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# GIS coupled multiple criteria decision making approach for classifying urban coastal areas in India

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A R T I C L E I N F O

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A B S T R A C T

Coastal area classification in India is a challenge for decision makers due to unclear directions in implementation of coastal regulations and lack of scientific rational about existing classification methods. To improve the objectivity of the coastal area classification is the aim of the present work. A Geographical Information System (GIS) coupled Multi-criteria Decision Making (MCDM) approach is developed in this work to provide scientific rational for classifying coastal areas. Utility functions are used to transform the physical coastal features into quantitative membership values. Different weighting schemes for coastal features are applied to derive Coastal Area Index (CAI) which classifies the coastal areas in distinct categories. Mumbai, the coastal megacity of India, is used as case study for demonstration of proposed approach. Results of application of GIS-MCDM approach showed the clear demarcation of coastal areas based on CAI is possible which provides a better decision support for developmental and planning authorities to classify coastal areas. Finally, uncertainty analysis using Monte Carlo approach to validate the sensitivity of CAI under different scenarios was carried out.

## 1. Introduction

India, surrounded by Arabian Sea, Bay of Bengal and Indian Ocean with a 7500 km long coastline is inhabited by nearly 25% of population within the vicinity of 50 km towards the coast (Nayak, Chandramohan, & Desai, 1992). Indian coastal states support national economy with developmental activities (largest in the South Asian Region) and numerous marine resources located in 2.02 million km$^2$ Exclusive Economic Zone (EEZ). At another hand, these states are under extreme pressure of natural hazards because of vulnerable geographical locations (Alcántara-Ayala, 2002; Smith & Petley, 2008) and anthropogenic development (Nair & Gopinathan, 1981; Ramesh, Lakshmi, George, & Purvaja, 2015). India harbors some of the world's fastest growing coastal megacities such as Mumbai and Kolkata, with Chennai joining the league shortly.

The implications of coastal cities are pollution and natural hazards which are inevitable and the effect can be destructive in urban coastal regions with huge population (Cenci et al., 2015; Nayak et al., 1992; Newton, Carruthers, & Icely, 2012). Specifically (Vaz, 2014), reports that in Mumbai there is observed transformation of 36% of mangrove eco-system area to urban land since 1973 due to urbanization. Along with urbanization there is industrial belt development along the Indian coasts causing effluent discharges from cities and industrial belts (Datta, Chakraborty, Jaiswar, & Ziauddin, 2010; Ramachandran, 1999; Shirodkar et al., 2009). On the east coast, increased metal concentration in the coastal waters of Pondicherry as reported by Govindasamy and Azariah (1999) was a result of the effluent discharges of nearly 16 major and minor industries.

### 1.1. Coastal regulations in India

Coastal area classification for developmental activities in urban areas is a challenging task due to conflicts among associated stakeholders. Different countries have various mechanism to manage their coastal resources with the help of policies. These policies are aimed at creating balance between human development and coastal biodiversity. Similar efforts have been made by State and Central Government in India to direct the development in the coastal areas using regulatory frameworks. One of the most prevailing regulation is Coastal Regulation Zone (CRZ) policy (Krishnamurthy, DasGupta, Chatterjee, & Shaw, 2014). The Ministry of Environment, Forest and Climate Change (MoEF & CC) had issued the Coastal Regulation Zone (CRZ)

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Notification, 1991 under the Environment (Protection) Act, 1986 and there have been continuous amendments in this notification since then. The CRZ notification was issued with a vision of sustainable development and conservation of marine resources.

Present coastal regulations (CRZ, 2011) has issues related to implementation at administrative level and violations at private/government level. Considerable variations have been observed in the application and interpretation of coastal regulations in various Indian states (Sonak, Pangam, & Giriyan, 2008). Lack of clarity and definitions in CRZ regulations has led to subjective interpretations. This subjectivity stems from the basic definitions used to classify the coastal areas. For example, in prevailing CRZ regulation, areas come in CRZ-I are ecologically subtle areas like mangroves (if area more than 1000 square meters, a buffer area of 50 m shall be provided), corals, sand dunes, salt marshes, bird & turtle nesting grounds, horse shoe crab habitats, sea grass beds, mudflats and the area between Low Tide Line and High Tide Line and it's hard to demarcate these areas independently. Chouhan, Parthasarathy, and Pattanaik (2016) reported the violation of coastal regulations in Mumbai city leading to the destruction of ecosystem and biodiversity in coastal region due to rapid uneven population growth and developmental activities. Parthasarathy (2011) discussed the land encroachment issues and its associated effects on coastal communities in Mumbai. Ignorance of coastal communities existence by administrations has resulted into commercial exploitation and loss of biodiversity despite the coastal communities are meant to be protected according to CRZ (2011) regulations (Krishnamurthy et al., 2014). Absolute gap at institutional level for CRZ implementation has been reported by academicians and expert's working in the area of coastal resource management in India (R Dhiman, June 2015, Personal Communication).

There is a need to bring all the priorities related to the development, natural disasters and environment in decision-making related with Indian coastal cities (Srinivas & Nakagawa, 2008). All these issues related to futile regulations, policy violations and fragile institutional framework urge the requirement for management of coastal resources in a sustainable manner which is possible through suitable planning and policy improvement. Quantitative decision analysis is one of the suitable approaches answering strategic or policy decisions with large uncertainties and multiple conflicts (Zhou, Ang, & Poh, 2006). Therefore, present work focuses on improvement for coastal area classification methods in Indian cities through advancement in decision analysis.

