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ORIGINAL ARTICLE

Appraisal of culture-based fisheries of giant freshwater prawn (*Macrobrachium rosenbergii*, De Man, 1879) in reservoirs of Sri Lanka

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Abstract

The introduction of high economic value species like giant freshwater prawn (GFWP) makes culture-based fisheries (CBF) a substantial source of income and simultaneously supports the livelihood development of rural fishers in Sri Lanka. However, this CBF strategy has been implemented without any scientific basis, and therefore, this paper evaluated the stocking and production data of GFWP in Sri Lankan reservoirs from 2011 to 2017 to identify interventions for achieving future sustainability. We used two distinct approaches to appraise the CBF strategies practised so far and decrypt the identified shortcomings in the initiatives. The first approach was a straight-head univariate generalized additive model (GAM) analysis of stocking density (SD), production (PRD), recapture efficiency (RCE) and reservoir surface area (A). The latter approach was a hybrid PCoA-GAM for detained data mining for a better management perspective. The relationships among SD, PRD RCE and A were significant and, stochastic PRD and RCE were reasoned by the biased stocking practices identified in the GAM analysis. The hybrid PCoA-GAM is seemingly robust in predicting and explaining the deviances of PRD and RCE of GFWP CBF. Results indicated that the present practices of CBF of GFWP in Sri Lankan reservoirs suffer several weaknesses, overstocking in minor and understocking in both medium and major reservoirs are primarily under consideration, which includes *inter alia*, the need for effective tools for identification of suitable reservoirs, the inefficient harvesting practices, non-optimal SDs coupled with the possible vulnerability of stocked postlarvae to high mortalities. According to the study, we prefer to set the optimum SD as 1500 PLs ha^{-1} to all reservoirs. A comprehensive study has been launched for the enhancement of CBF of GFWP in Sri Lankan reservoirs.

KEYWORDS
culture-based fishery, fisheries enhancement, *Macrobrachium rosenbergii*, tropical reservoirs

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1 | INTRODUCTION

Appraisal of stocking protocols is vital in the culture-based fishery (CBF) to evaluate the pros and cons, but in developing countries, it is rarely applied. CBF is an aquaculture paradigm, holistically representing enhancement practices in water bodies that are generally incapable of supporting sustainable fisheries because of the non-self-replenishing fish population (Amarasinghe, 2010; De Silva, 2003) which is a different approach from other enhancement approaches (Cowx, 1994, 1999; Lorenzen, 2001; Welcomme et al., 2010). The contemporary driver of inland fisheries is the widespread vision of a culture-based approach for inland fisheries in the face of escalated human interventions, which is reflected by studies from all regions (De Silva, 2016; Lorenzen et al., 2001; Welcomme et al., 2010). Recent advancements and increased monetary benefits have made CBF an incumbent source for inclusive growth and human development of rural fishing communities globally. Worldwide case studies showed that the role of inland CBF in the livelihood development of rural fishers is gradual, offering food security (Béné et al., 2015; De Silva, 2016; Youn et al., 2014), poverty redemption (Béné et al., 2010; Subasinghe et al., 2009) and a specialist occupation (Amarasinghe & De Silva, 1999; Nunan, 2020; Pushpalatha et al., 2020; Smith et al., 2005) through progression.

Sri Lanka is endowed with more than 12,000 reservoirs with a total extent of 206,000 ha (Wijenayake et al., 2021) and potential from other wetlands (Figure 1). The inland fisheries are primarily reservoir-based (Amarasinghe & De Silva, 1999), whose primary functions are for either irrigation, hydropower or both. According to National Aquaculture and Development Authority (NAQDA) under the Ministry of Fisheries and Aquatic Resources, reservoirs are classified as perennial or seasonal according to the associated hydrological regimes. The perennial reservoirs of the country are categorized based on their size as minor (< 200 ha), medium (200–800 ha) and major (> 800 ha).

Giant freshwater prawn (*Macrobrachium rosenbergii* (De Man, 1879)) (GFWP) is a high economic value species, well established in the tropical freshwater riverine and brackish water environments throughout the Indo-Pacific region (Ismael & New, 2000; Short, 2004). GFWP is well-known for its aquaculture farming around the world (Kutty, 2005; Marques & Moraes-valenti, 2012; Nair & Salin, 2012; New, 2005). According to New et al. (2000), little attention has been given to GFWP capture fisheries, due to the perceived much greater production potential of farming. CBF of GFWP is an emerging development strategy adopted by some developing nations in Asia, prominent examples are: practices in reservoirs of Kerala in India (Nair et al., 2007); Pak Mun dam in Thailand (Jutagate & Kwangkhang, 2015; Sripatrprasite & Lin, 2003); and in reservoirs of Sri Lanka (Chandrasoma & Pushpalatha, 2018; Pushpalatha & Chandrasoma, 2010; Wijenayake et al., 2005), where it is growing and increasing in significance (New & Kutty, 2010). Published information on the characteristics of CBF for GFWP is sparse, but valuable information on reservoir fishery enhancement activities is available for Bangladesh (Ahamed et al., 2014), India (Nair et al., 2007; Nair & Salin, 2012), Indonesia, Myanmar (New & Kutty, 2010) and Thailand (Jutagate & Kwangkhang, 2015). Further relevant data are available for fishery enhancement in rivers of Malaysia (New & Kutty, 2010), lake-based cage culture in the Philippines (Cuvin-aralar et al., 2013), reservoir pen culture (Limpadani & Tansakul, 1980) in Thailand, river pen culture (Lan et al., 2006; Son et al., 2005) and fence culture (Phuong et al., 2006) in Vietnam.

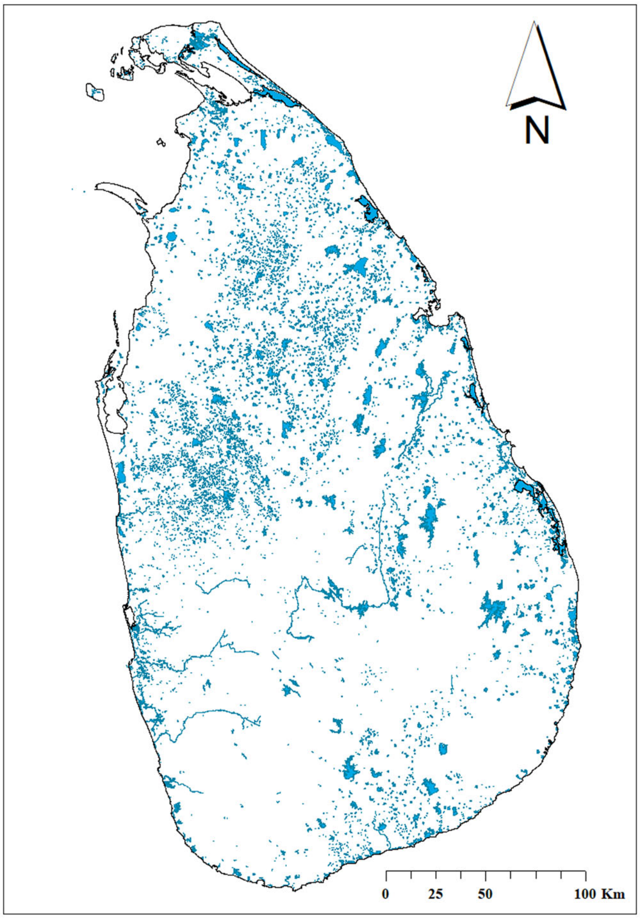

FIGURE 1 Map of identified potential inland reservoirs for the enhancements of giant freshwater prawn in Sri Lanka

In Sri Lankan reservoirs, the production of *M. rosenbergii* is essentially culture-based, limited to extensive stocking along with carp and tilapia (Pushpalatha et al., 2020). There is some production of GFWP from a capture fishery reported mainly from rivers and flood plains of the Mahaweli River (Hettlarachchi & Kularatne, 1988; Jayasekara, 2007); however, yields were small (Figure 2). The introduction of GFWP to reservoirs was initially commenced in the 1980's but failed to progress. In 2001, the NAQDA recommenced GFWP stocking in the scope of creating a new fishery. Recent increased demand for *M. rosenbergii* (commonly known as *Scampi* in the export market) in the world trade presented an opportunity to several export ventures in Sri Lanka, which subsequently offered attractive financial benefit to fishers well above that earned for the finfish even with lower capture rates (Pushpalatha et al., 2015; Wijenayake et al., 2005).

The strong interest in GFWP CBF has revealed a range of questions including: (1) why did the earlier stock enhancement trials fail; (2) why

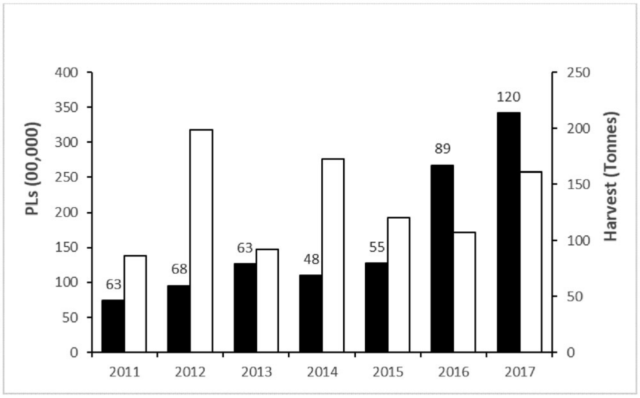

FIGURE 2 Total annual stocking (Black) and annual harvest (White) of GFWP in perennial reservoirs of Sri Lanka from 2011 to 2017. The values above dark columns are number of reservoirs stocked

are recapture rates for GFWP lower than for finfish; and (3) what are the requirements to enhance and sustain the fishery establishment. This study was developed to address the knowledge gaps regarding GFWP CBF practices. It seeks to explain the patterns of yield according to stocking practices applied to date, through deciphering stocking and yield data to provide scientifically robust measures to overcome the issues for future benchmark decision-making.

