Original Article

River discharge, fishing effort and catch composition of prawn fisheries in coastal Tanzania

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Abstract

This study examined the relationships between river discharge, fishing effort and catch composition of prawn fisheries in coastal Tanzania. Key assumptions were that river discharge would be a good indicator of rainfall and that the number of fishing vessels would reflect fishing intensity. We investigated whether reduced river discharge or increased fishing effort caused the collapse of the industrial prawn fishery in 2007, and which of these factors delayed recovery prior to reopening the fishery in 2017. The analysis showed a positive relationship between Catch Per Unit Effort (CPUE) and river discharge, with decreased river flow resulting in reduced prawn catches. The number of fishing vessels had little impact on CPUE before 2003, but thereafter CPUE declined even when fishing effort was reduced by 50%. A shift in trawl catches from a prawn-dominated fishery to a fish-dominated fishery was observed four years before the collapse. The trend in river discharge persisted below average (22 m^3/s) between 2000 and 2007. Forewarning of low river discharge, changing trawl catch composition, and increasing effort may have led to developing proactive strategies to minimise the impact of a changing regime on fish stocks and dependent communities. We recommend establishing a monitoring system to anticipate similar events in the future.

Keywords: industrial fisheries, prawn species, overfishing, fisheries management

Introduction

Fluctuations in prawn catch are a worldwide concern (Schlenker *et al*., 2023; Silas, 2011); recently, these have been attributed to the growing influence of anthropogenic pressures, including pollution, mangrove cover loss, reduced river flow, erratic rainfall patterns, and climate change (Cheung *et al*., 2012; Gammelsrød, 1992; Hoguane, 2012; IPCC, 2021; Kasan *et al*., 2023; Perry *et al*., 2005; Schilling *et al*., 2023; Silas *et al*., 2023). Like many other aquatic organisms, prawns are highly sensitive to environmental changes. Their relatively short lifespan further exacerbates their vulnerability to these varying conditions (Silas, 2011). The studies by Turschwell *et al.* (2022) and Blamey *et al.* (2022) have highlighted the intricate relationship between prawns and their habitat, indicating that even slight alterations in environmental parameters can have far-reaching consequences on their populations. As such, the fluctuations in prawn catch are not solely due to natural variations but are deeply rooted in human-induced disturbances to their ecosystems.

Given the intricate relationship between prawns and their environment and the numerous anthropogenic pressures they face, managing prawn populations has become an arduous task. Balancing the economic interests of fisheries and the ecological well-being of prawn populations requires comprehensive strategies that address the root causes of fluctuations. Finding solutions to mitigate the impact of anthropogenic pressures while safeguarding sustainable growth of prawn populations present a significant challenge to fisheries management (Silas, 2011; Turschwell *et al*., 2022). This study aimed to delve into the complexities surrounding fluctuating prawn catches in Tanzania, shedding light on the underlying causes and potential implications, and proposing avenues for effective and sustainable management in the face of such challenges.

The prawn fishery is an important economic activity supporting Tanzania's economy and the livelihood of coastal communities (Malauene *et al*., 2021; Silas, 2011; Swaleh *et al*., 2015). Despite the benefits provided, this fishery was closed in 2007 due to low catches of all prawn species common in Tanzania (Appendix 1). Before the closure however, industrial fishers had already begun to reduce their fishing vessels since 2004 (Silas, 2011; TAFIRI, 2021). In 2007, the Ministry of Livestock and Fisheries of Tanzania banned industrial prawn fishing to allow the diminished stock to recover (Mwakosya *et al*., 2010). In 2017, a decade after the ban, the prawn fishery was reopened with improved measures to ensure long-term sustainability (TAFIRI, 2021). These additional regulations included a closed fishing season between September and March for the northern fishing grounds (encompassing Bagamoyo and Pangani) and between August and April for the southern fishing grounds (including Kilwa and Kisiju) (Fig. 1). Also, fishing vessels were limited to four on each of the two major fishing grounds (MLF, 2022). Furthermore, following the reopening, previously established management measures that were in effect before the closure in 2007, including limitation on fishing operations to a 12-hour window during daylight to prevent unregulated practices at night, the imposition of a vessel capacity not exceeding 500 HP, and the strict prohibition of tickler chain usage were also reinstated for improved sustainability (MLFD, 2009; Silas, 2011).

