32	0.03	0.69	0.01	-0.42	-0.68	-0.83
Tr	-0.41	0.41	-0.88	-0.95	0.68	-0.15	0.24	-0.99	0.79	-0.96	-0.32	0.04	-0.40	-0.05	0.50	0.89	0.97
WpH	0.47	-0.47	-0.91	-0.82	1.00	0.69	-0.62	-0.68	0.00	-0.37	-0.27	-0.17	-0.97	0.01	0.16	0.19	0.43
Temp	-0.99	0.99	0.17	-0.01	-0.48	-0.98	1.00	-0.22	0.83	-0.57	-0.01	0.24	0.74	-0.06	0.33	0.71	0.50
DO	0.80	-0.80	-0.66	-0.51	0.87	0.93	-0.89	-0.31	-0.42	0.06	-0.17	-0.23	-0.98	0.03	-0.07	-0.24	0.01
BOD	-0.08	0.08	1.00	0.98	-0.95	-0.35	0.25	0.92	-0.39	0.71	0.33	0.08	0.79	0.02	-0.35	-0.57	-0.75
COD	-0.02	0.02	1.00	0.99	-0.93	-0.29	0.20	0.94	-0.44	0.74	0.31	0.04	0.76	0.00	-0.39	-0.61	-0.78
NH_4	0.99	-0.99	-0.19	-0.01	0.50	0.99	-1.00	0.21	-0.82	0.55	0.06	-0.19	-0.76	0.12	-0.27	-0.70	-0.50
NO2	-0.07	0.07	-0.99	-1.00	0.89	0.20	-0.10	-0.96	0.53	-0.80	-0.32	-0.02	-0.69	-0.01	0.42	0.68	0.83
NO3	1.00	-1.00	-0.12	0.07	0.44	0.97	-0.99	0.28	-0.86	0.61	0.08	-0.19	-0.71	0.12	-0.30	-0.75	-0.56
OP	-0.45	0.45	0.92	0.83	-1.00	-0.68	0.60	0.69	-0.01	0.38	0.23	0.12	0.96	-0.05	-0.21	-0.21	-0.43
TH	-0.85	0.85	-0.47	-0.62	0.15	-0.68	0.74	-0.77	1.00	-0.95	-0.21	0.17	0.18	-0.07	0.51	0.99	0.92
TA	-0.83	0.83	-0.50	-0.65	0.19	-0.65	0.72	-0.80	0.99	-0.96	-0.22	0.16	0.14	-0.07	0.52	1.00	0.93
GPP	-0.09	0.09	-0.99	-1.00	0.88	0.19	-0.09	-0.97	0.54	-0.81	-0.34	-0.04	-0.68	-0.03	0.41	0.69	0.84
NPP	-0.01	0.01	-1.00	-0.99	0.92	0.27	-0.17	-0.95	0.47	-0.76	-0.34	-0.06	-0.74	-0.03	0.38	0.63	0.80
PD		-1.00	-0.07	0.12	0.39	0.96	-0.98	0.32	-0.89	0.65	0.07	-0.22	-0.67	0.08	-0.35	-0.78	-0.59
ZD			0.07	-0.12	-0.39	-0.96	0.98	-0.32	0.89	-0.65	-0.07	0.22	0.67	-0.08	0.35	0.78	0.59
MD				0.98	-0.94	-0.34	0.24	0.92	-0.40	0.71	0.31	0.06	0.79	0.00	-0.37	-0.57	-0.75
MB					-0.87	-0.16	0.06	0.97	-0.56	0.83	0.32	0.02	0.66	0.02	-0.43	-0.71	-0.85
MPD						0.63	-0.55	-0.74	0.08	-0.44	-0.27	-0.13	-0.94	0.03	0.22	0.27	0.50
MPB							-1.00	0.05	-0.73	0.42	-0.02	-0.22	-0.85	0.08	-0.23	-0.58	-0.35
CPGE^g								-0.15	0.79	-0.50	0.01	0.24	0.79	-0.07	0.29	0.65	0.44
CPGE^n									-0.73	0.93	0.39	0.04	0.48	0.11	-0.42	-0.85	-0.95
CPUE^g										-0.93	-0.25	0.13	0.25	-0.12	0.46	0.98	0.90
CPUE^n											0.37	-0.02	0.12	0.15	-0.45	-0.98	-1.00
RFD												0.92	0.18	0.95	0.65	-0.29	-0.43
RFB													0.17	0.95	0.89	0.10	-0.06
RFP														-0.06	-0.06	0.06	-0.19
EFD															0.81	-0.11	-0.21
EFB																0.49	0.39