2 | MATERIALS AND METHODS

2.1 | Nature of data and data collection

Scientific inputs (Amarasinghe & Wijenayake, 2015) have had a significant impact on the initiatives of the government fisheries authorities (Chandrasoma et al., 2015) to establish CBF in Sri Lankan reservoirs, broadly grouped as seasonal or perennial depending on the seasonal water availability. Perennial reservoirs are further grouped into three size categories as minor (< 200 ha), medium (200–800 ha) and major (> 800 ha). Accordingly, systematic annual stocking of reservoirs has been reckoned as a major inland fisheries development strategy of the NAQDA. Initially, non-native (Chinese and Indian) carp species, which are widely reputed for inland fisheries enhancement, were used as stocking material. Subsequently, in 2006, NAQDA commenced stocking postlarvae (PLs) of GFWP, *M. rosenbergii* as an additional stocking candidate. However, the stocking of GFWP has been haphazard and without any scientific basis. NAQDA has introduced a logbook recording system with periodic monitoring, providing reasonably accurate inland fisheries production statistics in a database maintained by NAQDA. For the present analysis, stocking and production data of GFWP were gleaned from that database from the period from 2011 to 2017. The number of reservoirs used from the database for the present analysis ranged from 48 in 2014 to 120 in 2017 (Table 1). The rationale for selecting these reservoirs for the present analysis was that stocking and production data of GFWP were considered reliable on basis of well-organized fishers' societies in these reservoirs, likely to provide accurate data logs. In addition to stocking and production data of GFWP, information about the extent of the reservoirs' supply level was gathered from irrigation authorities.

The landings of GFWP were essentially incidental catches in the gillnets (mesh size ranges from 4 to 7 inches, the average is 5 inches) used for harvesting finfish species in the reservoirs. It was noted that stocking was staggered and stocked GFWP PLs re-appeared as consumption-sized prawns in the landings generally about 6 months after stocking. For consistency, annual stocking data were treated as those stocked from the 1st of July in a given year to the 30th of June of the next year. When GFWP catches were not reported continuously for about 18 months, such reservoirs were treated as those without sufficient stocking of GFWP PLs and were removed from the analysis. Daily data of GFWP catches were summed for the whole year to estimate annual GFWP production. Accordingly, the final dataset contained discrete annual details of stocking (numbers ha^{-1}) and production (kg ha^{-1}) of GFWP in each reservoir from 2011 to 2017 and the reservoir surface area (ha). The summary of reservoir details is given in Table 1, where the reservoir area of the reservoirs considered for the study ranged from 3 to 7793 ha.

2.2 | Data analysis

For deriving predictive models and further analysis, stocking density (SD) (PLs ha^{-1} yr^{-1}), production (PRD) (kg ha^{-1} yr^{-1}) and recapture efficiency (RCE) (kg PLs^{-1} ha^{-1} yr^{-1}) were calculated using the following equations:

$$\mathrm{SD}_i = \frac{N_i}{A_i}, \tag{1}$$

$$\mathrm{PRD}_i = \frac{C_i}{A_i}, \tag{2}$$

$$\mathrm{RCE}_i = \frac{C_i}{N_i \times A_i}, \tag{3}$$

where N_i, C_i and A_i are, respectively, the number of GFWP PLs stocked per year, GFWP catch and the surface area of the ith reservoir.

2.3 | Yield predictive models

Using linear regression analyses, the dependent variables of SD, PRD and RCE were related to reservoir surface area. Also, the influence of SD on PRD and RCE was investigated using linear regression approaches.

2.4 | Generalized additive model

In the present study, the generalized additive modelling (GAM) (Hastie & Tibshirani, 1986, 1990) approach, which is a non-parametric generalization of the generalized linear model, was used. GAM comprises

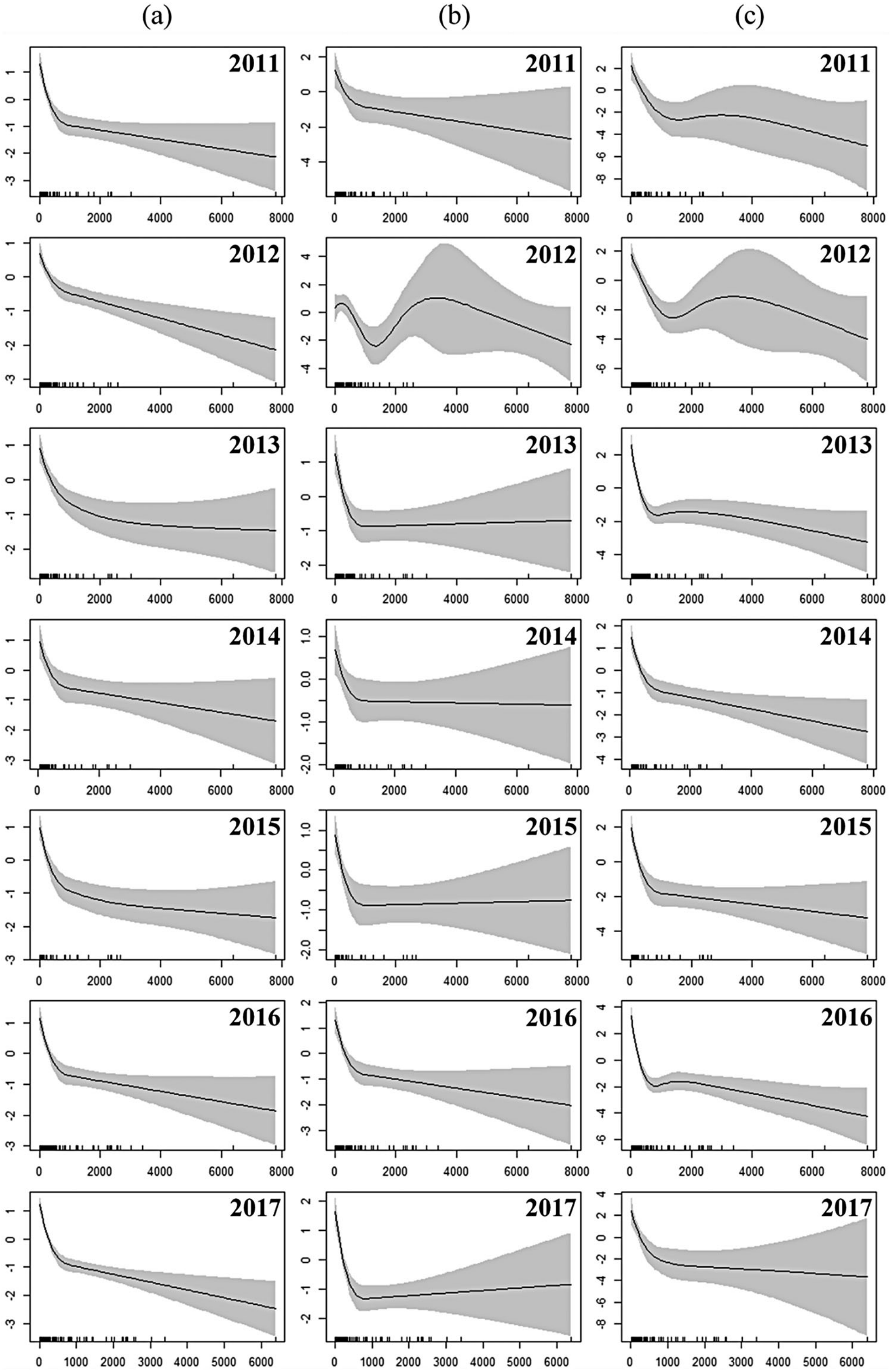

FIGURE 3 GAM-derived response curves for variations of SD (stocking density), PRD (production) and RCE (recapture efficiency) against A (reservoir surface area). Columns are dedicated for: column a for SD in PLs ha^{-1} yr^{-1} (y-axis) (model 1); column b for PRD in kg ha^{-1} yr^{-1} (y-axis) (model 2); column c for RCE kg PLs^{-1} ha^{-1} yr^{-1} (y-axis) (model 3), on predictor variable A in ha (x-axis): shaded area is 95% confidence zone. The relative density of data points is shown by the rug plot on the x-axis

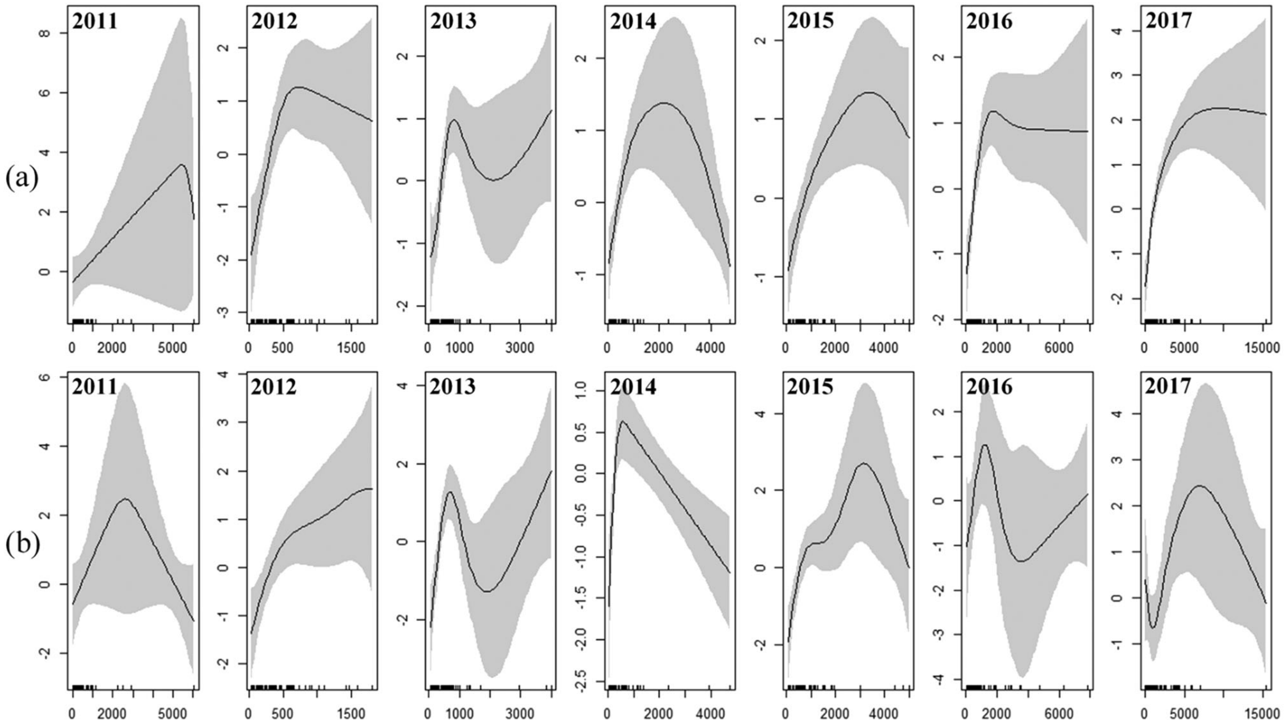

FIGURE 4 Smoothed curve of estimated (a) PRD in kg ha^{-1} yr^{-1} (model 4) (y-axis) and RCE in kg PLs^{-1} ha^{-1} yr^{-1} (model 5) (y-axis), for the predictor variable SD in PLs ha^{-1} yr^{-1} (x-axis) in the GAM. Shaded area represents 95% confidence intervals, marks along the lower axis represent a single observation. Abbreviations: PRD, production; RCE, recapture efficiency; SD, stocking density

