

Climate change impact and vulnerability assessment of Mumbai city, India

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Abstract

Climate Change (CC) is one of the most challenging problems of today which need to be understood. Climate change impact studies at the urban centers are the need of the hour. Mumbai is one of the most vulnerable port cities in the World and one of the most densely populated cities in the world. The city is vulnerable to climate change induced hazards, including sea level rise, storm surge, flooding, and coastal erosion. In this study, it is tried to do the spatial integration of vulnerability from these hazards to portray the overall climate change-induced impacts in Mumbai city. This study portrays the overall vulnerability of the Mumbai megacity, considering SLR, long-term coastal erosion, and flooding. This integrated vulnerability assessment reveals that 123.35 sq.km (24%) of the Mumbai regions are demarcated as composite vulnerable regions. They are mostly around the coastal tracts. Within the vulnerable regions, inland flood-affected areas from the past floods area are 37.13 sq.km, which is around 30 % of the demarcated most vulnerable regions. Remaining vulnerable areas are falling in built up, barren, forest, vegetation, and mangrove regions. The most worrying impact would be in the 44 sq.km of the built-up areas, which is around 35% of the vulnerable regions. It pulls the city to one of the most vulnerable cities of the world due to the exposure of the higher population. Rest of all the classes can cope up as they are naturally covered, not covered, and the human population is not residing over those regions currently. Since the city is expanding rapidly, other LULC classes apart from built-up land have to be converted based on the need. Available barren land can be kept for rehabilitation in the future. This study provides vital information about the climate change induced vulnerability of Mumbai city.

Keywords: Climate change, Mumbai, sea level rise, erosion, remote sensing.

1 Introduction

As the days are passing, it is getting more evident that the impacts of climate change are a real threat not only to humanity but even the existence of life on Earth. Since climate change impacts vary in different ways, it is necessary to understand the vulnerability with a multi-disciplinary approach. Geospatial techniques are efficient to understand the spatial vulnerabilities. Coastal megacities will be the prior victims of climate change. Sea level rise (SLR), vanishing Green land ice sheets, temperature rise, frequent forest fires, droughts, bleaching of coral reefs, super storms, intense cyclones, frequent floods & change in seasons are some of the visible & direct impacts. Scientists started predicting the extinction scenarios of lives on Earth due to climate change (Crick 2004; Thomas et al. 2004; Hoegh-Guldberg et al. 2007; Le Conte and Navajas 2008). Since the impacts of climate change are getting severe and frequent than the usual, it is becoming more explicit about the necessity of climate change control and mitigations. Household food security index under IPCC dimension of climate change was analysed using principal component analysis for Odisha (Sam A.S et al. 2018).

Climate change can cause global as well as local impacts. Coastal cities will be prior victims of the climate change impacts since climate change in coastal regions can affect huge population. The high population in the coastal zones makes coastal cities more vulnerable than in inland regions. De Sherbinin et al. (2007) identified the most vulnerable global cities due to climate change effects, and India has many vulnerable hotspots. At this juncture, it is important to understand the impacts associated with climate change to know the extent of the vulnerability in each mega coastal city. It would help in proper planning to prepare for it as well as to device the mitigation measures. Hanson et al. (2011) studied climate change extremes in world port cities and identified Mumbai is the riskiest city because of its highest population exposed to climate change. However, that study did not specify in particular, the vulnerable areas spatially within the Mumbai city.

Mumbai city, the financial capital of India, was just seven isolated islets as Isle of Bombay, Mahim, Colaba, Parel, Mazagon, Worli, and Little Colaba (Fig 1). These islets were merged into a single large land mass by reclaiming from the sea. The seven islands, as well as the Salsette Island in the north of Mumbai, were home for just 10,000 people in the mid-seventeenth century while it is inhabited presently by more than twelve million people. The continuous increase in the population made the city as one of the most densely populated cities in the world.

Mumbai city was a definite encroachment to natural phenomena which was made to become a place for millions of people. The major threats to the city are coastal flooding due to SLR and storm

surges. Mumbai is also facing the problem of coastal erosion. Tirkey et al. (2005) pointed out the shoreline changes and the eroding coastal regions in some parts of the Mumbai coast. Zope et al. (2014) studied the flood vulnerability in different return period intensities and influences of urbanisation on flooding. Long-term tide gauge data were used to identify the relative SLR trends (Shankar and Shetye 1999; Unnikrishnan and Shankar 2007). Church and White (2011) have estimated around 3.2mm/yr SLR on the 21st century, and the rate would increase in future. If the SLR trend continues as per the previous study, more than 60 cm of sea level will undoubtedly increase than today's mean sea level in the next 100 years. Shaji et al. (2014) estimated 1.5 m surge amplitude and 4.5 m maximum water level from the detailed storm surge studies. In a hypothetical scenario, future SLR in addition to surge conditions at Mumbai would be devastating. The objective of this study is to find out the probable coastal flooding areas for a value of 1 m rise in water level which may happen as per the estimated SLR trend and when storm surge strikes the city. If that happens, the loss will be beyond the imagination and will harm the normal life. The efficiency of the Geographic Information System (GIS) and remote sensing techniques are utilised in many studies for the integration of spatial entities (Mahendra et al. 2011; Mani Murali et al. 2013; Sankari et al. 2015). Even though Mumbai is found to be one of the most vulnerable coastal cities in the world, no significant studies are stating the vulnerability of the Mumbai megacity spatially for the considered situation. This study portrays the vulnerability of the Mumbai megacity because of coastal flooding. The probable coastal inundation regions were estimated up to the 1 m water level rise. This 1 m rise may be assumed value combined with SLR and an unpredicted surge at the same time in future.

