# Beyond the tradition: using Fuzzy Cognitive Maps to elicit expert views on coastal susceptibility to erosion in Bangladesh

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## Abstract

This paper portrays the application of Fuzzy Cognitive Maps (FCMs) to elicit expert views on current condition and future scenario of coastal susceptibility to erosion in Bangladesh. The geomorphological characteristic of the coastal area is highly dynamic where land erosion and accretion with different rates are constant phenomena. This research focuses on three coastal zones: western, central and eastern that comprise the entire coastal area of the country. Using 'Mental Modeler' software this study quantified experts' judgements on the issue and developed FCMs by way of arranging workshops. At the basis, this study identified 33 factors of susceptibility to erosion for current baseline conditions. Considering future projections of hydro-climatic phenomena, this study accentuated potential factors of susceptibility to erosion for future scenario under three time-slices: near-future (2020), future (2050) and far-future (2080). The results generated from FCMs show that some factors such as sedimentation, soft and unconsolidated soils, shelf bathymetry, funnel shape of the Bay of Bengal, wave action, river discharge, monsoon wind, cyclone and storm surges, excessive monsoon rain, high tidal energy, variations of tidal range and sea level rise are highly influential that yielded higher centrality scores for both current and future susceptibility of the area to erosion. The experts' interpretations demonstrate that the future susceptibility to erosion might be higher in the central zone compared to the western and eastern zones of the coastal area. This is the first time that FCM based approach was applied to evaluate expert views on coastal susceptibility to erosion for the country. This study suggests coastal managers, planners and policymakers to consider the current and future factors of susceptibility of coastal lands for taking specific measures options. This study is also significant from socio-economic and demographic contexts of any densely populated coastal area like Bangladesh.

**Key words:** accretion; coast; erosion; FCM; susceptibility.

## 1. Introduction

Coastal areas of the world are identified as important zones for human settlement where about 21% of world population lives within 100 km distance of the coasts (du Gommes et al. 1997; Brooks et al. 2006; IPCC, 2007a). These areas are marked as buffer zones between land and sea that are physically dynamic in nature (Hanson and Lindh, 1993). Coastal erosion is taking place in about 70 percent of world's beaches in different forms (Ghosh et al., 2015). It is reported that the magnitude and frequency of climate induced coastal disasters are increasing as a result of global warming and consequent sea level rise (Choi et al., 2016). This situation might increase the future rate of erosion in coastal areas of the world. However, the coastal area of Bangladesh is highly dynamic where erosion and accretion of land is a continuous process. The coastal area of the country is densely populated (949 persons/ km$^2$) that comprises 32 percent of the total land area and 28 percent of the total population (Islam, 2004). Hence, interpretation of susceptibility to erosion in the coastal area is an important task for Bangladesh society.

The susceptibility of the coastal area to erosion depends on a number of factors (often termed as forces). Some are endogenic forces (from interior of the earth) such as the shifting of river channels by earthquake and some are exogenic forces (on the earth surface) such as the changes in geomorphology (Sarker et al., 2011). The driving forces can also be categorized as physical factors and human induced factors. The physical factors ranging from earthquake, sedimentation and sea level rise to wave action, rainfall, prevailing south-western wind, soil compaction, vegetation cover, and storm surges etc. whereas, human induced factors ranging from construction of embankments, polders and dykes to deforestation, cross dam and modification of river flow etc. (Goodbred et al., 2003; Brammer, 2014). The variation of susceptibility to erosion in different parts of the coastal area relies on the combined strength of these physical and human-induced factors and hence the factors do not act in a simple static way. Very often, one of the factors might be a dominating driving force for a region, which might not be common for another areas of the coast.

However, the effects of climate-driven factors such as water discharge, rainfall, wind speed, tidal variation and mean sea level etc. are found to be varied in the coastal area of the country for the last few decades (Huq et al., 1999). Hence, the rate of changes in coastal lands could further be increased by future changes in climate and associated sea level rise. For instance, rapid geomorphological changes are taking place in the Meghan estuary of the central coastal zone (Karim and Mimura, 2006; MoEF, 2007) that might be the result of such changes. Furthermore, future sea level rise could accelerate erosion in relatively older lands of major islands in the Meghna estuary (Brammer, 2014). The changes in future drivers could lead to the changing morphological pattern as well as current susceptibility of the coastal area to erosion in future. However, there is still a great uncertainty in research as to how exactly the drivers of land dynamics (e.g. erosion and accretion) are influenced by the rising sea level (Huq et al., 1999). It is also uncertain how the coastal areas of Bangladesh will respond with future changes of climate scenarios.

Coastal susceptibility to erosion has largely been studied by applying different approaches, methods and techniques such as GIS based Decision Support Systems, Dynamic Computer Modeling and Coastal Vulnerability Index (Ramieri et al., 2011). Since a number of physical and human-induced parameters are associated with coastal susceptibility to erosion, it is uncertain how precisely the aforementioned methods address the factors of coastal susceptibility to erosion. Furthermore, the evaluation of individual contributions of parameters in computer-based models require a number of sensitivity tests that would necessitate more time and manpower for computations. However, to expand knowledge on the issue beyond the traditional approach of generating computer-assisted models bears significant reasons. In reality, scientific knowledge essentially generate from humans which can largely be influenced by social, cultural and political values (Edge, 1995). The scientific ‘truth’ generally falsify the previous truth (Popper, 1963) and hence, exist more than one truth in the scientific community on any concerned issue (Kuhn, 1962). Expert views are important to expand knowledge on a dynamic system (Morgan et al., 2001). Expert judgements are considered to be more diverse in nature (Hansson and Bryngelsson, 2009) that may lead to ascertain a comprehensive representation of a system. Moreover, individuals at local levels have their ‘hazard perception threshold’ (Kates, 1971) that depends on their knowledge, perceptions and experiences on any hazards. Additionally, scientists and experts are considered as most highly trusted sources of information (Hargreaves et al., 2003; CLAMER, 2011) since, their knowledge is based on shared understanding of established facts and theories (Breakwell, 2007).

There are two types of ‘temporal repertoire’ in the scientific community regarding how the experts think about future (van-Asselt et al., 2010). The first group follows historic determinism in which, future can be determined by considering the past and present whereas, the second group follow futuristic difference in which the future is disconnected from past. In particular, most of the reports that addressed climate uncertainties are inclined to central tendency of model values (Kunreuther et al., 2013) and hence are not as critical for the governments as a full exploration of uncertainty (Oppenheimer et al., 2007). In contrast, the process of presenting expert views by subjective probability elicitations is an established approach (Spetzler and Stael, 1975) in which individuals’ probabilistic idea can be converted into numbers (Jenkinson, 2005) as well as allow individuals to rate the levels of uncertainty on the given idea (Zickfeld et al., 2007). However, addressing future by way of generating cognitive maps is more participatory in nature that represents individual's unique knowledge structure (Kearney and Kaplan, 1997). Cognitive maps facilitate to address multiple viewpoints of different experts since, the ideas and viewpoints on a particular issue are reasonably different among experts (Zickfeld et al., 2010). Additionally, changes in knowledge is an intrinsic human nature where existing mental construct can be replaced by the assimilation of new knowledge (Boyle, 1969). Mental models carry essence in that the decisions people take, can largely be determined by the cognitions and perceptions they have in their mind (Breakwell, 2007). Mental models are good representations of datasets that derive from reasoning (Oberauer, 2006) and hence, able to provide a reliable ground for evaluating perceptions. Moreover, cognitive approach has been used for previous researches to evaluate the perceptions and understanding of individuals on climate change and hazards (Bostrom et al., 1994; Lowe and Lorenzoni, 2007). However, the nexus between future climate scenarios and coastal susceptibility to erosion has yet to be evaluated by applying cognitive approach at local, regional as well as global levels.

In recent years, Fuzzy Cognitive Mapping (FCM) has become a popular participatory method. It has been used in fields ranging from fisheries management to agricultural development, climate vulnerabilities, environmental problems and policy design (Gray et al., 2014a). The benefits of using the approach are attached to the popularity of using 'bottom-up' approach and their ability to incorporate a range of individuals, community and expert into an accessible and standardized format (Gray et al., 2014b). Although Fuzzy Cognitive Map (FCM) based modeling approach is highly suitable for future studies (Jetter and Kok, 2014), only a few studies (Amer et al., 2011; Biloslavo and Dolinsek, 2010; Jetter and Schweinfort, 2011; Salmeron et al., 2012; Soler et al., 2012; van-Vliet, 2011) are identified in the field of climate change and natural disasters. Most of the studies were mainly devoted to focus future states of wind and solar energy and land cover changes. There is, however, still a great scope of using FCM based mental modeling approach for future climate change, hazard and disaster related issues (Gray et al., 2014b). The adoption of experts' judgements by FCMs insights into not only the details of the problem but also identify the causal relations among and between both physical and human-induced driving forces (Jetter and Kok, 2014; Moschoyiannis et al., 2016).

This study applied FCM based approach to evaluate experts' judgements on the current components associated with the coastal susceptibility to erosion in Bangladesh. This study then identified potential factors of future susceptibility of the coastal area to erosion with an aim to address the impacts of future changes in climate drivers on erosion susceptibility in the area for different time-slices. This research addressed the implicit assumptions of experts' opinions into explicit causal-relations among and between a number of physical and human induced components of current and future susceptibility of the coastal area to erosion. The study supports discussion on the interrelationships between different components of coastal susceptibility to erosion that would be useful for coastal managers and policymakers in managing coastal lands.

## 2. Data and methodology

### 2.1. Study area

The reason for choosing the coastal area of Bangladesh is due to its dynamic nature along with diverse coastal characteristics identified by IPCC (2007 a, b) that includes most of the natural coastal systems such as beaches, deltas, estuaries, lagoons and mangroves. The total coastal area covered is 47,200 km² (MoEF, 2007) which includes the land area (including islands), internal rivers, Meghna estuary and near shore water bodies (Fig. 1). The inland boundary of the coast from the coastline has been fixed up to the threshold limit of tidal movement with having both direct and indirect influences of the Bay of Bengal. On the basis of geomorphological characteristics, Pramanik (1988) first divided the coastal area into three zones: western, central and eastern (Shibly and Takewaka, 2012). These three zones cover approximately 27150 km², 12040 km² and 8010 km² of the coastal lands respectively. Based on the exposure to the Bay of Bengal, the coastal area can also be marked as interior coast (23265 km²) and exterior coast (23935 km²) (PDO-ICZMP, 2006; Islam et al., 2006). The exposed coast directly merges with the Bay of Bengal and the lower Meghna estuary (MoWR, 2005) and hence, highly influences by the tidal movement, salinity, cyclone etc. (PDO-ICZMP, 2006).