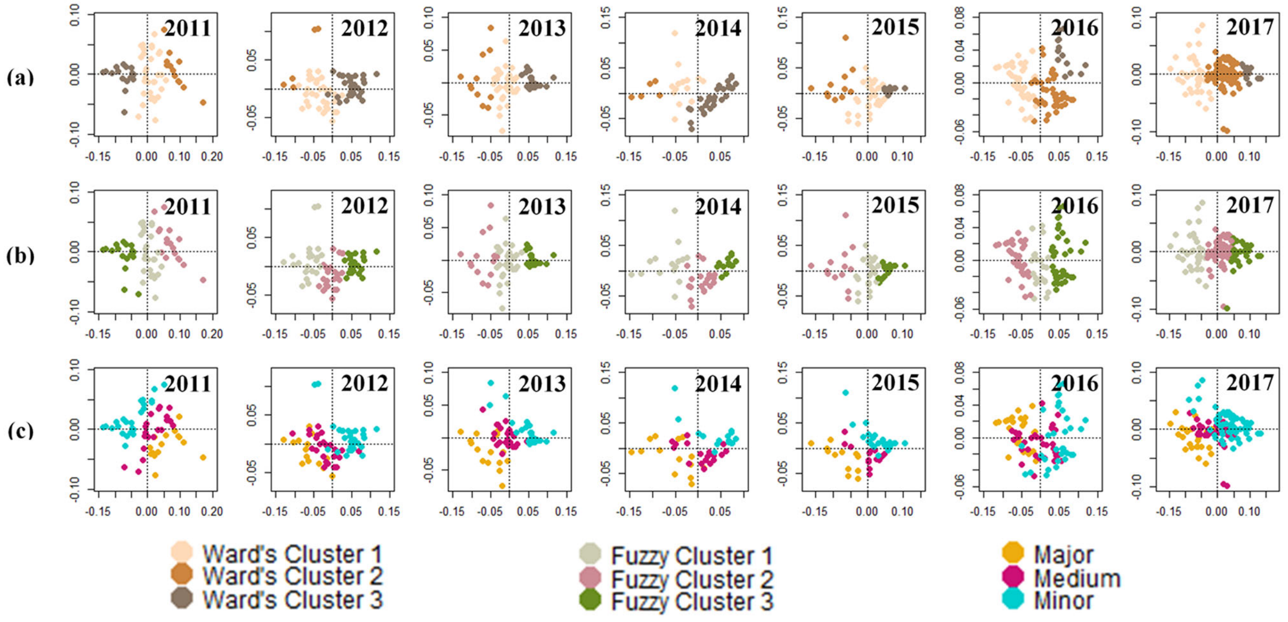

FIGURE 5 Visualization of clusters on principal coordinates analysis (PCoA) in two-dimensional space (horizontal axis: Coordinate 1; vertical axis: Coordinate 2); rows are dedicated for (a) Ward's cluster method, (b) Fuzzy cluster method and (c) Reservoir types according to the hydrological regimes. Abbreviations: Major, major reservoirs; Medium, medium reservoirs; Minor, minor reservoirs

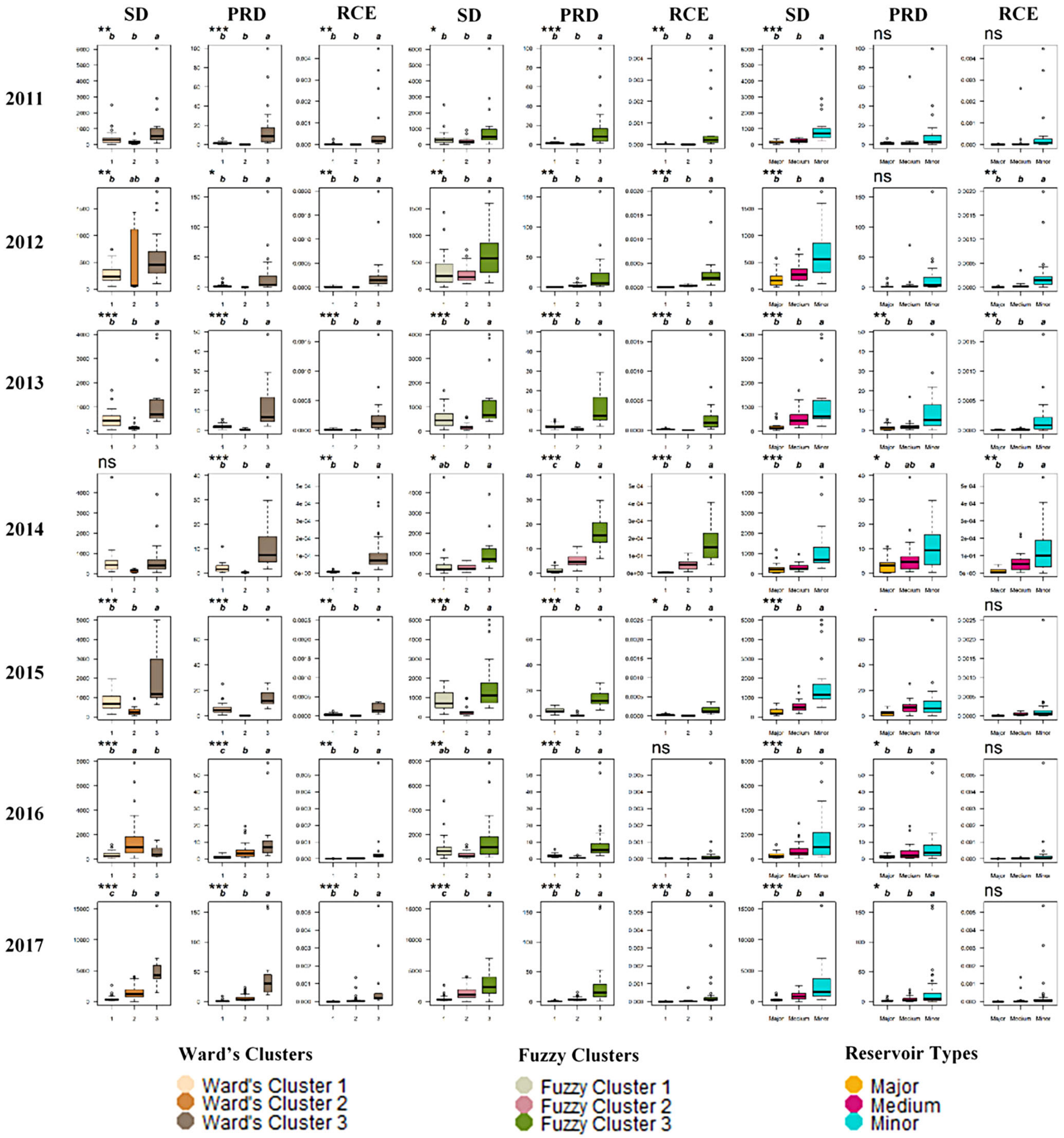

FIGURE 6 Box and whisker plots illustrating the variation of SD (stocking density), PRD (production) and RCE (recapture efficiency) between optimized clusters and reservoir types from revised NAQDA data during 2011–2017. Stars indicate the significance of the differences among groups (Ward clusters, Fuzzy clusters and reservoir types) for each variable; the means of boxes with similar letters (a, b or c) were not significantly different; ns, not significant; significance levels: · – ≤ 0.1, * – ≤ 0.05, ** – ≤ 0.01 and *** – ≤ 0.001

a collection of non-parametric and semi-parametric regression techniques for exploring relationships between response and predictor variables. The advantage of GAM is that making any prior assumption is not necessary on the functional form linking the two sets of variables, as these relationships are modelled with smooth functions (Solanki et al., 2016). Globally, studies have been carried out on various applications using GAM in fisheries, like the prediction of migratory species distribution (Pleydell & Chrtien, 2010; Rubec et al., 2016), environmental factors (Drexler & Ainsworth, 2013; Murase et al., 2009) and catch (Maunder & Punt, 2004; Potts & Rose, 2018; Venables &

TABLE 1 The number of reservoirs, and their extent, from which annual stocking and fish production data were gleaned

Year	Number of reservoirs	Reservoir extent range (ha)	Cumulative reservoir extent stocked (ha)	Mean± SE stocking density (numbers ha^{-1})
2011	63	3–7793	45,836	553±112
2012	69	10–7793	46,205	436±45.5
2013	63	10–7793	47,986	658.3±96.3
2014	48	51–7793	42,803	631±129
2015	55	10–7793	40,625	1013±144
2016	89	10–7793	70,623	959±136
2017	120	5–6390	66,245	1542±174

Note: Mean annual stocking densities of PL_{45} of *Macrobrachium rosenbergii* are also given here.
Abbreviations: PL_{45}, PL stage after the 45 days since the release of fertilized eggs from female brooders; SE, standard error.

Dichmont, 2004). Here, GAM-derived response curves were determined for variations of SD, PRD and RCE on the predictor variable of reservoir surface area. Similarly, response curves of PRD and RCE on SD as predictor variables were derived for each year based on GAM.