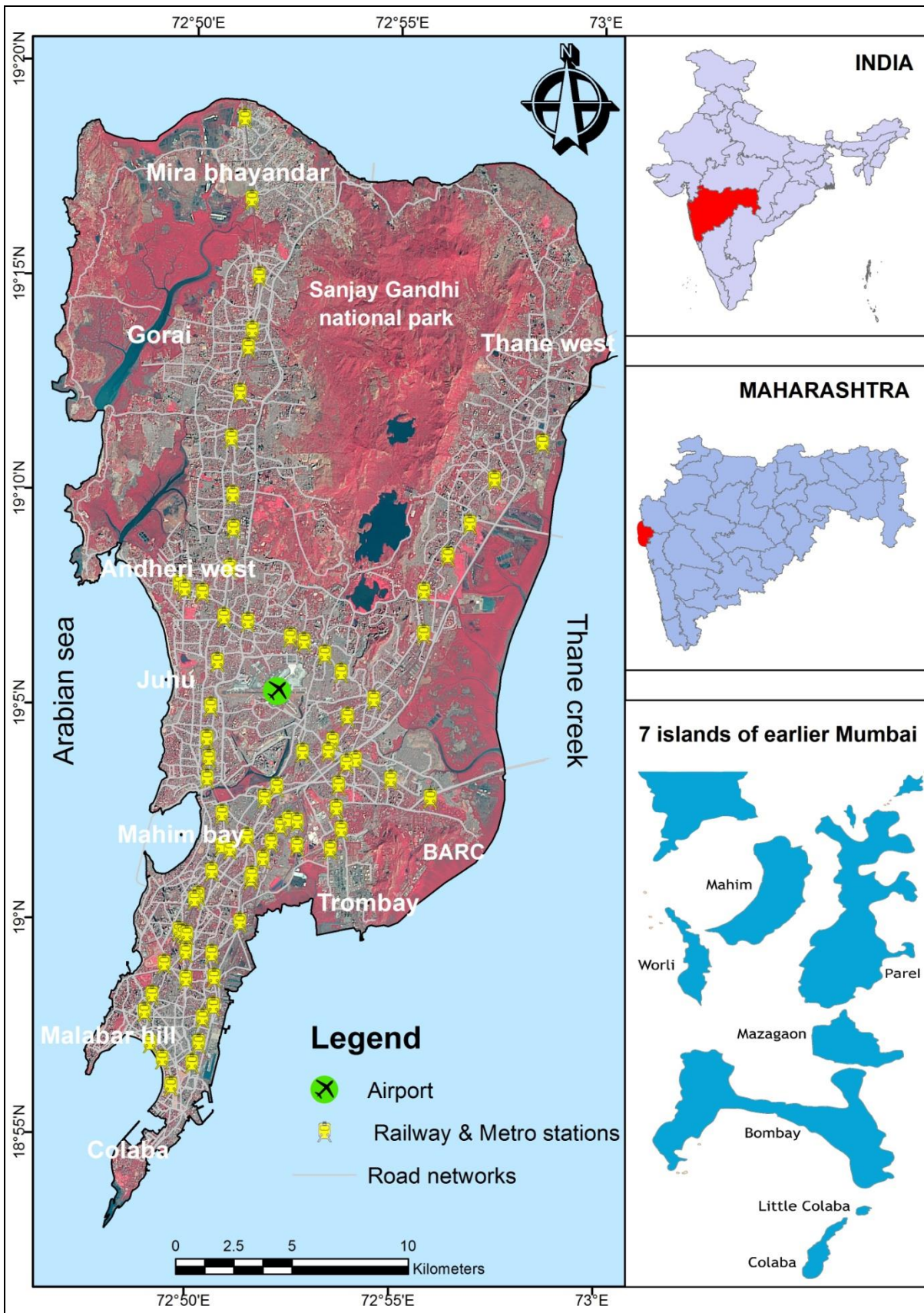


Fig. 1 Study area

2 Data & Methodology

A composite vulnerability assessment was done for Mumbai city by considering the erosion spots from shoreline change analysis, Land Use / Land Cover (LULC), Digital Elevation Model (DEM), and past flood occurred regions. One meter low lands adjoining the sea and creek side were demarcated from DEM. Land use/land cover (LULC) map is used to understand how this vulnerability will affect different LULC classes. All the vulnerability regions are overlaid on a single map sheet using GIS software. The derived composite vulnerability includes SLR of 1m, coastal erosion and the flood patches identified from the 26 July 2005 flood.

The vulnerability assessment was carried out by considering equal importance to all the parameters. In this study, more weightage to some parameter and less to some other was not given as all considered parameters are equally important. All the regions which were affected by each parameter were given equal importance and considered in arriving final spatial vulnerability map of Mumbai city. Many studies were carried out to derive the vulnerability index. In that methodology, some areas become less vulnerable, and some areas become more. In this study, it was indented to categorise the vulnerable areas rather demarcate all the possible vulnerable areas spatially. This study proposed this unique methodology by considering all parameters equally important; hence, very few inevitable parameters were used. Details of data used are provided below.

2.1 Coastal erosion spots:

Shoreline can be defined as an imaginary boundary which discriminates water and land on a coast. The shorelines are manually digitised from satellite imagery by on-screen digitising. Table 1 shows the details of satellite images used for shoreline digitisation. Tide height at the time of satellite image acquisition is calculated using the WXTide software. Datasets with a similar tidal condition are preferred for the study to reduce the uncertainty from the different tidal conditions. Digital Shoreline Analysis System (DSAS) is a plug-in developed by USGS for ESRI ArcGIS product (Thieler et al. 2009). DSAS has proved its efficiency in many of the shoreline and other boundary change studies worldwide (Appeaning Addo et al. 2011; Cowart et al. 2011; Murali et al. 2015). Endpoint rate (EPR) statistics method was used in this study to compute the shoreline change rate since there are multiple shoreline inputs. Coastal erosion spots which are susceptible to higher damage due to SLR was identified and included in preparing the composite vulnerability map.

