Assessment of regional flood vulnerability: a case of Kuttanad Wetland System, Kerala, India

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The Kuttanad Wetland System (KWS), widely known as "the rice bowl of Kerala, India", is witnessing a series of devastating floods, the repercussions of which are impacting the local population's adaptive capacity. A region's vulnerability to floods is frequently defined purely by the physical elements that contribute to it; however, an approach that includes an additional layer of socio-economic and biophysical sensitivity would identify the system's most vulnerable community. The rationale behind the research is to develop robust metrics that integrate a sense of risk and vulnerability, as well as to conduct a governance study on the processes that mitigate vulnerability, promote adaptive action, and foster resilience. This research investigates the socio-economic and biophysical vulnerability of local self-government bodies within the ecological boundary of KWS to flooding, a persistent threat to their way of life. The flood vulnerability index (FVI) was computed using principal component analysis in SPSS and eight inter-correlated quantitative dependent variables grouped under three categories, namely land use, socio-economic, and biophysical characteristics. The index values are mapped geographically to produce a flood risk map, which serves as the basis for future capacity building training programmes and regional initiatives. In addition, spatial representations of each component were developed to comprehend the priority domain. This study report outlines a systematic technique applicable to locations with comparable attributes.

Keywords:
adaptive capacity,
flood vulnerability index,
principal component analysis,
resilience

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Introduction

Climate disasters impact communities universally, but climate vulnerability experienced by each community and household is distinctive. 'Vulnerability is the state of susceptibility to harm from exposure to stresses associated with environmental and social changes and absence of the capacity to adapt' to it (Adger 2006). There may be people within the extremely vulnerable population who are more vulnerable than others in terms of infrastructural accessibility, financial resources, etc (Croot–Holmes 2010). So, the variables chosen for vulnerability assessment should also represent the socio-economic and biophysical state of the system under examination. The vulnerability assessments often focus on realistic, concrete, and insightful aspects of a system that give a sense of the bigger picture (UNESCO n.d.).

Flood risk management and assuring the safety of the communities is a prime responsibility of the authorities for which prioritising vulnerable areas and communities for adopting effectual measures to increase resilience is significant (Nasiri et al. 2016). A concatenation of extreme and often permanent, circumstances exist, spiralling community exposure and situating the livelihood activities inordinately fragile for certain social groups (Cardona 2013). The shift in the land use pattern due to haphazard urbanization unfavourably affects the hydrological regime, leading to a degenerating water environment (Suriya–Mudgal 2012, Bueno et al. 2019). The evolution of a catchment from natural or rural conditions and then to urban settings involve pronounced changes to water and soil resources on a time scale, distinct from most of the other natural processes. This is further exacerbated by human-caused climate change, due to escalating concentrations of greenhouse gases (GHG). This can potentially surge the intensity of precipitation enhancing the eventual risk of flash flooding, pluvial and fluvial flooding etc (Bang–Burton 2021). Flood-prone regions would be confronting more floods in the future because of climate change, urbanisation, and increasing land use & land cover (LULC) change.

Similarly, the flood vulnerability of a region is often decided by the physical factors contributing to it (Hidayah et al. 2022, Lewis 2014). The connections between vulnerabilities caused by the changing exposure to flood due to climate change and the socio-economic aspects of a community that influence their capacity to adapt to the vulnerabilities is rarely explored (Mortsch 2014). This issue, if ignored, would deteriorate and eventually break the overall resilience of the system, including that of human beings, to deal with the negative impacts of flooding in the region. The dilemma is compounded by the traditional spatial planning process, which concentrates largely on delineating human settlements and physical infrastructure development regardless of the land-water interactions and other ecological considerations (Sonu et al. 2022). Such planning mechanisms often result in individualised planning for administrative divisions whose political boundaries dictate their administrative boundaries. This demands an integrated watershed-based planning and implementation framework. However, it is not pragmatic to outline an inclusive flood risk reduction strategy by generalizing these problems without explicitly scrutinizing the hotspots and main drivers (Birkmann 2007, Nazeer–Bork 2019), based on which the regions could be prioritized accordingly.

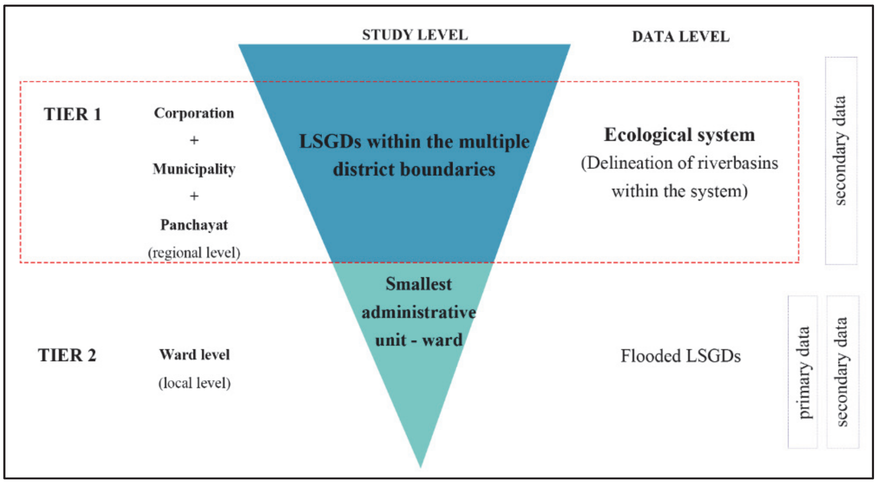
This paper inquiries into the socio-economic and biophysical vulnerability of the local self-governments[1] (LSG), or the Panchayats falling within the ecological boundary of Kuttanad Wetland System (KWS), of Kerala (India) which is largely below mean sea level. The seasonal floods are constantly posing a threat to lives and livelihoods here. With parts of the landscape lying below mean sea level and its hydrology is subjected to severe manipulations, KWS is vulnerable to climate change. The frequent incidences of cyclonic depressions on the western coast of India have intensified this vulnerability. In the wake of the recent Kerala floods, which badly affected this landscape, there is a need to understand and address the climatic vulnerabilities to which stakeholders and the ecosystems are exposed. There is also infrastructure vulnerability which enhances the impact of disasters faced by people residing in low-lying areas.

This exercise is expected to help in developing a framework for prioritising the LSGs for capacity building for adaptation and mitigation. The sequence of maps and list of panchayats based on flood vulnerability indexing (FVI) will help in prioritizing the domain of interventions within the LSGs to incorporate in designing or planning adaptive measures.

The scope of the research is limited to the Tier 1 level (see Figure 1) of the Panchayats (LSG) of the KWS to address the flood vulnerability of environmentally sensitive regions, particularly wetlands.

Figure 1

Thematic research framework for prioritising the LSGs for capacity building



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[1] Local self-government is the management and governance of local affairs by a local body or authority. These local bodies may be municipal corporations, municipalities, or panchayats.

Research background

Measuring flood vulnerability

Vulnerability is considered as the extent of harm, which can be prophesied under conditions of exposure, susceptibility, and resilience (Balica et al. 2012). Precisely, a system is susceptible to floods due to exposure in concurrence with its capacity/ incapacity to be resilient, to cope, recover or adapt to the extent (Balica et al. 2012). Generally, population density is found higher in coastal areas especially closer to the water bodies where the exposure to inundation is high and so the number of people who get affected also is more. In countries like the Netherlands which are extremely vulnerable to floods, people are protected by various structural and non-structural mitigation and adaptation measures that are part of the resilience strategy of the state (Zeeberg 2009). While in some other places, especially in the developing world, even if the region confronts cataclysmic floods, no flood defence mechanisms have been employed, largely due to the economic condition of the country (Ives 2021). Understanding the intensity of floods and the carrying capacity of the system is indispensable for the decision-makers to strategically guide investment (Balica–Wright 2009), since it, in all sense, affects the weakest within the system. Literature studies available on understanding the flood vulnerability of the region were found to be very subjective to the contexts addressed in them. There is no standard approach for assessing flood vulnerability since it need to be tailored to the specific geographical situation. There are several elements that might contribute to flood susceptibility. Few studies have explored the issue on a regional scale with extra layers of socio-economic and biophysical variables, although a great deal of research has focused on physical aspects alone.

Methods and variables for flood vulnerability assessment

There are many approaches to assess the flood vulnerability of a region that the selection of the most appropriate methodology becomes impertinent for policymakers and managers. Most widely accepted methods are vulnerability curve method, indicator-based methods, disaster loss data method and computer modelling tools (Nasiri et al. 2016). The vulnerability curve method is a quantitative method (Papathoma-Köhle et al. 2017) that works on the actual damage survey data collected from the site after a disaster occurs. Unlike other methods, this was found to be resource and time-consuming. This method cannot be replicated in other regions since it works on primary data and is usually conducted for post-disaster need assessment. The disaster loss data method works on the extensive loss data collected after the disaster by various organizations which could possibly have data gaps and overlaps, as well as biases that could affect the credibility of the research (Fakhruddin et al. 2017). The computer modelling method primarily works with topography and hydrographic information (Nasiri et al. 2016) so its result would solely depend on the precision of the data used. The vulnerability indicator method is observed to be commonly used by policymakers because of its clarified vulnerability image over space, making use of the available information to determine priorities and make decisions regarding land use and emergency planning (Papathoma-Köhle et al. 2019).

Vulnerability indicator methods also have complications since the approach involves a diverse variable list that need not have visible interdependencies while a combination of indices (composite variable) can determine the degree of vulnerability. This approach also needs to perform standardization since variables need not be of the same attribute. The best-proposed solution for this concern is weighting variables to reduce their impact in forming a final expression (Lein–Abel 2010). Some of the currently used techniques are the analytic hierarchy process (AHP), geographically weighted regression (GWR), principal component analysis (PCA), etc (Sruthi–Firoz 2020). In AHP, individual expert experiences are utilized to estimate the relative magnitudes of factors through pairwise comparisons. It is not practical when there is a large volume of data that needs comparison whereas PCA works on dimensionality reduction while preserving as much of the data's variation as possible. Weighted regression fails if two or more input variables are correlated. Hence, PCA was employed in this research due to its obvious advantage over the other methods and the reason that it can work with a large volume of datasets that need not have any interdependencies (Chao–Wu 2017).