2.5 | Modelling approaches used

2.5.1 | Approach 01: Simple univariate smoothing in GAM

For this approach, SD, PRD and RCE were separately considered as response variables fitted against the surface area of the reservoir (A), likewise, PRD and RCE were discretely fitted with the predictor variable of SD. All following univariate smoothing GAMs were fitted with a gamma distribution with a log link function model given below:

$$\log \mathrm{SD_i} = s\,(\mathrm{A_i}) + \epsilon_i \quad \text{Model 1,}$$

$$\log \mathrm{PRD_i} = s\,(\mathrm{A_i}) + \epsilon_i \quad \text{Model 2,}$$

$$\log \mathrm{RCE_i} = s\,(\mathrm{A_i}) + \epsilon_i \quad \text{Model 3,}$$

$$\log \mathrm{PRD_i} = s\,(\mathrm{SD_i}) + \epsilon_i \quad \text{Model 4,}$$

$$\log \mathrm{RCE_i} = s\,(\mathrm{SD_i}) + \epsilon_i \quad \text{Model 5,}$$

where s(x) is the spline smoothing function of variables SD, PRD and RCE, ϵ_i is the error term in the i^{th} reservoir and all other variables as defined above.

2.5.2 | Approach 02: Multivariate grouping of reservoirs and variable smoothing in GAM

Cluster analysis based on Bray–Curtis similarity matrices (Bray & Curtis, 1957) of log-transformed reservoir data, that is A_i, SD_i, PRD_i and RCE_i, was used to categorize reservoirs concerning the performance of GFWP fisheries using Ward's method and Fuzzy method (Borcard et al., 2018). Ward's clustering is a widely used method in the hierarchical realm and it is strategic in minimizing the variance within clusters. Fuzzy clustering is another approach to clustering that recognizes that, sometimes, cluster limits may not be as clear-cut as one would like them to be, in which each element has a probability of belonging to each cluster. In other words, each element has a set of membership coefficients corresponding to the degree of being in a given cluster. An object that is linked to a given cluster has a strong membership value for that cluster and weak (or null) values for the other clusters, Thus, in this analysis, the highest membership coefficient has been taken into account to simplify the analysis. The grouping of clusters was restricted to 3 for ease of comparison with hydrological regimes of perennial reservoirs. Clusters were analysed using a permutational multivariate analysis of variance (PERMANOVA) followed by LSD multiple comparisons which are adopted with Holm's correction, using the same configuration as ANOVA (Holm, 1979), and box and whisker plots for each year were produced. Weighted principal coordinates analysis (PCoA), a distance-based unconstrained ordination method, also known as a weighted classical multidimensional scaling technique, run on a Bray–Curtis similarity matrix (Borcard et al., 2011), was used to assess the effects of the stocking strategies and validate our distance grouping hypothesis. After exploring the reservoir data by PCoA, variables were fitted by smooth surfaces using penalized splines (Wood, 2003) in GAM, on the first and second ordination axes. In the present approach, all statistical analyses were performed, respectively, using the *mgcv* R package (Faraway, 2016; Wood, 2006, 2017) and *vegan* R package (Borcard et al., 2011; Dixon, 2013) in R statistical software (R Core Team, 2020).

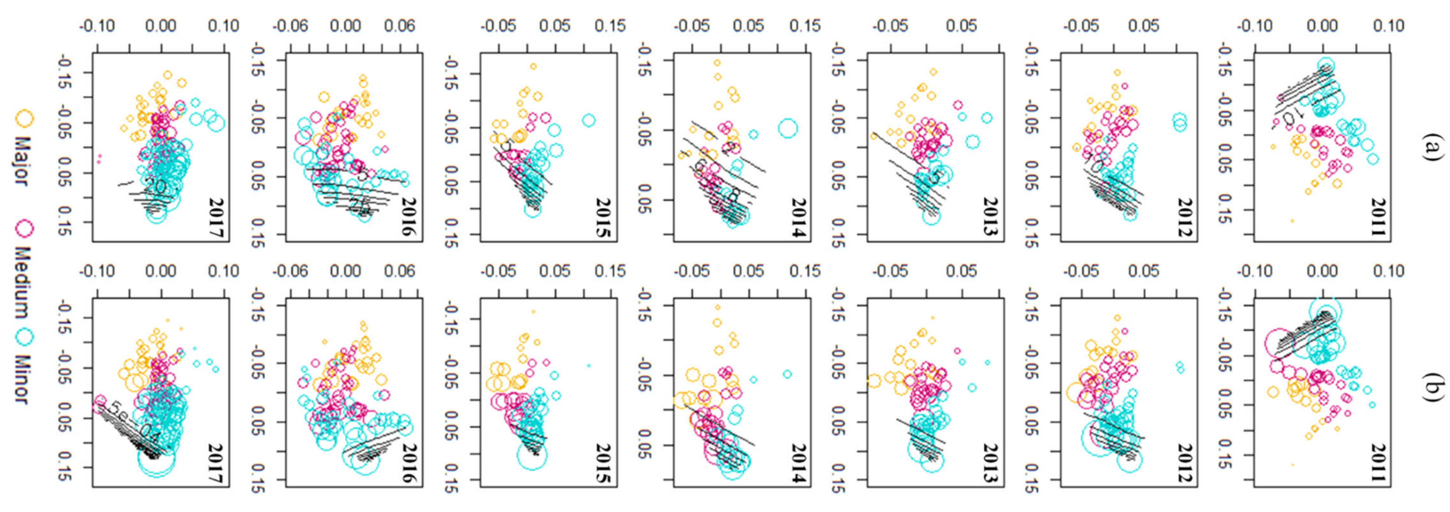

FIGURE 7 Visualization of GAM on the PCoA two-dimensional space with reservoir types: columns are dedicated for (a) SD in bubbles plot with superimposed PRD contour splines, and (b) PRD in bubbles plot with superimposed RCE in contour splines. The size of bubble represents relative magnitude of SD in column a and PRD in column b for each reservoir type in the PCoA ordination. Superimposed contour splines on column a is PRD and RCE is on column b. Abbreviations: PRD, production; RCE, recapture efficiency; SD, stocking density

TABLE 2 Summary of yield predictive models 1, 2 and 3 of approach 1

		Stocking density versus area					Production versus area					Recapture efficiency versus area				
Year	*N*	*p*-value	Ex.Dev. (%)	*R*-adj	edf	REML	*p*-value	Ex.Dev. (%)	*R*-adj	edf	REML	*p*-value	Ex.Dev. (%)	*R*-adj	edf	REML
2011	63	0.0000	58.50	0.2390	1.9550	436.15	0.0032	23.60	0.7170	1.8440	150.34	0.0000	42.10	0.1260	3.0480	−544.77
2012	69	0.0000	38.50	0.2360	1.9030	471.54	0.0017	27.60	0.0129	3.5290	201.75	0.0000	49.40	0.1090	3.2170	−592.09
2013	63	0.0000	46.50	0.2790	2.5940	455.74	0.0000	31.10	0.1930	1.8100	148.22	0.0000	62.50	0.2280	2.7720	−589.13
2014	48	0.0000	42.60	0.2160	1.8830	347.69	0.0061	16.50	0.1640	1.6130	141.68	0.0000	41.20	0.3510	1.9030	−424.86
2015	55	0.0000	58.60	0.3640	2.5040	415.31	0.0000	22.80	0.1720	1.7390	158.08	0.0000	51.70	0.1470	1.9450	−493.03
2016	89	0.0000	40.90	0.2360	1.9310	679.59	0.0000	36.90	0.2080	1.9160	197.57	0.0000	73.10	0.1390	3.1990	−869.10
2017	120	0.0000	51.30	0.3850	1.9620	959.44	0.0000	38.50	0.2080	1.8810	323.11	0.0000	46.10	0.1200	2.8620	−1098.30

Abbreviations: edf, effective degrees of freedom; Ex.Dev. (%), explained deviance in percentage; *N*, number of observations (reservoirs); *p*-value, probability value of the significance; *R*-adj, adjusted correlation coefficient; REML, restricted maximum likelihood.

3 | RESULTS

3.1 | Stocking and harvest of FWP (2011–2017)

The total annual stocking and harvest of GFWP in perennial reservoirs of Sri Lanka (Figure 2) indicate that there has been an increasing trend of stocking but the harvests were apparently related to the number of reservoirs stocked in each year. From the data in the present analysis (as reported in the database of NAQDA), it is clearly evident that number of reservoirs and their cumulative extent stocked with PLs of GFWP increased annually, and mean SD was not consistent (Table 1), mean SD ranged from 436 to 1542 PLs ha^{-1} for the reservoirs considered in this study from 2011 to 2017. During the study, NAQDA hatcheries followed a protocol via which PLs were issued after 5 days from the day 50% free-swimming PLs have been identified (averagely, it takes 45 days since the release of fertilized eggs from female brooders), can be identified as PL$_5$(which will weigh around 0.009 g). The harvest weight differs from 150 to 750 g in reservoirs of Sri Lanka, which depends on the day of harvest from the date of stocking.

3.2 | Simple univariate smoothing GAM

The GAM is an unorthodox method that identifies the relationship between two variables without any presumptions. Using a range of reservoir surface area values, we analysed the trends of SD, PRD and RCE over the years by the models 1, 2 and 3 described above. The inverse response curve of SD against reservoir extent depicted in Figure 3 infers that GFWP enhancements were generally effective in reservoirs of < 1000 ha (Figure 3a). Moreover, higher stocking density practices were confined to reservoirs with an extent of < 400 ha. The response curves of PRD and RCE to reservoir extent were the same as the SD, indicating that GFWP enhancement strategies practised so far have been based on ad hoc stocking. A summary of models is given in Table 2, which describes that all three models having inverse response curves during the study period were significant at least at 0.01 probability levels.

In GAM plots of models 4 and 5 in which responses of PRD and RCE to SD of FWP from 2011 to 2017 (Figure 4) showed trend maxima except in 2012 and 2013. In 2012, SD appears to be insufficient for achieving maximum RCE, whereas, in 2013, both PRD and RCE showed troughs at around SD of 2000 PLs ha^{-1} but increased SD is needed for further increase of PRD and RCE, whereas the SD is exceptionally confined to around 1500 PLs ha^{-1}. Except for PRD and RCE in 2011 and for RCE in 2016, there were significant relationships of SD with PRD and RCE over the years that we have analysed (Table 3). Meanwhile, we have identified different phenomena in Figure 4, they are: (1) the increasing trend of both PRD and RCE was observed in all curves, where SD is < 1500 PLs ha^{-1} except in 2017, typically relevant to an understocked condition; (2) inclined rate of increase in PRD with unchanged (especially in 2015, between 1000 and 2000 1500 PLs ha^{-1}) or lessening RCE (in 2015–2017, as the SD exceeds 2000 PLs ha^{-1}, which reflects the state of overstocked; (3) degree of increase in RCE is greater than PRD, which is a special case to be discussed. These relationships indicate that at the present exploitation strategy (i.e. exploiting as by-catch in the gillnet fishery targeting finfish species), optimal SD during 2011–2017 was around 1500 PLs ha^{-1}. We abide by this because drawing the line with the lower number of samples will make the whole study to be sceptical (for reference, use the marks along the lower axis to represent a single observation in Figures 3 and 4), to utilize the effective results from the study, we confided the contentions over SD, PRD and RCE amicably to the space where the sample representation is significant and satisfactory. It must also be noted that wide confidence intervals in the GAM results occur when there are fewer data points mostly at higher SD (e.g. PRD of 2011) or due to high variability of the dataset (e.g. RCE in 2012).