Since prawns have a high fecundity rate, between 40 000 to 320 000 eggs (Teikwa and Mgaya, 2003), after a short period of closure, it could have been expected that the population of prawns would bounce back; however, the recovery took a decade (i.e., from 2007 to 2017) (Mwakosya *et al*., 2010; TAFIRI, 2021). Assessing other factors that might have been at play or contributed to prawn collapse and possibly a delayed recovery is vital. For Tanzania, research studies that examine factors linked to prawn catch are scarce, and the available studies are restricted to some bays (Mosha and Gallardo, 2013; Semba *et al*., 2016). Consequently, extrapolating the findings to the entire coastline is challenging. For instance, Mosha and Gallardo (2013) highlighted how salinity affects prawn availability and abundance in the Pangani estuarine environment, whilst Semba *et al*. (2016) examined the relationship between phytoplankton and prawn productivity in the Rufiji delta, both studies being confined to a local area; however, effective management requires a broader understanding of varying conditions and habitats where organisms are found (Silas *et al*., 2023).

In that regard, limited information on factors affecting prawn catches at a larger scale, for example, in coastal Tanzania, creates a challenge for managers. Without a comprehensive understanding of the factors determining prawn catches and availability at a larger scale, they have no choice but to rely solely on input control measures, including traditional effort controls. This is because other management options, such as habitat restoration and pollution control, require a better understanding of the factors involved (Farmery *et al*., 2015; Swaleh, *et al*. 2015). This article aims to fill the knowledge gap regarding the long-term trend of prawn harvests and their relationship with precipitation patterns. To achieve this, river discharge was examined as a proxy for rainfall patterns to determine whether changes in prawn catches were associated with river discharge before the closure of the prawn fishery in 2007. Doing so provides a more comprehensive understanding of the factors influencing prawn availability beyond fishing pressure. This knowledge is essential for improved prawn resource management and may help to explain the delayed recovery a decade after the moratorium in 2007.

Materials and Methods

Study area

The three main prawn-fishing zones on Tanzania's coastline are examples of the nation's abundant and diverse aquatic life, and they also provide habitat for other fisheries like sardines (Silas, 2022). Zone 1 is situated in the northern part of the coast, close to Bagamoyo and Saadani, and estuarine conditions are supported there by the Pangani, Wami and Ruvu rivers, which originate from the Kilimanjaro and Nguru mountain ranges, and the Uluguru Mountains, respectively. Zone 2 is located at the mouth of the Rufiji River which is the largest and longest river in Tanzania, originating from the Poroto and Kipengere mountain ranges in the southern highlands. Zone 3 is south of the Rufiji Delta, also influenced by the Rufiji River. Tanzania's prawn fisheries benefit from the favourable conditions created by these major rivers (see Fig. 1).

Data Sources

The data utilised in this study pertains to the period before closure in 2007 and encompasses prawn catch and effort data, as well as river discharge data between rainfall patterns and marine fish catch and migration, as highlighted by other studies (Cheung *et al.*, 2012; IPCC, 2021; Perry *et al.*, 2005).