Table 1 Details of satellite images used for shoreline extraction

Date	Sensor	Spatial resolution (m)
1972/01/11	MSS	68 x 83
1977/02/20	MSS	68 x 83
1991/01/07	TM	30 x 30
1998/03/15	TM	30 x 30
1999/01/13	TM	30 x 30
2000/02/15	ETM+	30 x 30
2001/03/31	ETM+	30 x 30
2002/03/02	ETM+	30 x 30
2003/03/05	ETM+	30 x 30
2005/12/07	ETM+	30 x 30
2009/12/10	TM	30 x 30
2011/01/14	TM	30 x 30
2013/04/25	OLI	30 x 30
2014/03/27	OLI	30 x 30
2015/01/09	OLI	30 x 30

2.2 Landuse/land cover (LULC)

Landsat 8 OLI satellite image of 2015 was used for the LULC classification. Level-2 National Remote Sensing Center (NRSC) classification system was followed for the final LULC. The classification contains 13 classes such as built-up land, aquatic vegetation, barren land, cropland/grassland, fallow land, forest, mangroves, marshy land, mudflats, salt pan, sand, vegetation & water. It was done by supervised classification method taking around 100 training sites for each class, and manual re-coding was done for further improvement. The field visit was conducted in the study area, and 53 sample points were taken for the validation of the classification.

2.3 Digital Elevation Model

Shuttle Radar Topographic Mission (SRTM) 1 arc second Digital elevation model (DEM) was used as the source data for the SLR related inundation mapping. DEM sinks are filled to increase the quality of the DEM by avoiding false voids. One meter contours were extracted from the DEM. Only the first contour of the outer water body is considered for the study because the inundation will occur

from the sea/creek to the land region; thus; it will not cross the first contour line. Rest of the contours were removed, and the selected contours are joined properly to make a single contour representing the true line of inundation. Contour lines of 1m contours are constructed representing the inundation limit of SLR scenario.

2.4 Flood inundation

Mumbai megacity experienced one of the worst floods on 26 July 2005 flood. Rainfall of 994mm in 24 hrs time caused a disastrous situation. Even though this rainfall is one of the highest ever in this city, there are many factors which enhanced the impact of the hazard. The unplanned urbanisation and the poor management of the city were discussed as a major cause of the high impact of the flooding (Bhagat et al. 2006; Ranger et al. 2011). (Gupta 2007) had reviewed the flooding event, the background of this flooding and the actions taken by this event. The flooded regions map developed by Government of Maharashtra, 2006 was used to represent the flooded regions. This map was geo-referenced properly before digitising the flood-affected regions from flooding. These flooded regions were considered in addition to coastal inundation spots to derive the composite vulnerable regions of Mumbai.

3 Results & discussion

3.1 Land use/land cover

Fig 2 shows the LULC of Mumbai city in 2015. One major specialty of the city is abundant in the build-up as well as the mangrove regions. As a city grows thick & wide, usually the forest cover reduces drastically. Even though reports are proving a decline in the vegetation cover in Mumbai city (Samant and Subramanyan 1998; Shafizadeh Moghadam and Helbich 2013; Vaz 2014), much area is kept untouched from nature's way. Sanjay Gandhi national park & mangrove around creeks are good examples for that. The accuracy of the classification attained by cross-checking with the sample ground points is 98.28%.

