FINAL REPORT

RISK PROFILING FOR THE SEA LEVEL RISE IN COASTAL AREAS OF SINDH PROVINCE

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List of Abbreviations

GIS	Geographic Information System
LULC	Land Use Land Cover
DSAS	Digital Shoreline Assessment System
EPR	End Point Rate
SCE	Shoreline Change Envelope
IPCC	Intergovernmental Panel on Climate Change
AR5	Fifth Assessment Report
UNEP	United Nations Environment Programme
ICT	Information Communication and Technology
GDP	Gross Domestic Product
SLR	Sea Level Rise
GW	Ground Water

DEM	Digital Elevation Model
UTM	Universal Trans Mercartor
POI	Point of Interest
USGS	United States Geological Survey
SSP	Shared Socio-Economic Pathway

Executive Summary

Coastal areas are sensitive and vulnerable to meteorological and geomorphic hazards such as cyclones, storm surges, sea-level rise, coastal erosion, change in shoreline, coastal flooding etc. which are further triggered by anthropogenic intervention. Coastal zones are economically important to most nations and are subject to a variety of human impacts and drivers for boosting economic activity. Moreover, the UNEP included Pakistan within the group of vulnerable countries in 1989 through their Regional Seas program. Therefore, the present study focuses on the effect of climate change and its associated impacts like sea-level rise, coastal erosion, changes in land use, and therefore identification of potential risk zones in coastal areas of South Pakistan.

Inundation was calculated using three different kinds of elevation data namely SRTM, ASTER and MERIT. The relative elevation data depicts the possible inundated areas under different future sea-level rise scenarios. Coastal erosion, which is an indirect effect of sea-level rise, was calculated using Digital Shoreline Assessment System (DSAS). The EPR data was also utilized for prediction in case of sea-level rise reaches 0.5 m to 2 m. Changes in the pattern of land use and land cover were also estimated using object-oriented classification. The classification was performed in two parts- spatial clustering of the contiguous and similar pixels and then classifying using Random Forest and Support Vector Machine (SVM). The clustering of pixels was developed in e-Cognition by implementing Simple Non-Iterative Clustering (SNIC) and Grey-Level Co-occurrence Matrix (GLCM) algorithms.

The risk zones were identified through a combination of erosion and inundation data as inputs. Areas with different degrees of erosion and inundation were classified using a continuous scale. Based on the normalized values of each scale, a score has been assigned to each zone and their relative risk potential has been identified. This report may serve as a baseline for the coastal zone management in the coastal area of Sindh Province.

Along with identification and quantification of risk in the study area, this report also provides guidance for the development and implementation of Coastal Risk Management Plan (CRMP) to mitigate and manage the risks arising in coastal areas due to interaction with multiple hazards and further exacerbated by climate change and sea level rise. The report broadly discusses the risk mitigation measures for four levels of coastal risk. Irrespective of the mitigation measures, reflection of socio-cultural and historical perspectives in the risk management plan through multi-level communication and inclusion of all stakeholders and end-users can not only help in decision-making process but also work towards changing risk perception. Based on these principles, the report recommends for the development of Pakistan Coastal Resilience Index (PCRI) through appropriate assessment and case studies to assist the short, medium and long-term planning and development of the region. Similarly, multi-hazard risk assessment of critical infrastructure will prove useful in planning future investment and development. Finally, community-based risk information system developed in the coastal communities can help improve the adaptation capacity to address existing vulnerabilities.

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1 BACKGROUND

Coastal areas being the transitional zone between land and sea are identified as dynamic, complex and ecologically productive geomorphic units. Globally, coasts, to a great extent, are sensitive and vulnerable to meteorological and geomorphic hazards such as cyclones, storm surges, sea-level rise, coastal erosion, submergence of coasts, change in shoreline, coastal flooding etc. which are further triggered by anthropogenic interventions. Coastal zones, in general, serve as economic hubs and are subject to various human impacts and drivers for boosting economic activity for developing countries like Pakistan. Among different natural hazards that possess a threat to the low-lying coastal areas, sea-level rise and resultant coastal erosion are the most significant ones.

Sea level rise is a global phenomenon that refers to a sustained increase of the mean sea level over a definite time duration owing to various eustatic and isostatic changes among which global warming is the predominant one. The major cause of this phenomenon is the melting of the glaciers and ice sheets from the vast expanses of the ice which covers Antarctica and Greenland and contributes to almost two-third of global sea-level rise. Most of the melting stems from warm air interaction with ice surface which causes melting of the upper surface in the ice sheet as well as break up or calving of glaciers which is eventually released in the sea. Effects of rising sea levels, however, are not constant around the globe. The effect can be seen higher in some coastal areas and very nominal in other parts of the world.

The densely populated coastal districts will be subjected to coastal erosion and intense storm surge along with land loss due to sea-level rise. The coastline and associated process of erosion accretion has always been dynamic in nature, but climate change and changes in nearshore physical processes speed up the process. The major impact of climate change in the coastal zone will be reflected in sea-level rise and combined with possible increase in frequency and intensity of storm surges which will affect the changes in the pattern of erosion and sedimentation, increased risk of permanent and frequent flooding along with changes in the distribution of coastal land use. The UNEP included Pakistan within the group of vulnerable countries in 1989 through their Regional Seas Program. Based on the trend observed in the recent past, a 50 mm (5cm) rise in sea level can be expected in the next 50 years in and around the coast of Pakistan. Among the different countries along the Arabian Sea, Pakistan is considered to be one of the most severely risked countries by sea-level rise and resultant consequences like coastal erosion and coastal flooding.

2 INTRODUCTION

Intergovernmental Panel on Climate Change (IPCC) fifth assessment report (AR5) identified sea level rise as one of the most important risks faced by the nations and communities in South Asia in coming decades. The low lying densely populated costal districts will be subjected to costal erosion and intense storm surge along with land loss due to sea level rise. Therefore, it is important to understand the severity of the effect in short and long-term, assessing the physical and social damages due to changes done in the past decade. This project aimed to deliver integrated assessment of the impact of future sea level rise, coastal erosion, and land use change on coastal socio-economy for selected coastal districts of Pakistan. For disaster managers who are tasked to formulate coastal defenses and adaptation measures, this study can be used not only as a baseline but also for a clear understanding of what will happen if proper measures are not taken in time. Furthermore, it will assist them to understand the effectiveness and shortfall of any adaptive measures taken in the past and the scope and opportunities for improvement.

Given the spatial and temporal nature of the data, effective resource management requires the application of methods and software tools pertaining to the Information and Communication Technologies (ICT) sector such as spatial data management and numerical modelling. Thus, the project will also prepare state-of-the-art integration of GIS containing a database of readily available secondary data as well as an interactive dashboard reflecting common indicators to help policy planners and provincial administrators. The proposed system will have ample flexibility to enhance its capability to incorporate the further need of the administrator. The challenges identified are not specific to this project. Other provinces/municipalities throughout South Asia (coastal provinces) experience similar barriers (i.e., financial implications, coastal planning predicaments, data paucity, knowledge and capacity, and legal and political challenges). Thus, methodology adopted during this project can be easily replicated.

The major impact of climate change in coastal zone will be reflected in sea level rise and possible increase of storm surges in frequency and intensity which will affect the changes in the pattern of erosion and sedimentation, increased risk of permanent and frequent flooding along with changes in the distribution of coastal land use. The coastline and associated process of erosion accretion has always been dynamic in nature; climate change and changes in near shore physical processes speed up the changes. This will have a profound impact on coastal community in low lying areas and can lead to impacts ranging from loss in economic opportunity to permanent relocation. Coastal zones have immense economic importance across the world and are subjected to a variety of human impacts and drivers for boosting economic activity in developing countries like Pakistan.

Significant sea level rise of 1 mm along coastal Sindh observed over hundreds of years has resulted in sea water intrusion inland. Intruding sea water has a strong impact on the coastal communities. Recurrence of cyclones with increased frequency and intensity in the Arabian Sea over the past 50 years due to climate change has economic repercussions in urban communities like Karachi, Sujawal and Thatta. Economic importance of Sindh coastal region is evident and the cost of negligence with respect to this phenomenon will be huge. Results of climate changes are already costing around $14bn/ year, equivalent to 5% of Pakistan’s GDP. Continued losses due to sea level rise will have a further negative impact on the fragile coastal economy. Karachi and the Indus Deltaic coastal areas are vulnerable to the threat of sea level rise. Thus, the need is to evaluate the trade-off between business-as-usual scenario, mitigation and adaptation options. Once damage to coastal recourses and structure has been done, then this will lead to capital loss.

A large coastal area has already been lost as a result of erosion by the strong long-shore currents developed by the intensive wave action during the southwest monsoon seasons of the consecutive years (Tabrez, 2012). The rate of erosion varies across the coastal region with a general trend of erosion increasing from west to east in the Indus Delta region (IDR), and the highest average erosion rate is 27.46 m/yr.

For tropical cyclones, there is an anticipated increment of 10-20% in the power of storms with an increase in ocean surface temperature of 2-4 ℃ in Asia. Karachi, one of the most populous cities of Pakistan is located on the coast; the impacts of sea level rise might trigger a calamity of enormous extent. Other highly populated seaside areas and towns of coastal Sindh, Sujawal and Thatta are also vulnerable.

3 OBJECTIVES

Sea level rise and associated hazards like coastal erosion and inundation will have a profound impact on the coastal community and can lead to a loss of economic opportunity or permanent relocation. Understanding the changes in the climatic indicators or components (like sea-level rise) through a long time could reveal solid insight about the drivers and could predict the future scenario resulting in better management. Therefore, this project aimed at:

1. Deliver integrated assessment on the impact of future sea-level rise by 0.5, 1, 1.5 and 2 m through inundation mapping based on spatial modelling of relative elevation data.
2. Assessment of the coastal erosion of Thatta and Sujawal through historical dataset implementing Digital Shoreline Assessment System (DSAS) in order to predict the future trend of the process.
3. Detect the changes in land use and land cover pattern of Thatta, Sujawal, Karachi and Badin for the past three decades and subsequent predictions for land use in future.
4. Identification of risk zones along the coastal belt of Thatta and Sujawal by incorporating erosion and inundation data.

4 METHODOLOGY AND STUDY AREA

Our general approach is delimited in three stages, each characterized by three separate activities: data collection, data processing and outputs. The different stages of the study are described graphically in figure 1 below. Stages 1 and 2 are parallel steps dealing with the physical processes and the spatial distribution of population and assets affected, respectively. Stage 3 is a sequential step that combines the above and generates a comprehensive picture of local socio-economic costs.

Other studies focus on vulnerability index building but offer little in the way of general methods or attention to socio-economic costs associated with coastal vulnerability. While most of the costs of sea-level rise (SLR) and extreme coastal flooding (EF) are felt at the local level, much emphasis is paid to assessing these costs at the national level. This methodology minimizes this spatial gap and analyses the costs of sea-level rise (SLR) and extreme flooding at the local level through a systematic framework.

Global SLR scenarios for the 21st century range from 0 to over 2 m (Grinsted et al., 2010). Due to this variability, we will use five different equal interval SLR scenarios: 0, 0.5, 1, 1.5 and 2 m to portray realistic scenario in temporal scale. Periodic flooding will be estimated by considering return periods (probabilities) of extreme high tides and extreme events. Periodic flooding scenarios will be combined with the SLR scenarios to account for the entire range of possible permanent inundation. We will also take coastal erosion into account. Long term shoreline change study will be done using simple **Digital Shoreline Analysis System**.

Understanding the rate and process of land-use/land-cover (LULC) change in a coastal area is essential for managing natural resources and achieving sustainable development. Therefore, this study aims to analyze historical LULC change from 1980 to 2020 and project future changes in 2030, 2040, 2050. Existing land use and land cover maps will be reclassified into different economic archetype based on type of industry or use of the land (Open, Public, Commercial, Industrial, Residential, Agricultural) to understand sectors will be affected by the permanent inundation.

The next stage is to collect social and economic data at different aggregate levels and to distribute it spatially. This allows us to generate estimates of the costs of SLR in social and economic terms, at a level of spatial disaggregation not generally available. This will be done combining social survey, government reports (revenue) and consulting with regional experts/economists. This will enable us to estimate the value of each residential region as well as the value of non-residential (industrial, Shipping and Trade. Fisheries Mangroves, Sociological aspects). The Final objective will be to understand ***Spatially Distributing Assets and Population and Calculating various loses (direct, indirect, natural capital, community) due to sea level rise***.

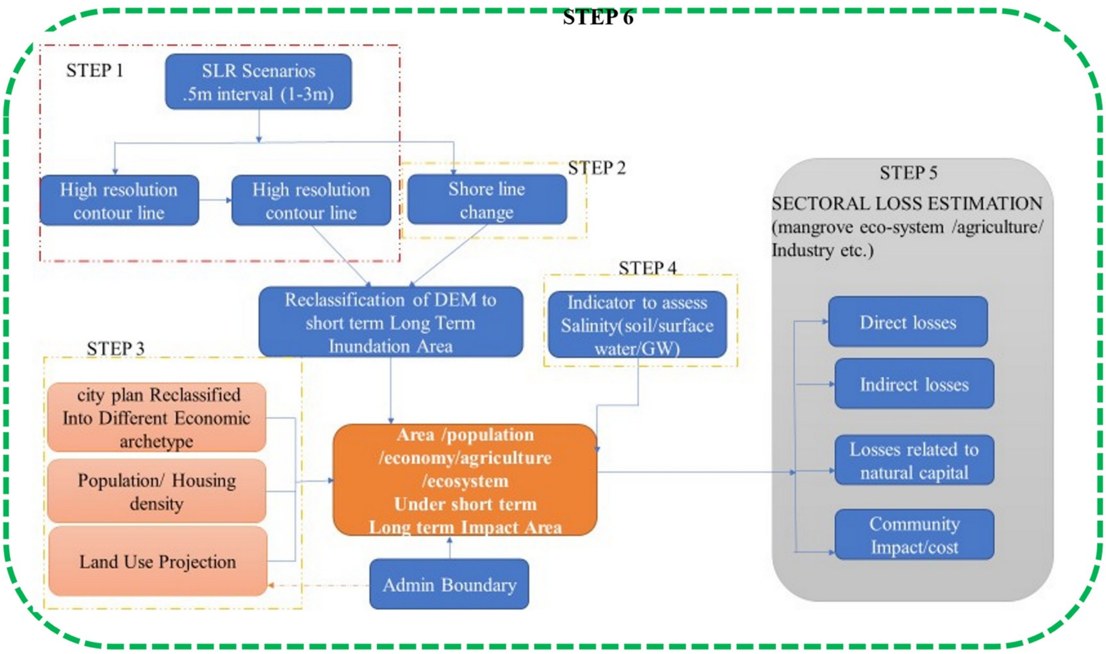


Figure 1: Systematic flow diagram of project methodology

The project will follow an indicator-based approach in understanding the risk. In the entire risk-management framework, spatial information plays a crucial role, as the hazards are spatially distributed, and so are the vulnerable elements-at-risk. Future risk communication and involving local stakeholders is priority for success of risk management plan and will be embedded in the key activities within it.

All findings from above deliverables will be communicated in advance with the concerned authorities and stakeholders. A two-day virtual workshop will be arranged to communicate risk, learnings from local experience and regional experts, and lessons will be incorporated as a policy document in the final report.

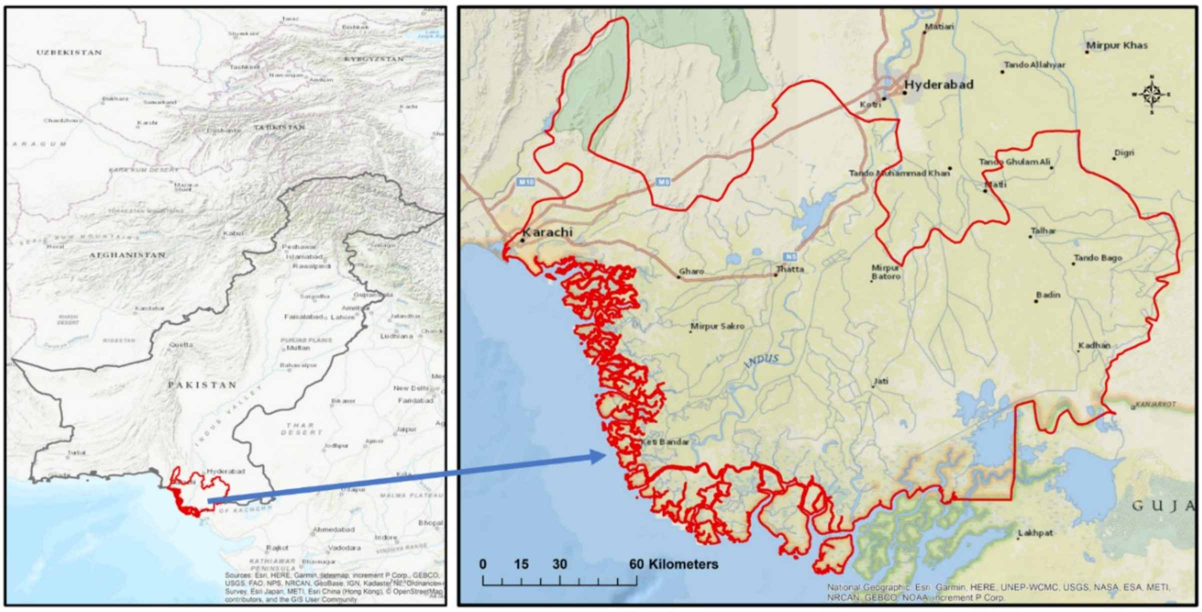


Figure 2: Proposed Study Area

Sindh is one of the four provinces in Pakistan, located in the south eastern part of the country (figure 2). Sindh is the third largest province in Pakistan considering its area. It shares the land boundary with Baluchistan and Punjab provinces in Pakistan and Rajasthan and Gujarat in India. Southern part of the province is surrounded by the Arabian Sea. The landscape feature of the Sindh province consists of alluvial plains created by the Indus River with its age-old depositions. Thar Desert is the eastern margin of this province whereas Kirthar range is the western margin.

In the concerned report, four districts namely East Karachi, Thatta, Sujawal and Badin of Sindh province have been considered for the Risk-Profile analyses. All the four districts consist of active deltaic portions of the Sindh River and fall under UTM zone 42N. It is worth to mention that Sujawal was the Sub Divisional Headquarter of Sujawal Sub Division of Thatta District of Sindh in Pakistan. The local government of Sindh granted Sujawal the status of a district after the approval of Chief Minister of Sindh, with the notification issued by the Revenue Department of Pakistan on 12th October in 2013.

5 GIS DATABASE

Several GIS databases are being created under the objectives of this pilot project like:

1. Land Use Land Cover
2. Transportation network
3. Critical infrastructures i.e., Point of Interest.
4. Multi temporal coast lines
5. Geomorphology

All the information will be integrated in the spatial database and represented through a common platform.

5.1 GIS Database, Data and Source

For the purpose of the risk profiling, various spatial and temporal data are generated, processed and analyzed using Geographic Information Systems (GIS).

The identification and analysis of land-use land-cover (LULC) characteristics of a region provides crucial information on the vulnerability towards hazards. The temporal analysis of LULC can also shed light on the process of evolution of the geographic and socio-economic characteristics of the region under study, and help in assessment of risks, not just in the present but also a projection of the future. The table 1 below describes the various data and information collected and analyzed for the purpose of identification and analysis of LULC in the study areas, over a course of two decades from 2000 to 2020.

Table 1: Land Use Land Cover for the Year 2000, 2011 and 2020

Year	Satellite	Date	Resolution	Path	Row	Source
2000	Landsat TM	13-02-2000	30	152	43	https://glovis.usgs.gov/
	Landsat TM	20-04-2001	30	152	42	
2011	Landsat TM	26-01-2011	30	152	43	
	Landsat TM	26-01-2011	30	152	42	
2020	Landsat OLI	19-01-2020	30	152	43	

Landsat OLI	04-02-2020	30	152	42

Similarly, geographic information data on coastlines and erosion were also analyzed over a duration of 20 years to identify the change in coastline, and its impacts. Table 2 describes the data and information used for the analysis.

Table 2: Coastline and erosion 2000,2011 and 2020

Year	Satellite	Date	Resolution	Path	Row	Source
2000	Landsat TM	13-02-2000	30	152	43	
2011	Landsat TM	26-01-2011	30	152	43	https://glovis.usgs.gov/
2020	Landsat OLI	19-01-2020	30	152	43	

Table 3 shows the different physical and socio-economic parameters that will be used in the risk analysis in the study areas, and their relevant source of data. In particular, elevation, slope, geology, precipitation, soil and drainage information were collected and analyzed from various satellite and remote sensing images. Similarly, network and POI data were generated from Open Street Map and Google Earth that include infrastructure and facilities.