The coastal area of Bangladesh possesses diverse characteristics in terms of underlying physical elements such as geomorphic heights and features, bathymetry, soil and geological formation and hydro-climatic conditions such as discharge of water from coastal rivers, rainfall, mean sea level and wind speed and directions. For instance, geomorphic heights of the coastal land ranging from 0 meter to 327 meters but, most of the areas fall between 0 to 6 meters of height from mean sea level (USGS, 2017). The heights of the areas attached to coastline and the islands ranging from 0 to 3 meters whereas, the eastern zone of the coast along with Meghna estuary belongs to 3-6 meters of height . However, the interior coastal areas bear 6-9m and 9-12m heights and the heights of eastern Chittagong hilly areas are beyond 12 meter. In contrast, the off-shore bathymetry represents a depth ranging from 0 to -1096 meters whereas the near-shore bathymetry represents a depth ranging from 0 to -44 meters (MGDS, 2017). The central estuarine part of the coastal area characterizes with varying depths. The upper portion of the Sandwip island shows the depth ranging from -32 to -44 meters. The meghna river channels have the depth ranging from -20 to -32 meters. But, the depths in most of the eastern coast vary from -6 to -20 meters. However, the geological formation of the coastal area is segmented into 21 types of geological areas (BARC, 2017). The interior part of the coast mostly exhibits pleistocene and pliocene formations, deltaic silt and marsh clay and peat whereas, the exterior coast governed by estuarine deposits, pleistocene and neogene formations, tidal deltaic deposits and tidal muds. In addition to geological formations, about 63 percent of the coastal soils are inclined to moderate and rapid permeability classes which indicates the higher susceptibility of the soils to erosion whereas, 94 percent of the Meghna estuary area fall under this moderate to rapid permeability classes.

The hydro-climatic characteristics of the coastal area vary between the seasons and zones. For instance, the discharges from existing major rivers in the area show the lowest values 13.76, 4.30, 4.69, 29.07 and 16.06 $m^3/s$ and highest values 30626, 8816, 14013, 65396 and 34280 $m^3/s$ of water for yearly average, winter, pre-monsoon, monsoon and post-monsoon seasons respectively (BWDB, 2016). Mean sea levels of six stations set by Bangladesh Inland Water Transport Authority (BIWTA) demonstrate the mean value as 1.58 meter whereas, the histogram of the data for reveal that most of the values fall between the range of 1.61 and 2.76 meters (BIWTA, 2017; PSMSL, 2017; UHSLC, 2017). Moreover, the lowest values 1.84, 1.61, 1.72, 2.12 and 1.95 meter and the highest values 3.50, 3.20, 3.41, 3.78 and 3.53 meter of mean sea levels found for yearly average, winter, pre-monsoon, monsoon and post-monsoon respectively. However, the average rainfall in the coastal area ranges from a low of 123 millimeter to a high of 301 millimeter whereas, the minimum and maximum rainfalls vary for different seasons (BMD, 2016). The minimum rainfalls of 10.22, 90, 303 and 86 millimeter and the maximum rainfalls of 16.79, 186, 896 and 176 millimeter were found for winter, pre-monsoon, monsoon and post-monsoon seasons respectively. Most part of the eastern coast exhibits a higher rainfall whereas, the estuarine and central parts of the exposed coast also show moderate to high rainfall. The wind speeds in the coastal area vary from a low of 0.76, 0.52, 1.15, 0.96 and 0.36 m s-1 to a high of 2.79, 1.99, 3.49, 3.84 and 1.86 m s-1 for average, winter, pre-monsoon, monsoon and post-monsoon respectively (BMD, 2016). The maximum speeds blow over the eastern and the central zones of the coast area.

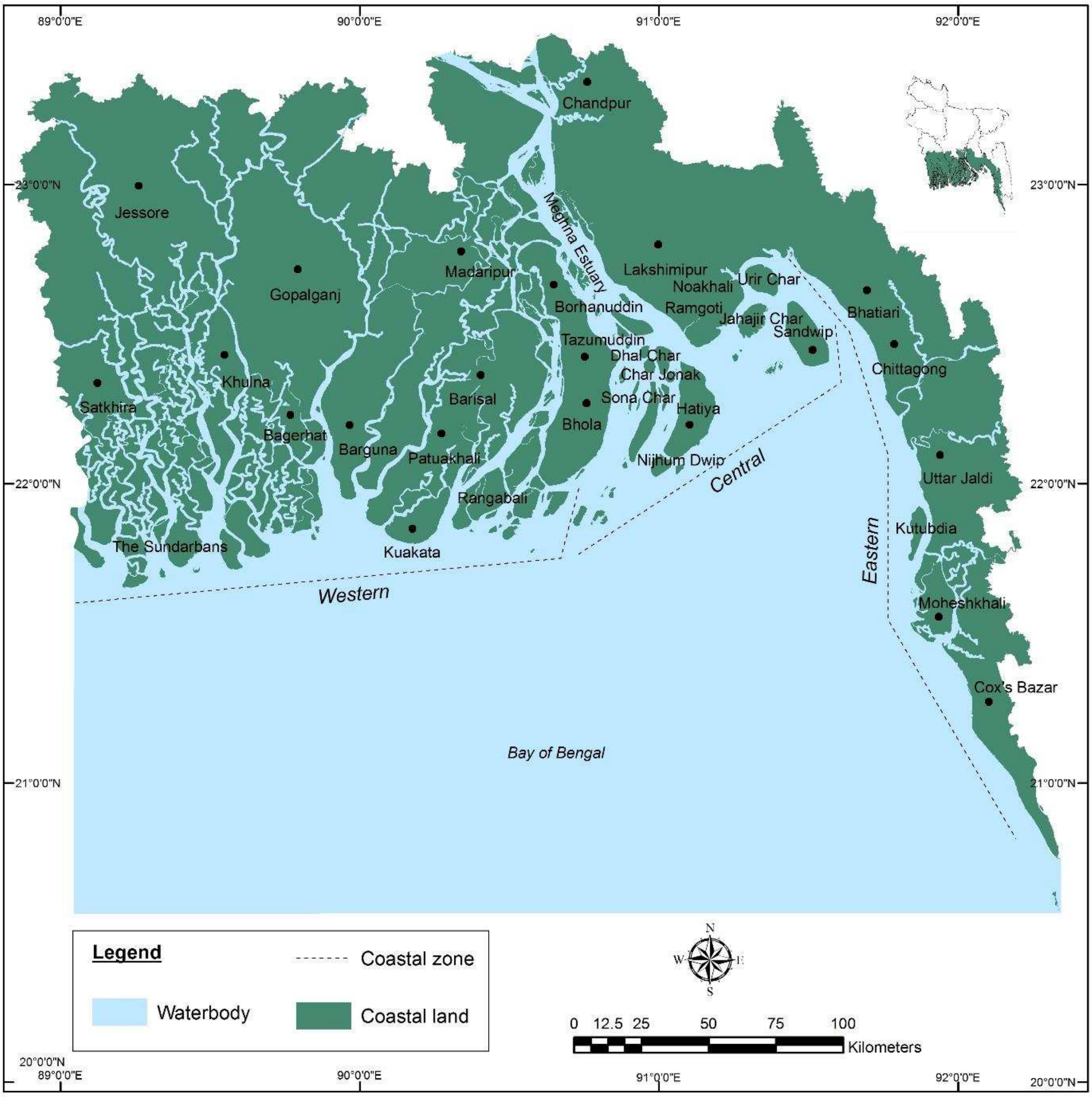



**Fig. 1.** The study area (coastal area of Bangladesh).

## 2.2. Concept of FCMs

Fuzzy Cognitive Mapping (FCM), originally developed by Kosko (1986), is a semi-quantitative method to structure qualitative knowledge and perceptions of an individual (Gray et al., 2015). The outputs are cognitive maps that represent structured associations of a person's internal knowledge on a specific subject (Novak and Caňas, 2008). Fuzzy Cognitive Maps (FCMs) comprise variables and map the causal relationships between those variables identified by individuals (i.e. experts) (Özesmi and Özesmi, 2004). Fundamentally, FCMs represent a system graphically that depict the nature and degree of relationships between concepts and their individual weights (Fig. 2) (Gray et al., 2015). The directed logical connections between concepts build the structures of FCMs (Novak and Caňas, 2008) that derive from constructivist psychology (Gray et al., 2014a). Individuals construct knowledge by way of using their internal associative representations (Raskin, 2002) in which FCMs are external illustrations of that knowledge (Jones et al., 2011). FCMs provide the base of participatory outputs that formulate the foundations of quantification which eventually bridge the gap between storylines and models (van-Vliet, 2011).