### *1.2. Use of GIS and MCDM for area classification*

Geographical Information System (GIS) tool is a set of computer hardware and software which is used to process and store the spatially referenced data to derive information (Burrough & McDonnell, 1998). One of the key application of GIS is land suitability analysis (Collins, Steiner, & Rushman, 2001) targeting the identification of appropriate spatial configurations for upcoming land uses based on specific criteria and requirements (Brail & Klosterman, 2001). Specific land suitability applications of GIS include urban and regional planning (Baud, Scott, Pfeffer, Sydenstricker-Neto, & Denis, 2015; Janssen & Rietveld, 1990), selecting site for public and private sector facilities (Longley, Goodchild, Maguire, & Rhind, 2005), habitant selection for animal and plant species (Schmoldt, Kangas, Mendoza, & Pesonen, 2001), environmental impact assessment (Gontier, Mörtberg, & Balfors, 2010), coastal vulnerability assessment (Le Cozannet et al., 2013; Mani Murali, Ankita, Amrita, & Vethamony, 2013).

GIS is acknowledged as an appropriate decision support tool for analyzing and solving problems with integration of spatially referenced data (Brown & Kyttä, 2014). Major limitation of GIS to be designate as complete decision support tool is that, GIS doesn't incorporate preferences (evaluation criteria/alternatives) of decision makers (Malczewsk, 1999). Coupling GIS with Multiple Criteria Decision Making (MCDM) approach provides better decision support and has been widely practiced (Malczewski, 2006). A detailed literature survey by Keefer, Kirkwood, and Corner (2004) has highlighted the significant growth in use of decision analysis approach for decision making in interdisciplinary areas. One of the most suitable fundamental decision analysis approach is MCDM (Feizizadeh & Blaschke, 2014). Coupling of GIS with MCDM can transform the geographical data and combine the preferences from decision makers (value judgments) to derive the information for decision making (Drobne & Lisec, 2009). Capabilities of GIS coupled MCDM methods can be utilized for benefits of advancement in theoretical and applied research areas (Malczewski, 2004).

In literature, we observed numerous applications of coupling GIS with MCDM in the area of agricultural resource management (Ananda & Herath, 2003a), natural resource management (Mendoza & Martins, 2006), urban planning (Bryan, 1988), forest management (Ananda & Herath, 2003b), environmental management (Howard, 1991; Munda, Nijkamp, & Rietveld, 1993), energy policy analysis (Greening & Bernow, 2004), wetland management (G A; Mendoza & Martins, 2006), selection of storm water management options (Gogate, Kalbar, & Raval, 2017) and food security (Renwick, 2015). Alves, Coelho, Coelho, and Pinto (2011) interestingly demonstrates development of coastal zone risk map with the help of vulnerability modelling for the northwest Portuguese Coastal Zone.

Some of literature studies have attempted Analytical Hierarchical Process (AHP) methods for development of disaster resilient index to assess coastal communities (Orencio & Fujii, 2013), conservation of coastal areas in Iran (Pourebrahim, Hadipour, Mokhtar, & Taghavi, 2014), comprehensive framework for coastal reclamation in China (Feng, Zhu, & Sun, 2014), optimizing strategies for protection of coastal landscape (Baby, 2013), protection priority in coastal environment of Taiwan (Chang, Liou, & Chen, 2012) and coastal vulnerability assessment (Sudha Rani, Satyanarayana, & Bhaskaran, 2015). However, utility based and compensatory approaches have not been attempted so far for management of coastal areas in Indian coastal cities.

### *1.3. Problem definition*

The above literature suggests that there is lack of quantitative scientific rational method applied presently in India for classifying coastal areas. The present work attempts to fulfill this gap by developing a coastal area classification method based on GIS coupled MCDM approach. Main objective of this research is to develop area classification method which is technically robust and easy to use for decision making in coastal planning. Such a decision-making method will synergies developmental activities and environment conservation in coastal cities of India by appropriately classifying coastal areas using quantitative approach.

## 2. Methods

Present study relies on application of GIS and MCDM for coastal areas. A case study is used to demonstrate the application of the method. Results obtained from the case study are validated and rigorous sensitivity analysis was performed. The overall methodology followed in this work is represented in Fig. 1. Next sub-sections describes the case study and the methods in details.

### *2.1. Study area*

We selected Mumbai, Indian coastal megacity as primary study area for validation of coastal area classification method using GIS coupled MCDM approach. Coastal area of Mumbai has high environmental value territory exposed to anthropic activities. Furthermore, this coastal area is subjected to major urban issues related to water shortage, seasonal monsoonal flooding, untreated pollution discharge in adjacent creeks, direct solid waste dumping in mangroves (Pacione, 2006). Severe coastal pollution leading to depletion of coastal ecosystem made