PRM=Pre-monsoon, MON=Monsoon, POM=Post-monsoon, SpH=Sediment pH, SOC=Sediment organic carbon (%), Tr=Transparency (cm), WpH=Water pH, TH=Total Hardness (ppm), TA=Total alkalinity (ppm), GPP/NPP=Gross/Net primary productivity (gC m^{-3} d^{-1}), PD=Phytoplankton density (no. l^{-1}), ZD=Zooplankton density (no. l^{-1}), MD=Macroinvertebrate density (no. m^{-3}), MB= Macroinvertebrate standing biomass (g m^{-3}), MPD=Macrophyte density (no, m^{-3}), MPB= Macrophyte standing biomass (g m^{-3}), CPGE^g = Fish catch per gear effort (g e^{-1}), CPGE^n= Fish catch per gear effort (n e^{-1}), CPUE^g= Fish catch per unit effort (g h^{-1}), CPUE^n= Fish catch per unit effort (n h^{-1}), RFD=RAW Fish density (no. m^{-3}), RFB=RAW fish standing biomass (g m^{-3}), RFP= RAW fish productivity (g m^{-2} d^{-1}), RAW=Recorded area of water body, EFD=EWSA fish density (no. m^{-3}), EFB=EWSA Fish standing biomass (g m^{-3}), EFP^2= EWSA Fish productivity (g m^{-2} d^{-1}), EFP^3= EWSA Fish productivity (g m^{-3} d^{-1}), EWSA=Effective water spread area

(g e^{-1}) and macrophytes biomass. Similarly significant negative correlations were also found between water ammonium nitrogen content and zooplankton density; macroinvertebrate density and transparency/water pH; fish CPGE (g e^{-1}) and phytoplankton density as well as macrophytes density/biomass and RAW fish productivity (g m^{-2} d^{-1}).

Physicochemical properties and fish production

The fish productivity (g m^{-2} d^{-1}) showed positive correlation with sediment organic carbon content and BOD, chemical oxygen demand (COD), orthophosphate (OP), macroinvertebrates density, CPGE (n e^{-1}), catch per unit effort (CPUE) (n h^{-1}) and fish density in RAW in contrast with ESWA, where the fish productivity (g m^{-2} d^{-1}) showed positive correlation with water transparency, water pH, primary productivity (r=0.69) and macrophytes density. The fish productivity (g m^{-2} d^{-1}) of both RAW and EWSA exhibited positive correlations with temperature, hardness and alkalinity, zooplankton density, CPGE (g e^{-1}) and CPUE (g h^{-1}) and showed negative correlation with sediment pH and NH_4. EWSA fish productivity (g m^{-2} d^{-1}) strongly correlated (r=1) with total alkalinity (Table 4). In the analyses on correlation coefficients of different physicochemical parameters and EWSA fish productivity, the latter was influenced by almost all the parameters studied and remarkably by the sediment pH, transparency, hardness, alkalinity, CPUE and CPGE whereas the RAW fish productivity is considerably influenced by the water pH, DO, orthophosphate, macrophytes density and biomass as well as CPGE. Fish productivity of the EWSA was found strongly correlated with the total alkalinity but inversed to the sediment pH. The correlation coefficients (r=0.79) of CPUE and CPGE indicate similarity in their meaning. The correlation coefficient (r=0.90) between the fish density and its standing biomass in both RAW and EWSA indicated highly significant positive correlation between them.