Table 3: Parameters used for hazard and risk analysis

Layer	Data	Date	Resolution	Source
Elevation	23-09-2014	SRTM DEM	1 Arc	https://earthexplorer.usgs.gov/
Slope	23-09-2014	SRTM DEM	1 Arc	https://earthexplorer.usgs.gov/
Geology	1998	U.S, Geological Survey		https://certmapper.cr.usgs.gov/data/apps/world-maps/
Precipitation	2003 - 2020	PERSIAN	0.25 deg	https://chrsdata.eng.uci.edu/
Soil	1992	FAO		http://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/faounesco-soil-map-of-the-world/en/
Drainage	19-01-2020	Landsat OLI	30 m	https://earthexplorer.usgs.gov/
Transportation network	Open Street Maps and Google Earth			
POI	Open Street Maps and Google Earth			

5.2 Sharing GIS Database

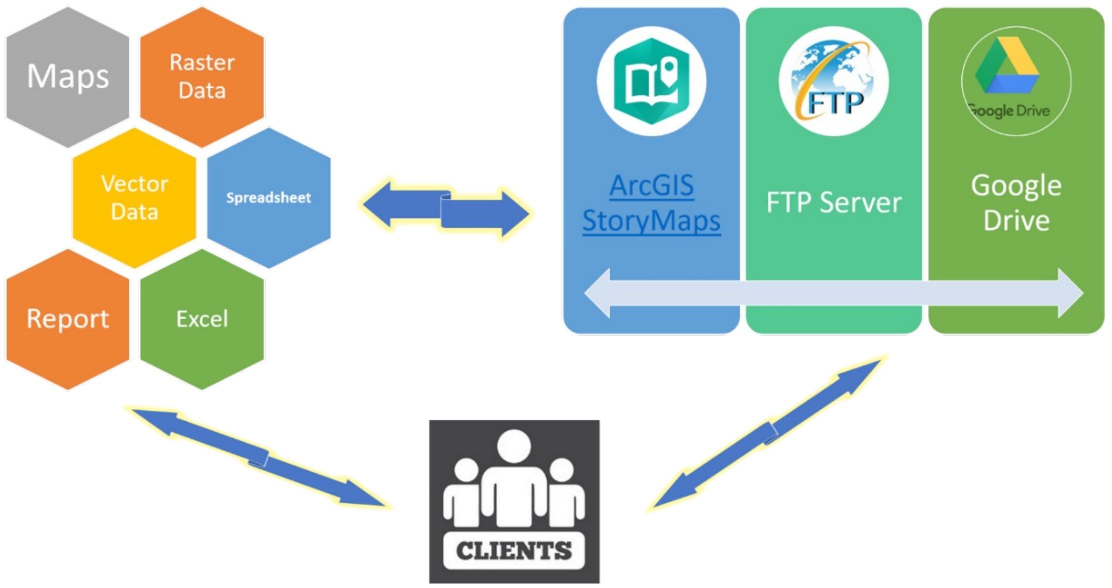


Figure 3: GIS Database Sharing Flow Diagram

The flowchart in figure 3 shows the tools used and type of information that will be shared through the GIS database. The database created in this project will contain raster data, vector data, excel spreadsheets, maps and reports. The data sharing plan is three-fold. The final outcomes of this project like maps, analysis and reports will be held in ArcGIS Story Maps and will be accessible to the clients from anywhere in the world using the simple internet connection. However, there will be security protocols if required to avoid unauthorized access. The raw data generated from this project will be uploaded in designated FTP servers and also in Google drive. Using specific Username and Password the users can access all the Raster's and vectors and other data from the FTP access. The data can be downloaded from anywhere in the globe with the security protocol.

Upon completion of this Pilot project, the entire database may be reformatted and transferred on Web GIS platform where authorized users can view, query, analyze and create user specific outputs.

5.3 Land Use and Land Cover

The flowchart in figure 4 below describes the process and methodology used for the analysis of land use and land cover change in the study areas. For the LULC classification, three different LANDSAT images from the years 2000, 2011 and 2020 were used. Traditionally, pixel-based classification approach was used which utilizes spectral signatures of different classes by training of selected algorithms in specific software. Efficient image segmentation in recent times made the object-based classifications more popular (Blaschke, 2010). In this study, an object-based approach was used to classify 13 different classes based on their pixel clustering. The general workflow consists of two major parts; pre-processing and composition of datasets and implementing different object-oriented classification approaches. Atmospheric correction was performed in ENVI using the Fast Line-of-sight Atmospheric Analysis of Hypercubes (FLAASH) algorithm. FLAASH incorporates Moderate Resolution Atmospheric Transmission (MODTRAN) radiation transfer code while calculating the radiance at the detector from the reflectance at the surface. For further edge enhancement, a 9×9 Lee filter was run through the entire dataset. Three separate spectral indices namely Normalized Difference Vegetation Index (NDVI), Normalized Difference Water Index (NDWI) and Bare Soil Index (BSI) were calculated for each year. NDVI is efficient in delineating vegetation, NDWI can separate water bodies from the rest of the classes and BSI was used to differentiate agricultural and non-agricultural land cover types. These indices are broadly used in LULC classification to improve accuracy. In the next step, data augmentation was achieved through the calculation of three main statistical parameters- mean, standard deviation and maximum. A band median was separately generated from the edge-enhanced image and used as an input in classification along with the augmented bands.

Supervised object-oriented classification was performed on this dataset with 90 training points and 30 validation points. The classification could be divided into two parts-spatial clustering of the contiguous and similar pixels and then classifying using Random Forest and

Support Vector Machine (SVM). The clustering of pixels was developed in eCognition by implementing Simple Non-Iterative Clustering (SNIC) and Grey-Level Co-occurrence Matrix (GLCM) algorithms. SNIC is a modified version of SLIC super-pixel segmentation, which was designed to reduce the limitations of SLIC. SNIC is essentially non-iterative, enforces connectivity, performs using low memory and the benchmark values are even better than traditional SLIC (Achanta and Susstrunk, 2017). The GLCM is used for texture analysis as texture effectively helps to separate adjacent classes as spatial information might not correlate with spectral information of a particular class; so, adding a measure is proved to enhance the accuracy of classification (Hall-Beyer, 2017). An additional Digital Elevation layer was also added to increase the effectiveness of texture separation. Principal Component Analysis (PCA) was performed on the GLCM output and out of the seven relevant metrics; a single representative band was selected which contains most textural information. Merging of the SNIC cluster output and the first PC output was used for final classification through two different algorithms, RF and SVM. The RF algorithm implements several tree classifiers where a separate classifier is created from a random vector independently selected from the input vectors and every separate tree in the classifier casts a single vote for the most popular class (Pal, 2005). SVM is a machine learning technique often used for classification and regression problems using a supervised learning strategy (Cortes and Vapnik, 1995; Friedman et al., 2001). The output classified images were used for validation and accuracy assessment.

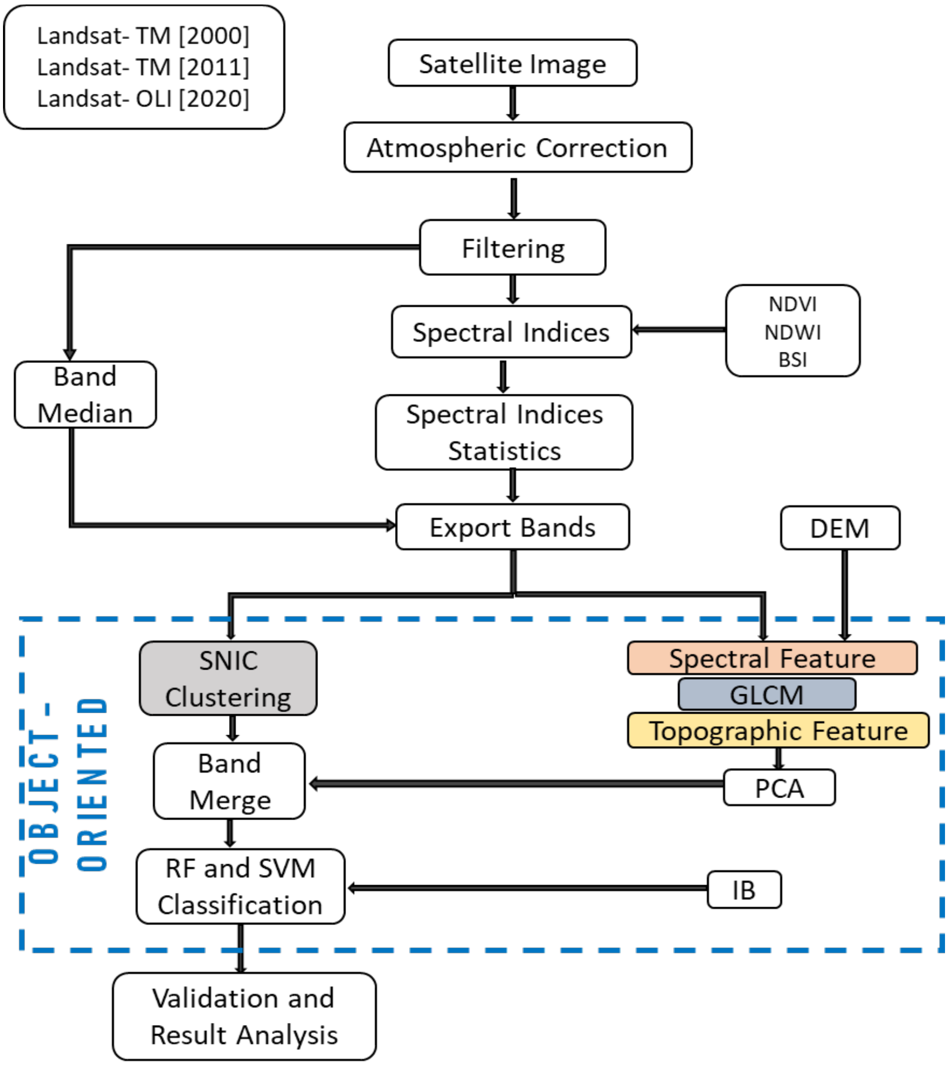


Figure 4: LULC methodology Flow Chart

5.3.1 Thatta LULC Report

Land Use and Land Cover (LULC) change in the Thatta district for the past 20 years has been assessed using LANDSAT images. For classification purposes, a single representative data was selected for each year i.e., 2000, 2011 and 2020. An object-based classification approach was taken in this research and employing Support Vector Machine (SVM) and Random Forest (RF) algorithms, 13 separate classes were obtained (Figure 5). Change detection analysis was carried out to demonstrate the apparent changes in land use for the past two decades. The change in the total area of the canals and settlement is negligible indicating very little or no anthropogenic pressure over the study area, although there is a noticeable increase in settlement area from 2000 to 2020 (figure 5; table 4).

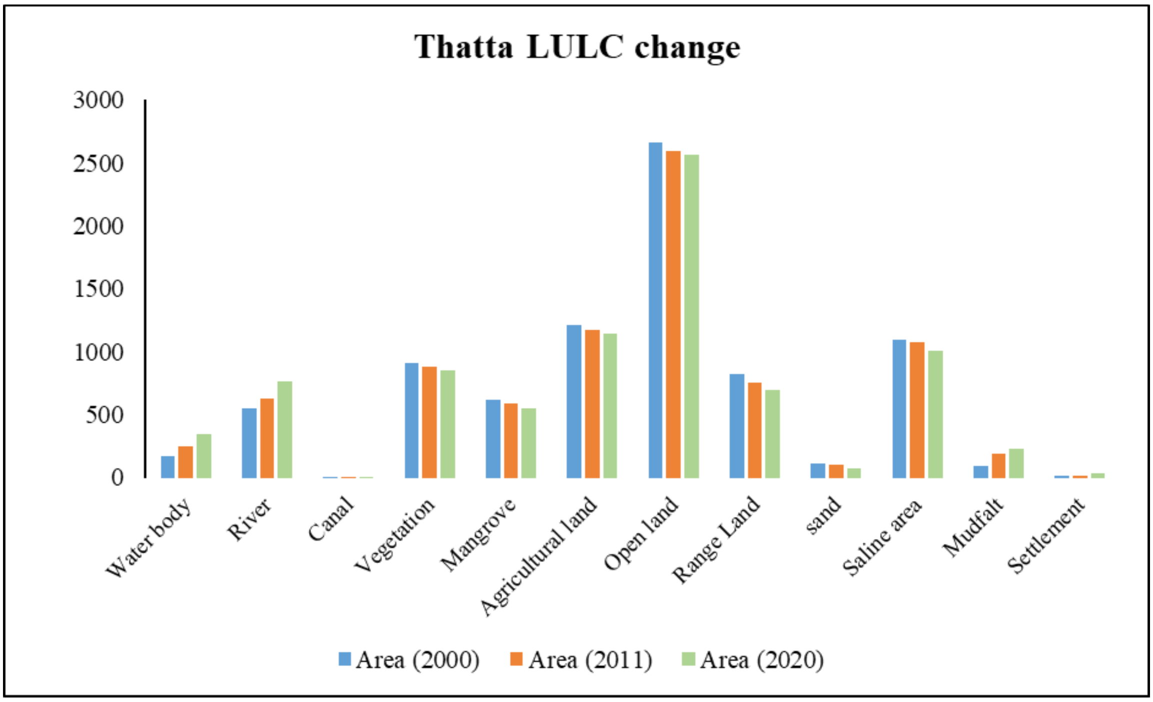


Figure 5: Change in Land Use and Land Cover in Thatta for the past 20 years (sq km)

A small decrease in total vegetation cover in Thatta was observed in the past two decades. While the change in vegetation cover has been decreased, a decline in the total agricultural area suggests that there was almost no conversion of forest area into agriculture. A decrease in the total area of range land further supports the claim. A completely different picture can be obtained from the coastal area. An increase in waterlogged area as well as mudflat, decrease in total mangrove vegetation and saline area indicate a slow but steady water intrusion in the coastal regions. As there is no significant anthropogenic activity, the main reason behind this observation must be climatic pressure. From figure 6, it is evident that with time, the saline blanks have been pushed inland, reducing the total area of rangeland which is also a signal of seawater intrusion.

Table 4: Area of the classes in Thatta for 2000, 2011 and 2020. All areas are represented in sq. km

Class	2000	2010	2020	2050
Water body	174.424928	249.779822	344.519695	562.8898
River	554.002942	630.787731	768.786197	1092.8571
Canal	2.73822	2.91012	3.14142	3.7092

Class	2000	2010	2020	2050
Vegetation	906.8049	885.3174	854.3475	800.856
Mangrove	622.3302	587.7666	550.5057	479.9142
Agricultural land	1210.4325	1172.0421	1141.5753	1058.3217
Open land	2663.3979	2591.577	2561.0688	2454.9155
Range Land	821.6694	758.2941	694.71	513.3618
sand	110.3283	104.8005	76.8096	39.7539
Saline area	1090.9314	1072.3977	1004.8185	887.4846
Mudfalt	93.8637	187.7289	226.5624	309.3453
Settlement	11.8983	19.4184	35.9793	59.4151
Total	**8262.82269**	**8262.820373**	**8262.824412**	**8262.8242**

Along the eastern border of Thatta, an increase in the total water body is well documented in figure 6. Sea Level Rise in this particular area is alarming as the Indus valley delta has a slope of only 0.1 degrees (Wells and Coleman 1984). Further rise in sea level might cause an increase in the waterlogged area and in the future seawater might claim the entire eastern boundary.

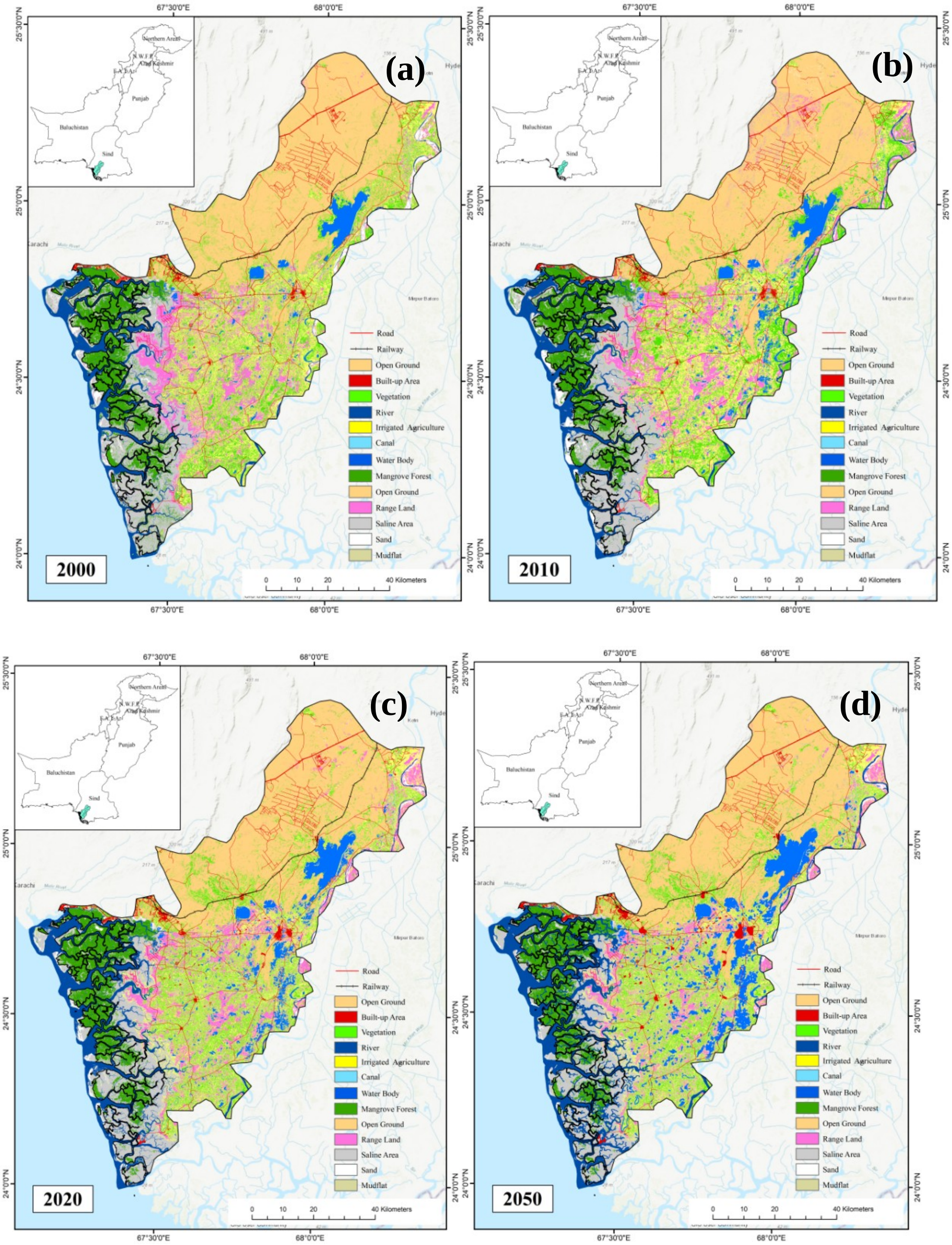


Figure 6: a) LULC for Thatta in 2000; (b) LULC for Thatta in 2011; (c) LULC for Thatta in 2020; (d) LULC for Thatta in 2050 (Projected)

5.3.2 Sujawal LULC report

Similar to Thatta, an object-based classification approach has been adapted to determine the changes in land use in Sujawal state. Multispectral LANDSAT data for the years 2000, 2011 and 2020 has been used in the Support Vector Machine (SVM) and Random Forest (RF) algorithms to implement a supervised classification. Total 120 ground control points have been identified in field visits and out of them, 90 points have been used to train the algorithms and 30 points have been used to check the accuracy of the classification. Change detection analysis revealed the conversion between land use classes in the past two decades (Figure 7). The total settlement area in the Sujawal state has been doubled (Table 5) since 2000 indicating a rise in population and thereby the growing need for infrastructure. Total vegetation cover has been reduced by approximately 100 sq. km in the past 20 years. It will be vague to assume that anthropogenic pressure is the main reason behind it since the total area covered by agricultural land and range land has also been decreased in that time frame. One of the possible reasons behind it might be the rapid development of unsustainable aquaculture farms or intrusion of seawater inland which is evident from Table 5. An increase of total saline area in the southeast part of the state (Figure 8) further helps to support the claim.