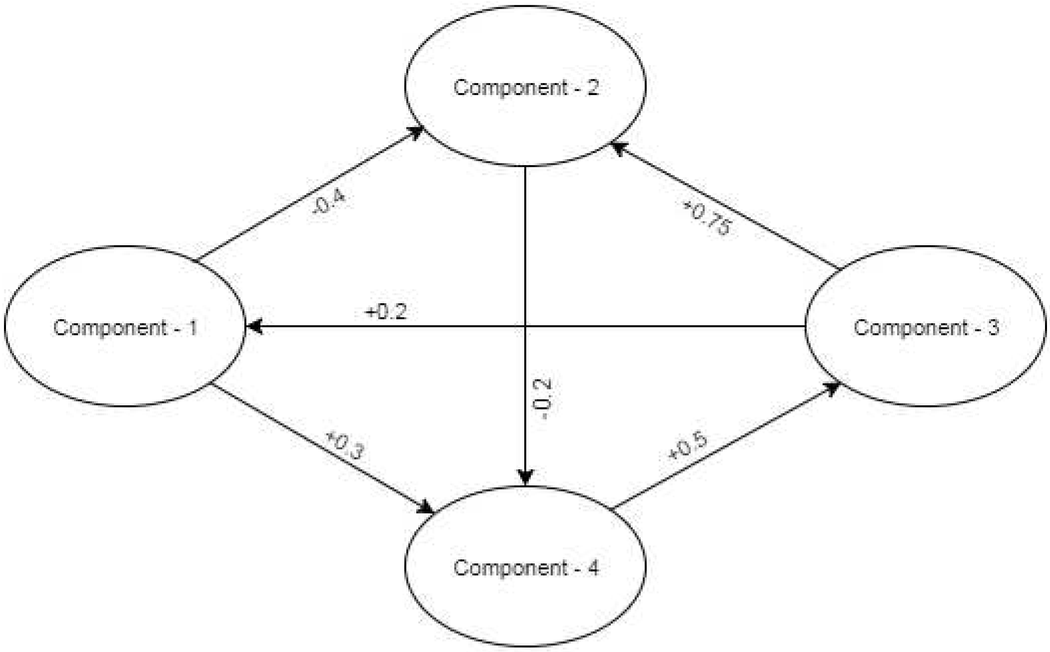



**Fig. 2.** Example of a generalized Fuzzy Cognitive Map (FCM).

**Table 1:** Adjacency matrix recorded from the example in figure 2.

| | Component -1 | Component -2 | Component -3 | Component -4 |
|---|---|---|---|---|
| Component -1 | 0 | -0.4 | 0 | +0.3 |
| Component -2 | 0 | 0 | 0 | -0.2 |
| Component -3 | +0.2 | +0.75 | 0 | 0 |
| Component -4 | 0 | 0 | +0.5 | 0 |

Using basic principles of fuzzy logic, FCMs construct highly structured and parameterised cognitive maps (Glykas, 2010) in influential diagrams (Gray et al., 2015). Since FCMs use the notions of cognitive mapping and are semi-quantitative, they can be represented by mathematically pairwise associations either qualitatively such as low, medium and high or quantitatively by assigning negative (-1) to positive (1) weights of connections between concepts (or nodes) (Wei et al., 2008). The strength of relationships can be measured by calculating simple mathematical average of these pairwise weights of the connections in an adjacency matrix (Table 1).

**2.3. FCMs structure**

The generation of FCMs can be accomplished by using a number of available software such as FCMapper, FCM Modeler, FCM Designer, Mental Modeler, Java FCM, Intelligent Expert System based on Cognitive Maps (ISEMK) and FCM Tool (later on FCM Expert) (Felix et al., 2017). This research used 'Mental Modeler' software to visualize expert views on coastal susceptibility to erosion by generating FCMs. The benefit of using this software inclined to its web-based modelling implementation (Felix et al., 2017) that is freely available to use. This software is highly suitable for generating FCMs in a workshop involving experts and stakeholders where relevant experts are asked to quantify themselves their storylines, depending on their knowledge and experience.

The structural design of FCMs in 'Mental Modeler' software is segmented into three interfaces: concept, matrix and scenario. In concept mapping interface, the identified concepts by the experts can be shown. Concepts are the variables (components) in FCMs in which, higher number of variables represents higher concepts in the model (Özesmi and Özesmi, 2004). The matrix interface includes concepts and connections (positive and negative) between the concepts. Concepts can be of three types: transmitter, receiver or ordinary depending on the nature of relationships. Transmitter concepts are those which have forcing functions and effect other components but are not be affected by others. Receiver components are those which have only receiving functions and are affected by other components in the system but have no effect on others (Eden et al., 1992). On the other hand, the components that have both transmitting and receiving functions in the system are marked as ordinary components. Connections indicate the interactions between variables; a higher number of connections symbolises a higher degree of interactions and vice versa (Özesmi and Özesmi, 2004). A positive connection (blue tint) resembles the increase of influence of a transmitter component over a targeted receiver component whereas, a negative connection (grey tint) indicates an inverse condition. For instance, if experts are of the opinion that 'monsoon wind' could increase the 'wave action' then there will be a positive relationship between the transmitter (monsoon wind) and the receiver (wave action) in the FCM model and the matrix of this relationship will show a positive value (e.g. 0.45) of the degree of influence on a scale of -1 to 1. An inverse relationship can be established where the influence between a transmitter and a receiver is potentially negative. It is important to note that the FCMs are efficient to address the types of influences or relationships (i.e. positive, negative) but, lacks in mapping the kinds of relationships (e.g. linear, non-linear, exponential etc.). However, the word 'fuzzy' itself necessarily means no strict patterns of relationships between components in the FCMs.

Each of the FCMs provides values for in-degree, out-degree, centrality, complexity and density scores for the model. In-degree (id) is the sum of column of absolute values of a particular variable in the matrix that indicates the inward cumulative strength of relationships (Equation 1) where N is the total number of variables and $a_{ki}$ is the cumulative strength of relationships entering into that variable (Nyaki et al., 2014). On the other hand, out-degree (od) is the sum of row of absolute values of a particular variable in the matrix that indicates the outward cumulative strength of relationships (Equation 2) where N is the total number of variables and $a_{ik}$ is the cumulative strength of relationships exiting from that variable (Nyaki et al., 2014). Whereas, centrality ($C_D(V)$) is the sum of both in-degree and out-degree (Equation 3) that measures the relative importance of a component within the FCMs (Gray et al., 2014b). In connection with centrality, a complexity score of a FCM indicates a ratio of receiver variables to transmitter variables that is a measure to which outcomes of driving forces in the system are considered. The density score indicates the number of connections compared to the number of all possible connections in the system (Özesmi and Özesmi, 2004).

$$\mathrm{id}(v_i) = \sum_{k=1}^{N} \overline{a}_{ki} \qquad (1)$$

$$\mathrm{od}(v_i) = \sum_{k=1}^{N} \overline{a}_{ik} \qquad (2)$$

$$c_D(V) = \sum \big(id(v) + od(v)\big) \qquad (3)$$

### 2.4. Selection of experts

There is always being a predisposition to amalgamate the margin between experts and public (Collins and Evans, 2002). However, it bears importance to distinguish between these two groups of people in order to develop cognitive models based on expert judgements. Fundamentally, there is no universally accepted definition based on what experts can be separated from public (Lowe and Lorenzoni, 2007). Experts can be defined based on their approach of explaining a particular problem (O'Hagan et al., 2006). They can also be defined based on their acquired experiences on the concerned topic (Collins and Evans, 2002). However, they can simply be defined as the individuals whose knowledge we think to be elicit (Garthwaite et al., 2005). The most important factors of selecting appropriate experts depend on their expertise, experiences, perspectives and publications (Lowe and Lorenzoni, 2007). Some other factors might include their balance of view and availability (Arnell et al., 2005). However, there are two approaches in terms of whose knowledge is being modelled: traditional expertise and non-traditional expertise (Gray et al., 2014a). Traditional experts are those who have in-depth understanding of the concerned problem. In contrary, non-traditional experts include stakeholders where participatory planning and management need to be given priority. In relation to the selection of experts, there are two separate methods as to how FCMs can be collected: individual and group modeling (Gray et al., 2014a). However, the strength of group facilitation over individual collection relies on the free association of concepts in FCMs.

This study identified 15 relevant experts considering that they have threshold experience and expertise on the issues concerned (Table 2). This number of selected experts followed no sampling procedure since it is recommended (Morgan and Keith, 1995) to select favourable number of experts with a view to obtain diversified opinions from the experts. Instead, an in-depth review of available literatures has been carried out prior to the workshops with a view to understand that what sorts of knowledge gaps can be covered by integrating expert views in FCMs. Furthermore, coastal susceptibility to erosion largely influenced by a number of local and regional forces and hence, the selected experts were local having international exposure on their field of expertise.

**Table 2:** List of experts participated in the study. To make the study anonymous, the names and institutions of the experts are not provided herewith (alphabets are used instead).

| Expert | Expertise | Affiliation | Year of experience |
|---|---|---|---|
| A | Coastal geomorphology | Academic | 14 |
| B | Coastal sedimentation | Academic | 8 |
| C | Meteorology | Government | 10-11 |
| D | Climate change | Academic | 8-10 |

| | | | |
|---|---|---|---|
| E | Soil science | Government | 14-15 |
| F | Water management | Government | 16 |
| G | Modeling coastal dynamics | Consultant | <6 |
| H | Marine science | Academic | 5-6 |
| I | Geology | Academic | 13-14 |
| J | Hydrology | Academic | >8 |
| K | Coastal zone management | Government | 11 |
| L | Land dynamics | Academic | 9 |
| M | Land policy | Government | 15-16 |
| N | Land management | Government | 8-10 |
| O | Forestry | NGO | 5 |

This study invited the selected experts in workshops where face-to-face interactions among the experts were possible. This method of interactions bears essence that expedite a continuous re-moulding of individual's viewpoints by interacting with others through visual cues (Stephens, 2007). Furthermore, the development of FCMs is quite difficult if the experts are not present in a participatory workshop. Considering the nature of problem, this study involved traditional experts in the study that disentangled their knowledge. This study followed group-wise modeling of FCMs.

### 2.5. Design of workshops and input data

Before started the workshops, a detailed description on the pattern and rates of erosion and accretion for the three coastal zones from 1985 to 2015 has been presented to the experts. This information has previously been gathered by assessing Landsat satellite images compiled over the past 30 years ranging from 1985 to 2015 with 30m X 30m pixel resolution. Furthermore, raster GIS based Coastal Erosion Susceptibility for Bangladesh (CESB) model has been derived as a part of the current study to generate the current levels and A1B (AR4 business-as-usual), RCP2.6 (low), RCP4.5 (moderate) and RCP8.5 (high) climate scenario-based future physical susceptibility of the coastal area to erosion for three time-slices such as 2020, 2050 and 2080. The CESB used nine parameters in the model domain among which five are identified as underlying physical elements such as geomorphic features and heights, bathymetry, soil permeability, geological formation and distance from coastline whereas, four are selected as climate-driven triggering factors such as coastal river water discharge, mean sea level, rainfall and wind speed. The parameters have been selected from an in-depth review of available literatures. The recent data sets on underlying physical elements have been collected from different sources (BARC, 2017; GMRT, 2017; USGS, 2017) whereas, trends of observed data sets on current climate-driven factors collected from real-ground stations by BIWTA (2017), BMD (2016) and BWDB, (2016), have been used for the CESB model. The regionally downscaled projected data sets on future scenarios of climate-driven factors for three time-slices collected from CCCR (2016), IPCC (2013c), IWFM (2012), Kamal et al. (2013), Kay et al. (2015) and World Bank (2016), have been used for the same model. These data sets, along with the outputs of CESB model, have been presented to the experts to facilitate the workshops with observed and scenarios of climate-driven factors in the study area. The scenarios of future climatic drivers used for the CESB model and presented in the workshops are given in the table (Table 3).