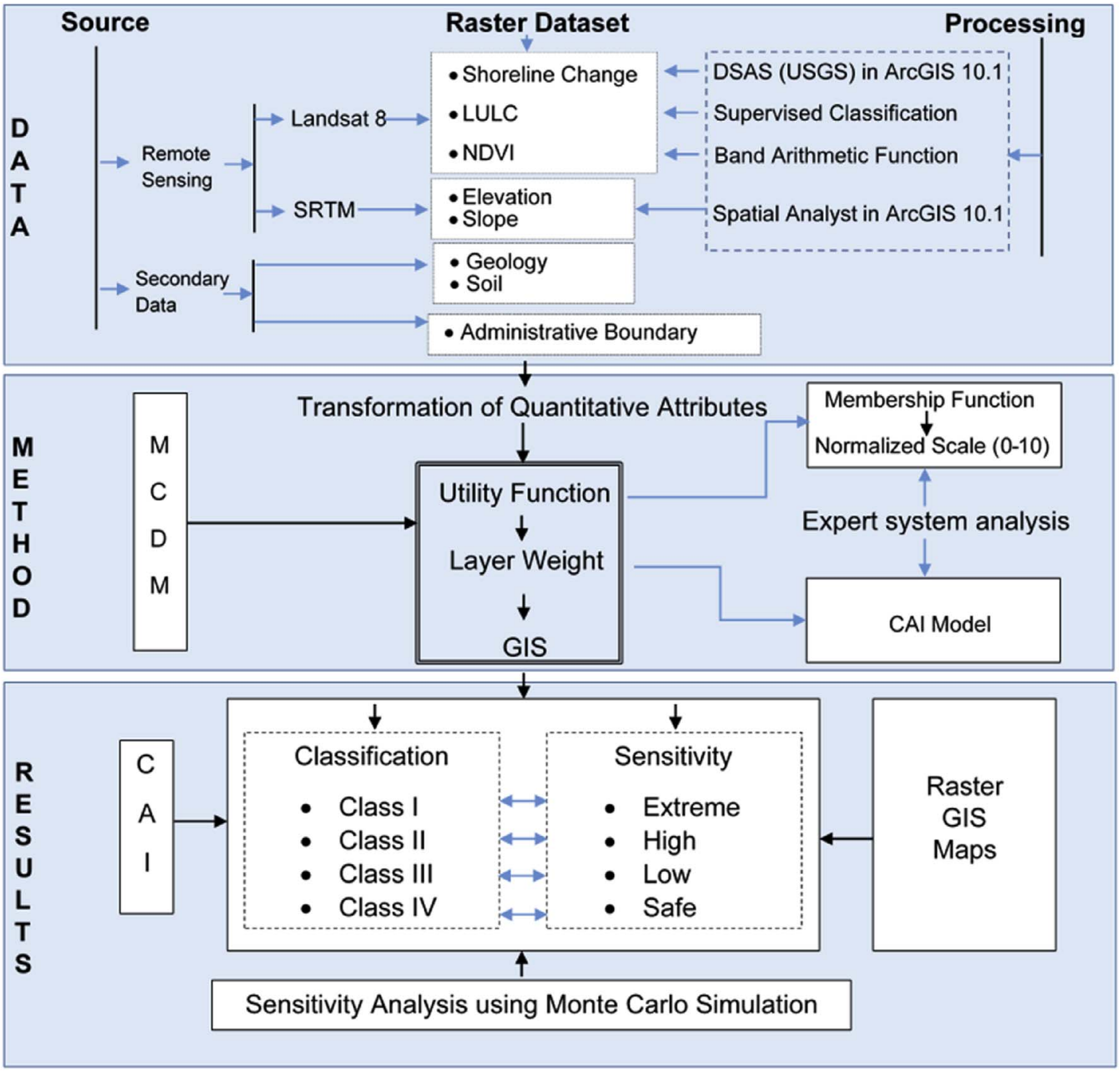


**Fig. 1.** Methodology for computation of CAI using GIS coupled MCDM approach.

the coastal areas unsuitable for environment management and sustainable planning of developmental activities (Murthy, Rao, & Inamdar, 2001).

Present study derives primary datasets from remote sensing which is further processed in GIS and secondary datasets from literature, and other national as well as state level government agencies. A detailed description about sources of data is given in Table 1.

### 2.2. Data processing

This study used remote sensing dataset for year 2016 from LANDSAT 8 (USGS) with a resolution of 30 m for different coastal features (refer to Table 1) for Mumbai coast where we have considered the area within the 1 km range towards land from high tide at intact shoreline of Mumbai coast. Dataset in GIS was processed for estimation of Land Use, Land Cover (LULC) and coastal geomorphology for year of 2016 using supervised image classification technique (Figure S1 in Supplementary Information 1). Land Use in the area is dominated by urbanization (habitation/built-up land) and developmental activities (salt pan, ports) whereas Land Cover is dominated by mangroves, mudflats and marshy land. Some part of the study area is covered under sandy beaches, rocks and vegetation. Coastal slope and elevation measurements are evaluated using satellite imagery from SRTM dataset in GIS (Figure S2, S3). Coastal slope of study area is < 25% and most of the area is below 10 m of elevation characterizing the flat or low-lying topography. Soil and Geology maps for Mumbai city are used as secondary data from Survey of India as shown in Figure S4 and S5 respectively. Raster images of Soil and Geology maps are digitized and geo-referenced in GIS environment. In Mumbai, most land is reclaimed using backfilled soil during the course of the city's development. Study area has majority of reclaimed and marshy soil so there are three major classes of soil type - mud, backfilled and clay. Normalized Difference Vegetation Index (NDVI) maps are being used in agriculture, forestry, ecology and more. Healthy vegetation (or chlorophyll) reflects more near-infrared (NIR) and green light compared to other wavelengths. It

**Table 1**
Types and Sources of Dataset used for GIS coupled MCDM approach.

| Coastal Features | Source | Resolution (meters) |
|---|---|---|
| Geomorphology | Landsat 8 | 30 |
| Land Use | Landsat 8 | 30 |
| Land Cover | Landsat 8 | 30 |
| Shorelines/Inter Tidal Zone | Landsat 8 | 30 |
| Elevation | SRTM | 30 |
| NDVI | Landsat 8 | 30 |
| Coastal Slope | SRTM | 30 |
| Geology | Survey of India | Vector Dataset |
| Soil | Survey of India | Vector Dataset |

absorbs more red and blue light. We have derived NDVI map from Landsat 8 satellite imagery where calculations of NDVI for a given pixel always result in a number that ranges from minus one (−1) to plus one (+1); however, no green leaves gives a value close to zero (Figure S6). Negative values (0 to −1) represent water and zero means no vegetation and close to +1 (0.8–0.9) indicates the highest possible density of green leaves.

Another important aspects for coastal planning is to understand the process of erosion, accretion, sediment transportation along the shoreline to understand the regional dynamic behaviors of the coast (Murali et al., 2015). In recent study, by Cenci et al. (2017) integration of remote sensing and GIS techniques were attempted for management of crucial coastal areas with the help of monitoring and modelling of shoreline changes. We assessed the shoreline change and Inter Tidal Zone (gives insights about erosion and accretion happening at particular location) at temporal scale (2003–2017) using data from various Landsat Missions which is presented in Figure S7. Digital Shoreline Analysis System (DSAS) in GIS is a useful tool for mapping shoreline change and the same is used for this study. Intertidal Zone is the area between HTL (High Tide Line) and LTL (Low Tide Line) and this area is measured using the difference between temporal shorelines at decadal scale in the current study. Further, entire dataset was transformed into raster format which produced pixel based layers for each available coastal feature.

