

A Framework for Risk-Based Assessment of Urban Floods in Coastal Cities

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Research Article

Keywords: Eastern India, coastal cities, climate induced disasters, urban flood risk index, flood management

Posted Date: June 2nd, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-547336/v1>

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Version of Record: A version of this preprint was published at Natural Hazards on September 10th, 2021. See the published version at <https://doi.org/10.1007/s11069-021-05024-w>.

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Abstract

Many coastal cities in developing countries are at the risk of flooding due to a progressive increase in the built-up areas and poor management of stormwater. The flooding situation in coastal cities gets accentuated further due to climate induced natural disasters such as cyclones and climate change induced sea-level rise that adversely impact the city's natural drainage potential. This study developed a composite urban flood risk index consisting of three sub-indices and 20 key natural, physical, social, and economic influencing variables for a coastal city (i.e. Cuttack) in eastern India, the intensity of storm runoff being one among the many. The intensity-duration-frequency curve developed shows that the city can experience floods with a peak discharge of 1,320 cubic metre per second every alternate year for a rainfall intensity of 2-hour duration. The urban flood risk index computed for all the city wards shows that out of the 59 wards, only one ward has low flood risk (index value < 0.40) and 20 wards are at high risk (index value 0.55 and above) from the urban flood. Thereafter, factors leading to high risk due to urban floods were identified and the institutional capacities available with the urban utility for fighting floods analyzed.

Key Words: Eastern India, coastal cities, climate induced disasters, urban flood risk index, flood management

1 Introduction

Coastal cities play an important role in a country's economy through their contribution to marine output and the tourism sector (Samonte-Tan et al. 2007; Papageorgiou 2016). However, owing to their unique geographic location, i.e. within the flood plains of large rivers, low elevation areas, and proximity to the coastline, they experience floods on a frequent basis. Flooding is regarded as among the most damaging of all natural disasters as it leads to loss of human life, livestock, property, and infrastructure (Douben 2006). As per the estimates, the total population exposed to coastal flooding would increase to 120 million by 2070 (Hanson et al. 2011), and the global economic exposure to river and coastal flooding on account of increase in population density is projected to be USD 158 trillion by 2050 (Jongman et al. 2012). Much of this impact will be in the coastal cities of Asia and Africa that continue to experience substantial inward migration (Tibbetts 2002; Brecht et al. 2012).

As is the case worldwide, most of the large coastal cities in India are at the risk of flooding due to a progressive increase in the population, built-up areas, and inadequate or poorly designed stormwater drainage systems (Patankar 2015; Kumar et al. 2020). Most of the mega coastal cities in India, for example Mumbai and Chennai, have suffered major flood related-disasters during the last decade. In such cities, on one hand, the urbanisation leading to land use change is resulting in catchments losing their infiltration capacity that increases the magnitude of peak floods by up to eight times, and flood volumes by up to six times in comparison to flooding in rural areas or the riparian zones (NDMA 2010). Thus, the magnitude of storm runoff is high and it occurs very quickly due to a very short flow duration. On the other hand, the natural drainage potential of coastal cities is adversely impacted due to developments on reclaimed land (Daniela and Marco 2017) and climate change induced sea-level rise (Marfai and King 2008; Kumar et al. 2020). While, the former lead to changes in land use and increase in built up area, the latter cause inundation of land, both further complicating the flood management in coastal cities.

Floods pose serious challenges to growth and socio-economic development in urban areas (Hammond et al. 2005; Kumar et al. 2020). It disrupts urban transport; power supply and public

101 water supply services, and the functioning of sewerage systems. While it hits the economic
102 activities, the public health impact of urban floods can also be serious (Shoaf and Rotiman 2000;
103 Kumar et al. 2020). The ‘poor localities’ are generally the worst affected, as the quality of services
104 (water supply, sewerage, drainage facilities) available to them is often very poor, and their ability
105 to cope up with emergencies is poor. The people living in low-lying areas also get affected badly
106 by urban floods due to poor natural drainage.

107
108 Within flood research, it has been widely accepted that absolute flood protection cannot be
109 achieved (Schanze 2006). Instead, growing attention has been given to the new paradigm of flood
110 risk management based on the effective establishment of both risk mitigation (structural technical
111 flood defence measures such as dams, dikes, or polders) and adaptation (non-structural, “soft”
112 measures such as preparation of the local people, flood insurances, information management,
113 social networks) measures (Krysanova et al. 2008; Li et al. 2016).

114
115 In the past, attempts have been made in India to assess flood risk through flood hazard mapping
116 (Sanyal and Lu 2006; Saxena et al. 2013) and vulnerability assessment of flood hazard (Saini and
117 Kaushik 2012; Rani et al. 2015; Singh et al. 2018). However, to prepare for the risk posed by
118 climate-induced disasters (urban flooding in this case), it is important to assess the hazard,
119 exposure, and vulnerability that risk is composed of (Messner and Meyer 2006; Mauro 2014).

120
121 The objective of this research study is to develop an analytical framework for assessing urban
122 flood risks in coastal cities that can support the design of strategies for climate resilience of coastal
123 cities. Section 2 of the paper presents the methodology specifically the framework for the
124 development of the urban flood risk index and its computation. Section 3 discuss results obtained
125 from the analysis of daily rainfall data of the selected coastal city (Cuttack) in eastern India,
126 intensity-duration-frequency of the storm event, peak flood flow volume, developed urban flood
127 risk index, and computed value of the index for various administrative units (referred to as wards)
128 of Cuttack city. Section 4 discusses various natural, physical, economic, social, and institutional
129 factors that increase the flood risk in Cuttack, the institutional capability available with the city
130 municipal corporation to fight floods, and the usefulness of the risk-based assessment approach in
131 better management of floods in coastal cities. The last section presents the study conclusion.

132 133 **2 Methodology**

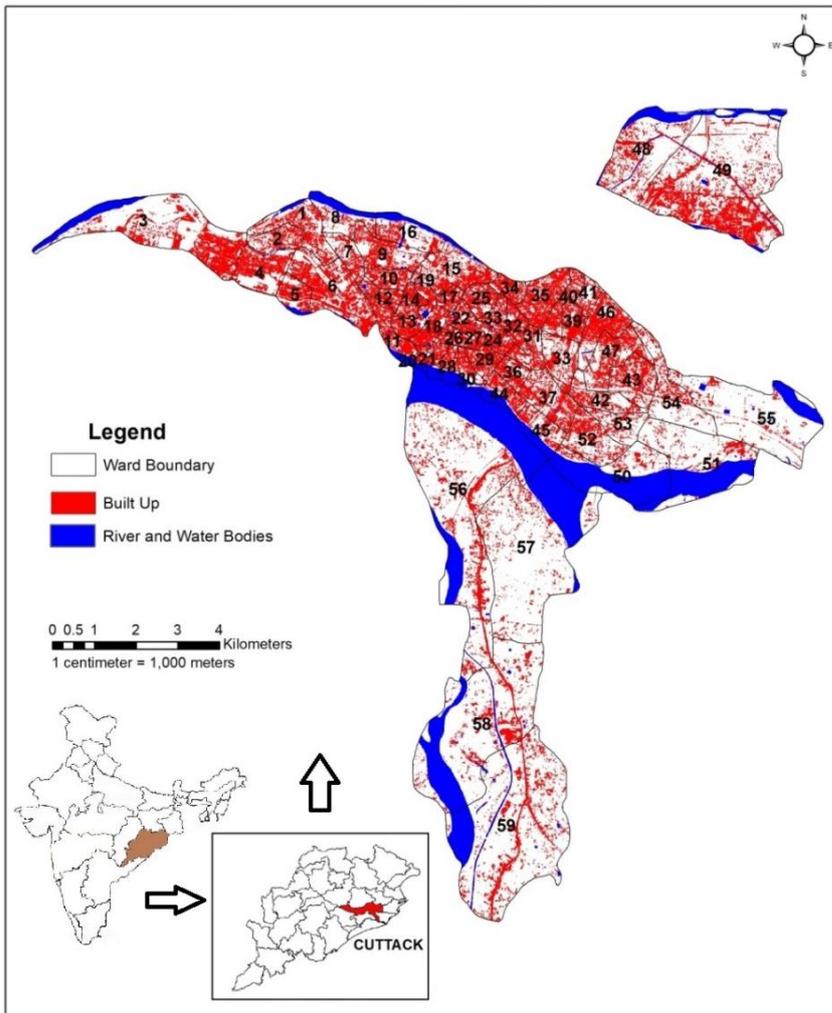
134 135 **2.1 Description of the study area**

136
137 Cuttack city is located at latitude 20°31’23” and 20°52’30” North and longitude 85°47’17” and
138 85°78’80” East in the coastal plains region of Odisha in eastern India. It lies in the delta formed by
139 the river Mahanadi and its distributary river *Kathajodi*. As per the Census of India 2011, the city
140 has a geographical area of 192.5 sq. km and an overall population of 6.1 lakh that is distributed
141 among 59 administrative units referred to as wards (GoI 2011) (Figure 1). The city experiences a
142 tropical wet and dry climate and receives an average annual rainfall of about 1800 mm.

143
144 The city has a total drainage network of about 1,280 km, out of which only 1.5 percent is natural
145 and the remaining is the constructed one. The city core area is drained by Main Drain 1 and 2
146 which empties into river *Kathajodi* and river Mahanadi, respectively. However, due to the
147 inadequate sewerage infrastructure and poor maintenance of the existing drainage network, large
148 parts of the city face problem of waterlogging during the rainy season.

149
150 Further, the city is highly prone to natural disasters such as floods and cyclones due to its
151 topography and geographical location. It is saucer-shaped, has highly fertile deltaic land that is
152 densely populated (3100 people per sq. km), crisscrossed by hundreds of rivers and rivulets, and a
153 short distance (about 80 km) from the Bay of Bengal. Also, a large portion of the city has low lying
154 areas with an average elevation of only about 36 meters above mean sea level and thus gets

155 submerged easily during floods. As per the flood hazard atlas of Odisha, the city falls in ‘high’
156 (inundated 7-9 times during 2001-2018) to ‘very high’ (inundated 10-14 times during 2001-2018)
157 flood hazard categories (NRSC 2019).
158



159 **Fig.1 Map showing ward wise land use land cover of the Cuttack city**
160 (Source: Developed by authors)
161
162

163 2.2 Development of intensity-duration-frequency curve and estimation of peak flood flow

164

165 The intensity of flood-causing rains and the peak flood volume in the study area were estimated
166 using the historical data on rainfall. For this, the intensity-duration-frequency (IDF) curve of
167 rainfall was developed using the daily rainfall data from 1901 to 2019 for Cuttack city. Out of the
168 119 years that were considered, the rainfall data was not available for 18 years (1970-1987). For
169 estimating the missing rainfall data, the linear regression method was used to establish a
170 correlation between the daily rainfall data of the Cuttack and Bhubaneswar (which is at an aerial
171 distance of 19km from Cuttack city) cities. Then the missing data for Cuttack were estimated using
172 a linear regression equation. Nevertheless, even for the city of Bhubaneswar, daily rainfall data
173 was missing for five years (1970, 1971, 1972, 1975, and 1976).
174

175 Using the available 114 years data set on daily rainfall, the maximum daily precipitation that
176 occurred in a particular year was identified for all the years. From the daily (24 hours) precipitation
177 data, hourly rainfall depth corresponding to 1, 2, 6, and 12 hours was estimated using the Indian
178 Meteorological Department’s empirical reduction formula that is presented in equation (1). The

179 method is widely used for estimating the short duration rainfall values, especially in areas where
 180 the data is scarce or is limited in extent (Rathnam et al. 2001; Chowdhury et al. 2007; Andimuthu
 181 et al. 2019; Namitha and Vinothkumar 2019).
 182

$$183 \quad P_t = P_{24} \sqrt[3]{\frac{t}{24}} \dots\dots\dots(1)$$

184
 185 Where, where P_t is required rainfall depth in mm at t-h duration, P_{24} is daily rainfall in mm, t is the
 186 duration of rainfall in h.
 187

188 To determine the return period (frequency) of storms of different intensities and duration,
 189 Gumbel's probability distribution was used (Chow et al. 2013). As a first step, the frequency
 190 factors (K_T) for the desired return periods (T) was computed using the equation (2). For this
 191 purpose, the return period of 2, 5, 10, 25, and 50 years were considered.
 192

$$193 \quad K_T = -\frac{\sqrt{6}}{\pi} \left\{ 0.5772 + \ln \left[\ln \left(\frac{T}{T-1} \right) \right] \right\} \dots\dots\dots (2)$$

194
 195 In the second step, the rainfall intensity corresponding to the different durations and their return
 196 period was estimated using equation (3) which is based on Chow et al. (2013).
 197

$$198 \quad X_T = \bar{X} + K_T S \dots\dots\dots (3)$$

199
 200 Where, X_T is rainfall intensity at a given return period, \bar{X} is the mean of a particular time, S is the
 201 standard deviation, and K_T is a frequency factor.
 202

203 From the estimated rainfall intensity of different duration and frequency, the peak flood flow for
 204 the city was estimated using equation (4) based on Rodriguez-Iturbe et al. (1979).
 205

$$206 \quad Q_T = 0.278 \times I_T \times A \dots\dots\dots (4)$$

207
 208 Where, Q_T is the design peak discharge in m^3/s , with a return period of T years; I_T is the average
 209 rainfall intensity of design rainfall in mm/h, with a return period of T years and with rainfall
 210 duration being equal to the time of concentration, and A is the catchment area in km^2 . The time of
 211 concentration (T_C) was estimated using equation (5) which is based on Kirpich (1940).
 212

$$213 \quad T_C = 0.02L^{0.77}S^{-0.385} \dots\dots\dots (5)$$

214
 215 Where, T_C is a time of concentration (min), L is the maximum length of travel (m), and S is a
 216 slope, that is equal to H/L , where H is the difference in elevation between the most remote point in
 217 the watershed/basin and the outlet.
 218

219 **2.3 Urban flood risk index development: A framework**

220
 221 Risk comprises three components, hazards, exposure, and vulnerability. A framework for assessing
 222 the urban flood risk index, including the three components of flood hazard, exposure of the city to
 223 flood hazard, and vulnerability of the community to disruptions caused by flood hazards was
 224 mainly developed based on research undertaken by the authors on assessing the climate induced
 225 risk in water, sanitation and hygiene (WASH) (IRAP and UNICEF 2017a, b; Kumar et al. 2020;
 226 Kumar et al. 2021), and vulnerability of rural households to the problem of water supply for
 227 multiple uses due to climate variability (IRAP, GSDA, and UNICEF 2013; Kabir et al. 2016).
 228

229 The degree of risks induced by intense storms and floods depends on a variety of natural, physical,
230 social, economic, cultural, environmental, and institutional factors. Many of these factors can
231 change from one locality to another with a region. Hence the degree of risk posed by urban floods
232 can vary within the same city limits (Kumar et al. 2020).

233
234 The magnitude of climate-induced flood hazards is determined mainly by natural and physical
235 factors. These include the probable rainfall intensities, surface morphological condition,
236 groundwater levels, terrain slopes soil infiltration rates, the proportion of impervious cover, the
237 occurrence of high tide (relevant for coastal cities), etc. (Kumar et al. 2020; Kumar et al. 2021).