**Table 3:** Changes in climate drivers from base data (past average of stations) under different climate scenarios. The base corresponds to 2015 whereas, the values in bracket for future times indicate positive (+) and negative (-) changes of percentages for the associated drivers.

| Driver | Time-slice | Climate scenario | | | |
|---|---|---|---|---|---|
| | | A1B | RCP2.6 | RCP4.5 | RCP8.5 |
| Water discharge ($m^3/s$) (Base: 5790.71) | 2020 | 6008.24 (+ 6.1) | 5414.32 (- 6.5) | 6149.74 (+ 6.2) | 6051.30 (+ 4.5) |
| | 2050 | 6333.28 (+ 16) | 5993.39 (+ 3.5) | 6618.79 (+ 14.3) | 6508.76 (+ 12.4) |
| | 2080 | 6809.16 (+ 30.7) | 6584.04 (+ 13.7) | 7377.37 (+ 27.4) | 8054.88 (+ 39.1) |
| MSL (mm) (Base: 2499.11) | 2020 | 2779.11 (+ 0.08) | 2539.11 (+ 0.04) | 2549.11 (+ 0.05) | 2559.11 (+ 0.06) |
| | 2050 | 2989.11 (+ 0.24) | 2679.11 (+ 0.18) | 2739.11 (+ 0.24) | 2809.11 (+ 0.31) |
| | 2080 | 3239.11 (+ 0.42) | 2799.11 (+ 0.30) | 2859.11 (+ 0.36) | 2979.11 (+ 0.48) |
| Rainfall (mm) (Base: 196.86) | 2020 | 217.16 (+ 2.85) | 189.77 (- 3.60) | 198.99 (+ 1.08) | 201.50 (+ 2.36) |
| | 2050 | 223.09 (+ 13.19) | 191.37 (- 2.79) | 192.27 (- 2.33) | 192.15 (- 2.39) |

| | | | | | |
|---|---|---|---|---|---|
| | 2080 | 260.81 (+ 27.46) | 192.86 (- 2.03) | 205.76 (+ 4.52) | 223.95 (+ 13.76) |
| Wind (m s-1) (Base: 1.58) | 2020 | 1.57 (- 0.90) | 1.57 (- 0.92) | 1.57 (- 0.84) | 1.57 (- 0.51) |
| | 2050 | 1.62 (+ 3.45) | 1.61 (+ 1.64) | 1.64 (+ 3.62) | 1.64 (+ 3.84) |
| | 2080 | 1.63 (+ 2.63) | 1.61 (+ 2.12) | 1.64 (+ 3.73) | 1.66 (+ 5.31) |

Similarly, data, maps and information relating to the locations of potential human-induced drivers of susceptibility such as embankments, polders, dykes and mangrove afforestation have been synoptically presented to the experts. Furthermore, future policy options of the government such as 'Delta Plan 2100', future 25 years plan by Bangladesh Water Development Board, Coastal Land Zonation Project and Land Reclamation Plan have been discussed in the workshop. The presented data and information could be helpful for the experts to identify the current and potential future drivers of coastal susceptibility to erosion in the area and to assign weights of the connections (relationships) between the identified drivers.

The first workshop was segmented into three interfaces: concept mapping, matrix and scenario involving eleven experts among which some experts having expertise on physical aspects and some experts having expertise on human aspects of erosion susceptibility (Table 2). Prior to concept mapping, the experts were given a research question: what factors do you think contribute to the existing susceptibility of the coastal area to erosion? To secure answers, the experts were asked in concept mapping interface to identify current baseline components of susceptibility to erosion for the area studied. The identified components were presented on- screen and a discussion held on the components with an aim to facilitate any changes if required. In the matrix interface, the experts were asked to rate the relationships between the identified drivers in a rating scale from -1 to 1. The quantitative values on the rate of relationships then inserted in rows and columns in an adjacency matrix to find out the in-degree, out-degree and centrality scores of the components. The arrangement of relationships between the components were shown on screen during the session for further modifications. The complexity and density scores of the FCMs were also shown in the workshop by using the software.

In scenario interface, this research identified the factors significant for future susceptibility of the coastal area to erosion. To address potential factors for future susceptibility, this study engaged the experts in three subjective probability elicitations for three time-slices such as near-future (2020), future (2050) and far-future (2080). However, the common problem relating to scenario generation in 'scenario' interface of the software by changing baseline values of relevant components is that the results yield some changes in the relationships of FCM steady state condition but, lacks to integrate additional future components in the model. Hence, this study initiated experts' oriented generation of future FCMs where it is possible to capture new components and their degree of relationships. In the scenario interface, the experts were given a different research question to respond: how do you evaluate the future susceptibility of the coastal area to erosion? Additionally, the experts were asked to consider future the scenarios of climate drivers provided for different time-slices while identifying new future drivers and rating the relationships between the drivers. To do this, a number of 'what if' situations were presented in the workshop based on the mentioned climate scenarios for future time-slices and the experts were asked to rate the changes of the relationships between the identified components of future susceptibility to erosion.

However, to facilitate discussions on the identified and rated factors of current and future susceptibility of the coastal area to erosion, this study provided a further research question to the experts: what implications do the current conditions and future changes of hydro-climatic drivers have on future susceptibility of the coastal area to erosion? Finally, to address future uncertainties, this study coded the 'confidence rating' for the established connections (relationships) in the FCMs models. The experts were also asked to rate their level of confidence on the assigned values of individual relationships between the components in a seven points scale where, 1= very low; 2=low; 3=moderate low; 4= neutral; 5= moderate high; 6= high and 7= very high confidence.

### 2.6. Validation of FCMs

Since FCMs are based on diverse understanding of a system and hence formal validation of the FCMs are not possible (Özesmi and Özesmi, 2004). These qualitative models (FCMs) produce outputs that are not possible to measure directly in the field. Rather, how well the outputs of individual experts matched with the reality can be measured qualitatively by performing reality checks (Özesmi and Özesmi, 2004). Validation might be occur even if the results are qualitatively consistent with the empirically established relationships (Hobbs et al., 2002; Özesmi and Özesmi, 2004). Hence, the number of variables and their relationships might be independent in nature (Klein and Cooper, 1982). It is important to note that the FCMs do not come up with estimates of real values or inferential statistical tests for the parameters (Craiger et al., 1996). In parallel, the FCMs are capable of illustration 'what-if' but do not model 'why' of a system (Kim and Lee, 1998). This study assigned the other four experts to the second workshop. After having a number of iterations performed by the software, the final outputs of the first workshop went through reality checks by the second group of experts in the second workshop. The validated final outputs were then presented on screen to check the consistency of the results.

## 3. Results

### 3.1. FCMs on current susceptibility to erosion

The outputs of combined FCMs on current susceptibility (2015) for the entire coastal area show a total number of 33 components that were identified by the experts in the workshops.

Among the identified components, most of them (21 components) represent physical drivers of susceptibility whereas, the remaining (12 components) are human-induced drivers (Table 5). The figure 3 shows the Fuzzy Cognitive Map where the nature of relationships between the components are outlined. Out of the components, 26 are ordinary drivers that have both transmitting and receiving flow of relationships with other components. Among the remaining 7 components, 6 are identified as transmitter and 1 as receiver. Highest centrality score found for ‘rate of sedimentation’ (8.9) followed by ‘wave action’ (8.81) whereas, the lowest centrality score occurred for ‘decomposition of undecomposed materials’ (0.2). A total number of 149 connections established in the map that yielded 4.51 connections per components on average. This baseline FCM shows a 0.14 density score and 0.16 complexity score for the matrix.