Twenty regression equations were confirmed based on the relationship of primary production and fish production in the COLE (Table 5). Out of which, 4 regression equations of primary productivity (GPP and NPP) and fish productivity (g m^{-2} d^{-1}) were calculated to be with negative slopes as they are negatively correlated in case of RAW and another 4 of them with negative intercepts but with the best positive correlation coefficients (0.79 and 0.84) when fish productivity was considered in g m^{-3} $d^{-1}$for EWSA. But as both the primary (X) and secondary productions (Y) are positively correlated (r=0.69 and 0.63) in EWSA, the remaining 12 regression equations were shown positive. The regression equation in EWSA is calculated as log Y =6.89+0.22X, r=0.64, where gross primary productivity and fish productivity (EFP) are in g O_2 m^{-3} day^{-1} and natural logarithm value in kg ha^{-1} yr^{-1} considered respectively. The equation became Y =0.10+0.18X, r=0.69, when we considered GPP in gO_2 m^{-3} d^{-1} and EWSA fish productivity (EFP) in g m^{-2} d^{-1}, again became Y =0.10+0.49X, r=0.69, for GPP in gC m^{-3} d^{-1} and EFP in g m^{-2} $d^{-1}$and Y = 0.40X-0.22, r=0.84, for EFP in g m^{-3} d^{-1}. Likewise considering NPP in gO_2 m^{-3} d^{-1}, we found Y =0.17+0.21X, r=0.63 for EFP in g m^{-2} d^{-1} and Y = 0.18X-0.17, r=0.79, for EFP in g m^{-3} d^{-1}.

It is obvious from the equations that fish production (secondary production) is related to primary production in the oxbow lake. Good correlation was also found between primary productivity and secondary fish productivity (kg ha^{-1} yr^{-1}) besides positive regression equations in EWSA. Several workers reported strong relationships between primary production (or chlorophyll-a as a proxy of primary production) and fish yield in freshwater environments (Goodyear *et al*., 1972; Srinivasan, 1972; Melack, 1976; Noreiga-Curtis, 1979) as well as in ocean and coastal environments (Iverson, 1990; Ware and Thomson, 2005; Frank *et al*., 2006; Chassot *et al*., 2007; Friedland *et al*., 2012). The fish production efficiency which is the fish yield (g m^{-3} d^{-1}) expressed as a percentage of the primary production (GPP in gC m^{-3} d^{-1}) varied between 16.11 - 32.02% in EWSA of the present oxbow lake and

Table 5. Relationship of primary production and fish production ($p<0.05$)

COLE	Primary productivity (X)	Fish productivity (Y)	Regression equation	
	Unit	Unit	Through Oxygen production	Through Carbon production
RAW	GPP (gO_2 m^{-3} d^{-1})	RFP kg ha^{-1} y^{-1}	log Y = 7.66 -0.19 X, r=-0.60	-
EWSA		EFP kg ha^{-1} y^{-1}	log Y = 6.89+ 0.22X, r=0.64	-
		EFP g m^{-2} d^{-1}	Y =0.10+0.18X, r=0.69	-
		EFP g m^{-3} d^{-1}	Y = 0.15X-0.22, r=0.84	-
		pFP g m^{-2} y^{-1}	Y =28.76+55.48X, r=0.69	-
RAW	GPP (gC m^{-3} d^{-1})	RFP kg ha^{-1} y^{-1}	-	log Y = 7.66 -0.51 X, r=-0.60
EWSA		EFP kg ha^{-1} y^{-1}	-	log Y = 6.89+ 0.60X, r=0.64
		EFP g m^{-2} d^{-1}	-	Y =0.10+0.49X, r=0.69
		EFP g m^{-3} d^{-1}	-	Y = 0.40X-0.22, r=0.84
		EFP g m^{-2} y^{-1}	-	Y=28.76+147.96X, r=0.69
RAW	NPP (gO_2 m^{-3} d^{-1})	RFP kg ha^{-1} y^{-1}	log Y =7.71 - 0.27 X, r=-0.67	-
EWSA		EFP kg ha^{-1} y^{-1}	log Y = 7.00+ 0.25 X, r=0.57	-
		EFP g m^{-2} d^{-1}	Y =0.17+0.21X, r=0.63	-
		EFP g m^{-3} d^{-1}	Y = 0.18X-0.17, r=0.79	-
		EFP g m^{-2} y^{-1}	Y=52.25+63.43X, r=0.63	-
RAW	NPP (gC m^{-3} d^{-1})	RFP kg ha^{-1} y^{-1}	-	log Y =7.71 - 0.71 X, r=-0.67
EWSA		EFP kg ha^{-1} y^{-1}	-	log Y = 7.00+ 0.67 X, r=0.57
		EFP g m^{-2} d^{-1}	-	Y =0.17+0.56X, r=0.63
		EFP g m^{-3} d^{-1}	-	Y = 0.47X-0.17, r=0.79
		EFP g m^{-2} y^{-1}	-	Y=52.25+169.14X, r=0.63