Similarly**,** vulnerability must be defined using a set of factors that may contribute to the underlying causes. There would be communities inside a system that are more vulnerable than others. There may be people within the extremely vulnerable population who are more vulnerable than others in terms of infrastructural accessibility, financial resources, etc (Croot–Holmes 2010).

While assessing the social vulnerabilities due to flood hazards in the Dutch Province of Zeeland, Kirby et al. (2019) considered economic resources, infrastructure type and density, and demographic characteristics of people and combined those to produce FVI. Similarly, in some European communities, researchers have evaluated socio-economic variables (Penning-Rowsell et al. 2011) to determine flood vulnerability, whereas in Belgium (Mees et al. 2018), researchers used an additional layer of flood risk maps on top of socio-economic vulnerability to identify flood-prone communities and modified variables from the social FVI developed by the British Flood Hazard Research Centre (Kirby et al. 2019). The greater the number of variables, the greater the accuracy of the final index values (McLaughlin et al. 2010) However, others caution about being extremely particular about selecting variables, since a mixture of factors is likely to have a significant correlation and influence the result (Balica–Wright 2009). The socio-economic position of the population, evaluation of the system's morphological alteration, and flood history are the major inputs necessary to comprehend the vulnerability and coping capability of any flood-prone ecological system (Leta–Adugna 2023).

Regional context

The state of Kerala is situated as a narrow strip land sandwiched between the Arabian ocean and the Western Ghats. According to Kerala State Disaster Management Authority (KSDMA 2020), approximately 14.52% of the total area of the state is susceptible to floods, which is mostly concentrated on the lowland region and 14% is prone to landslides, which is concentrated mainly on the highlands. The coastal district of Alappuzha where this study was conducted is particularly vulnerable to floods where more than 50% of its area is identified as flood prone. It is not astounding that floodplains and their associated wetlands remain the most threatened by unprecedented urbanisation, particularly in coastal areas (Monk et al. 2019) as human beings started settling on riverbanks. The distribution of urban settlements across the topography shows a decadal urban growth rate of 33% in the highlands[2], 200%, and 182% in Kerala's midland and lowland regions, primarily because of employment shift from the primary sector to tertiary sector jobs (Sonu et al. 2022). The midland and lowland regions, particularly central Kerala, have seen unprecedented changes in land use because of this transformation from rural to urban (Sruthi–Firoz 2021).

The study region, KWS is not an outlier because, since the year 2005 central Kerala had seen pronounced socio-economic and extensive physical infrastructure growth resulting in inordinate landscape changes in the region (Sonu et al. 2022). The involuted hydrologic network of Kerala has a decisive impact on its natural morphology and dynamics of the floodplains. Because of this peculiar hydrologic regime, the low-lying areas get flooded frequently after every heavy downpour. The unplanned urbanisation has put many communities to confront cataclysmic disasters. The low-lying KWS (Sreeja et al. 2015) is confronting consecutive disastrous floods in the recent past, with the impact outstretching the adaptive capacity of the local people. The population density of KWS is 700/square km, which is 40% higher than the national average of 425/square km (Missions Atlas Project 2022). This region, which is largely reclaimed from Vembanad Lake (Ramsar site), the second largest wetland system in the country underwent extensive land reclamation over the years due to population pressure.

According to a recent assessment by the intergovernmental panel on climate change (IPCC) of the United Nations, average surface temperatures of the earth have

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[2] Kerala can be divided into 3 geographical regions. 1) highlands, 2) midlands, and 3) lowlands. The highlands slope down from the Western Ghats. The midlands lying between the mountains and the lowlands, is made up of undulating hills and valleys. The lowlands or the coastal area, which is made up of the river deltas, backwaters, and shore of Arabian sea, is essentially a land of coconuts and rice.

increased by approximately one degree compared to the previous century, leading to a rise in the frequency of tropical storms over the Arabian Sea. This in turn, has resulted in more and/or unexpected rainfall over Kuttanad (Sukumaran–Birkinshaw 2024). Though seasonal floods were a routine to KWS, central Kerala has experienced three back-to-back unprecedented intense floods in 2018, 2019, and 2020 causing massive destruction and losses in terms of lives and economy. About 6,000 families have already migrated to urban centres, shifting their work sector from agriculture (Shaji 2021, Sukumaran–Birkinshaw 2024).

KWS is the floodplain of five major watersheds namely Pamba, Meenachil, Manimala, Muvattuppuzha, and Achankovilar (see in Appendix, Figure A1, M S Swaminathan Research Foundation [MSSRF] 2012). The region is spread over 3 revenue districts[3] of Kerala; Alappuzha (57%), Kottayam (30%) and Pathanamthitta (13%) (Government of Kerala 2018). The region was fringed with mangroves earlier which functioned like buffers against coastal erosion (Kumar 2018) and the paddy cultivation was carried out historically on the flood plain. Due to the increase in demand for rice, almost 60 of the Vembanad estuary was reclaimed for paddy cultivation in last 150 years. This has led to large scale emigration of people to KWS. Because of such undecipherable alterations of flood plains, KWS falls under the category of seriously threatened wetland systems of India (Rajan et al. 2008, Kumar–Devadas 2016). Fishing and farming are the major livelihoods of poor working people of KWS, which are inextricably linked to the Vembanad lake (Government of Kerala 2012). These communities are especially vulnerable to climate change, increasing temperatures, erratic precipitation, and coastal currents. This is exacerbated when their main supply of protein (i.e. fish) is interrupted, further reducing their adaptability to change owing to their relatively tiny or weak economies and poor human development indices (Center 2007).

Materials and methods

Study area delineation

The flood-prone panchayats of KWS were identified by superimposing flood maps for 2018, 2019, and 2020 on the LSG maps (see in Appendix, Figure A2a–d). These are the only available flood history maps for the state of Kerala. In 2018, 2019, and 2020, the extent and depth of floods varied, and Panchayats with even minor flooding were considered for the analysis.

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[3] Any local area which for the purposes of revenue administration is under the charge of a collector.

Materials and data

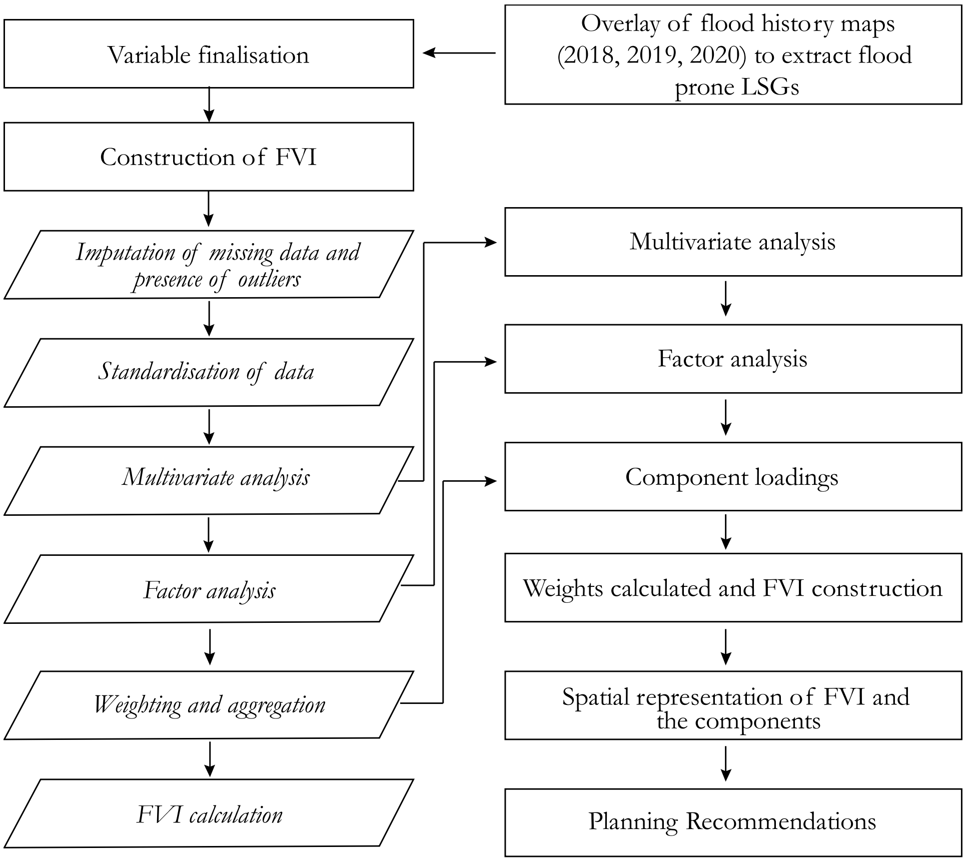
Data for inter-correlated quantitative dependent variables to investigate the underlying patterns and relationships were calculated from the census data 2011, Panchayat Level Statistics (PLS) 2011 (Government of Kerala 2012) and LULC map of 2015. Flood history maps were taken from KSDMA (2020).

Methodology

The factors and indicators for the flood vulnerability assessment and index calculation were adopted from the literature study (Csizovszky–Buzási 2023). The FVI for the LSGs in the study area was calculated using a weighted linear combination (Sruthi–Firoz 2020). The weights were derived by using PCA, using SPSS software.