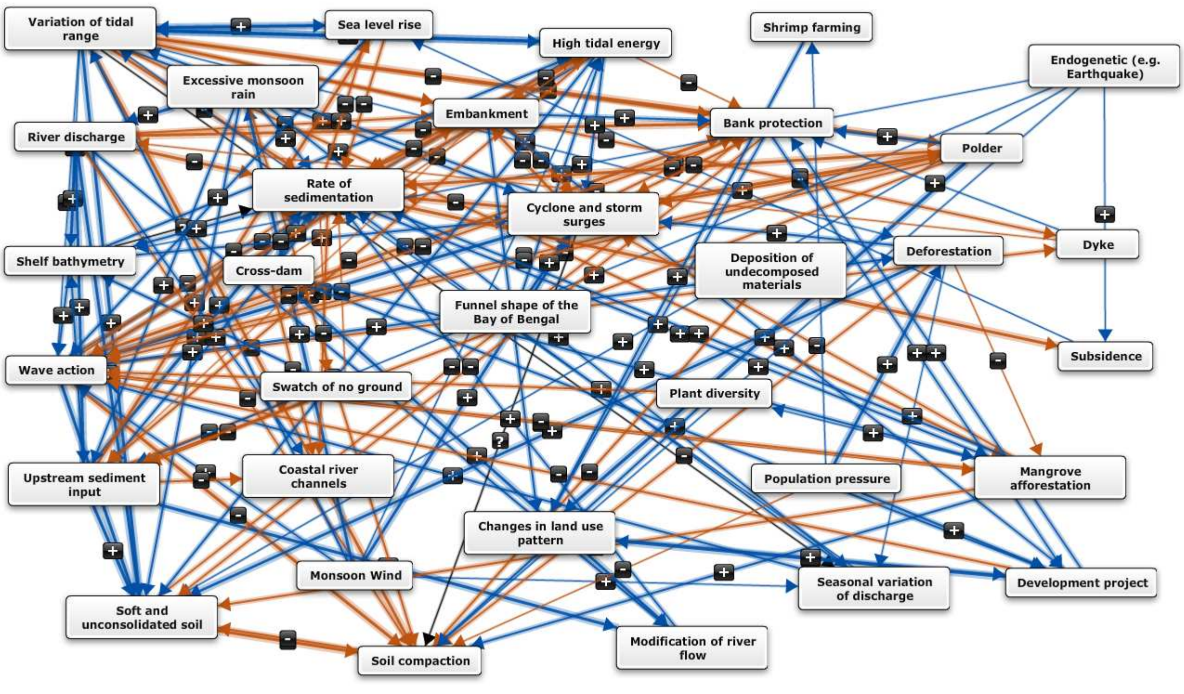



**Fig. 3.** FCM components and their relationships for baseline conditions of susceptibility.

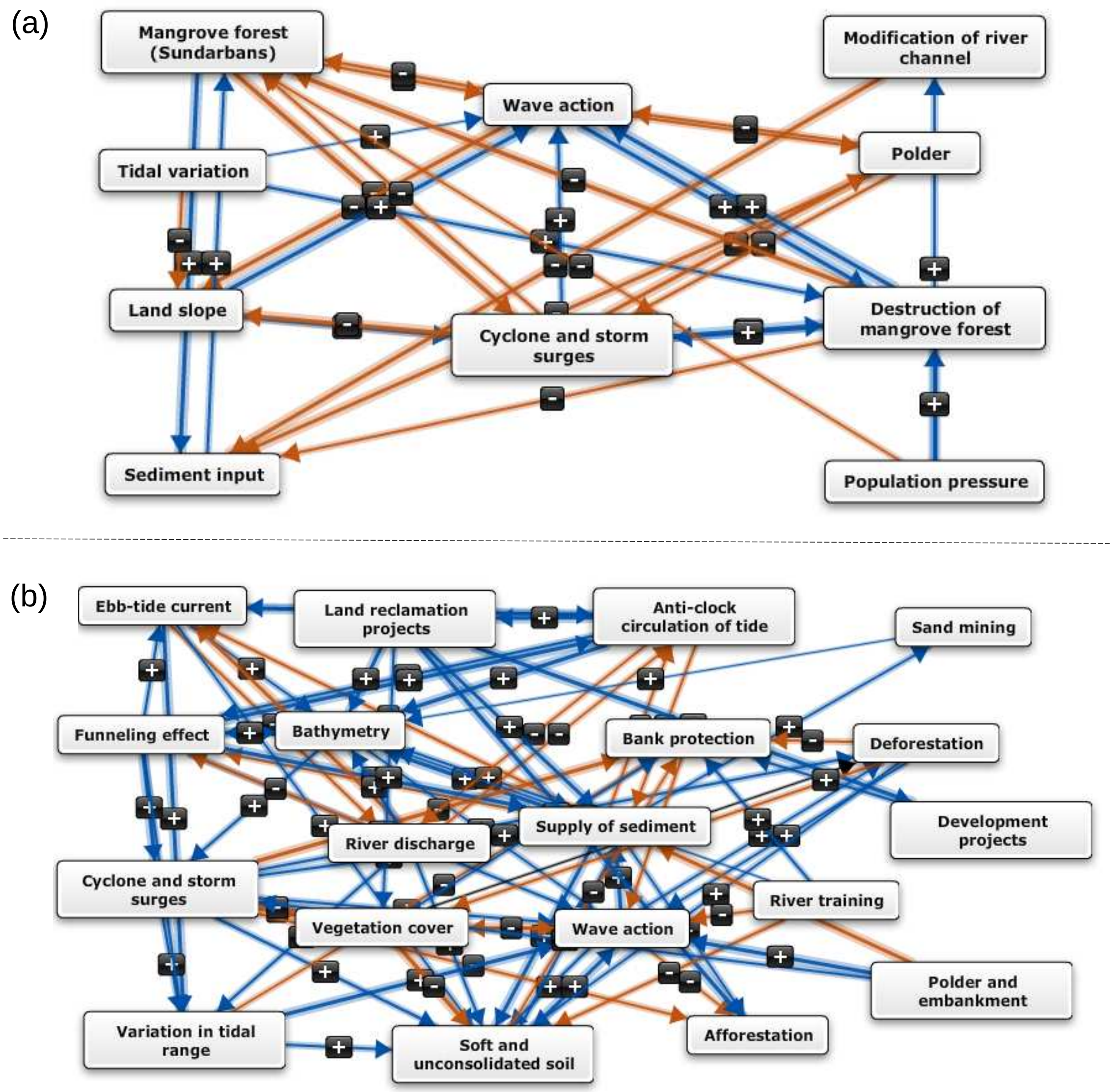
### 3.1.1. Zonal variations

The workshops investigated zonal variations of current baseline susceptibility of the coastal area to erosion in which, substantially varied factors have been identified for the three coastal zones. A total number of 10 components have been identified for both western and eastern zones whereas, 19 components have been recognised for the central coastal zone that indicate the diverse nature of factors exist in the central coastal zone compared to the other zones (Table 4). However, a total number of 29, 79 and 18 connections among the components have been identified for the western, central and eastern coastal zones respectively (Fig. 4). Hence, the connections per components have also found to be higher for the central zone (4.15) compared to the western (2.9) and eastern (1.8) zones. The complexity score is also higher for the central zone (0.5) in comparison with the western (0.0) and the eastern (0.0) zone. The highest number of 03 transmitter components (rock type, development projects and population pressure) have been identified for the eastern coastal zone whereas, no receiver component found for the western and eastern coastal zones, except one (afforestation) for the central zone.

**Table 4:** Variations of FCM components in three coastal zones for current susceptibility to erosion.

| Zone | Component | **In-degree** | **Out-degree** | **Centrality** | **Type** |
|---|---|---|---|---|---|
| **Western Coastal Zone** | Mangrove forest (Sundarbans) | 2.09 | 1.68 | 3.77 | ordinary |
| | Tidal variation | 0 | 0.68 | 0.68 | transmitter |
| | Wave action | 2.73 | 1.95 | 4.68 | ordinary |
| | Land slope | 1.56 | 0.98 | 2.54 | ordinary |
| | Cyclone and storm surges | 1.89 | 2.54 | 4.43 | ordinary |
| | Sediment input | 2.13 | 0.46 | 2.59 | ordinary |
| | Modification of river channel | 0.46 | 0.55 | 1.01 | ordinary |
| | Polder | 0.85 | 1.43 | 2.28 | ordinary |
| | Destruction of mangrove forest | 2 | 2.13 | 4.13 | ordinary |
| | Population pressure | 0 | 1.31 | 1.31 | transmitter |
| **Central Coastal Zone** | Supply of sediment | 4.86 | 2.79 | 7.65 | ordinary |
| | Ebb-tide current | 1.85 | 2.49 | 4.34 | ordinary |
| | Bathymetry | 3.8 | 1.5 | 5.3 | ordinary |
| | Cyclone and storm surges | 2 | 3.15 | 5.15 | ordinary |
| | Wave action | 4.46 | 1.88 | 6.34 | ordinary |
| | Variation in tidal range | 1.77 | 1.05 | 2.82 | ordinary |
| | Anti-clock circulation of tide | 1.59 | 2.58 | 4.17 | ordinary |
| | Funnelling effect | 1.4 | 3.57 | 4.97 | ordinary |
| | River discharge | 0.82 | 3.84 | 4.66 | ordinary |
| | Vegetation cover | 1.32 | 2.12 | 3.44 | ordinary |
| | Soft and unconsolidated soil | 3.51 | 1.5 | 5.01 | ordinary |
| | Land reclamation projects | 0.58 | 2.91 | 3.49 | ordinary |
| | Deforestation | 0.75 | 1.21 | 1.96 | ordinary |

| | | | | | |
|---|---|---|---|---|---|
| | River training | 0 | 0.90 | 0.90 | transmitter |
| | Afforestation | 1.76 | 0 | 1.76 | receiver |
| | Sand mining | 0.3 | 0.07 | 0.37 | ordinary |
| | Development projects | 0.55 | 0.4 | 0.95 | ordinary |
| | Polder and embankment | 0 | 1.63 | 1.63 | transmitter |
| | Bank protection | 2.52 | 0.25 | 2.77 | ordinary |
| **Eastern Coastal Zone** | Counter clock-wise tidal circulation | 0.4 | 0.65 | 1.05 | ordinary |
| | Cyclone and storm surges | 1.11 | 1.15 | 2.26 | ordinary |
| | Wave action | 2.92 | 0.24 | 3.16 | ordinary |
| | Rock type | 0 | 2.19 | 2.19 | transmitter |
| | Sandy beach | 0.5 | 0.72 | 1.22 | ordinary |
| | Bank protection | 2.13 | 0.98 | 3.11 | ordinary |
| | Development projects | 0 | 1.15 | 1.15 | transmitter |
| | Afforestation | 0.85 | 0.42 | 1.27 | ordinary |
| | Population pressure | 0 | 0.4 | 0.4 | transmitter |
| | Supply of sediment | 0.89 | 0.9 | 1.79 | ordinary |



(c)

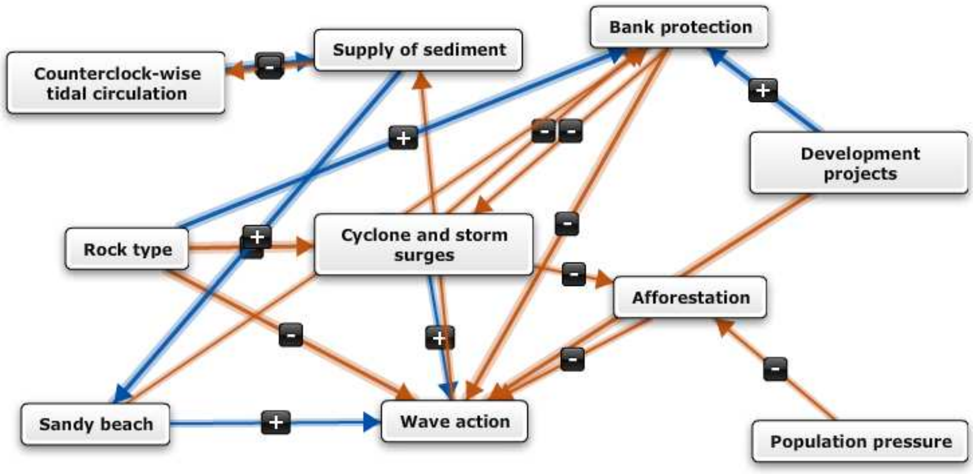



**Fig. 4.** Zone-wise FCMs for current susceptibility to erosion. The figure represents (a) western; (b) central and (c) eastern coastal zones of the area studied.