RFP=Raw fish productivity, EFP=EWSA fish productivity, RAW=Recorded area of water body, EWSA=Effective water spread area, d=Day, y=Year, h=Hour, Y= Fish yield or fish production, COLE= Chhariganga Oxbow Lake ecosystem was higher in values compared to the observations by Olah *et al*. (1986). Higher fish production efficiencies in the present study may be attributed to the extra auto stocking of fish in flood water influx from river Ganga during monsoon. As there was no fish stocking done for culture purpose by the fishers associated with the oxbow lake ecosystem under study and only fish auto stocking occurring during monsoon along with the water influx from the Ganga River, the above regression equations of fish production obtained are purely based on fish capture alone unlike in case of other correlation studies.

Fish abundance and fish production

In finding relationships between fish abundance, availability and fish productivity (g m^{-3} d^{-1}), 12 regression equations were obtained between any two of the seasons (S. Nos. 01-12 of the Table 6) when respective seasonal mean values of fish catch per gear effort (g e^{-1}), fish catch per unit effort (g h^{-1}), RAW fish standing biomass (g m^{-3}), RAW fish productivity (g m^{-3} d^{-1}), EWSA fish standing biomass (g m^{-3}) and EWSA fish productivity (g m^{-3} d^{-1}) were considered. Only one equation between the pre-monsoon and post-monsoon is negative among all because of negative intercept during the post-monsoon compared to pre-monsoon, whereas rest 11 equations have positive intercepts. We also found another 6 regression equations (S. Nos. 13-18 of the Table 6) when fish productivity (g m^{-3} d^{-1}) and fish relative biomass abundance parameters like CPGE, CPUE and standing crop were considered both in recorded and effective area of the oxbow lake. Fish productivity (g m^{-3} d^{-1}) had 4 negative intercepts with CPGE and CPUE and also had almost no slopes (regression coefficients) except very little one with CPUE in both the areas.

Physicochemical properties and biodiversity

A very strong correlation of phytoplankton richness was found with the water pH. Strong correlation was also noted between phytoplankton Shannon Weiner Index (SWI) and its richness, water pH and water orthophosphate content. While the zooplankton SWI showed strong correlation with water total alkalinity, both the zooplankton richness and its SWI showed too very strong correlation with water transparency, total hardness and alkalinity. Macroinvertebrate richness showed strong correlation with water NO_3-N content, whereas its SWI showed very strong correlation with water pH and phytoplankton richness but inversed to the water OP content. Macrophyte richness as well as its SWI showed very strong correlation with phytoplankton SWI as well as strong correlation with water pH and DO content. Fish richness was found strongly correlated with GPP and NPP but inversely correlated with sediment organic content, BOD and COD. Similarly fish Evenness index showed highly significant correlation with

Table 6. Seasonal relationship between fish abundance and fish production ($p<0.05$)