Figure 2

Methodology flow chart

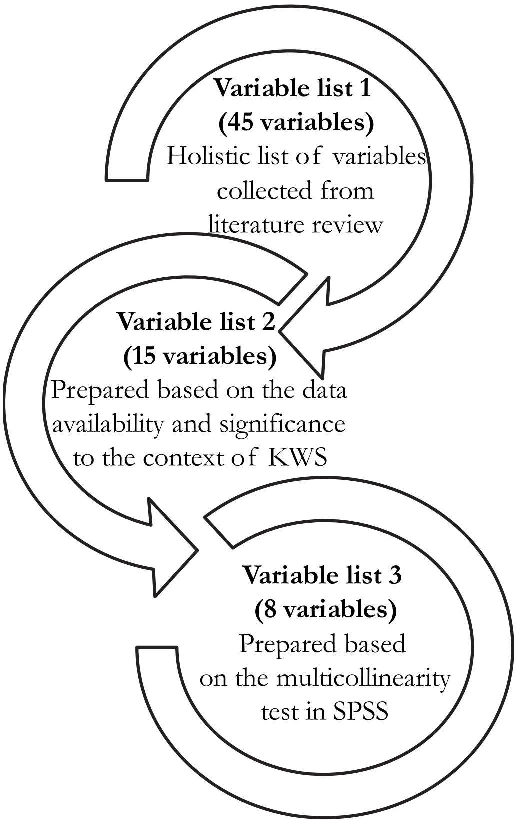


Variable finalization

A preliminary set of 45 variables that were identified as contributing to floods was generated from the secondary data (Croot–Holmes 2010, Balica et al. 2012). These variables were categorised under social, economic, environmental, and physical factors. However, since the study is on a finer scale (panchayat level), variables that lacked sufficient data on vulnerability were removed from the database (Kirby et al. 2019). This resulted in a list of 15 variables was prepared based on the data availability and significance to the context of KWS. A few variables were combined to form composite variables, reducing the number of variables in the list, and renamed.

Figure 3

Variable list from whole to final set



Construction of FVI

The FVI for the LSGs in the study area was determined using a weighted linear combination (Sruthi–Firoz 2020, Wu 2021) were derived using PCA after exploring the nature and type of the data. The following steps were performed in the construction of FVI.

Imputation of missing data and presence of outliers

The data were verified to avoid missing values and outliers among the collected data (Musse et al. 2018). It was observed that there were a few missing data in PLS 2011 which was replaced with the mean values of the corresponding variable. There were no outliers in the dataset.

Standardisation of data

The range of the continuous initial variables were standardised so that all the variables contribute equally to the analysis and avoid biased results (Syms 2019, Sruthi–Firoz 2020). So, the conversion of data to a comparable scale was imperative. This was done using the following mathematical *formula (1)* given below.

$$\textit{Standard Score}, Z = \frac{value - mean}{standard\ deviation}$$

Multivariate analysis

The transformed data were validated for the presence of multicollinearity using the Pearson correlation coefficient matrix (Huntjens et al. 2014). The final variables were determined based on the correlation between the variables with the acceptable range between 0.3 and 0.95 (Sruthi–Firoz 2020). The variables displaying a very high correlation; 0.95 or more were removed from the dataset as it could give a biased result (Pallant 2010). Seven variables (population density, percentage of female illiterates, percentage of strong houses, percentage of LSG-wise evacuation centres, percentage of wet area, percentage of wasteland, and percentage of vulnerable population) were thus removed from the shortlisted 15 variables.

Factor analysis

To determine the suitability of the data for conducting PCA, a Kaiser Meyer Olkin (KMO) test was carried out. KMO value higher than 0.5 is generally considered appropriate or conducting PCA (Pallant 2010, Sruthi–Firoz 2020, Kallingal–Firoz 2022) and such datasets were selected. Also, Bartlett's test of sphericity was run to test the null hypothesis stating that the correlation matrix is an identity matrix (Nardo et al. 2005) with a p-value < 0.05 (Sruthi–Firoz 2020). Finally, PCA was performed on the data using varimax rotation simplifying the loadings of items by removing the middle ground and more specifically identifying the factor upon which data load (Allen 2017, Sruthi–Firoz 2020).

Weighting and aggregation

The weights for each component were calculated by taking the ratio between the corresponding percentage of variance to the cumulative percentage. The weighted linear combination method was done using the formula (2) given below (Musse et al. 2018, Pallant 2010, Sruthi–Firoz 2020).

$$\textit{Non-standardized FVI for each LSG} = w1 * FA1 + w2 * FA2 + w3 * FA3$$

where, w1, w2, w3 are the weights of the component and FA1, FA2, FA3 are the factor scores for each component.

FVI calculation and its spatial representation

FVI calculation was finally conducted using the formula (3)

$$Standardized\ FVI\ for\ each\ unit = \frac{Index\ of\ unit1\ - Min.index}{Max.index\ - Min.index} X100$$

Results and discussions

Multivariate analysis

The final list of eight factors that positively contribute to flood vulnerability was determined, and a strong correlation was observed between them. It was shown that the vulnerable working population and flooded areas had a strong link with the proportion of weak dwellings in the region, indicating that there is a large probability of economic loss since their residential units are unstable. Similarly, unstable dwellings belonging to the vulnerable working population are mostly established near the water bodies in the lower elevation profile of the area experiencing recurrent flooding. Likewise, the proportion of built-up area has strong interlinkage with the flooded area, since built-up affects the perviousness of the land, hence accelerating surface runoff and increasing the chance of flooding. The percentage of built-up area and the percentage of the agricultural plantation was found to be inversely corelated. The loss of vegetation accelerates surface runoff, resulting in water accumulation downstream (Gabriels et al. 2022). The agricultural lands with canopy cover protect the soil during heavy rainfall and aid in the percolation of water to the region's deep aquifers, whereas those without canopies, such as paddy fields, face challenges surviving heavy rainfall, resulting in economic losses for farmers and farm labourers.

Kerala has a high rate of educated unemployment among youth which is 36.9% in rural areas and 33.8% in urban areas (Francis 2022) increasing the dependency on the earning members of the family. Around 60% of the working population in KWS is dependent on agriculture and fishing for a livelihood (Government of Kerala 2012) making them more susceptible to floods. The correlation between vulnerable working groups and literacy reveals a negative relation, indicating a prevalence of illiteracy within the vulnerable working groups. In the context of flood vulnerability, household density was found more relevant than population density. Therefore, flood relief measures and any factors contributing to flooding should be addressed at the household level. At the eventuality of a disaster, individuals migrate as a family unit rather than individually. The final analysis variable list is reported in Table 1, and spatially represented in Figures A3a–d and A4a–d.

Table 1

Variables selected for flood vulnerability assessment

Number	Variable (LSG wise)	Selection criteria/ relationship with vulnerability	Data sources and pre-processing
1.	*Exposure* **household density** (HH_Dens)	Higher the number of households per square km, higher the vulnerability.	Census data 2011 (censusindia.gov.in)
2.	*Susceptibility* percentage illiterates **(Perc_illit)**	Higher the number of people who cannot read or write, higher the vulnerability.	
3.	*Economic component susceptibility* percentage unemployment **(Perc_Unempl)**	Higher the dependency rate, higher the vulnerability.	Census data 2011 (censusindia.gov.in)
4.	Percentage vulnerable working population **(Perc_Vw_pop)**	Higher the number of vulnerable working population, higher the risk of economic losses due to floods and food insecurity.	PLS, 2011
5.	Percentage weak houses (tiled/asbestos/thatched) **(Perc_WkHou)**	Higher the number of unstable houses, higher the vulnerability.	Land use landcover map 2015, KSDMA
6.	Percentage agricultural plantation **(Perc_AgriPl)**	Higher the paddy cultivation area, higher the economic losses during floods. Higher the tree cover vegetation, lesser the likelihood for soil erosion and associated losses.	KSDMA
7.	Percentage built-up area **(Perc_BU)**	Higher the built-up area, higher the surface runoff and chances of flooding.	
8.	*Environmental component exposure* percentage flooded area **(Perc_fldarea)**	Higher the flooded area, higher the geographic vulnerability of the region	

Factor analysis

The factor analysis results obtained for Kaiser–Meyer–Olkin is 0.638. The anti-image correlation values were also found to be greater than 0.5 which signifies a finer outcome (Sruthi–Firoz 2020, Zehba–Firoz 2024), that the components are considered to be capable to capture a significant amount of information from the variables.

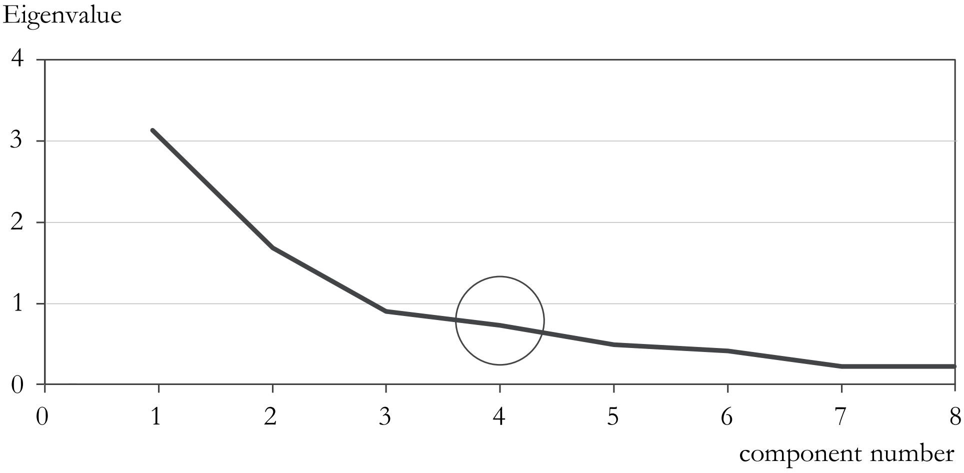
Table 2

Factor analysis

KMO and Bartlett's test	
Kaiser–Meyer–Olkin measure of sampling adequacy	0.638
Bartlett's test of sphericity	
approximately chi-square	281.210
degrees of freedom	28
significance	<0.001

Figure 4

Scree plot of the eigenvalues



The scree plot of the principal components analysis (see Figure 4) showed that there are three components with eigenvalue >1, that could be retained in the analysis. The variance percentages obtained for components 1, 2, and 3 are 26.743%, 24.209%, and 23.028% respectively as tabulated in Table 3 shown below. The model resulted in a cumulative percentage of variance of 73.979% which is acceptable as it indicates that a large portion of the total variability in the original data is captured by the retained principal components (UCLA 2020).