238
239 The degree of exposure of the assets, services, and properties to urban flood hazards is determined
240 by a whole range of natural, physical, socio-economic, and institutional factors. The exposure can
241 be in the form of accumulation of flood waters in a locality; reduced supply of water from the
242 public system for domestic water needs or reduced access to water supply from the public systems;
243 resulting from the breakage/damage to water supply pipelines due to heavy storms, cyclones and
244 floods or flooding of the localities where standposts are located; extent of damage to raw water
245 treatment, and sewerage infrastructure (including drains, sewage treatment plants, etc.) ; the extent
246 to which access to water sources and sanitation facilities by the households is affected; chances of
247 contamination of drinking water during collection and conveyance, contamination of water supply
248 lines from sewage due to pipeline breakage; contamination of water in drinking water wells with
249 biological matter and pathogens; and precautions taken by the water utilities and disaster
250 mitigation agencies to prevent flooding of low-lying areas, or prevent water contamination (IRAP
251 and UNICEF 2017a, b; Kumar et al. 2020).

252
253 Similarly, the degree of vulnerability of the urban population to the disruptions in the services and
254 damage to assets caused by flood hazards is determined by a whole range of natural, social,
255 cultural, economic, and institutional factors (Kumar et al. 2020). This vulnerability can be due to
256 lack of alternate sources of freshwater for drinking and domestic uses at the household level in the
257 wake of the area getting inundated; population congestion, favourable climatic conditions/weather
258 for the spread of disease, lack of social cohesion and ingenuity; and lack of facilities to treat
259 contaminated water or financial resources to buy bottled drinking water or get medical treatment in
260 the case of water-borne or water-based or water-related diseases (IRAP, UNICEF, and GSDA
261 2013; Kabir et al. 2016; Kumar et al. 2021).

262
263 Based on the urban flood risk assessment framework discussed above, a composite index was
264 developed to assess the overall ‘climate-induced flood risk of urban areas’, which captures the
265 degrees of hazard, exposure, and vulnerability.

266 **2.4 Computation of the urban flood risk index**

267
268
269 For the computation of the urban flood risk index, the data pertaining to the identified natural,
270 physical, social, and economic conditions, and the overall cultural and institutional factors of
271 different wards were collected. These included: the natural drainage pattern; overall topographical
272 conditions; the water supply, sewerage, and stormwater drainage; power distribution and road
273 network; the social profile; economic conditions of the wards; the conditions with regard to nature
274 and degree of access to water supply and sanitation systems; population density; and climatic
275 conditions.

276
277 The composite urban flood risk index ($RiFu$) was estimated for various wards of the Cuttack city
278 by separately computing the values of three sub-indices, viz., hazard sub-index (Hsi), exposure
279 sub-index (Esi), and vulnerability sub-index (Vsi) as:

280
281
$$RiFu = Hsi \times Esi \times Vsi \dots\dots\dots (6)$$

282

283 The value of each sub-index was computed by adding up the numerical values (score) assigned for
 284 each one of the factors and normalizing it, by considering equal weightage for each sub-index. This
 285 means the total computed value of each sub-index was divided by the number of factors considered
 286 for computing it. Hence, the maximum value possible for each sub-index and also for the risk
 287 index is 1.0 (indicating the highest level of risk). The computed urban flood risk index was used
 288 categorizing the city wards at high risk, moderate risk, and low risk. For this, the ward-wise
 289 computed index values were arranged in increasing order, and the average value of the first 20
 290 wards (1st group) and the last 19 wards (the 3rd group) were taken as the benchmarks. The overall
 291 urban flood risk was considered to be low for the wards with index value up to 0.40, moderate for
 292 the wards having index value from 0.41 to 0.54, and high for the wards with index value 0.55 and
 293 above.

294

295 3 Results

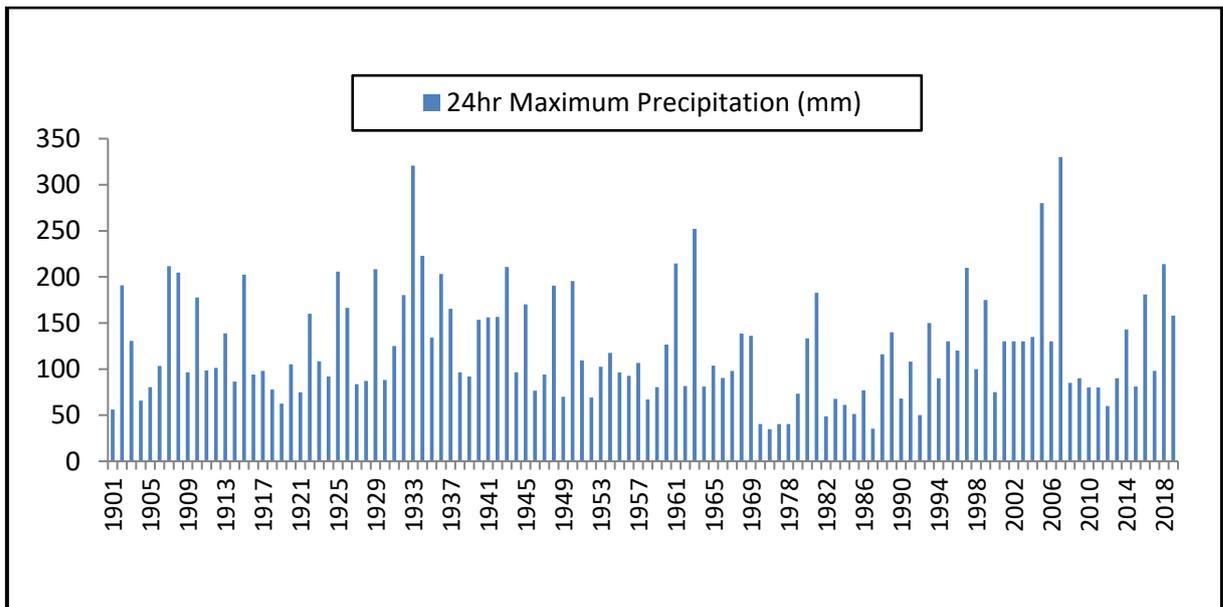
296

297 3.1 IDF curve for the Cuttack city

298

299 The analysis of the daily rainfall data of Cuttack city shows that rainfall exhibits high inter-annual
 300 variability. Between 1901 and 2019, the maximum daily precipitation varied from 35 millimetres
 301 (mm) to 330 mm (Figure 2). The variability in maximum daily precipitation as indicated by the
 302 coefficient of variation in rainfall was estimated to be 48%.

303



304

305 **Fig.2 Variation in daily maximum precipitation, Cuttack City**

306

307 *(Source: Authors analysis using data set from the Indian Meteorological Department and the*
 308 *website of Special Relief Commissioner, Govt. of Odisha)*

309

310 From the rainfall depths estimated using eq. (1), the rainfall intensity corresponding to different
 311 durations and their mean and standard deviation are provided in Table 1. The computed K_T values
 312 using eq. (2) for different return periods of rainfall are provided in Table 2.

313

314 **Table 1 Mean and standard deviation of rainfall intensity of different durations**

Rainfall Duration (hr)	1	2	6	12	24
Mean (mm/hr)	42.5	26.8	12.9	8.1	5.1
Standard Deviation	20.3	12.8	6.2	3.9	2.4

314

(Source: Authors own analysis)

315
316

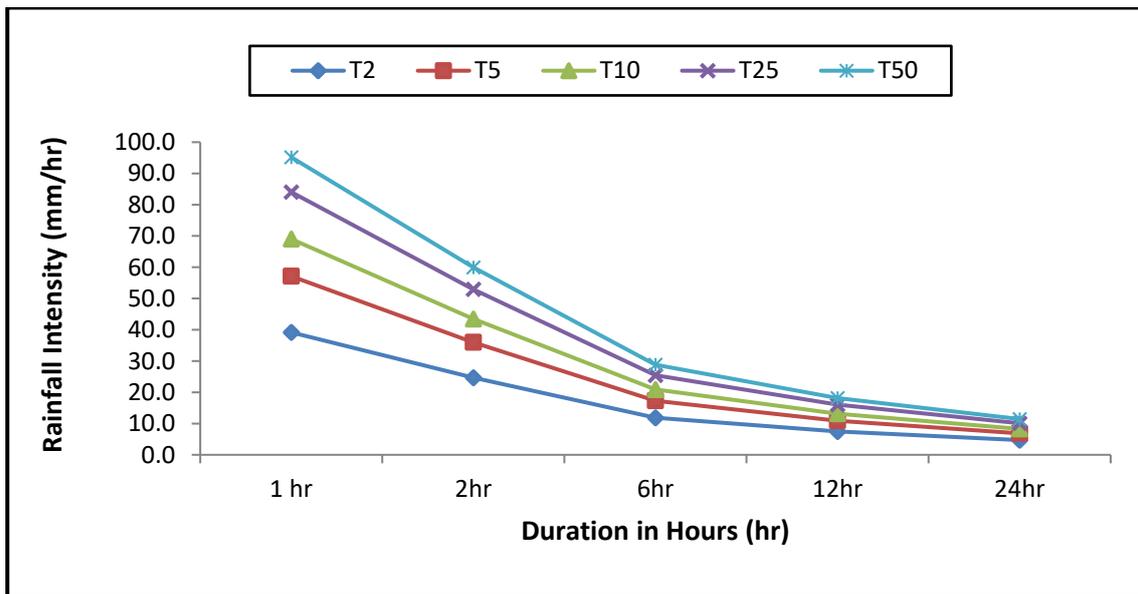
Table 2 K_T values for different return periods

Return Period (years)	2	5	10	25	50
K_T	-0.16	0.72	1.31	2.04	2.59

317 (Source: Authors own analysis)

318

319 The overall results using the estimates of rainfall intensity, duration, and frequency are presented in
320 an IDF curve (Figure 3). The analysis shows that every alternate year, a rainfall intensity of 39.2
321 mm/hr (considering rainfall of one-hour duration) can be expected. Every fifth year the rainfall
322 intensity increases to 57.1 mm/hr, and every tenth year to 69 mm/hr. The high one-hour rainfall
323 intensity of 84 mm/hr and 95.2 mm/hr is expected after every 25 and 50 years respectively.
324



325

326 **Fig.3 Intensity-Duration-Frequency curve for the Cuttack city**

327 (Source: Authors own analysis)

328

3.2 Estimated peak flood flow for the Cuttack city

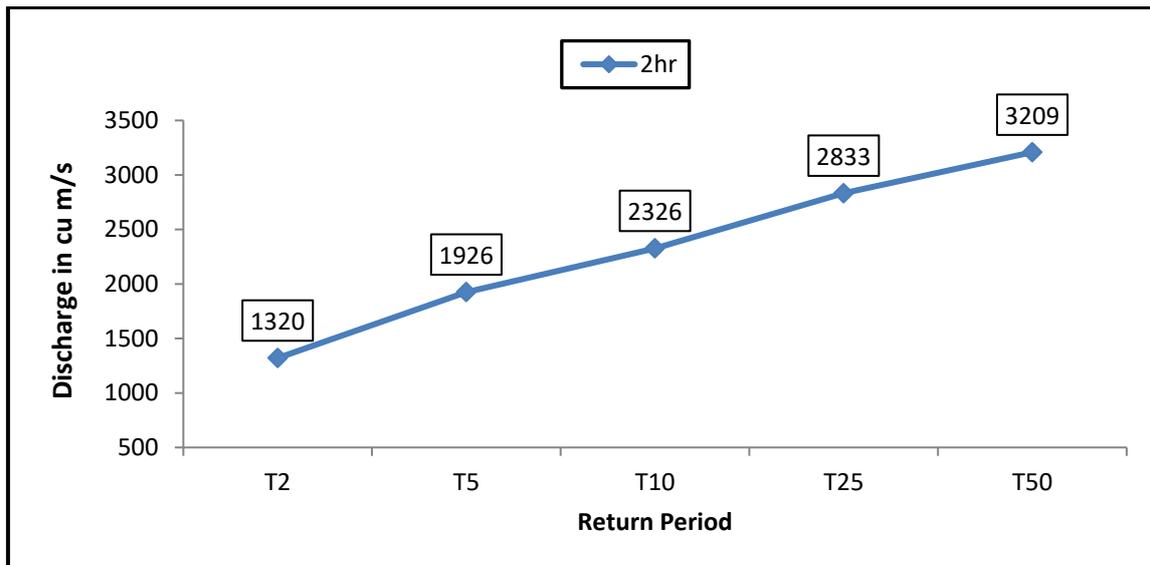
329

330 The time of concentration (T_C), using equation (5), was estimated at 155 minutes or 2.6 hours.
331 Since, T_C represents the time needed for water to flow from the most remote point in a watershed to
332 its outlet, rainfall intensity corresponding to a duration of 2 hours and return period of 2, 5, 10, 25,
333 and 50 years was considered for estimating the peak flood flow from the total catchment. The
334 entire city of Cuttack was considered as one watershed for the estimation.
335

336

337 The estimated peak flood flow for the entire city of Cuttack is presented in Figure 4. Every
338 alternate year a peak discharge of 1,320 cubic metres per second (cu m/s) is expected, while a very
339 high peak discharge of 3,209 cu m/s can be expected after every 50 years. This means that every
340 alternate year, a discharge of 7 cu m/s/km² and every 50 years 17 cu m/s/ km² of the catchment
341 area is expected in the city.
342

342



343 **Fig.4 Peak discharge with the return period for the Cuttack city**

344 (Source: Authors own analysis)

345
346
347 **3.3 Urban flood risk index**

348
349 An index for assessing the urban flood risk, including the three components of flood hazard,
350 exposure of the city to flood hazard, and vulnerability of the community to disruptions caused by
351 flood hazards are presented in Table 3. Overall 20 factors that influence risk associated with urban
352 floods were considered based on the framework discussed in section 2.3. Out of these, four factors
353 influence hazard, 10 factors influence exposure, and six factors influence vulnerability. Table 3
354 also provides the rationale for the selection of all the factors, and criteria used for assigning value
355 to them.