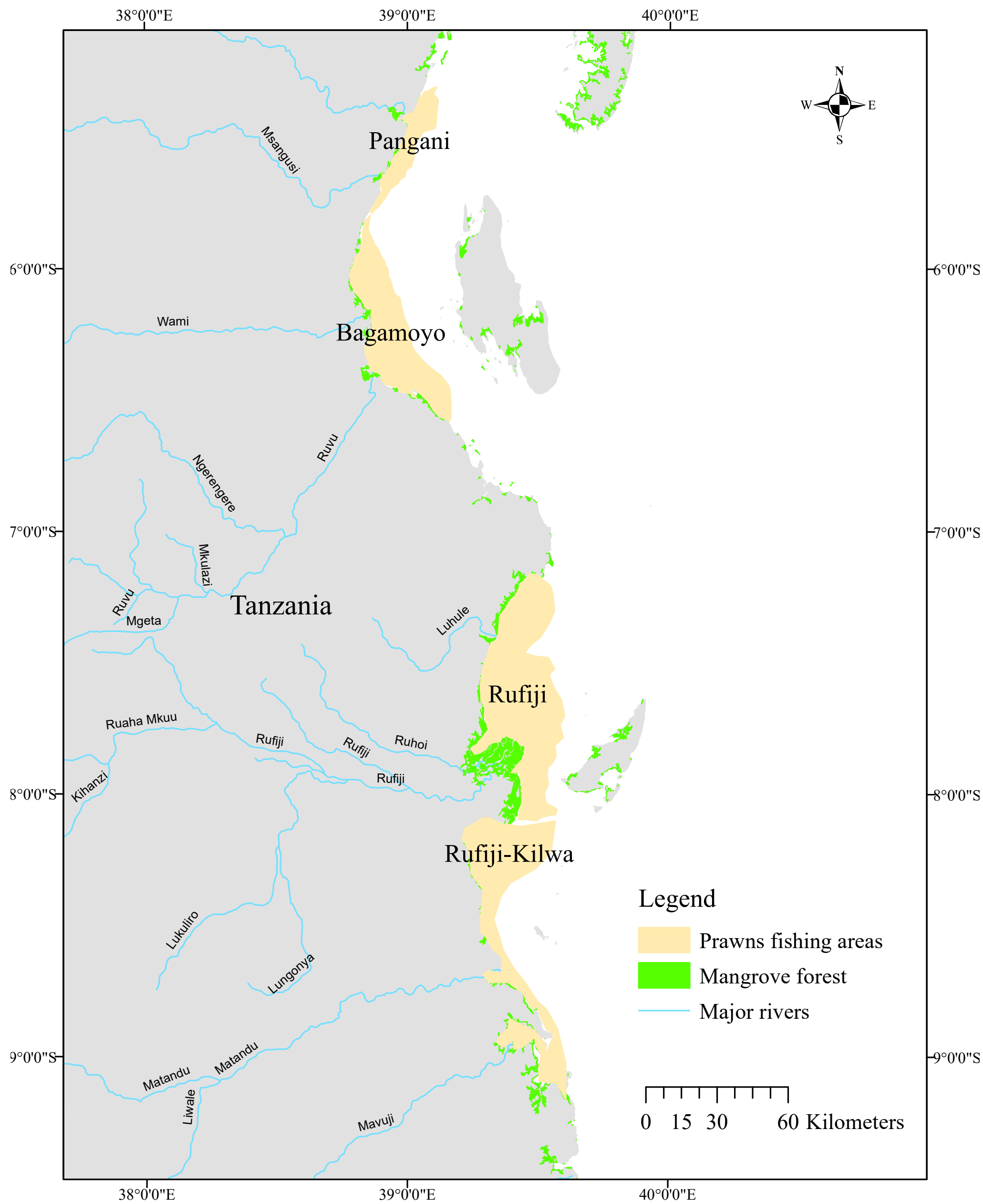

Figure 1. Map of the prawn fishing zones on the coast of Tanzania.

from 1988 to 2007. River discharge data was used to evaluate its impact on prawn catches, given its role in determining availability and catch variability in other coastal regions of the Western Indian Ocean, including neighbouring Mozambique (Malauene *et al.*, 2021). This study also considered the relationship

Prawn catch data

Several data sources, including logbooks, vessel monitoring systems (VMS), at-sea inspections, port sampling, and an observer programme, were used to obtain information on industrial prawn catch and fishing effort and ensure data quality. Prawn trawlers are obliged by law to keep logbooks that record their fishing operations, including the date, time, location, time spent fishing, species of prawns caught and information on bycatch. All commercial prawn trawlers have VMS devices that communicate satellite position, speed, and direction information to the Fisheries Department. Before submitting data recorded in the logbooks to the Fisheries Department, the onboard observer checks the information logged to ensure accuracy. The Fisheries Department then digitises and includes the information in the annual statistics report books and also submits data to the Food and Agriculture Organisation of the United Nations (MLF, 2020).

River discharge data

Daily discharge data in cubic meters per second (m^3/s) was extracted from the Hydrological Year Book of Tanzania (https://www.maji.go.tz/) for the major rivers flowing into the main prawn fishing grounds in the coastal Indian Ocean. Although the Hydrological Year Book contains long-term data, this analysis was limited to data for the study period.