Table 3

Rotation sums of squared loadings

Component	Total	% of variance	Cumulative %	Weights calculated
1	2.139	26.743	26.743	0.361
1	1.937	24.209	50.951	0.327
3	1.842	23.028	73.979	0.311

Component loadings

The rotation components obtained from PCA were named according to the correlation of variables falling in the same column of the matrix (Musse et al. 2018). The variables of component 1 as shown in Table 4, have a moderate to strong positive correlation with the land use component (household density, percentage built-up, agriculture plantation). The positive values of household density and percentage built-up increase the surface runoff rate and would need more to increase the score of the component. The negative value associated with agriculture field suggests that large parcels of contiguous agricultural land, if available, has the potential to store more floodwaters. However, at the same time, it comes with the trade off with largescale damage to agriculture. This is more relevant to a landscape where people have a higher dependency on agricultural income. Component 2 shows a strong positive correlation with the socio-economic components (percentage illiteracy, percentage vulnerable working population, percentage unemployment) (Table 4). This indicate that an increase in illiteracy, unemployment, and lack of capacity of the working population to adapt, could lead to an escalation of the component score and consequently the FVI. Component 3 shows a strong positive correlation with biophysical components (percentage flooded area, percentage weak houses). The positive values of these variables indicate that the increase in flooded areas and the presence of unstable houses in the region contributes to the flood vulnerability of the region.

Table 4

Rotation component matrix explained

Variable	Component 1	Component 2	Component 3
HH_Dens	0.858		
Perc_AgriPl	–0.849		
Perc_BU	0.742	–0.407	
Perc_illit		0.880	
Perc_Unempl		0.741	
Perc_Vw_pop		0.634	0.547
Perc_WkHou			0.844
Perc_fldarea			0.806

Weights calculated and FVI construction

The panchayats were categorized into 5 classes, ranging from 0.60–1.00 (extremely vulnerable), 0.34–0.59 (highly vulnerable), 0.21–0.33 (moderately vulnerable), 0.13–0.20 (less vulnerable), 0.00–0.12 (least vulnerable) based on the FVI (Kirby et al. 2019). The analysis revealed that the panchayats located near the lake, coastal regions, and floodplains of rivers ranked highest in flood vulnerability (see in Appendix, Figure A5). Figures A3a–d and A4a–d (see in Appendix) illustrate that these panchayats have significantly higher population and household densities compared to others and have a larger proportion of vulnerable population. Additionally, the literacy rate in these panchayats is notably low, primarily due to the socio-economic backwardness of the working population. The PLS indicate that more than 60% of the working population comprises fisherfolk, agricultural laborers, and women (Government of Kerala 2012), similar to the other coastal villages in the state. Moreover, over 70% of dwelling units in these areas poorly constructed weak or 'cutcha' houses, with thatched, tiled, or asbestos sheet roofs, (and without a strong basement). Furthermore, the analysis reveals a surprising pattern: certain panchayats irrespective of their vulnerable geographic position, experience a lower extent of flooding compared to moderately vulnerable panchayats. This finding implies that relying solely on geographical factors is not sufficient for accurately determining disaster vulnerability of the population. It is essential to consider socio-economic conditions of the community also be considered to assess the true level of vulnerability. The flood history of an area can only serves as one variable contributing to the overall vulnerability of a region.

Panchayats with the numbers '27', '83', '38', '36', '53', '74', '86', '75', '31', and '54' exhibit a significant percentage of weak houses, which contribute to their high FVI. Moreover, panchayats with the numbers, '27', '31', '50', '51', '53', '74', '73', '87', and '54' have experienced more than 50% flooding during the Kerala floods in 2018, mainly due to their geographical positions (in lower elevation areas). Panchayats '83', '76', '50', '31', and '54' have more than 80% of their land dedicated to agricultural purposes, mainly rice paddy cultivation. These panchayats suffered substantial economic losses during the Kerala floods in 2018 (Kerala State Planning Board 2019, Singh Amitha 2018). Furthermore, the acidity of the soil in these areas has significantly increased due to heavy sediment inflow from the upstream region. Soil degradation resulting from extreme events poses a threat to the primary economic source of the dependent population, thereby reducing their adaptive capacity with the rising economic vulnerability.

The conversion of 1 acre of agricultural land to other land uses would decrease the water holding capacity by 2.5 million litres (Balica–Wright 2010). Given the recent non-profitability of paddy agriculture due to increased labour and input costs, farmers have started converting their fields into perennial plantations or commercial properties. This fragmentation of large land parcels into smaller ones disrupts water flow and the resilience of the ecological system. Panchayats '37', '38', '41', and '60' have witnessed fragmentation of over 30% of their parcels into smaller ones disrupting water flow and the resilience of the ecological system. Panchayats '37', '38', '41', and '60' have also witnessed over 30% of their land being converted to built-up areas over time. The increase in built-up areas reduces surface roughness, accelerating surface runoff and causing faster inundation in lower elevation areas. Additionally, these panchayats have higher household and population densities, which could be the primary reasons for their higher FVI.

Panchayats '27', '60', '53', '74', '57', '50', '73', '75', and '87' are found to have over 60% of their population classified as vulnerable. The flood vulnerability of a region is closely linked to gender dynamics, as women often bear disproportionate family obligations (Walker–Burningham 2011). They frequently face barriers in accessing power, rights, resources, opportunities, and income. Women's economic activities may be limited in certain cases (Rufat et al. 2015), making them more vulnerable. However, it is important to note that this gender vulnerability is subjective, as there is no empirical evidence supporting this hypothesis. Similarly, children in the age group of 0–6 are more vulnerable during disasters due to their limited ability and dependence, whereas school-going children can better adapt and contribute to community resilience through their social networks formed in school.

Panchayats '27', '83', '36', '76', '86', '50', and '54' are identified as having over 50% vulnerable working population. These panchayats, located near the Vembanad lake, depend on agriculture, fishing, and daily wage jobs for their livelihoods. The study also establishes that all flood-vulnerable panchayats within KWS have over 60% of their population dependent on the primary breadwinners, further impacting the household coping capacity (Government of Kerala 2012).

The coping capacity of a community is influenced by several factors (refer to Table 4). It was observed that regions with lower household density, less agricultural land fragmentation, and a lower percentage of built-up areas exhibited higher resilience. Additionally, regions with higher literacy rates and more stable physical infrastructure displayed greater resilience. The coping capacity of vulnerable populations and vulnerable working populations depends on the level of community capacity building and the dependency ratio.

Furthermore, FVI maps were generated for each component to analyze and develop strategies for reducing the values and flood hazards associated with each variable. The land use component was identified as the most significant contributor to flood risk, followed by the socio-economic and biophysical components.

Land use component

As depicted in Figure A6a (see in Appendix), the variables 'hh dens' (household density), 'perc agriPl' (percentage of agricultural land), and 'perc BU' (percentage of built-up area) cluster together, representing the land use component. Panchayats '37', '22', '41', '59', '51', '38', '4', and '60' exhibit the highest concentration of built-up areas and household density. The population density in these areas makes evacuation efforts more challenging, consequently increasing vulnerability and the risk of damage (Nazeer–Bork 2019). Moreover, these panchayats have less than 45% of their land under agricultural use, whereas other flood-vulnerable panchayats have more than 50% dedicated to farming.

Socio-economic component

As shown in Appendix in Figure A6b, the variables 'perc illit' (percentage of illiterate population), 'perc unempl' (percentage of unemployed population), and 'perc vw pop' (percentage of vulnerable working population) are considered to represent the socio-economic component and are grouped together. The panchayats '5', '4', '70', '69', '83', and '76' were identified as hotspots for socio-economic vulnerability. The driving factor contributing this is the higher proportion of vulnerable working-class population in these panchayats, and majority of them rely on fishing for their livelihood, due to the proximity of coastal location, while others in this group are engaged in casual labor. The higher female labour force participation and a lower literacy rate compared to the other Panchayaths, are the additional variables contributing to their socio-economic vulnerability. It is important to note that the unemployment rate alone is not the sole determining factor of socio-economic backwardness of these panchayats, as both educated and unskilled employment these Panchayaths exceed 60%.

Biophysical component

Figure A6c (see in Appendix), shows a hotspot cluster in the central part, which is the low-lying terrain of KWS specifically the river mouth. These areas constitute the most ecologically sensitive parts of the river basins and are prone to inundation during the periods of high-water discharge. Notably some panchayats that experienced heavy flooding but did not get categorized as extremely vulnerable because they had more stable houses. This implies that irrespective of a panchayath lower elevation profile, the presence of strong physical infrastructure can help to mitigate vulnerability. On the other hand, if a region is located in a lower elevation and has a higher percentage of weak houses, the coping capacity and resilience of the community will undoubtedly constrained. This indicates that vulnerability is intricately connected to the economic well-being of households. (The panchayath level flood vulnerability and ranking are given in Table 5).

Table 5

Flood vulnerability index calculated and priority list

Rank	LSG number	Flood vulnerable LSGs within KWS (ranking from the most vulnerable LSG)	FVI calculated
1	4	Ambalapuzha North	1.000
2	69	Punnapra South	0.813
3	70	Purakkadu	0.709
4	5	Ambalapuzha South	0.649
5	37	Kumaranalloor	0.586
6	27	Kainakary	0.514
7	83	Udayanapuram	0.500
8	38	Kurichi	0.494
9	60	Pandalam	0.465
10	22	Ettumanoor	0.436
11	41	Manarkkad	0.428
12	51	Nattakam	0.414
13	36	Kumarakam	0.412
14	76	Thalayazham	0.401
15	53	Nedumudi	0.398
16	74	Thakazhi	0.373
17	86	Vechoor	0.363
18	64	Pallippadu	0.359
19	50	Muttar	0.358
20	73	Ramankary	0.358
21	75	Thalavadi	0.353
22	31	Kavalam	0.346
23	87	Veeyapuram	0.343
24	54	Neelamperoor	0.340
25	16	Cheruthana	0.331
26	64	Peringara	0.326
27	59	Panachikkavu	0.318
28	12	Champakulam	0.275
29	30	Karuvatta	0.273
30	6	Amballur	0.269
31	18	Chunakkara	0.260
32	56	Niranam	0.248
33	25	Kadapra	0.246
34	88	Veliyanadu	0.246
35	61	Pandalam Thekkekkara	0.246
36	80	Thiruvarppu	0.242
37	15	Cheriyanadu	0.239
38	2	Aimanam	0.238
39	85	Vazhappally	0.236
40	20	Edathwa	0.230
41	14	Cheppadu	0.227
42	89	Velloor	0.222
43	62	Pandanadu	0.214

(Table continues on the next page.)