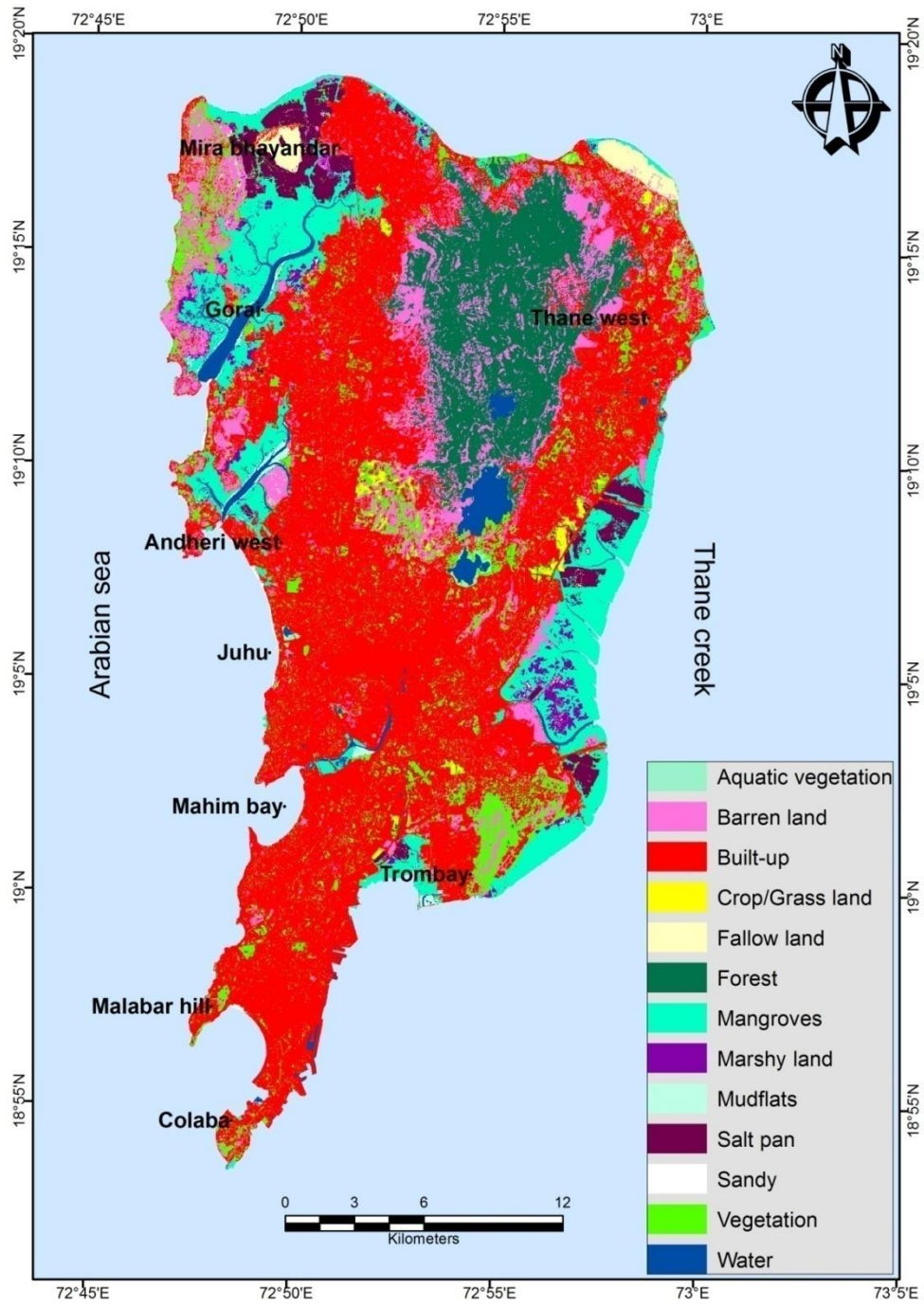


Fig. 2 LULC map of the study area

3.2 Erosion

The erosion rate was calculated by analysing 15 shorelines from different years between 1972 and 2015. From Fig 3, it is clear that the northwest beaches are under high erosion. Juhu beach is found to be a critical spot since the entire beach undergoes prominent erosion. The maximum erosion EPR rate found is 10.2 m/yr. A total of 2.39 sq.km of the area is eroded in 43 years. The erosion spots were put in the composite vulnerability as they are potential sites for accelerating the damages by SLR triggered inundation. Details of morphological changes of Mumbai city is under preparation as a manuscript concentrating only the shoreline changes occurred in the past few decades. These eroding coasts are signatures of permanent loss of land which might be due to SLR and is still not quantified. In this study, almost four decades of satellite images were used to extract the erosion spots. Erosion is a local indicator of regional or global phenomena. Eroding regions are spots which may be facing accelerated damage, hence erosion study was carried out, and we strongly believe that climate change role is there in triggering the erosion.

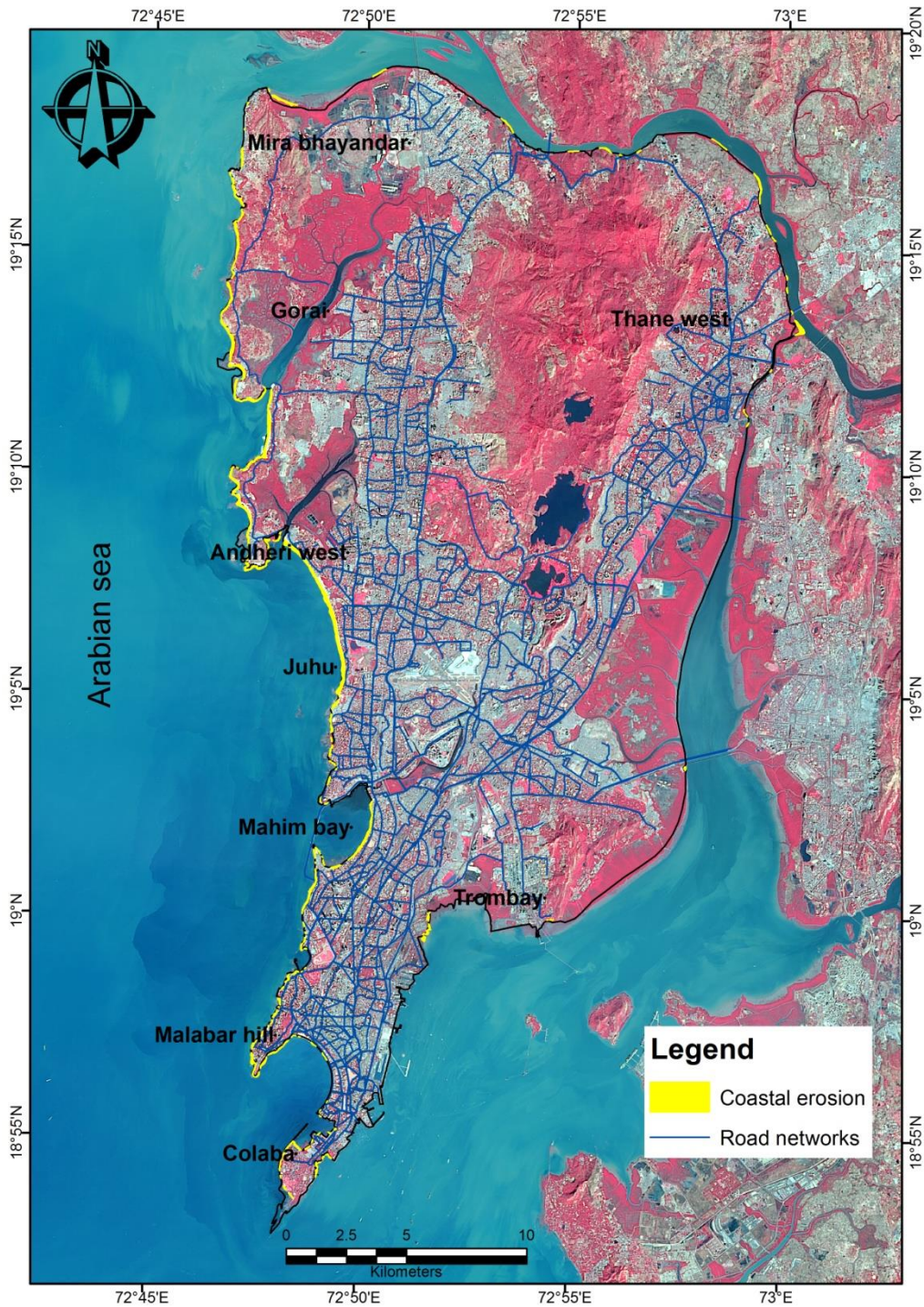


Fig. 3 Eroding coasts

3.3 Sea level rise

SLR scenario of 1m is presented in Fig 4. One meter of SLR can cause submergence of approximately 86.22 sq.km. North-west region is the most vulnerable region in this scenario. The high altitude land portions near Mira bhayandar can get almost isolated from other lands by SLR.

The major two waste dumping spots are Deonar dumping spot & in Mulund may increase pollution threat if connected under SLR conditions.