S. No.	Y	X	Fish productivity (g m^{-2} d^{-1})	Fish productivity (g m^{-3} d^{-1})
1	PRM	MON	Y=2.57+1.21X, r=0.82	Y=2.55+1.21X, r=0.82
2	MON	PRM	Y=2.85+0.56X, r=0.82	Y=2.80+0.56X, r=0.82
3	PRM	POM	Y=1.96X-0.29, r=0.94	Y=1.96X-0.28, r=0.95
4	POM	PRM	Y=1.16+0.46X, r=0.94	Y=1.14+0.46X, r=0.95
5	PRM	YR	Y=2.16+0.62X, r=0.91	Y=2.07+0.62X, r=0.91
6	YR	PRM	Y=1.62+1.34X, r=0.91	Y=1.69+1.34X, r=0.91
7	YR	POM	Y=3.21+2.42X, r=0.79	Y=3.28+2.42X, r=0.79
8	POM	YR	Y=2.73+0.26X, r=0.79	Y=2.67+0.26X, r=0.79
9	YR	MON	Y=7.64+1.42X, r=0.66	Y=7.65+1.42X, r=0.66
10	MON	YR	Y=5.16+0.30X, r=0.66	Y=5.06+0.31X, r=0.66
11	MON	POM	Y=0.19+1.36X, r=0.96	Y=0.17+1.36X, r=0.96
12	POM	MON	Y=0.61+0.68X, r=0.96	Y=0.60+0.68X, r=0.96
13	RFP	RFB	Y=0.35+0.001X, r=0.17	Y=0.141+0.0004X, r=0.20
14	RFP	$CPGE^g$	Y=0.01X-0.07, r=0.79	Y=0.005X-0.001, r=0.95
15	RFP	$CPUE^g$	Y=0.23+0.04X, r=0.25	Y=0.04X-0.013, r=0.94
16	EFP	EFB	Y=0.54+0.004X, r=0.49	Y=0.20+0.002X, r=0.39
17	EFP	$CPGE^g$	Y=0.03X-0.11, r=0.65	Y=0.011X-0.07, r=0.44
18	EFP	$CPUE^g$	Y=0.33X-0.63, r=0.98	Y=0.20X-0.52, r=0.90

PRM=Pre-monsoon, MON=Monsoon, POM=Post-monsoon, YR=year, $CPGE^g$= Fish catch per gear effort (g e^{-1}), $CPUE^g$= Fish catch per unit effort (g h^{-1}), RFB=RAW fish standing biomass (g m^{-3}), RFP= RAW fish productivity (g m^{-3} d^{-1}), RAW=Recorded area of water body, EFB=EWSA fish standing biomass (g m^{-3}), EFP= EWSA fish productivity (g m^{-3} d^{-1}), EWSA=Effective water spread area macrophyte SWI. The fish Simpson's diversity index (FSI) had strong correlation with fish SWI unlike macrophyte SWI (Table 7). Physicochemical parameters including water pH, transparency, BOD, COD (except temperature, ammonium nitrogen, and nitrate nitrogen) and biological parameters (primary productivity and biodiversity) were found to be having significant impacts on fish richness. Parameters including water temperature, DO, NH_4-N, NO_3-N, phytoplankton SWI, macroinvertebrate richness as well as macrophyte richness and its SWI had more effects on fish diversity (SWI). Fish SWI showed positive correlation with zooplankton richness and SWI among the diversity indices of other community. The fish SWI had no linear relationship with water transparency but had inverse relationship with water DO content, which may also be attributed to the fish and turbid flood water influx from the river and higher organic solids due to jute retting event leading to poor transparency and DO levels as well as highest fish catch during the monsoon.

Biodiversity and productivity

Phytoplankton richness and SWI showed strong correlation with fish richness (r=0.87, 0.75) but inversed to fish SWI (Table 8). Zooplankton richness and diversity index were strongly correlated with fish richness, diversity and productivity. Zooplankton diversity was strongly correlated with fish productivity (g m^{-2} d^{-1}). Macroinvertebrates richness and diversity index were strongly correlated with fish richness but inversed to fish diversity (SWI). Their SWI of diversity was strongly correlated with fish productivity (g m^{-2} d^{-1}) but not with their richness. Their richness highly correlated with fish richness (r=0.71). Overall fish richness and fish diversity (SWI) were correlated with fish productivity (g m^{-2} d^{-1}). Fish diversity (SWI) also strongly correlated

Table 7. Correlation coefficients of physicochemical parameters and biodiversity indices ($p<0.05$)