(Continued.)

Rank	LSG number	Flood vulnerable LSGs within KWS (ranking from the most vulnerable LSG)	FVI calculated
44	65	Piravam	0.213
45	17	Chettikulangara	0.198
46	79	Thiruvanvandoor	0.191
47	24	Iraviperoor	0.190
48	77	Thalayolaparampu	0.189
49	46	Mavelikkara-Thekkekkara	0.188
50	24	Koipram	0.183
51	72	Ramamangalam	0.179
52	58	Pampakuda	0.177
53	23	Harippad	0.173
54	29	Kanakkary	0.173
55	28	Kallara	0.171
56	8	Arpookara	0.170
57	44	Mannar	0.169
58	82	Thumpamon	0.168
59	33	Kidangoor	0.164
60	78	Thazhakkara	0.156
61	3	Ala	0.155
62	66	Poothrikka	0.154
63	39	Kuttoor	0.151
64	67	Pulinkunnu	0.150
65	81	Thottapuzhassery	0.149
66	55	Neendoor	0.144
67	48	Mulakkulam	0.144
68	10	Bharanikkavu	0.143
69	71	Puthuppally	0.143
70	13	Chennithala-Thripperunthura	0.137
71	40	Mallappuzhassery	0.134
72	1	Aikaranad	0.126
73	26	Kaduthuruthy	0.122
74	35	Kulanada	0.115
75	68	Puliyoor	0.112
76	25	Bhudhanoor	0.096
77	7	Aranmula	0.092
78	47	Mazhuvannoor	0.092
79	43	Manjoor	0.081
80	19	Edakkattuvayal	0.076
81	84	Valakam	0.074
82	9	Ayarkkunnam	0.074
83	42	Maneed	0.073
84	49	Mulakkuzha	0.072
85	90	Venmoney	0.067
86	63	Payippadu	0.065
87	32	Kaviyoor	0.063
88	21	Elanji	0.042
89	45	Marady	0.025
90	52	Nedumpram	0.000

Recommendation

Given the unpredictability of natural catastrophes (Krishnadas 2016), planning for uncertainties is essential and there are no "one-size-fits-all" solutions. Since this is a high-level study, there is limitation in providing Panchayat-specific recommendations; instead, the hotspots identified are linked under the high-level recommendations given for each component. For disaster mitigation and adaption in a climate challenged landscape like KWS, it is imperative to embrace a combination of both technical and nature-based solutions.

From the analysis, it was evident that the land use component is the most influential contributor to flood hazards in KWS. Therefore, it is vital to focus on maintaining the structural complexity of the ecological system, which is challenging but essential for ensuring ecological compatibility in land-use planning. To address these issues, it is imperative to develop policies at a landscape level rather than just at the local management levels for the entire KWS catchment system. Special focus should be given to the identified hotspots (see Figures A6a, A6b, A6c). For the Panchayaths identified as hotspots in the land use component such as Kumaranallur, Ettumanoor, Manarkkad, Panachikavu, Nattakam, Kurichi, Ambalappuzha North, and Pandalam, it is crucial to develop a land suitability plan by determining the carrying capacity of the region. This can be achieved by calculating the ecological footprint and environmental thresholds based on available data. Swift implementation of land use laws and zoning ordinances is necessary to regulate and guide the type, scale, and distribution of development within flood-prone areas as implemented in the countries like Netherlands (Delta Programme 2023), United Kingdom (UK Government 2023), Japan (Koike 2021) and so on. This proactive measure is vital to mitigate potential risks and ensure responsible land use practices in these Panchayats. This may involve limiting development to low-impact activities in flood-prone locations and adopting transformative strategies that focus on sustainable horizontal growth ensuring minimal land use changes. Update and expand floodplain mapping to accurately identify and demarcate flood-prone areas, enabling informed decision-making in land use planning. This approach can help reduce impervious land cover while preserving sufficient sponge area for water to trickle into shallow and deep aquifers.

In the meantime, at panchayath or ward level mitigation measures should be adopted. Restoring vegetated buffer zones along rivers and water bodies can help to stabilize banks, reduce erosion, and provide natural floodplain storage during heavy rains. The roads and infrastructure constructed without considering the natural flow of water in KWS, causes water accumulation, deterioration of watershed and eventually contribute to intensifying flood. Roads and infrastructure should be carefully designed, considering the hydrology into account and providing enough channels and culverts facilitating flow. Allowing rivers to access their natural floodplains. This will also help to dissipate floodwaters across a wider area during high-water events, reducing the impact on specific regions.

In response to the socio-economic component's findings, specifically addressing the shift in occupation and land fragmentation driven by agriculture unprofitability targeted measures are proposed for LSGs identified as hotspots – Ambalappuzha north and south, Purakkad, Punnapara South, Udayanapuram and Thalayazham. Implementing transformative measures to enhance agricultural viability, collaborating with top agricultural experts, entrepreneurs, landowners and farmers. This collaboration is indispensable to develop the knowledge and technology required for resilient, productive, and sustainable below mean sea level agriculture.

The Department of Agriculture, in partnership with LSG institutions, should explore the possibility of promoting climate-resilient paddy and other agricultural crops in the area. The minimum support price strongly influences and restricts the prices at which farmers can sell their products, which are not based on demand and supply. Capacity-building initiatives, such as courses, field tours, and on-farm demonstrations should be provided to inhabitants engaged in or interested in agriculture. This will boost their confidence and encourage their continued involvement in the sector.

Recognizing that the development of agriculture and fishing is crucial for attracting and retaining youth participation, especially considering the larger population dependent on these sectors in Kuttanad, community-based tourism initiatives should be established in the identified hotspots. These initiatives aim to empower local communities with a purposeful participation approach, primarily targeting youngsters in their skill development in emerging industries and entrepreneurship.

Additionally, aquaculture can play a vital role in diversifying and enhancing the productivity of agricultural systems, ensuring the resilience of the food chain. To address economic vulnerabilities, social safety nets and support systems, including micro-financing schemes, should be established to assist vulnerable populations during economic downturns or natural disasters.

Furthermore, evaluating the disaster-response resiliency of the people is essential, as enhancing this resilience can lead to a reduction in risk (de Brito et al. 2017). Capacity-building programs, public education, and targeted outreach campaigns, especially for vulnerable populations, are necessary to sensitize about flood dangers and how to prepare for and respond to flooding. During floods, vulnerable people, such as the elderly, children, and those with disabilities, should be recognised and given the necessary support. Communities should prepare emergency response plans and be prepared to respond to flooding. Providing flood insurance coverage can help lessen the economic impact of floods on individuals and businesses. New European drainage standards require handling 1–in–30-year flood events, but recent Norwegian cases have extended insurance claims to 1–in–100-year events (Crichton 2008).

Likewise, measures should be identified to employ both educated and unskilled unemployed individuals, reducing dependence on the primary workforce. Improving the network of Kudumbasree (women self-help groups) and micro-credit networks within the KWS can assist the female population economically, reducing the reliance on primary breadwinners and addressing financial instability, a significant cause of socio-economic vulnerability. Vocational training for female non-workers should be organized in collaboration with neighbouring research institutions. Understanding the vulnerability of landscapes, agricultural systems, and fisheries systems is essential for planning future investments in adaptation and mitigation (Center 2007) to reduce the potential economic losses associated with floods.

Improving prediction models and providing decision-makers with vulnerability maps and other analyses at various scales, particularly at the local level, is crucial. Hotspots with biophysical vulnerability, located predominantly in the low-lying central part of the system should focus on strategies to strengthen houses against flood impacts. Thorough investigations into the causes of flooding within LSG boundaries should inform short-term, medium-term, and long-term mitigation and adaptation strategies, with immediate action plans considering financial capacity and potential funding sources.

The most transformational strategy to prevent floods is to restore floodplains to their natural state potentially through building codes or the relocation of existing development away from flood-prone locations. However, feasibility assessments are required, considering the close ties of local livelihoods to lakes and rivers. Adequate compensation for willing migrants should be ensured, and the state emergency management budget should include funds for relocation purposes. Reforesting degraded upland landscapes with the support from experts, implementing upstream storages to retain the rainfall and reduce downstream flow duration, similar to the approach adopted by Glasgow in Scotland, and prioritizing wetland restoration initiatives are effective measures to alleviate surface runoff and reduce flood intensity. Training LSGs in proposal writing for region-specific restoration activities, integrating coastal regulation zone policies into master plans and establishing a river regulatory zone in Kerala are recommended. Maintaining natural drainage networks, implementing soil and water conservation measures, and establishing monitoring mechanisms for changes in the wetland ecosystem's hydrological regime are essential components of a comprehensive flood risk reduction strategy.

