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Potentiality of Kernel Density Estimation Tool for Tropical Cyclone Frequency Analysis in Bangladesh

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Abstract: Bangladesh is particularly vulnerable to cyclones and storm surges because of its unique geographical location and climatic variability. Bangladesh suffered numerous destructive cyclones that destroyed lives and property. The 1970 Bhola cyclone, 1991 Gorky cyclone, and 2007 Sidr cyclone caused many deaths, massive economic loss, and infrastructural destruction. In this context, cyclone risk zoning provides crucial insights and viewpoints that help communities, governments, and organizations plan for and reduce its consequences. Hence, using kernel density estimation to analyze cyclone risk zoning in Bangladesh may offer valuable comprehension. The researcher collected the required secondary data from BMD, IMD, EM-DAT, JTWC etc., to prepare a vast GIS database for cyclone hazards in Bangladesh. The spatial distribution of tropical cyclones in Bangladesh has been analyzed using ArcGIS tools like, track digitization, kernel density estimation etc. The kernel density estimation has been performed in 1960 to 2023 cyclone frequency and track data. A detailed mapping of cyclonic events across the Indian Ocean was followed by an analysis of tropical cyclone frequency in Bangladesh, taking into consideration their Bay of Bengal distribution. The geographical distribution of cyclonic activity shows that the northern Bay of Bengal is more prone to tropical cyclones than the southern bay. The kernel density calculation illustrates three prominent cyclone risk zones: high-risk, moderate-risk, and high-wind-risk. Kernel density analysis provides a detailed comprehension of regions characterized by a high concentration of cyclone impact. This strategy can help with resource allocation and focusing activities on areas that demand more concern.

Keywords: Spatial distribution, Geostatistics, Monsoon, Bay of Bengal, Cyclone susceptibility, Cyclone Risk Zoning.

1. Introduction

Severe cyclones and storm surges are more prevalent in Bangladesh (Khalil, 1992; Hossain, 2015; Murty & Neralla, 1992). The country's geographical position, unique natural surroundings, and tropical monsoon climate vary and control the climatic conditions, making it more sensitive to cyclones and floods (Mirza, 2003; Rahman, 2013; Poncelet et al., 2010). The physical and meteorological parameters required for tropical cyclone formation exist in the Bay of Bengal (Patnaik et al., 2014; Murty & Flather, 1994; Dube et

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al., 2009); it is said to be among the most favorable circumstances for cyclone development and it has 6-10% of the world's tropical cyclones (Alam & Dominey-Howes, 2015; Kotal et al., 2008). Bangladesh is hit by at least one strong cyclone yearly and an average of 12–13 depressions (Haque & Blair, 1992; Wahiduzzaman, 2021; Ahamed et al., 2012).

Bangladesh has been hit by several devastating cyclones, including those in 1822, 1876, 1961, 1965, 1970, and 1991 (Shamsuddoha & Chowdhury, 2007; Paul & Routray, 2011; Paul & Routray, 2013; Hossain & Mullick, 2020; Badhan et al., 2016; Ali, 1999; Khatun et al., 2017). According to previous research, Bangladesh accounts for 80-90% of global damages and 53% of all cyclone-related deaths worldwide (Alam & Rahman, 2014; Eckstein et al., 2021; Paul & Routray, 2013). Over the last two centuries, around 42% of deaths in Bangladesh have been attributed to cyclones (Doocy et al., 2013; Parvin et al., 2019). For example, in 1971, the entire death toll from a storm was believed to be around 300,000 to 500,000, with 100,000 persons missing; estimated damage was at USD 450 million (Paul & Routray, 2013; Paul, 2014). Following the 1991 cyclone, the official fatalities were 140,161, with a total impacted population of 10,721,707; estimated damage ranged from USD 1.8 billion to 4.3 billion (Paul & Routray, 2013; Islam, 2014).

In the present context, the analysis of cyclone frequencies holds significant importance for Bangladesh owing to the nation's increased vulnerability to tropical cyclones. The understanding of cyclone frequencies plays a crucial role in assisting meteorological organizations and disaster management authorities in Bangladesh to build precise and efficient early warning systems (Akhand, 2003). Through the examination of historical data pertaining to the frequency, patterns, and intensities of cyclones, authorities could enhance their ability to forecast and notify people of prospective cyclone hazards. The provision of timely warnings facilitates the preparedness, evacuation, and implementation of essential measures within communities (Rubiera Torres & Puig, 2012), hence resulting in the safeguarding of human lives and the mitigation of damage. The investigation of cyclone frequencies facilitates the identification of regions with high-risk levels along the coastal areas (Zhang et al., 2021). These regions have a higher occurrence of cyclone landfalls, thereby rendering them more susceptible to cyclone-induced perils, including storm surges, inundation, and powerful winds. This research aims to provide valuable insights for the evaluation and implementation of risk assessment and management techniques, hence exerting influence on land-use planning, infrastructure development, and disaster response plans. The utilization of kernel density analysis in investigating cyclone frequencies holds significant academic merit in the context of cyclone risk zoning in Bangladesh. The analysis of cyclone frequency involves comprehending the spatial distribution of cyclonic events. Kernel density analysis offers a refined and uninterrupted depiction of the distribution, facilitating a clearer viewing of areas with high and low densities.

Enhancing the comprehension of cyclone frequency in the Bay of Bengal is crucial for the implementation of efficient disaster preparedness, response strategies, and long-term planning. The Bay of Bengal experiences a notable frequency of cyclones annually as a result of favorable atmospheric and oceanic conditions (Sahoo & Bhaskaran, 2016; Nath et al., 2016). Gaining knowledge about the frequency of these cyclones aids in the anticipation of their occurrence and assessment of their impact on society. Numerous heavily inhabited coastal regions in the vicinity of the Bay of Bengal have a significant susceptibility to cyclonic events, storm surges, and inundation. The availability of precise data regarding the frequency of cyclones plays a crucial role in evaluating the possible hazards posed to both human lives and infrastructure. The acquisition of accurate and consistent cyclone frequency data is crucial in order to enhance the efficacy of early warning systems (Roy et al., 2015). This technology enables meteorological authorities to enhance their ability to forecast and disseminate information regarding the probability of cyclones, affording people additional time to undertake necessary preparations and evacuation measures. Cyclone risk zoning entails the identification of regions that exhibit a higher vulnerability to the impacts of cyclones. The kernel density method is employed to quantify the spatial distribution of cyclone events across various geographical regions. The density surface that is obtained can be evaluated in order to identify regions that have a higher level of cyclone risk. The locations with high cyclone frequency can be regarded as regions characterized by an increased likelihood of cyclone occurrence. Kernel Density Analysis can be a valuable tool for cyclone risk zoning, offering insights into the spatial distribution of cyclone occurrences.

2. Methodology

The study relies on secondary data sources. The researcher collected the required secondary data from BMD, IMD, EM-DAT, JTWC, World Bank and IBTrACS to prepare a precise tropical cyclone database for the Bay of Bengal. The various databases of cyclone intensity, wind speed, cyclone tracks etc. have been prepared from these sites. The spatial distribution of tropical cyclones has been analyzed using ArcGIS tools like georeferencing, track digitization, kernel density analysis etc.

