Journal of
Water & Climate Change

 Journal of Water and Climate Change Vol 15 No 8, 4177 doi: 10.2166/wcc.2024.373

Evaluating the climate change–induced vulnerability of the Pichavaram mangrove ecosystem through a stakeholder-centric multiscale approach

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ABSTRACT

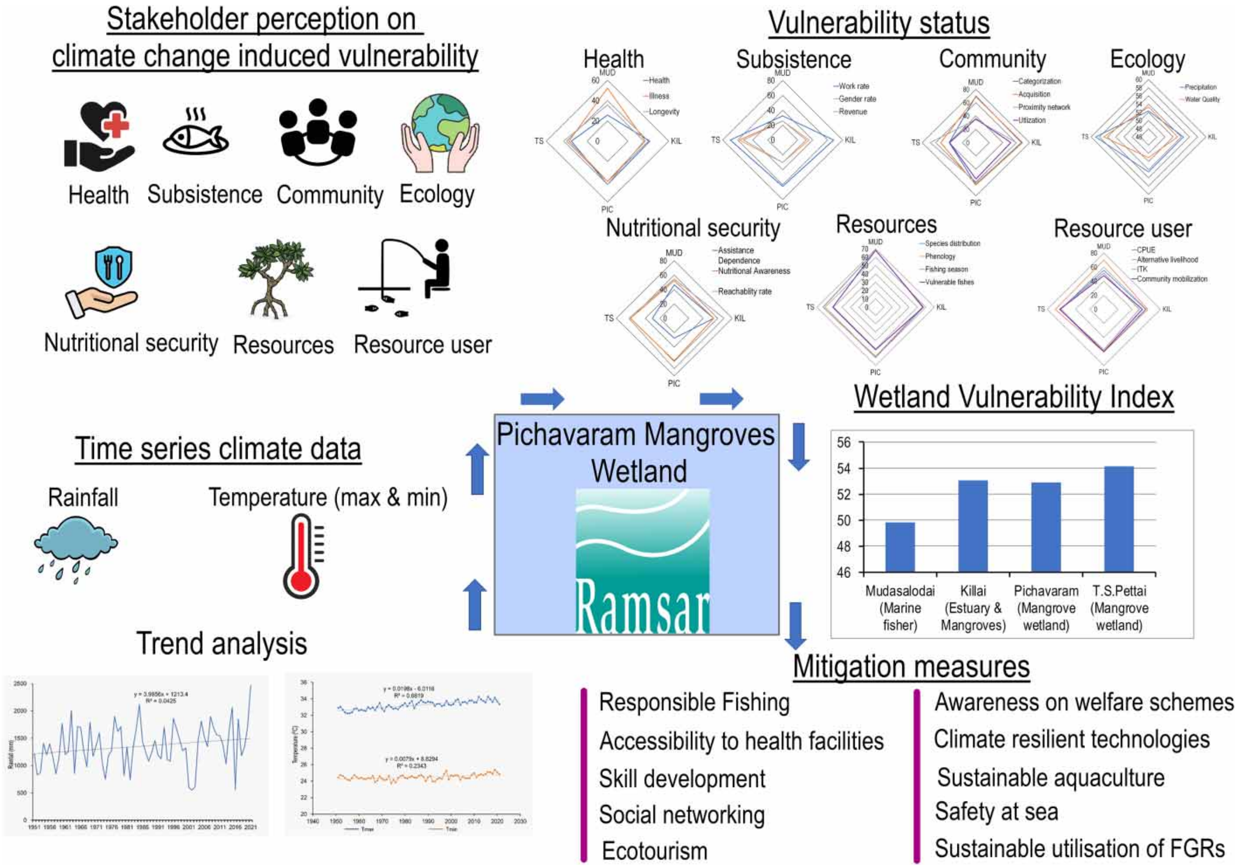
Mangrove-inhabited coastal areas are seriously threatened by climate change that disturbs the sustenance of dependent native communities. This study assesses the status of climate variables to identify and evaluate climate change–induced vulnerabilities to fishers and recommend mitigation measures at a regional scale in the Pichavaram Mangroves, a Ramsar wetland of international importance in India. The time series climate data (1951–2021) revealed an insignificant increase in annual rainfall ($p > 0.05$) and a significant increasing trend ($p < 0.05$) for mean annual temperature. The results of the stakeholder-based approach ($n = 240$) indicate that mangrove dwellers experience ecological and health-based vulnerabilities and estuarine fishers face community and nutritional issues. Fishers of this wetland are prone to resources (60.5) and user-based vulnerabilities (59.03). The overall vulnerability index places fishers of the mangrove/estuary (T.S.Pettai: 54.13; Killai: 53.04; Pichavaram: 52.91) more vulnerable than the marine region (Mudasalodai: 49.84). This study suggests social networking, skill development, awareness of welfare schemes, ecotourism, sustainable fishing, climate research for developing mitigation strategies, and fisheries enhancement to combat climate change impacts. Furthermore, building resilience among the stakeholders and resource management through a citizen science approach is crucial to lessen climate change vulnerability in coastal wetlands in India, and elsewhere.

Key words: adaptation strategies, coastal wetland, indicators, mitigation, rainfall, Ramsar wetland

HIGHLIGHTS

- The climate change vulnerability of Pichavaram Ramsar wetland was assessed using the stakeholder-based approach.
- Time series data (1951–2021) revealed a significant change in the mean annual temperature.
- Fishers are highly prone to fishery resources, users, community, and ecosystem vulnerabilities.
- Vulnerability to climate change indicated that mangrove and estuarine fishers and more vulnerable than marine fishers.
- The mitigation measures proposed in this study may also be useful in similar ecosystems elsewhere.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Mangroves are more beneficial to humans, including protecting coastlines, creating habitats for fish and wildlife, filtering sediment and pollutants, and sequestering carbon (Spalding 2010; Bouillon 2011). In the last several decades, mangrove regions have drastically decreased (Giri *et al.* 2011), and many of the remaining habitats are negatively impacted by unsustainable activities. The loss and degradation of these coastal buffering systems as a result of climate change and direct human influences reduce the protection the coasts offer from catastrophic events and make the coasts more vulnerable to climate change. Mangrove wetlands in India face severe threats due to rise in sea level (cyclonic activity, soil erosion, and accretion), irregular inundation (changing rainfall patterns), habitat degradation (mangrove encroachment), urbanization (land cover change), pollution (waste disposal, reduced freshwater inflow), and overexploitation (Kantharajan *et al.* 2017; Baidya *et al.* 2023). In particular, the coastal Ramsar mangrove wetlands in India are at a high risk of flooding associated with extreme rainfall, urbanization, and sedimentation in the future (Rakkasagi *et al.* 2024). This seriously affects both the ecosystems and the dependent community, especially on the social, economic, and environmental fronts (Villanueva-Fragoso *et al.* 2010).

Vulnerability is an encompassing concept for examining the interconnected social–ecological response to environmental change (Polsky *et al.* 2007; Adger & Brown 2009; Mertz *et al.* 2009), defined as the propensity or predisposition to be adversely affected (Oppenheimer *et al.* 2015). Climate change has compounded the effects of direct human pressures (Wang *et al.* 2010), which have followed the interpretation of vulnerability (Remling & Persson 2015). Three major components have been identified in the conceptualization of vulnerability: exposure to shocks, corresponding sensitivity, and related adaptive capability (Paavola & Adger 2006; Polsky *et al.* 2007). The mitigation of exposure and its avoidance through sector-specific and technical adaptation strategies are meant to reduce the adverse effects of climate change. Fishing communities consider small lakes and backwater habitats to be invaluable resources because they provide a range of ecosystem services that support their way of life and provide food security. According to several studies, climate change has a significant impact on the flora and faunal richness, water chemistry, and spread dynamics of coastal wetlands (Sarkar & Borah 2018; Rakkasagi *et al.* 2024).