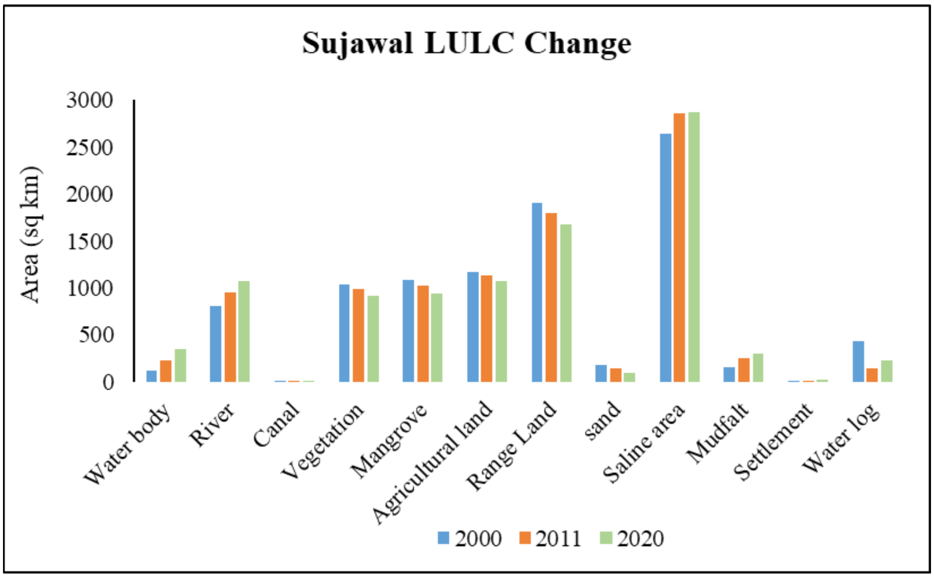


Figure 7: Change in Land Use and Land Cover in Sujawal for the past 20 years

Total mangrove vegetation has been decreased which can easily be associated with the increase of mudflat and saline blanks depicting the poor health status of the mangroves in Sujawal. A phenomenal decrease in mangrove vegetation along the southeastern border of the state and converting the area into saline might be an indication of slow but steady sea level rise in the area (Figure 8).

Table 5: Area of the classes in Sujawal for 2000, 2011 and 2020. All areas are represented in sq. km

Class	2000	2011	2020
Water body	120.241	232.431	345.402
River	805.009	946.256	1074.543
Canal	0.816	0.835	1.276
Vegetation	1034.091	986.090	912.502
Mangrove	1080.761	1029.365	938.577
Irrigated Agriculture	1168.335	1129.417	1069.367
Range Land	1903.957	1801.191	1679.511
sand	184.088	137.500	96.031
Saline area	2645.397	2863.457	2872.074
Mudfalt	154.163	252.136	300.483
Settlement	9.134	12.001	18.771
Water logged Area	428.987	144.295	226.442
Total	**9534.979**	**9534.975**	**9534.977**

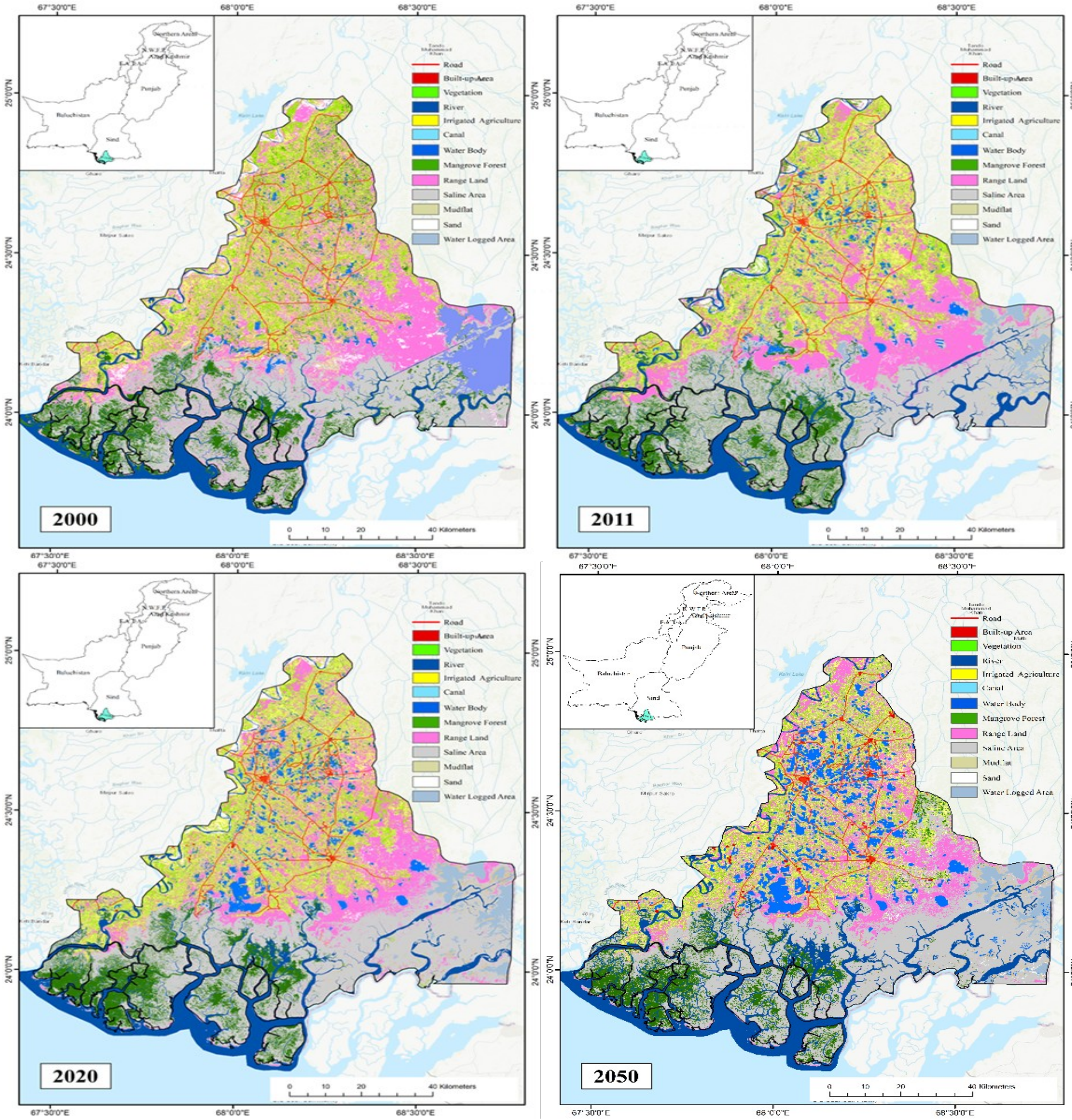


Figure 8: (a) LULC for Sujawal in 2000; (b) LULC for Sujawal in 2011; (c) LULC for Sujawal in 2020 (d) Projected LULC required

5.3.3 Sujawal Morphometric report

The morphometry of landscape of Sujawal has been assessed on the basis of two respective elements like contour and aspect as represented in figure 9 below.

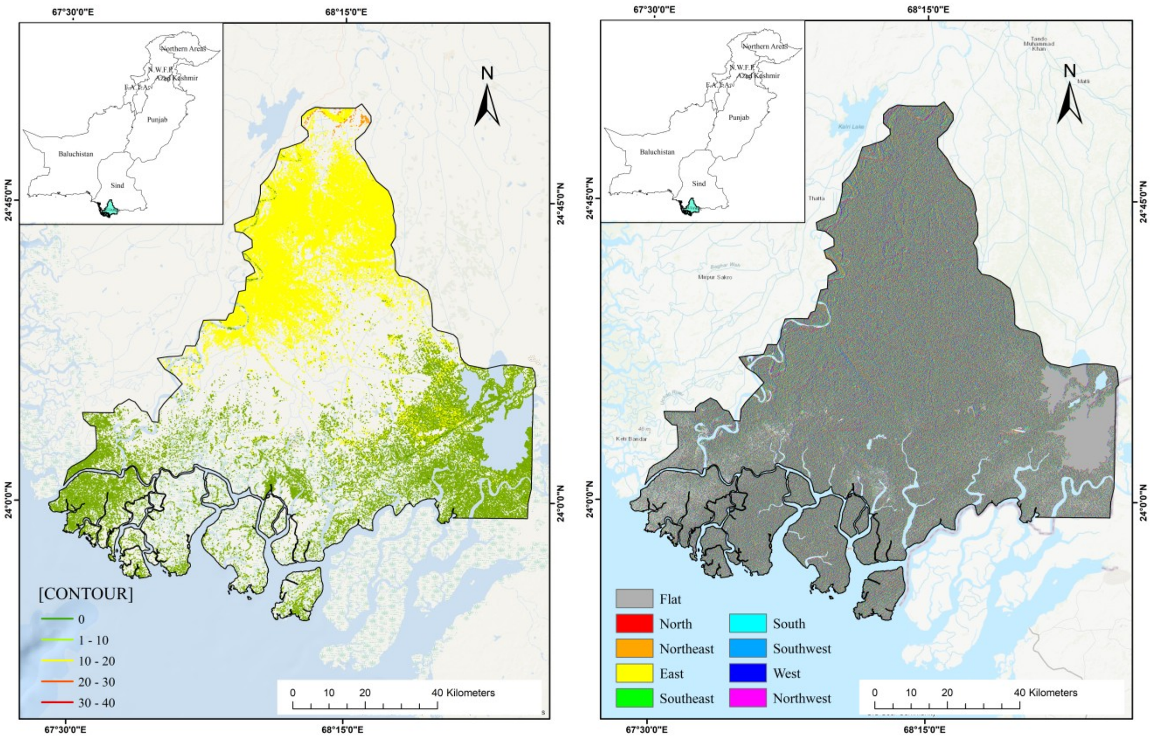


Figure 9: Morphometry of Sujawal District

From the perspective of morphometry of Sujawal, maximum elevation is found to be 40m above msl. The elevation gradually increases towards north. The aspect map shows that majority of aspect is flat.

5.3.4 Karachi LULC report

Results from the LULC analysis of Karachi over four distinct stages, 2001, 2009 and 2021 are presented in Figure 10 and Table 6 below. Additionally, based on the changes observed in the past two decades, the projected LULC for 2050 is also derived and shown in the figure and tables.

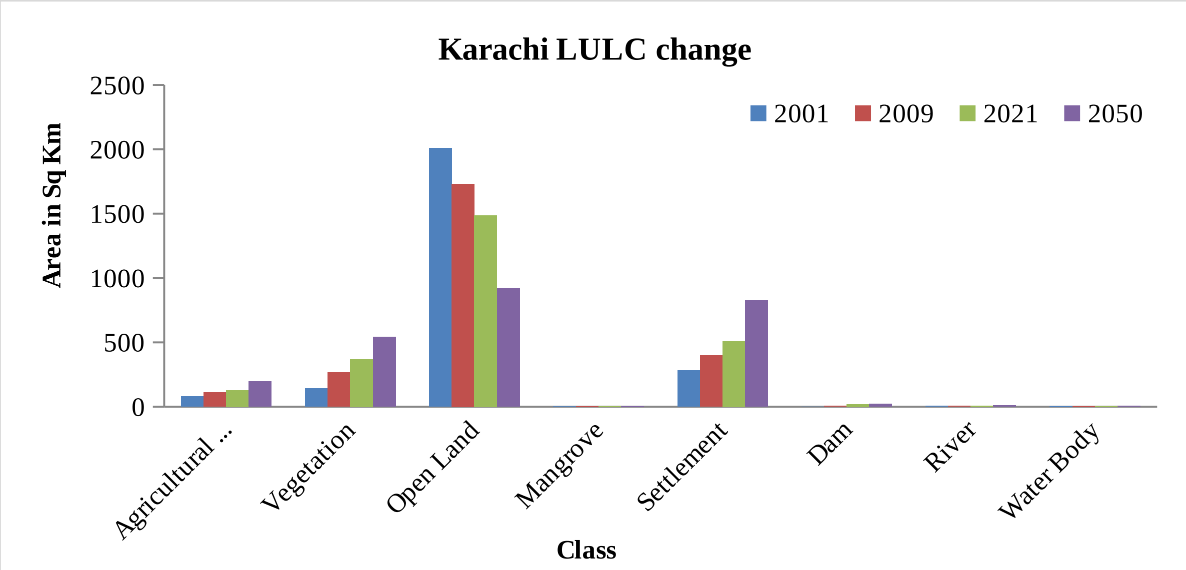


Figure 10: Change in Land Use and Land Cover in Karachi East for the past 50 years

It can be seen that between 2001 and 2021, open land has been reduced by more than 25%, while settlements have increased by nearly 80% from 281 sq km to 509 sq km. Agricultural land has also increased by 60%. These points out to the increase in settlement and farming activities in the region. Much of the settlement areas, however, is concentrated on the southern coastal region and expanding towards the north. The region has also experienced slight increase in vegetation and mangrove coverage. Projections for the LULC in 2050 show that the expansion of settlements and agricultural land in the region is expected to increase, which will further increase the exposure of infrastructure and facilities towards the coastal hazards.

Table 6: Area of the classes in Karachi East for 2000, 2011 and 2020. All areas are represented in sq. km

Class	2001	2009	2021	2050
Agricultural Land	80.1234	111.3795	128.2199	197.0505
Vegetation	143.1981	266.7195	369.1692	541.962
Open Land	2010.8727	1731.8187	1488.1347	922.5853
Mangrove	3.2508	3.5307	3.9114	4.7643
Settlement	281.6604	398.8413	509.2379	826.1754
Dam	0.6858	6.8841	19.1291	21.6505

River	6.2892	6.9048	7.6527	9.1651
Water Body	3.7692	3.771	4.3947	6.4965
Total	**2529.8496**	**2529.8496**	**2529.8496**	**2529.8496**

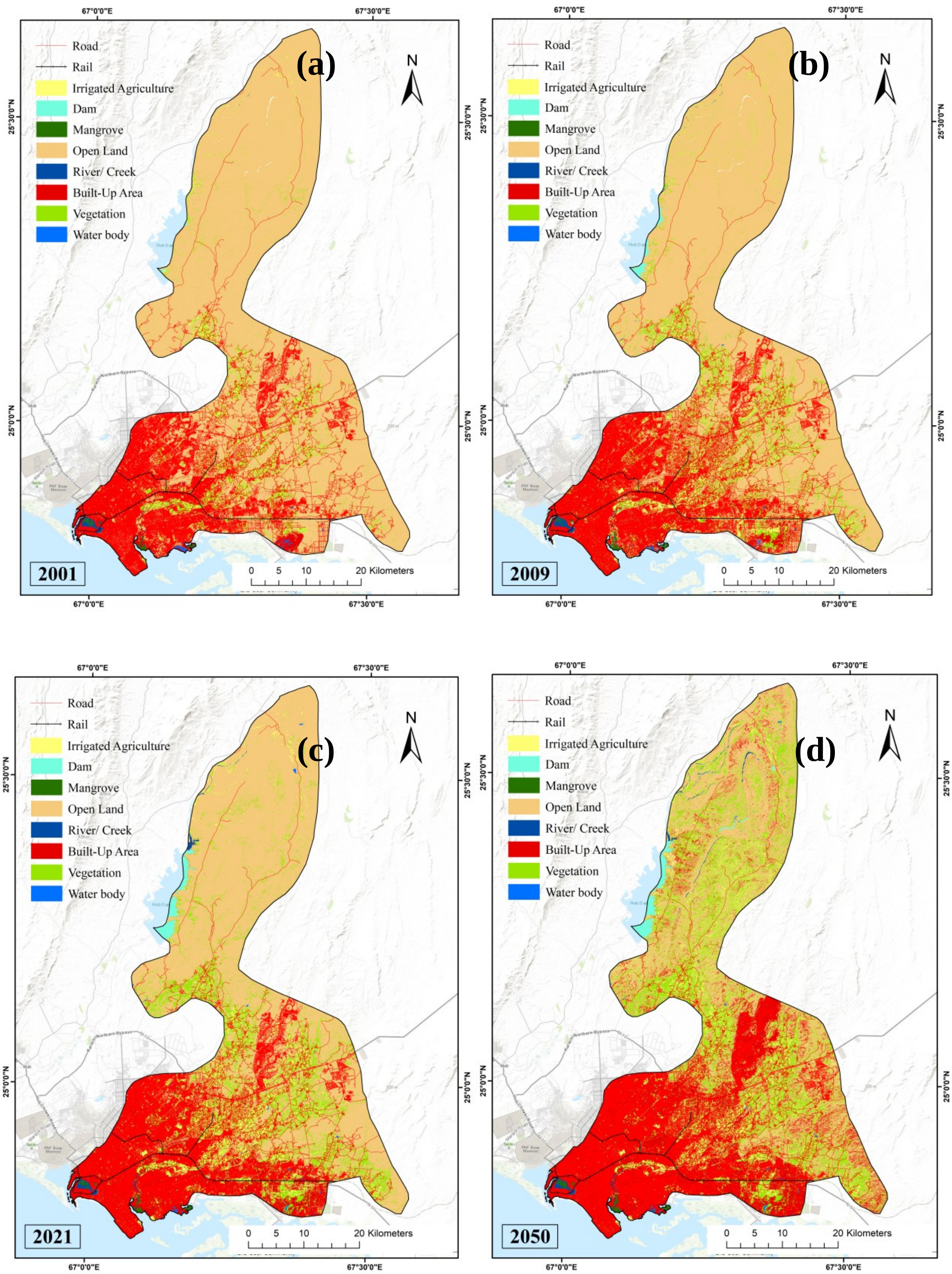
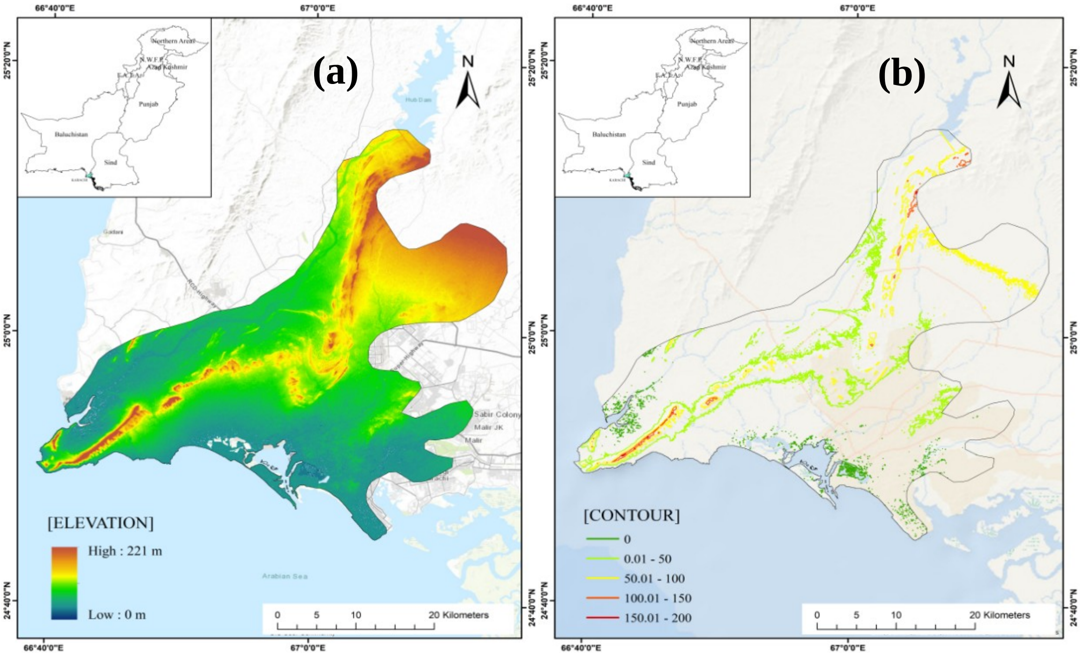


Figure 11: (a) LULC for Karachi in 2000; (b) LULC for Karachi in 2011; (c) LULC for Karachi in 2020 (d) LULC for Karachi in 2050

5.3.5 Karachi Morphometric report:

The morphometry of landscape of Karachi has been assessed on the basis of five respective elements like elevation, contour, slope, aspect and hill shade as represented in figure 12 below.

The elevation of Karachi is primarily higher towards the north eastern region, with a line of high elevation going across the region. At its highest, the elevation is 221m above sea level. Towards the coastal areas, the elevation decreases significantly to as low as 0m above sea level.