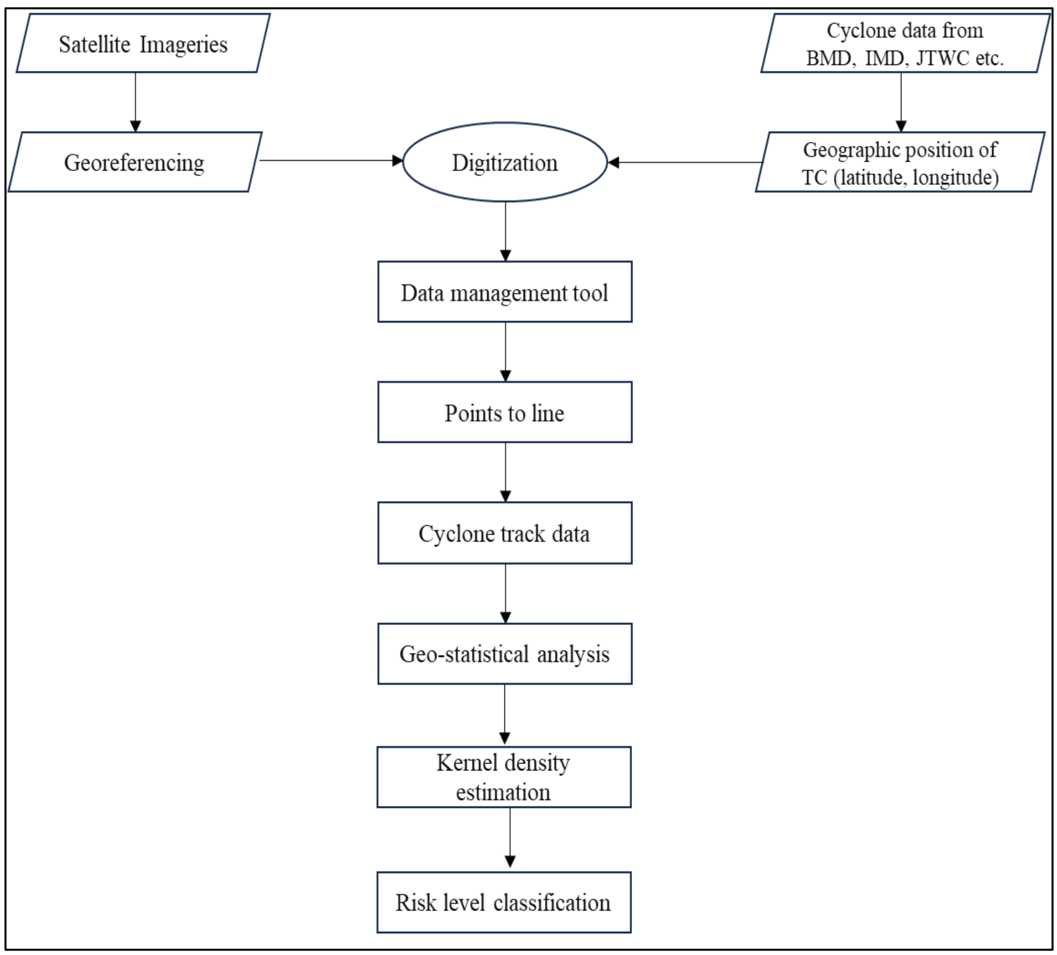
2.1 Data Sources and Data Types:

A spatial database was developed using tropical cyclone track records for the Indian Ocean and Bay of Bengal from the BMD, IMD, EM-DAT, JTWC, World Bank, IBTrACS, and other sources from 1960 to 2023. National meteorological agencies such as BMD and international agencies like EM-DAT, JTWC, and the World Bank are responsible for collecting and disseminating cyclone data. The cyclone tracks were digitized from satellite imageries provided by Zoom Earth. The database comprises the geographical coordinates in terms of latitude and longitude, together with the maximum wind speed associated with the tropical cyclone. The database comprised two distinct categories of shapefiles suitable for spatial analysis: tropical cyclone tracks, represented as line data, and tropical cyclone locations, represented as point data. The cyclone track data illustrates the trajectory that a cyclone traverses when progressing across a given geographical area. Tracks provide data regarding the geographical coordinates of the cyclone at various temporal intervals, its velocity, and the path it follows. The dataset pertaining to cyclone intensity encompasses recorded values of the cyclone's highest sustained wind speeds, central pressure, and corresponding categories based on several cyclone scales. This information is essential for comprehending and predicting the behavior of cyclones, which can have substantial effects on human populations, infrastructure, and the environment.

2.2 Methods

This research has used geospatial and geostatistical tools to analyze the tropical cyclone frequency in Bangladesh. The kernel density analysis tool is under the spatial analyst tool of density calculation. The kernel density estimation is a geospatial operation. On the other hand, the geographic distribution of tropical cyclones has been analyzed from the spatial statistics tools measuring geographic distributions. The georeferencing and digitizing tools have been employed to prepare the GIS database for tropical cyclones in the Bay of Bengal. The trajectory points of cyclones on variation location have been converted to line data from ArcGIS data management tools.

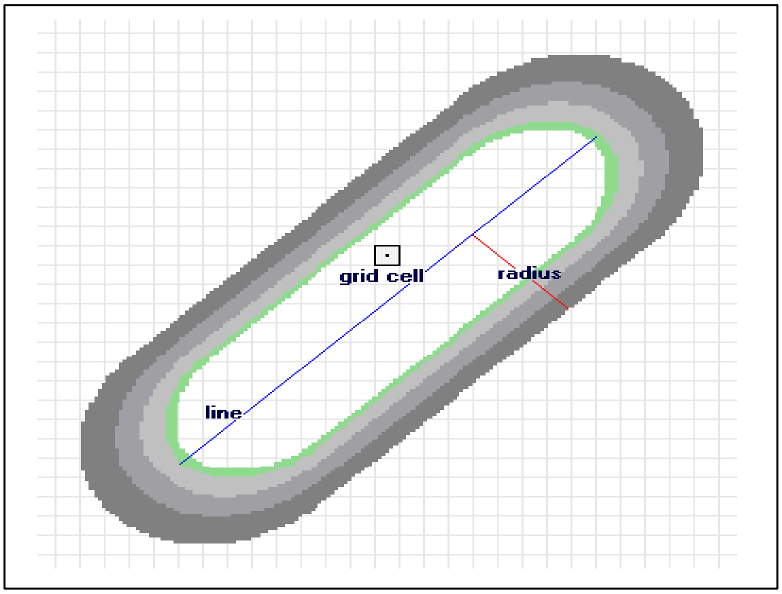
Figure 1: Methodological framework of this study.



Kernel Density Estimation

The Kernel Density tool determines the density of features in the area closest to them. By fitting a smoothly curved surface to each point or polyline using a kernel function, it calculates a magnitude-per-unit space from the point or polyline properties. Kernel Density can be used to calculate the density of lines in the vicinity of each output raster cell. Each line has a smoothly curved surface that is logically matched to it. Its value is highest on the line and decreases as it advances away until reaching zero at the specified Search radius distance. The density at each output raster cell is calculated by adding the values of all the kernel areas that overlap the raster cell center.