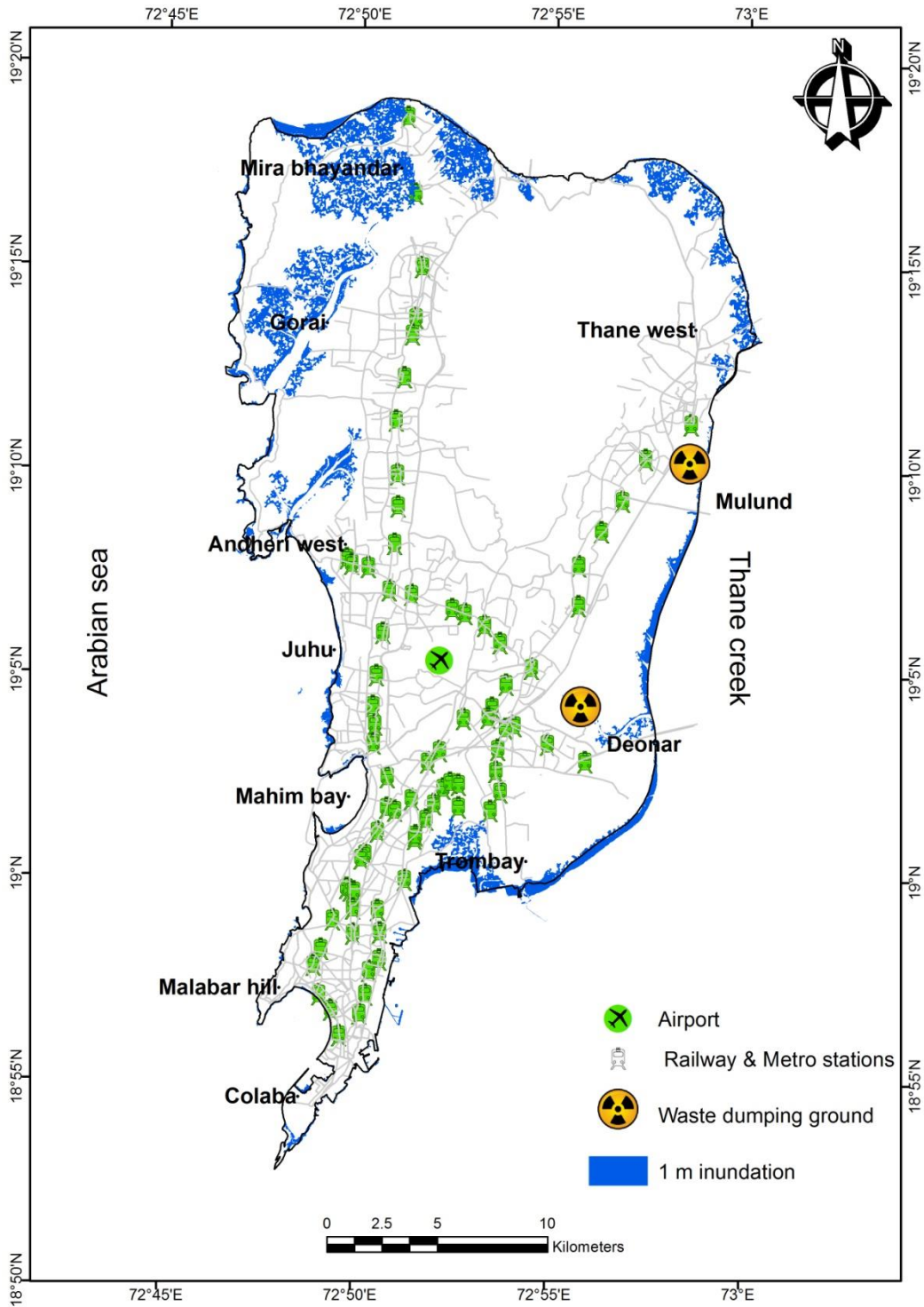


Fig. 4 Probable inundation regions of 1m SLR

It is clear that the mangrove systems can have direct higher impacts from this. More than three sq.km of mangrove regions are exposed to SLR. Also, it is observed that more than 43 sq.km of built-up regions are also exposed. Most of the exposed built-up are concentrated in the Mira bhayandar region, where the inundation can cause land isolation. This could make the conditions worse due to the possible difficulties on the mitigation actions and can create more impact near Mira bhayandar regions.

Mumbai city alone produces around 6.11% of the total waste produced in India. Approximately 9600 tons of waste is collected every day from the city (Bhalerao 2016). The treatment plants in this dumping spots can manage only a portion of the daily intake and rest of the waste is kept untreated. It is observed that the yard is surrounded by water, which is having a direct connection to the Thane creek. It portrays the higher possibility of getting affected by the rise in water level. When the waste dump spot comes in contact with open water, then this will have impacts in most of the ecosystems, including, water, coastal, and mangroves. Fig 5 is the ground images of Mulund waste dumping yards. The wastes are kept untreated, making a hill out of wastes. Water flowing from the waste hill is just a few meters away from the mangrove forest along Thane creek. Since this place is vulnerable to water level rising, the waste will come in direct contact with the mangrove forest and to the Thane creek. This is a serious threat since this will affect mangrove forests of Thane creek which acts as lungs of the Mumbai city, the water ecosystem of Mumbai city.



Fig. 5 Water coming from the dumping ground flowing along the mangroves

3.4 Flood vulnerability

The flooded area on 26/07/2005 is digitised and plotted in Fig 6. The total area of these patches is 69.6 sq.km. It is observed that flood-prone regions are all along the major built-up regions. It is noticed that the flood patches are following the same directions of the railway/ metro stations located. It is clear from Table 2 that major inundation happened on built-up land. When built-up contributes 84% of the total flooded regions, rest all of the classes contribute less than 16%. This reveals the fact that urbanisation, or in other words, unplanned development is the root factor for the flood happened. The similar situation may arise along the coastal tracts if unplanned development is allowed without considering the climate change factors.