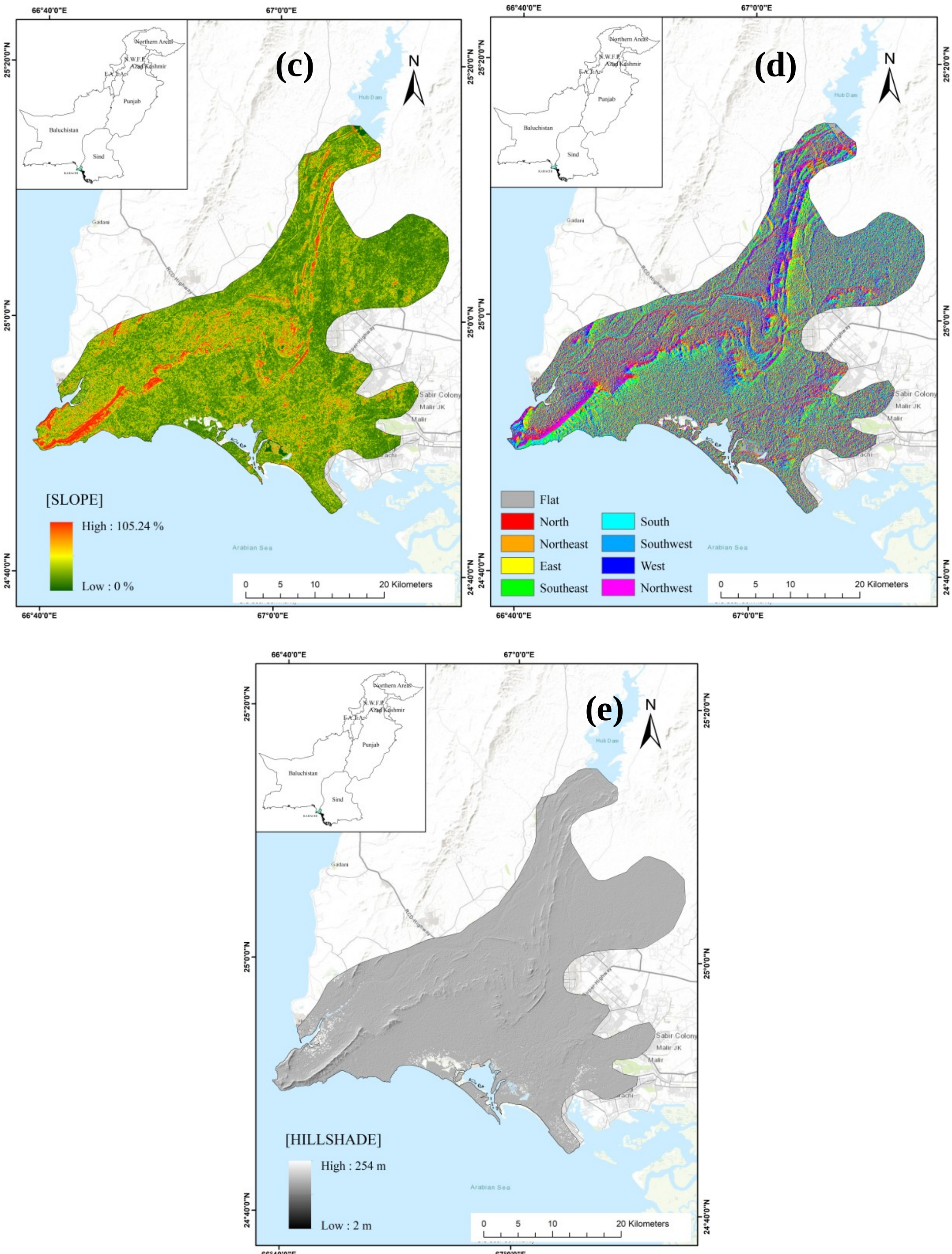


Figure 12: (a) Elevation of Karachi; (b) Contour of Karachi; (c) Slope of Karachi; (d) Aspect of Karachi; (e) Hill-shade of Karachi

From the perspective of morphometry of Karachi, maximum elevation is found to be 221m from msl. Maximum slope of 105.24% is found along the higher ground surface stretching from north east to south west of the region. Majority of aspect is found to be towards North West which receives higher solar potential. Moderate hill-shade is found almost all over the region.

5.3.6 Badin LULC report

The LULC analysis of Badin is presented in figure 13 and table 7 below. The changes are presented with a comparison of ten different forms of LULC between the years 2000, 2009 and 2020 with a projection for the year 2050. In Badin, the largest proportion of land-use and cover is found to be in vegetation, agricultural land and range land. However, it can be seen that the region is facing a gradual decline in these forms of lands, while an increase is seen in water-body and mud-flats. Increase can also be seen in saline area, up from 151 sq.km in 2000 to 189 sq.km in 2020, suggesting sea-water intrusion along the coastal region.

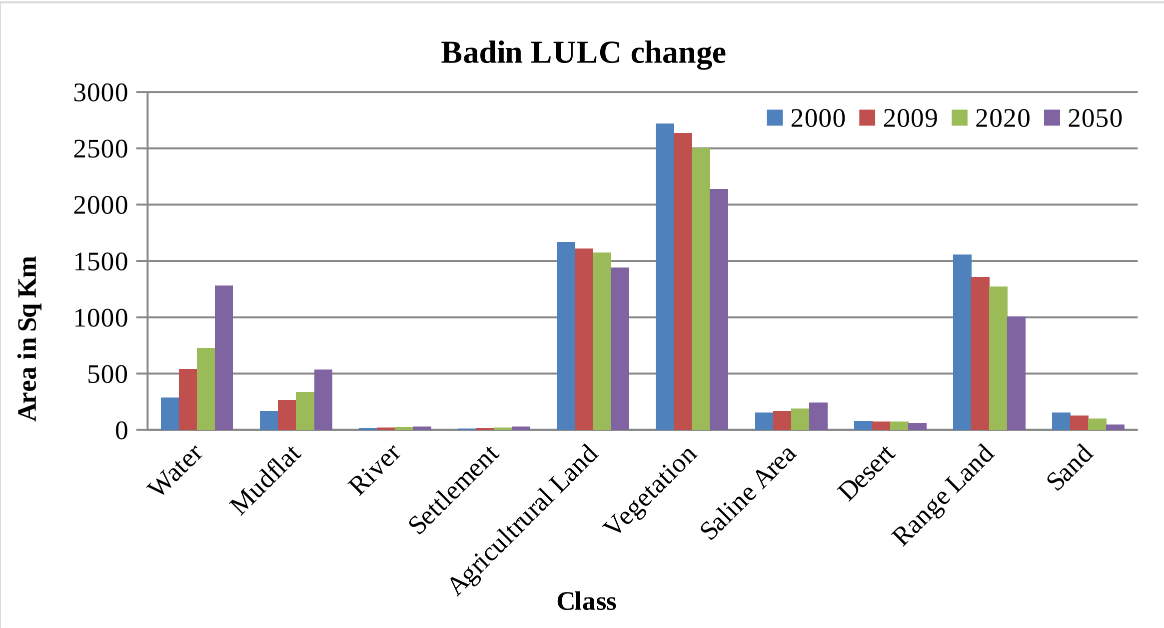
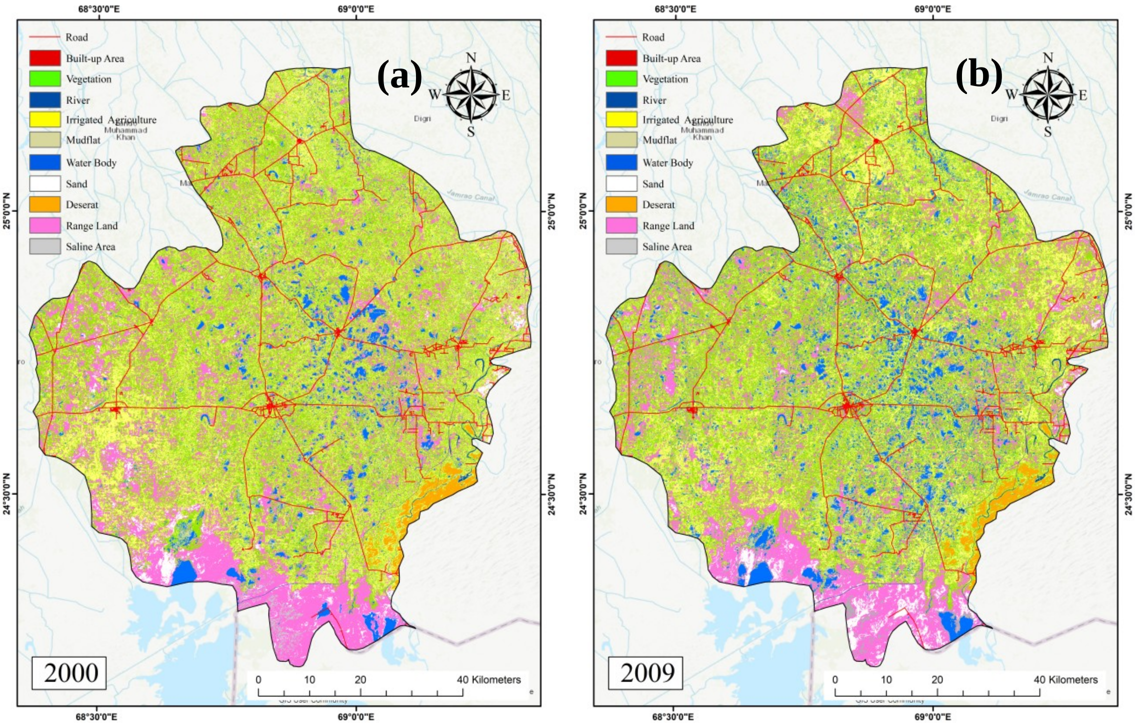


Figure 13: Change in Land Use and Land Cover in Badin for the past 50 years

Table 7: Area of the classes in Badin for 2000, 2011, 2020 and 2050. All areas are represented in sq. km

Class	2000	2009	2020	2050
Water	284.3946	540.5103	725.2704	1280.2856
Mudflat	167.8203	265.716	333.9738	536.572
River	17.118	20.9907	24.5709	30.381
Settlement	13.0419	15.7995	19.2105	30.8192
Agricultural Land	1667.0466	1607.9949	1573.3845	1439.229

Class	2000	2009	2020	2050
Vegetation	2720.1879	2635.7994	2500.4916	2136.7708
Saline Area	151.2954	164.0205	189.7047	242.4603
Desert	77.5458	75.357	72.3564	61.8156
Range Land	1557.3816	1358.3124	1270.908	1005.2571
Sand	155.0394	126.3834	101.0133	47.2935
Total	**6810.8715**	**6810.8841**	**6810.8841**	**6810.8841**



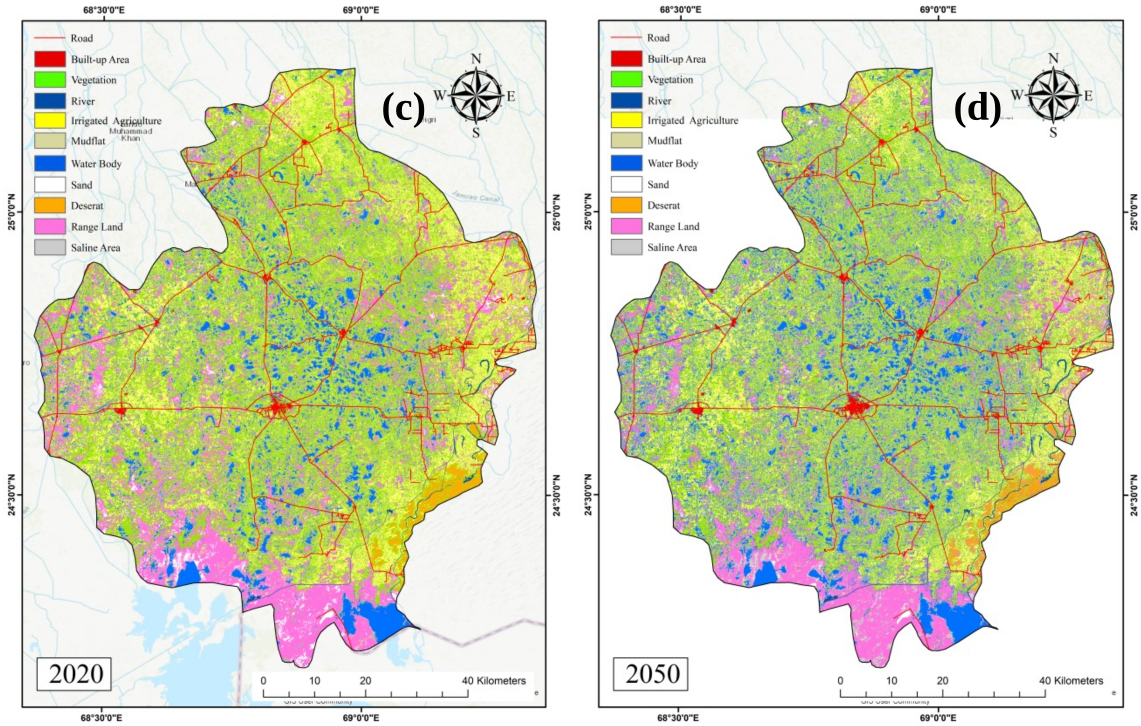


Figure 14: (a) LULC for Badin in 2000; (b) LULC for Badin in 2011; (c) LULC for Badin in 2020 (d) LULC for Badin in 2050

5.4 Socio-Economic Infrastructure

Among the socio-economic elements, the public utility infrastructure deserves the main attention whereas communication network and Point of Interest are of main concern. Four districts of deltaic Sindh province retain sufficient fabric of communication network in terms of road, rail and waterways deep to the active deltaic portion. Karachi, Thatta and Badin are well connected with the Karachi-Lahore-Peshawar Main Railway Line and Hyderabad–Badin Railway Branch Line. The waterways mainly persist in the form of canals. Maximum road density is found in the Karachi district though sufficient road network is found all over the region. The road network is well extended even upto the active deltaic portion of the region.

Points of Interest are the locations which demonstrate the richness of activities in this region. From the viewpoint of POI existence, all the concerned districts show the versatile socio-economic activities at the present spatio-temporal framework. Among all the categories of POI, about thirty premium categories e.g. Govt. Office, Health Center, School, College, University, Rice-Flour Mill, Gas-Petrol Station etc. are found to execute the major socio-economic activities in these districts.

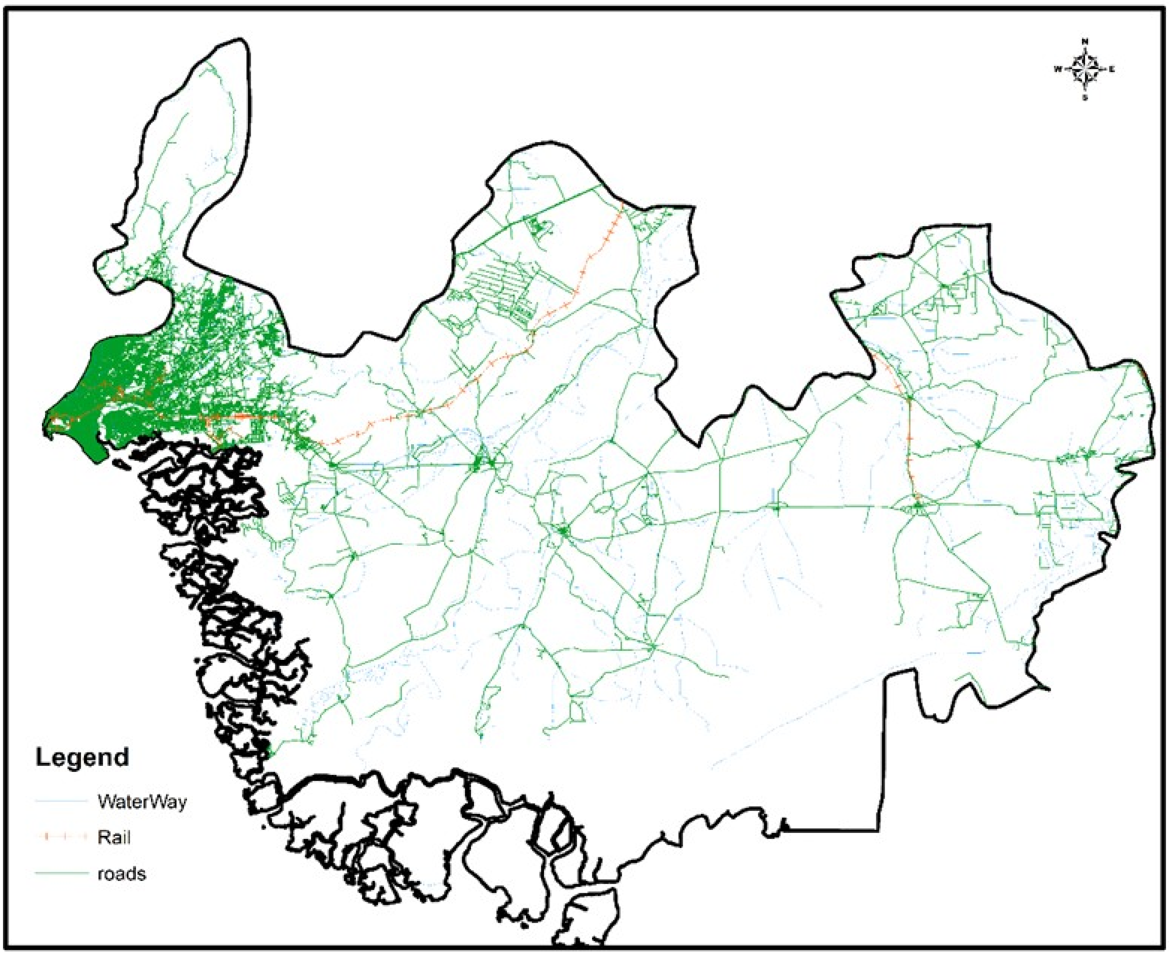


Figure 15: Transportation Network of all districts

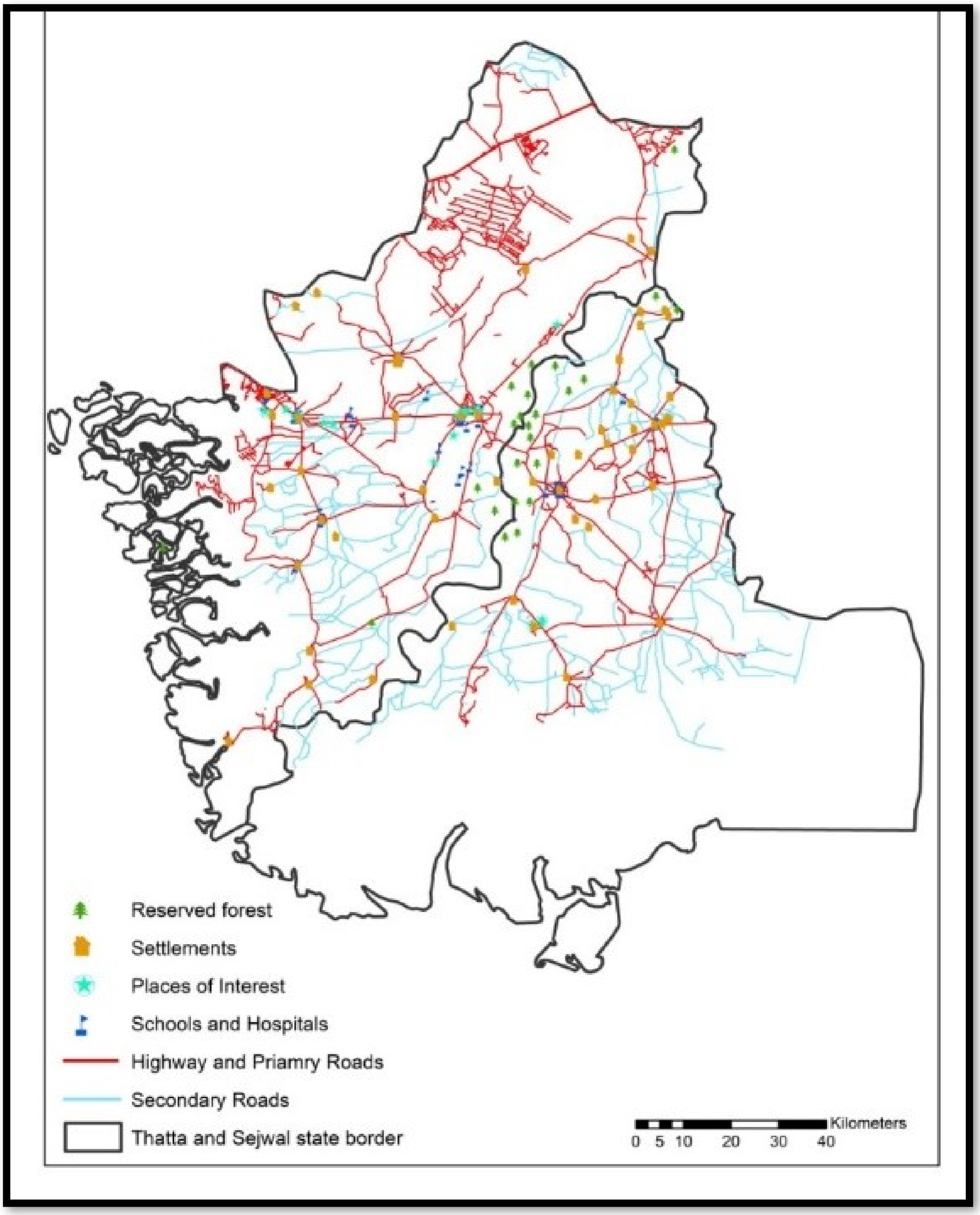


Figure 16: Transportation Network of Coastal Zone

5.5 Geomorphology and Climate

From the general viewpoint, discussion on geomorphology and the climate deserves significance and have been discussed briefly in this section. The analysis was done through a division of the study area into two regions, central and coastal. Figure 17 shows the maps of various geomorphological and climatic aspects of central zone. It is found that comparatively highland is found to the northern part of the central region with an elevation of around 48m above sea level. Geologically, the entire region is composed of Quaternary sedimentary rock.