Figure 2: Kernel density output for lines.



Source: Kernel Density (Spatial Analyst)—ARCMap, n.d.

The provided visual representation in figure 2 depicts a linear segment accompanied by the kernel surface that has been appropriately fitted onto it. The density of a line segment is determined by the value of the kernel surface at the center of the corresponding raster cell. The selection of a unit is determined by the linear unit in the projection specification of the input polyline feature data, or as explicitly stated in the Output Coordinate System environment parameter.

Predicting the density of points,

$$Density = \frac{1}{(radius)^2} \Sigma \sum_{i=1}^{n} [\frac{3}{\pi} . pop_i \left(1 - \left(\frac{dist_i}{radius}\right)^2\right)^2] \qquad (1)$$

For $dist_i < radius$

Where,

i = 1,…,n are the input points. Only include points in the sum if they are within the radius distance of the (x,y) location.

pop_i is the population field value of point i, an optional parameter.

$dist_i$ is the distance between point i and the (x,y) location.

Default search radius,

$$Search\ Radius = 0.9 * \min\left(SD\sqrt{\frac{1}{\ln(2)}D_m}\right) * n^{-0.2} \quad (2)$$

Where,

Dm is the (weighted) median distance from (weighted) mean center.

n is the number of points if no population field is used or if a population field is supplied, and n is the sum of the population field values.

SD is the standard distance.

Unweighted distance,

$$SD = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{X})^2}{n} + \frac{\sum_{i=1}^{n}(y_i - \bar{Y})^2}{n} + \frac{\sum_{i=1}^{n}(z_i - \bar{Z})^2}{n}} \quad (3)$$

Where,

x i, y i and z i are the coordinates for feature i

{x̄, ȳ, z̄} represents the mean centre for the features

n is equal to the total number of features.

Weighted distance,

$$SD_w = \sqrt{\frac{\sum_{i=1}^{n} w_i(x_i - \bar{X}_w)^2}{\sum_{i=1}^{n} w_i} + \frac{\sum_{i=1}^{n} w_i(y_i - \bar{Y_w})^2}{\sum_{i=1}^{n} w_i}} + \frac{\sum_{i=1}^{n}(w_i(z_i - \bar{Z}_w)^2}{\sum_{i=1}^{n} w_i} \quad (4)$$

Where,

wi is the weight at feature i

{x w, y w, z w} represents the weighted mean center

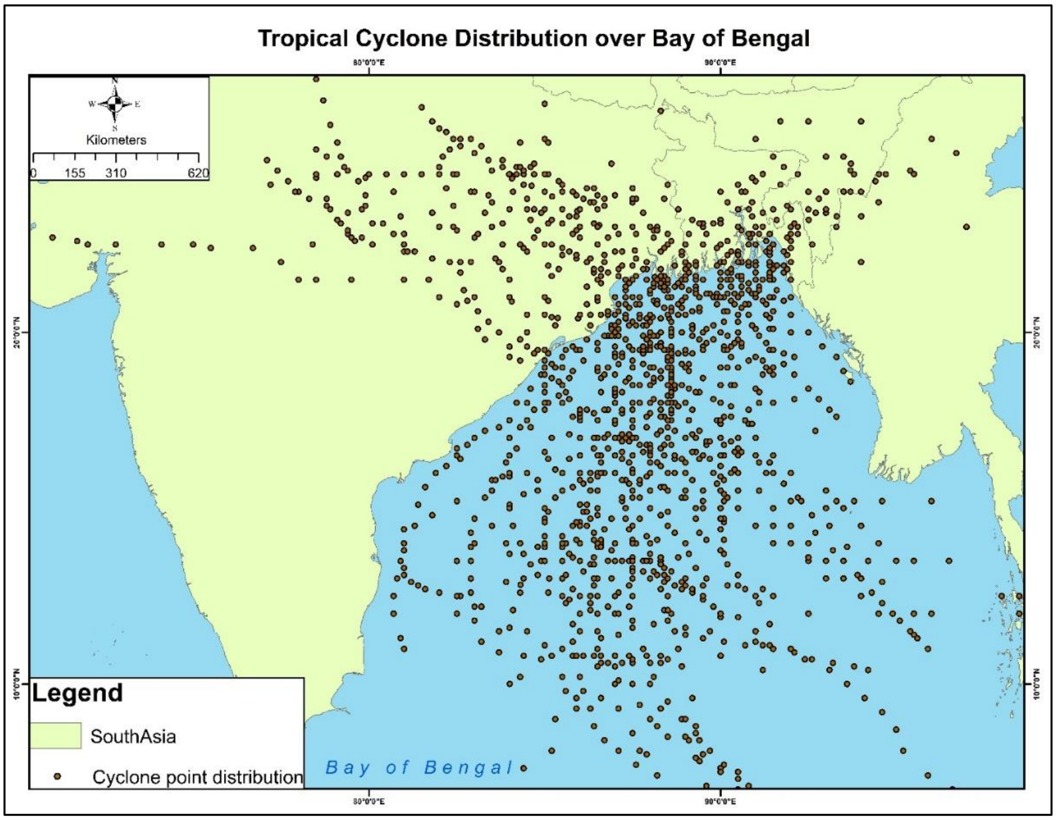
3. Results & Discussions

The research aims to focus on the analysis of tropical cyclone frequency characteristics in the Bay of Bengal by kernel density estimation, which ultimately leads to the mapping of cyclone risk zones. The kernel density estimation is a widely used method for risk zoning due to its ability to accurately investigate the density of occurrences. Kernel density estimation offers a detailed examination of the spatial distribution of events. This research attempted to explore the potentiality of kernel density estimation to analyze tropical cyclone frequencies in Bangladesh.

3.1 Spatial Distribution of Tropical Cyclones in the Bay of Bengal

Tropical cyclones are frequently observed in the Indian Ocean, particularly in the Bay of Bengal, which is recognized as a highly active area for cyclone genesis. The region experiences frequent cyclone genesis, and these cyclones often have significant impacts on the countries and coastal regions surrounding the Bay of Bengal.

Figure 3: Spatial distribution of cyclonic events over the Bay of Bengal.