Data processing

Prawn relative abundance was estimated by a method described by Harley *et al*. (2001), whereby fish catch rates (CPUE) were standardised by dividing the total weight of fish landed by the number of fishing vessels involved in the fishing. Using this method, it was possible to compute an index which was employed to approximate the prawn population's relative abundance:

$$\text{Catch rate (CPUE)} = \frac{Wt}{No}$$

Where 'Wt' represents the wet weight of landed prawns and/or fish measured in kg, and 'No' is the number of fishing vessels involved when fishing.

Since the available prawn catch data were recorded on a yearly basis and lacked seasonal representation, an alternative approach had to be adopted. Therefore, the mean annual river discharge was computed as a proxy to compare with the limited prawn catch data. This allowed investigation of potential correlations or relationships between the two variables despite the low resolution of the prawn catch data.

Analysis

R version 4.2.0 was used for all statistical analyses and ggplot2 for plotting (R Core Team 2013, 2021). To investigate whether fishing effort or other factors influenced prawn catch, detrended indices of precipitation and prawn catch were developed. This process helped eliminate noise and other irregularities, thus enhancing the precision of predictions. For detrending, a yearly mean discharge rate in $m^{-3} s^{-1}$, mean prawn catch in tons/day, and mean proportion of prawn to fish catch was used. This was used to assess the relationship between prawn catch and discharge rates between 1988 and 1997 with a generalised linear model. Bar charts of detrended CPUE and discharge were also prepared to see when the values were above or below average.

Furthermore, a table was constructed examining the association between detrended discharge values and the detrended proportion of the prawn-to-fish catch ratio to assess if any and when changes occurred in the catch composition based on the prawn-to-fish catch ratio (Table 1).

Results

The impact of fishing effort on the prawn fishery

Prawn catches (measured in CPUE) fluctuated from the late 1980s to the closure in 2007 (Fig. 2). Prawn CPUE declined while effort increased until early 2003, when the maximum number of 26 fishing vessels was reached (Fig. 2). After that period, prawn catch dropped by 50 % from 1 320 to 661 tons in just a year (between 2003 and 2004) in spite of no drop in effort. The drop in catch prompted industrial fishers to reduce the number of fishing boats for the following three years, but CPUE continued to decline. In 2005, only 14 fishing vessels (56 % of the 25) were left operational. In 2007, the fishing companies further reduced the number of fishing vessels to 10, with no increase in CPUE. In 2007, the fisheries department officially closed the prawn fishery.

Trends of prawn catch and river discharge rate

Figure 3 illustrates the deviation from the long-term average of river discharge (m^3/sec) and CPUE (ton/day). Positive values indicate above-average conditions, while negative values indicate below-average conditions. There was a gradual rise in river discharge since 1988, which peaked in 1992. In the subsequent years, discharge rates fell below the long-term average, reaching their lowest levels in 1993 and 1994. However, from 1995 to 1996, the discharge rates increased and exceeded the long-term average. In 1997, the discharge rates fell below the long-term average again, followed by an increase in discharge rates from 1998 to 2000. Below-average discharge rates characterised the period from 2001 to 2007.