The multiscale approaches have been widely applied to study climate systems using time series climate data through network models (Jusup *et al.* 2022). Stakeholder engagement is crucial in the decision-making process concerning climate change mitigation and adaptation (Sebos et al. 2023). Wang *et al.* (2020) reported the influence of volunteer groups (size, communication, and behavioral type) on the social dimension of climate change mitigation. The stakeholder-based approach employed climate change vulnerability assessments in various terrestrial and aquatic ecosystems both globally and in India (Babcock *et al.* 2016; Nyangoko *et al.* 2022; Sebos et al. 2023; Vijhani *et al.* 2023). The stakeholder-based approach was employed to understand drought mitigation and identify nature-based solutions in Ramsar wetlands in Europe for effective management (Ždero *et al.* 2024). Naskar *et al.* (2022) employed this approach to assess the vulnerability of wetland fisheries to climate change to prioritize them for strategic planning in West Bengal, India. Another study by Sarkar *et al.* (2022) combined the stakeholder perception and ecological approaches to evaluate the vulnerability of floodplain wetlands under changing climatic conditions. Another study by Debnath *et al.* (2024) gauged the vulnerability of 12 coastal wetlands in the Gangetic estuarine regions of India through a multiscale approach involving stakeholder perception. Mondal *et al.* (2022) evaluated the negative effects of climate change-related multi-hazards in diverse geographical regions in the Indian Sundarbans and recorded the mitigation measures followed to combat hazards related to climate change. Paul *et al.* (2024) assessed the vulnerabilities of wetland fishers to climate variability based on indicators grouped under seven drivers, *viz*., health, livelihood, social, food, ecological, resource, and resource user in Vembanad, a coastal Ramsar wetland in India.

The present study was conducted in the Pichavaram Mangrove Region (backwaters) on the southeast coast of India, located in the northern extreme of the Cauvery Delta, near the mouth of the Kollidam River. The total area of the region is about 1,350 ha and colonized by 13 true mangrove species including *Rhizophora* spp. In 2022, the region was declared as a Ramsar site, i.e., wetlands of international importance. The Pichavaram mangrove wetland is also rich in fish diversity (177 spp.) and supports diverse meiobenthos (40 spp.) and macrobenthos (52 spp.) communities (Kathiresan 2000). Annually about 245 tons of fishery produce is harvested from this wetland, of which prawns alone constitute 208 tons (85%) of the catch (Selvam *et al.* 2010). The people belonging to 17 hamlets of five revenue villages utilize the fishery and forestry resources of the wetlands. A total number of 1,900 full-time fishers are dependent on these resources for their livelihood and ≈1,000 fishers are seasonally involved in fishing in this region. Despite the importance, existing knowledge of the Pichavaram mangrove ecosystem concerning climatic variability and fisheries is very limited. Given the above, the present study was undertaken to evaluate the status of climate variables based on historical data and assess the climate change–induced vulnerability of the fishers and ecosystem in the Pichavaram mangrove, a Ramsar wetland through a stakeholder-centric multiscale approach. The findings of the present study will provide a comprehensive overview of climate change–induced vulnerability through the lens of stakeholder's perception and mitigation measures to combat the negative impacts of climate change on the ecosystem and dependent community.

2. MATERIALS AND METHODS

2.1. Sampling sites

The Pichavaram mangrove wetland (Latitude: 11.36–11.48° N; Longitude: 79.77–79.80° E) is located between the Vellar and Kollidam estuaries along the Bay of Bengal on the East coast of India. The region comprises 51 islets ranging in size from 10 m^2 to 2 km^2 (Kathiresan 2000). The mangroves cover an area of about 1,100 ha of which 50% is covered by mangroves, 40% by water, and the rest by mud flats and sand (Krishnamurthy *et al.* 1984). About 75–90% of the rainfall in this region occurs during the northeast monsoon (October–December) followed by tropical depressions in the Bay of Bengal (Kathiresan *et al.* 1996). The climate in Pichavaram is tropical wet and dry characterized by very hot and humid summers, where the maximum temperature reaches 34–40 °C followed by mild and pleasant winters (25 °C).

2.1.1. Data collection of socioeconomic status

A detailed stakeholder-based survey was conducted in four selected villages surrounding the Pichavaram mangrove wetlands, namely, Mudasalodai, Killai, Pichavaram, and Thandavarayan Sozhan Pettai (T.S. Pettai) in the Cuddalore District of Tamil Nadu, India (Figure 1). Mudasalodai is a marine fishing village located on the northern side of the wetland near the shoreline, whereas Killai mostly focuses on the estuarine and mangrove patches, and Pichavaram and T.S. Pettai concentrate solely on

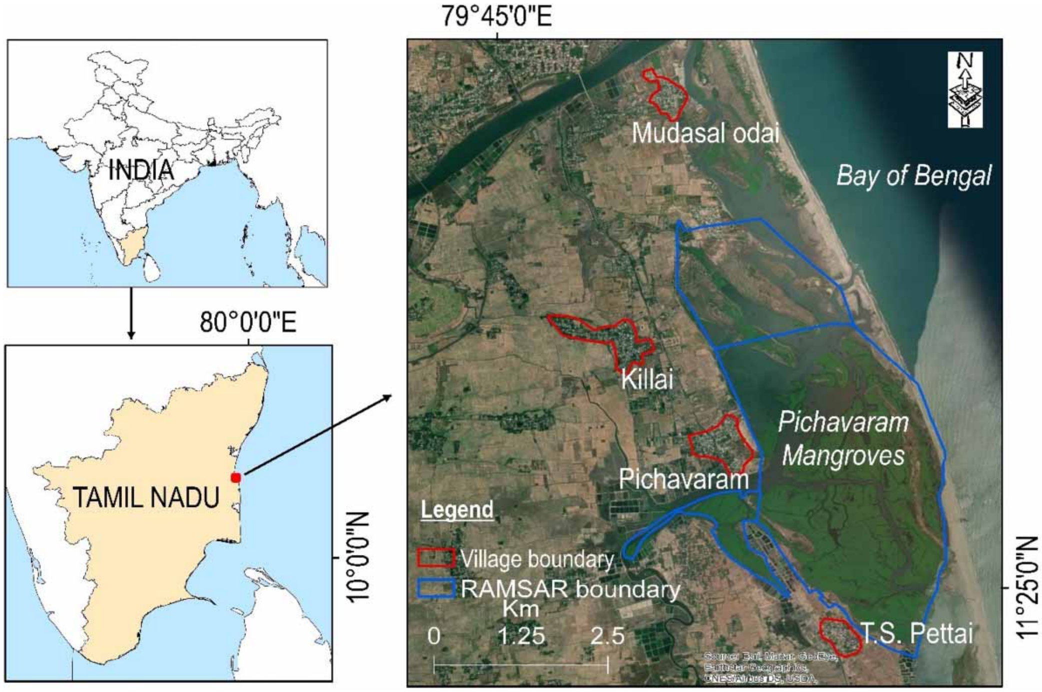


Figure 1 | Map representing the study area along the Pichavaram region in Tamil Nadu, India.

the mangrove regions. The questionnaire was prepared by modifying the schedule of similar studies conducted through the stakeholders approach (Hahn *et al.* 2009; Paul *et al.* 2024). The questionnaire was modified to capture the holistic perspectives of the climate change–induced vulnerability of the fishers by including a total of 22 vulnerability indicators under 7 categories, *viz.*, health (3), subsistence (3), community (4), nutritional security (3), ecology (2), resources (4), and its users (3) (Figure S1). Apart from these, the personal details of the interviewee and general habitat and fisheries information about the wetland were also collected (Annexure 1).