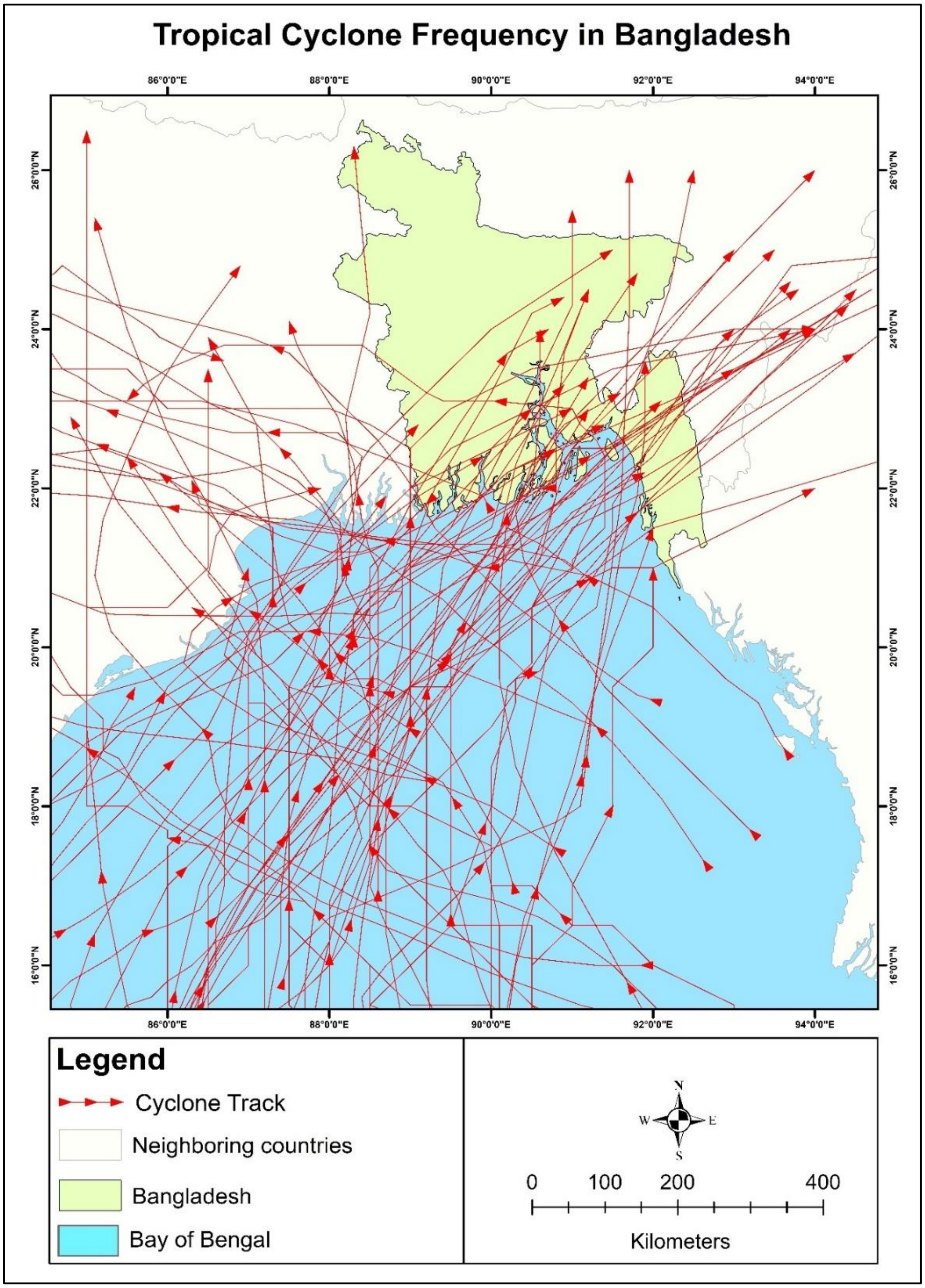
The Bay of Bengal is renowned for its propensity to foster tropical cyclone formation due to the presence of higher sea surface temperatures and conducive meteorological conditions. The presence of higher sea surface temperatures is a crucial factor in the formation and intensification of cyclones. The Bay of Bengal generally sustains high temperatures during the cyclone season, thereby supplying the requisite thermal energy for the amplification of cyclones. The phenomenon of monsoon winds in the Indian Ocean, characterized by their seasonal reversal, exerts a significant influence on the creation and trajectory of cyclones. During the transitional stages of the monsoon, there is a shift in wind direction, which leads to creating a conducive environment for the formation of cyclones. Favorable meteorological conditions, such as lower vertical wind shear and higher humidity levels, play a significant role in the genesis and intensification of cyclonic systems. The frequency of tropical cyclones in the Bay of Bengal is comparatively higher in relation to other regions within the Indian Ocean. The Bay of Bengal cyclone season normally lasts from April to December, with the peak being between September and November.

The figure 3 shows that the cyclonic events are distributed over the entire northern Bay of Bengal. The dispersion of cyclonic events across the whole northern Bay of Bengal is a notable observation that highlights the region's high cyclone activity. The northern Bay of Bengal, which embraces the coasts of India, Bangladesh, and Myanmar, is notorious for its cyclone risk. The coastal area of Bangladesh is particularly vulnerable to cyclonic events, as the distribution of TC shows a highly clustering scenario over there. However, the lower northern Bay of Bengal shows a low density of the events.

3.2 Tropical Cyclone Frequency in Bangladesh

The paths and frequency of cyclones in Bangladesh are influenced by its geographical positioning, its close vicinity to the Bay of Bengal, as well as a range of atmospheric and oceanic factors. Bangladesh exhibits significant exposure to the consequences of tropical cyclones due to its geographically low-lying coastal terrain and its proximity to places prone to cyclonic activity (Islam et al., 2016). Most cyclones that affect Bangladesh originate in the Bay of Bengal. Warm sea surface temperatures, particularly during the pre-monsoon and post-monsoon seasons, foster the formation of cyclones. Cyclones in the Bay of Bengal often move northwest and make landfall along Bangladesh's coastline. Bangladesh's flat and low-lying geography allows cyclones to travel inland, causing substantial damage even after landfall. Coastal areas, notably in Bangladesh's southwest and southeast, are particularly vulnerable to the effects of cyclones (Paul, 2009). Strong winds, torrential rainfall, storm surges, and flooding are common in these areas. The Bay of Bengal cyclone season normally lasts from April to December, with the peak being between September and November (Duan et al., 2021). The conditions are most favorable to produce cyclones during this time period. On an annual basis, Bangladesh encounters an average of 2 to 3 tropical cyclones.