Conclusion

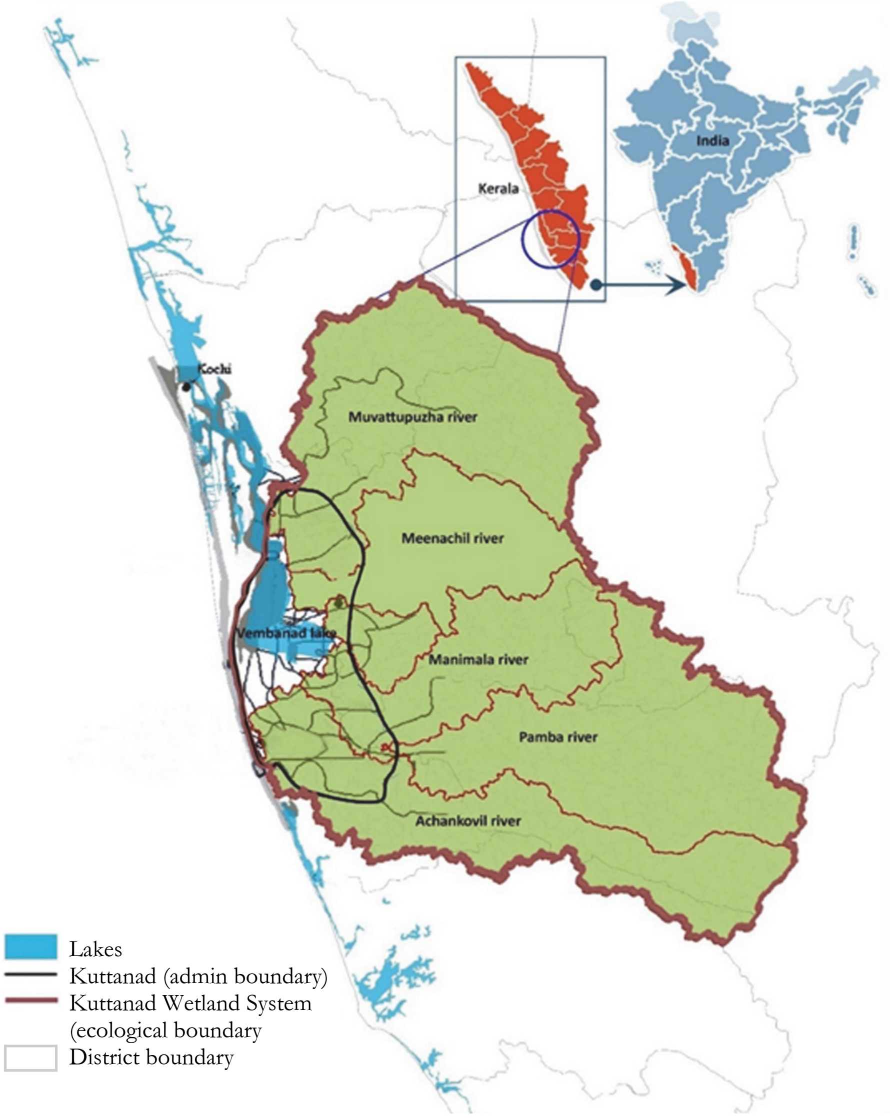
This study elucidates the multifaceted interplay among social, economic, and environmental factors, underscoring their collective contribution to vulnerability in and adequate education, enabling them to comprehend and respond to emergencies, may not be vulnerable to flooding even when residing in inundated locations.

Furthermore, the study identifies a lack of awareness as a key factor amplifying the risk of flooding. It is evident that flood vulnerability is an outcome of broader social disparities and systemic challenges, extending beyond natural disasters alone. To bolster the resilience of the system, policymakers and regulators can utilize the identified individual component hotspots as a foundation for prioritizing modifications to be made. Although the study primarily focuses on the process rather than providing specific recommendations, it offers high-level suggestions for the identified hotspots, leaving ample room for more comprehensive research. Consequently, further in-depth investigation at the tier 2 level, incorporating additional variables and primary surveys for ground truth data, can be undertaken. The study's conclusions have significant implications for policymakers and governments, enabling them to optimize resource allocation for flood protection and crisis management. Additionally, it empowers decision-makers to enhance their preparedness for uncertainties and crises through improved planning.

Ultimately, these research underscores the criticality of collaborative and coordinated efforts among governments, communities, and stakeholders to mitigate flood risk and enhance resilience in vulnerable areas. By addressing both the physical and socio-economic dimensions of vulnerability, we can strive towards a more equitable and sustainable future.

Appendix

Figure A1
The ecological boundary of Kuttanad Wetland System with all 5 watersheds

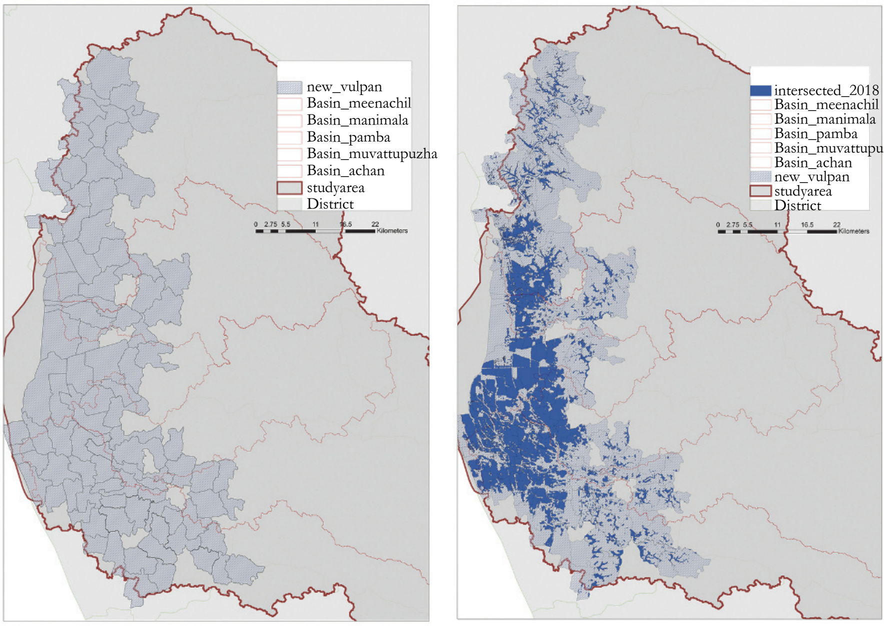


Source: Sonu et al. 2022.

Figure A2

Flood-prone panchayats within Kuttanad Wetland System

a) Vulnerable panchayats b) Flooded LSGs in 2018



c) Flooded LSGs in 2019 d) Flooded LSGs in 2020

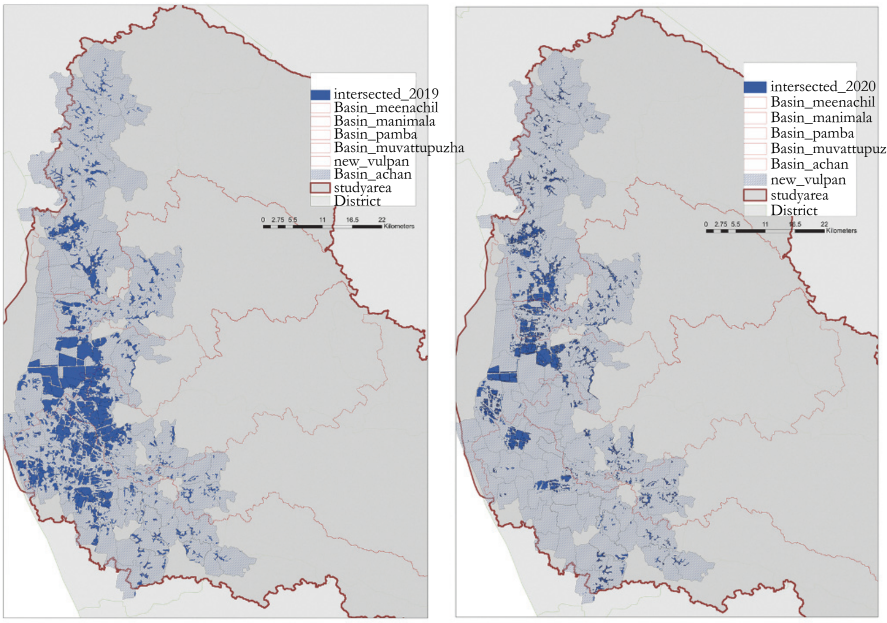
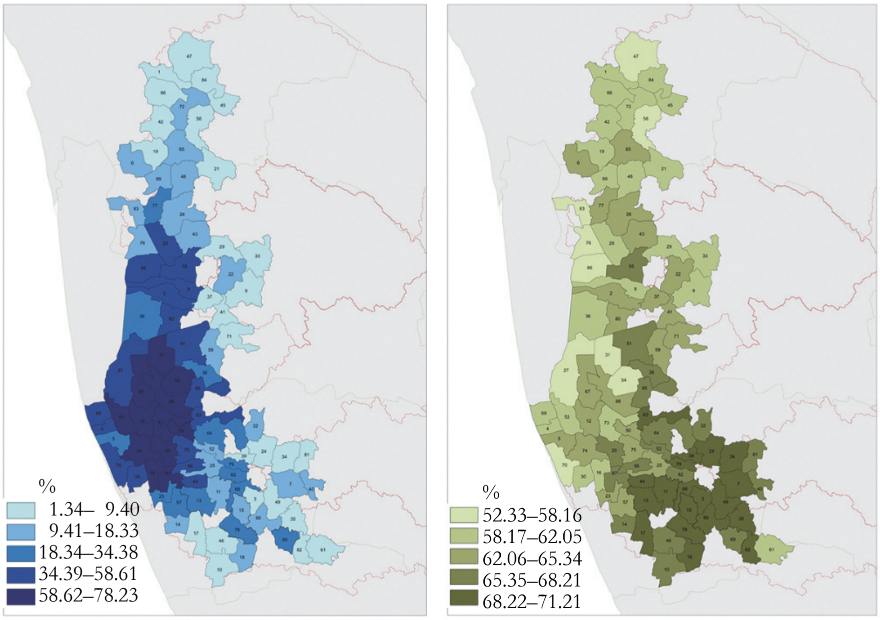