To ensure the representation of respondents from a range of socioeconomic and professional backgrounds, the questionnaire survey was carried out from key informants, including fishermen, members of fish exporters, fish and dry fish vendors, laborers, women fisherfolks, and office bearers of village panchayats in the selected villages. A total of 240 stakeholders (190 men and 50 women) were interviewed from 60 individuals per village *via* random sampling from July to October 2023. The detailed profile of demography (age and education) and occupation (type and experience) of the respondents is depicted in the Supplementary material (Figures S2–S5).

To avoid stakeholder indifference, the targeted stakeholders were explained about the importance and relevance of the study before the interviews. However, exaggeration of the original problems/issues faced by the respondents due to climate change is one of the potential sources of error in this study. Hence, such doubtful responses were duly validated through triangulation with well experienced key informants and official or published documents. Furthermore, the outcomes of this study are based on a limited sample size; hence, the results may not be generalized for the entire study area.

2.1.2. Climate data extraction

To ascertain the perception of the respondents on climate change in the Pichavaram region, climatic variables data, *viz.*, Rainfall (mm), Temperature-max (°C), and Temperature-min (°C), were extracted for the period 1951–2021 (71 years) from the Indian Meteorological Department (IMD) (https://www.imdpune.gov.in/) for the trend analysis. The data on rainfall (0.25 × 0.25 deg), T_{max} (1.0 × 1.0 deg), and T_{min} (1.0 × 1.0 deg) were extracted in the delimited data format (.csv) for the Pichavaram region (Latitude: 11.50° N, Longitude: 79.75° E) from the gridded binary weather data (Srivastava *et al.* 2010; Pai *et al.* 2016) through Google Colab, a cloud-based platform (https://colab.research.google.com/).

2.1.3. Data analysis

The vulnerabilities faced by the fishers of the Pichavaram region in various aspects were ranked based on the socioeconomic survey records. The data on multiple aspects were segregated into various vulnerability drivers (health, subsistence, community, nutritional security, ecological, resource, and resource-based user factors) derived from published sources (Shyam *et al.* 2014, 2016; Paul *et al.* 2024) to arrive at the Wetland Vulnerability Index (WVI) (Paul *et al.* 2024) for the selected villages in the Pichavaram mangrove region. The drivers were evaluated using a five-point raking system as follows; 5 – strongly agree, 4 – agree, 3 – no opinion, 2 – disagree, and 1 – strongly disagree.

Garrett ranking was used to transform the ranks of vulnerability into percentile scores.

$$\text{Percent position} = 100 \times \frac{(R_{ij} - 0.5)}{N_j}$$

where R_{ij} is the rank given for the ith variable by jth respondents and N_j is the number of variables.

The % positions were then converted to Garrett ratings for every attribute using the Henry Garret table. The WVI was estimated by combining the cumulative scores for each driver to create vulnerability indices. These calculated indices give the fishermen's perspective on the vulnerability factors affecting wetland fishers (Shyam *et al.* 2014). The Kruskal–Wallis test (H), a nonparametric alternative to the one-way ANOVA, was applied to these Garrett scores to ascertain whether the medians of the four villages differed statistically.

$$H = \frac{12}{(n(n+1))} \times \sum \frac{R_j^2}{n_j - 4\,(n+1)}$$

where n is the total sample size and ${R_j}^2$ is the sum of ranks; for the jth group, n_j is the sample size of the jth group. Under the null hypothesis, H follows a Chi-square distribution with k − 1 degrees of freedom.

To determine the best mitigation strategy for each vulnerability driver, the most vulnerable attribute was also estimated using an average ranking. The vulnerability drivers were graded as 0 for non-vulnerability, 1 for low, 2 for medium, and 3 for very high after estimating the total Garrett scores (Sathiadas *et al.* 2014; Paul *et al.* 2020). The vulnerability indicators and their drivers are depicted in Figure S1 (modified from Hahn *et al.* 2009; Paul *et al.* 2024).

The nonparametric Mann–Kendall test is employed to detect monotonic trends in time series climate variables, *viz.*, annual rainfall and mean annual T_{min} and T_{max} for the period 1951–2021. Apart from this, the one-sample *t*-test was employed to test the statistically significant difference in the annual rainfall with the mean value during the study period. The analysis was performed using the PAST program (v. 4.03) (Hammer & Harper 2001) and Microsoft Excel 2010.

3. RESULTS AND DISCUSSION

3.1. Climate change in the Pichavaram region

Coastal wetlands are vulnerable to climate change effects including changes in rainfall patterns, extreme rainfall events, and cyclones (Rakkasagi *et al.* 2024). Understanding the vulnerabilities of fishing communities to climate change and their adaptive capacity is urgently needed, as fishers worldwide are already being affected by the changing climatic conditions (Luna *et al.* 2014). As part of the study, we analyzed the changes in the climate variables recorded in the Pichavaram region for seven decades (1951–2021). The Mann–Kendall test revealed an insignificant increase in the annual rainfall ($p > 0.05$) while a statistically significant increasing trend ($p < 0.05$) was observed for both mean annual T_{max} and T_{min} in the Pichavaram region (Table 1). These observations are in line with the study by Khan *et al.* (2014), wherein they reported an increasing trend in the mean annual rainfall and temperature in the Pichavaram region for the period 1951–2010. The increasing rainfall was reported in in Bhitarkanika wetlands, and warming conditions were reported in Bhitarkanika and Keoladeo wetlands (Dwevedi *et al.* 2022). The spatiotemporal inundation mapping of Ramsar wetlands in China revealed a significant change in the water spread trend and attributed to the regional geographical and climatic conditions (Goyal *et al.* 2023). Furthermore, the one-sample *t*-test revealed that the annual rainfall is statistically different from the mean value of the study period for the selected climate variables.

Table 1 | Results of statistical analysis of climatic parameters

Climatic variable	Mean	Range (min–max)	Standard deviation	*t*-statistics	Mann–Kendall statistics
Mean annual T_{max} (°C)	33.249	32.220–34.257	0.494	567*	<0.05*
Mean annual T_{min} (°C)	24.492	23.713–25.370	0.336	614*	<0.05*
Annual rainfall (mm)	1,356.87	549.93–2,465.16	398.85	28.66*	0.069

*Significant at 0.05 level.

The highest mean annual rainfall was observed to be 2,465 mm in 2021 and the lowest was 550 mm in 2002 (Figure 2). The mean annual maximum temperature (T_{max}) and minimum temperature (T_{min}) were reported to be 33.249 and 24.492 °C, respectively (Figure 3). During this survey, the inland fishers of Pichavaram region linked their exposure to climate change to the multitude of vulnerabilities they faced. The fishers opined that they face extreme monsoonal rainfall and extended summers in this region. The positive trend in temperature rise in this region validates the responses of the stakeholders on climate change.