Figure 4: Cyclone tracks and frequency in Bangladesh

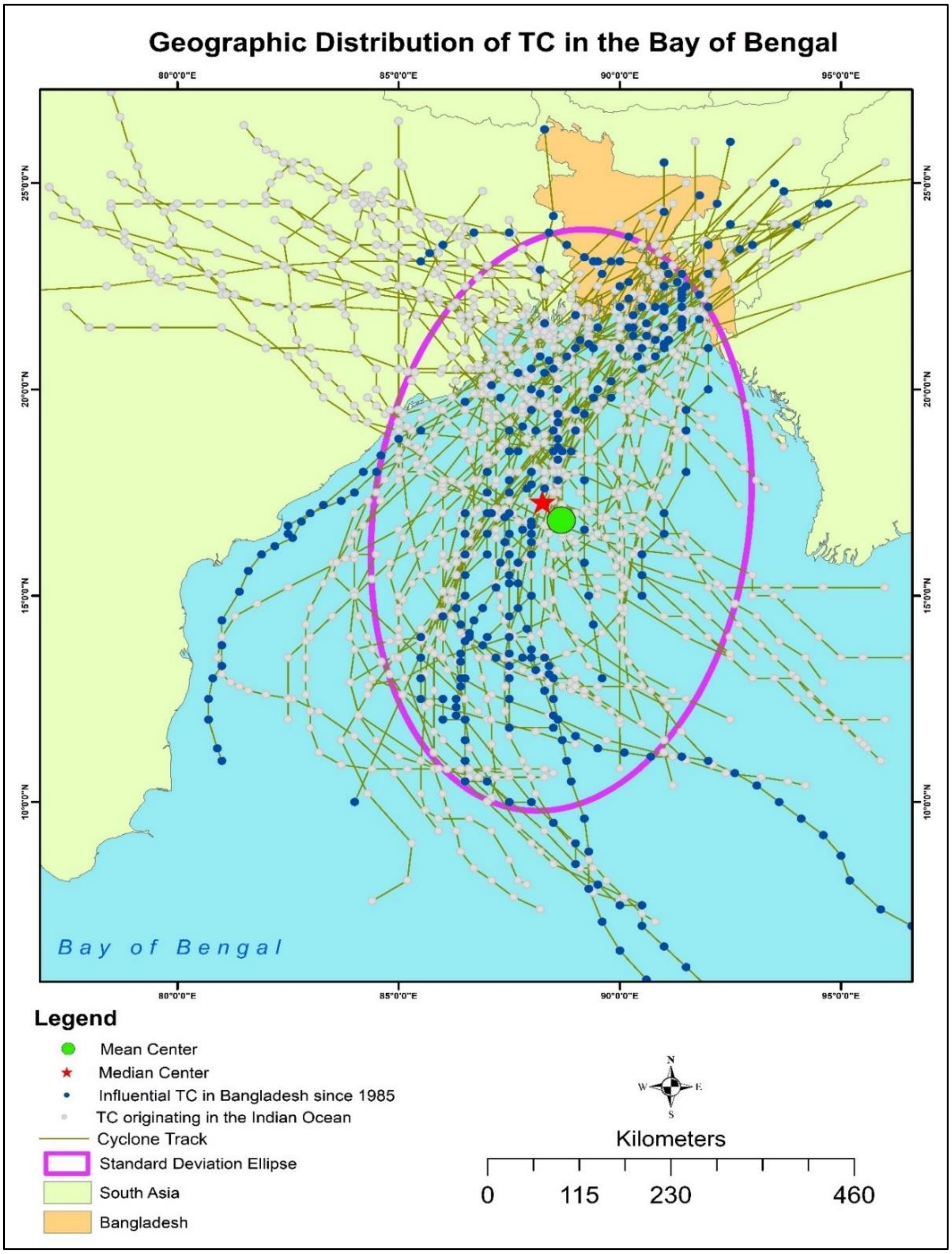


However, the amount might vary greatly from year to year due to weather and marine conditions. Several factors, including sea surface temperatures, atmospheric conditions, and the El Nio-Southern Oscillation (ENSO) phenomena, might influence the frequency of tropical cyclones in Bangladesh (Christensen, 2012). The energy required for the formation and intensification of tropical cyclones is provided by warm sea surface temperatures. When sea surface temperatures (SSTs) are higher, there is more evaporation, which increases the amount of moisture in the atmosphere. This can be a factor in the production of convective activity and cyclones. Cyclones have a greater chance of occurring in areas of the ocean that have sea surface temperatures (SSTs) that are continuously warm. The Bay of Bengal is a prime instance of such a location. Wind patterns and moisture availability, among other factors, play a significant role in cyclone development and intensification. Low vertical wind shear (change in wind direction and speed with height) is favorable for cyclone formation because it allows the tropical cyclone to maintain its structure (Riemer, 2013). Humid air near the surface is required for energy to enter the cyclone system. El Nio is a climate phenomenon that mostly affects the Pacific Ocean region, where sea surface temperatures rise above normal. While El Nino's direct effects are most noticeable in the Pacific region, its influence can spread to other parts of the earth, including the Indian Ocean and the Bay of Bengal.

3.3 Geographic Distribution of Tropical Cyclone in the Bay of Bengal:

The Bay of Bengal is a hotspot for tropical cyclone activity (Soeb et al., 2023; Sarkar, n.d.; Bandyopadhyay et al., 2021), and Bangladesh, lying along the Bay's northeastern shore, is particularly vulnerable to the effects of these cyclones. Although the entire Bay of Bengal basin is susceptible to the formation of tropical cyclones, the frequency, intensity, and courses of cyclones can vary considerably across the basin. Cyclones form more frequently in the northern Bay of Bengal, near the shores of Myanmar and Bangladesh, than in other places. The center region of the Bay of Bengal may experience cyclone formation, although at a lower frequency than the northern part. Cyclones that form here can occasionally travel longer distances, allowing them to intensify over the warm seas of the Bay before hitting land. The frequency of cyclone development in the southern Bay of Bengal is comparatively lower, particularly in areas that are more distant from the Indian subcontinent. The presence of cooler sea surface temperatures and less favorable atmospheric conditions typically reduces the probability of cyclone formation in this particular region. The trajectories of cyclones in the Bay of Bengal can vary due to a range of circumstances, such as the influence of steering winds and atmospheric circulation patterns.

Figure 5: Geographic distributions of tropical cyclones in the Bay of Bengal.



Cyclones that originate in close proximity to the northern shore of the Bay of Bengal exhibit a higher propensity for landfall in regions such as Bangladesh, Myanmar, and the northeastern coast of India. It is noteworthy that although the northern region of the Bay of Bengal exhibits a higher susceptibility to cyclones, cyclonic systems can affect the entire basin. The Bay of Bengal is characterized by a significant level of cyclone activity, which can have extensive consequences for the countries situated along its coastlines. The intricate patterns of cyclone formation and movement in the Bay of Bengal are influenced by the diverse terrain, oceanic conditions, and atmospheric dynamics present in the region. Analyzing the geographic distribution of cyclones in the Bay of Bengal is an intriguing endeavour that can provide insight into the spatial patterns, frequency, and intensity of cyclonic events in the region. The point distribution and cyclone track data from 1960 to 2023 have been analyzed to estimate the geographic distribution of tropical cyclonic events in the Bay of Bengal basins. This analysis demonstrates the cyclonic hazard scenario very profoundly in the context of Bangladesh. The findings shows that the entire coastal region of Bangladesh is highly susceptible to cyclonic hazard, where the mean and median center of the hazard is in the northern Bay of Bengal.

Tropical Cyclone Distribution with Categories

The categorization of tropical cyclone distribution in the Bay of Bengal can be based on multiple characteristics that extend beyond intensity, frequency, and impact. Tropical cyclones in the Indian Ocean, including the Bay of Bengal, are classified using a specific scale by the Indian Meteorological Department (IMD). This scale is known as the IMD Indian Ocean Cyclone Scale, and it classifies cyclones based on their highest sustained wind speeds. According to IMD, the cyclone scales are categorized into Depression, Deep Depression, Cyclonic Storm, Severe Cyclonic Storm, Very Severe Cyclonic Storm, Extremely Severe Cyclonic Storm, and Super Cyclonic Storm.

Various categories of cyclonic hazards have been observed in the northern Indian Ocean basin causing severe damage to the coastal region of Bangladesh, India and Myanmar. However, the most powerful cyclones have been noticed to cause destruction over south-western (Sundarbans and deltaic region) and south-eastern coasts (Cox,s Bazar, Teknaf region) of Bangladesh and the north-eastern coast of India (Particularly Odisha).