356
357 **Table 3 Urban flood risk index for coastal cities**

Key influencing factors	Rationale for selection	Criteria for assigning value to factors
Flood hazard		
1] Magnitude of annual rainfall of the area	Greater the frequency of occurrence of rainfalls of high magnitudes, higher the chances of occurrence of floods	A coefficient: ratio of no. of years in which rainfall exceeds 1,000mm, out of 10 years, divided by 10
2] Frequency of occurrence daily rainfall with magnitude exceeding 100mm	Greater the frequency of occurrence of rainy events of high magnitude (above 100mm), higher the chances of occurrence of floods	1 incident in 20 years = 0.10; 1 in 10 years = 0.25; 1 in 5 year=0.50; 1 in 3 years =0.60; once in two years=0.80; one or more than once in a year =1.0
3] Characteristics of land use	Higher the proportion of built-up area, the higher will be the runoff	A coefficient: ranging from '0' for all pervious area to '1' for fully built up area
4] Elevation with reference to the mean sea level (MSL)	If the area is located above MSL or HFL of the river, then surface drainage will not be problematic; if below, then the danger of flooding is very high	A coefficient: '0' if above MSL or HFL, and '1' if below MSL or HFL
Exposure of the city to flood hazards		
1] The presence of storm water drainage system in	The stormwater drainage systems can reduce the exposure of the	Binary coefficient: Yes='0'; No='1'

the locality	locality to the urban flood hazard to an extent	
2] Presence of natural drainage system in good condition	Presence of natural drainage system will also help evacuate the flood water from the locality	A coefficient: '0' if in good condition, otherwise '1'
3] Rainfall intensity for which the stormwater drainage system was designed against the intensity of rainfall of the standard return period for the area	If the rainfall intensity for the drainage system designed is less than the design storm, then the system will not be in a position to evacuate floodwaters that occur from rare events	A coefficient: Ratio of the design rainfall intensity and the rainfall intensity with a return period of 50 years, subtracted from '1'. If the ratio is more than '1', the value of the coefficient should be considered '0'
4] Type of sewerage systems in the locality	If the sewers are closed, then overflowing of sewers due to mixing of sewage with stormwater which contaminates the latter can be avoided	A coefficient: Open sewer= high exposure='1'; Sewer pipes = no exposure='0'.
5] Proportion of people who are dependent on common water points for municipal water supply	Exposure of drinking water to contaminants will be more in the case of common water points (standposts)	A coefficient: ratio of people dependent on common water points to total population having access to water sources
6] Proportion of people dependent on common toilets outside the premises or open defecation	During floods, access to common toilets located outside the dwelling premises will be restricted	A coefficient: ratio of people dependent on common toilets to total population having access to sanitation facilities
7] Proportion of people living in temporary structures in the locality	Temporary structures are likely to get damaged during floods and living in such buildings can expose people to hazards	A coefficient: ratio of people living in temporary structures to the total population
8] Presence of dilapidated buildings in the locality	Presence of dilapidated buildings will increase the overall exposure to hazards	A coefficient: ratio of dilapidated building to total number of building
9] Presence of high-risk power installations	Will increase the disruptions in movements of people, and vehicles due to the danger of electrocution	Binary coefficient: Yes='1'; No='0'
10] Level of transformers & sub-stations w. r. to High Flood Level (HFL)	If located below the HFL, it will increase the chances of disruptions in power supply to the locality	A coefficient: '0' If well above, '1' if below.
Vulnerability of the community to disruptions caused by flood hazards		
1] Proportion of people in the ward, living below poverty line	Poor people generally are more vulnerable to disruptions in life caused by natural hazards like floods	Coefficient: if there are no poor people, then the value of coefficient will be zero.
2] Provision for alternative power supply in case of 'power blackouts' due to floods	Access to alternate source of power supply will reduce the vulnerability to disruptions in power supply due to floods	Binary coefficient: Yes='0'; No='1'
3] Proportion of people having access to individualized sources of	Access to private and individual sources of water supply will reduce the vulnerability to	A coefficient: if no one, the value becomes '1'; if all households have, then the value will be taken

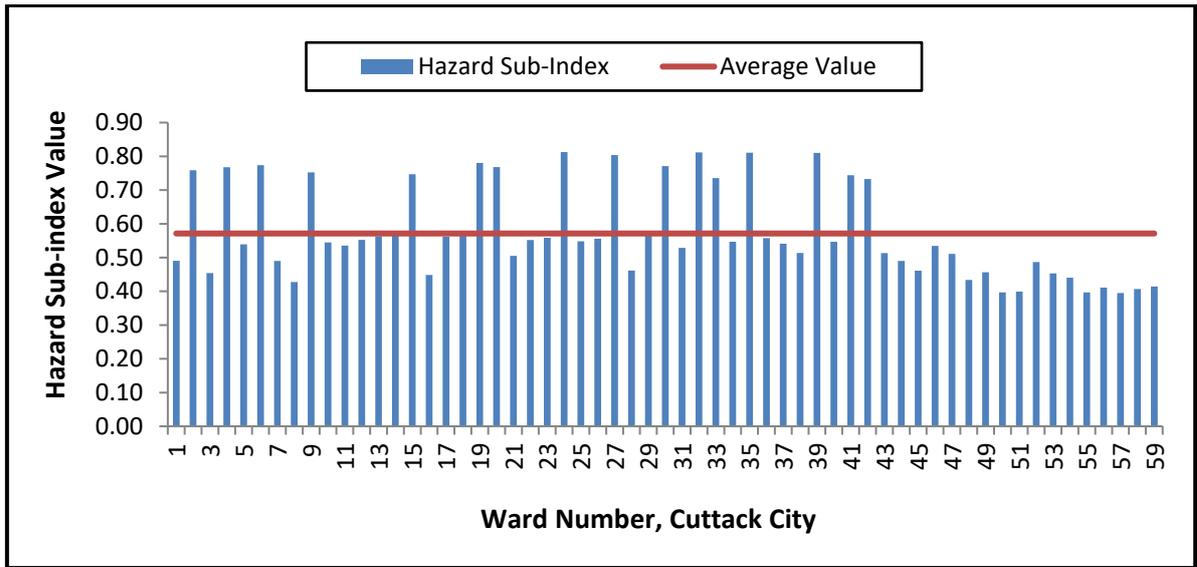
domestic water supply	disruptions in public water supply	as '0'
4] Ability of the Disaster Response Force (DRF) to reach the locality on time to undertake food-fighting operations	Experience shows that the DRF's ability to reach the affected areas for flood-fighting will reduce the impacts on life and properties	A coefficient: '0' if DRF is present and is able to access the locality; '1' if not present and also if present but unable to access
5] Availability of pumping machinery in the locality (ward) and boats	Availability of pumping machinery will increase the ability to fight localized flooding phenomena	A coefficient: '0' if adequate availability of boats and pumping machinery; '1' if completely absent
6] Population Density	Increase in population density will increase the chances of spreading of water-related diseases and vector borne diseases	A coefficient: ratio of the difference between population density of an administrative unit in the city (X) and the unit with the lowest population density (X_{MIN}), and the difference between the units with highest X_{MAX} and lowest population densities (X_{MIN})

(Source: Developed by Authors)

3.4 Urban flood risk in Cuttack city

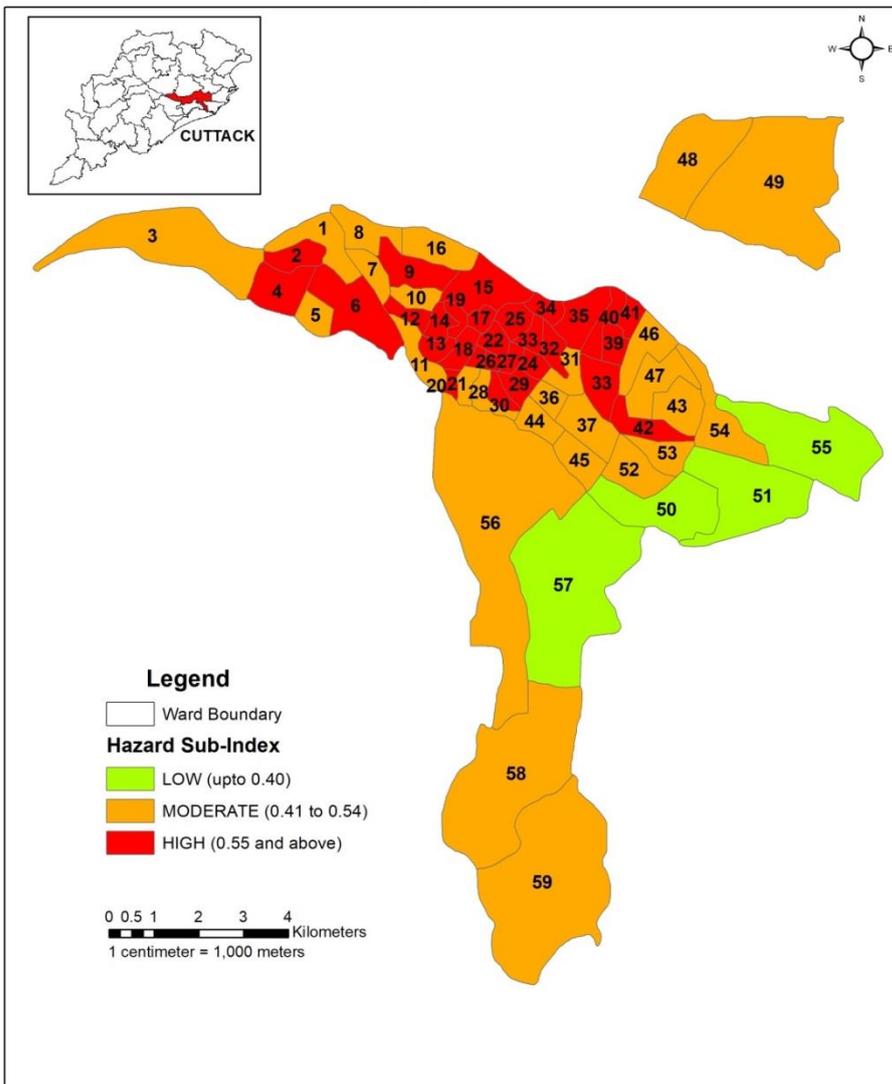
The average sub-index value of flood hazard is 0.57 for the Cuttack city, highest for ward number (no.) 24 (0.813), and lowest for ward no. 57 (0.39) (refer Figure 5). Since for two of the four parameters influencing the hazards, i.e., magnitude of the annual rainfall of the area and frequency of occurrence of daily rainfall with a magnitude exceeding 100 mm, all the wards are assigned the same value, the major difference is due to the characteristics of land use (extent of impervious area) and the elevation with reference to high flood level (HFL) of the river. For all the wards, the average annual rainfall was above 1000 mm in eight out of the last 10 years (2010-2019), and the daily rainfall exceeding 100 mm occurs after every 2.5 years (refer Figure 2).

The extent of built-up area is highest in ward no. 12, 13, 14, 17, 18, 22, 23, 24, 26, 27, 29, 32, 34, 35, and 39 (refer Figure 1). Out of these, ward no. 24, 27, 32, 35, and 39 are also the ones with low lying areas (w.r.t. to the HFL). Thus, the hazard sub-index value is among the highest for these wards. It was 0.804 for ward no. 27, 0.811 for both ward no. 35 and for 39, 0.812 for ward no. 32, and 0.813 for ward no. 24. Thus, these five wards are the ones that are expected to generate surplus runoff and to be worst affected during an intense storm. Overall, 4 wards are categorised under low, 26 wards under moderate, and 29 wards under high flood hazard (Figure 6).



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Fig.5 Hazard sub-index value of different wards in Cuttack city
(Source: Authors' computation)



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384

Fig.6 Categorisation of CMC wards as per the urban flood hazard sub-index

385 (Source: Map developed by Authors)

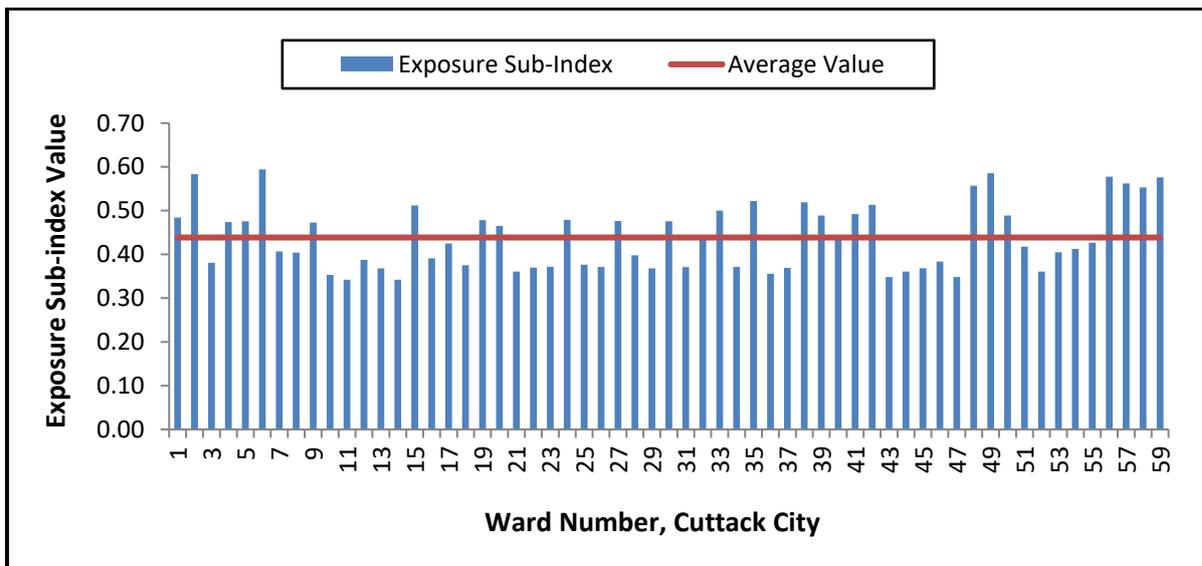
386

387 The sub-index for exposure has an average value of 0.44 for the city, with ward no. 6 having the
388 highest (0.59) and wards no. 11 and 14 having the lowest values (each having 0.34) (refer Figure
389 7). Out of the 10 key parameters influencing the exposure of the city to flood, for three parameters,
390 all wards have the same score. These parameters are: the condition of the natural drainage system
391 that is poor in all the wards; the high risk power installations (high tension power line) that are
392 present in all the wards; and, the stormwater drainage system that is designed for 8 mm rainfall for
393 all the wards. However, the stormwater drainage system was absent in 11 wards, these include
394 ward no. 1, 2, 5, 6, 48, 49, 50, 56, 57, 58, and 59.

395

396 In 45 wards, more than 50% of the existing sewerage system is open. It is more than 75% in 12
397 wards that include wards no. 7, 28, 48, 49, 51, 53, 54, 55, 56, 57, 58, and 59 (most of the wards in
398 city fringes). Out of these, in ward no. 56, 57, 58, and 59 (all in city fringe area) more than 40% of
399 the population access community toilets and/or practice open defecation. Also, in these four wards,
400 more than 30% of the population access water from the common water supply points. Further, the
401 proportion of people living in temporary structures varies from only 0.36% in ward no. 9 and
402 34.4% in ward no. 38. Also, ward no. 38 is the one with the highest percentage of dilapidated
403 buildings (20.2%).