Slope is something higher in sporadic portion to the east having 37.29%. Bifurcation or diversification of waterways is greater towards the active deltaic margin in the south.

Precipitation is comparatively higher towards the east and maximum annual precipitation is found to be 573mm.

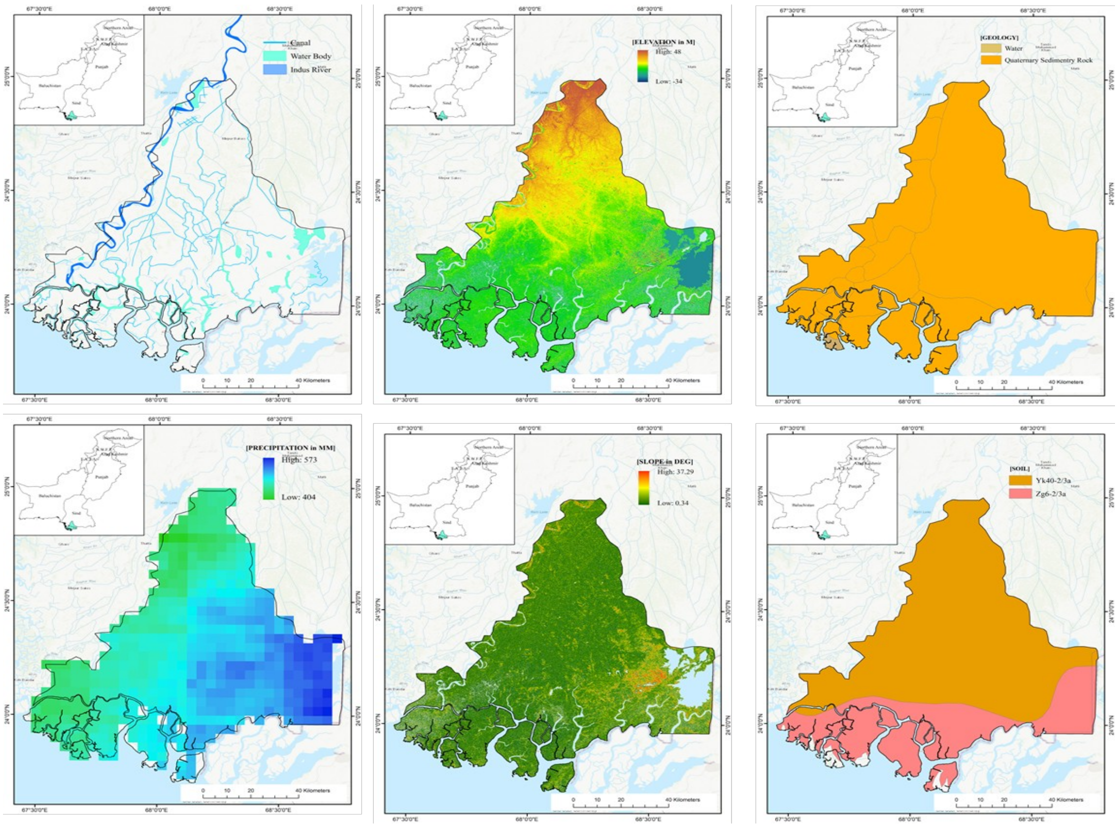


Figure 17: Geomorphology and Climate of Central Zone

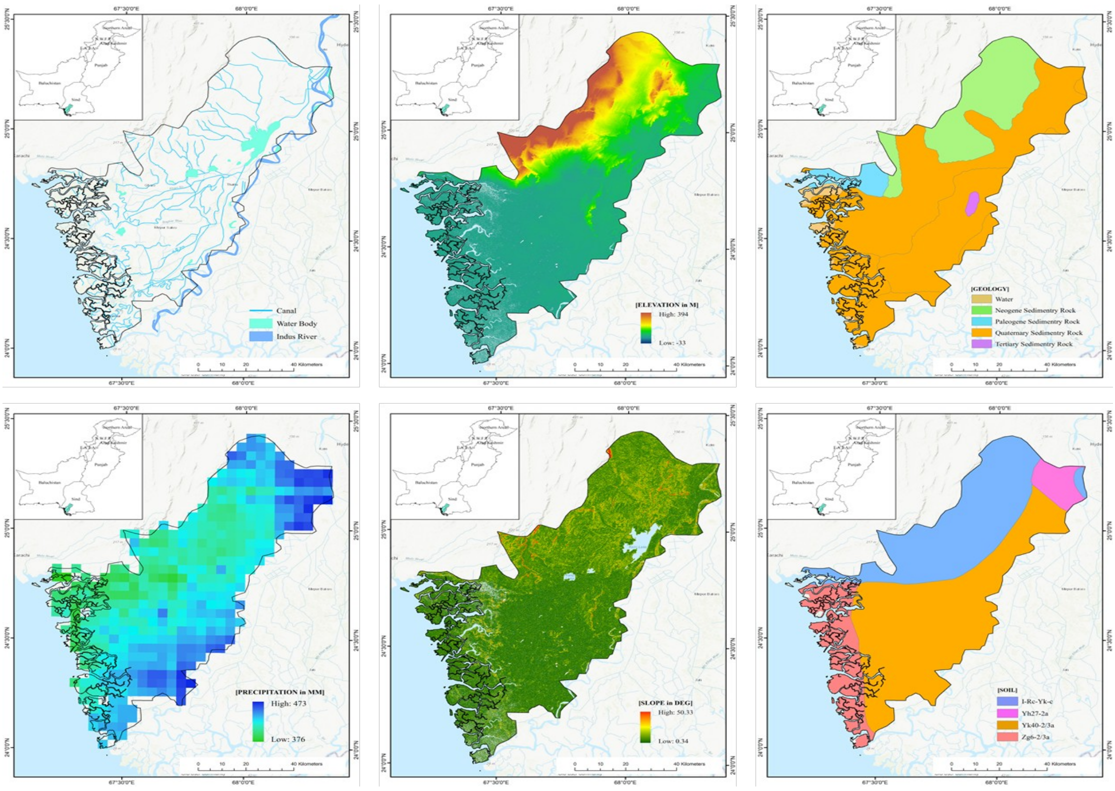


Figure 18: Geomorphology and Climate of Coastal Zone

In the coastal zone, the augmented analysis of geomorphology and climatic conditions is done with the main coastal part of this region. The results are presented in maps in Figure 18 above. The elevation is comparatively higher towards north- west with the highest elevation of around 395m above sea level. Bifurcation or diversification of waterways is more or less high with the Indus River, a major river channel flowing along the eastern boundary. Majority of this region is made up of Quaternary sedimentary rock whereas Neogene sedimentary rock is found to the north-west and an isolated portion of Tertiary sedimentary rock in the east. Almost the entire region has a very low slope.

Precipitation is distributed along the region, and is comparatively higher towards the north-east and south-east and annual precipitation varies between 376 - 473 mm.

5.6 Arc GIS Story Map

ArcGIS Story Maps is a story authoring web-based application that enables you to share your maps in the context of narrative text and other multimedia content. You can use ArcGIS Story Maps to do the following:

- Author stories with the story builder. Stories can include maps, narrative text, lists, images, videos, embedded items, and other media.

- Publish and share your stories. Published stories each have their own URL, and you can use these URLs to share your stories within your organization, to specific groups, or with everyone.
- Create and publish collections. Collections can include stories and ArcGIS web apps bundled together for easy sharing and presenting.
- Manage your stories. View and edit your stories from the Stories page, find stories authored by others in your organization, and add stories to your favorites list.

The following GIS datasets and spatial analysis products have been developed as Arc GIS story maps for the study area.

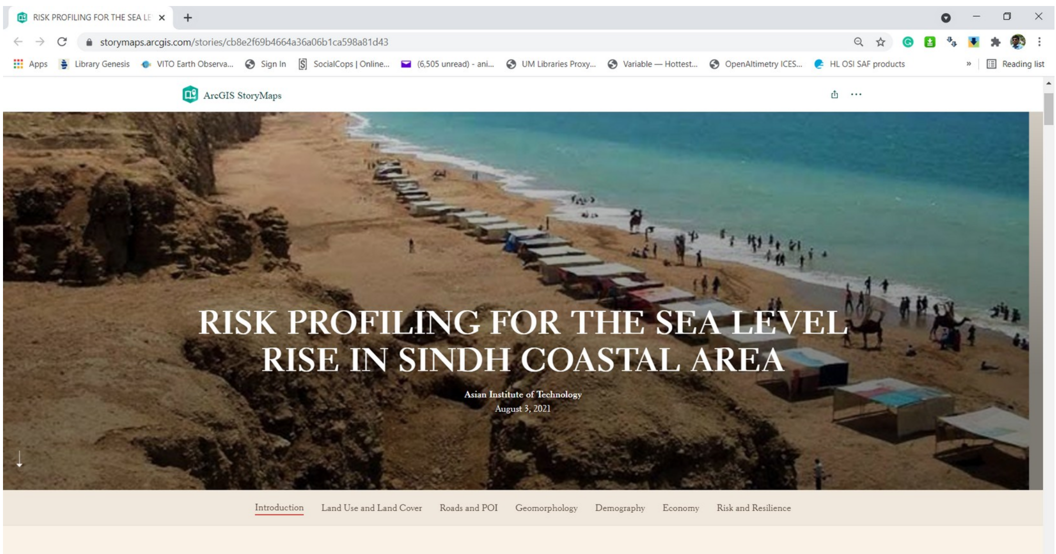
i. Land Use and Land Cover change has been done for the Thatta Province for the years 2000, 2011, 2020.

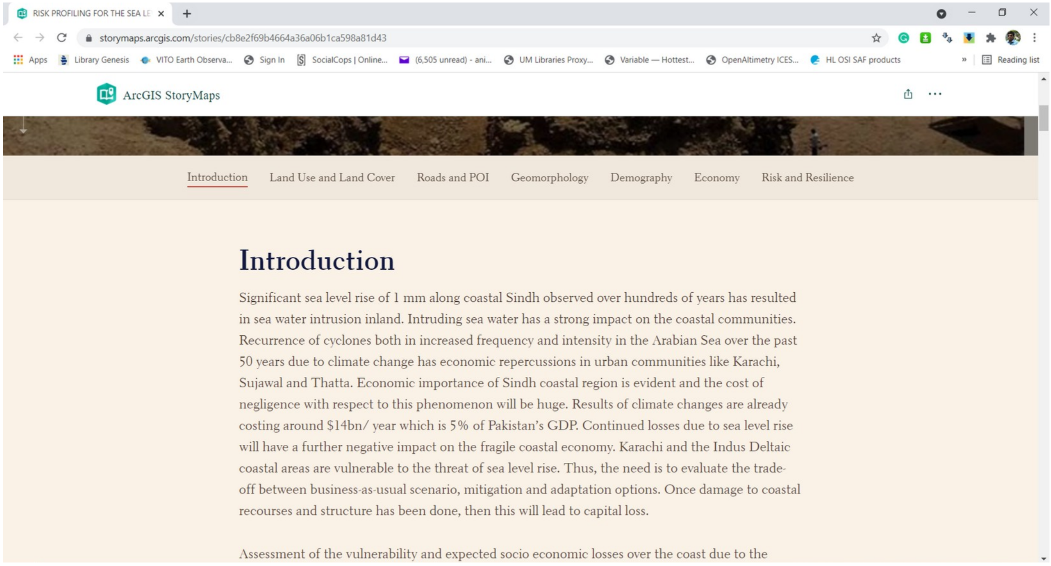
ii. A comparison of the LULC changes for the year 2000 and 2020 can be done by using a swipe function in arc story map.

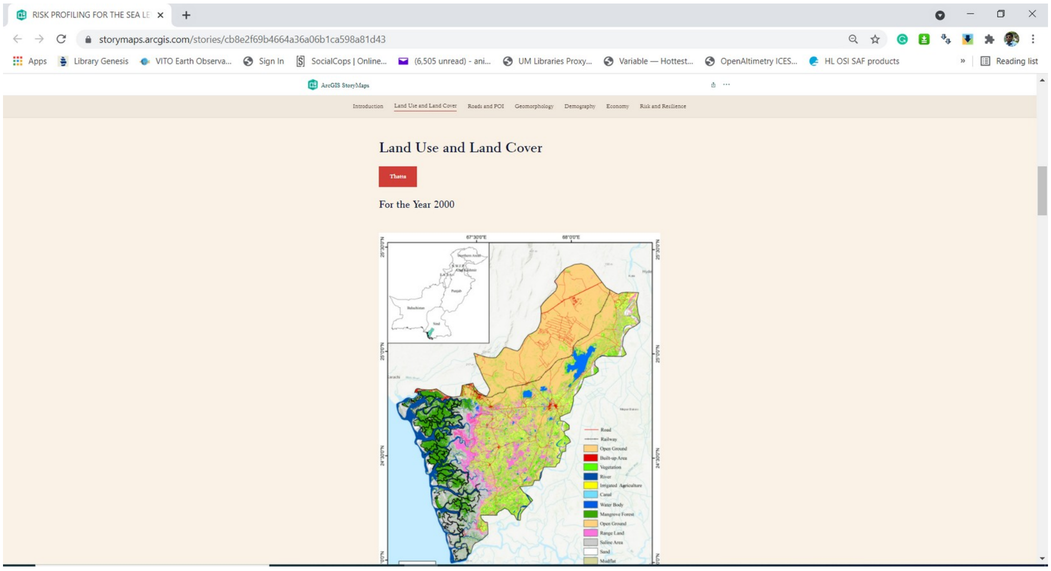
iii. The stories with the story builder can include maps, narrative text, lists, images, videos, embedded items, and other media.

iv. The stories can be published using their own URL (web address). The URLs can be used to share your stories with concerned stakeholders or with the public upon authorization.4

The photos in figure 19 below shows the snapshots of the various features and products of Arc GIS story maps developed as a product of this report.







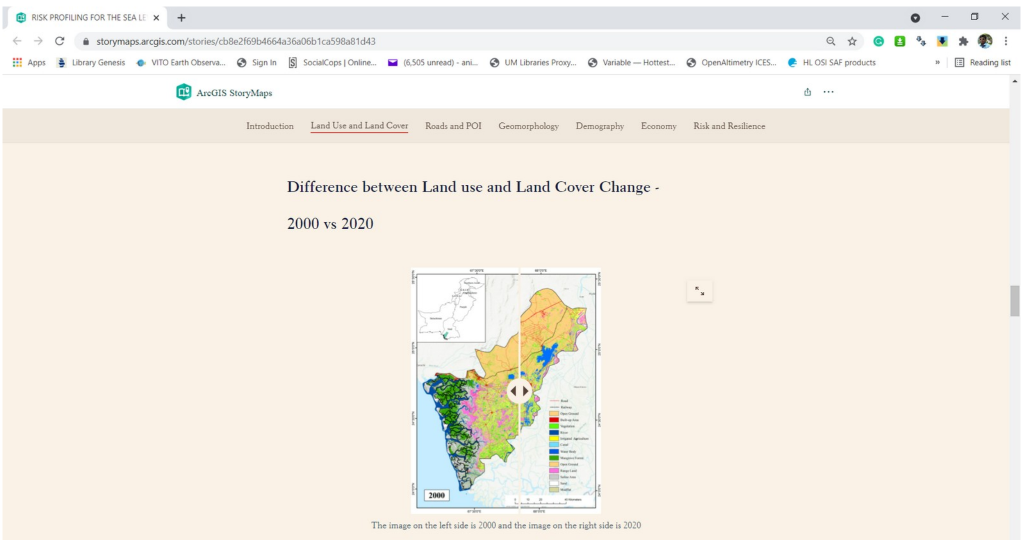


Figure 19: Snapshots of Arc GIS story maps showing the various features.

6 COASTAL EROSION

The shoreline assessment was done through three decades, with a representative LANDSAT data for each decade. Radiometric correction of the datasets was carried out in ENVI software, which considers the effect of sun and view angle and sensor calibration with additional atmospheric correction. The input parameters were extracted from the metadata file provided with LANDSAT data documentation. Tasseled cap transformation (TCT) was performed on the three data for better delineation of land and water class. TCT arranges available spectral information of all the bands and projects into three components utilizing the coefficients derived from the spectral character of different classes. The wetness component of TCT is used to differentiate land and water. For a better result, three indices namely Normalized Difference Water Index (NDWI), Modified Normalized Difference Water Index (MNDWI) and Automated Water Extraction Index (AWEI) were calculated. Additionally, vegetation indices like Normalized Difference Vegetation Index (NDVI), Enhanced Vegetation Index (EVI) and Mangrove Recognition Index (MRI) were also used to separate coastal vegetation and water body. Particularly MRI was used due to the presence of mangrove vegetation along the coastline of the study area. With the help of all these layers, binary classification was carried out and subsequently, the shoreline was extracted. Reference baseline was created by generating a buffer with the help of all three data and the transects were placed 200 meters apart. The erosion was calculated as shown in figure 20 below

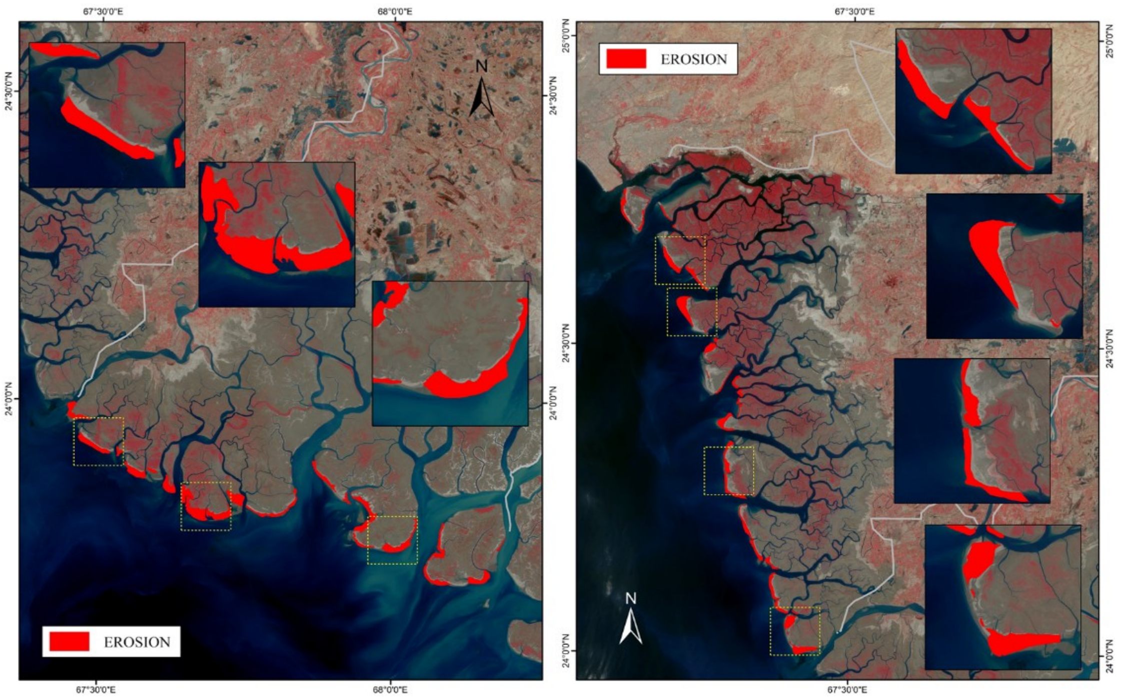


Figure 20: Erosion from 2000 to 2020

The Digital Shoreline Analysis System (DSAS) is a freely available application extension of ESRI ArcGIS software which calculates the rate of change statistics for a given vector type shoreline data. DSAS requires a reference shoreline in terms of a consistent linear feature such as high or low water line, vegetation line, or shoreline extracted from satellite imagery. The rate of change of a particular shoreline is computed by measuring the distance between a shoreline intersection across a transact and the common reference line. To compute the shoreline change statistics, DSAS requires a positional uncertainty associated with each shoreline. The uncertainty arises from various pre-processing steps, or sampling and measurements error, which in turn defies the reliability of the output of shoreline change rate, calculated by DSAS (Anders and Byrnes, 1991; Crowell et al., 1991; Moore, 2000). Ruggiero et al (2003) documented the process of combining various uncertainty components into a single value that could be used in DSAS as an input feature.

In this study, shoreline assessment was carried out using two different measurement calculations - the end point rate (EPR) and the shoreline change envelope (SCE). The EPR is calculated by dividing the distance between two given shorelines by the time elapsed between the oldest and recent shoreline, whereas SCE reports a distance (in metres) and does not document a change rate. The Linear Regression Rate (LRR) is used to predict the future changes of the shoreline. The regression line is placed in such a way so that the sum of the squared residuals is minimized. Finally, the mechanism of shoreline assessment and prediction is summarized in Figure 21.