### 3.2. FCMs on future susceptibility to erosion

#### 3.2.1. Near future (2020)

The FCM for near-future (2020) did not vary significantly from the baseline conditions in respect of the total number and nature (transmitter, receiver and ordinary) of components, complexity and density scores (Fig. 5). However, the total number of connections increased to 153 and hence, connections per components on average (4.60) increased from the baseline conditions. This scenario of increased connections indicates higher interactions between the components in near-future than the existing conditions. The confidence ratings for each of the near-future components are shown in the table (Table 5).

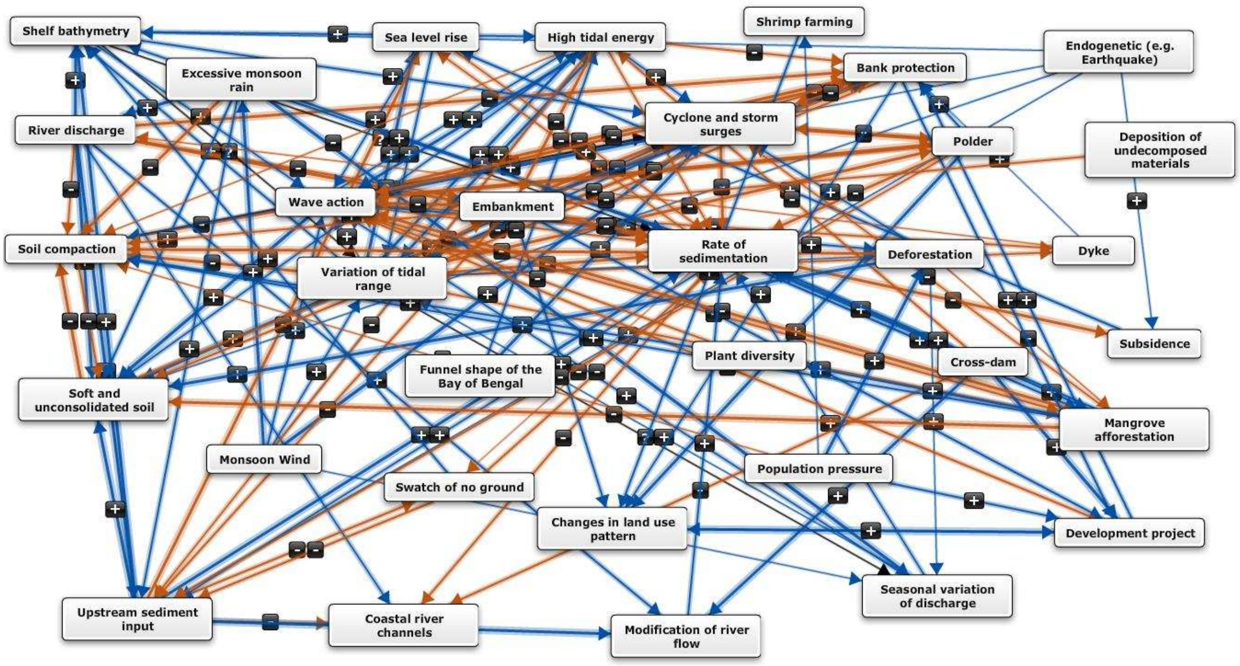



**Fig. 5.** FCM components and their relationships for near-future (2020) susceptibility to erosion.

### 3.2.2. Future (2050)

The FCM based scenario for future (2050) time-slice indicates a diverse nature of relationships between the components. Although only three components were added to the total, this FCM included 13 new components and excluded 10 components from the previous one that makes 36 components in total (Table 6). Total number of connections for this time-slice also increased substantially (293 in total) and hence, number of connections per components (8.13) also increased consequently on average from the previous states (Fig. 6). Most of the components (33) in this FCM are ordinary in nature in which, only 2 and 1 components have been identified as transmitter and receiver respectively. Density (0.23) and complexity (0.5) scores of this FCM also show higher than the previous times.

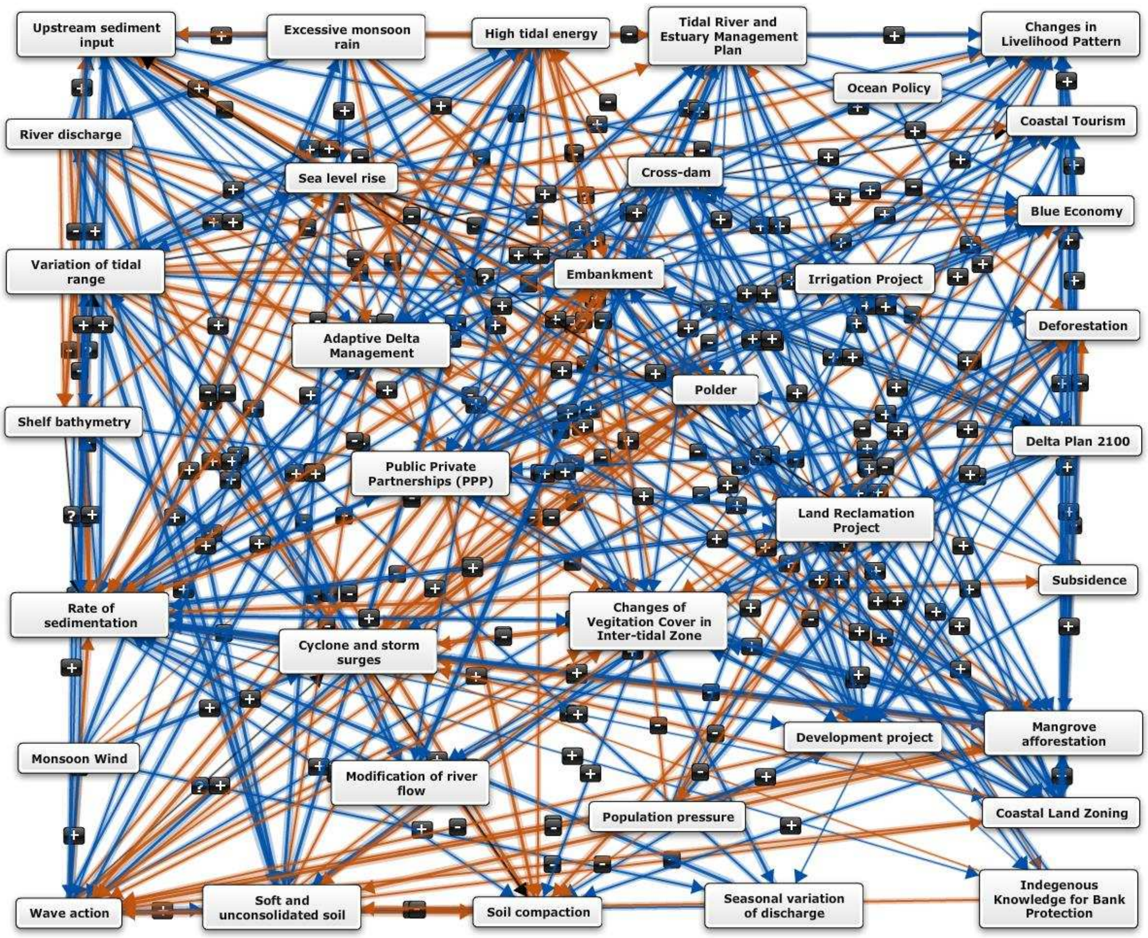



**Fig. 6.** FCM components and their relationships for future (2050) susceptibility to erosion.

**Table 5:** Common components and associated confidence ratings for the three time-slices in relation to baseline condition identified and quantified by the experts.

| Component | Level of Confidence | Centrality (In-degree + Out-degree) | | | |
|---|---|---|---|---|---|
| | | Baseline (2015) | Near future (2020) | Future (2050) | Far future (2080) |
| Rate of sedimentation | Very High | 8.9 (6.8+2.1) | 9.76 (7.47+2.29) | 15.59 (9.4+6.19) | 20.28 (12.21+8.07) |
| Wave action | Low | 8.81 (4.78+4.03) | 9.82 (5.22+4.6) | 11.59 (6.58+5.02) | 16.83 (10.16+6.67) |
| Variation of tidal range | High | 7.79 (1.65+6.14) | 8.3 (1.78+6.53) | 10.53 (2.41+8.12) | 13.86 (3.45+10.41) |
| Cyclone and storm surges | Moderate Low | 7.4 (4.2+3.2) | 7.93 (4.59+3.34) | 9.49 (5.1+4.39) | 10.07 (5.63+4.44) |
| Soft and unconsolidated soil | Very High | 5.89 (4.84+1.05) | 6.53 (5.38+1.15) | 8.59 (6.3+2.29) | 11.53 (9.28+2.25) |

| | | | | | |
|---|---|---|---|---|---|
| Upstream sediment input | Moderate High | 5.55 (2.5+3.05) | 6.04 (2.79+3.25) | 10.75 (3.65+7.1) | 11.39 (3.08+8.32) |
| River discharge | High | 5.48 (0.9+4.58) | 5.81 (0.93+4.88) | 7.36 (1.22+6.14) | 10.33 (1.61+8.72) |
| Embankment | High | 5.01 (2.21+2.8) | 5.42 (2.45+2.97) | 10.64 (5.28+5.36) | 10.71 (6.54+4.17) |
| High tidal energy | Moderate High | 4.73 (1.63+3.1) | 5.39 (1.79+3.59) | 8.45 (2.95+5.49) | 11.08 (4.21+6.87) |
| Soil compaction | Very High | 4.43 (4.25+0.18) | 5 (4.78+0.22) | 5.99 (5.74+0.25) | 8.42 (7.68+0.74) |
| Polder | High | 4.16 (1.66+2.5) | 4.41 (1.75+2.66) | 8.44 (5.37+3.07) | 9.77 (6.08+3.69) |
| Excessive monsoon rain | High | 3.15 (0.7+2.45) | 3.47 (0.75+2.72) | 6.33 (0.83+5.49) | 7.71 (0.89+6.82 |
| Mangrove afforestation | High | 3.05 (1.09+1.95) | 3.66 (1.29+2.37) | 8.92 (5.27+3.65) | 10.17 (5.91+4.26) |
| Cross-dam | High | 2.75 (0+2.75) | 2.99 (0+2.99) | 9.56 (1.81+7.75) | 7.42 (1.39+6.030 |
| Shelf bathymetry | Very Low | 2.73 (1.73+1) | 2.93 (1.93+1) | 4.51 (2.05+2.46) | 7.06 (4.02+3.04) |
| Development project | Moderate High | 2.7 (1.55+1.15) | 2.84 (1.67+1.17) | 5.15 (4.73+0.42) | 7.75 (5.89+1.86) |
| Deforestation | Low | 2.67 (1+1.67) | 2.89 (1.05+1.84) | 5.35 (2.8+2.55) | 7.08 (4.22+2.86) |
| Sea level rise | High | 2.59 (1.64+0.95) | 2.77 (1.71+1.06) | 7.12 (2.38+4.74) | 10.35 (3.19+7.15) |
| Modification of river flow | Neutral | 2.15 (1.7+0.45) | 2.31 (1.83+0.48) | 3.94 (3.42+0.52) | 4.16 (2.47+1.69) |
| Monsoon Wind | Low | 2.12 (0+2.12) | 2.32 (0+2.32) | 3.4 (0+3.4) | 4.74 (0+4.74) |
| Population pressure | High | 1.3 (0+1.3) | 1.3 (0+1.3) | 2.95 (0.32+2.63) | 3.51 (0.45+3.06) |
| Seasonal variation of discharge | Moderate High | 1.19 (0.64+0.55) | 1.49 (0.74+0.75) | 2.21 (0.94+1.27) | 3.27 (0.95+2.32) |
| Subsidence | Neutral | 0.70 (0.55+0.15) | 0.74 (0.57+0.17) | 1.89 (0.95+0.94) | 2.32 (1.46+0.86) |