3.3 | Multivariate grouping of reservoirs and variable smoothing in GAM

In the present analysis, we used PCoA as a deduction technique to visualize the representation of the reservoirs in Ward and Fuzzy clusters in the two-dimensional spaces derived on A, SD, PRD and RCE (Figure 5). The ordination of reservoirs based on hydrological regimes (major, medium and minor) is also shown (Figure 5) for comparison. The three clusters representing major, medium and minor reservoirs of both Ward's and Fuzzy methods within a given year were identical in most years (Figure 5). However, those produced by both Ward's and Fuzzy methods were identical for minor reservoirs throughout the period of study (Table 4). The corresponding post-hoc comparisons of groups and the boxplots of the selected variables (SD, PRD and RCE) split by clusters (Figure 6) and the tabulated results (Table 5) show that minor reservoirs were subjected to higher SD compared to major and medium reservoirs during the period considered in the present study. PRD was significantly higher in minor reservoirs than in the other two categories, but RCE was insignificant from 2015 to 2017. The GAM thin-plate splines based on PCoA (Figure 7) show that the biased stocking strategies practised in CBF of FWP in Sri Lankan perennial reservoirs during the study period have direct relationships with PRD in minor reservoirs. Also, the influence of PRD on RCE was related to minor reservoirs. Throughout the study period, there was a high level of statistical significance (Table 6).

4 | DISCUSSION

Although attaining an accurate evaluation of the fish stocks in reservoirs is challenging, its importance as an objective of scientific research is unquestionable (Lorenzen, 2014). The present study is an "eye-opener" regarding the CBF practices of GFWP in the Sri Lankan context. *M. rosenbergii*, which is one of the components of multispecies CBF in Sri Lankan reservoirs (Jayasinghe et al., 2006; Wijenayake et al., 2005), represents a lucrative export value, developed due to market-driven demand in the recent past. According to Marques and Moraes-valenti (2012) categorization criteria, the GFWP harvested

TABLE 3 Results of yield predictive models 4 and 5 of approach 1

		Production versus stocking density					Recapture efficiency versus stocking density				
Year	*N*	*p*-value	Ex.Dev. (%)	*R*-adj	edf	REML	*p*-value	Ex.Dev. (%)	*R*-adj	edf	REML
2011	63	0.1260	15.20	0.2100	0.8881	152.80	0.1080	14.30	0.0798	0.9466	−533.03
2012	69	0.0000	34.60	0.0627	2.4270	193.73	0.0005	22.00	0.1240	2.4400	−577.46
2013	63	0.0000	34.60	0.1280	3.3930	149.59	0.0000	37.60	0.0872	3.3790	−569.33
2014	48	0.0000	25.20	0.2180	1.7440	138.98	0.0002	17.00	0.1310	0.9240	−417.31
2015	55	0.0000	23.30	0.2630	2.1480	158.25	0.0000	39.70	0.4280	3.5500	−483.57
2016	89	0.0000	34.80	0.1300	2.6660	199.88	0.0850	18.30	0.0080	2.3340	−810.95
2017	120	0.0000	46.30	0.2600	2.9140	314.89	0.0055	25.90	0.1670	2.5420	−1073.80

Abbreviations: edf, effective degrees of freedom; Ex.Dev. (%), explained deviance in percentage; *N*, number of observations (reservoirs); *p*-value, probability value of the significance; *R*-adj, adjusted correlation coefficient; REML, restricted maximum likelihood.

TABLE 4 Results of cluster analysis and number of reservoirs grouped under each of the three clusters in Ward's and Fuzzy method in comparison with reservoir type

		Ward cluster			Fuzzy cluster			Reservoir type		
Year	Number of reservoirs	Clus1	Clus2	Clus3	Clus1	Clus2	Clus3	Minor	Medium	Major
2011	63	33	12	18	27	17	19	26	22	15
2012	69	33	5	31	22	23	24	31	24	14
2013	63	32	11	20	30	14	19	24	24	15
2014	48	14	5	29	15	20	13	15	19	14
2015	55	30	11	14	22	13	20	27	15	13
2016	89	35	41	13	23	30	36	32	34	23
2017	120	37	70	13	36	54	30	60	36	24

from reservoirs of Sri Lanka that have an average weight of around 220 g are considered as 'premium' prawns (larger than 50 g) that have had an increased demand among restaurants and hotels in recent years, with prices ranging from USD 20 to 23 kg^{-1} (in November 2021, USD 1 ≈ LKR 200.94). Globally, the massive production of farm-based aquaculture of GFWP (New, 2005) has masked the potential of CBF-based GFWP production in livelihood development in rural reservoir communities. In Sri Lanka, the increasing yields of CBF-produced GFWP may herald a worldwide upsurge in CBF.

The capacity of Sri Lankan reservoirs (Figure 1) to support the GFWP CBF is immense (Wijenayake et al., 2005). Regardless of the availability of a wide array of reservoirs (Amarasinghe & De Silva, 2016), supportive management frameworks (Wijenayake et al., 2021) and supplies of GFWP PLs (Chandrasoma & Pushpalatha, 2018), the production of GFWP is comparatively attenuated, unutilized and underestimated. It is a prerequisite to assess the adaptability and behavioural biology of riverine species, such as *M. rosenbergii*, when introduced to lacustrine systems, such as irrigation reservoirs (De Silva & Funge-Smith, 2005).

The present analysis of GFWP stocking and production data of NAQDA was aimed at investigating the present status of the management of GFWP CBF in Sri Lankan reservoirs. This analysis is the first initiative to identify the areas where interventions are needed. According to Figure 2, it is evident that there is an increase in stocking as well as a catch in the reservoirs, highest total production of nearly 198 tonnes was reported as a result of 9.5 million PLs stocked in 63 reservoirs, still, the stocking strategy plan that has been practised so far becomes inefficient as in 2017 around 120 reservoirs were stocked with a total of 34 million PLs which gave a gross production (161 tonnes) of which is lesser than the prior.

First of all, the initiation by involving more reservoirs in the GFWP CBF is essential, as CBF payoff in time through trial and error, a systematic study with an array of SD densities across reservoir regimes will be a solution to the most unanswered questions. This analysis clearly indicated that the SD practices of stocking PLs of GFWP were rather ad hoc, and that under the present practices of exploitation, stocking was more effective in reservoirs of less than 1000 ha. Also, it is evident that the SDs applied so far have been insufficient to achieve optimal PRDs, according to Figure 3.

Low catchability under the current fishery practice (Pushpalatha & Chandrasoma, 2010), which is essentially a by-catch in the gillnet fishery targeting finfish species, is a major concern, which requires suitable intervention, such as the introduction of effective means of targeted harvesting stocked prawns.

The enigma of anticipated catches in stocked reservoirs is apparently due to PL's susceptibility to early mortality by means of

TABLE 5 Results of pair-wise comparison of groups produced in cluster analysis in PCoA