### 2.3. GIS coupled MCDM approach

In this work a novel method for classification of coastal areas based on coastal features in GIS environment using MCDM approach (Fig. 2) is introduced. MCDM, a type of decision analysis, is a structured framework for analyzing decision problems characterized by complex multiple objectives. MCDM can also deal with long-term time horizons, uncertainties, risks and complex value issues (Nijkamp, Rietveld, & Voogd, 1990). Ananda and Herath (2009) has suggested interactive use of the MCDM methods to improve the efficiency of the planning process and advocated the use of more than just one MCDM method or a hybrid approach. GIS-based multi-criteria decision making (GIS-MCDM) approach has extended in recent times to solve planning problems that involve conflicting multi-objectives such as land use allocation problems (Eastman, 1995; Janssen & Rietveld, 1990; Yeh & Li, 1998). In this work Coastal Area Index (CAI) based on GIS-MCDM approach is developed by applying utility membership functions to coastal features for classification of coastal areas according to their importance and sensitivity towards developmental activities.

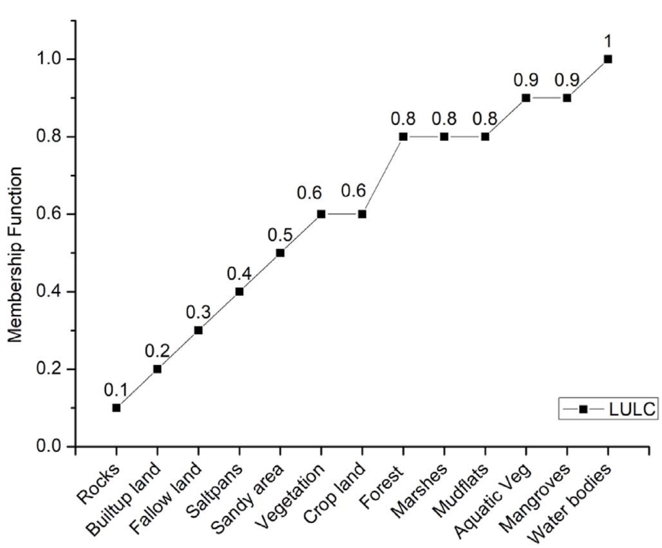


**Fig. 2.** Utility function applied for Land Use and Land Cover.

#### 2.3.1. Use of utility functions for area classification

A utility function can be defined as a mathematical function of preferences assigned to goods or services. Typically, utility function captures the stakeholders' preferences by assigning a utility number to each group of goods and services. Some of the applications of utility function in interdisciplinary research are related to protection of marine area (Fernandes, Ridgley, & Van't Hof, 1999), water policy and supply planning (Joubert, Stewart, & Eberhard, 2003), ground water management (Almasri & Kaluarachchi, 2005), measure of welfare indices (Hajkowicz, 2006) available in literature. Multiple criteria analysis problems deals with indicators having different units which require transformation using a common scale using utility function, mostly 0 to 1, so that indicators can be meaningfully integrated in the overall index (or score).

There are total 6 coastal features i.e. layers (LULC, Geology, Soil, NDVI, Slope and DEM) used for deriving CAI in this work. We established a distinct membership function for each of this layers, transforming individual pixel values into membership values. The established membership function is shown in Fig. 2 for LULC layer and for other coastal features the defined membership functions are given in Figure S8 (a - e). The membership values obtained by applying membership functions to coastal features are used for computing CAI.

For example in Fig. 2, for LULC layer, highest importance or maximum utility value (0.9 and 1) is given to mangroves and water bodies like creeks and estuaries respectively. These higher utility values are supported by the fact that mangroves plays important role in preserving coastal ecosystem. Newton et al. (2012) and Rog, Clarke, and Cook (2017) gives detailed review about importance of mangroves in terrestrial ecosystem. Following the same analogy of valuing the ecosystem services aquatic vegetation was given a membership value of 0.9. Marshes, forest and mudflats were assigned a membership value of 0.8 based on their importance in primary productivity of coastal system (Burford et al., 2016). Similarly, according to the comparative study on faunal biodiversity of Mumbai Coast (Datta et al., 2010), a membership value of 0.6 and 0.5 was assigned to vegetation and crop lands and sandy areas respectively. Referring to literature providing importance of coastal feature such salt pan, fallow land a membership value of 0.4 and 0.3 was assigned respectively (Abadie, Galarraga, & de Murieta, 2017; Surjan, Parvin, Atta-ur-Rahman, & Shaw, 2016).

#### 2.3.2. Development of Coastal Area Index (CAI)

We computed the CAI using membership function values at pixel level for coastal features against individual layer of available dataset. A detailed framework for method is shown in Fig. 1 and computation procedure for CAI is presented in Fig. 3. The membership functions for each layers are derived in normalized scales (0–1) using the earlier mentioned approach. According to importance of these layers ad-hoc weights are assigned based on authors' understanding of the specific case study of Mumbai (refer to Table 2). Further, the normalized values of pixels are multiplied with weights of the respective layers and aggregated by Linear Weighted Sum (LWS) method to obtain CAI.