404



405

406

Fig.7 Exposure sub-index value of different wards in Cuttack city

407

(Source: Authors' computation)

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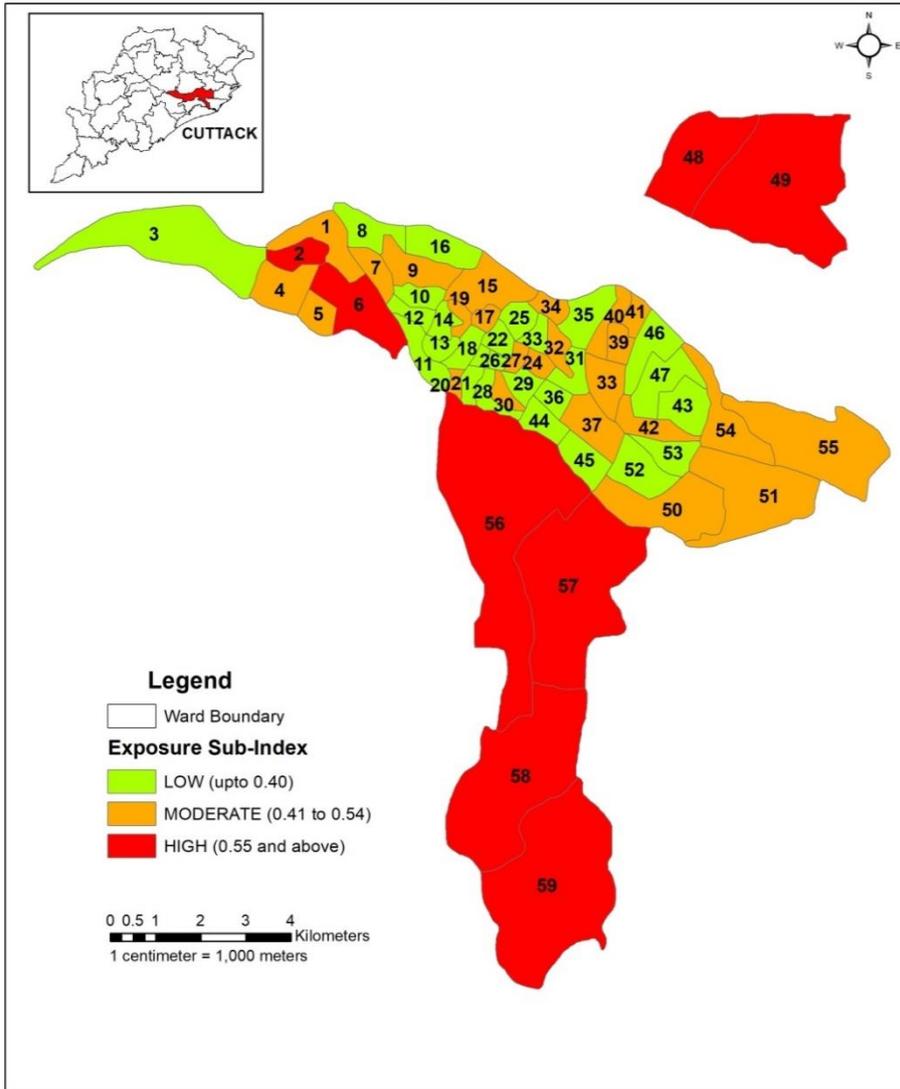
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417

The sub-index value is above 0.55 for the eight wards, i.e., ward no. 58 (0.553), 48 (0.557), 57 (0.562), 59 (0.576), 56 (0.577), 2 (0.583), 49 (0.585), and 6 (0.594). All these wards are with no stormwater drainage system and have a substantial open sewerage system, increasing exposure of the locality in these wards to the urban flood hazard. Further, in ward no. 56, 57, 58, and 59, a high proportion of the people do not have access to improved water and latrine facilities that increase their exposure to poor quality water, leading to adverse impacts on health. Overall, 27 wards are categorised under low, 24 wards under moderate, and 8 wards under high exposure in case of the flood hazard (Figure 8).



418
419 **Fig.8 Categorisation of CMC wards as per the urban flood exposure sub-index**
420 (Source: Map developed by Authors)
421

422 The vulnerability sub-index average value for the city is 0.46, highest for ward no. 20 (0.65) and
423 lowest for ward no. 59 (0.30) (refer Figure 9). Out of the six parameters that were considered, two
424 variables had the same score. These include provision for alternative power supply during floods
425 (that was not there in any of the wards) and the ability of the district response force to reach the
426 wards on time to undertake flood fighting operations. Further, the pumping machinery to drain
427 flood water was available on almost all the wards (except for wards no. 2, 4, 5, 6, 20, and 32).
428 However, the provision of boats to evacuate people stuck during floods was not available with any
429 of the wards.

430
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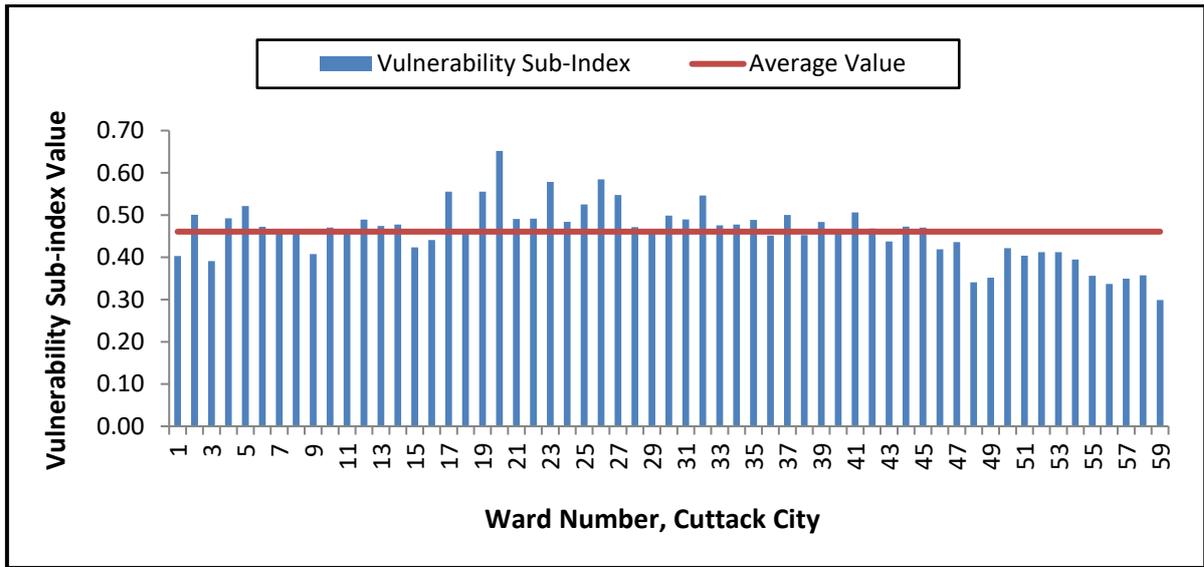
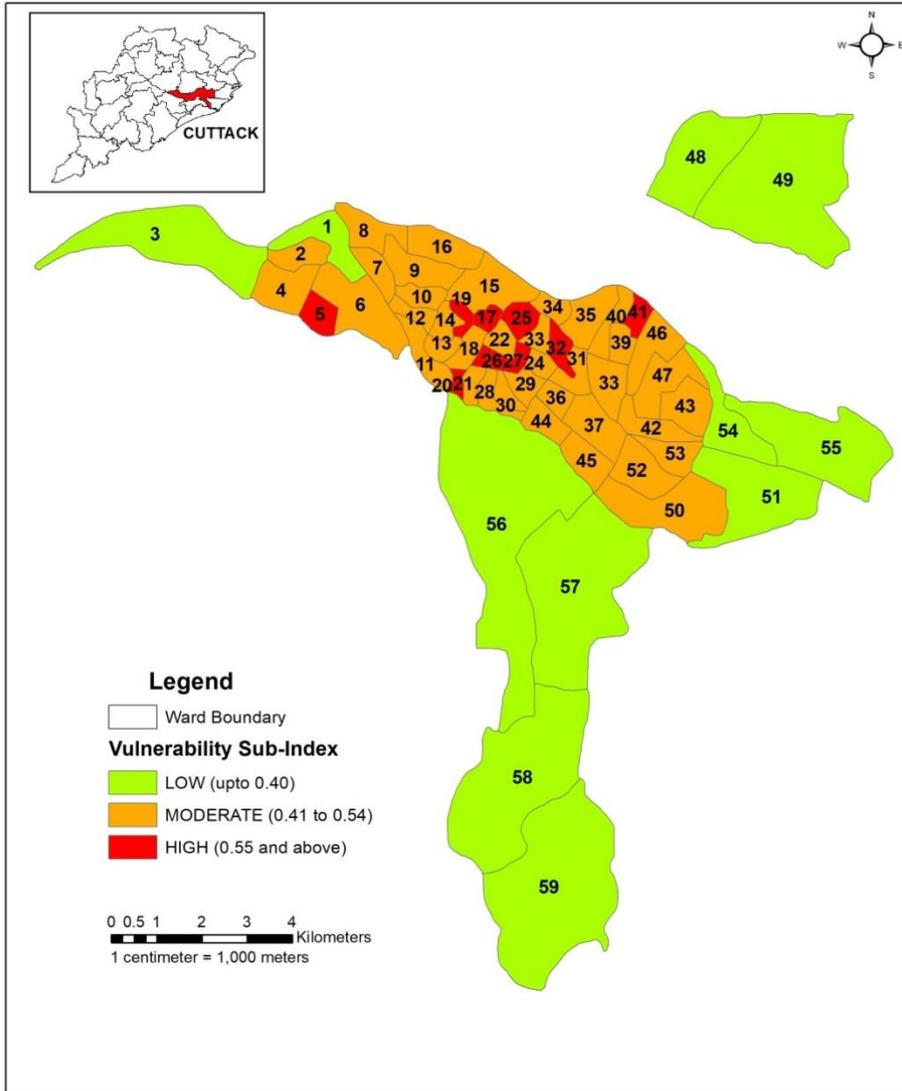


Fig.9 Vulnerability sub-index value of different wards in Cuttack city
 (Source: Authors' computation)

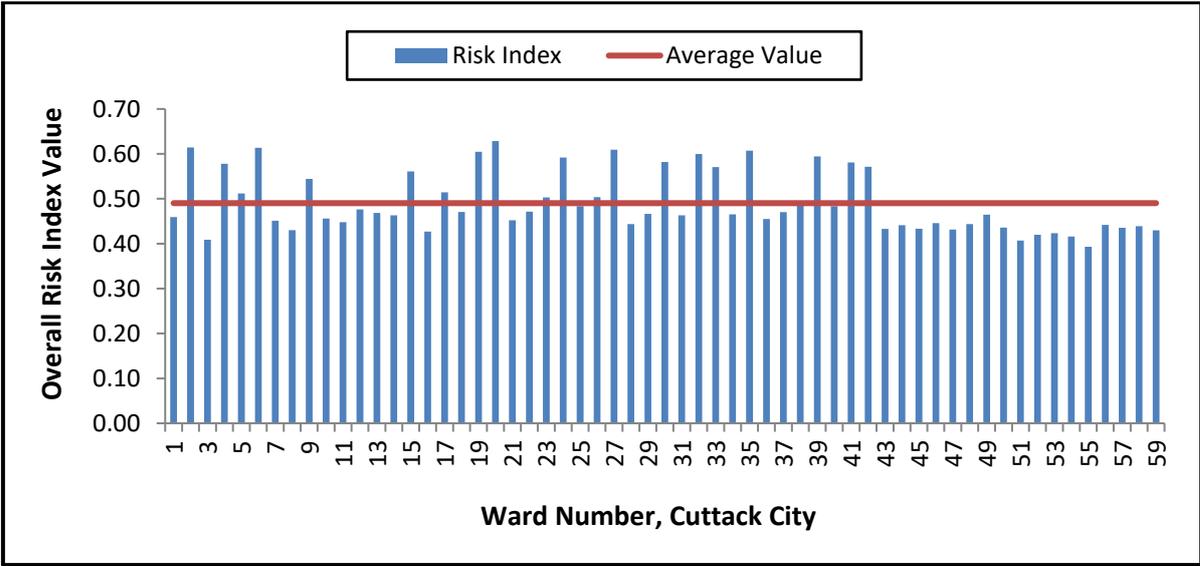
The other main factors influencing the vulnerability of the community to flood hazard are the proportion of poor people, i.e., people living below the poverty line (estimated by considering the slum population), and the population density of the wards. The population density was high in the wards falling in city core areas (no. 17, 19, 20, 23, 26, 27, and 30) and low in the wards towards the city fringes (no. 3, 48, 49, 50, 51, 55, 56, 57, 58, and 59). However, ward no. 17, 25, 38, 55, 56, 57, and 58 (a mix of those in core and city fringes) are the ones with more than 40% of the population living in slums.

A high population density and a large proportion of the population living in slums increase the chances of spreading of water-related diseases and vector-borne diseases. Considering the scores on these variables, the vulnerability of five wards, i.e., no. 17 (0.555), 19 (0.556), 23 (0.579), 26 (0.585), and 20 (0.652), is among the highest. Overall, 11 wards are categorised under low, 41 wards under moderate, and only 7 wards under high vulnerability (Figure 10).



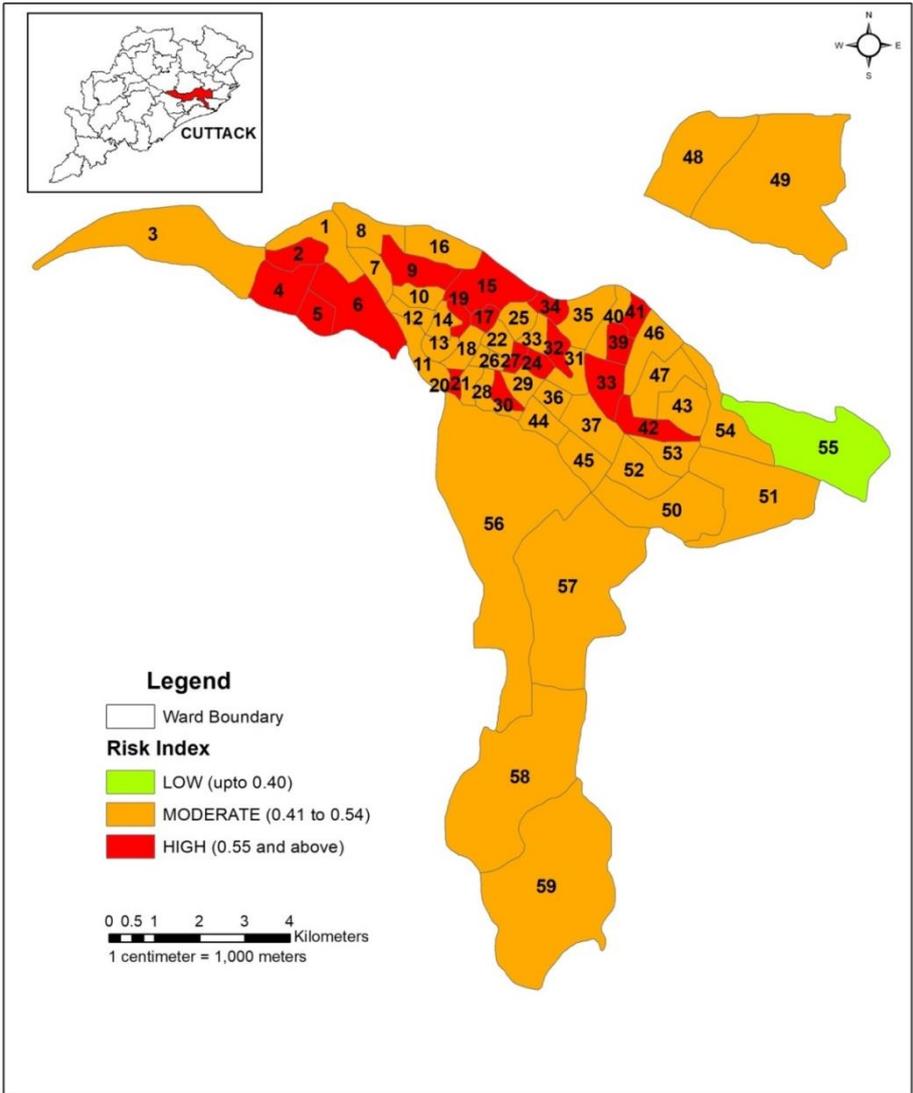
451
452 **Fig.10 Categorisation of CMC wards as per the flood hazard vulnerability sub-index**
453 (Source: Map developed by Authors)

454
455 The city level average value for the urban flood risk index is 0.49, with the highest value for ward
456 no. 20 (0.63) and lowest for ward no. 55 (0.39) (refer Figure 11). Overall, risk index is high (value
457 0.55 and above) for 15 wards, i.e., no. 2, 4, 6, 15, 19, 20, 24, 27, 30, 32, 33, 35, 39, 41 and 42, most
458 of them in the city core area (refer Figure 1). These are the wards with high urban flood hazard and
459 where the vulnerability of the community to disruptions in urban services caused by flood hazards
460 is also high (refer Figure 6 and 10). Only ward no. 55 has low risk (index value up to 0.40).
461 Though a large number of wards (43 in total) fall in the moderate risk category, some of these
462 wards in the city fringes (especially wards no. 48, 49, 56, 57, 58, and 59) have a high degree of
463 exposure to flood hazards (Figure 12).