		Ward cluster				Fuzzy cluster				Reservoir types			
		1	2	3		1	2	3		Major	Medium	Minor	
Year	Variables	Mean ± SE	Mean ± SE	Mean ± SE	p-value	Mean ± SE	Mean ± SE	Mean ± SE	p-value	Mean ± SE	Mean ± SE	Mean ± SE	p-value
2011	**SD**	^{b}407.08 ± 79.31	^{b}187.88 ± 52.48	^{a}1065.53 ± 337.84	0.0095	^{b}421.51 ± 93.58	^{b}251.41 ± 56.83	^{a}1011.22 ± 324.15	0.0198	^{b}145.36 ± 25.65	^{b}241.37 ± 24.97	^{a}1052.97 ± 239.90	0.0004
	PRD	^{b}1.64 ± 0.21	^{b}0.14 ± 0.02	^{a}19.00 ± 6.28	0.0002	^{b}1.78 ± 0.23	^{b}0.24 ± 0.05	^{a}18.20 ± 5.99	0.0002	1.49 ± 0.44	4.42 ± 3.15	10.70 ± 4.05	0.1703
	RCE	^{b}2.33e-05 ± 7.44e-06	^{b}1.24e-06 ± 2.24e-07	^{a}7.81e-04 ± 3.10e-04	0.0011	^{b}1.86e-05 ± 3.02e-06	^{b}1.94e-06 ± 3.35e-07	^{a}7.53e-04 ±2.95e-04	0.0014	7.95e-06 ± 2.38e-06	1.44e-04± 1.18e-04	4.44e-04 ±2.10e-04	0.1751
2012	**SD**	^{b}285.26 ± 29.09	^{ab}538.51 ± 303.18	^{a}580.02 ± 77.13	0.0049	^{b}367.6 ± 75.70	^{b}281.06 ± 35.17	^{a}647.31± 92.37	0.0016	^{b}203.12 ± 42.94	^{b}314.22 ± 36.99	^{a}635.54 ± 82.11	0.0001
	PRD	^{b}2.95 ± 0.46	^{b}0.04± 0.08	^{a}30.95 ± 0.60	0.0184	^{b}0.86 ± 0.11	^{b}3.39 ± 0.68	^{a}21.50 ± 6.94	0.0014	2.68 ± 1.10	5.03± 2.86	14.66 ± 5.30	0.1351
	RCE	^{b}1.69e-05 ± 2.83e-06	^{b}1.68e-06 ± 5.37e-07	^{a}2.65e-04 ± 7.20e-05	0.0014	^{b}4.33e-06 ± 5.42e-07	^{b}3.65e-05 ± 4.26e-06	^{a}3.27e-04 ±8.94e-04	0.0000	^{b}8.21e-06 ± 2.45e-06	^{b}3.65e-05± 1.43e-05	^{a}2.52e-04 ±7.27e-05	0.0050
2013	**SD**	^{b}487.74 ± 62.38	^{b}176.31 ± 45.32	^{a}1196.20 ± 245.11	0.0001	^{b}530.99 ± 70.35	^{b}209.27 ± 46.06	^{a}1190.08 ± 258.29	0.0003	^{b}213.40 ± 56.41	^{b}516.56 ± 75.79	^{a}1078.02 ± 211.41	0.0008
	PRD	^{b}1.97 ± 0.22	^{b}0.45 ± 0.14	^{a}11.70 ± 2.56	0.0000	^{b}2.12 ± 0.23	^{b}0.55 ± 0.14	^{a}12.13 ± 2.66	0.0000	^{b}1.67 ± 0.43	^{b}2.34 ± 0.66	^{a}9.18 ± 2.30	0.0018
	RCE	^{b}1.29e-05 ± 1.56e-06	^{b}1.97e-06 ± 5.65e-07	^{a}2.36e-04 ± 8.21e-05	0.0007	^{b}1.39e-05 ± 1.60e-06	^{b}2.57e-06 ± 5.79e-07	^{a}2.48e-04 ±8.58e-05	0.0004	^{b}6.89e-06 ± 1.99e-06	^{b}1.38e-05 ± 2.25e-06	^{a}1.97e-04 ± 7.06e-05	0.0059
2014	**SD**	765.18 ± 317.39	154.59 ± 45.50	648.36 ± 147.97	0.4265	^{ab}629.41 ± 305.53	^{b}300.99 ± 37.90	^{a}1140.54 ± 257.58	0.0273	^{b}304.69 ± 87.34	^{b}335.73 ± 46.46	^{a}1309.57 ± 347.57	0.0009
	PRD	^{b}2.43 ± 0.75	^{b}0.35 ± 0.11	^{a}11.11 ± 1.66	0.0003	^{c}1.32 ± 0.38	^{b}5.23 ± 0.63	^{a}17.97 ± 2.59	0.0000	^{b}3.66 ± 0.95	^{ab}7.01 ± 2.06	^{a}11.56± 2.44	0.0356
	RCE	^{b}8.36e-06 ± 1.67e-06	^{b}1.02e-06 ± 3.65e-07	^{a}1.23e-04 ± 2.37e-05	0.0014	^{b}3.80e-06 ± 7.21e-07	^{b}4.97e-05 ± 6.83e-06	^{a}2.02e-04 ± 4.35e-05	0.0000	^{b}1.32e-05 ± 4.72e-06	^{b}6.45e-05 ± 1.43e-05	^{a}1.51e-04 ± 4.34e-05	0.0026
2015	**SD**	^{b}801.83 ± 98.23	^{b}344.99 ± 99.00	^{a}1991.07± 423.98	0.0000	^{b}842.72 ± 113.27	^{b}315.68 ± 85.48	^{a}1654.05 ± 322.74	0.0007	^{b}291.31 ± 69.88	^{b}597.51 ± 100.86	^{a}1591.67 ± 240.27	0.0001
	PRD	^{b}5.60 ± 0.89	^{b}0.28 ± 0.06	^{a}17.57 ± 4.66	0.0000	^{b}4.09 ± 0.47	^{b}0.70 ± 0.30	^{a}15.91± 3.39	0.0000	2.24 ± 0.64	7.27 ± 1.67	10.33± 2.80	0.0975
	RCE	^{b}3.48e-05 ± 6.18e-06	^{b}1.65e-06 ± 4.92e-07	^{a}3.41e-04 ± 1.69e-04	0.0087	^{b}2.26e-05 ± 3.69e-06	^{b}2.15e-06 ± 5.37e-07	^{a}2.66e-04 ± 1.20e-04	0.0283	4.19e-06 ± 1.27e-06	4.79e-05 ± 1.05e-05	1.88e-04 ± 9.15e-05	0.2102
2016	**SD**	^{b}376.58 ± 52.07	^{a}1584.55 ± 259.14	^{b}553.92 ± 120.49	0.0000	^{ab}922.66 ± 217.88	^{b}348.87 ± 51.69	^{a}1490.56 ± 278.82	0.0011	^{b}326.43 ± 59.81	^{b}736.32 ± 106.99	^{a}1650.15 ± 325.09	0.0002
	PRD	^{c}0.97 ± 0.16	^{b}4.54 ± 0.68	^{a}13.55 ± 5.12	0.0000	^{b}1.90 ± 0.24	^{b}0.68 ± 0.11	^{a}9.22± 1.98	0.0000	^{b}1.29 ± 0.21	^{ab}3.44 ± 0.75	^{a}7.79 ± 2.26	0.0120
	RCE	^{b}2.71e-06 ± 6.18e-07	^{b}2.08e-05 ± 1.95e-06	^{a}6.69e-04 ± 4.27e-04	0.0012	1.06e-05 ± 1.88e-06	1.97e-06 ± 2.60e-07	2.59e-04 ± 1.60e-04	0.1610	3.18e-06 ± 6.87e-07	1.64e-05 ± 3.01e-06	2.82e-04 ± 1.79e-04	0.1366

(Continues)

TABLE 5 (Continued)

Year	Variables	Ward cluster 1 Mean ± SE	Ward cluster 2 Mean ± SE	Ward cluster 3 Mean ± SE	Ward cluster p-value	Fuzzy cluster 1 Mean ± SE	Fuzzy cluster 2 Mean ± SE	Fuzzy cluster 3 Mean ± SE	Fuzzy cluster p-value	Reservoir types Major Mean ± SE	Reservoir types Medium Mean ± SE	Reservoir types Minor Mean ± SE	Reservoir types p-value
2017	**SD**	^{c}446.30 ± 77.97	^{b}1471.15 ± 122.46	^{a}5041.23 ± 975.51	0.0000	^{c}465.52 ± 81.47	^{b}1374.64 ± 130.63	^{a}3134.68 ± 542.88	0.0000	^{b}349.98 ± 69.02	^{b}942.55 ± 108.39	^{a}2378.30 ± 303.69	0.0000
	PRD	^{b}0.94 ± 0.26	^{b}5.51± 0.60	^{a}48.56 ± 14.04	0.0000	^{b}0.66 ± 0.11	^{b}4.02 ± 0.40	^{a}27.02 ± 6.96	0.0000	^{b}1.52 ± 0.42	^{ab}4.25 ± 0.79	^{a}14.37 ± 3.81	0.0153
	RCE	^{b}2.63e-06 ± 4.85e-07	^{b}6.65e-05 ± 2.23e-05	^{a}8.76e-04 ± 4.39e-04	0.0000	^{b}2.32e-06 ±4.40e-07	^{b}3.29e-05 ± 1.43e-05	^{a}4.76e-04 ± 2.02e-04	0.0008	3.01e-06 ± 6.84e-07	7.35e-05 ± 4.24e-05	2.24e-04 ± 1.03e-04	0.2238

Note: The same letters in each row for each variable in the three clusters are not significantly different at 0.05 probability level.

Abbreviations: *p*-value, probability value of the significance; PRD, FWP production in kg ha^{-1} yr^{-1}; RCE, recapture efficiency in kg PLs^{-1} ha^{-1} yr^{-1}; SD, stocking density in PLs ha^{-1} yr^{-1}; SE, standard error.

immediate post-release predation (Wijenayake et al., 2005), size-dependent mortality at ecdysis (moulting) (Ismael & New, 2000; Lorenzen, 2006), cannibalism (Romano & Zeng, 2017) and vulnerability to voracious predators (Kwangkhang et al., 2019). *M. rosenbergii* prefers sheltering on the bottom of the waterbody (New, 2002; Tidwell et al., 1998), and as such, the provision of suitable hiding places for stocked PLs may be considered as a means of increasing the survival of stocked PLs. Moreover, harvests of GFWP from unstocked reservoirs occur and are purported to be the result of both downstream and upstream migration of *M. rosenbergii* as a result of the hydrological fluctuation (Lourantou et al., 2007; Ng'onga et al., 2019; Yan et al., 2020) and water management for irrigation (Nadarajah et al., 2019). Sripatrprasite and Lin (2003) reported a similar encounter in the Pak Mun dam (Run-of-River type dam), where 79.5% of prawn production was caught in a reservoir and 20.5% downstream. In Sri Lanka, PLs were introduced between PL$_{40}$ and PL$_{45}$ stages (Pushpalatha & Chandrasoma, 2010) to reservoirs, whereas Limpadani and Tansakul (1980) have discussed the benefits of the optimization process via a selection of different introductory stages with consideration of economic viability in small reservoirs in Thailand and PL$_{5}$ stages were stocked in Indian reservoirs (Nair et al., 2007).

The study was unable to quantify the carrying capacity of GFWP in major and medium reservoirs, as most of the reservoirs were understocked and underutilized, which is clearly revealed by Figures 2 and 7. Though similar PRDs and RCEs for major and medium reservoirs were reported by Amarasinghe and Wijenayake (2015) and Chandrasoma and Pushpalatha (2018) at lower SDs than those applied in the current analysis, more comprehensive research is warranted before robust conclusions can be made. CBF practices of GFWP have been reported in Kerala, India (Nair et al., 2007) and Pak Mun dam (Run-of-River type reservoir) in Thailand (Sripatrprasite & Lin, 2003). In several reservoirs of Kerala (159–2313 ha), which were stocked in a range of 22–716 PLs ha^{-1}, GFWP yields were reported as 3–13.3 kg ha^{-1} (Nair et al., 2007). In Pak Mun dam, an improved PRD of 3.39 kg ha^{-1} during 1999–2000 from 2.38 kg ha^{-1} during 1995–1998 was achieved through a threefold reduction of SD (407.42 PLs ha^{-1}) (Sripatrprasite & Lin, 2003), which provides a practical example of the impact of manipulating SD to optimize PRD.

In the present study, the results of GAM and cluster analysis shown in Figure 5 and Table 5 have scientific implications in (1) identifying reservoirs for future potential enhancements; (2) deploying constraints; and (3) application of best-management practices.