CAI for the *ith* pixel can be computed using following equation:

$$CAI_i = \sum_{j=1}^{n} w_j . x_{ij} \quad for\ i = 1,2,3....., m \tag{1}$$

Where,

*i* is pixel number in the layer (there are *m* number of pixel in the one layer)
*j* is layer number (there are *n* number of layers)
$x_{ij}$ is the pixel value of the *ith* pixel in the *jth* layer
$w_j$ is the weight of the *jth* layer

The CAI obtained using Eq. (1) is further normalized to express on a scale of 0–10. To check the sensitivity of the applied weighting scheme

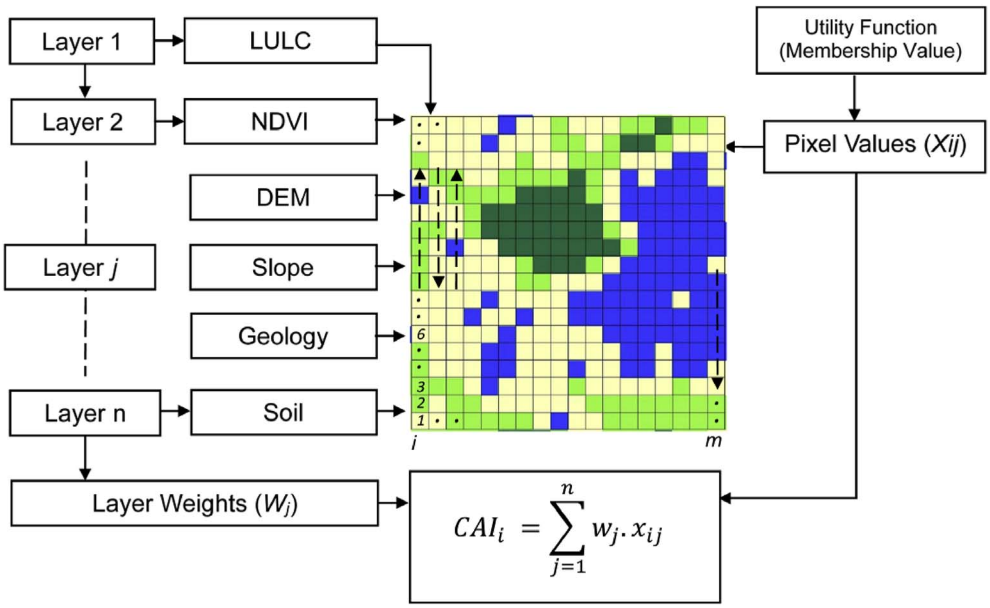


**Fig. 3.** Model description for computing Coastal Area Index in GIS.

**Table 2**
Different Scenarios of weights for sensitivity analysis of CAI.

| | LULC | DEM | GEO | NDVI | SLOPE | SOIL |
|---|---|---|---|---|---|---|
| Ad-hoc Weights | 30 | 20 | 10 | 15 | 15 | 10 |
| Random Weights | 10 | 10 | 25 | 30 | 20 | 05 |
| Equal Weights | 16.6 | 16.6 | 16.6 | 16.6 | 16.6 | 16.6 |

two different weights sets are also tested as shown in Table 2 and explained in next section.

Classification of coastal areas in CAI is based on the sensitivity of coastal features towards developmental activities where Class 1 is extremely sensitive, Class 2 is highly sensitive, Class 3 is moderately sensitive and Class 4 is low sensitive against the anthropogenic development. In CAI, Class 1 is the intertidal zone of coastal Mumbai which is highly dynamic in nature and much important for demarcation of land from sea. Intertidal zones contain high nutrients which supports the productivity of marine life and hence this is considered as no development zone for any kind of developmental activities. Class 2 represent the highly sensitive areas including mangrove covers and mudflats along the coastline and any kind of development should be avoided except environmental conservational activities. Class 3 is moderately sensitive zone and shows the balanced areas for developmental and conservational activities where human interventions can be allowed after comprehensive environmental impact assessment and developing mitigation plans. Finally, Class 4 in CAI is low sensitive because this area is already overexploited for development resulting into depletion of sensitive environmental features. The proposed method for CAI clearly demarcated the boundary lines among these 4 classified areas which is useful for planning process by associated stakeholders such as planning authorities and Urban Local Bodies (ULBs).

### 2.3.3. Sensitivity analysis

Rigorous sensitivity analysis has been carried out to assess the uncertainty and sensitivity of weights assigned to the layers for calculation of CAI using Monte Carlo simulation. Three different scenarios are considered, ad-hoc weights (given by authors considering understanding about case study), equal weights and random weights for layers (coastal features). In this setup, 1000 random numbers with variation of ± 50 of each scenario listed in Table 2 were generated. These values were further transformed and normalized to get the weighting norm as 1 for each of the iteration. The difference between the CAI values obtained using given set of weights and the mean of the CAI results of 1000 test runs normalized with standard deviation, which is basically a z-score, serves as a good indicator of the reliability of the weights (Benke & Pelizaro, 2010; Feizizadeh & Blaschke, 2014).

## 3. Results and discussions

In our present study, we assessed the major coastal features representing physical characteristics *viz.*, – LULC, DEM, Slope, NDVI, Soil and Geology of Mumbai coast. These feature are further quantified into sub-classes at 30 m spatial resolution. The detail maps of these sub-classes are provided in Figure S1-S6 in SI. Mumbai coast is observed under permanent erosion due to developmental activities at specific locations whereas accretion and erosions at seasonal scale are observed along the entire coastline (Figure S7). This assessment of coastal features provides deeper understanding of spatial distribution of physical characteristics along Mumbai coast.

### 3.1. Results of CAI

The main result of this study is CAI for case study area which is shown at 30 m resolution in Fig. 4. As evident from Fig. 4, the CAI demarcates coastal areas in different classes of sensitiveness, which is basically prioritization of coastal areas. Extremely sensitive area is denoted by class 1 which is intertidal zone and it is extremely dynamic (daily and seasonal scale) in nature. Class 1 is independent of computation procedure of CAI as the area which comes under intertidal zone is directly considered as extremely sensitive. Class 2 is designated as highly sensitive and CAI index range for this class is 6–10, majorly distributed along the Thane Creek in Mumbai considering the biodiversity including mangroves, mudflats and other important indicators of primary productivity in the area. Area classified under class 3 of CAI within a range of 3–6 is showing moderate sensitivity because this area is majorly influenced by open spaces and barren land which can be considered for both conservational and developmental activities as per the requirement in the area. Low sensitive area in CAI is represented by class 4 with index range of 0–3, depicting most of the urbanized area in Mumbai City.