3.2. Health vulnerabilities

The *H* (Kruskal–Wallis) value of 4.2 reported for health vulnerability (critical *H*-value, H_c, is 5.6) indicates a significant difference in vulnerability. The health of fishing communities needs to be assessed as there are various factors influencing them that are mostly interactive and out of the individual's control. The health issue in a family has an economic and physiological impact not only on the individual but also on the entire household (Shyam *et al.* 2014). Fisherfolks have been regarded as a susceptible group due to poor health compared to the general population. Heat stress and waterborne and vector-borne diseases would be more prevalent key health challenges related to climate change in India (Dhara *et al.* 2013). The same may be the causative factor for the significant difference observed in the present study. Garret scores and average ranks of various attributes of health vulnerability are presented in Table 2 and Figure 4.

3.2.1. Accessibility to health services

Garret rankings show that fishers of Pichavaram (42.83) are more vulnerable to diseases and have less accessibility to hospital services than other villages. Hospitals were located 3 km away from the settlements around the Vembanad Lake, making

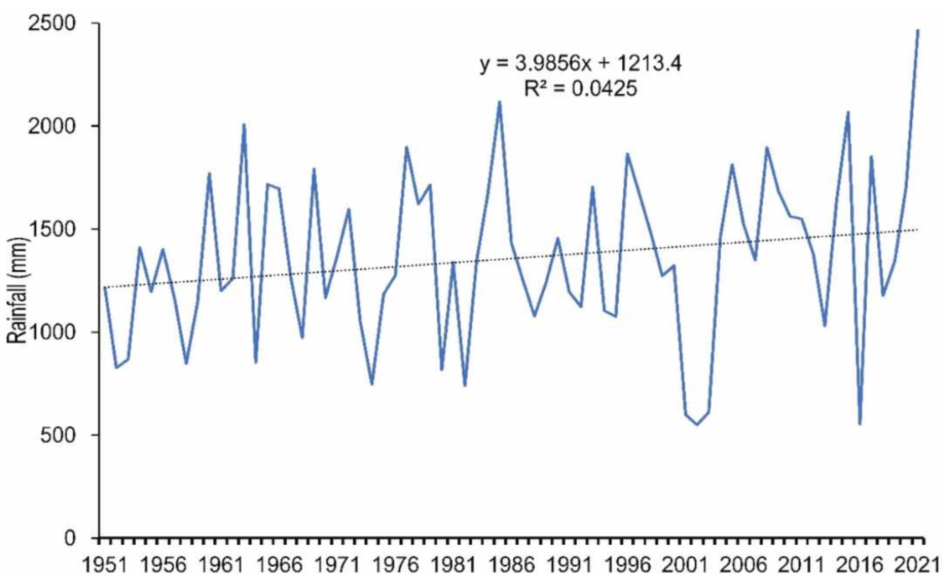


Figure 2 | Trend analysis of Rainfall data in Pichavaram region. Mann–Kendall test revealed a statistically insignificant increase in the annual rainfall ($p > 0.05$).

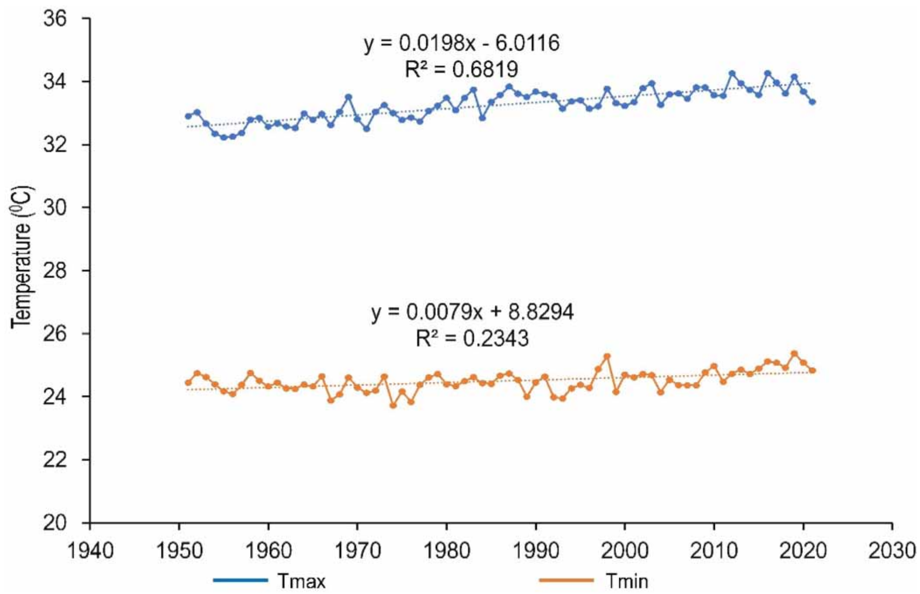


Figure 3 | Trend analysis of T_{max} and T_{min} data in the Pichavaram region. Mann–Kendall test revealed a statistically significant increasing trend ($p < 0.05$).

them more vulnerable to health access (Paul *et al.* 2020). This justifies that mere transportation facilities and distance to access healthcare facilities (Jin *et al.* 2015) are the problems faced by the fishers for gaining good healthcare services.

3.2.2. Rate of reported illness

The analysis revealed that more than 60% of fishers had ailments. Most of the fishers from villages under study suffered from skin-related ailments due to long-term fishing activity. Chronic illnesses such as heart attacks, respiratory diseases, diabetes, sunburn, and skin ulcers are prevalent in the region. Similarly, fishers of Alaska were reported to have hearing loss, upper extremity disorders, and sleep apnea risk factors (Eckert *et al.* 2018). Most of the fishers in the region use hand grappling to catch shrimps and crabs in their natural habitats. Catfish stings, getting bitten by crabs, and cuts from stepping into oyster beds are other major causes of injury and illness. Toenail fungal infections are also prevalent among the fishers performing hand grappling as they are exposed long-term being in the water and causing skin wrinkles. Hand-grappling fishers use indigenous palm leaf-made bags to store the shrimps caught. These palm bags that are attached to a rope and fishers while performing hand grappling have a hold of the bag through a rope held in their mouth. Prolonged exposure of the mouth being open in water with the rope causes abrasions in the lips leading to other infections and wounds. The study revealed that Mudasalodai fishers (score being 52.23) were more vulnerable to climate-attributed diseases compared to other villages thereby emphasizing a need for more health support and healthcare systems from governmental agencies (Figure 4). The study showed that women are more vulnerable toward skin infection and water-borne diseases in Bangladesh and Burkina Faso in East Africa, respectively (Chowdhury & Chowdhury 2011; Dickin *et al.* 2021). Effective management of diseases related to climate change should depend on the timeliness and effectiveness of the interventions implemented (Hahn *et al.* 2009). The use of tobacco and alcohol is also very prevalent among the fisherfolk in the Pichavaram region.

3.2.3. Average longevity

Average longevity is the measure of the eldest person in the community. The average life expectancy at birth in India is 69 years (67.8 years for males and 70.4 years for females), while it was reported as 71.7 years for Tamil Nadu (69.9 for males and 73.7 for females) during 2013–2017 (PIB 2020). The fishers of T.S.Pettai (42.88) were found to be more vulnerable to health-related components followed by Pichavaram (42.83), Mudasalodai (35.66), and Killai (35.66). Average longevity has very important implications for transferring knowledge and obtaining traditional ideas and whereabouts about the region.