Figure 6: Tropical cyclones point distribution, tracks and categories.

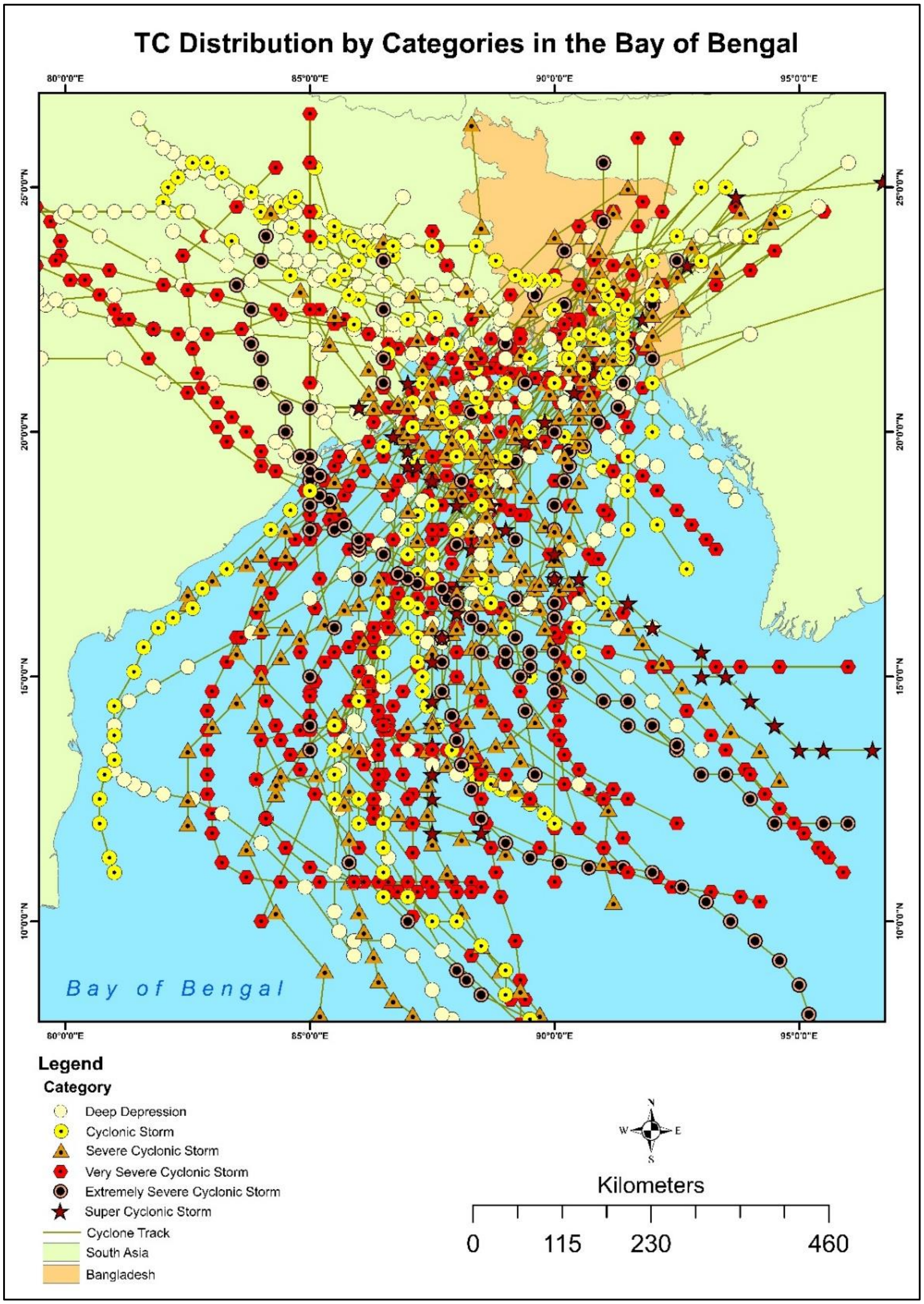


Table 1: Cyclone scale according to Indian Meteorological Department (IMD).

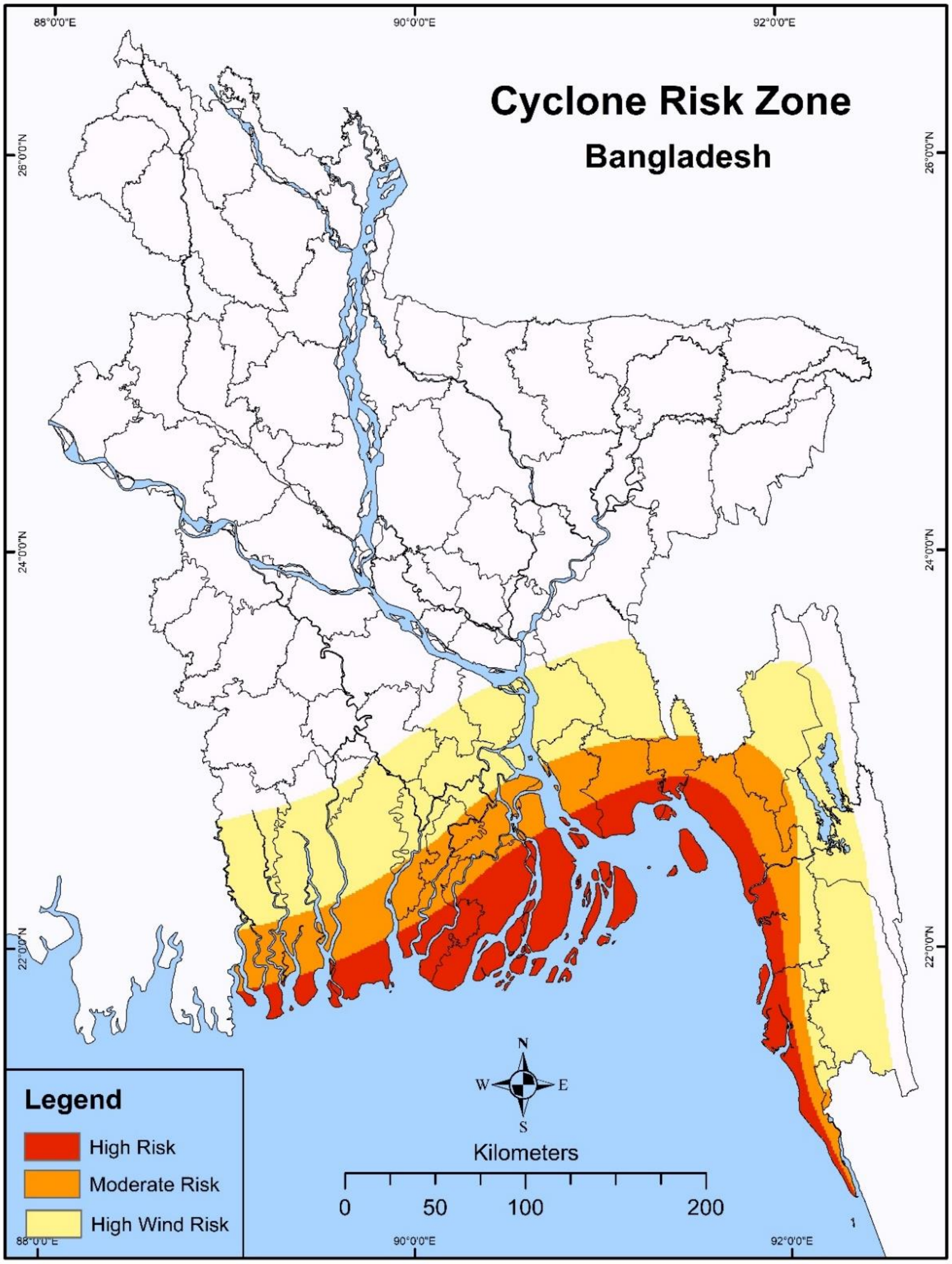
Categories	Sustained Wind Speed (3 minutes average)
Super cyclonic Storm	≥221 km/h
Extremely Severe Cyclonic Storm	166–220 km/h
Very Severe Cyclonic Storm	118–165 km/h
Severe Cyclonic Storm	89–117 km/h
Cyclonic Storm	63–88 km/h
Deep Depression	51–62 km/h
Depression	31–50 km/h