To validate the derived CAI in this work, a small area of 540 m × 540 m in Colaba area in Mumbai was selected. As shown in Fig. 5, each layer representing individual coastal feature is illustrated at pixel level (30 m). For example, for LULC layer in this small area of

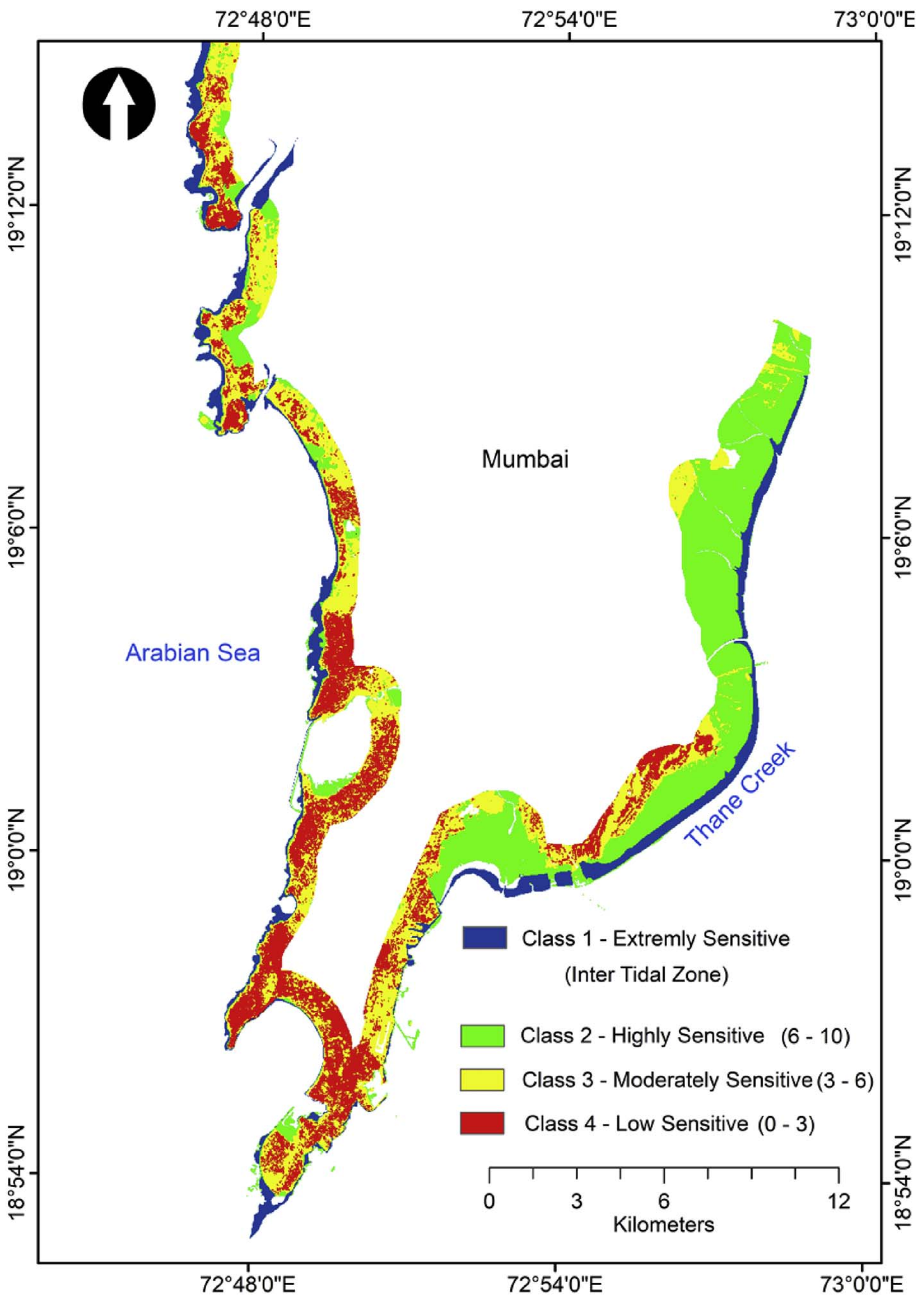


**Fig. 4.** Coastal Area Index for Mumbai showing sensitivity based classification of coastal areas.

0.29 $km^2$, four distinct sub-classes are present which are transformed into membership values using membership function given in Fig. 2. In similar way other coastal features are also transformed into respective membership values. Layer weights are also shown in Fig. 5. Using the mathematical approach shown in Fig. 3, the CAI for each of this pixel is obtained and shown in Fig. 5. If we compare the obtained CAI value for each pixel with satellite imagery of the Colaba region under evaluation, the CAI values objectively classifies this area into distinct CAI indices. For example, we have demonstrated the calculation of CAI for one corner most (southernmost) pixel in Fig. 5. For this pixel the CAI was estimated to be 6 and the area attributed for this pixel in the image is vegetation surrounded by built up area, which was also confirmed by the field visit to this area, hence it is classified as moderately sensitive. This shows that CAI is a robust measure that can be used for classifying urban coastal areas.

### *3.2. Sensitivity analysis*

The CAI in this study is derived using applying weights to the layers. This induces uncertainty in the CAI values. CAI results for first scenario (based on ad-hoc weights) are shown in Fig. 4. For the other two scenarios results of CAI are shown in Figure S9 (a, b). These results of CAIs shows significant disagreement between the three scenarios.

In Monte Carlo simulation setup for sensitivity analysis, we obtained the z-score which is the difference between the CAI results of a given ad-hoc weight and the mean of 1000 test runs of CAI values normalized using standard deviation obtained using ad-hoc weights. Results of this test are shown in Fig. 6 (a). The z-score lies between $-1$ and 1 for ad-hoc weight scenario.