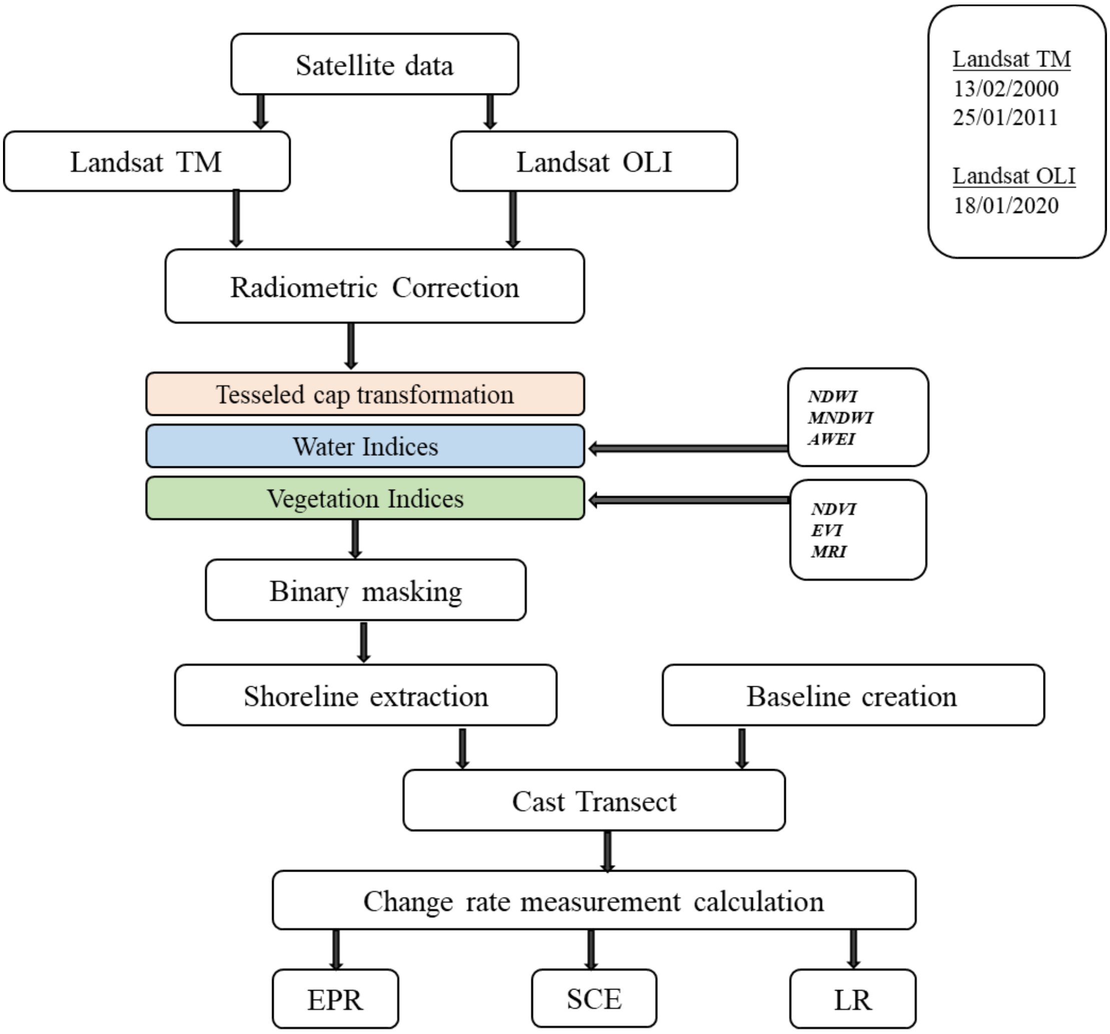


Figure 21: Workflow for calculating shoreline change in Digital Shoreline Assessment System (DSAS)

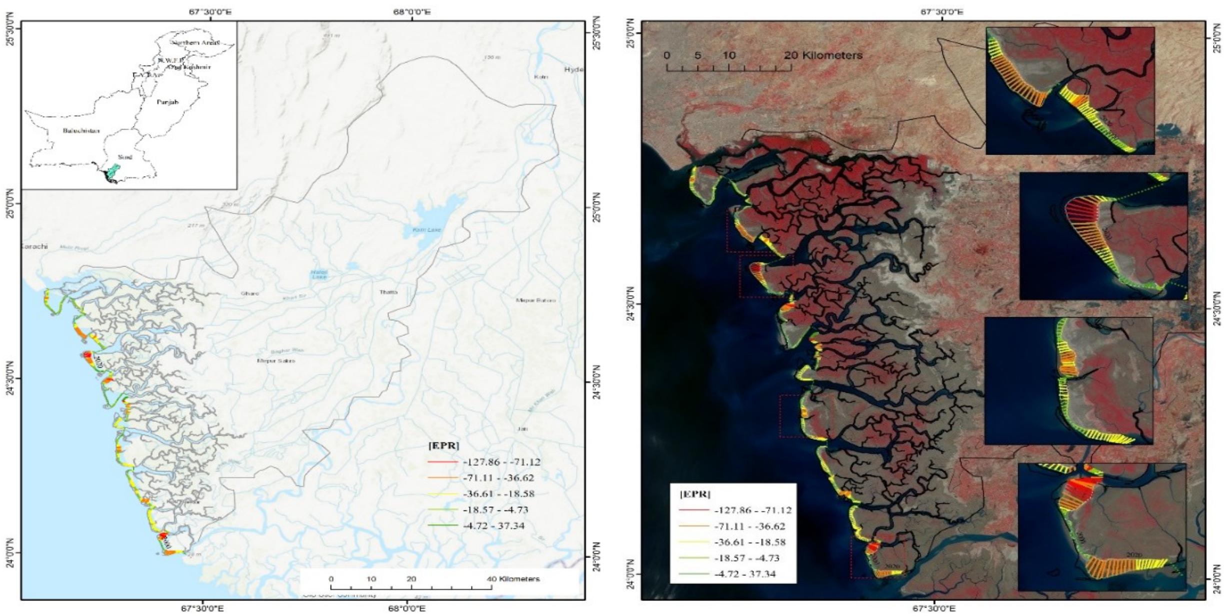


Figure 22: Coastal Erosion Rate

6.1 Erosion along Thatta coastline:

In this study, the rate of erosion, as well as the total eroded coastline, have been calculated using LANDSAT multispectral dataset. The Digital Shoreline Analysis System (DSAS), which is an extension in ESRI ArcGIS, has been used to determine coastal erosion from 2000 to 2020. Extraction of coastline was achieved through the separation of land and water classes. Shoreline assessment was carried out using two different measurement calculations - the end point rate (EPR), the shoreline change envelope (SCE). In the EPR, the coastline of 2000 was compared to the coastline of 2020 which is depicted in Figure 23 (a). The EPR in Thatta ranges from 4.72 m to 127.86 m. From the SCE (figure 23 (b)) the range of shoreline retraction was determined to be 185.51 m to 2557.28 m. One of the alarming facts extracted from the results is some places along the Thatta coast, the shoreline has been retracted up to 2.5 km. The changes have been observed mainly towards the low-lying small islands where mangrove vegetation is predominant. Approximately 49.38 sq km area has been eroded along the Thatta coastline from 2000 to 2020. Figure 24 accurately describes the erosion-prone areas on the Thatta coast. This report should be considered as a baseline for future erosion accretion studies in Thatta. The government and policymakers should act accordingly considering more future erosion can pose a severe threat to the coastal population and infrastructure.

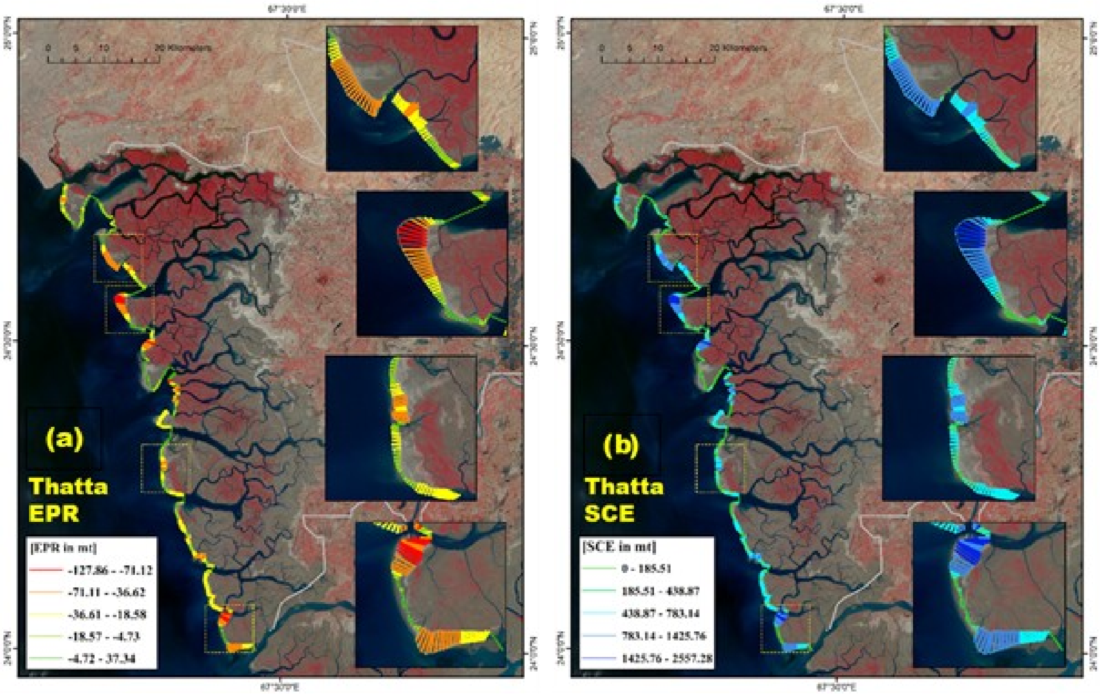


Figure 23: (a) EPR and (b) SCE along Thatta coastline

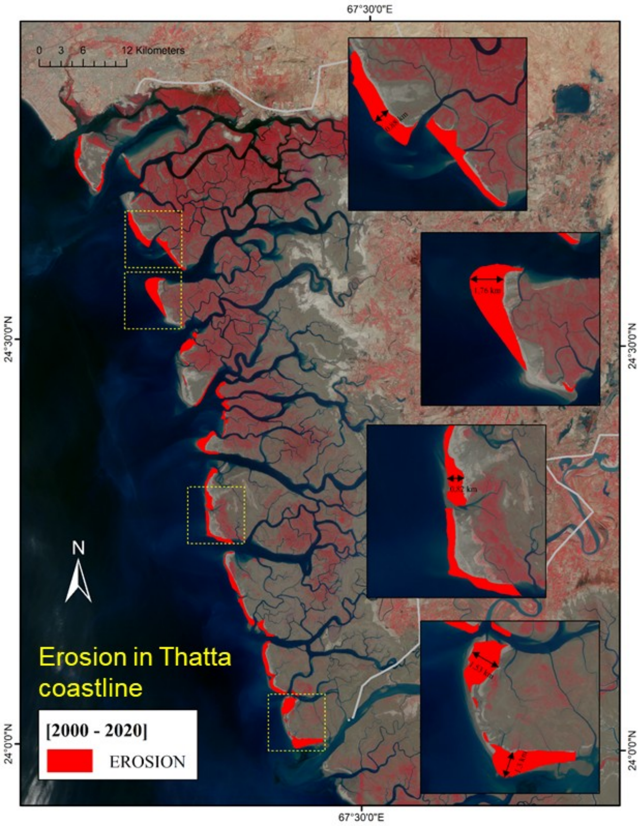


Figure 24: Erosion on the Thatta coast

6.2 Erosion along Sujawal coastline:

Similar to Thatta, coastal erosion in Sujawal state has been assessed using LANDSAT multispectral data. A similar methodology has been adapted to determine the coastal erosion from 2000 to 2020 in Sujawal. Reference baseline was created by generating a buffer around 2000 shoreline and the transects were placed 200 meters apart to calculate SCE and EPR. From the EPR image (Figure 25(a)) it can be inferred that the rate of erosion ranges between 8.40 m to 133.76 m. Shoreline change envelope depicts a net change between 220.98 m to 2675.29 m.

The massive renounce of shoreline in Sujawal as well as Thatta should be considered as an indirect effect of Sea Level Rise along Pakistan coastline. As a result, a total of 73.10 sq km area has been lost or reclaimed by the sea in the past 20 years in Sujawal (figure 26). The erosion along the coastline is continuous and affecting the coastal vegetation i.e., mangrove and thereby disrupting the coastal ecosystem.

The depletion of mangroves in the coastline will make the area more vulnerable to sea-level rise and natural phenomena like storm surges and cyclones. Adaptation and mitigation strategies should be taken immediately to prevent further damage to the coastal ecosystem in Sujawal.

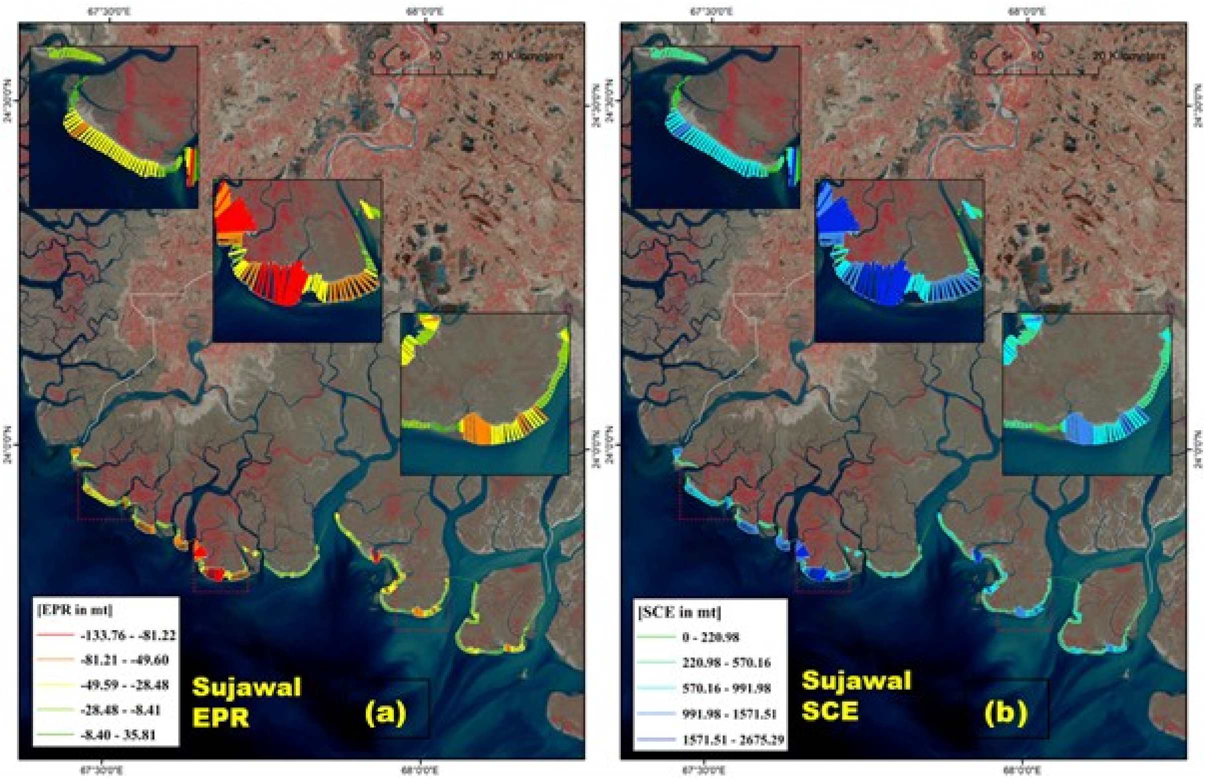


Figure 25: (a) EPR and (b) SCE along Sujawal coastline

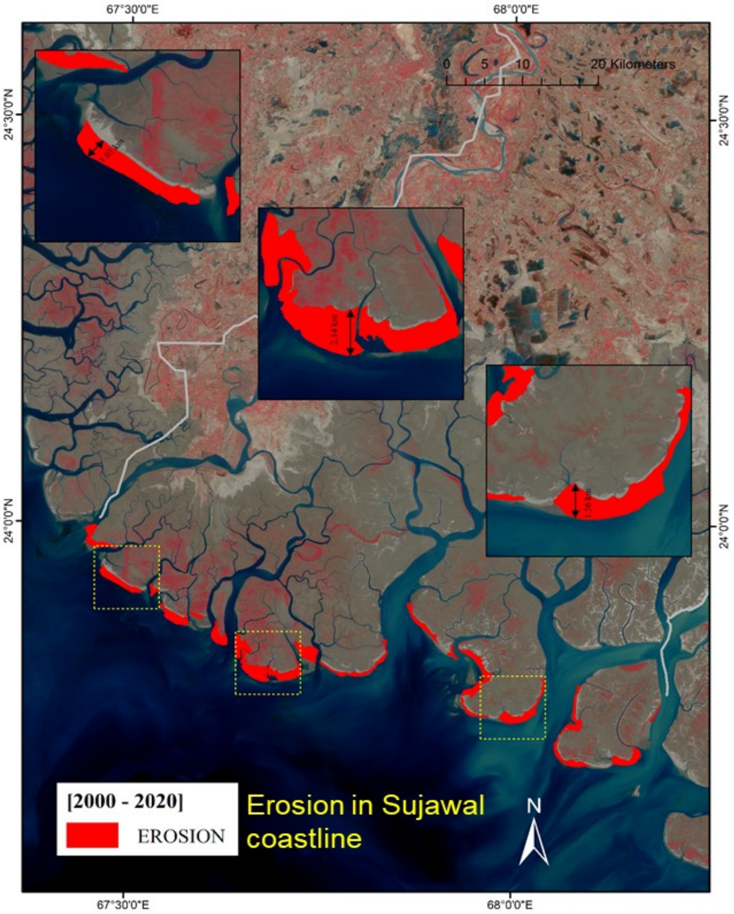


Figure 26: Erosion on the Sujawal coast

7 SEA LEVEL RISE

Coastal areas are sensitive and vulnerable to meteorological and geomorphic hazards such as cyclone, storm surges, sea level rise, coastal erosion, submergence of coasts, change in shoreline, coastal flooding etc. which are further triggered by anthropogenic interventions. (Sahana et al.,2019). Sea level rise is a global phenomenon which refers to a sustained increase of the mean sea level over a definite time duration.

Effects of rising sea level is dynamic, with some regions experiencing higher degrees of effects than others. Ocean currents, upwelling, transportation of heat, nutrients, fresh water and earth's gravitational pull play an important role in moving water masses around. It has been observed by NASA that melting water from icesheet reduces the gravitational pull of the ice sheet and cold-water speeds towards coast which also causes warmer current to speed up, as well as have potential to tilt the surface of the ocean. These changes in regional and global scale must be measured and carefully recorded to estimate or project the future changes in coming years with greater confidence. Therefore, the role of earth-ocean observing satellite and other ocean measurement processes must be strengthened with immense importance to characterize the future inundation risk due to sea level rise.

The UNEP included Pakistan within group of vulnerable countries in 1989 through their Regional Seas program. Based on that trend observed in recent past, 50 mm (5cm) rise in sea level can be expected in the next 50 year in and around the Pakistan's coast. This estimated value falls under eustatic SLR as the global range lies between 1-2mm/year. Based on recorded historic data of last 35 years, an increasing trend has also been observed in air temperature by 0.67℃ and 0.30℃ in sea surface temperature in a decade (Khan et al 2010). Sindh coastal area is more vulnerable than the other parts of the coast (Baluchistan coast) in Pakistan because of regional geological activity. As subduction of the Indian ocean plate is active at a rate of 1-2 mm/year, it acts as a natural protection for Baluchistan coast against adverse effects of the current SLR trend. The coast near Karachi which is a part of the Indus deltaic creek system is not only vulnerable to natural phenomenon such as erosion and accretion, SLR, Storm surge & stronger ocean current, continuous human activity and economic development in and around Karachi also plays a major role (Khan et al 2010).

It is estimated that the eastern coastal areas with a rise of 33m to 60m in sea level would lead the coast to retreat towards land by 23m and 41m respectively while the western coast would retreat landwards by 18m and 33m for a similar rise in the sea level (Al Saafani et al., 2018). It has been observed that the annual sea level rise along Aden situated in Yemen is 2 mm/year and is at par with global sea level rise (Al Saafani et al., 2018). The Indian state of Gujarat along the Arabian sea also encounters the adverse consequences of sea level rise and erosion. Various studies have shown that the annual rate of erosion along the coast of Gujarat is 39.76 m/year resulting in the erosion of 35.98% of the Gujarat coast (Patel et al., 2021, Mahapatra et al.,2015). Based on the coastal vulnerability index, 45.67% accounting to almost 785 km of the Gujarat coast is categorized as highly vulnerable to sea level rise and erosion and it comprises of western and north-western portion of Kachchh and north-western region of Gulf of Khambat (Mahapatra et al.,2015). Akin to other countries along the Arabian Sea, Pakistan also encounters the alarming threat of sea level rise and its inevitable consequences of coastal erosion and flooding (Khan et al., 2002). Among the different countries along the Arabian sea Pakistan is considered to be one of the most severely affected countries by sea level rise and resultant consequences like coastal erosion and coastal flooding (Pakistan, M.F.F., Coastal Erosion in Pakistan: A National Assessment Report, 2014).