Table 2 | Garret scores and ranks of vulnerability indicators of the Pichavaram Region

Vulnerability category and indicators	Garret score: Mudasalodai	Garret score: Killai	Garret score: Pichavaram	Garret score: T.S. Pettai	Pichavaram wetland average	Average ranking: Mudasalodai	Average ranking: Killai	Average ranking: Pichavaram	Average ranking: T.S. Pettai
Health	**37.86**	**38.04**	**41.78**	**38.70**	**39.09**	**4**	**3**	**1**	**2**
Accessibility to health services	25.7	41.53	42.83	35.45		4	2	1	3
Rate of reported illness	52.23	36.93	39.68	37.78		1	4	2	3
Average longevity	35.66	35.66	42.83	42.88		3	3	2	1
Subsistence	**29.24**	**44.86**	**44.26**	**61.25**	**44.90**	**4**	**2**	**3**	**1**
Work rate	32.36	68	62.4	69.86		4	2	3	1
Gender labor rate	29.76	35.25	40.1	61.66		4	3	2	1
Revenue	25.6	31.33	30.3	52.23		4	2	3	1
Community	**52.2**	**62.46**	**59.89**	**49.87**	**56.10**	**3**	**1**	**2**	**4**
Categorization rate	69.86	68	62.66	39.71		1	2	3	4
Acquisition rate	68.8	69.33	63.46	52.33		2	1	3	4
Proximity network rate	34.43	60.51	58.91	68.26		4	2	3	1
Utilization rate	35.71	52	54.53	39.2		4	2	1	3
Nutritional security	**51.09**	**59.28**	**52.12**	**51.15**	**53.41**	**4**	**1**	**2**	**3**
Assistance dependence ratio	46.41	54.53	27.6	30.3		2	1	4	3
Nutritional awareness rate	52.33	54.53	58.91	60.51		4	3	2	1
Reachability rate	54.53	68.8	69.86	62.66		4	2	1	3
Resource	**53.33**	**53.08**	**51.03**	**56.93**	**60.50**	**1**	**3**	**4**	**2**
Species diversity	68.26	56.93	60.51	62.16		1	4	3	2
Phenology	68.8	55.63	59.06	62.16		1	4	3	2
Fishing season	68.53	56.3	59.8	62.75		1	4	3	2
Vulnerable fishes	68.26	56.93	51.03	51.03		1	2	4	3
Ecological	**53.93**	**53.80**	**54.97**	**54.63**	**54.33**	**3**	**4**	**1**	**2**
Precipitation	54.53	54.53	58.91	52.33		4	3	1	2
Water quality	53.33	53.08	51.03	56.93		3	2	4	1
Resource user	**56.12**	**56.41**	**59.76**	**63.83**	**59.03**	**4**	**3**	**2**	**1**
CPUE	55.36	59.01	61.01	62.13		4	3	2	1
Alternative livelihood options	69.86	62.13	60.8	68.53		1	3	4	2
Indigenous traditional knowledge	51.41	50.11	57.33	62.66		3	4	2	1
Community Mobilization	47.86	54.41	59.91	62.		4	3	2	1
Overall average (WVI)	**49.84**	**53.04**	**52.91**	**54.13**	–	–	–	–	–

Bold values indicate the average value of the particular group heading.

Poor health and reduced mangrove cover are vulnerabilities to human safety from coastal storms and surges (Ghosh *et al.* 2015a, 2015b).

3.3. Subsistence vulnerability

The Kruskal–Wallis test revealed that the value calculated for subsistence vulnerability ($H = 4.7$) was less than the critical value ($H_c = 5.6$), showing a significant difference between the subsistence vulnerability of the villages. Garret scores and average ranks of various attributes of subsistence vulnerability are represented in Table 2 and Figure 4.

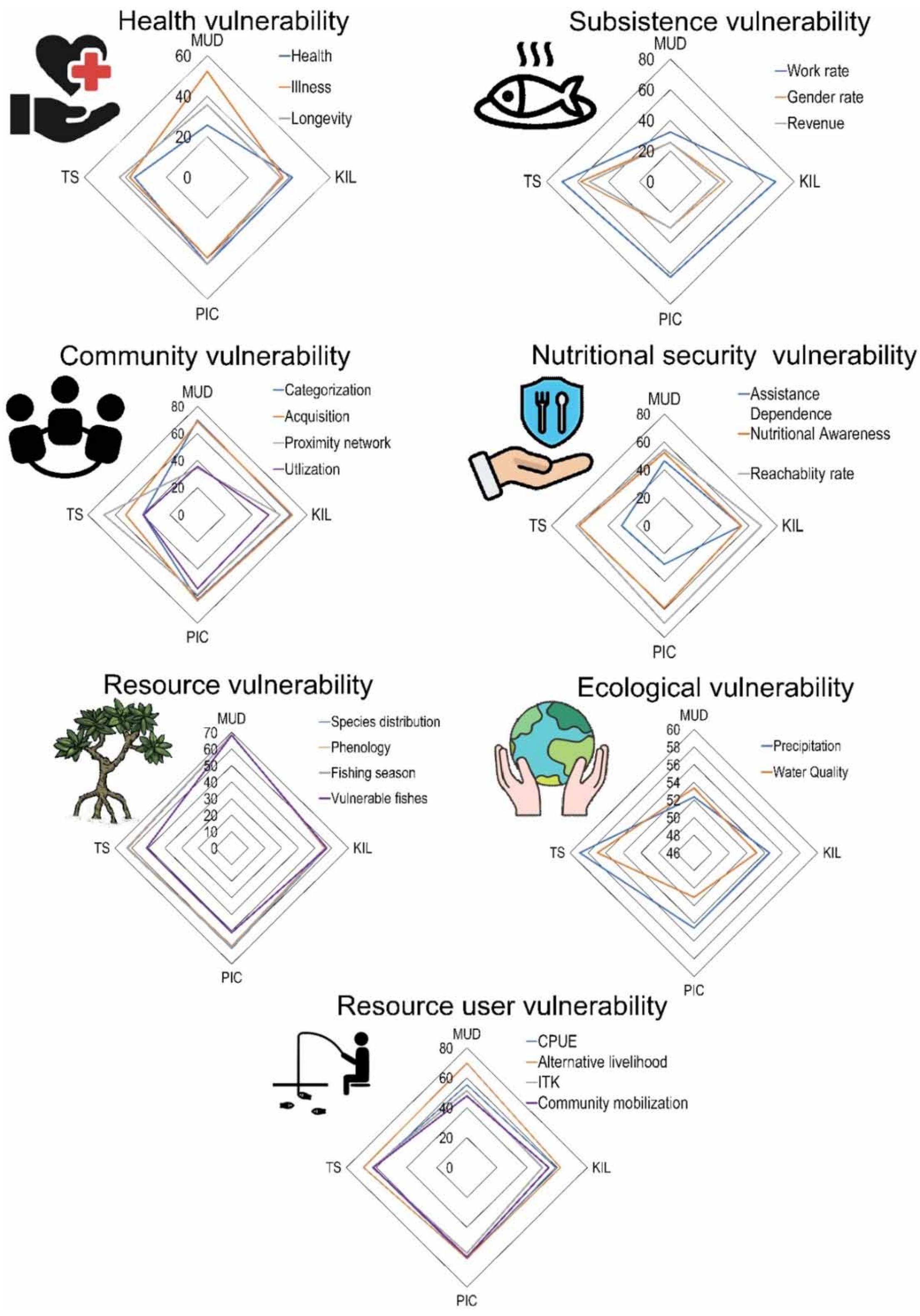


Figure 4 | Scores of various indicators under vulnerability criteria of selected villages (MUD – Mudasalodai, KIL – Killai, PIC – Pichavaram, and TS – T.S.Pettai) in the Pichavaram region, India. The vulnerability scores of indicators varied among the villages except for resource vulnerability, in which all villages scored high values; T.S.Pettai is ecologically vulnerable and Killai is vulnerable to nutritional security.