The findings of this study clearly indicated that the present practices of CBF of GFWP in Sri Lankan reservoirs suffer from several weaknesses, which include *inter alia*, the need for effective tools for the identification of suitable reservoirs, inefficient harvesting practices, non-optimal SDs, coupled with the possible vulnerability of stocked PLs to heavy mortalities. Multi-criteria decision-making systems as applied by Wijenayake et al. (2016) to select suitable reservoirs for CBF of finfish species also appear to be a useful tool for selecting reservoirs for CBF of GFWP. A comprehensive study is already launched in selected irrigation reservoirs of Sri Lanka under the auspices of the Australian

TABLE 6 Outcomes of PCoA used in the current study

Year	N	Production versus PCoA					Recapture efficiency versus PCoA				
		p-value	Ex.Dev. (%)	*R*-adj	edf	REML	*p*-value	Ex.Dev. (%)	*R*-adj	edf	REML
2011	63	0.0000	91.90	0.7100	5.366	80.336	0.0000	97.90	0.8760	7.731	−647.05
2012	69	0.0000	89.70	0.5500	7.452	136.14	0.0000	96.40	0.8400	6.929	−680.67
2013	63	0.0000	89.00	0.7690	5.205	94.241	0.0000	96.50	0.6390	7.188	−658.55
2014	48	0.0000	82.20	0.6730	3.561	107.49	0.0000	94.40	0.7670	4.283	−478.16
2015	55	0.0000	93.30	0.8050	5.094	95.186	0.0000	96.20	0.8770	7.012	−556.31
2016	89	0.0000	82.10	0.8380	6.357	145.56	0.0000	99.00	0.8030	8.65	−1006.1
2017	120	0.0000	89.80	0.8850	7.949	219.23	0.0000	98.30	0.9550	8.591	−1306.6

Abbreviations: edf, effective degrees of freedom; Ex.Dev. (%), explained deviance in percentage; *N*, number of observations (reservoirs); *p*-value, probability value of the significance; *R*-adj, adjusted correlation coefficient; REML, restricted maximum likelihood.

Centre for International Agricultural Research (https://www.aciar.gov.au/project/fis-2018-157).

5 | CONCLUSIONS

During the last decade or so, the fisheries and aquaculture authorities of Sri Lanka embarked on extensive stocking of PLs of *M. rosenbergii* in several reservoirs of the country. Although this strategy has resulted in the enhancement of GFWP production in reservoirs to a certain extent, the present analysis indicated that the overall performance of this CBF initiative has been far from optimum. The absence of a scientific basis for the selection of suitable reservoirs, the ad hoc nature of stocking and the non-availability of effective means of harvesting GFWP from the reservoirs are significant aspects that need intervention for optimizing production. In the present study, we illustrated the need for practical decision-making, scientific stocking strategies with regard to the optimum CBF production of GFWP. This can be achieved through resource evaluation in a combination of conceptual, empirical and technical aspects that have been identified. Although not dealt with in the present analysis, socioeconomic aspects of CBF, which include identification of market forces, value chain and gender aspects, are also important for the purpose. Our results reflect the underutilization of reservoirs in the context of CBF of GFWP. The approach might be handy in similar situations encountered in CBF practices elsewhere.

AUTHOR CONTRIBUTIONS

Dayananda Digamadulla: Conceptualization, data curation, formal analysis, methodology, writing - original draft. Jayasinghe Asoka: Data curation, investigation, methodology. Clive Jones: Project administration, supervision, validation, writing - review & editing. Udith Jayasinghe-Mudalige: Formal analysis, investigation. W.M.H. Wijenayake: Data curation, funding acquisition, methodology, resources, supervision. Upali Amarasinghe: Conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, supervision, validation, visualization, writing - review & editing. M.D.S.T. de Croos: Conceptualization, formal analysis, funding acquisition, investigation, methodology, project administration, supervision, validation, visualization, writing - review & editing.

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CONFLICTS OF INTEREST

The authors have no conflicts of interest to declare.

DATA AVAILABILITY STATEMENT

Data are available from the corresponding author upon request.

ETHICS STATEMENT

This research, being an R & D research project, was approved by the Ethics Committee of the Wayamba University of Sri Lanka. The study was based on secondary data obtained from the government organization.

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REFERENCES

Ahamed, F., Fulanda, B., Siddik, M.A.B., Hossain, M.Y., Mondol, M.M.R., Ahmed, Z.F. et al. (2014) An overview of freshwater prawn fishery in Bangladesh: present status and future prospect. *Journal of Coastal Life Medicine*, 2(7), 580–588.

Amarasinghe, U.S. (2010) Inland fisheries resource enhancement and conservation in Sri Lanka. In Miao, W., De Silva, S.S. & Davy, B. (Eds.), *Inland fisheries resource enhancement and conservation in Asia*. FAO Regional Office for Asia and the Pacific, pp. 113–126.

Amarasinghe, U.S. & De Silva, S.S. (1999) Sri Lankan reservoir fishery: a case for introduction of a co-management strategy. *Fisheries Management and Ecology*, 6(5), 387–400.

Amarasinghe, U.S. & De Silva, S.S. (2016) Fishes and fisheries of Asian inland lacustrine waters. In Craig, J. (Ed.), *Freshwater fisheries ecology* (pp. 384–403). Wiley-Blackwell Science.

Amarasinghe, U.S. & Wijenayake, W.M.H.K. (2015) Results of a decade of R & D efforts on culture-based fisheries in Sri Lanka. In De Silva, S.S., Ingram, B.A., & Wilkinson, S. (Eds.), *Perspectives on culture-based fisheries developments in Asia* (pp. 59–71). Bangkok, Thailand: Network of Aquaculture Centres in Asia-Pacific.

Béné, C., Barange, M., Subasinghe, R., Pinstrup-Andersen, P., Merino, G., Hemre, G. et al. (2015) Feeding 9 billion by 2050 – putting fish back on the menu. *Food Security*.

Béné, C., Hersoug, B. & Allison, E.H. (2010) Not by rent alone: analysing the pro-poor functions of small-scale fisheries in developing countries. *Development Policy Review*, 28(3), 325–358.

Borcard, D., Gillet, F. & Legendre, P. (2011) *Numerical ecology with R*, 1st edition. Springer.

Borcard, D., Gillet, F. & Legendre, P. (2018) *Numerical ecology with R*, 2nd edition. Springer International Publishing.

Bray, J.R. & Curtis, J.T. (1957) An ordination of the upland forest communities of Southern Wisconsin. *Ecological Monographs*, 27(4), 325–349.

Chandrasoma, J. & Pushpalatha, K.B.C. (2018) Fisheries enhancements in inland waters in Sri Lanka with special reference to culture based fisheries: current status and impacts. *Sri Lanka Journal of Aquatic Sciences*, 23(1), 49–65.

Chandrasoma, J., Pushpalatha, K.B.C. & Fernando, W.A.J.R. (2015) Impact of introduction of culture-based fisheries on fish production in perennial reservoirs. In De Silva, S.S., Ingram, B.A. & Wilkinson, S. (Eds.), *Perspectives on culture-based fisheries developments in Asia* (pp. 83–90) Bangkok, Thailand: Network of Aquaculture Centres in Asia-Pacific.

Cowx, I.G. (1994) Stocking strategies. *Fisheries Management and Ecology*, 1, 15–30.

Cowx, I.G. (1999) An appraisal of stocking strategies in the light of developing country constraints. *Fisheries Management and Ecology*, 6, 21–34.

Cuvin-aralar, M.L.A., Lazartigue, A.G. & Aralar, E.V. (2013) Net mesh size affects production of giant freshwater prawn *Macrobrachium rosenbergii* cultured in lake-based cages. *Journal of Applied Ichthyology*, 29, 833–838.

De Silva, S.S. (2003) Culture-based fisheries: an underutilised opportunity in aquaculture development. *Aquaculture*, 221(1–4), 221–243.

De Silva, S.S. (2016) Culture based fisheries in Asia are a strategy to augment food security. *Food Security*.

De Silva, S.S. & Funge-Smith, S. (2005) *A review of stock enhancement practices in the inland water fisheries of Asia*. Asia-Pacific Fishery Commission.

Dixon, P. (2013) VEGAN, a package of R functions for community ecology. *Journal of Vegetation Science*, 14(6), 927–930.

Drexler, M. & Ainsworth, C.H. (2013) Generalized additive models used to predict species abundance in the Gulf of Mexico. An ecosystem modeling tool. *PLoS One*, 8(5)e64458

Faraway, J.J. (2016) *Extending the linear model with R: generalized linear, mixed effects and nonparametric regression models*, 2nd edition. Taylor & Francis.

Hastie, T.J. & Tibshirani, R.J. (1986) Generalized additive models. *Statistical Science*, 1(3), 297–318.

Hastie, T.J. & Tibshirani, R.J. (1990) *Generalized additive models*. Chapman & Hall.

Hettlarachchi, A. & Kularatne, M. (1988) Observations on small-scale pond culture of giant freshwater prawn. *Journal of Inland Fisheries*, 4, 25–29.

Holm, S. (1979) A simple sequentially rejective multiple test procedure. *Scandinavian Journal of Statistics*, 6(2), 65–70.

Ismael, D. & New, M.B. (2000) Biology. In New, M.B. & Valenti, W.C. (Eds.), *Freshwater prawn culture: the farming of Macrobrachium rosenbergii* (pp. 18–35). Blackwell Science.

Jayasekara, A.M. (2007) Status of freshwater prawn (*Macrobrachium rosenbergii*) farming in Sri Lanka. Freshwater prawns: advances in biology, aquaculture and marketing. Kochi, Kerala.

Jayasinghe, U.A.D., Amarasinghe, U.S. & De Silva, S.S. (2006) Culture-based fisheries in non-perennial reservoirs of Sri Lanka: influence of reservoir morphometry and stocking density on yield. *Fisheries Management and Ecology*, 13, 157–164.

Jutagate, T. & Kwangkhang, W. (2015) Culture-based fishery of giant freshwater prawn: experiences from Thailand. In De Silva, S.S., Ingram, B.A. & Wilkinson, S. (Eds.), *Perspectives on culture-based fisheries developments in Asia* (pp. 91–97). Bangkok, Thailand: Network of Aquaculture Centres in Asia-Pacific.

Kutty, M.N. (2005) Towards sustainable freshwater prawn aquaculture – lessons from shrimp farming, with special reference to India. *Aquaculture Research*, 36, 255–263.

Kwangkhang, W., Jutagate, A., Saowakoon, S. & Jutagate, T. (2019) Trophic interactions and energy flows in ponds used for culture-based fisheries, with emphasis on giant freshwater prawn. *Agriculture and Natural Resources*, 53, 274–282.