### 3.2.3. Far future (2080)

Although the FCM based scenario for far-future (2080) identified a total number of 42 components that were identified as potential for future susceptibility of the coastal area to erosion, this scenario included 09 new components and excluded 03 components from the previous scenario (2050) (Fig. 7). Along with the number of components, total connections (377) and consequently connections per component (8.97) also increased on average from the previous state. Among the total number of 39 ordinary components identified, only 3 components have been found as transmitter.

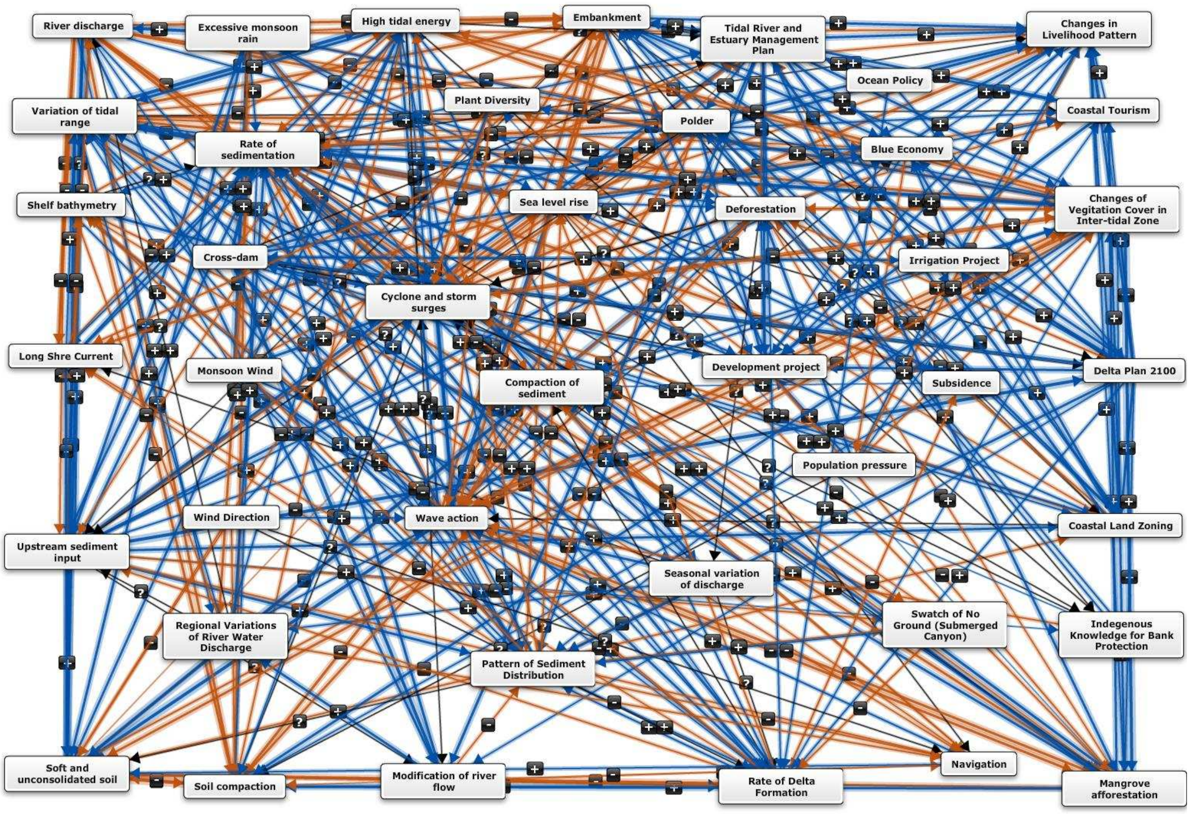



**Fig. 7.** FCM components and their relationships for far-future (2080) of susceptibility to erosion.

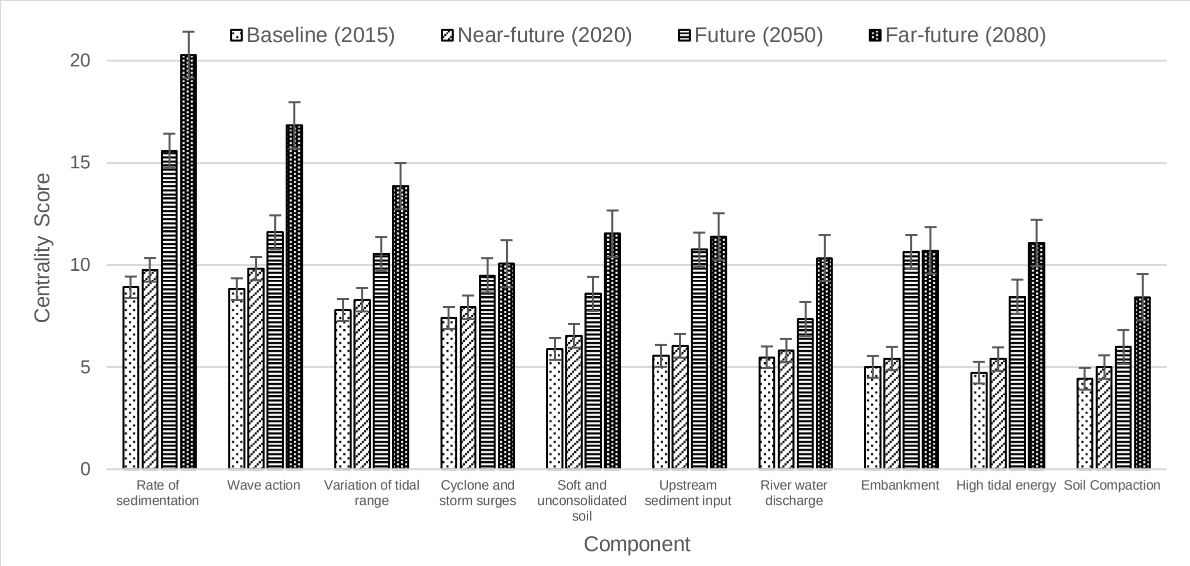



**Fig. 8.** Top 10 FCM components (based on centrality score) common for current (baseline) and future scenario of susceptibility to erosion for three time-slices.

## 4. Discussion

The workshops attempted to identify the nature and causes of relationships between the identified drivers of susceptibility to erosion. The discussions were the basis of final values in the matrices and the layouts of the developed FCMs. Among the identified factors for current susceptibility, most of the physical components were identified as having higher centrality scores (Table 5 and Fig. 8) that indicate the higher interactions and influences of the factors of susceptibility to erosion. The experts were agreed that the rate of sedimentation, soft and unconsolidated soils, shelf bathymetry, funnel shape of the Bay of Bengal, Swatch of No Ground (deep sea trench), and coastal river channels are the most influential geological and geomorphological factors of susceptibility to erosion. They identified wave action, river discharge, monsoon wind, cyclone and storm surges, excessive monsoon rain, high tidal energy, variations of tidal range and sea level rise as dominating hydro-climatological factors of current susceptibility to erosion.

Further discussions on the developed FCMs noticed that the bathymetric depths in the coastal area greatly influence the susceptibility to erosion. The higher depths in the coastal river channels (due to erosion) and comparatively lower depths in and around the coastline (due to sedimentation), make the discharge of the rivers to act predominantly at the interior coast. However, tidal energy and wave action play significant roles for erosion at the exterior coast. Currently, most of the newly developed small islands and major parts of the comparatively large islands located in the central coastal area are highly susceptible to erosion. The experts put emphasis on the linkages of continuous wave action, high permeability of water into soils and variations in tidal ranges with the high susceptibility of the islands to erosion. For instance, major land areas of Sandwip island located in the active delta region of Meghna estuary has been eroded from 1980s until recently. Erosion has also taken place at the north of Hatia, north-east of Bhola and the south-west of the former Ramgati island. Additionally, the occurrences of excessive rainfall accentuate the volume of water discharge in the coastal area that contribute to the high level of susceptibility to erosion. Along with a high volume of river discharge, continuous wave action initiating by south-western monsoon wind accelerate the process of erosion in most parts of the coastal area; especially in the central coastal zone. However, the soft and unconsolidated soils are highly sensitive to the waves that results in a high rate of erosion in the Meghna estuary, Kuakata, Moheshkhali, Kumira and Kutubdia coastal areas. Frequent occurrences of tropical cyclones and consequent storm surges during April to June and September to November make the coastal area highly susceptible to erosion, they added. The identified factors from the discussions are also found with higher centrality scores in the FCMs (Table 5).