464
465
466
467

Fig.11 Overall flood risk index of different wards in Cuttack city
(Source: Authors' computation)



468
469

Fig.12 Categorisation of CMC wards as per the flood hazard risk index

470 (Source: Map developed by Authors)

471

472 **4 Discussions**

473

474 **4.1 Factors responsible for high urban flood risk in different wards of Cuttack city**

475

476 Concerning the hazard component, all the wards with greater frequency of occurrence of rainfall
477 (annual and daily) of high magnitude, high proportion of impervious area, and presence of low
478 lying areas are expected to receive floods more frequently than the other wards. The built-up area
479 is more than 70% in wards in the core of the city (refer Figure 1).

480

481 For the exposure component, the wards that lack stormwater drainage systems, have a substantial
482 proportion of open sewerage systems, and have a high proportion of the people without any access
483 to improved water and latrine facilities are at greater exposure to the urban flood hazard. Even the
484 wards that have a stormwater drainage system, the design capacity (8 mm) is inadequate to capture
485 the peak flood flow (60 mm for rainfall with a return period of 50 years). Further, none of the
486 wards have a natural drainage system in good condition that increases exposure to floods.

487

488 Regarding the vulnerability component, high population density and a large proportion of the
489 population living in slums (poor people) were the two major factors identified for increasing the
490 vulnerability of the community to flood hazards as they increase the chances of spreading water-
491 related diseases and vector-borne diseases. The ward-level highest population density was 69,051
492 persons/sq. km (based on data presented in GoI 2011 and CMC 2020) and it is expected to increase
493 further in all the wards. Further, about 21% of the total population lives in slums at present (CMC
494 2020).

495

496 Thus, the risk-based assessment of floods in Cuttack city highlights that the stormwater drainage
497 system is unable to handle severe floods that occur once in 20 or 50 years. Further, with major
498 developments happening in the city with the growth of urban infrastructure, and the city becoming
499 densely populated, the current capacity of the stormwater drainage system becomes inadequate.
500 However, replacing the existing stormwater drainage system with a new one with higher capacity
501 or strengthening the existing stormwater drainage network in areas where nothing existed may not
502 be feasible. So, options to reduce the stormwater runoff generation need to be explored. Further,
503 the city, being located in the delta of two rivers, poses challenges when it comes to draining out the
504 collected stormwater. So there have to be specific interventions to drain out the water, along with
505 strengthening the natural drainage system.

506

507 **4.2 Institutional capacity available for fighting urban floods in Cuttack city**

508

509 At the state (province) level, Odisha State Disaster Mitigation Authority (OSDMA) prepares
510 response to various natural disasters including cyclones and floods. Also, there is a State
511 Emergency Operations Centre (SEOC) that coordinates with OSDMA and provides support to
512 other key disaster management agencies (identified by the OSDMA) in the event of a major
513 disaster. At the district level, the Collector/District Magistrate (DM) is the head of the district
514 disaster management cell and is in-charge of disseminating warnings and coordinating disaster
515 events for the whole district. At the city level (like Cuttack), the Municipal Commissioner (MC) is
516 a supervising authority for preparing response during a natural disaster. In Cuttack city, the office
517 of the MC is assisted by the officers from other line departments in the city, including water
518 resources, power, transport, Public Health Engineering Organisation (PHEO). For preparing an
519 effective response and ensure coordination with all the agencies involved, a Control Room is set up
520 in the MC's office. All the complaints during a disaster, for instance on water logging, choking of
521 drains, fallen trees, road culvert damages, etc. are received and registered by the Control Room.
522 The Deputy Municipal Commissioner's office is responsible for checking the complaints registered

523 daily and disseminate the information to the relevant agencies for them to undertake corrective
524 measures.

525

526 Further, the Cuttack Municipal Corporation (CMC) has prepared a City Disaster Management Plan
527 (CDMA) under a project on ‘Developing Resilient Cities through Risk Reduction in the context of
528 Disaster & Climate Change’. It acts as a guidebook for the city administration and concerned
529 stakeholders to prepare, plan, and prevent disasters along with the relief, rehabilitation, and
530 reconstruction post-disaster. Also, there is an ongoing Japan International Cooperation Agency
531 (JICA) assisted ‘Odisha Integrated Sanitation Improvement Project’ under which two main water
532 drains in the city are being renovated and rehabilitated. The objective is to modify the existing two
533 main drains to reduce the volume and duration of flooding for the two year design storm. However,
534 the progress in certain specific stretches is slow as the areas around the main drains (especially
535 main drain 1 that passes through the city core) are encroached and densely populated.

536

537 However, the CMC has not explored new methods of stormwater management that apply the
538 emerging concepts in integrated stormwater management, particularly the structural and non-
539 structural measures aimed at controlling floods. As a result, all the city wards (except one) are in
540 the moderate to a high flood risk category (refer Figure 12). In this context, the risk-based approach
541 to flood assessment as developed and discussed in this research study can be of major support to
542 the CMC.

543

544 **4.3 How a risk-based approach can improve flood management in coastal cities**

545

546 The coastal cities present a unique challenge to the design of stormwater drainage systems. Such
547 areas are vulnerable to the effects of tides, have high groundwater table, and relatively flat terrain
548 conditions that presents little scope for swift drainage or natural storage of flood waters. While
549 during high tides, low lying areas get inundated making disposal of stormwater difficult, during
550 intense storms, the discharge of stormwater through drains is ineffective (due to backflow of water
551 from the river/sea) resulting in water logging and flooding.

552

553 Risk-based assessment framework for urban floods, as demonstrated for a coastal city, help
554 identify the areas that need priority action, and also provide insights into the key physical, social,
555 economic, and institutional factors, which need to be altered through various interventions in
556 regions/zones identified as having ‘high risk’, to reduce the three different dimensions of climate
557 induced risk and to improve the climate-resilience of the coastal cities. The framework will help
558 guide the preparation of the Integrated Stormwater Management Plan focusing on the approaches
559 that would help reduce the flood risk; exposure of the assets, services, and properties to the flood;
560 and to an extent the steps that would reduce the vulnerability of the population.

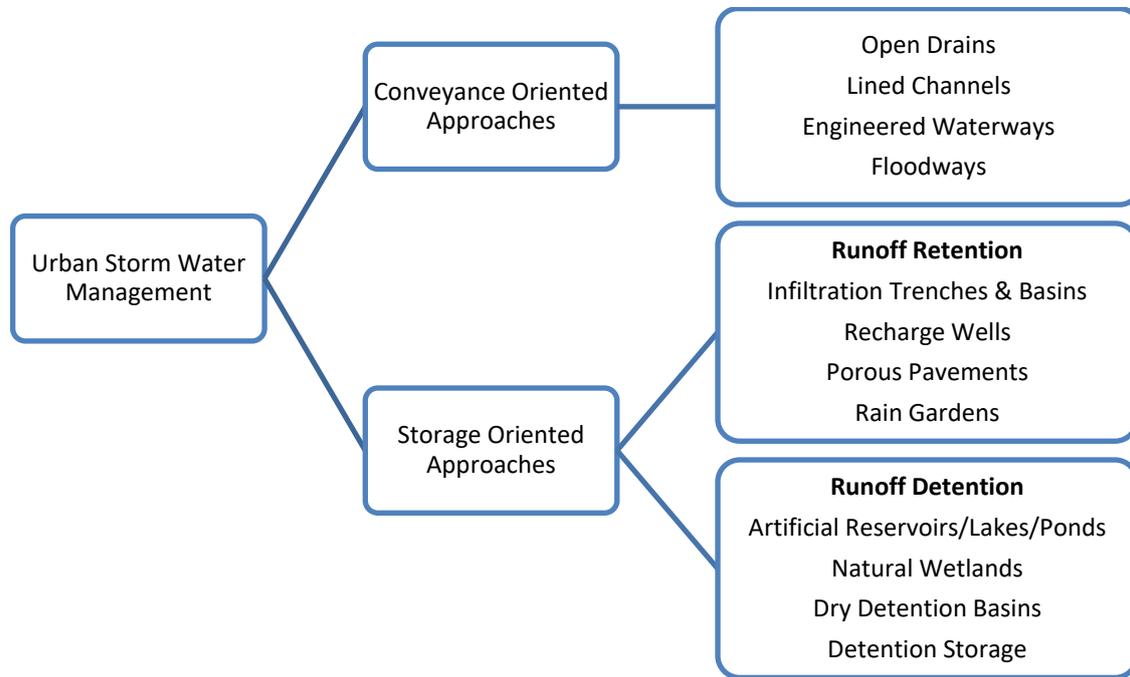
561

562 As per the results from the computation of the urban flood risk index, both structural and non-
563 structural measures can be prioritised to manage stormwater. The structural measures are both
564 conveyance-oriented and storage-oriented. While the objective of the conveyance approaches is to
565 collect runoff generated by storm and its rapid conveyance to the point of discharge (river or sea)
566 thus minimising damage, the storage approaches focus on providing temporary storage of
567 stormwater runoff and subsequently slow release to the receiving water body (detention), or
568 infiltration into the surrounding soil (retention) (Figure 13). Non-structural measures usually focus
569 on capacity building at the institutional level, e.g., setting or strengthening early warning flood
570 systems; implementing land use regulations; designing and building climate-resilient water supply
571 infrastructure; and educating the masses about precautions to be exercised during disasters.

572

573 As demonstrated through the risk-based assessment approach, the integrated stormwater
574 management solutions that work for an area, however, would be dependent on a range of natural
575 (climatic, rainfall, soils, and geohydrology), physical factors (natural drainage system, the drainage

576 infrastructure and extent of built-up area in the city) and the institutional capacity available for
 577 planning, designing, and managing stormwater management systems.
 578
 579



580
 581
 582 **Fig.13 Various structural approaches to stormwater management**
 583 *(Source: Based on the Government of Malaysia 2011)*
 584

585 **5 Conclusions and Policy Implications**

586
 587 Given the frequent occurrence of climate related disasters such as floods in many of the coastal
 588 cities in the developing world, an index for assessing urban flood risk was developed and
 589 computed for the city of Cuttack in eastern India. The developed urban flood risk index consists of
 590 20 key natural, physical, social, and economic influencing variables that are organised into three
 591 sub-indices (hazard, exposure, and vulnerability). The flood risk assessment for Cuttack city shows
 592 that 15 wards (25% of the total wards in the city) are at high risk from the urban flood and 43
 593 (73%) are at moderate risk. Only one ward, i.e., 55, is at low risk. The flood hazard is moderate to
 594 high for 93% wards, exposure to flood hazard is moderate to high for 54% wards, and the
 595 vulnerability of the community is ‘moderate to high’ in 81% of the wards.

596
 597 Further, the institutional capacity in terms of human resources and infrastructure to manage urban
 598 floods is inadequate in the city. Also, the design capacity of the secondary and tertiary stormwater
 599 drainage system is insufficient (8 mm against a 2 hourly rainfall intensity of about 60 mm for a 50-
 600 year return period), the natural drainage system is in the poor condition due to encroachments and
 601 a high proportion of the built-up area in the city core area. Also, replacing the existing stormwater
 602 drainage system with a new one with higher capacity, or strengthening the existing stormwater
 603 drainage network in areas where nothing existed may not be feasible, as has been experienced
 604 under the ongoing JICA assisted drains renovation project.

605
 606 The developed urban flood risk index can be used for other coastal cities for mapping urban flood
 607 risk. The approach will allow for the ranking of cities or pockets within cities in the order of risk
 608 posed by urban floods, thereby identifying priority areas where stormwater management measures
 609 are required.

610

611 **Declarations**

612

613 **Funding:** This paper is based on a research study that received financial support under the USAID,
614 the Ministry of Home Affairs (Government of India), and the UNDP partnership ‘Developing
615 Resilient Cities through Risk Reduction in the context of Disaster and Climate Change’.

616

617 **Conflicts of interest/Competing interests:** There is no conflict of interest.

618

619 **Availability of data and material:** Not applicable

620

621 **Code availability:** Not applicable

622

623 **Authors' contributions:** The research was conceptualized by Dr. M. Dinesh Kumar and Mr.
624 Manish Mohandas. Dr. M. Dinesh Kumar and Mr. Nitin Bassi developed the methodology for the
625 study. Data collection was undertaken by Dr. Saurabh Kumar and coordinated by Mr. Pradipta
626 Kumar Mohanty. Data were analyzed by Mr. Nitin Bassi. All authors contributed equally to the
627 writing of the paper.

628

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Figures

Built Up Area Classified Map Overlaid with Ward Boundary Cuttack City, Odisha

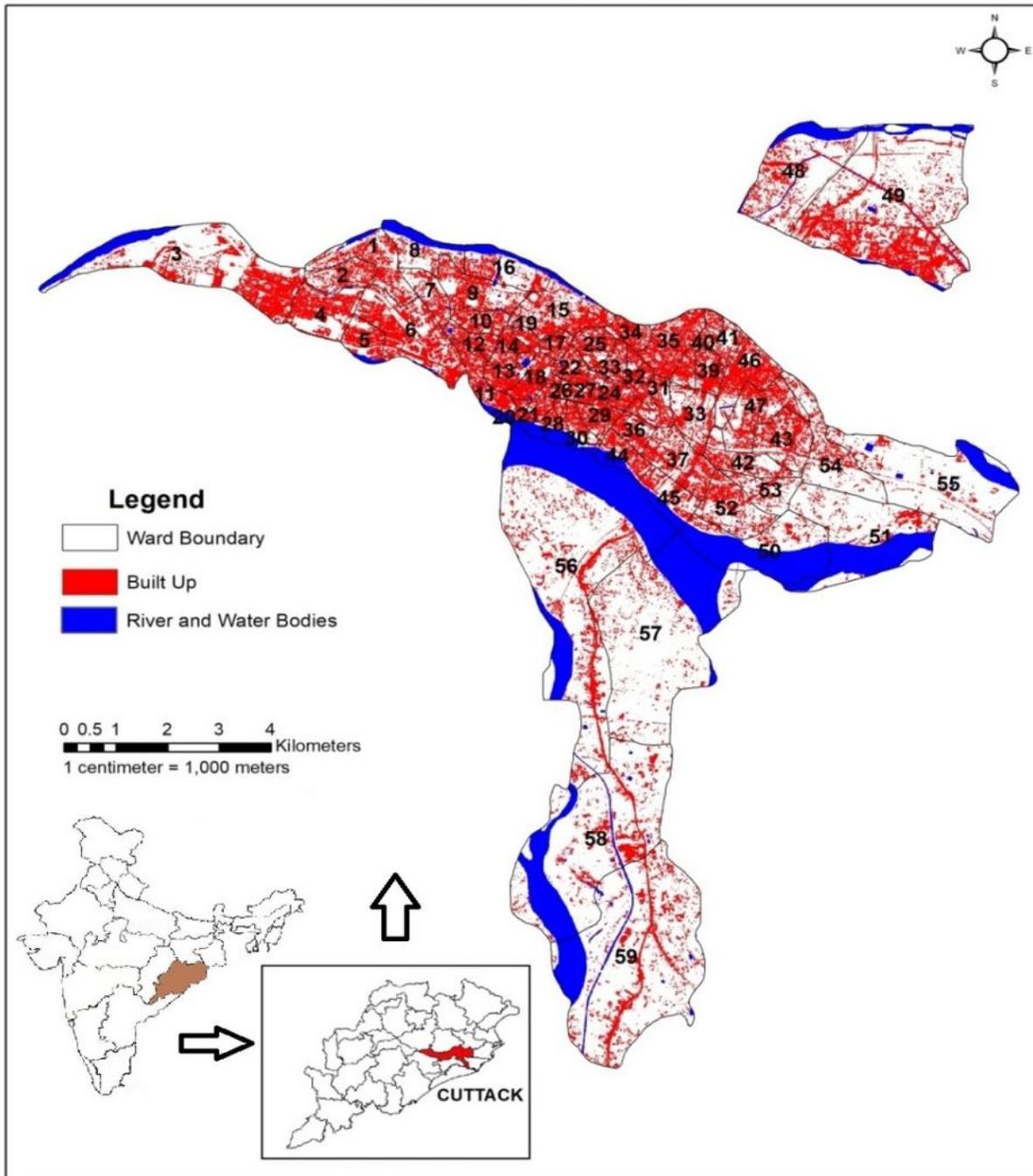


Figure 1

Map showing ward wise land use land cover of the Cuttack city (Source: Developed by authors) Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country,

territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

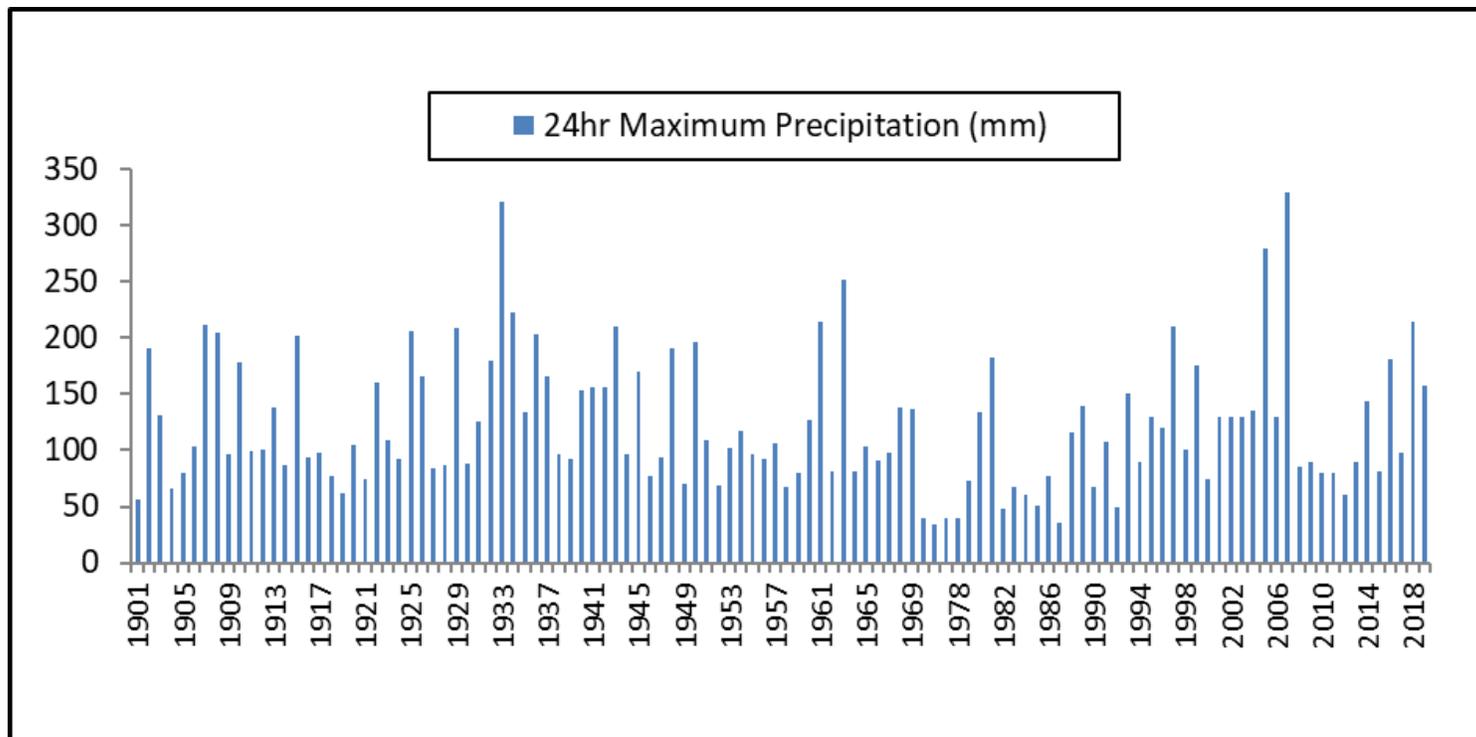


Figure 2

Variation in daily maximum precipitation, Cuttack City (Source: Authors analysis using data set from the Indian Meteorological Department and the website of Special Relief Commissioner, Govt. of Odisha)

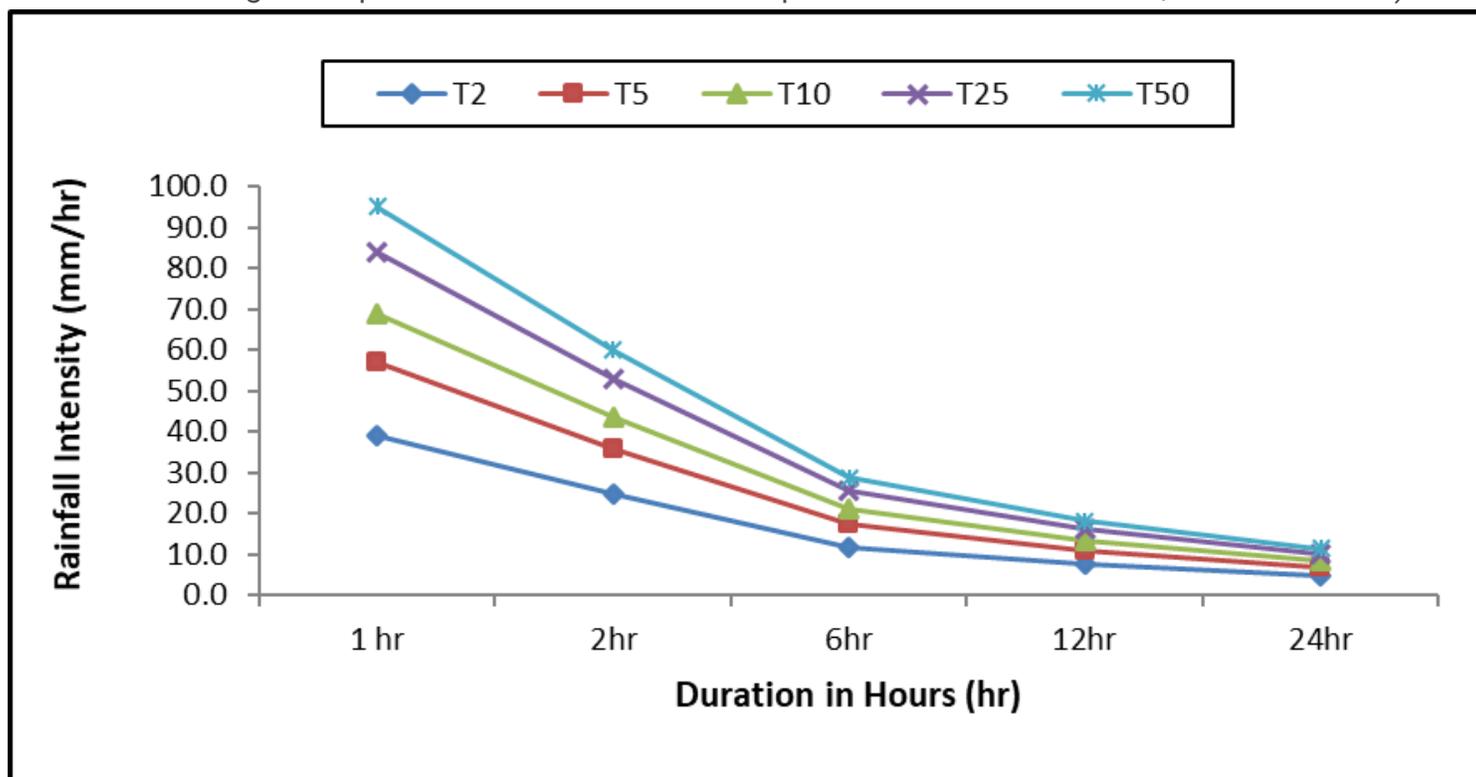


Figure 3

Intensity-Duration-Frequency curve for the Cuttack city (Source: Authors own analysis)

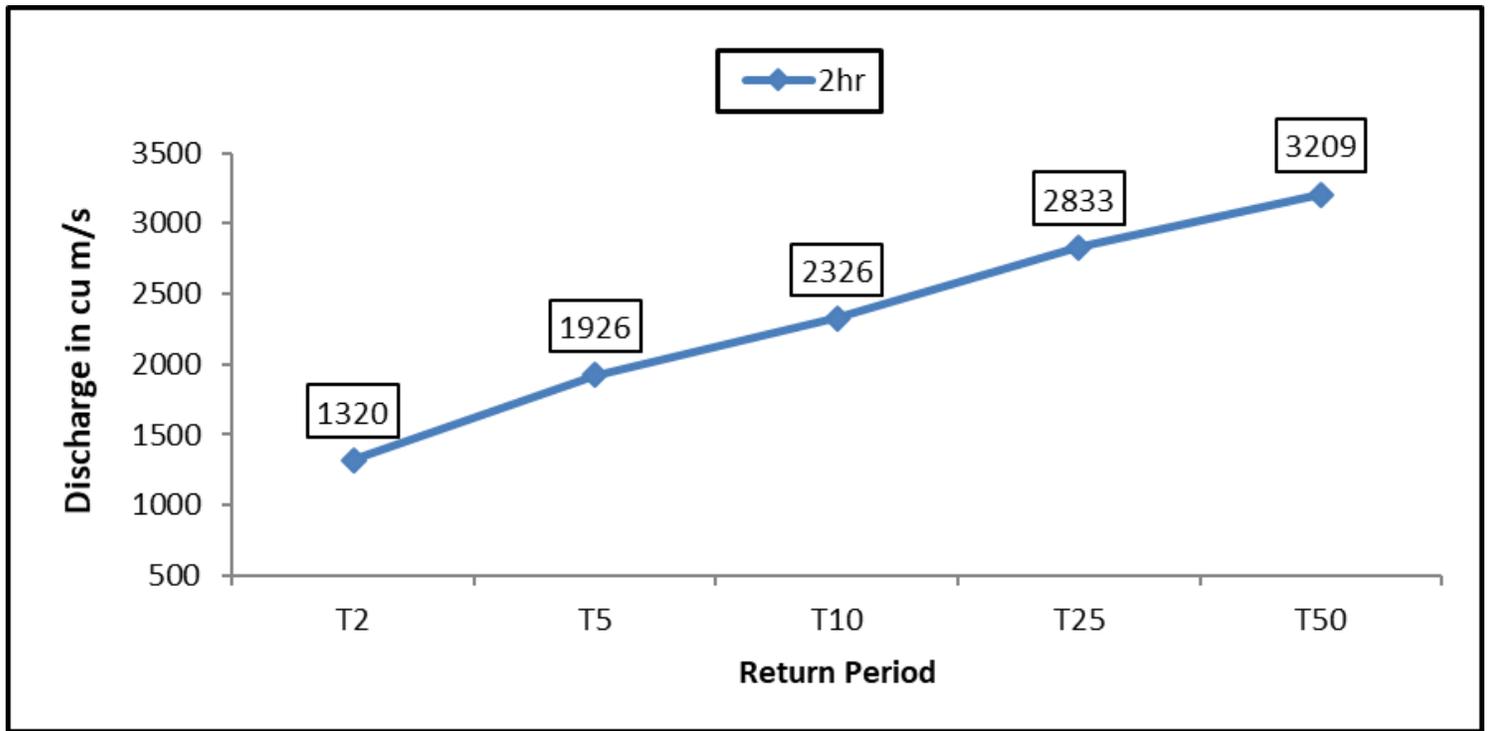


Figure 4

Peak discharge with the return period for the Cuttack city (Source: Authors own analysis)

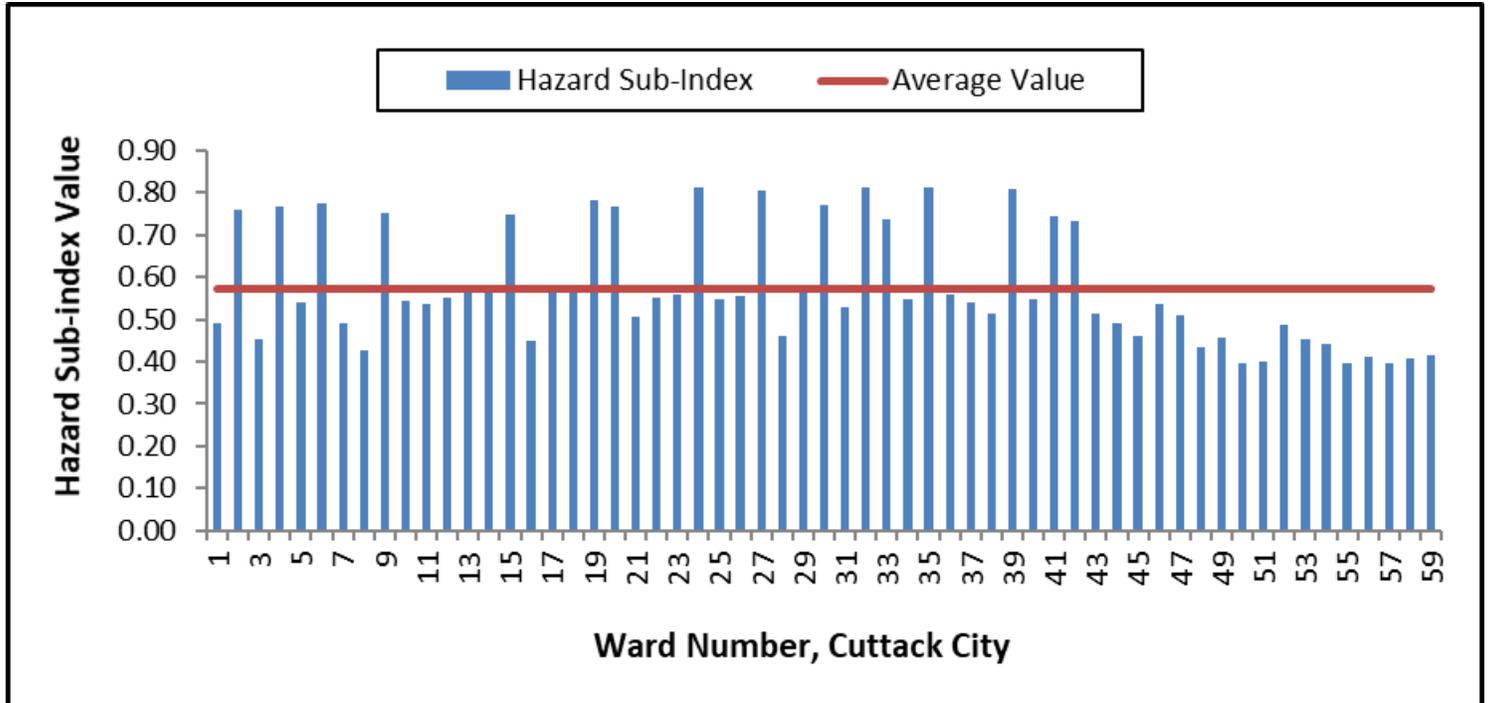


Figure 5

Hazard sub-index value of different wards in Cuttack city (Source: Authors' computation)