Lan, L.M., Long, D.N. & Micha, J. (2006) The effects of densities and feed types on the production of *Macrobrachium rosenbergii* (De Man) in the rotational rice – prawn system. *Aquaculture Research*, 37, 1297–1304.

Limpadani, D. & Tansakul, R. (1980) Culture of giant freshwater prawn (*Macrobrachium rosenbergii*) in a small reservoir. *Aquaculture*, 20, 257–260.

Lorenzen, K. (2001) Enhancement. In Welcomme, R.L. (Ed.), *Inland fisheries: ecology and management* (pp. 241–253). Fishing New Books. Blackwell Science.

Lorenzen, K. (2006) Population management in fisheries enhancement: gaining key information from release experiments through use of a size-dependent mortality model. *Fisheries Research*, 80, 19–27.

Lorenzen, K. (2014) Understanding and managing enhancements: why fisheries scientists should care. *Journal of Fish Biology*, 85, 1807–1829.

Lorenzen, K., Amarasinghe, U.S., Bartley, D.M., Bell, J.D., Bilio, M., De Silva, S.S., et al. (2001) Strategic review of enhancements and culture-based fisheries. In Subasinghe, R.P., Bueno, P., Phillips, M.J., Hough, C. & McGladdery, S.E. (Eds.), *Technical Proceedings of the Conference on Aquaculture in the Third Millennium* (pp. 221–237). Aquaculture in the Third Millennium.

Lourantou, A., Thomé, J. & Goffart, A. (2007) Water quality assessment of a recently refilled reservoir: the case of Bütgenbach Reservoir, Belgium. *Lakes & Reservoirs: Research and Management*, 12, 261–274.

Marques, H.L.D.A. & Moraes-valenti, P.M.C. (2012) Current status and prospects of farming the giant river prawn (*Macrobrachium rosenbergii* (De Man 1879) and the Amazon river prawn *Macrobrachium amazonicum* (Heller 1862)) in Brazil. *Aquaculture Research*, 43, 984–992.

Maunder, M.N. & Punt, A.E. (2004) Standardizing catch and effort data: a review of recent approaches. *Fisheries Research*, 70, 141–159.

Murase, H., Nagashima, H., Yonezaki, S., Matsukura, R. & Kitakado, T. (2009) Application of a generalized additive model (GAM) to reveal relationships between environmental factors and distributions of pelagic fish and krill: a case study in Sendai Bay, Japan. *ICES Journal of Marine Science*, 66, 1417–1424.

Nadarajah, S., Wijenayake, W.M.H.K. & Amarasinghe, U.S. (2019) Influence of hydrology on water quality and trophic state of irrigation reservoirs in Sri Lanka. *Lakes & Reservoirs*, 24, 287–298.

Nair, C.M., Kutty, M.N., Salin, K.R. & Nambudiri, N.N. (2007) Emerging culture-based fisheries of *Macrobrachium* in reservoirs of Kerala, India. Aquaculture, 2007, San Antonio, Texas, USA, 26 Feb–2 March, 2007.

Nair, C.M. & Salin, K.R. (2012) Current status and prospects of farming the giant river prawn *Macrobrachium rosenbergii* (De Man) and the monsoon river prawn *Macrobrachium malcolmsonii* (H. M. Edwards) in India. *Aquaculture Research*, 43, 999–1014.

New, M.B. (2002) *Farming freshwater prawns: a manual for the culture of the giant river prawn (Macrobrachium rosenbergii)*. Rome: Food and Agriculture Organization of the United Nations.

New, M.B. (2005) Freshwater prawn farming: global status, recent research and a glance at the future. *Aquaculture Research*, 36, 210–230.

New, M.B. & Kutty, M.N. (2010) Commercial freshwater prawn farming and enhancement around the world. In New, M.B., Valenti, W.C., Tidwell, J.H., D'Abramo, L.R. & Kutty, M.N. (Eds.), *Freshwater prawns: biology and farming* (pp. 346–400). Wiley-Blackwell Science.

New, M.B., Singholka, S. & Kutty, M.N. (2000) Prawn capture fisheries and enhancement. In New, M.B. & Valenti, W.C. (Eds.), *Freshwater prawn culture: the farming of Macrobrachium rosenbergii* (pp. 411–435). Blackwell Science.

Ng'onga, M., Kalaba, F.K., Mwitwa, J. & Bright, N. (2019) The interactive effects of rainfall, temperature and water level on fish yield in Lake Bangweulu fishery, Zambia. *Journal of Thermal Biology*.

Nunan, F. (2020) The political economy of fisheries co-management: challenging the potential for success on Lake Victoria. *Global Environmental Change*, 63, 102101.

Phuong, N.T., Hai, T.N., Hien, T.T.T., Bui, T.V., Huoung, D.T.T., Son, V.N. et al. (2006) Current status of freshwater prawn culture in Vietnam and the development and transfer of seed production technology. *Fisheries Science*, 72, 1–12.

Pleydell, D.R.J. & Chrtien, S. (2010) Mixtures of GAMs for habitat suitability analysis with overdispersed presence absence data. *Computational Statistics and Data Analysis*, 54, 1405–1418.

Potts, S.E. & Rose, K.A. (2018) Evaluation of GLM and GAM for estimating population indices from fishery independent surveys. *Fisheries Research*, 208, 167–178.

Pushpalatha, K.B.C. & Chandrasoma, J. (2010) Culture-based fisheries in minor perennial reservoirs in Sri Lanka: variability in production, stocked species and yield implications. *Journal of Applied Ichthyology*, 26, 99–104.

Pushpalatha, K.B.C., Fernando, W.A.J.R. & Chandrasoma, J. (2015) Impact of introduction of culture based fisheries on fish production in two perennial reservoirs in Sri Lanka. *International Journal of Fisheries and Aquatic Studies*, 2, 5–9.

Pushpalatha, K.B.C., Kularatne, M.G., Chandrasoma, J. & Amarasinghe, U.S. (2020) Production trends and technical efficiencies of culture-based fisheries in five tropical irrigation reservoirs: a case study from Sri Lanka. *Fisheries Management and Ecology*.

R Core Team. (2020) *R: a language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing.

Romano, N. & Zeng, C. (2017) Cannibalism of *Decapod crustaceans* and implications for their aquaculture: a review of its prevalence, influencing factors, and mitigating methods. *Reviews in Fisheries Science & Aquaculture*, 25(1), 42–69.

Rubec, P.J., Kiltie, R., Leone, E., Flamm, R.O., McEachron, L. & Santi, C. (2016) Using delta-generalized additive models to predict spatial distributions and population abundance of juvenile pink shrimp in Tampa Bay, Florida. *Marine and Coastal Fisheries*, 8(1), 232–243.

Short, J.W. (2004) A revision of Australian river prawns, *Macrobrachium* (Crustacea: Decapoda: Palaemonidae). *Hyrobiologia*, 525(1980), 1–100.

Smith, L.E.D., Nguyen-khoa, S. & Lorenzen, K. (2005) Livelihood functions of inland fisheries: policy implications in developing countries. *Water Policy*, 7, 359–383.

Solanki, H.U., Bhatpuria, D. & Chauhan, P. (2016) Applications of generalized additive model (GAM) to satellite-derived variables and fishery data for prediction of fishery resources distributions in the Arabian Sea. *Geocarto International*.

Son, V.N., Yi, Y. & Phuong, N.T. (2005) River pen culture of giant freshwater prawn *Macrobrachium rosenbergii* (De Man) in South Vietnam. *Aquaculture Research*, 36, 284–291.

Sripatrprasite, P. & Lin, C.K. (2003) Stocking and recapture of freshwater prawn (*Macrobrachium rosenbergii* De Man) in a Runof-River Type Dam (Pak Mun Dam) in Thailand. *Asian Fisheries Science*, 2(16), 167–174.

Subasinghe, R., Soto, D. & Jia, J. (2009) Global aquaculture and its role in sustainable development. *Reviews in Aquaculture*, 1, 2–9.

Tidwell, J.H., Coyle, S.D. & Schulmeister, G. (1998) Effects of added substrate on the production and population characteristics of freshwater prawns *Macrobrachiurn rosenbergii* in ponds. *Journal of the World Aquaculture Society*, 29(1), 17–22.

Venables, W.N. & Dichmont, C.M. (2004) GLMs, GAMs and GLMMs: an overview of theory for applications in fisheries research. *Fisheries Research*, 70, 319–337.

Welcomme, R.L., Cowx, I.G., Coates, D., Béné, C., Funge-Smith, S., Halls, A. et al. (2010) Inland capture fisheries. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 365, 2881–2896.

Wijenayake, W.M.H.K., Amarasinghe, U.S. & De Silva, S.S. (2016) Application of a multiple-criteria decision making approach for selecting non-perennial reservoirs for culture-based fishery development: case study from Sri Lanka. *Aquaculture*, 459, 26–35.

Wijenayake, W.M.H.K., Jayasinghe, U.A.D., Amarasinghe, U.S., Athula, J.A., Pushpalatha, K.B.C. & Silva, S.S.D.E. (2005) Culture-based fisheries in non-perennial reservoirs in Sri Lanka: production and relative performance of stocked species. *Fisheries Management and Ecology*, 12, 249–258.

Wijenayake, W.M.H.K., Najim, M.M.M. & Amarasinghe, U.S. (2021) Constraints in culture-based fisheries of Sri Lanka and strategies for future development. *Sri Lanka Journal of Aquatic Sciences*, 26(2), 81–95.

Wood, S.N. (2003) Thin plate regression splines. *Journal of the Royal Statistical Society. Series B: Statistical Methodology*, 65(1), 95–114.

Wood, S.N. (2006) *Generalized additive models: an introduction with R*, 1st edition. Taylor & Francis Group.

Wood, S.N. (2017) *Generalized additive models: an introduction with R*, 2nd edition. Taylor & Francis Group.

Yan, S., Wang, X., Zhang, Y., Liu, D., Yi, Y., Li, C., et al. (2020) A hybrid PCA-GAM model for investigating the spatiotemporal impacts of water level fluctuations on the diversity of benthic macroinvertebrates in Baiyangdian Lake, North China. *Ecological Indicators*, 116, 106459.

Youn, S., Taylor, W.W., Lynch, A.J., Cowx, I.G., Beard, T.D., Bartley, D. et al. (2014) Inland capture fishery contributions to global food security and threats to their future. *Global Food Security*, 3(3–4), 142–148.

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