3.3.1. Work rate

Work rate is the number of members in the family associated with fishing and allied activities. About 85% of the fishers affirmed that they were involved in fishing and related business in this region. The womenfolk of Pichavaram and Killai accompany their partners in dug-out canoes for fishing, whereas most fisherwomen of Mudasalodai are fish vendors (especially dry fish). Most of the fishers were involved in fishing activities except for T.S.Pettai where only 60% are fishers and the rest have changed their profession. Most of the traditional fishers have migrated outside the village and left their occupation due to low catch and conflict with the mechanized fishers. Such internal and international migrations are facilitated by various factors including family and its social groupings like kinship and marriage relations, and negotiation by senior women in the Cuddalore region (Rao & Sophia 2023). A few marine fishermen have also opined that they restricted their fishing territory to mangrove and freshwater areas of the Pichavaram regions. The small-scale coastal fisherfolk in the Mumbai region are forced to move far into the sea for fishing due to climate change (Senapati & Gupta 2017). This shows the livelihood potential of the Pichavaram mangrove wetland for fishers of this climate change stressed region.

The Garrett score indicated that fishers of T.S.Pettai (69.86) were more vulnerable followed by Killai (68), Pichavaram (62.4), and Mudasalodai (32.36) due to the low occupational rate (Table 2). This indeed emphasizes the need for diversification of existing livelihoods, training and support, and mobilization of the fishers to new fishing grounds to ensure generating income.

3.3.2 Gender labor rate

A total of 67% of the fisher families across the villages reported that the females were also earning members in the family. Women fishers accompany men in canoes for fishing, involve in shrimp and crab grappling, and serve as auctioneers in landing centers. Some people have moved abroad for jobs, but most of them return and go back fishing in their hometown. The migration strategies of the fisherwomen in the Cuddalore region were influenced by the mechanization and modernization of fishing industries, changes in the guidelines/schemes, and developments post-Indian Ocean Tsunami of 2004 (Azmi & Lund 2022).

The Garrett score estimates indicated that T.S.Pettai fishers (61.66) were more vulnerable to the absence of earnings by female family members compared to other villages (Figure 4). The study thus revealed that despite being served with limited physical infrastructure and access to basic services such as credit and insurance, the household's income on account of women's employment considerably reduced the livelihood vulnerabilities faced by fishers. Linking fishing households to new occupational sectors can effectively reduce the employment dependency of fishers (Cinner *et al.* 2012) and financial vulnerabilities.

3.3.3. Revenue

Revenue states the daily average income of a fisher and around 70% of the fishers across the villages of Pichavaram mangrove wetland revealed that their average weekly income is below INR 2,000. Vulnerability studies indicated that fishers across T.S.Pettai were more vulnerable than other villages. Support is being provided by NGOs in the region with the provision of additional benefits such as solar dryers and skill development for fishery-based value-added products to enhance the income of women fisher folks. The majority of the fishers of Sundarbans received an annual income of INR 50,000–1,00,000 and others received INR 50,000 (Ghosh *et al.* 2015a, 2015b).

3.4. Community vulnerability

Community vulnerability is the measure of social support as a community, organizational ties, and village group as a shared community (Sherrieb *et al.* 2010). The indicators used to estimate the community vulnerability in the present study were categorization rate, acquisition rate, proximity network rate, and utilization rate. It was found that the observed value ($H = 4.31$) is less than the critical H-value ($H_c = 5.6$) indicating a significant difference in community participation (Table 2). Similarly, Meeran & Jeyaseelan (1999) reported that shrimp farmers of Thanjavur region in Tamil Nadu have a low level of social participation.

3.4.1. Categorization rate

The percentage of people found in a group is called as categorization rate. The Mudasalodai fishers (69.86) were found to be more vulnerable toward the community categorization followed by Killai (68) and Pichavaram (62.66) with a marginal difference and T.S.Pettai (39.71) with a significant difference.

3.4.2. Acquisition rate

This defines the group of people who get aid/support during and after a natural calamity. The study revealed that about 65% of the fishers have received help during distress times. The help was provided by the government and other intergovernmental, private, and semi-government organizations. The Cuddalore coast is prone to cyclones and hence gets affected often (Geetha *et al.* 2017). The mangroves around Mudasalodai, Pichavaram, and Killai region acted as a bio-shield and saved many lives during the Indian Ocean Tsunami of 2004. Furthermore, this study indicates that fishers of Mudasalodai and Killai were found to be more vulnerable with Garret scores being 69.33 and 68.8, respectively.

3.4.3. Proximity network rate

This indicator is defined as the percentage of close friends that live nearby. Family connections are a more important source of social networks which majorly serve as a resource in disaster and distress times (Aldrich & Meyer 2015). These social networks are important sources of climate change information that lead to group innovation (Rotberg 2013) and livelihood diversification strategies (Antwi-Agyei *et al.* 2014).

T.S.Pettai (68.26) is found to be more vulnerable to loneliness among the villages due to the lack of entertainment options and reduced community interaction followed by Killai (60.51), Pichavaram (58.91) and Mudasalodai (34.53). Social and political marginalization leaves many fishers with little capacity to adapt to climate impacts thus making them more vulnerable (WorldFish Centre 2007).

3.4.4. Utilization rate

This criterion shows the facilities available to socialize in the village such as cooperative offices, party halls, convention centers, etc. Among the villages, Pichavaram had a Garret score of 54.53 being more vulnerable, followed by Killai (52), T.S.Pettai (39.2) and Mudasalodai (38.71). Pichavaram and Mudasalodai have amenities, *viz.*, party halls, places of worship, and other government offices in the neighborhood for socializing compared to the other two villages.

3.5. Nutritional security vulnerability

The nutritional security vulnerability indicated a significant difference ($H = 3.43 < H_c = 5.6$) between the villages. The relevance of this study was supported by Scholze *et al.* (2006) who related climate change to the attainment of food security in global economies. Garret scores and average ranks of various attributes of nutritional vulnerability are represented in Table 2 and Figure 4.

3.5.1. Assistance dependence rate

This criterion assesses the dependency of the people on the public distribution system (PDS) for their food. About 80% of the fishers associated with the villages availed all the ration from the PDS based on their economic status. The highest Garret score was reported for Killai (54.43) followed by Mudasalodai (46.61), T.S.Pettai (30.3), and Pichavaram (27.6). A study done on PDS by Swaminathan (2008) indicated that an average of 52% of agricultural households in India had no card or an above poverty line PDS card.