Parameter	PS	PH'	ZS	ZH'	MS	MH'	MPS	MPH'	FS	FH'	FE	FSI
SpH	-0.23	-0.01	-0.94	-1.00	0.65	-0.26	0.03	0.43	-0.68	-0.46	-0.35	-0.47
SOC	-0.87	-0.75	-0.39	-0.67	-0.12	-0.89	-0.72	-0.38	-1.00	0.34	0.46	0.34
Tr	0.65	0.47	0.69	0.89	-0.23	0.67	0.43	0.04	0.94	0.00	-0.13	0.01
WpH	1.00	0.99	-0.16	0.18	0.63	1.00	0.98	0.81	0.84	-0.79	-0.86	-0.79
T	-0.51	-0.68	0.91	0.72	-1.00	-0.49	-0.72	-0.94	-0.03	0.95	0.90	0.95
DO	0.88	0.96	-0.56	-0.25	0.90	0.87	0.97	0.98	0.54	-0.97	-0.99	-0.97
BOD	-0.94	-0.84	-0.25	-0.56	-0.27	-0.95	-0.81	-0.51	-0.99	0.48	0.59	0.47
COD	-0.92	-0.81	-0.31	-0.60	-0.21	-0.93	-0.78	-0.46	-1.00	0.43	0.54	0.42
NH_4-N	0.53	0.70	-0.90	-0.70	1.00	0.51	0.73	0.94	0.05	-0.95	-0.91	-0.96
NO_2-N	0.87	0.75	0.39	0.67	0.12	0.89	0.72	0.38	1.00	-0.34	-0.46	-0.34
NO_3-N	0.46	0.64	-0.93	-0.76	0.99	0.44	0.68	0.92	-0.03	-0.93	-0.88	-0.93
OP	-1.00	-0.98	0.14	-0.19	-0.61	-1.00	-0.97	-0.80	-0.85	0.78	0.85	0.77
TH	0.12	-0.10	0.98	0.99	-0.74	0.14	-0.15	-0.53	0.59	0.56	0.45	0.57
TA	0.16	-0.06	0.97	1.00	-0.71	0.19	-0.11	-0.49	0.62	0.53	0.41	0.53
GPP	0.87	0.74	0.41	0.69	0.10	0.88	0.70	0.36	1.00	-0.33	-0.45	-0.32
NPP	0.90	0.79	0.33	0.62	0.18	0.92	0.76	0.44	1.00	-0.41	-0.52	-0.40
PS		0.98	-0.10	0.23	0.59	1.00	0.96	0.78	0.87	-0.76	-0.83	-0.75
PH'			-0.31	0.01	0.75	0.97	1.00	0.90	0.75	-0.88	-0.93	-0.88
ZS				0.94	-0.87	-0.08	-0.36	-0.70	0.40	0.73	0.63	0.73
ZH'					-0.65	0.26	-0.03	-0.43	0.68	0.46	0.35	0.47
MS						0.56	0.78	0.96	0.11	-0.97	-0.94	-0.97
MH'							0.96	0.76	0.89	-0.74	-0.82	-0.73
MPS								0.92	0.71	-0.90	-0.95	-0.90
MPH'									0.38	-1.00	-1.00	-1.00
FS										-0.34	-0.46	-0.33
FH'											0.99	1.00
FE												0.99

SpH=Sediment pH, SOC=Sediment organic carbon, Tr=Transparency, T=Temperature, WpH=Water pH, TH=Total hardness, TA=Total alkalinity, PS=Phytoplankton richness, PH'=Phytoplankton Shannon Wiener diversity index, ZS= Zooplankton richness, ZH'= Zooplankton Shannon Wiener diversity index, MS=Macroinvertebrate richness, MH'= Macroinvertebrate Shannon Wiener diversity index, MPS=Macrophytes richness, MPH'= Macrophytes Shannon Wiener diversity index, FS=Fish richness, FH'=Fish Shannon Wiener diversity index, FE=Fish Evenness index, FSI=Fish Simpson's diversity index (SDI)

Table 8. Correlation coefficients of biodiversity and fish productivity ($p<0.05$)

Indicator	RFP	FS	FH’	EFP[2]	EFP[3]
PS	-0.95	0.87	-0.76	0.24	0.47
PH’	-1.00	0.75	-0.88	0.03	0.27
ZS	0.39	0.40	0.73	0.94	0.82
ZH’	0.07	0.68	0.46	1.00	0.95
MS	-0.80	0.11	-0.97	-0.65	-0.43
MH’	-0.95	0.89	-0.74	0.27	0.49
MPS	-1.00	0.71	-0.90	-0.02	0.22
MPH’	-0.93	0.38	-1.00	-0.42	-0.18
RFP		-0.69	0.92	0.06	-0.19
FS			-0.34	0.68	0.83
FH’				0.45	0.21