The research took a total 80 cyclones to study from 1960 to 2023 and found the most frequent cyclones are in the category of Very Severe Cyclonic Storms (118–165 km/h) which were 26 in numbers among the samples. On the other hand, the rest of the categories show Deep Depressions, Cyclonic Storms, Severe Cyclonic Storms, Extremely Severe Cyclonic Storms, and Super Cyclones are 20, 10, 16, 6, and 2 in numbers accordingly. The most frequent cyclones are quite powerful as they often have wind speeds of 118 to 165 kilometers per hour and impact the region frequently. The other frequent cyclones are in the category of deep depressions and severe cyclonic storms. Whereas the strongest cyclones like extremely severe cyclonic storms and super cyclones are not as frequent as the other categories.

3.4 Cyclone Risk Zoning by Analyzing TC Frequencies:

Through the examination of historical cyclone data and cyclone tracks, the utilization of kernel density analysis can facilitate the identification of regions that exhibit a higher vulnerability to cyclone impacts. Kernel density research can assist in identifying regions in which cyclone-related events like landfalls, high wind speeds, and storm surges have occurred more frequently in the past. These high-density spots on the density surface suggest places that are more likely to be affected by similar occurrences in the future. The researcher has identified cyclone risk zones based on the kernel density analysis, which reflects different levels of sensitivity to cyclone impacts. High-risk zones are defined by places with the highest kernel density values (high density of cyclone frequency spot), whereas low-risk zones are defined by areas with lower density values.

Figure 7: Cyclone risk zoning in Bangladesh



In this study, the researcher has analyzed three distinct cyclone risk zones in Bangladesh. The zones are- high-risk, moderate risk and high-wind-risk zones. The high-risk zone is expected to encompass coastal regions that are particularly vulnerable to the direct consequences of cyclonic events. These regions have a historical record of recurrent cyclone occurrences and consequential substantial devastation. During cyclonic events, residents in these zones are more likely to experience storm surges, flooding, and strong winds. Infrastructure, housing, and critical facilities within this zone may require heightened resilience measures and disaster preparedness strategies. The moderate-risk zone includes places that are less vulnerable than the high-risk zones but nonetheless face a significant cyclone impact. Communities in this zone may experience cyclone impacts less frequently or with less intensity than communities in high-risk areas. In these areas, disaster management activities should remain robust, with a focus on effective early warning systems, evacuation strategies, and infrastructure resilience.

The high wind-risk zone most likely represents places that are more vulnerable to heavy winds during cyclonic occurrences. These are the areas with persistent wind risks more than the storm surges, comparatively to high-risk and moderate-risk areas. High wind speeds can cause damage to structures, infrastructure, and vegetation. In this zone, mitigation actions could include enforcing more durable construction rules, guaranteeing infrastructure structural integrity, and promoting the use of wind-resistant materials.

4. Conclusion

Kernel density analysis is a versatile method that is frequently employed in several disciplines. The approach under consideration is a multipurpose method of spatial analysis that can be effectively employed to comprehend the distribution, concentration, and intensity of various events or phenomena within a given geographic region. Risk zone analysis with kernel density entails evaluating the spatial distribution and magnitude of specific occurrences or phenomena within a given geographical area in order to discern areas with a high degree of risk. Kernel density analysis has been used as an invaluable technique for evaluating the zoning of cyclone risk in this study. Within the realm of cyclones, kernel density analysis can be employed to establish cyclone risk zones through the examination of past cyclone data and its associated consequences. It helps in the identification of high-risk areas and aids in disaster preparedness and mitigation efforts. Kernel density analysis gives important insights into spatial patterns that can be used to inform decision-making and resource allocation in a variety of sectors. Its capacity to show event concentrations and intensities makes it an indispensable tool for comprehending spatial phenomena. This analytical approach can subsequently inform the development and implementation of efficient disaster preparedness and mitigation methods.

References

Ahamed, S., Rahman, M. M., & Faisal, M. A. (2012). Reducing cyclone impacts in the coastal areas of Bangladesh: A case study of Kalapara Upazila. *J. Bangladesh Inst. Plan, 2075*, 9363.

Akhand, M. H. (2003). Disaster management and cyclone warning system in Bangladesh. *Early warning systems for natural disaster reduction*, 49-64.

Alam, E., & Dominey-Howes, D. (2015). A new catalogue of tropical cyclones of the northern Bay of Bengal and the distribution and effects of selected landfalling events in Bangladesh. *International Journal of Climatology*, *35*(6), 801-835.

Bandyopadhyay, S., Dasgupta, S., Khan, Z. H., & Wheeler, D. (2021). Spatiotemporal analysis of tropical cyclone landfalls in Northern Bay of Bengal, India and Bangladesh. *Asia-Pacific Journal of Atmospheric Sciences*, 1-17.

Baten, A., González, P. A., & Delgado, R. C. (2018). Natural disasters and management systems of Bangladesh from 1972 to 2017: Special focus on flood. *OmniScience: A Multi-disciplinary Journal*, *8*(3), 35-47.

Christensen, A. S. (2012). *Large-Scale Circulation Variability and Impacts on North Indian Ocean Tropical Cyclones* (Doctoral dissertation, Monterey, California. Naval Postgraduate School).

Doocy, S., Dick, A., Daniels, A., & Kirsch, T. D. (2013). The human impact of tropical cyclones: a historical review of events 1980-2009 and systematic literature review. *PLoS Currents*, *5*.

Duan, W., Yuan, J., Duan, X., & Feng, D. (2021). Seasonal variation of tropical cyclone genesis and the related large-scale environments: Comparison between the Bay of Bengal and Arabian Sea sub-basins. *Atmosphere*, *12*(12), 1593.

Dube, S. K., Jain, I., Rao, A. D., & Murty, T. S. (2009). Storm surge modelling for the Bay of Bengal and Arabian Sea. *Natural Hazards*, *51*, 3-27.

Ghorai, D., & Sen, H. S. (2015). Role of climate change in increasing occurrences oceanic hazards as a potential threat to coastal ecology. *Natural Hazards*, *75*, 1223-1245.