Urban Flood Hazard Sub-Index Map Cuttack City, Odisha

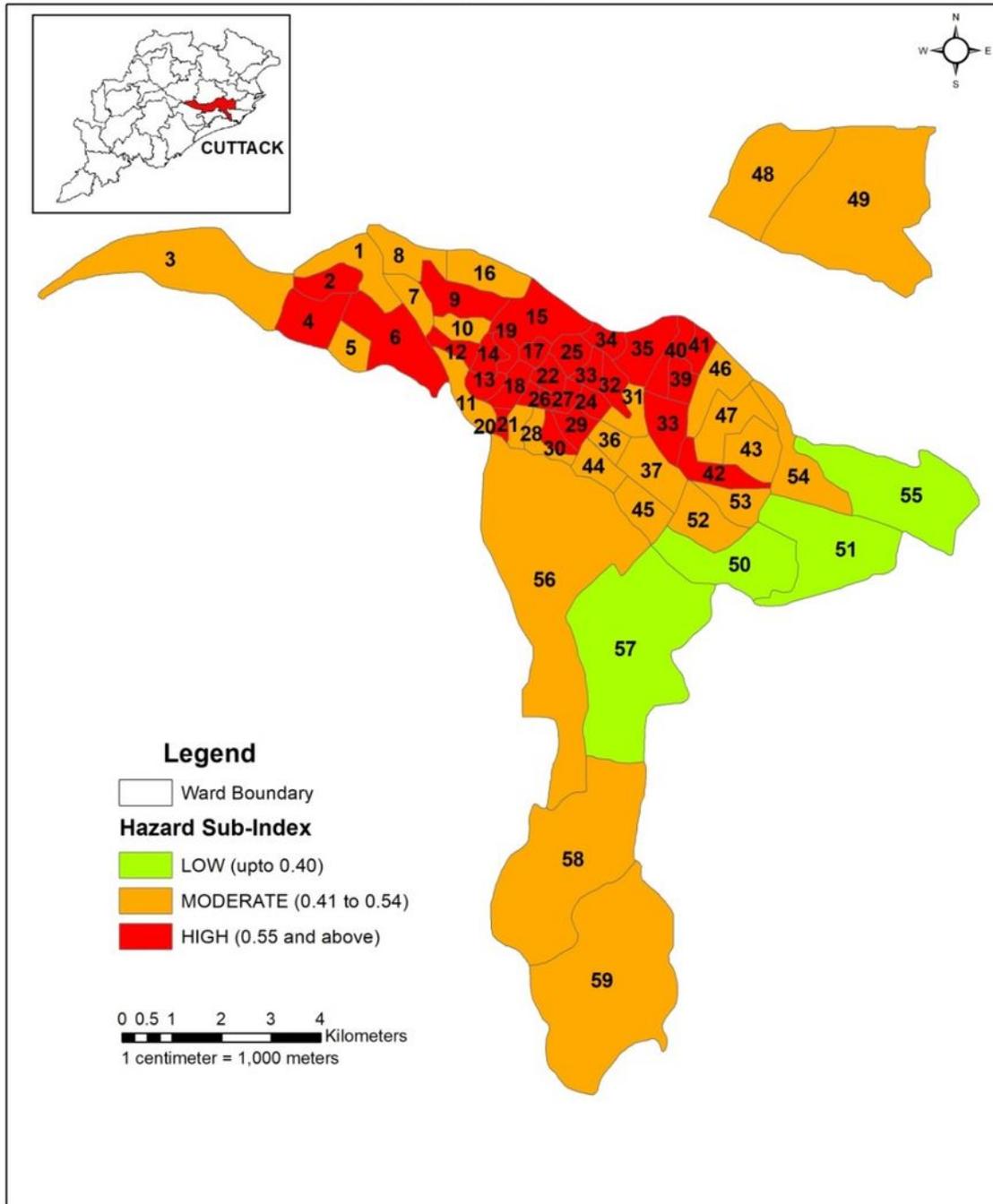


Figure 6

Categorisation of CMC wards as per the urban flood hazard sub-index (Source: Map developed by Authors) Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

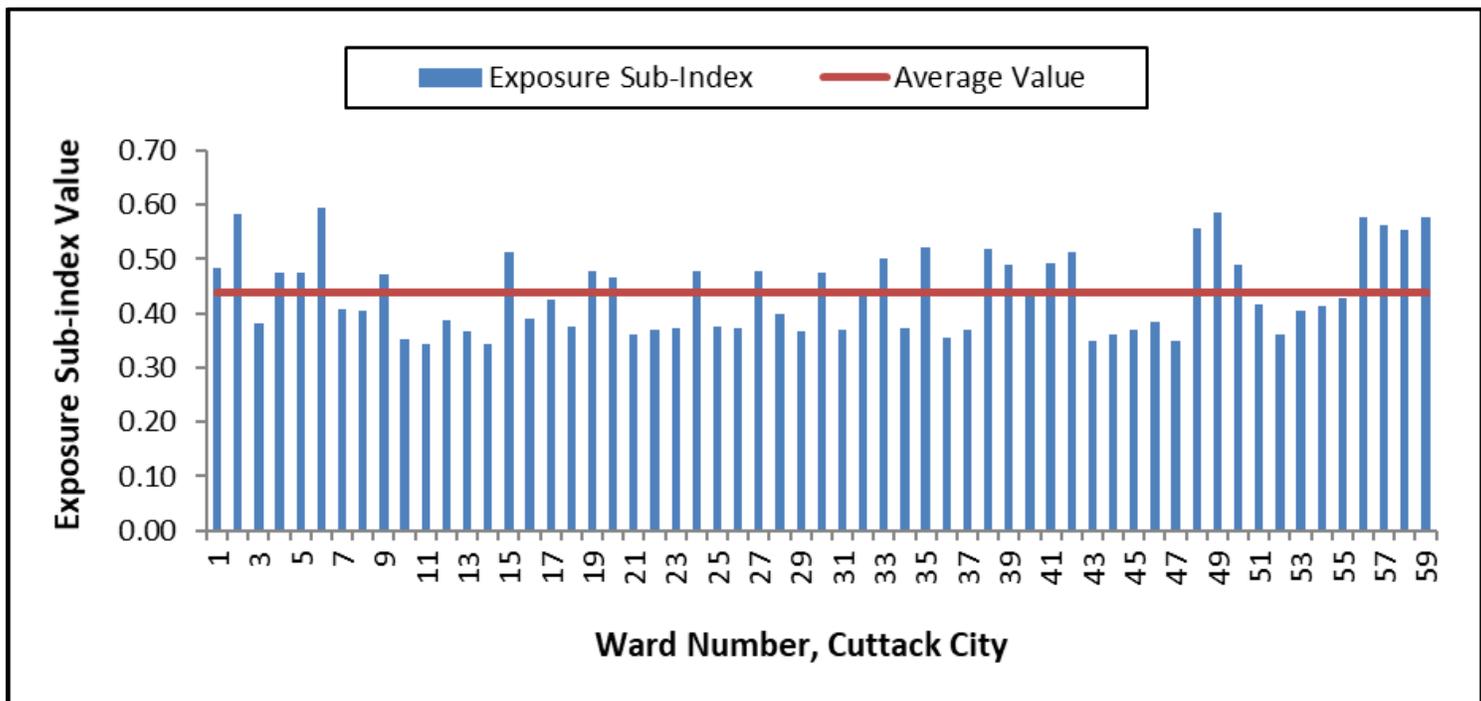


Figure 7

Exposure sub-index value of different wards in Cuttack city (Source: Authors' computation)

Urban Flood Exposure Sub-Index Map Cuttack City, Odisha

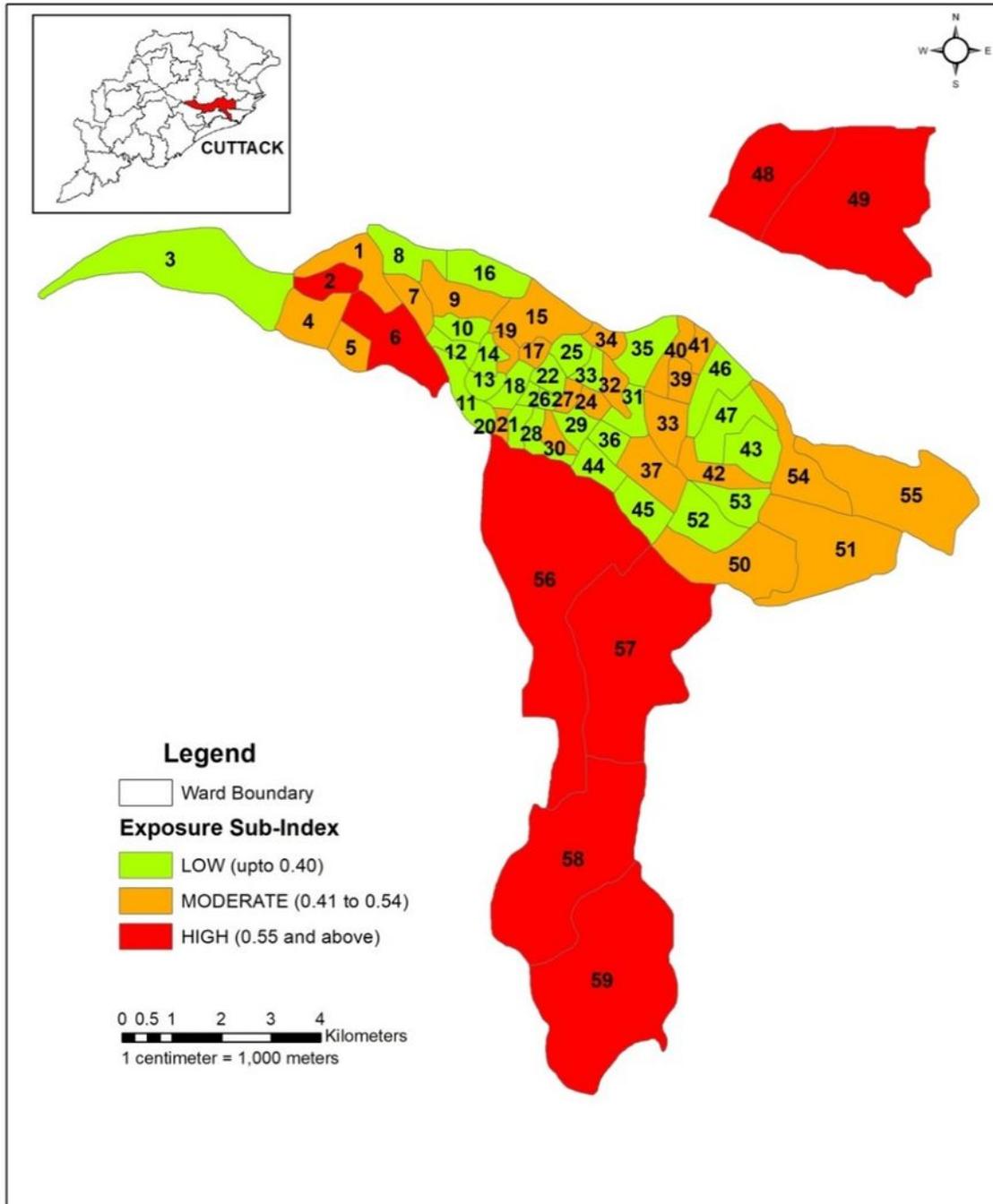


Figure 8

Categorisation of CMC wards as per the urban flood exposure sub-index (Source: Map developed by Authors) Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

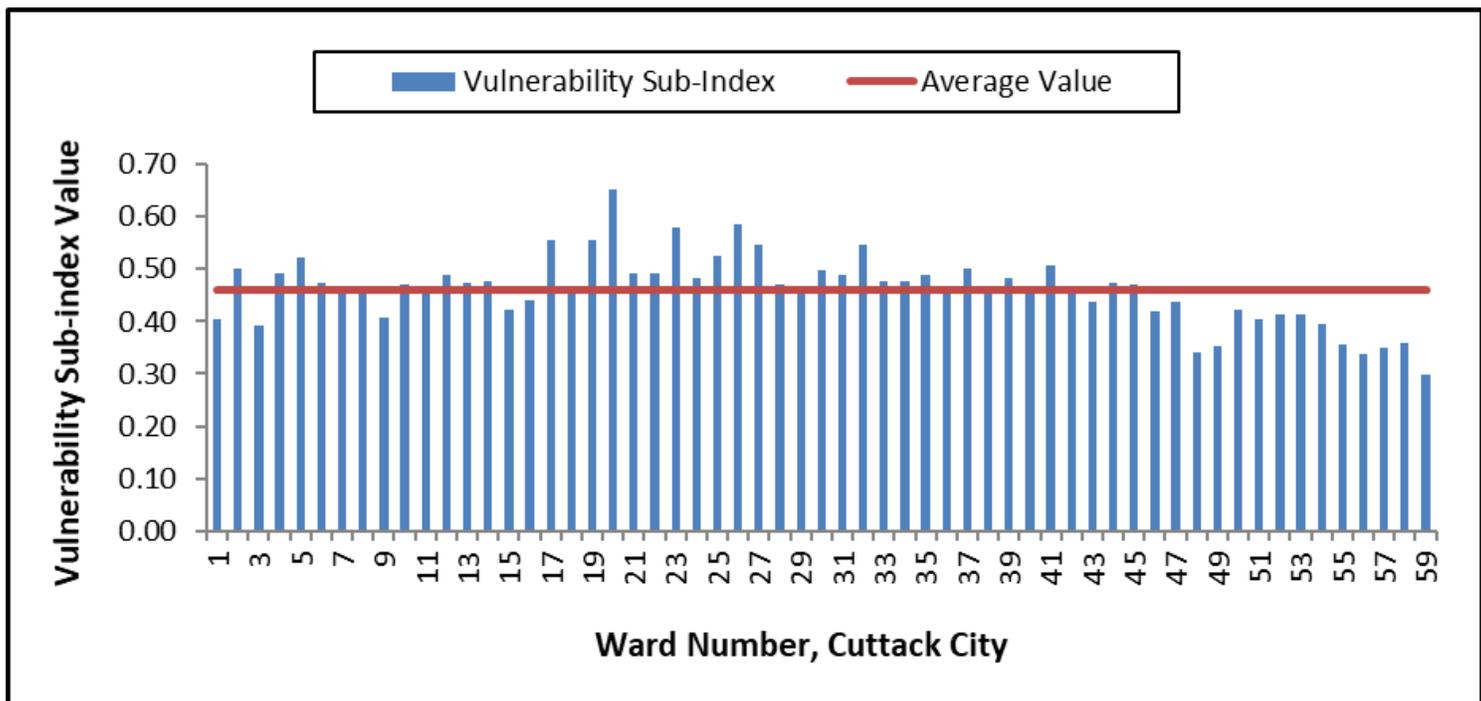


Figure 9

Vulnerability sub-index value of different wards in Cuttack city (Source: Authors' computation)