The FCMs especially developed for the three coastal zones indicate that some physical factors such as wave action, variations of tidal range, cyclone and storm surges, supply of sediments and bank protection works act similarly for susceptibility to erosion in all the three coastal areas (Table 4). However, the FCMs identified some spatial variations of the factors for the zones. For example, in the western coastal area the manifest role of mangrove forest to lessen the erosion susceptibility has been reported in the FCMs. Like mangrove, polders also showed positive relationship in the FCM matrix for erosion susceptibility. The synthesis of their opinions postulates that the Meghna estuary in the central zone of the coast is currently a very active part of Bengal basin and highly susceptible to erosion. Rapid geomorphological changes are taking place in the area where combined flow of water of the Ganges (Padma in Bangladesh), Brahmaputra and Meghna rivers initiates the process of erosion in one hand and supplies huge sediments in another hand. Furthermore, the wave action, cyclone and storm surges, soft and unconsolidated soils, tidal circulations, funnelling effects and bathymetric depths were identified in the FCM as high influential factors of susceptibility of the zone to erosion. On the other hand, positive relationships for bank protection works such as embankments, polders, development projects, river training as well as afforestation programme were noticed in the FCM for this coastal area. The experts were opined that rock types, flat and long sandy beach and bank protection works (e.g. marine drive from Cox's bazar to Teknaf) substantially reduced the level of susceptibility in the eastern coastal area. In contrast, counter clock- wise circulation of tidal water, wave action as well as human interventions in the coast contribute to the erosion susceptibility in the area.

The experts identified, however, a diversified nature of human-induced factors influential for current susceptibility to erosion that included the issues of bank protection and development activities. Some factors such as embankment, mangrove afforestation, modifications of river flow etc. scored higher centrality values in the FCMs than other factors (Table 5). For instance, the experts were opined that bank protection works of the Government such as embankment, dykes, polders lessen the susceptibility to erosion in Kuakata, Bhola, Sandwip, Chittagong and Cox's Bazar coastal areas but, the completed tasks seems currently not sufficient to protect the entire coast from erosion. Additionally, Government has taken major land reclamation projects in the coastal area, the ultimate results of which has already been observed in Noakhali coastal district. However, these reclamations of lands by diverting river water and tidal circulations created erosion in other parts of the coast that were highly visible in the eastern coastal area of Sandwip island. On the other hand, mangrove afforestation projects undertaken by the Government in newly developed islands and mud flats showed a significant contribution to minimising the susceptibility of those lands from erosion.

The workshops considered the changing nature of presented scenarios (e.g. business-as-usual, low, moderate and high) on future climate-driven forces and their overall impacts with a view to identify the potential factors of future susceptibility of the coastal area to erosion for different time-slices. The developed FCM for near-future time-slice (2020) identified more complex relationships between the identified parameters. The experts were opined that the areas under Moheshkhali, Kutubdia and St. Martine islands of the eastern zone might be moderate to high and very high susceptible to erosion by 2020. Most of the small islands and newly developed lands such as north of Monpura, Char Jonak, Bodnar Char and Dhal Char in the central zone might also be high and very high susceptible to erosion. Along with the increase of water discharge and rainfall, the probable increase of wind speed and mean sea level might affect the lands of the comparatively bigger islands in the central zone such as Bhola, Hatiya, Sandwip, Char Zahiruddin and Char Gazaria attached to the coast. The level of susceptibility to erosion might be increased for Urir Char, Jahajir Char and Char Piya during that time. Due to the increased wind speed, the wave action might be negatively effective for erosion susceptibility. Under changing scenarios of future climate, the funnelling effects of the Bay of Bengal might increase the effects of tidal energy that could change the off-shore and near-shore bathymetry of the coast, they opined. The supply of sediments from upstream might have substantial influences on the net balance of erosion and accretion especially in the estuarine part of the coastal area. However, the role of bank protection works and mangrove afforestation in the inter-tidal mud flat might be crucial for limiting the susceptibility to erosion. Along with these, positive changes in land use pattern, plant diversity in coastal lands and reduction of deposition of undecomposed materials might be effective for low susceptibility of the coastal area to erosion.

The relationships between the parameters of the developed FCM for future (2050) time-slice indicate that projected changes in climate-induced drivers for all of the scenarios might be responsible for higher susceptibility of the coastal area to erosion than previous times. The experts were in a common consensus that an increase in water discharge, mean sea level, rainfall and wind speed by 2050 might also increase erosion susceptibility in small islands, upper Meghna river and the central estuarine areas of the coast. Some areas along Chittagong coast, Cox's Bazar and Noakhali might also be high susceptible to erosion during that period. Besides addressing the potential physical factors of erosion susceptibility in the FCM for 2050, the workshops identified some human-driven measures such as delta plan 2100, land reclamation projects, ocean policy, indigenous knowledge for bank protection, changes in livelihood pattern, coastal land zoning, coastal tourism, blue economy (ocean based economic development), changes in vegetation cover in inter-tidal zone, adaptive delta management plan, tidal river and estuary management plan and Public Private Partnerships (PPP) that might have significant effects to limit the susceptibility of the coastal lands to erosion (Table 5). The experts were agreed that bank protection works and coastal river channels would be satisfactorily under control and hence were not included in the FCM developed for 2050 time-slice.

**Table 6:** Changes in the components of FCMs developed for 2050 and 2080 time-slices.

| **Time-slice** | **Component included** (with previous time-slice) | **Centrality** (In-deg. +Out-deg.) | **Component excluded** (from previous time-slice) | **Centrality** (In-deg. +Out-deg.) |
|---|---|---|---|---|
| Changes in the FCM | Coastal land zoning | 8.24 (3.37+4.87) | Bank protection | 5.25 (3.59+1.65) |
| | Delta plan 2100 | 7.98 | | |

| | | | | |
|---|---|---|---|---|
| | | (1.84+6.14) | | |
| | Land reclamation project | 6.9 (4.54+2.36) | Changes in land use pattern | 2.19 (2.05+0.15) |
| | Irrigation project | 2.51 (1.52+0.99) | Deposition of undecomposed materials | 0.2 (0+0.2) |
| | Changes of vegetation cover in inter-tidal zone | 9.51 (5.81+3.7) | Funnel shape of the Bay | 0.9 (0+0.9) |
| | Blue economy | 6.19 (4.57+1.62) | Endogenic | 0.48 (0+0.48) |
| | Coastal tourism | 3.63 2.76+0.87) | | |
| | Ocean policy | 0.56 (0+0.56) | Swatch of no ground | 1.1 (0.30+0.8) |
| | Indigenous knowledge for bank protection | 1.47 (0.65+0.82) | | |
| | Changes in livelihood pattern | 6.89 (6.89+0) | Shrimp farming | 0.4 (0.15+0.25) |
| | Tidal river and estuary management plan | 7.14 (2.42+4.72) | Dykes | 1 (0.8+0.2) |
| | Adaptive delta management plan | 4.19 (2.69+1.5) | Coastal river channels | 1.2 (1.2+0) |
| | Public Private Partnerships (PPP) | 3.92 (2.38+1.54) | Plant diversity | 0.58 (0.15+0.43) |
| Changes in the FCM for far future (2080) | Rate of delta formation | 8.72 (5.58+3.14) | Land reclamation project | 6.9 (4.54+2.36) |
| | Pattern of sediment distribution | 10.54 (7.98+2.56) | | |
| | Wind direction | 1.02 (0+1.02) | | |
| | Regional variations of river water discharge | 4.07 (2.05+2.02) | Adaptive delta management plan | 4.19 (2.69+1.5) |
| | Long shore current | 7.13 (3.74+3.39) | | |
| | Navigation | 2.97 (2.02+0.95) | | |
| | Compaction of sediment | 4.06 (3.30+0.76) | Public Private Partnerships (PPP) | 3.92 (2.38+1.54) |
| | Plant diversity | 2.78 (0.88+1.9) | | |
| | Swatch-of-no-Ground (submerged canyon) | 2.24 (1.11+1.13) | | |

The interactions between the factors for far-future (2080) susceptibility of the coastal area to erosion might be highly complex and highly uncertain under an ever-increasing trend of climate-driven forces by 2080 (Table 5). The increase of river water discharge, mean sea level, rainfall and wind speed in the coastal area by that time might alter the current susceptibility in most of the islands and newly developed lands in the central estuarine areas. Most of these areas might be attached to high and very high susceptibility categories along with some moderate susceptible areas. The areas at Kuakata coast and some small islands in the western coast might also be highly susceptible to erosion by that time. The situation might also be worsen at Moheshkahli, Kutubdia and St. Martine islands located in the eastern coastal zone. The domination of physical forces such as wave action, variations of tidal range, sea level rise, pattern and rate of sedimentation, long shore current, plant diversity etc. might be highly visible during that time (Table 5). The shapes of the offshore islands in the Meghna estuary and the location of Swatch-of-no-ground motivated the experts to opine that the submerged canyon might have influences on erosion by pulling sediments from that areas through anti-clock wise circulations of currents. Along with other human-driven factors, coastal navigation might be an important factor identified by the experts for erosion susceptibility along the numerous river channels existing in the western coastal area.

## 5. Conclusion

This study applied FCM based approach to assess the susceptibility to erosion for the entire coastal area of Bangladesh. The benefit of using this cognitive approach in this study over traditional models to address factors of current and future coastal susceptibility to erosion is significant. The FCMs identified 33 factors of susceptibility to erosion for current baseline conditions. Whereas, for future scenario under three time-slices this study identified 33, 36 and 42 factors of susceptibility to erosion for near future (2020), future (2050) and far future (2080) respectively. The identified factors include both physical and human-induced factors and their degree of relationships between them. The FCMs modelled higher centrality scores for rate of sedimentation, soft and unconsolidated soils, shelf bathymetry, funnel shape of the Bay of Bengal, wave actions, river discharge, monsoon wind, cyclone and storm surges, excessive monsoon rain, high tidal energy, variations of tidal range and sea level rise for both current baseline conditions and future scenario. The experts' interpretations demonstrate that the future rates of both erosion and accretion might be higher than the current in the central zone compared to the western and eastern zones of the coastal area. The outcomes of the FCM approach addressed how the experts' views on future scenario of coastal erosion susceptibility. The cognitive maps derived in the present study strongly depend on the group of experts. This research suggests coastal managers, planners and policy makers in managing coastal lands. This study identified some processes and inter-relationships of both physical and human-induced factors of coastal susceptibility to erosion, particularly for the three coastal zones, that might be helpful for policymakers to propose interventions in future for the coastal zones.

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