Table 8: Sea Level Rise as Observed by Different Researchers

Title of Paper	Authors	Year	Region	Sea Level Rise
Coastline Vulnerability Assessment through Landsat and Cubesats in a Coastal Mega City.	Nazeer et al.	2019	Pakistan coastline	3.9mm/year
Vulnerability of the Indus delta to climate change in Pakistan.	Rasul, Mahmood Sadiq Khan	Over the past decades	Pakistan coastline	3.1mm/year
Sea level variations and geomorphological changes in the coastal belt of Pakistan	Khan et al.	2002	Karachi Coastline	1.1mm/year
Sea level monitoring and study of sea level variations along Pakistan coast: A component of integrated coastal zone management.	Khan and Rabbani	2000	Karachi Coastline	1.1mm/year
Global Warming and Rise in Sea Level in the South Asian Seas Region, in the Implication of Climatic Changes and the impact of rise in Sea level in the South Asian Seas Region.	Quraishee	1988	Pakistan coastline	1.1mm/year

The recent projections based on IPCC Sixth Assessment Report are much more aggressive than the previous assessment. Sea level projections considering only processes for which projections can be made with at least medium confidence are provided, relative to the period 1995–2014, for five Shared Socioeconomic Pathway (SSP) scenarios. The scenarios are described in Table 9.

Compared to 1850-1900, globally averaged surface air temperature over the period 2081–2100 is very likely (with at least a 90% probability) to be higher by 1.0°C–1.8°C under SSP1-1.9, 1.3°C–2.4°C under SSP1-2.6, 2.1°C–3.5°C under SSP2-4.5, 2.8°C–4.6°C under SSP3-7.0, and 3.3°C–5.7°C under SSP5-8.5 (IPCC 6th assessment report).

In the sea level projections, likely ranges are assessed based upon the combination of uncertainty in the temperature change associated with an emission scenarios and uncertainty in the relationships between temperature and drivers of projected sea-level change, such as thermal expansion, ocean dynamics, and glacier and ice sheet mass loss. In general, 17th-83rd percentile results are interpreted as likely ranges, reflecting the use of the term likely to refer to a probability of at least 66%.

Table 9: Different Shared Socioeconomic Pathways considered for sea-level rise scenarios

SSP 1-1.9	Holds warming to approximately 1.5°C above 1850 -1900 in 2100 after slight overshoot (median) and implies net zero CO^2 emissions around the middle of the century.
SSP 1-2.6	Stays below 2.0°C warming relative to 1850 – 1900 (median) with implied net zero emissions in the second half of the century
SSP 2-4.5	is approximately in line with the upper end of aggregate Nationally Determined Contribution emission levels by 2030. SR1.5 assessed temperature projections for NDCs to be between 2.7 and 3.4°C by 2100., corresponding to the upper half of projected warning under SSP2-4.5. New or updated NDCs by the 2020 did not significantly change the emissions projections up to 2030, although more countries adopted 2050 net zero targets in line with SSP1-1.9 or SSP1-2.6. The SSP2-4.5 scenario deviates mildly from a 'no-additional-climate-policy' reference scenario, resulting in a best-estimate warming around 2.7°C by the end of the 21st century relative to 1850-1900.
SSP 3-7.0	Is a medium to high reference scenario resulting from no additional climate policy under the SSP3 socioeconomic development narrative. SSP3-7.0 has particularly high non-CO2 emissions, including high aerosols emissions.
SSP 5-8.5	Is a high reference scenario with no additional climate policy. Emission levels as high as SSP5-8.5 are not obtained by Integrated Assessment Models (IAMs) under any of the SSPs other than the fossil fueled SSP5 socioeconomic development pathway.

To indicate the potential impact of deeply uncertain ice sheet processes, about which there is currently a low level of agreement and limited evidence, low confidence projections are also provided for SSP1-2.6 and SSP5-8.5. For both the Greenland and Antarctic ice sheets, the low confidence projections integrate information from the Structured Expert Judgement study of Bamber et al. (2019). For the Antarctic ice sheet, the low confidence projections also incorporate results from a simulation study that incorporates Marine Ice Cliff Instability

(DeConto et al., 2021). The table results based on IPCC 6th assessment shown are likely ranges.

8 EFFECT OF COASTAL EROSION

The prediction of shorelines for 2030, 2040 and 2050 were performed using Digital Shoreline Assessment System (DSAS). DSAS is part of the "Coastal Change Hazards project" of USGS and provides a thorough and reproducible method of calculating regression rates that can be used to enormous quantities of datasets on a broad scale. It is a geospatial tool that may be used to identify the position and shape of the shoreline during the past or present. The ability of the DSAS to quantify rate change metrics on shoreline locations over time is a significant benefit in coastal erosion research. Statistics make it possible to assess and investigate the essence of coastal dynamics and shifting patterns.

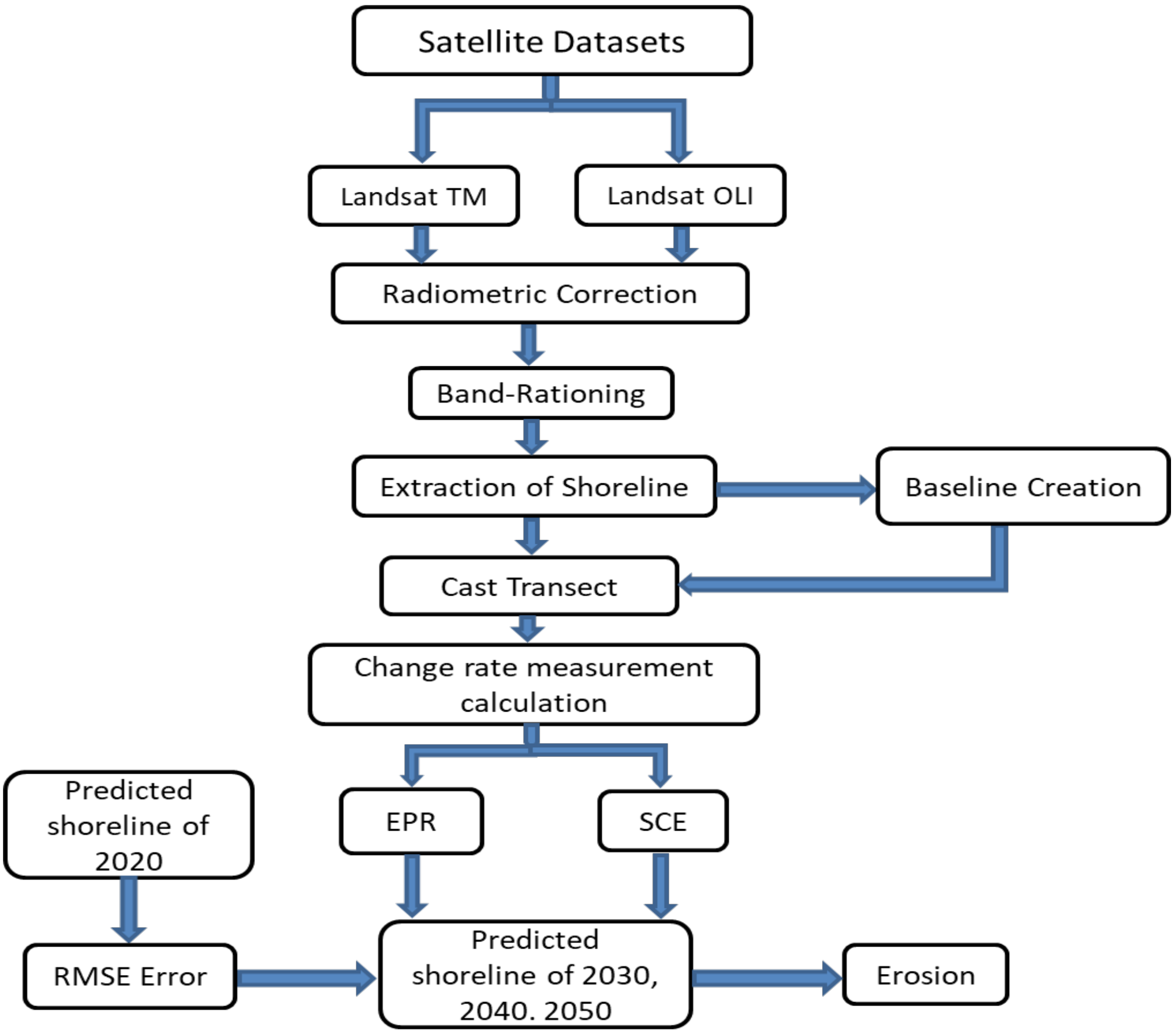


Figure 27: Flow chart depicting the methodology for shoreline prediction

The methodology (figure 27), for prediction, was performed using multispectral satellite imageries of the years 2000 and 2010. Geometric corrections were conducted initially, followed by radiometric corrections for each band of satellite imageries. The radiometric adjustment required two measures: first, converting DN values to radiance values and then to reflectance values. The current study was based on the band rationing approach, which used a ratio among band 2 and band 4, band 2 and band 5. The vegetation is removed by rationing among band 5 and band 2 along the shoreline in coastal regions. Water has a band 2 / band 5 mean of greater than 1, and land has a B2/B5 average of less than 1. The persistent shoreline locations of two distinct years were delineated using two separate years, 2000 and 2010. Thus, the binary raster image has been transformed to a vector dataset, and the shoreline boundaries have been defined. As a result, the benchmark is fixed at 1,000 meters offshore from the adjacent shoreline for this study. For several years, the transect lines were cast orthogonally along the shoreline from the baseline.

The rate of alteration in the coastline of the study area was calculated in this study using two essential mathematical models: the EPR (End Point Rate) and the SCE (Shoreline Change Envelope). First, divide the distance here between the earliest and newest shorelines in the dataset by the time variation between them to have the EPR. The rate of change of shoreline per year to measure the EPR is calculated by using Eq. 1 which is shown as,

$$S_r=f_o-f_y/n \quad (1)$$

Where Sr denotes the distance between the average and shoreline at the earliest point on a specific transect (xn), and fy denotes the distance between median and baseline. Subsequently, the shoreline at the very same transect previously (xn); n is the entire period from the beginning of the study to the present day. The key function of SCE is denoted by Eq. 2, which is rendered as

$$S_d=d_f-d_c \quad (2)$$

Where Sd denotes the variation in shoreline's distance (m), and df indicates the distance across the baseline and furthest shoreline (m) at a particular point. The transect (xn); dc is indeed the distance between both the baseline and the closest shoreline (m) along the same transect (xn). This analysis estimates the SCE as the distance across the farthest and closest shorelines from the baseline. The rate of coastal erosion and accretion has been considered while defining the baseline locations, and the total changes in shoreline movement are reflected for all available coastal sites for each transect.

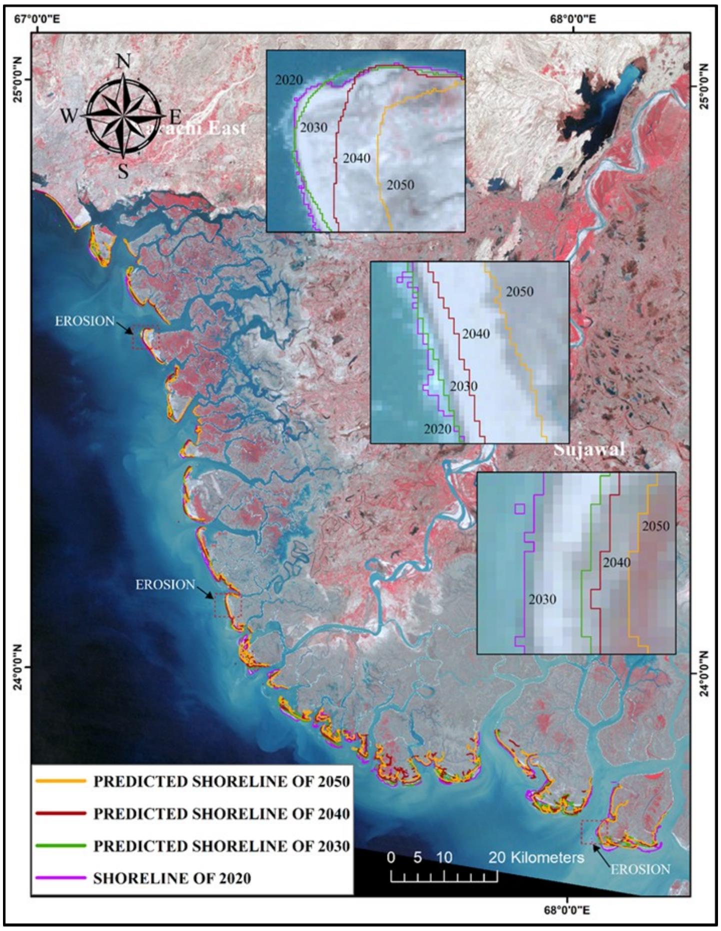


Figure 28: Estimated shoreline of 2020 and the predicted shoreline of 2030, 2040, and 2050 using DSAS

The zones of erosion and accretion of the regions under study (Sujawal and Thatta) have been delineated (Table 10), and the areal changes of the study site have been computed using this method. To determine the island's extent for a particular year, a polygon is created along the boundary of the GIS platform, yielding the island's area during that year. On the GIS platform, a polygon is constructed along the shoreline to estimate the extent of the study area throughout a given year. Overlay connects the polygons for two consecutive years at 10-year intervals (2000-2010) in decoding net aerial transition and measurement of erosion on the island. In the "union" overlay procedure, two shorelines can be linked.

After outlining the shorelines of Sujawal and Thatta in the years 2000 and 2010, using the EPR model, and taking their shoreline position in these two years (2000 and 2010) into account, the shoreline of the year 2020 has been forecasted. The actual shoreline of 2020 was delimited and compared with the predicted shoreline of 2020, and the RMSE error was detected for error correction, and the shoreline of 2020 (figure 28) was effectively defined. Then, utilizing the shorelines of 2010 and 2020, future estimates of the shoreline position during 2030, 2040, and 2050 were carried out. Following the execution of future shoreline estimates, the annual erosion and accretion rate has been estimated between 2020-2030, 2030-2040, and 2040-2050, based on the predicted shorelines of the years 2020, 2030, 2040, and 2050.

Table 10: Estimated erosion between the years 2020 and 2030; 2030 and 2040; 2040 and 2050 based on predicted shoreline position

Time Interval	Sajwal		Thatta		East Karchi	
	Accretion (km^2)	Erosion (km^2)	Accretion (km^2)	Erosion (km^2)	Accretion (km^2)	Erosion (km^2)
2020 - 2030	19.77	34.66	8.31	18.1	0.01	1.47
2030 - 2040	25.02	38.86	7.39	13.4	0.05	1.64
2040 -2050	22.32	36.24	7.13	18.2	0.01	2.27

As per table 10, the rate of erosion and accretion during 2020-2030, 2030-2040, and 2040-2050 have been estimated, based on the projected shoreline positions of Sujawal and Thatta In respective years mentioned above. According to the projected erosion and accretion rates, the region of Sujawal is projected to undergo the highest rate of shoreline erosion (25.02 km2) and the highest rate of shoreline accretion (38.06 km2) during 2030-2040. The region of Thatta is also projected to undergo a maximum rate of erosion (8.31 km2) during 2020-2030 and a maximum rate of accretion (18.2 km2) during 2040-2050.

9 EFFECT OF SEA LEVEL RISE

Due to the unavailability of high resolution/ accuracy DEM, the elevation data was taken from SRTM with a spatial resolution of 1 arc-second (30 metres) and ASTER GDEM ("Global Digital Elevation Model") data of 30 metres spatial resolution. Since the Digital Elevation data from SRTM begins at 1-meter elevation, an estimation of the inundated regions has been undertaken by considering a minimum Sea Level Rise of 1 meter (Figure 29). According to IPCC AR6, sea-level projection by NASA, sea level rise by 0.22 m is expected around Pakistan coast by 2050. To compare our results to the current global prediction, we had to establish a scenario that involves 0.5 m elevation results. In order to generate a scenario involving a 0.5 m sea-level rise, we have used a new dataset with 0.5 m lowest elevation data, but with coarse resolution.

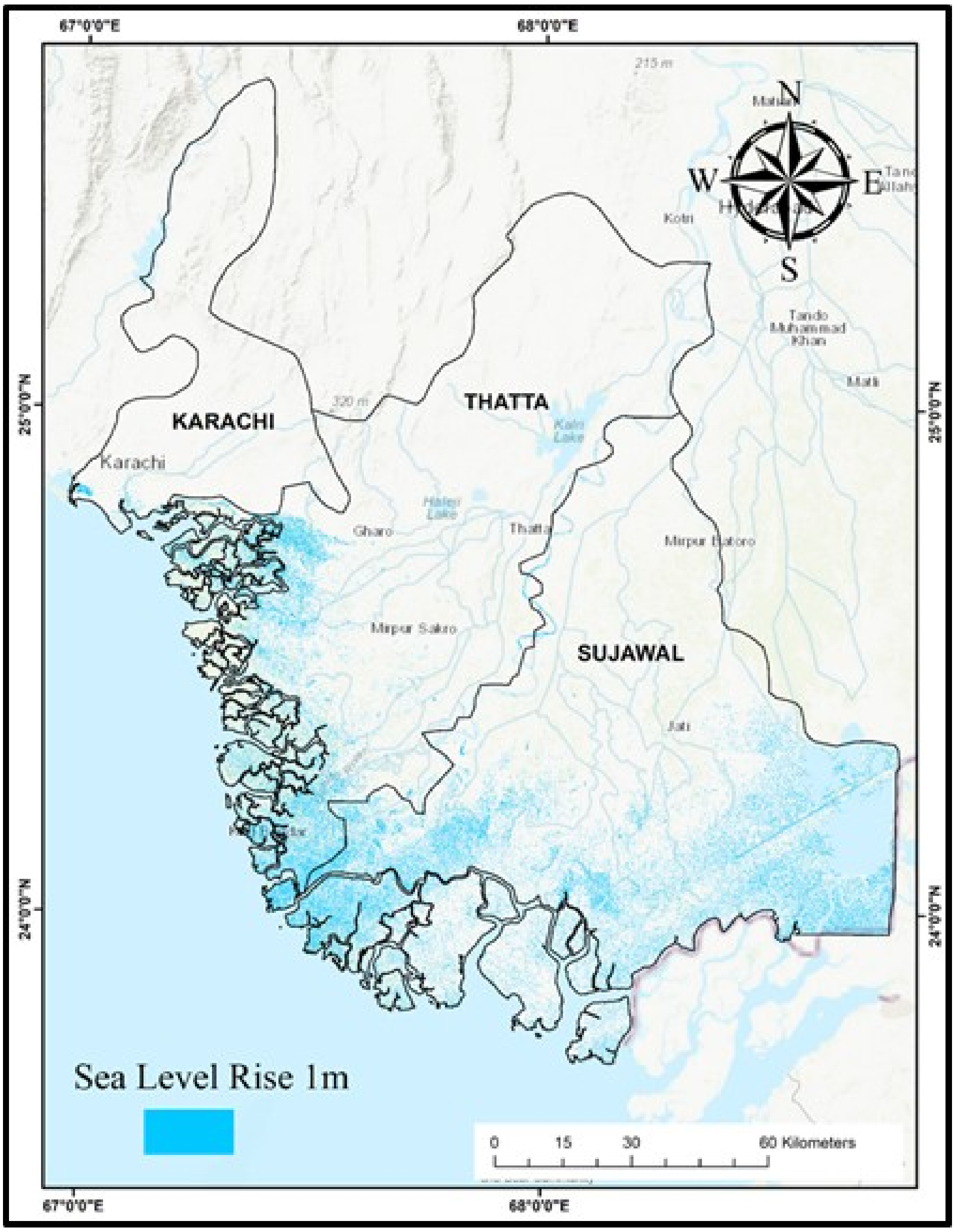


Figure 29: Projected Scenario of Inundation by the year 2050 if the sea level rises by 1 meter

In this report, MERIT (http://hydro.iis.u-tokyo.ac.jp/~yamadai/MERIT_Hydro/index.html) data has been introduced which provides a minimum of 0.5 m elevation. The new methodology (figure 30) utilizes void-filled SRTM data of 1 arc-second resolution (30 meters) (Earth Resources Observation and Science (EROS) Center, 2018), ASTER GDEM ("Global Digital Elevation Model") data of 30 meters (Sensor Information Laboratory Corporation,2019), and MERIT DEM 3 arc second resolution (90 m at the equator). Then the digital elevation datasets of SRTM, ASTER, and MERIT has been assigned UTM projection zone 42 and merged. The predicted sea level data was then combined with merged datasets to calculate the relative sea-level scenarios. Based on the simulations (SSP1-1.9, SSP2-4.5, and SSP5-8.5), the sea level could rise by 0.17, 0.19, and 0.22 meters by 2050, respectively.