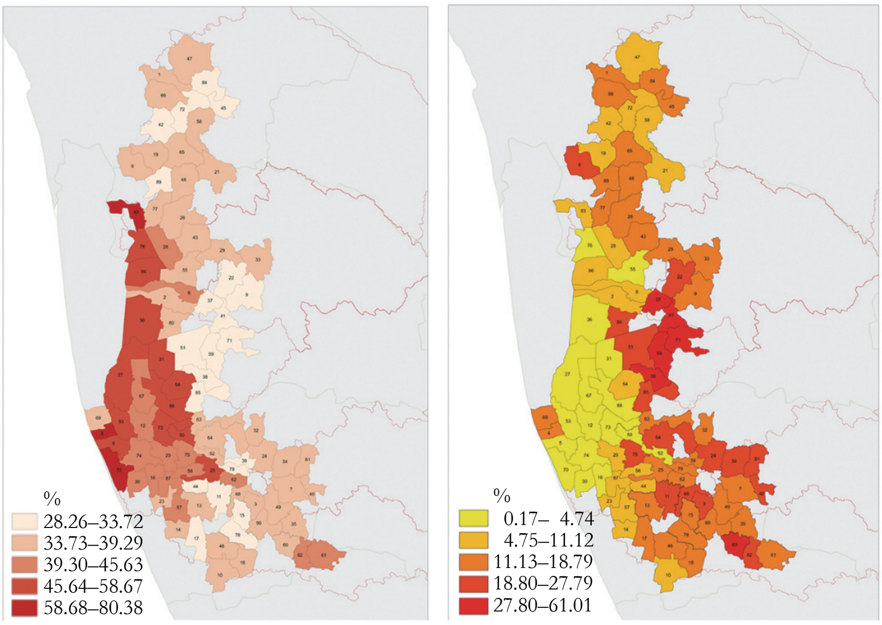
Figure A3

Spatial representation of variables



a) Flooded area

b) Unemployment



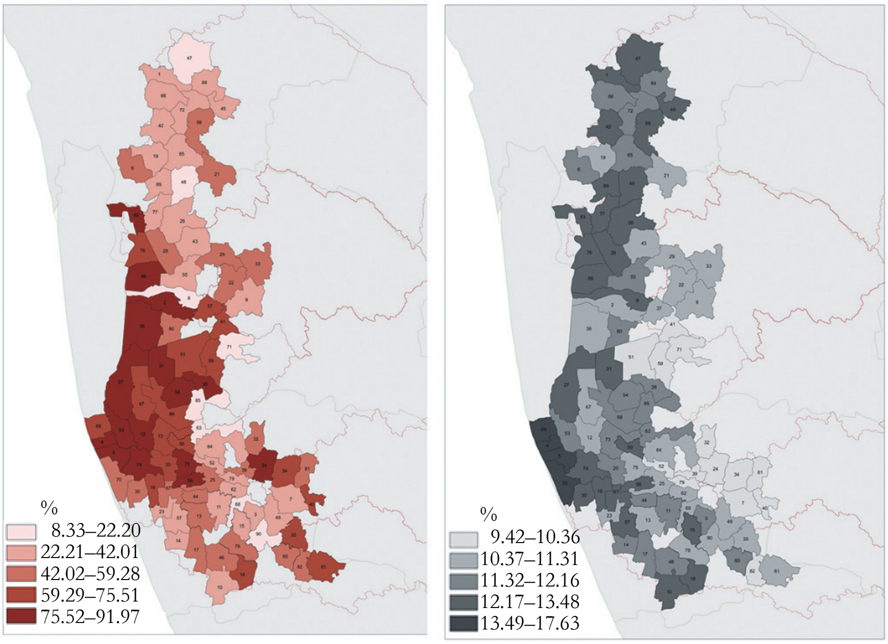
c) Vulnerable working population

d) Built-up

Figure A4

Spatial representation of variables

a) Weak houses b) Illiterates



c) Household density d) Agricultural land

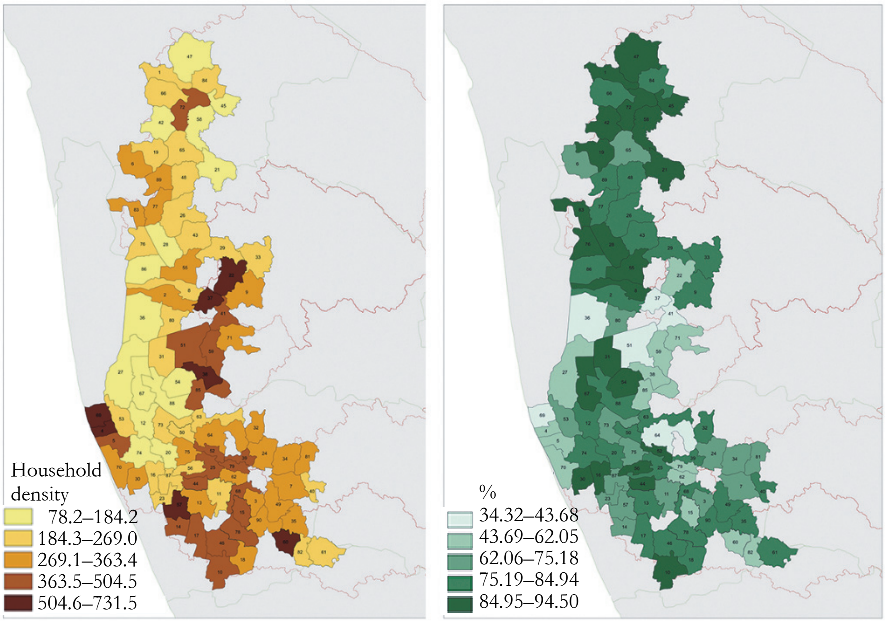


Figure A5

Spatial representation of flood vulnerability index