PS=Phytoplankton richness, PH’=Phytoplankton Shannon Wiener diversity index, ZS=Zooplankton richness, ZH’=Zooplankton Shannon Wiener diversity index, MS=Macroinvertebrate richness, MH’=Macroinvertebrate Shannon Wiener diversity index, MPS=Macrophytes richness, MPH’= Macrophytes Shannon Wiener diversity index, FS=Fish richness, FH’=Fish Shannon Wiener diversity index, RFP= RAW fish productivity ($g\ m^{-2}\ d^{-1}$), RAW=Recorded area of water body, EFP[2]= EWSA fish productivity ($g\ m^{-2}\ d^{-1}$), EFP[3]= EWSA fish productivity ($g\ m^{-3}\ d^{-1}$), EWSA=Effective water spread area

with the fish productivity ($g\ m^{-2}\ d^{-1}$) of RAW (r=0.92) than EWSA (r=0.45). Fish productivity in EWSA was strongly influenced by zooplankton diversity and macrophytes diversity, but not by phytoplankton diversity and macrophytes richness of the Chhariganga Oxbow Lake, whereas it was found inversed in relationship with macrophytes diversity. The fish diversity (SWI) was more correlated with its RAW productivity compared to its EWSA productivity. But fish productivity is more strongly correlated with its standing biomass of EWSA compared to RAW. This may also be attributed to fish influx through the flood water from the river during monsoon.

The poor health status assessed with the physicochemical properties does also corroborate with the findings of the studies on the same oxbow lake assessed with diversity indices of rotifer (Ghosh and Biswas, 2014), zooplankton (Ghosh and Biswas, 2015a), macroinvertebrates (Ghosh and Biswas, 2015b), macrophytes (Ghosh and Biswas, 2015d), phytoplankton (Ghosh and Biswas, 2015e), fish diversity (Ghosh and Biswas, 2017a; 2017c), fish productivity (Ghosh and Biswas, 2017b; 2017d) and physicochemical studies (Ghosh and Biswas, 2017e; 2018) undertaken during the same period of study in the same oxbow lake.

In the present oxbow lake ecosystem, lone fish productivity regression equation model between the pre-monsoon and post-monsoon season is found negative indicating huge decline in fish abundance, availability and productivity during the post-monsoon compared to pre-monsoon. Negative intercepts of fish productivity models with fish catch per unit or gear effort and almost no slopes with the fish abundance may also be attributed to the high anthropogenic activities including jute retting, indiscriminate use of fishing gears of various mesh size during monsoon and post-monsoon, which resulted in the decline in fish abundance, availability and productivity in the oxbow lake. The flooded turbid water from river Ganga and jute retting processes during the monsoon had significant impacts on fish diversity and fish productivity in the oxbow lake ecosystem. We also observed diverse trophic levels of the ecosystem under study. The ‘spillover’ of diversity occurs to other parts of the ecosystem. This ‘structure affecting structure’ argument goes in tune with the theory of consumers controlling species diversity (Worm *et al.,* 2002).

The present study including its outputs and their analysis was presented in the DPSIR (Driver-Pressure-State-Impact-Response) framework that could be adopted as a template for sustainable management of similar oxbow lake ecosystems satisfying the triple bottom lines of ecological/environmental protection, economic viability and social security (Fig. 2). The findings from the study will benefit the planning and management of sustainable fisheries and conservation of these natural resources at national level.

The fish diversity was significantly correlated with its productivity of recorded area than the effective area and the fish productivity was more strongly correlated with its standing biomass of the effective area than the recorded area due to fish influx through the flood water from the river during the monsoon. Fish productivity regression equation models (20 based on primary productivity and 18 based on fish abundance) obtained out of this study clearly explained that decline in fish abundance and productivity of the oxbow lake were due to high anthropogenic activities of jute retting and indiscriminate use of fishing gears (Ghosh and Biswas, 2015c; 2017a,b; 2017c,d) of various mesh sizes during monsoon and thereafter. Since this oxbow lake lacks earlier database to compare the impact of pollution and different anthropogenic activities over the years, this first ever study of its kind would definitely serve as baseline data for quantitative and comparative assessment of biodiversity for future studies.