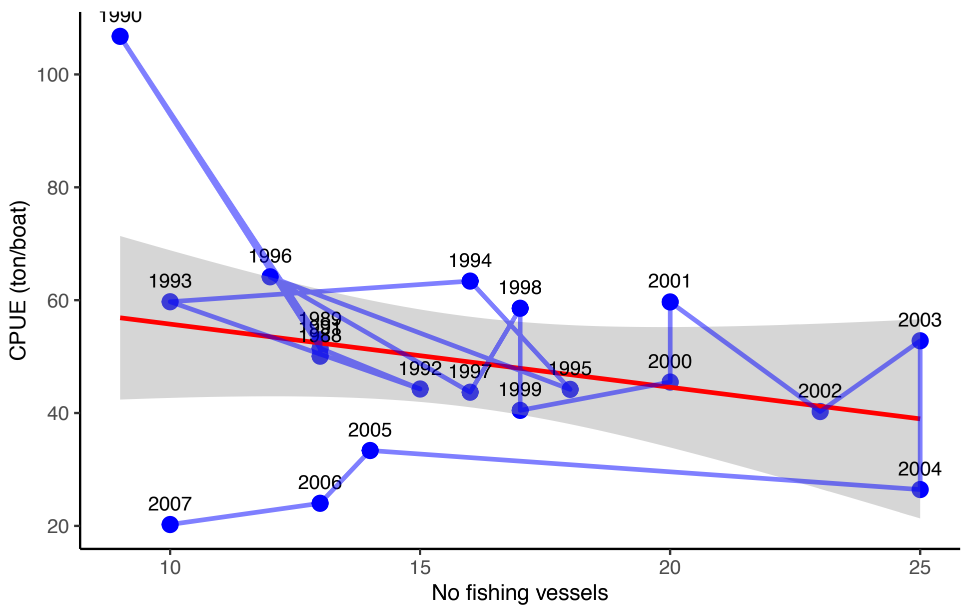

Figure 2. The relationship between CPUE; a tonnage-per-boat measure of relative prawn abundance, and the number of fishing boats from 1988 to the fishery's closure in 2007.

Except for 1989, CPUE values remained above average from 1988 to 1996, spanning almost a decade. However, in 1997, the CPUE dropped below the long-term average, and this trend persisted until the prawn fishery was officially closed in 2007. Notably, the highest CPUE value was recorded in 1990, after which there was a general decline in prawn CPUE until the fishery closure in 2007. In general, during the late 1980s to early 1990s, when the discharge rate was above average, the CPUE was also above average. Similarly, from early 2000 to 2007, when the discharge rate was below average, the CPUE was below average. However, between 1995 and 1997, discharge and CPUE were at their average levels.

Correlation between prawn catch and river discharge

Figure 4 shows a positive relationship between detrended CPUE and discharge data. This relationship implies the amount of water pouring into

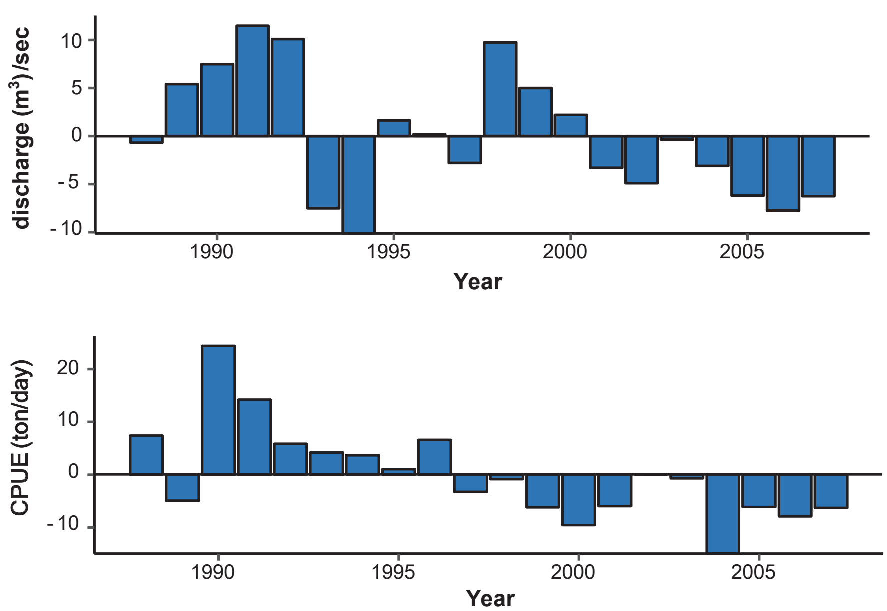

Figure 3. The trend of river discharge and prawn catch (CPUE) on the Tanzanian coast between 1988 to 2007. the CPUE and discharge rate data are detrended.