Haque, C. E., & Blair, D. (1992). Vulnerability to tropical cyclones: evidence from the April 1991 cyclone in coastal Bangladesh. *Disasters*, *16*(3), 217-229.

Hossain, M. N. (2015). Analysis of human vulnerability to cyclones and storm surges based on influencing physical and socioeconomic factors: evidences from coastal Bangladesh. *International journal of disaster risk reduction*, *13*, 66-75.

Islam, M. A. (2014). *Role of Bangladesh betar in reducing risk arising from natural calamities: a case study in Maheshkhali upazila of Cox's Bazar district in Bangladeh* (Doctoral dissertation, BRAC University).

Islam, M. A., Mitra, D., Dewan, A., & Akhter, S. H. (2016). Coastal multi-hazard vulnerability assessment along the Ganges deltaic coast of Bangladesh–A geospatial approach. *Ocean & Coastal Management*, *127*, 1-15.

Islam, M. N., van Amstel, A., Islam, M. N., Tamanna, S., van Amstel, A., Noman, M., ... & Ghosh, A. (2021). Climate change impact and comprehensive disaster management approach in Bangladesh: a review. *Bangladesh II: climate change impacts, mitigation and adaptation in developing countries*, 1-39.

Kang, M. S., & Banga, S. S. (2013). Global agriculture and climate change. *Journal of Crop Improvement*, *27*(6), 667-692.

Kernel Density (Spatial Analyst)—ARCMap | Documentation. (n.d.). https://desktop.arcgis.com/en/arcmap/latest/tools/spatial-analyst-toolbox/kernel-density.htm

Khalil, G. M. (1992). Cyclones and storm surges in Bangladesh: some mitigative measures. *Natural Hazards*, *6*, 11-24.

Kotal, S. D., Roy Bhowmik, S. K., Kundu, P. K., & Das Kumar, A. (2008). A statistical cyclone intensity prediction (SCIP) model for the Bay of Bengal. *Journal of earth system science*, *117*, 157-168.

Mirza, M. M. Q. (2003). Climate change and extreme weather events: can developing countries adapt? *Climate policy*, *3*(3), 233-248.

Murty, T. S., & Flather, R. A. (1994). Impact of storm surges in the Bay of Bengal. *Journal of Coastal Research*, 149-161.

Murty, T. S., & Neralla, V. R. (1992). On the recurvature of tropical cyclones and the storm surge problem in Bangladesh. *Natural Hazards*, *6*, 275-279.

Nath, S., Kotal, S. D., & Kundu, P. K. (2016). Decadal variation of ocean heat content and tropical cyclone activity over the Bay of Bengal. *Journal of Earth System Science*, *125*, 65-74.

Parven, A., Pal, I., Witayangkurn, A., Pramanik, M., Nagai, M., Miyazaki, H., & Wuthisakkaroon, C. (2022). Impacts of disaster and land-use change on food security and adaptation: Evidence from the delta community in Bangladesh. *International Journal of Disaster Risk Reduction*, *78*, 103119.

Parvin, G. A., Sakamoto, M., Shaw, R., Nakagawa, H., & Sadik, M. S. (2019). Evacuation scenarios of cyclone Aila in Bangladesh: Investigating the factors influencing evacuation decision and destination. *Progress in Disaster Science*, *2*, 100032.

Patnaik, K. V. K. R. K., Maneesha, K., Sadhuram, Y., Prasad, K. V. S. R., Ramana Murty, T. V., & Brahmananda Rao, V. (2014). East India Coastal Current induced eddies and their interaction with tropical storms over Bay of Bengal. *Journal of operational oceanography*, *7*(1), 58-68.

Paul, B. K. (2009). Why relatively fewer people died? The case of Bangladesh's Cyclone Sidr. *Natural Hazards*, *50*, 289-304.

Paul, S. K. (2014). Determinants of evacuation response to cyclone warning in coastal areas of Bangladesh: a comparative study. *Oriental Geographer*, *55*(1-2), 57-84.

Paul, S. K., & Routray, J. K. (2011). Household response to cyclone and induced surge in coastal Bangladesh: coping strategies and explanatory variables. *Natural Hazards*, *57*, 477-499.

Paul, S. K., & Routray, J. K. (2013). An analysis of the causes of non-responses to cyclone warnings and the use of indigenous knowledge for cyclone forecasting in Bangladesh. *Climate change and disaster risk management*, 15-39.

Poncelet, A., Gemenne, F., Martiniello, M., & Bousetta, H. (2010). A country made for disasters: environmental vulnerability and forced migration in Bangladesh. *Environment, forced migration and social vulnerability*, 211-222.

Rahman, M. S. (2013). Climate change, disaster and gender vulnerability: A study on two divisions of Bangladesh. *American Journal of Human Ecology*, *2*(2), 72-82.

Riemer, M., Montgomery, M. T., & Nicholls, M. E. (2013). Further examination of the thermodynamic modification of the inflow layer of tropical cyclones by vertical wind shear. *Atmospheric Chemistry and Physics*, *13*(1), 327-346.

Roy, C., Sarkar, S. K., Åberg, J., & Kovordanyi, R. (2015). The current cyclone early warning system in Bangladesh: providers' and receivers' views. *International journal of disaster risk reduction*, *12*, 285-299.

Rubiera Torres, J. M., & Puig, M. A. (2012). The tropical cyclone early warning system of Cuba. *Institutional Partnerships in Multi-Hazard Early Warning Systems: A Compilation of Seven National Good Practices and Guiding Principles*, 9-28.

Sahoo, B., & Bhaskaran, P. K. (2016). Assessment on historical cyclone tracks in the Bay of Bengal, east coast of India. *International Journal of Climatology*, *36*(1), 95-109.

Sarkar, D. Intensification of Tropical Cyclones due to climate change: A case study from Bay of Bengal (2001-2020).

Shamsuddoha, M., & Chowdhury, R. K. (2007). Climate change impact and disaster vulnerabilities in the coastal areas of Bangladesh. *COAST Trust, Dhaka*, 40-48.

Soeb, M., Ali, M. S., & Hassan, S. M. (2023, April). Simulation of Sidr-like cyclone using MRI storm surge model with various initial strength: A Bay of Bengal context. In *AIP Conference Proceedings* (Vol. 2713, No. 1). AIP Publishing.

Tiwari, G., Kumar, P., Javed, A., Mishra, A. K., & Routray, A. (2022). Assessing tropical cyclones characteristics over the Arabian Sea and Bay of Bengal in the recent decades. *Meteorology and Atmospheric Physics*, *134*(3), 44.

Vivekanandan, E., Hermes, R., & O'Brien, C. (2016). Climate change effects in the Bay of Bengal large marine ecosystem. *Environmental Development*, *17*, 46-56.

Wahiduzzaman, M. (2021). Major floods and tropical cyclones over Bangladesh: clustering from ENSO timescales. *Atmosphere*, *12*(6), 692.

Zhang, C., Yin, K., Shi, X., & Yan, X. (2021). Risk assessment for typhoon storm surges using geospatial techniques for the coastal areas of Guangdong, China. *Ocean & Coastal Management*, *213*, 105880.