Table 2 Details of different LULC classes under flooded regions on 26/07/2005 (Govt of Maharashtra, 2006)

Class	Area (sq.km)	Percentage (%)
Barren land	3.00	4.31
Built-up	58.71	84.40
Crop land/ grass land	0.09	0.13
Fallow land	0.01	0.02
Forest	0.66	0.95
Mangroves	0.90	1.30
Marshy land	0.02	0.03
Mudflats	0.30	0.44
Salt pan	0.02	0.02
Sandy	0.07	0.10
Vegetation	5.05	7.26
Water	0.65	0.93

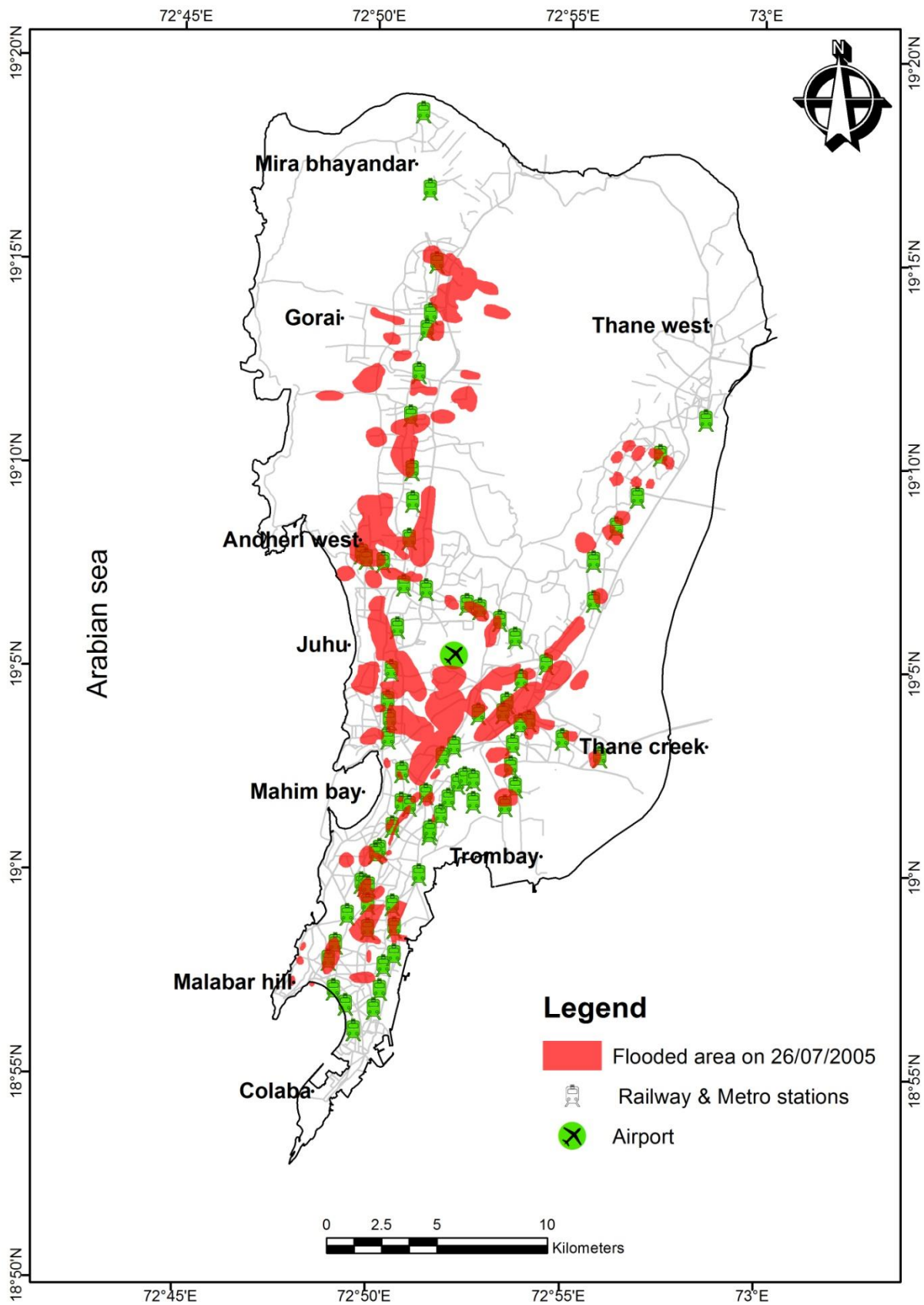


Fig. 6. Inundation regions on 26/07/2005 flood

3.5 Composite vulnerability assessment

The composite vulnerability map (Fig 7) contains the vulnerability from sea level rise, coastal erosion, and the flood-vulnerable regions. Some regions with specific purposes are masked for further results. This includes Sanjay Gandhi national park, Bhabha atomic research centre, Bharat petroleum refinery, and water bodies. This was done to analyse the scenarios more precisely in a societal point of view since the public cannot use this place for their needs, and these areas are large enough to mislead the overall result. Water bodies such as creeks are masked because it is already filled with water. So the protected areas, as well as the water bodies, are omitted from further discussion to convey the result more logical & more of demographic view. The study area covered is around 512.19 sq.km. In that, 24% of the area, which is equal to 123.35 sq.km, is demarcated as composite vulnerable regions. They are mostly around the coastal tracts. Within the vulnerable regions, inland flood-affected areas from the past floods area are 37.13 sq.km, which is around 30 % of the demarcated vulnerable regions. Remaining vulnerable areas are falling in built up, barren, forest, vegetation, and mangroves regions. The most worrying impact would be in the 44 sq.km of the built-up areas, which is around 35% of the vulnerable regions. Rest of all the classes can cope up as they are naturally covered and not covered, and human is not residing over those regions currently. Since the city is expanding rapidly, other LULC classes apart from built-up land have to be converted based on the need. Available barren land can be kept for rehabilitation in the future. In LULC classification of Mumbai region, 41.6 sq.km has been classified as barren land which is rocky exposure, barren, empty lands. In that, 8.1 sq.km is vulnerable as per this study. The nonvulnerable land becomes very important as they are available for genuine land use. When there is a mitigation plan for the climate change impact people, these regions which are inland are potential areas for relocation. Barren lands which are falling under the inundation areas can be avoided for further development. The protective mechanism may be debated for all other demarcated vulnerable areas.