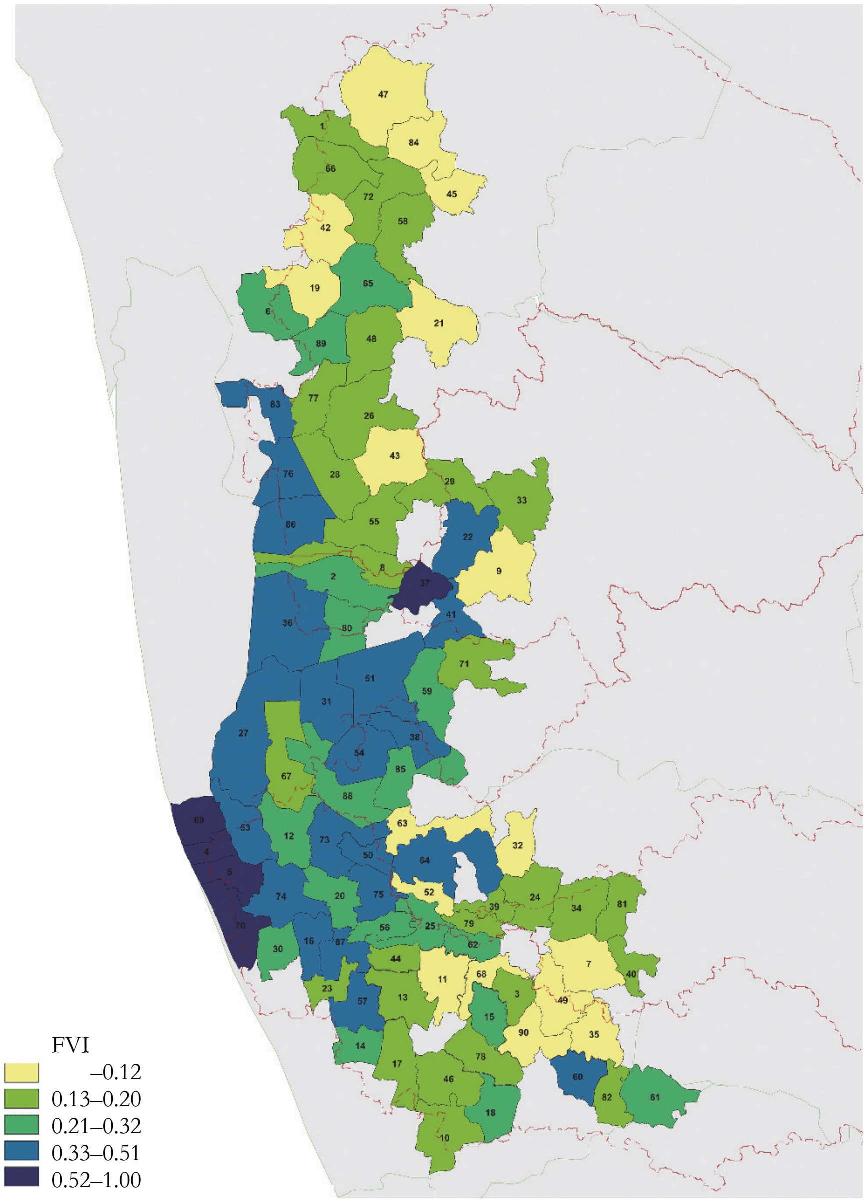


Figure A6a

Spatial representation of land use component

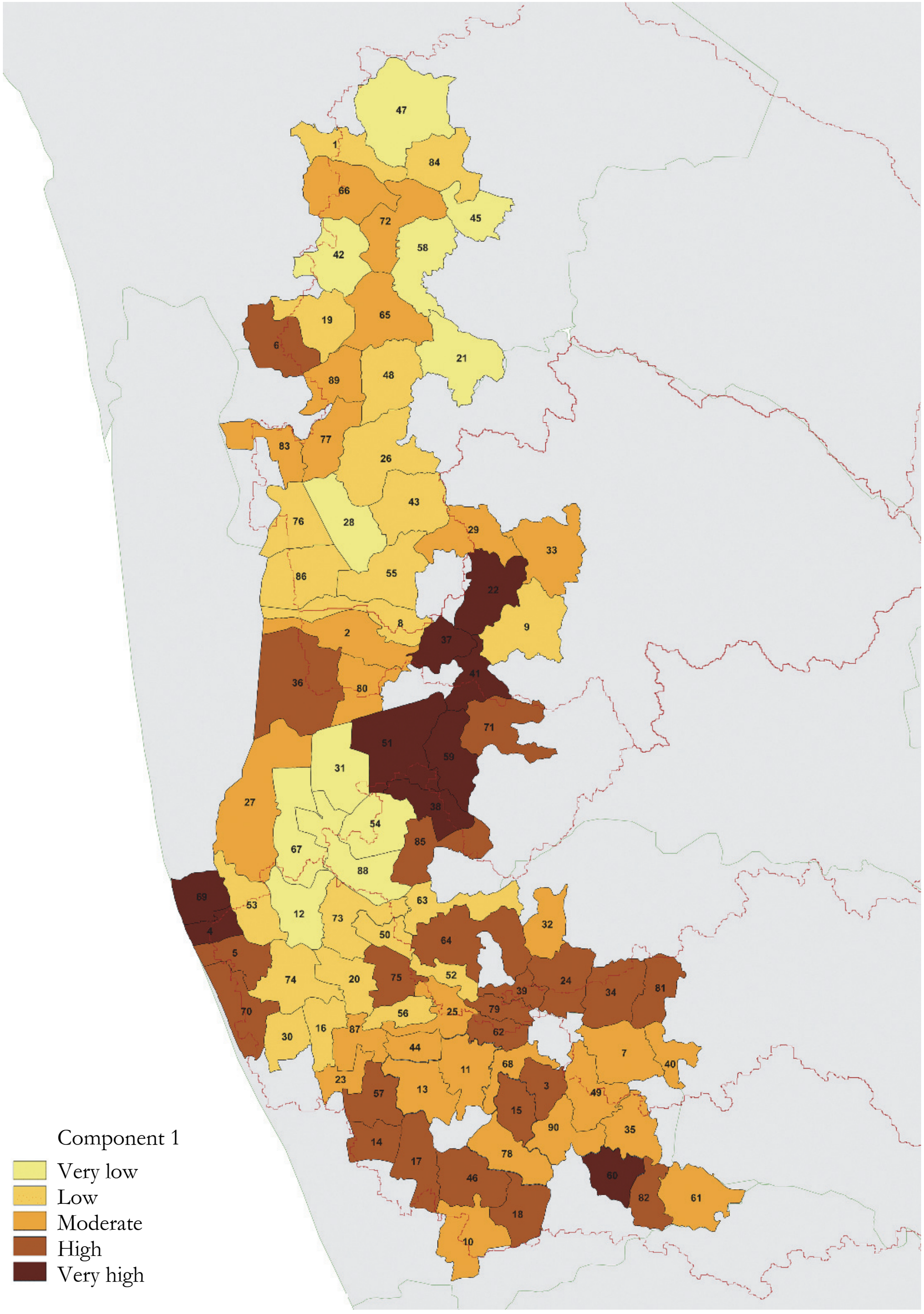


Figure A6b

Spatial representation of socio-economic component

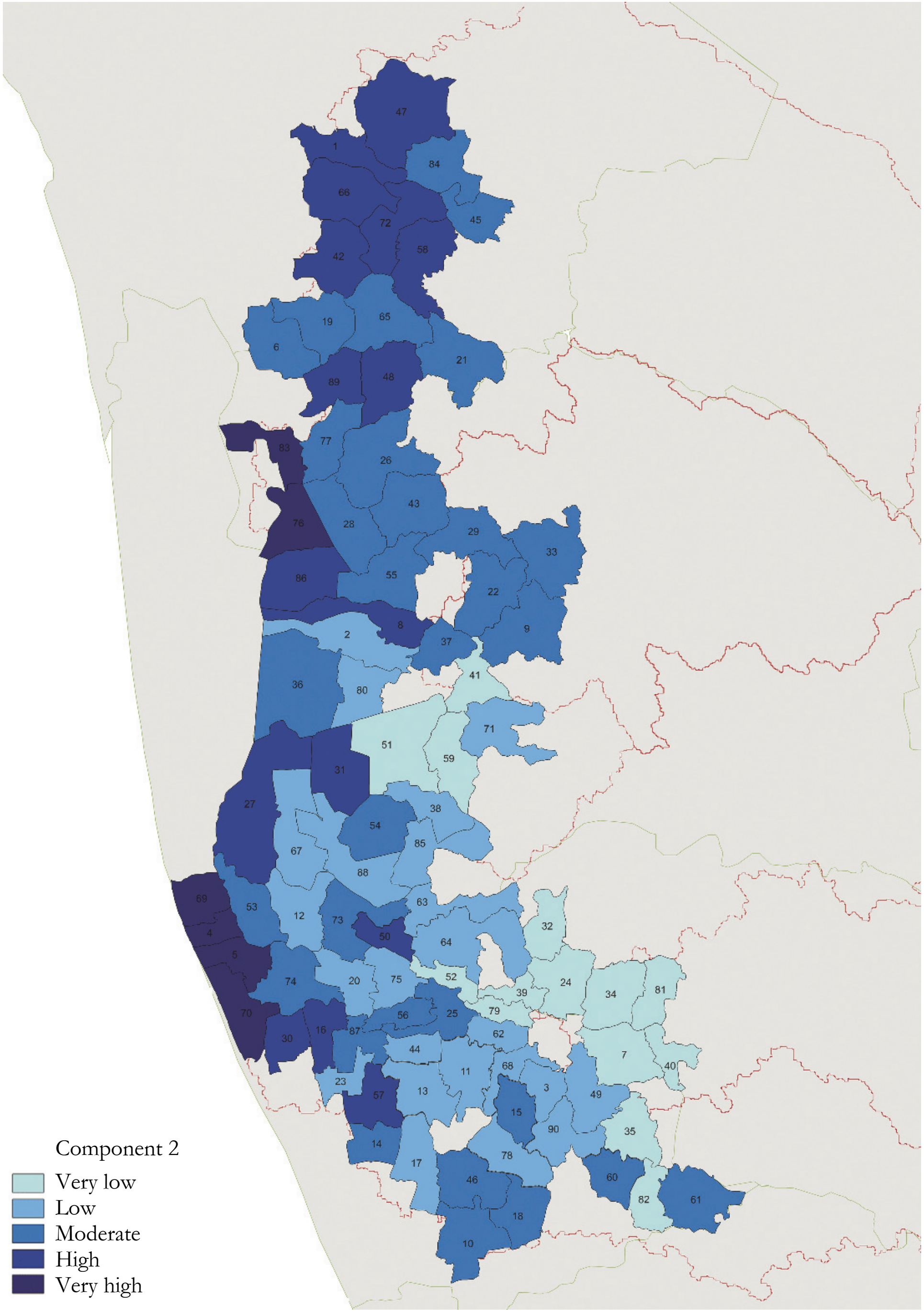
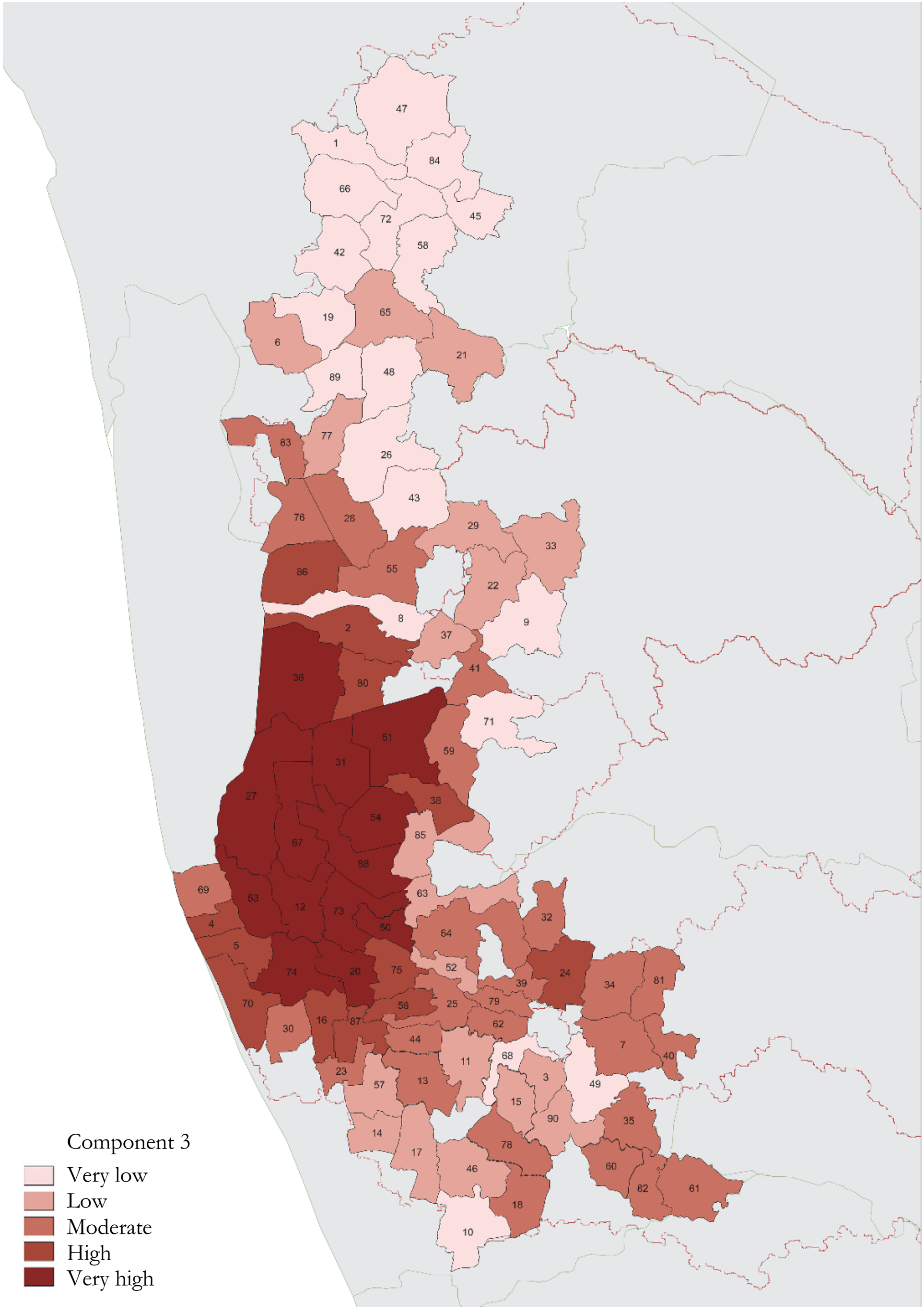


Figure A6c

Spatial representation of biophysical component



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