3.5.2. Nutritional awareness rate

This criterion is defined as the percentage of people who are aware of nutritional aspects. Most of the fishers were nutritionally aware of the items to be included in the diet. The calculated Garret's score value for T.S.Pettai was 60.51 followed by 58.91 for Pichavaram, 54.53 for Killai, and 52.53 for Mudasalodai. George & McKay (2019) stated that food distribution across societies is affected by unstable political conditions and climate change. Fishers of lower social class, lesser literacy rate, and are poverty stricken had a clear impact on the poor nutritional status in West Bengal (Dutta & Gupta 2022)

3.5.3. Reachability rate

Reachability is an index of the accessibility of the food the fisher wants. About 50–68% of the fishers expressed their vulnerability in obtaining the desired food. Garret's score ranked Pichavaram (69.86) and Killai (68.8) as more vulnerable than other villages, which have scores ranging between 50 and 56.

3.6. Ecological vulnerability

A significant difference ($H = 2.6 < H_c = 5.6$) in ecological vulnerability was reported among the villages under study. The variation in temperature and rainfall are interlinked with climate change (Rahman & Lateh 2017), which might be the factors for the ecological vulnerability of the region. Other than the rise in the sea level, climate change does alter the sea surface temperature resulting in storm surges and serious flooding (Khristodas *et al.* 2022). A study by Saxena *et al.* (2013) shows both erosion and accretion occurring in the shoreline of the Cuddalore coast on a long-term basis. Furthermore, Khan *et al.* (2014) have projected the rise in the sea level at a global scale ranging from 2.33 to 53.70 cm in Pichavaram corresponding to the Bay of Bengal for 2025–2100.

3.6.1. Precipitation

The change in the rainfall was witnessed by 70% of fishers across all the villages and attributed to climatic change. Irregular rainfall was observed both during the monsoon and non-monsoon seasons in this region. This was supported by the annual runoff value recorded in the Vellar River by CWC (2018) during 1991–2017, which ranged between 0 and 1434 million cubic meters and showed an insignificant decreasing trend (Mann–Kendall test; $p > 0.05$). Though these villages are located in very close proximity, the Garret score calculated based on the fisher's perception showed Pichavaram as more vulnerable (58.91) followed by Mudasalodai and Killai (each 54.53) and T.S.Pettai (52.33). Rainfall changes bring greater sensitivity to mangroves and reduce freshwater inflow into the coastal wetland, which affects biodiversity and ecosystem productivity (Alongi 2008). The reduction in rainfall led to a reduced influx of sediment and nutrients into the coastal waters, which are essential for supporting the ecosystem processes (Rogers *et al.* 2005). The reduction in precipitation is likely to increase salinity in the already hypersaline mangrove forests as well as limit the fluvial sediment supply, important for maintaining surface elevation. The reduced water flow in the Vellar River led to the rise in the average water salinity (35–45 ppt) in the estuarine complex (Killai backwater and Pichavaram mangroves) and caused detrimental effects on the biodiversity (Selvam 2003; Supriya & Krishnaveni 2018). Pichavaram mangroves are noted to have stunted growth compared to other mangroves in India due to the reduced freshwater inflow (Kathiresan 2000).

3.6.2. Water quality

More than 85% of fishers opined that the water quality of the Pichavaram wetland has changed over the years. Garret scores were higher in villages located in the vicinity of the mangrove ecosystem, *viz.*, T.S.Pettai (59.93) and Mudasalodai (53.33), than in the other villages. The influence of climate change on surface water hydrology was reported by many workers in coastal wetlands in India (Gopakumar & Takara 2009). About 80% of the fishers in Vembanad Lake reported a change in water quality (Paul *et al.* 2024). The change in the water quality in the Pichavaram wetland may be attributed to the reduced river inflow and mixing of sewage and industrial effluents. Loss of mangrove cover can primarily affect the water quality as the pollutants cannot be removed and transformed (Wu *et al.* 2008).

3.7. Resource vulnerability

The resource vulnerability of this region assessed through various indicators shows a significant difference ($H = 3.2 < H_c = 5.6$). Species delving in upper thermal limits, along coastlines, are more vulnerable to climate change. The catch decline of preferable fish species and the economic importance may impact the livelihood of the fishing community and global food security (Vinagre *et al.* 2019; IPCC 2022).

3.7.1. Species distribution and vulnerability

This is defined as the total number of species distributed in the region. The Pichavaram wetland is a diverse ecosystem with rich biodiversity. Around 85% of the fishers have expressed a decline in fish diversity in their catch, in recent days. The Garret analysis revealed Mudasalodai to be more vulnerable (68.26) followed by T.S. Pettai (62.16), Pichavaram (60.51), and Killai (56.93). Mudasalodai, being a marine fishing village, produces more bycatch during fishing operations. Hence, the perceived information may be related to the shift in the species assemblage and diversity due to climate change and other anthropogenic factors along the coast. The primary reason for the reduction of fisheries resources in this region is mostly due to the sand bar formation in the estuarine mouth, which blocks the tidal waters and the fish along with the mangrove wetland (Rajendran 1997; Kathiresan 1999). Dams constructed near the Pichavaram region for restricting the saltwater intrusion to upstream agricultural lands also restrict the freshwater inflow to mangroves, which is considered a serious threat (Ghosh *et al.* 2022). Climate change impacts the species distribution and abundance status in freshwater and marine ecosystems. Targeted fishes switch their geographical distributions, in addition to having a lot of expansion, fragmentation, and contraction, and these changes not only continue but, in turn, will certainly magnify in the coming generations (Poloczanska *et al.* 2013; Pecl *et al.* 2017).

3.7.2. Phenology

Phenology represents the change in growth, size, breeding season, maturation rate, etc. The change in the phenology of fish species was witnessed by more than 85% of the fishers across the selected villages in this region. Garret scores reveal Mudasalodai (66.8) to be more vulnerable to phenological changes due to climate change closely followed by T.S. Pettai (62.16), Pichavaram (59.06), and Killai (55.63). Very little supply of freshwater and seawater and their intermixing has a predominant influence toward the Pichavaram mangrove, particularly its fishery resources (Kathiresan 2000).

3.7.3. Fishing season

This examines the changes perceived by the fisherfolk regarding the fishing season of various commercially important species in this region. About 75% of fishers reported a change in the fishing season, and the highest Garret score was reported in Mudasalodai (68.53) followed by T.S. Pettai (62.75). This may be due to the dependence of the Mudasalodai fishing community on marine fisheries where the major changes were noted in the fishing season following the fish abundance compared to the estuarine area.

A study by Nayak (2017) revealed that the livelihood crisis resulted in an alteration of the age-old seasonal fishing routine in the Chilika Lake, which led to intensified fishing. Shift in the fishing calendar was considered one of the consequences of climate change by the fishing communities of the Sudd Wetlands in South Sudan (Benansio *et al.* 2022). The climate change impact on marine fishery is well evidenced through the shift in the distribution pattern (*Sardinella longiceps* and *Rastrelliger kanagurta*) and fishery length (*Nemipterus japonicus*) (Vivekanandan 2011; Mohanty *et al.* 2017).

3.7.4. Vulnerable fishes

The fish that have declined in recent years or have not even been caught in the near time come under this criterion. Garret scores show that Mudasalodai (68.26) and Pichavaram (56.93) were found to be highly vulnerable compared to T.S. Pettai and Killai (51). There is a decline in freshwater prawns, shrimps, and flatfishes in the estuarine region. Previous fish diversity assessments in the Pichavaram indicated a decline in the diversity of siganids and catfishes and catch reduction for most of the fish species reported in this region. The mud crab *Scylla serrata*, which was caught 40–50 per haul earlier, has drastically reduced (Selvam *et al.* 2010). The population assessment of *Scylla olivacea* in the Pichavaram region revealed high fishing pressure and overexploitation (Viswanathan *et al.* 2018). The discussion with fishermen in Mudasalodai reveals that fishes such as *Lactarius lactarius* have been not recorded for several years. Likewise, fishes such as *Ambassis* sp. and *Chanos chanos* catch have declined compared to past years in the Pichavaram mangrove wetland.