Urban Flood Vulnerability Sub-Index Map Cuttack City, Odisha

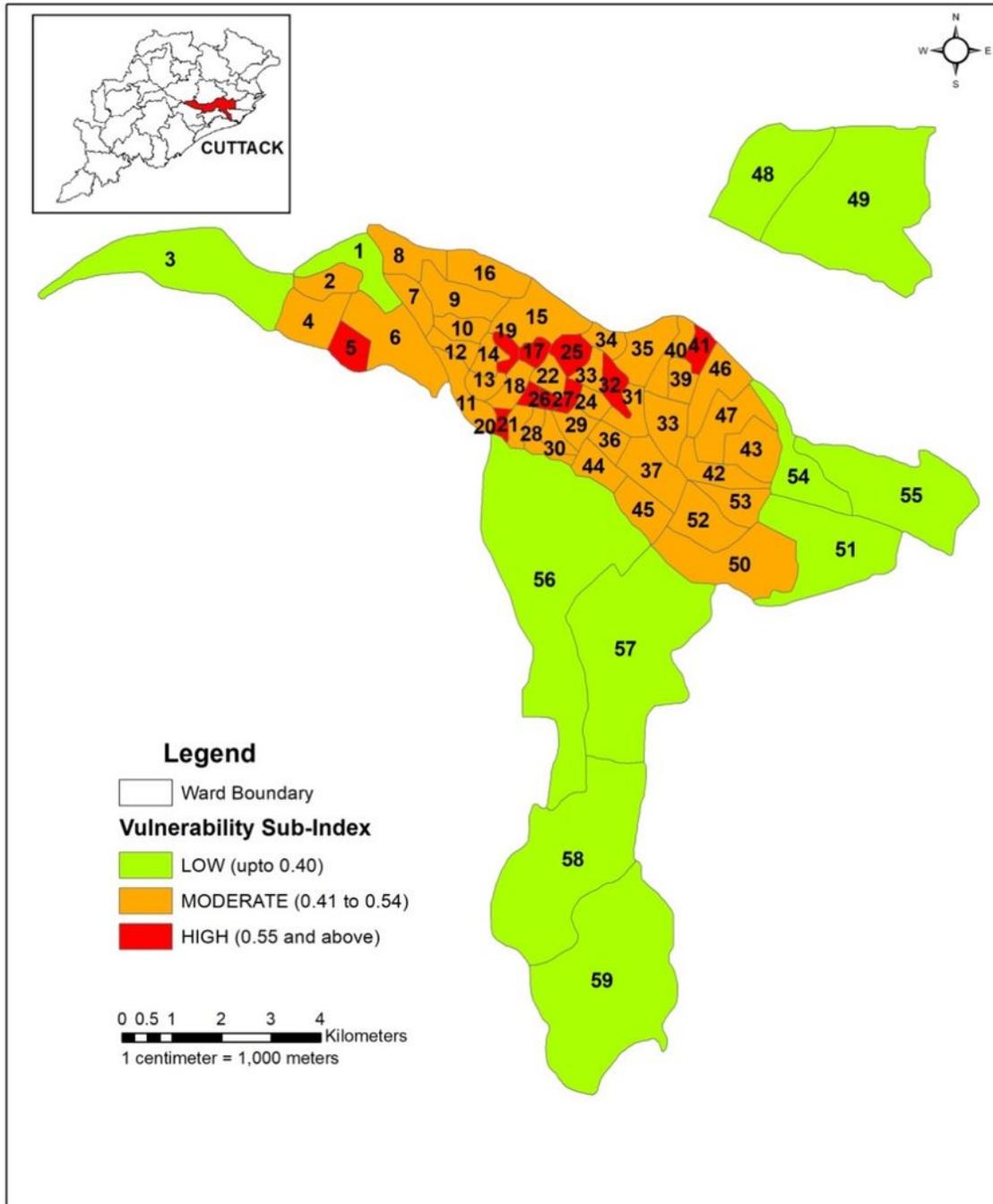


Figure 10

Categorisation of CMC wards as per the flood hazard vulnerability sub-index (Source: Map developed by Authors) Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

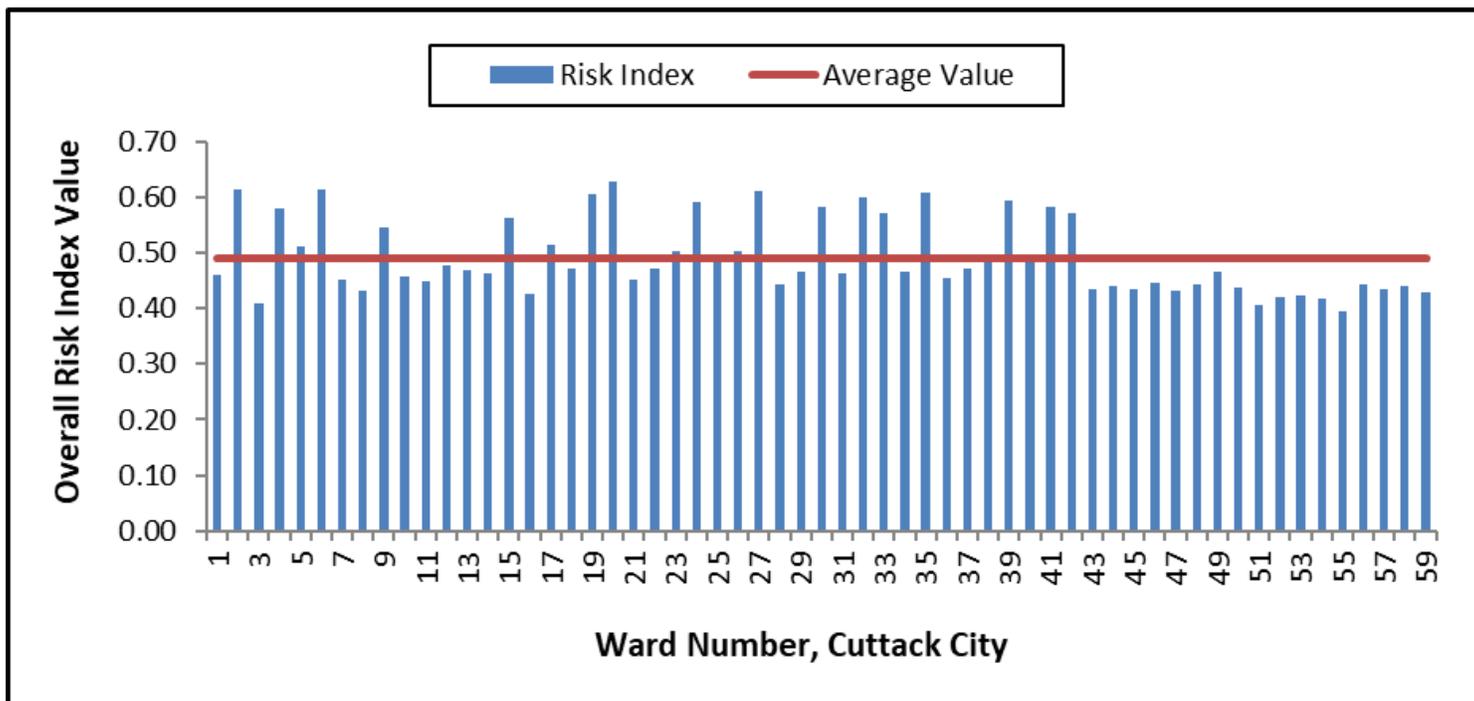


Figure 11

Overall flood risk index of different wards in Cuttack city (Source: Authors' computation)

Urban Flood Risk Index Map Cuttack City, Odisha

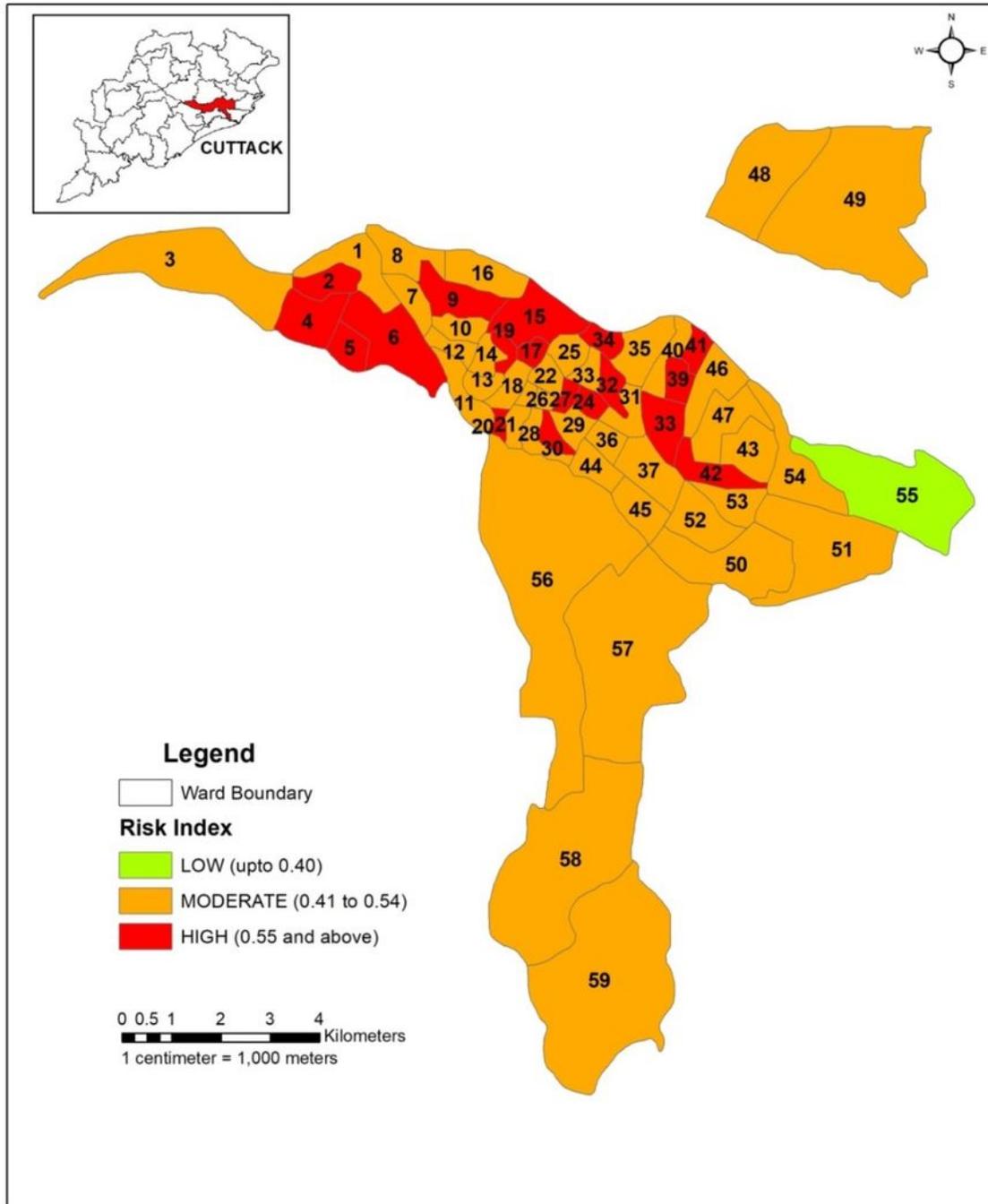


Figure 12

Categorisation of CMC wards as per the flood hazard risk index (Source: Map developed by Authors)
 Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

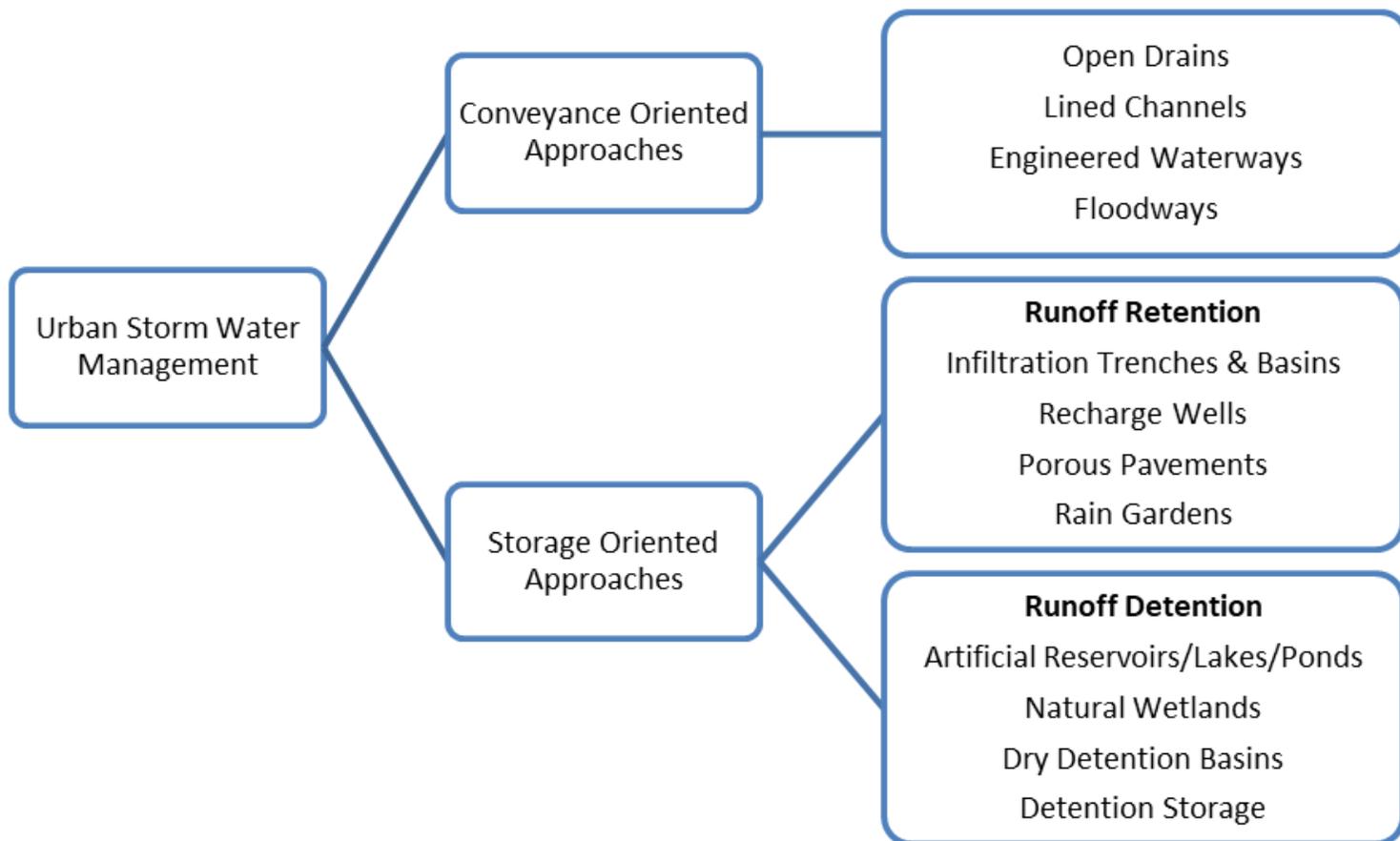


Figure 13

Various structural approaches to stormwater management (Source: Based on the Government of Malaysia 2011)