Similar approach of quantifying sensitivity for equal weights and random weights are followed and results are presented in Fig. 6 (b, c). These figures shows that high sensitivity of the applied weighting schemes in both scenarios. For example, the difference between mean of the CAI results of 1000 test runs and the CAI values obtained using

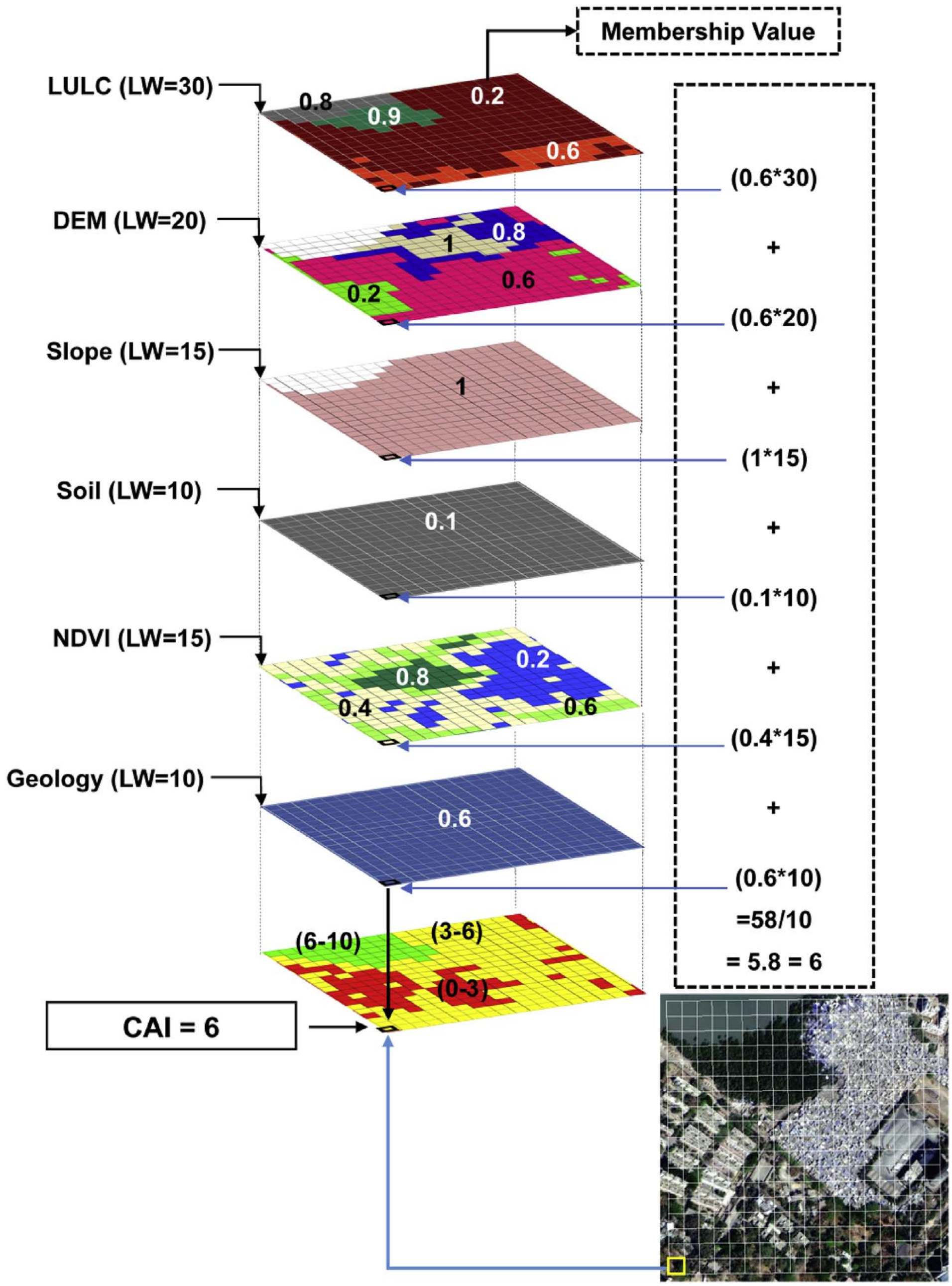


**Fig. 5.** Validation of CAI at selected location Colaba in South Mumbai and demonstration of the computation of the CAI for lower most left pixel (highlighted by the dark border). Membership function values are multiplied by the layers weights (LW) and aggregated to obtain CAI.

equal weights, the z-score of this test, lies in the range of −1.5 to 1.5 whereas for random weights z-score lies in the range of −2 to 2. These values are almost 2 times higher than the ad-hoc weighting scheme scenario results of sensitivity analysis. Hence, it is shown from these results that, ad-hoc weights are more robust in providing CAI for given case study (i.e. ad-hoc weights are less uncertain while compared with equal and random weights). Further, it can be argued that in comparative assessment of three scenarios with variation in layer weights shows that ad-hoc weights obtained using domain experts are most decisive in uncertain conditions.

To ascertain the sensitivity results towards applied aggregation method for deriving CAI, we also checked the correlations among different layers of coastal features and results are presented in Table 3. There exists no significant correlation among the layers which suggest that all different layers are independent and therefore there is no interdependence between these layers. Hence, as recently reported in (Kalbar, Birkved, Nygaard, & Hauschild, 2016) if the indicators are not interdependent then simple aggregation methods such as LWS can be used to derive the aggregated indices. Hence, the LWS approach and the ad-hoc weights that are used to derive the CAI in this study both provide robust and transparent results of coastal area classification.