3.8. Resource user-based vulnerability

A significant difference in user vulnerability was reported among the villages ($H = 2.3 < H_c = 5.6$). The reduction of freshwater inflow causes the death or stunted growth of mangroves and impacts the associated biodiversity. The negative influence of climatic variation on the reproductive cycles of fishes such as *Channa punctata*, *Johnius coitor* (Karnatak *et al.* 2018), *Mystus tengara*, and *Mystus cavasius* (Sarkar *et al.* 2019) was recorded in India.

3.8.1. Catch per unit effort (CPUE)

Catch per unit effort is used to find the total harvested organism and asses the fishing intensity in an ecosystem (Skalski *et al.* 2008). The garret ranking reveals T.S. Pettai (62.13) and Pichavaram (61.01) to be more vulnerable. This indicator shows the fish caught (in number or weight) with one standard unit of fishing effort. Most of the fishers have agreed to the reduction of CPUE due to climate change.

3.8.2. Alternative livelihood options

The availability of alternative livelihood options among the fisherfolk in the villages under study reveals Mudasalodai as the most vulnerable with Garret scores of 66. During the 1990s, the Pichavaram vicinity area was a hub for shrimp farms; however, due to the outbreak of shrimp diseases and clashes with the villagers, many such farms remain abandoned (Sandilyan 2017). Chronic mass mortality of mud crabs (*Scylla serrata*) in the rearing pen facility was observed near Pichavaram affected with mud crab reovirus (John *et al.* 2024). Natural calamities such as floods, cyclones, and disease outbreaks also cause frequent deaths of livestock and cattle in the region. Selvam *et al.* (2010) reported the mortality of cattle due to Blue Tongue Disease in this region. All these indicate the vulnerability of livestock resources to various diseases linked with climate variables.

3.8.3. Community mobilization

Community mobilization is the participation of people as a movement or groups and working toward some cause like climate change, global warming, etc. It was found that more than 70% of fishers were ready to follow and support the initiatives. The community mobilization capacity of T.S. Pettai (62.93) was found to be more vulnerable among the villages selected in this study.

3.8.4. Indigenous technical knowledge

ITK defines knowledge about the local environment as produced, held, and used by indigenous people and communities. These are transferred from one generation to another, and it enables them to survive during extreme climate events and sustain the fishery-based livelihood in changing climatic conditions (Geetha *et al.* 2015). This driver was a vulnerability factor with a Garret score of 62.93 in T.S. Pettai and 59.91 in Pichavaram followed by Killai (54.41) and Mudasalodai (47.86). Several indigenous practices such as groping in the trench and bundh fishing are being done in Killai (Selvam *et al.* 2010). The groping fishers use a bag made of palm leaves called Pari to keep the prawns/fish that they catch.

3.9. Wetland vulnerability indices

The resource (60.50) and resource-based users (59.03) were the most vulnerable criteria among all the villages. Pichavaram was found to be highly affected by health (41.78) and ecological (53.97) vulnerability, whereas T.S. Pettai was found to be more vulnerable toward subsistence (61.25) and resource vulnerability (63). Pichavaram was found to be the least affected toward resource vulnerability (51.09). Villages across the Pichavaram wetland are placed according to the WVI as follows: T.S. Pettai (54.13) > Killai (53.04) > Pichavaram (52.13) > Mudasalodai (49.84) (Table 2). This reveals that the fishers dependent on mangrove and estuarine resources are highly vulnerable to climate change than their marine counterparts.

4. LIMITATIONS

This study relies heavily on stakeholder perceptions collected through a questionnaire survey of respondents and qualitative data, which might not accurately represent the entire population, leading to sampling bias or inaccuracies. The results presented in this study are based on limited sample size and hence may not be generalized to the entire study area as mentioned by Jokonya *et al.* (2015). An equal sample size was considered for all villages selected, irrespective of their total population; hence, equal representation of stakeholders from each village is not ensured, which may influence the results. Similar to other studies, the stakeholder approach (in-person interviews) undertaken in this study is unable to establish consensus among the various stakeholders (O'Haire *et al.* 2011). Furthermore, the perception of the stakeholders may not necessarily predict the ecological outcomes of the ecosystems (McDonald *et al.* 2016).

5. MITIGATION MEASURES

- Better healthcare facilities including timely medical attention and medications must be provided in the region and awareness must be given regarding the environmental factors/natural calamities that could impact the health. Special assistance may be provided for the inhabitants of this region who are prone to insect and snake bites, catfish stings, oyster cuts, and other skin diseases due to their overexposure to water.
- Supply and demonstration of life-saving appliances.
- Experienced fishers use their traditional knowledge and are not in favor of emerging technologies. Providing skill development training on various alternative livelihood opportunities including ornamental fish culture, seaweed cultivation, and crab fattening will mitigate subsistence vulnerability.
- Better social networking scenarios and developing more socializing units may reduce the social vulnerabilities faced by fishers due to climate change and other natural calamities.
- Awareness about healthy diets, government schemes, and health insurance schemes would benefit and bring a change in fishers' livelihood.
- Promoting sustainable aquaculture with recent technologies and bio-security measures may help fulfill the nutritional requirements.
- Promoting ecotourism not only supports the livelihood of the native community but also spreads awareness of biodiversity conservation. Involving the local community in mangrove afforestation and other conservational activities may increase their spirit to conserve and protect the ecosystem.

- Funding research schemes for devising sustainable management plans and strategies for climate change mitigation in these vulnerable areas would help mitigate the looming threat of climate change.
- The usage of a more sustainable gear will reduce bycatch and overfishing. Implementing strict laws and regulations can also help conserve and protect endangered and critical species.
- Reduction in CPUE can be mitigated by deploying artificial reefs along the coastal area and fish aggregating devices. Furthermore, the ranching of threatened and vulnerable commercial fish species may be initiated for natural stock enhancement, and mass awareness of the negative impacts of illegal fishing and juvenile fishing will reduce overfishing in this region.

6. CONCLUSION

This study aimed to identify the climate change vulnerability indicators for the fishers of the four selected villages in the Pichavaram region. The results revealed a considerably high vulnerability in various criteria, which necessitate emphasizing mitigation and adoption strategies to bring change in fishers' livelihood. Vulnerability related to climate change and health serves as a baseline for predicting disease risks and helps devise monitoring and nullifying the measures. Scientific studies on the impact of reproductive biology and phenology of commercially important fishes are necessary to devise a suitable guideline for species-specific management under the changing climate. Furthermore, the migration of fishers from fishing due to low income may be avoided by diversifying the income sources by creating alternative livelihood options. More in-depth studies are needed to exactly look into the problems and come out with solutions by implementing appropriate management strategies. Moreover, the local communities must engage in devising a harmonious balance of the ecosystem as part of citizen science for safeguarding the resources for a very sustainable future.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the support extended by the Director, ICAR – National Bureau of Fish Genetic Resources, for the study. This study was supported by the Indian Council of Agricultural Research (ICAR), New Delhi, through the in-house funding program.

DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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First received 18 April 2024; accepted in revised form 8 July 2024. Available online 19 July 2024