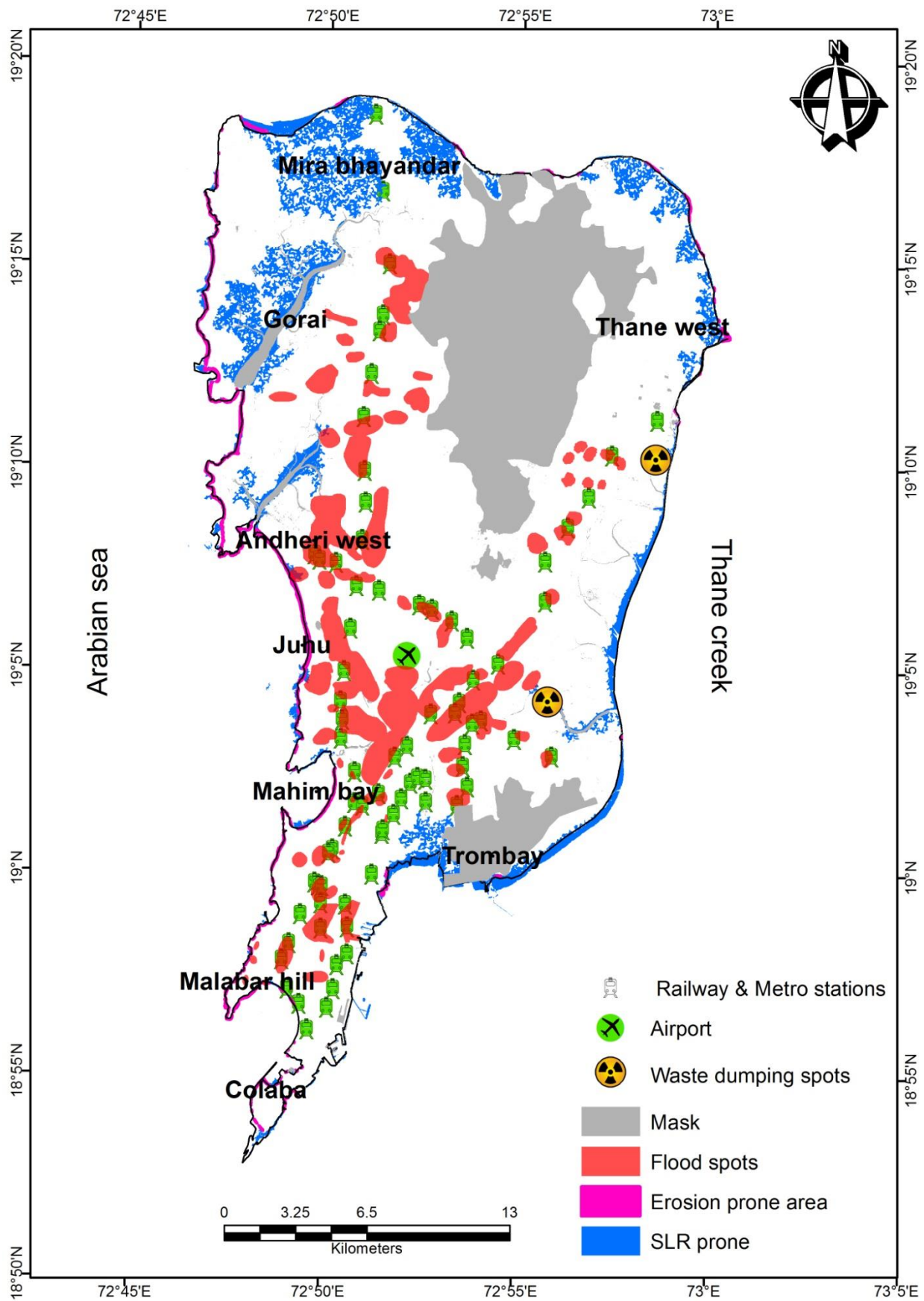


Fig. 7 Composite vulnerability map

4 Conclusion

This study provides vital information about the composite vulnerability of Mumbai city. Climate change induced vulnerability from the hazards causing the inundation and the past flood calamity details were considered. The spatial studies prove the efficiency of geospatial techniques for the more significant extent of the composite vulnerable regions of the study area. This study has brought out the vulnerable inland areas in addition to coastal vulnerable sites. Since the population is increasing exponentially and the city is expanding fast, it is necessary to understand the available lands and the safety of those regions of Mumbai city. Other than the inundation of land, SLR is a threat to other secondary severe risk issues including land isolation, spreading of waste materials to water bodies & mangrove degradation, etc. The limitation in the data resolution restricts this study at a city scale. Uncertainty of results is there to a certain degree because of the lack of ground subsidence and upliftment data of this region. Updated elevation values of the city with the highest accuracy are not available in the public domain, which will undoubtedly enhance the quality of the results. Nonavailability of those data has forced to restrict this study with uncertainty. Even then, the obtained results are very important and cater to the needs for future planning of climate change adaptation programs. Faster growth and development at various parts of this city may alter and modify the obtained results. This kind of study should be carried out with higher accuracy of latest elevation values such as LIDAR and very high-resolution satellite images to further understand the status of the vulnerability of this megacity at the micro level. A huge population is exposed to the demarcated vulnerable regions in Mumbai city. National and local decision-makers need to accept the truth and implement the policies considering climate change impacts and to benefit that huge population. The global crisis should be felt, and adaptation strategies at the local level and relocation plans should be drafted without any further delay. Extensive awareness programs at various levels should be planned to foresee and adapt to the forthcoming situation. Climate change is not anymore a dream and may affect everyone on this globe one way or another. Generous funding to address this issue from all sides is the best preventive option than to search for the investment after the calamity.