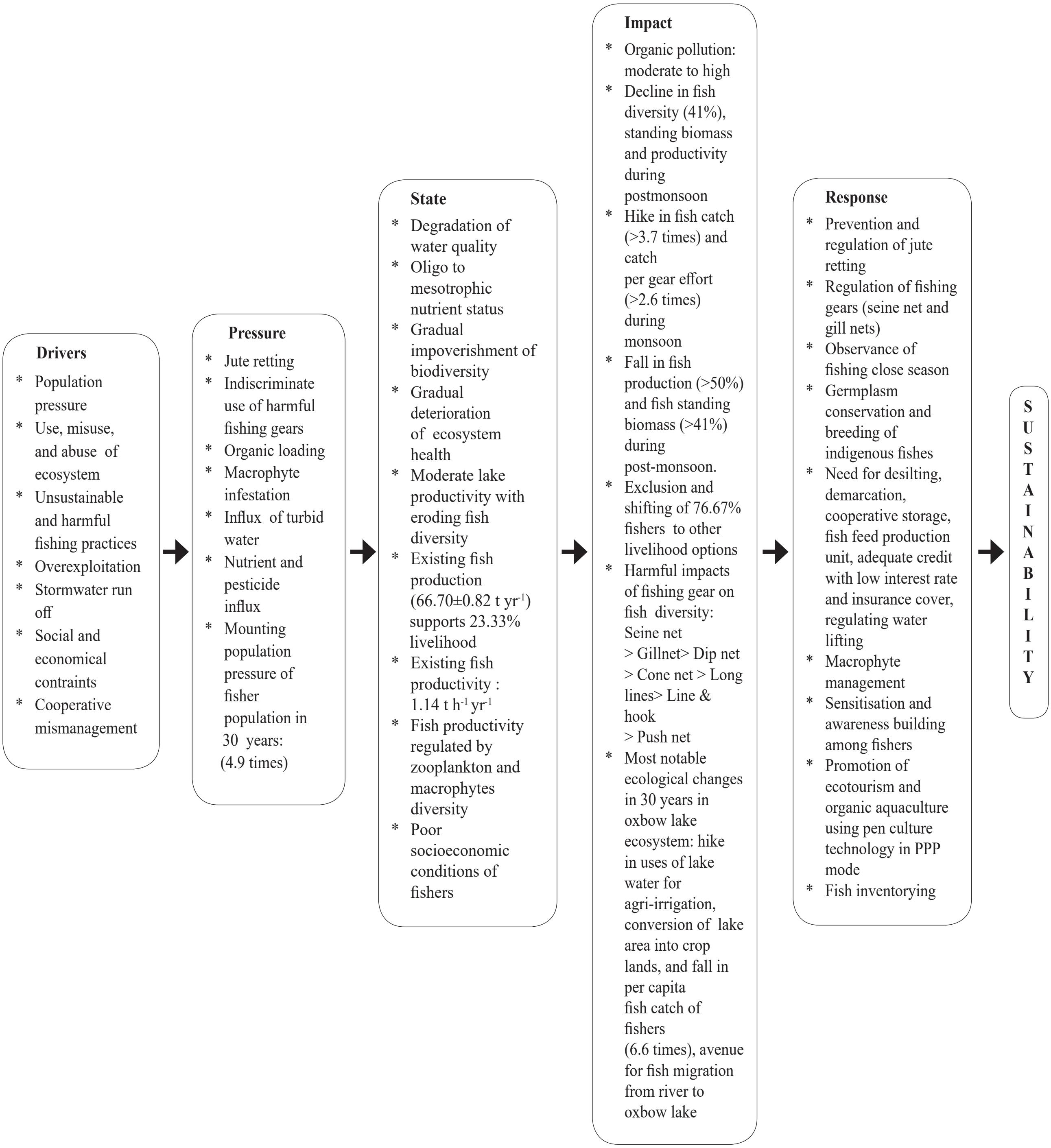

Fig. 2. DPSIR model depicting assessment and management of Chhariganga Oxbow Lake ecosystem towards sustainability through adoption of preventive, curative, adaptive and ameliorative measures

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