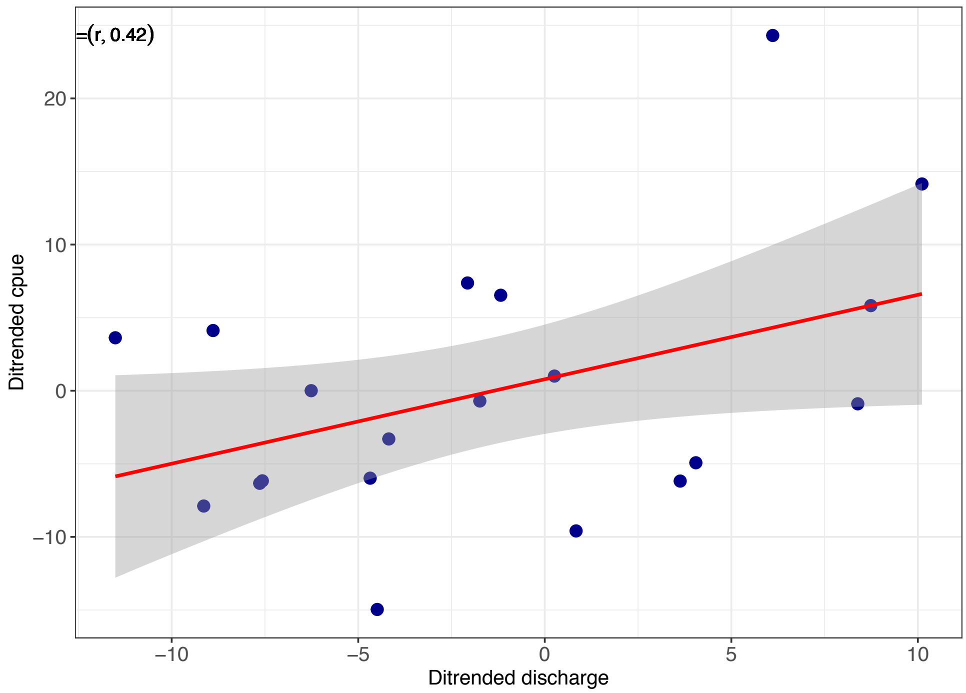

Figure 4. The relationship between prawn catch and discharge rate for two decadal periods from 1988 to 1997 on the coast of Tanzania. Data are detrended, and a generalised linear model is used for fitting while standard errors are presented in grey.

the ocean from the river or stream (discharge); if it decreases, the prawn catch per unit effort (CPUE) also declines, whereas an increase in discharge results in an increased catch.

Switch in trawl catch composition

The composition of trawl catches shifted from a prawn-dominated fishery in the 1980s to a fish-dominated one from early 2000 (see catch proportion column in Table 1). This shift was apparent nine years before the prawn fishery was closed. Based on these statistics, the change in trawl catch composition coincided with below-average river flow. This result indicates a possible link between river discharge trends and a switch in catch composition, particularly from the early 2000s. Therefore, increasing trawl vessels, particularly after the early 2000s, when changed to fish-dominated, increased bycatch levels. For instance, in the final years before the closures, the prawn composition comprised roughly 30 % of the catch, indicating that more fish were captured than prawns.

Discussion

The prawn fishery along the coast of Tanzania has been a crucial source of livelihood for coastal communities and a significant contributor to the country's economy (MLF, 2020; Silas, 2011). However, overfishing, combined with environmental factors such as decreased river flow, has led to a decline in prawn populations, ultimately resulting in the closure of the prawn fishery in 2007. This study aimed to investigate the link between extended-term trends of prawn harvest and precipitation patterns, using river discharge as a proxy for rainfall patterns. River discharge was chosen as it influences prawn populations and their well-being globally (Turschwell *et al.*, 2022). Variations in river flow, such as seasonal changes, flood events, and human-induced alterations, directly and indirectly impact prawn habitats and behaviour. During the wet season, for example, increased river flow facilitates juvenile prawn transportation into estuaries and coastal areas, promoting higher catch rates (Silas, 2011; Silas *et al.*, 2023).

Based on such considerations, the fluctuation of prawn catches for Tanzania was evaluated, and the findings suggest a positive relationship between detrended CPUE and river discharge. The presence of this relationship may suggest that a decrease in river or stream water flow (discharge) reduces the prawn abundance, resulting in low catches. Gammelsrød (1992) and Hoguane (2012) also documented comparable results of low catch at reduced discharges. The link between river flow and prawn abundance is also described for other regions. For regions where the wet and dry season persists, reduced river flow during the dry season

Table 1. Changes in trawl catch composition from prawn-dominated to fish-dominated from the prawn fishing grounds off the coast of Tanzania. Green values in the discharge column indicate above-average discharge rates, while red values indicate below-average discharge rates. In the catch proportion column, green values indicate years when the prawn catch was above-average, while red values show years when the catch was below average.