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References

- Appeaning Addo K, Jayson-Quashigah PN, Kufogbe KS (2011) Quantitative Analysis of Shoreline Change Using Medium Resolution Satellite Imagery in Keta, Ghana. *Mar Sci* 1:1–9. doi: 10.5923/j.ms.20110101.01
- Bhagat RB, Guha M, Chattopadhyay A (2006) Mumbai after 26/7 Deluge: Issues and Concerns in Urban Planning. *Popul Environ* 27:337–349. doi: 10.1007/s11111-006-0028-z
- Bhalerao S (2016) No plans to remove Deonar ' s 12 million tonnes of waste. *Hindustan times*.<https://www.hindustantimes.com/mumbai-news/no-plans-to-remove-deonar-s-12-million-tonnes-of-waste/story-xdFaeRKH5Lk8PMHWPODDGJ.html>. Accessed 31 July 2016
- Church JA, White NJ (2011) Sea-Level Rise from the Late 19th to the Early 21st Century. *Surv Geophys* 32:585–602. doi: 10.1007/s10712-011-9119-1
- Cowart L, Reide Corbett D, Walsh JP (2011) Shoreline change along sheltered coastlines: Insights from the neuse river estuary, NC, USA. *Remote Sens* 3:1516–1534. doi: 10.3390/rs3071516
- Crick H (2004) The impact of climate change on birds. *Ibis (Lond 1859)* 146:48–56. doi: doi: 10.1111/j.1474-919X.2004.00327.x
- De Sherbinin A, Schiller A, Pulsipher A (2007) The vulnerability of global cities to climate hazards. *Environ Urban* 19:39–64. doi: 10.1177/0956247807076725
- Gupta K (2007) Urban flood resilience planning and management and lessons for the future: a case study of Mumbai, India. *Urban Water J* 4:183–194. doi: 10.1080/15730620701464141
- Hanson S, Nicholls R, Ranger N, et al (2011) A global ranking of port cities with high exposure to climate extremes. *Clim Change* 104:89–111. doi: 10.1007/s10584-010-9977-4
- Hoegh-Guldberg O, Mumby PJ, Hooten AJ, et al (2007) Coral Reefs Under Rapid Climate Change and Ocean Acidification. *Science (80-)* 318:1737–1742. doi: 10.1126/science.1152509
- Le Conte Y, Navajas M (2008) Climate change : impact on bee populations and their illnesses. *Rev Sci Tech Int Des Epizoot* 27:485–497.
- Mahendra RS, Mohanty PC, Bisoyi H, et al (2011) Assessment and management of coastal multi-hazard vulnerability along the Cuddalore-Villupuram, east coast of India using geospatial techniques. *Ocean Coast Manag* 54:302–311. doi: 10.1016/j.ocecoaman.2010.12.008
- Mani Murali R, Ankita M, Amrita S, Vethamony P (2013) Coastal vulnerability assessment of Puducherry coast, India, using the analytical hierarchical process. *Nat Hazards Earth Syst Sci* 13:3291–3311. doi: 10.5194/nhess-13-3291-2013
- Murali RM, Dhiman R, Choudhary R, et al (2015) Decadal shoreline assessment using remote sensing along the central Odisha coast, India. *Environ Earth Sci* 74:7201–7213. doi: 10.1007/s12665-015-4698-7
- Ranger N, Hallegatte S, Bhattacharya S, et al (2011) An assessment of the potential impact of climate change on flood risk in Mumbai. *Clim Change* 104:139–167. doi: 10.1007/s10584-010-9979-2

- Samant H, Subramanyan V (1998) Landuse/land cover change in Mumbai-Navi Mumbai cities and its effects on the drainage basins and channels — A study using GIS. *J Indian Soc Remote Sens*, 26:1–6. doi: 10.1007/BF03007333
- Sam, A.S., Abbas, A., Surendran Padmaja, S. et al. (2019) Linking Food Security with Household's Adaptive Capacity and Drought Risk: Implications for Sustainable Rural Development. *Soc Indic Res*, 142: 363- 385. doi.org/10.1007/s11205-018-1925-0
- Sankari TS, Chandramouli AR, Gokul K, et al. (2015) Coastal Vulnerability Mapping Using Geospatial Technologies in Cuddalore-Pichavaram Coastal Tract, Tamil Nadu, India. *Aquat Procedia* 4:412–418. doi: 10.1016/j.aqpro.2015.02.055
- Shafizadeh Moghadam H, Helbich M (2013) Spatiotemporal urbanization processes in the megacity of Mumbai, India: A Markov chains-cellular automata urban growth model. *Appl Geogr* 40:140–149. doi: 10.1016/j.apgeog.2013.01.009
- Shaji C, Kar SK, Vishal T (2014) Storm surge studies in the North Indian Ocean : A review. *Indian Journal of Geo marine sciences*, 43:125–147.
- Shankar D, Shetye SR (1999) Are interdecadal sea level changes along the Indian coast influenced by variability of monsoon rainfall? *J Geophys Res* 104:26031. doi: 10.1029/1999JC900218
- Thieler ER, Himmelstoss EA, Zichichi JL, Ergul A (2009) Digital Shoreline Analysis System (DSAS) version 4.0— An ArcGIS extension for calculating shoreline change.
- Thomas CD, Cameron a, Green RE, et al (2004) Extinction risk from climate change. *Nature(London)* 427:145–148. doi: 10.1038/nature02121
- Tirkey N, Biradar RS, Pikle M, Charatkar S (2005) A study on shoreline changes of Mumbai coast using remote sensing and GIS. *J Indian Soc Remote Sens* 33:85–91. doi: 10.1007/BF02989995
- Unnikrishnan AS, Shankar D (2007) Are sea-level-rise trends along the coasts of the north Indian Ocean consistent with global estimates? *Glob Planet Change* 57:301–307. doi: 10.1016/j.gloplacha.2006.11.029
- Vaz E (2014) Managing urban coastal areas through landscape metrics: An assessment of Mumbai's mangrove system. *Ocean Coast Manag* 98:27–37. doi: 10.1016/j.ocecoaman.2014.05.020
- Zope PE, Eldho TI, Jothiprakash V (2014) Impacts of urbanization on flooding of a coastal urban catchment: a case study of Mumbai City, India. *Nat Hazards* 75:887–908. doi: 10.1007/s11069-014-1356-4