### 3.3. Limitations and future prospects

The methodology applied in this work is based on GIS - MCDM approach using weighted aggregation method. Detailed sensitivity analysis was carried to demonstrate uncertainty associated with the weighting scheme and applied aggregation method. Still there are some limitations applied to this work which are listed below and future direction of work that can address these limitations is suggested.

i. Applicability of CAI developed in this work is dependent on spatial resolution of available datasets in GIS. A better resolution of remote sensing imagery will give the better result under same testing conditions.
ii. The CAI index is heavily dependent on utility functions applied to

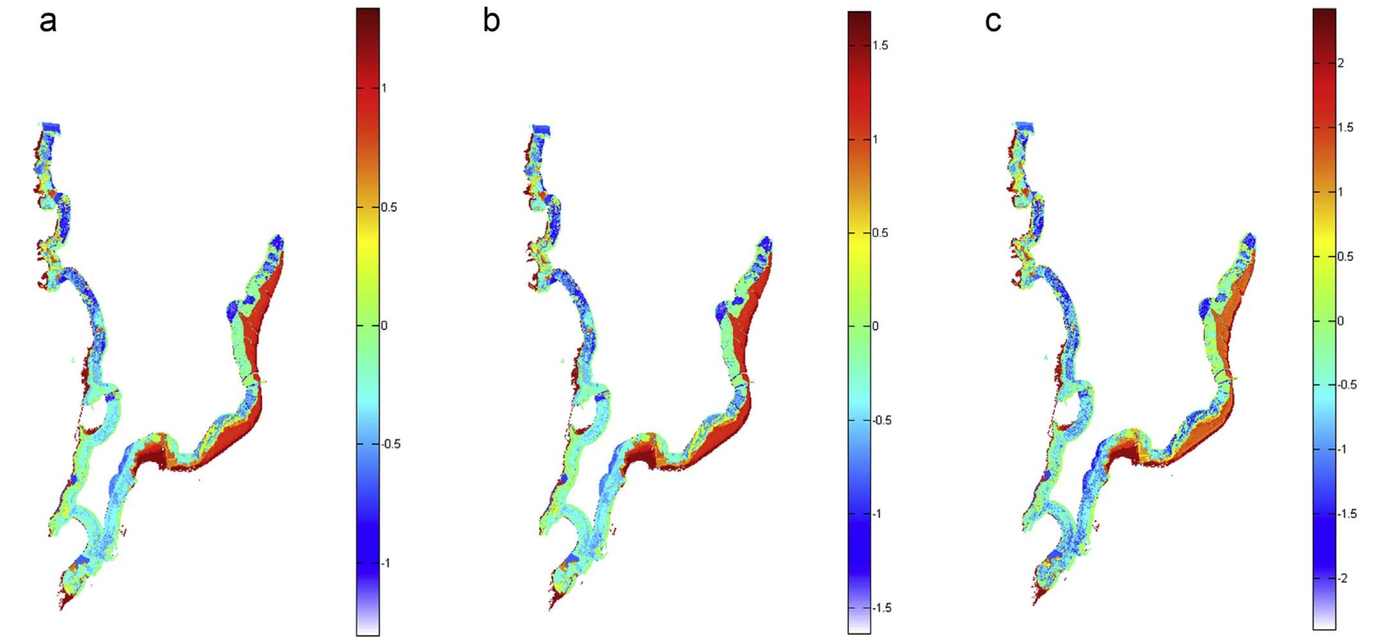


**Fig. 6.** (a) Comparison of CAI and relative mean of 1000 runs normalized with standard deviation for Ad-hoc weight scenario (z-score is shown on the axis). (b) Comparison of CAI and relative mean of 1000 runs normalized with standard deviation for equal weight scenario (z-score is shown on the axis). (c) Comparison of CAI and relative mean of 1000 runs normalized with standard deviation for random weight scenario (z-score is shown on the axis).

**Table 3**
Correlation matrix for membership function (pixel value) of different layers* ($R^2$ values, Pearson Correlation).

| | LULC | DEM | GEO | NDVI | SLOPE | SOIL |
|---|---|---|---|---|---|---|
| LULC | 1 | 0.459 | 0.343 | 0.588 | −0.006# | 0.425 |
| DEM | | 1 | 0.393 | 0.267 | 0.136 | 0.443 |
| GEO | | | 1 | 0.134 | 0.038 | 0.339 |
| NDVI | | | | 1 | −0.025 | 0.276 |
| SLOPE | | | | | 1 | 0.088 |
| SOIL | | | | | | 1 |

*All the values of $R^2$ are significant at the level of 0.001 except the value marked with #.

transform the GIS data into membership values used for aggregation. In this work we have defined the utility function based on the literature and our judgments, this has added the uncertainty to the results. Different utility functions can be tested in future to derive CAI.

iii. LWS method is applied for the aggregation of the weighted membership values. It is well known that aggregation functions applied change the final index and hence other methods of multi-criteria decision making should be applied and tested (Kalbar, Karmakar, & Asolekar, 2015).

iv. The test case for this work is Mumbai city and hence application of CAI in other coastal areas should be carried out only after validation and calibration.

## 4. Conclusions

Coastal area classification presents numerous challenges that have been elaborated in the current work. The lack of scientific rational in Indian coastal zone classification policy has been identified in this work. A novel GIS-MCDM based CAI approach to classify urban coastal areas has been proposed to serve as scientific rational for coastal area classification.

The developed approach is transparent where physical characteristics of coastal areas are transformed into quantitative measurements. Utility based membership functions are developed and applied to each of the coastal features. Weights are applied to each of the layers and results are aggregated into one index, called CAI. The applicability of the CAI is demonstrated using Mumbai city case study. The robustness of the results are validated using rigorous sensitivity analysis. The results of sensitivity analysis showed that the weights and membership functions used to derive CAI presented lower uncertainty than compared to the equal weights and random weight scenarios.

The methodology used is based on decision science where criteria relies on physical utility of coastal features rather than the subjective interest of stakeholders. This study provides the decision making framework for location specific coastal area classification. Classification of coastal areas based on proposed CAI will facilitate planning based on scientific principles. CAI generates the distinct categories of coastal areas where most effective urban coastal management options can be proposed. The CAI computation method is modular and scalable in nature and can be applied to different locations and datasets easily. Thus the CAI approach can further be used for developing integrated framework for sustainable coastal management.

The CAI results showed the usefulness to serve as decision support approach for urban planners and ULBs for classifying urban areas. We hope that CAI will be taken up by the researchers and the practitioners and will be widely used for classifying urban coastal areas by policy makers, coastal managers, coastal communities and other associated stakeholders.

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## Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.habitatint.2017.12.002.

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