Year	Discharge	Prawn (tons)	Fish (tons)	Prawn: Fish	Detrended Discharge	Detrended catch proportion
1988	21.42	650.93	988.25	0.66	▼0.71	▼0.55
1989	27.54	688.84	978.50	0.70	▲5.41	▼0.50
1990	29.6	960.69	647.47	1.48	▲7.47	▲0.28
1991	33.6	669.02	460.77	1.45	▲11.47	▲0.25
1992	32.23	663.85	462.85	1.43	▲10.10	▲0.23
1993	14.6	597.21	398.11	1.50	▼7.53	▲0.29
1994	11.98	1014.09	575.81	1.76	▼10.15	▲0.55
1995	23.75	795.44	765.54	1.04	▲1.62	▼0.17
1996	22.31	769.65	598.72	1.29	▲0.18	▲0.08
1997	19.31	699.06	610.50	1.15	▼2.82	▼0.06
1998	31.88	995.56	537.88	1.85	▲9.75	▲0.64
1999	27.12	688.01	609.52	1.13	▲4.99	▼0.08
2000	24.33	909.72	958.13	0.95	▲2.20	▼0.26
2001	18.81	1193.69	1010.31	1.18	▼3.32	▼0.02
2002	17.23	926.08	296.35	3.12	▼4.90	▲1.92
2003	21.75	1320.06	931.16	1.42	▼0.38	▲0.21
2004	19	661.06	862.36	0.77	▼3.13	▼0.44
2005	15.92	467.04	868.97	0.54	▼6.21	▼0.67
2006	14.35	312.08	792.64	0.39	▼7.78	▼0.81
2007	15.85	202.46	642.17	0.32	▼6.28	▼0.89

concentrates prawns in specific locations, making them more susceptible to fishing pressure (Broadley *et al.*, 2020). Also, flood events are linked to disrupting prawn habitats, causing short-term declines in the catch, but in some other areas, these events enhance coastal productivity, benefiting prawn populations in the long run (Duggan *et al.*, 2019; Malauene *et al.*, 2021). Such relationships may plausibly explain a delayed recovery of prawn populations following the ban of the industrial prawn fishery in 2007 to the subsequent reopening in 2017, as prawns are highly prolific.

Similarly, the composition of trawl catches along the coast of Tanzania changed from being predominantly prawn in the early 1980s to being dominated by fish in early 2000, nine years before the prawn fishery was officially closed (Table 1). Such evidence suggests that if the catch composition switch had been observed earlier (due to the increased retention of fish bycatch as CPUE of prawns decreased), it could have alerted managers of the possible outcome of a collapse. Additionally, the data indicates that the shift in prawn composition occurred nine years following below-average river flow, which suggests a potential correlation between river discharge trends and changes in trawl catch composition. Comparable changes have been documented in other regions, where early maturing fish populations dominate as they respond easily to changes (Galván *et al.*, 2022; Levine *et al.*, 2023). For example, in the Pacific Arctic, where the water temperature is increasing and salinity is reduced due to melting ice (a phenomenon similar to increased river flow), the fish composition is reported to have changed (Levine *et al.*, 2023), a comparable effect to fish composition change in the prawn fishery of Tanzania. Though prawns are less likely to be affected negatively by increased salinity at an estuarine scale, other species may be affected. An example of such change happened in Patagonia when alien species invaded the area due to such changing conditions (Galván *et al.*, 2022).

Rapid urbanisation and large agricultural expansion characterising the coastal regions has increased water usage in most countries, including Tanzania (Lazaro *et al.*, 2019; NBS, 2018; Seeteram *et al.*, 2019). Combined with extensive land-use changes, subsequent water diversions, and the creation of dams for power projects, it will likely continue to cause river volumes to decline further. These trends are expected to further escalate the impacts on fisheries productivity, including a continued decline in some important fisheries, including prawns and other species that depend on nutrient flux from major rivers. The persistence of reduced river discharges highlights the importance of implementing an Ecosystem Approach to Fisheries (EAF) management and other conservation efforts to help mitigate and safeguard vital ecosystems that support fisheries productivity, an important component of human livelihoods (Eriksson *et al.*, 2016; Silas, 2022).

Other conservation efforts, for example, input control (limiting fishing vessels and time), persisted before the fishery was closed, and neither had a positive impact. It is now emphasised that a practical management approach should consider other factors, including the environment. For example, had the managers observed the catch composition switch and decreased discharge, they would have responded earlier. Therefore, it is suggested that to achieve the fishery's long-term sustainability, an EAF should to be implemented (FAO, 2020). To ensure a consistent and sustainable prawn supply, effective fisheries management strategies that consider the complex interactions between fishing pressure, environmental factors, and the well-being of both prawn populations and the communities that rely on them should be considered.

Though a link was found between prawn catch, trawl catch composition and river discharge, several challenges were also encountered. One of the significant challenges was the lack of consistent and reliable data on prawn catches. The available data were often reported annually and scattered across different sources, making it challenging to comprehensively analyse the monthly relationships (at a much higher resolution). Also, the ban on the prawn fishery in 2007 limited data availability during the ban period, making it difficult to establish the long-term trends of prawn catches and river discharge during the ban. Another challenge was the difficulty separating the effects of fishing pressure from those of other factors, including the environment, in this case, discharge. However, errors were minimised by detrending the data sets used.

Considering the influence of various unexplored variables in this study, including seawater temperature and salinity, on prawn abundance (Hoguane, 2012; Ndunguru *et al.*, 2022), further research is advocated to unravel the complexities of these factors. If all factors had been investigated, the way could have been paved for developing more practical and feasible management strategies for prawns. In addition, since the industrial and artisanal fishery both depend on the same stock, it would be important to understand the coupling between the two fisheries. Also, it could have helped to understand how the artisanal fishery contributed to prawn collapse or a delayed recovery, as artisanal fishers continued fishing after the ban. Understanding these interactions would have provided a more comprehensive picture of how this fishery is affected, enabling the development of an effective monitoring plan involving all relevant stakeholders. In this type of fishery, where artisanal and industrial fishers target the same stock, it is important to have an effective and sustainable management strategy that safeguards resources for the benefit of the large numbers of the population that depends on them.

Conclusion and recommendations

The results of the is study indicate a correlation between changes in prawn catch and river flow, emphasising the need for stakeholders to prioritise and address challenges affecting fish supply; for example, managing watersheds with a multisectoral approach. This may include avoiding obstructing river flow to a degree where other users are impacted. For example, when constructing dams for hydropower stations or irrigation schemes, sufficient water should be left to continue downstream to maintain critical ecosystem processes. Additionally, it is recommended that other factors (e.g., change in mangrove cover, sea water temperature) that were not explored in this study, are investigated. It is also suggested that governments and NGOs invest in alternative livelihood opportunities to reduce reliance on fisheries as the only source of income. These alternatives may include promoting ecotourism activities, developing alternative fisheries, and offering training and education programmes to support entrepreneurship and small business development, as Silas *et al.* (2020) recommended when examining why fishing communities persist in fishing when catches are declining.

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Appendix

Appendix 1. Prawn species composition in the Tanzanian marine waters.

No	Scientific name	Common name
1	*Penaeus (Fenneropenaeus) indicus*	White prawn
2	*Metapenaeus monoceros*	Speckled shrimp
3	*Panaeus semisulcatus*	Green tiger prawn
4	*Penaeus monodon*	Giant tiger prawn
5	*Penaeus (Marsupenaeus) japonicus*	Kuruma prawn
6	*Exhippolysmata ensirostris*	Hunter shrimp
7	*Macrobranchium rude*	Hairy river prawn
8	*Nematopalaemon tenuipes*	Spider prawn
9	*Metapenaeus stebbingi*	Peregrine Shrimp
10	*Penaeus (Melicertus) canalculatus*	Witch prawn
11	*Penaeus (Melicertus) latisulcatus*	Western king prawn

Source: Silas (2011) and Mwakosya *et al*. (2009)