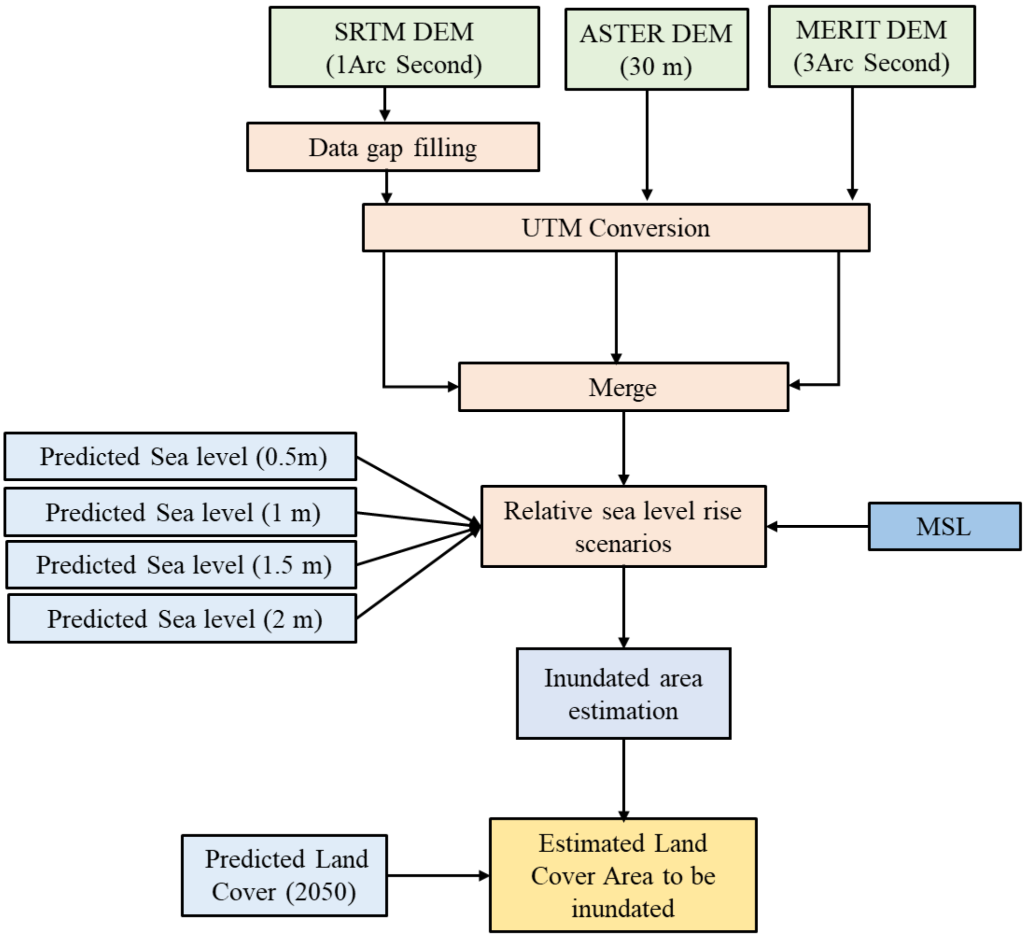


Figure 30: Flow chart depicting the methodology for inundation mapping due to sea-level

The potentially inundated areas as per the proposed scenario of sea-level rise at 0.5, 1, 1.5 and 2 m are illustrated in figure 31. The total area which is likely to be inundated along the coast of Sindh is listed in Table 11. As depicted in table 11, if the regions of Sajwal, Thatta and Karachi encounters a sea-level rise of 0.5 meters, then total 75.72 km2, 61.37 km2, and 1.14 km2 of these aforementioned respective regions in the study area could get flooded. Among the inundated area, saline regions of Sajwal (34.86 km2) and Thatta (30.51 km2) could be highly inundated.

In Karachi the settlement area could get flooded up to 0.91 km2, which could pose a vulnerable situation for the inhabitants of Karachi. Inundation follows a similar pattern if sea level increases by 1 meter, although the flooded region will increase owing to 1-meter rise in sea level. According to table 11 and figure 30 of projected inundation regions, if the sea level increases by 1 meter, 411.95 km2 of the saline land in Thatta, Sujawal, and 3.89 km2 of the inhabited area in East Karachi might be the highest inundated region. Whereas the least inundated areas could be the saline areas of East Karachi and the settlement areas (0.79 km2) of Thatta and Sujawal.

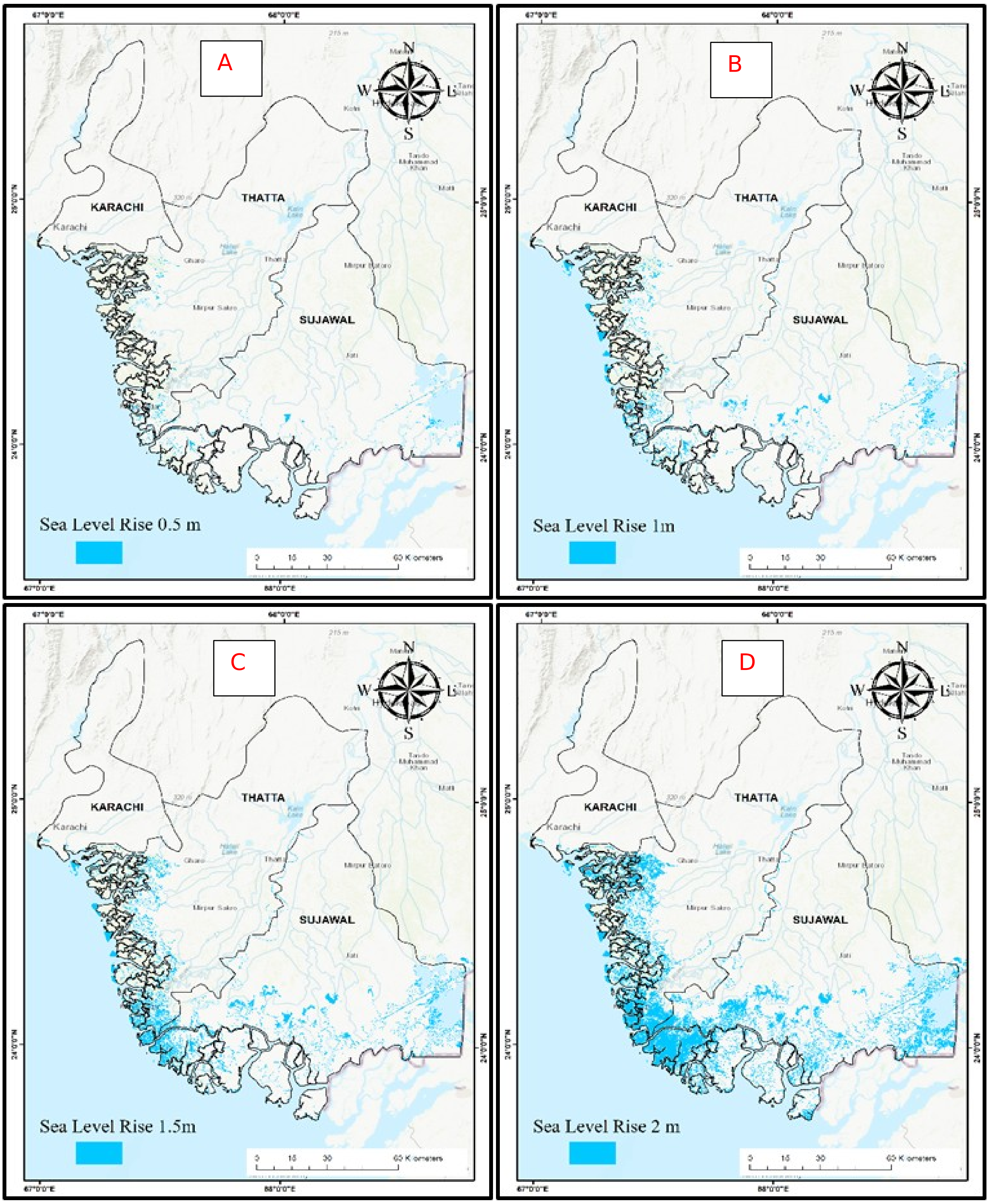


Figure 31: Projected inundated areas if the sea level rises by (A) 0.5 meter, (B) 1 meter, (C) 1.5 meter and (D) 2 meters

If the sea level increases by 1.5 meters in the same regions, as usual, a larger proportion of these regions (Sajwal, Thatta, and Karachi) would be inundated. If the sea level rises by 1.5

meters, 230.76 km2 and 236.92 km2 of the saline area will be flooded in Sajwal and Thatta, respectively as depicted in figure 30. In Karachi, the situation of flooding could be more vulnerable, because as per table 11 and figure 31, approximately 3.63 km2 of the settlement area could undergo devastating inundation.

Table 11: Predicted area to be inundated based on the considered sea level rise scenarios

Sea level rise	Expected Area (km^2) to be Inundated
0.5 m Sea level rise	144.3543
1 m Sea level rise	454.3253
1.5 m Sea level rise	927.4283
2 m Sea level rise	2010.9103

Table 12: The predicted area of different LULC classes that could be inundated under different sea-level scenarios

	Flooded Areas (km2) based on different Sea Level Rise Scenarios (in meters)											
Regions	SAJWAL				THATTA				KARACHI			
Class	0.5m	1m	1.5m	2m	0.5m	1m	1.5m	2m	0.5m	1m	1.5m	2m
Water body	0.75	2.98	13.33	38.56	1.44	4.61	6.55	10.38	0.04	0.15	0.35	0.48
River	24.22	56.41	102.64	148.36	19.69	47.89	67.23	84.86	0.05	0.22	0.46	0.60
Vegetation	0.35	0.68	1.90	10.52	0.73	3.20	4.30	8.10	0.01	0.02	0.09	0.22
Mangrove	11.55	42.00	116.59	322.56	5.36	16.40	51.36	166.96	0.13	0.30	0.61	0.90
Irrigated Agriculture	0.47	1.11	3.96	18.63	1.51	4.91	11.30	29.07	0.00	0.01	0.01	0.05
Range Land	0.79	4.89	10.40	37.42	1.05	3.12	6.87	24.82	-	-	-	-
sand	1.17	1.60	2.94	4.02	0.90	16.21	18.08	22.07	-	-	-	-
Saline area	34.86	105.07	230.76	594.97	30.51	118.01	236.92	414.04	-	-	-	-
Mudflat	1.56	6.15	13.29	27.48	0.08	0.22	0.47	2.12	-	-	-	-
Settlement			0.01	0.01	0.08	0.26	0.76	2.05	0.91	1.84	3.63	6.26
Open Land	5.99	15.11	21.33	32.63	0.12	0.97	1.25	2.71	0.02	0.03	0.04	0.09

The scenario of a 2 m sea level rise is rather extreme. From Table 12, it is evident that if the territories of Sajwal, Thatta, and Karachi encounter a 2 meters sea-level rise, approximately 1202.51 km2, 764.45 km2, and 8.52 km2 of these aforementioned respective regions could undergo massive inundation, as depicted also in figure 31. The inundation analysis was conducted based on the minimal available sea-level increase, as there was no coarse elevation data available. If high-resolution elevation datasets with more benchmark sites are provided along the coastal region, the model-derived prediction for flood mapping will have higher accuracy and will be in accordance with the relative scenarios of sea-level rise.

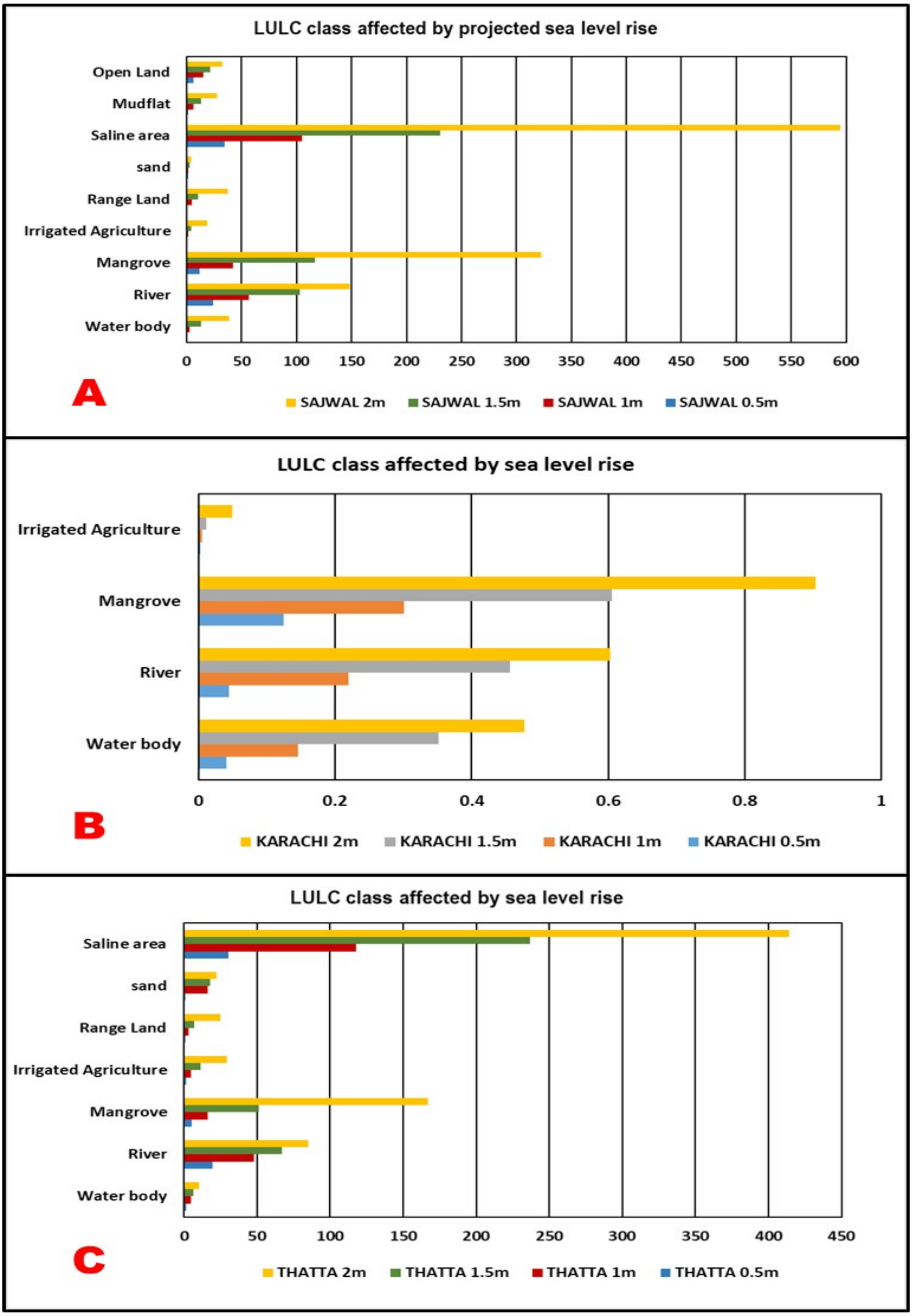


Figure 32: Predicted area from different LULC classes of (A)Thatta, (B) Karachi and (C) Sujawal that could be inundated under different sea-level rise scenarios

Figure 32 depicts the relative classes that could be affected under different sea-level rise scenarios considered in this study. Figure 32 A, B and C represent the different classes at risk in Sujawal, Karachi and Thatta respectively. In Thatta and Sujawal, the most affected classes by inundation are saline areas and mangroves. The coastal belt of Sindh is primarily dominated by mangroves and associated morphological features like saline blank mudflats etc. Due to the lack of human activity in the coastal areas, the inundation extreme is often overlooked as the loss of infrastructure and property is very low. But the serious damage of mangroves due to sea-level rise could pose a potential threat in future.

10 IDENTIFICATION OF RISK ZONES

The proposed study mainly focuses on assessing the risk due to the rise in sea level across the study area by 2050. The scenario of a 0.5-meter rise in sea level has been assessed by applying the MERIT DEM ((Dai Yamazaki, 2019) of 3 arc second resolution (90 m at the equator).

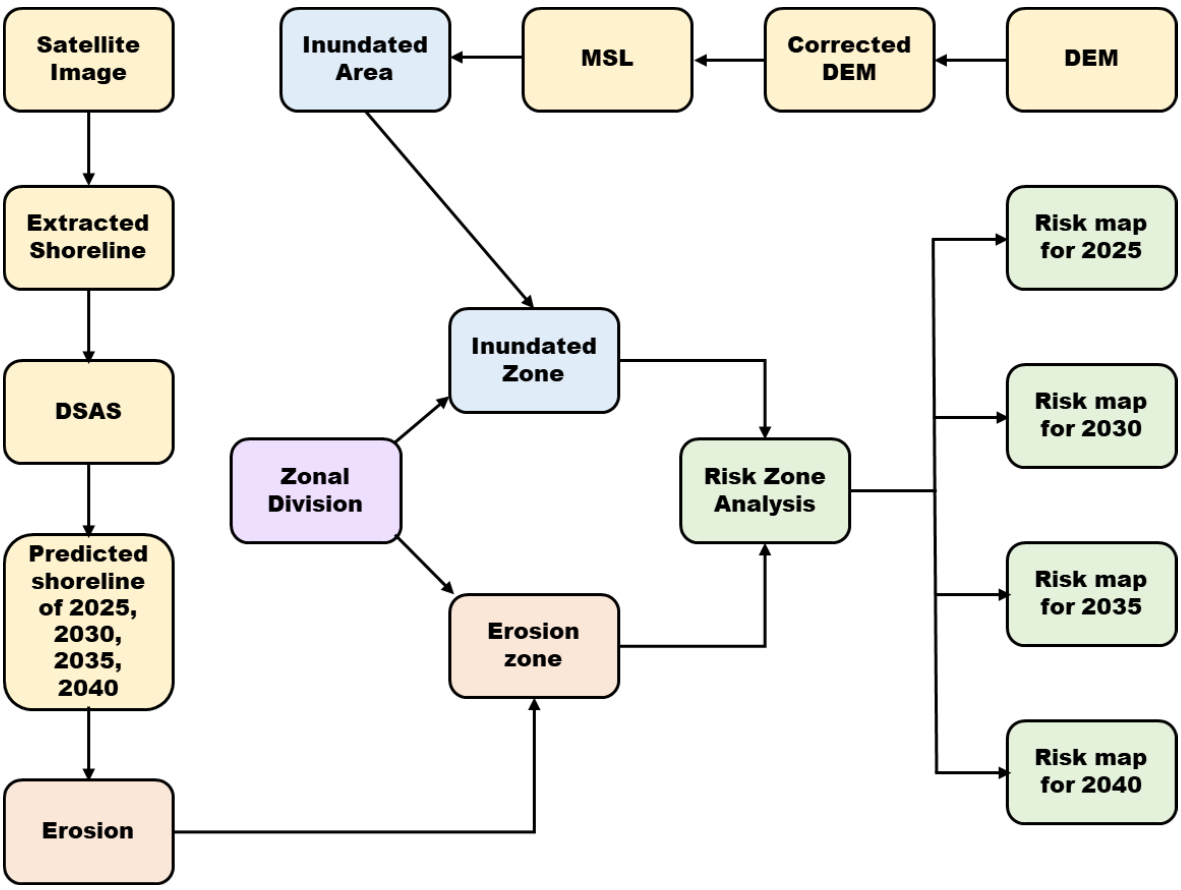


Figure 33: Flow Chart depicting the methodology of the current investigation

Figure 33 depicts the methodology adapted for risk zone identification. At first, the DSAS EPR model has been used to generate End Point Rates along the shoreline, particularly to predict erosion rate if sea level rose by 0.5 meters. If the sea level rises by 0.5 meters, the erosion will vary across the shoreline. Thus, it has been segmented into three zones (very high, high, and low) in figure 34(A) to indicate the range of vulnerability to risk. To properly comprehend the susceptibility of risk from sea-level rise, erosion zones ranging from extremely high to low have been defined. Thus, the three zones of erosion were identified as very high, high, and low rates of erosion in three distinct colours (Figure 34A). The EPR zones assessed by DSAS have been indicated in alphabetical order (A-Z). The EPR zones with a low rate of erosion (highlighted in yellow) are A, B, E, O-Q, and S-W, whereas the zones with a high rate of erosion (highlighted in orange) are C, D, F-H, M, N, and the zones with a very high rate of erosion are I-M. Thus, from the erosion risk zone, it can be observed that the region of Sujawal will undergo a very high rate of erosion, whereas East Karachi will experience a low rate of erosion if the sea level rises by 0.5 meters.

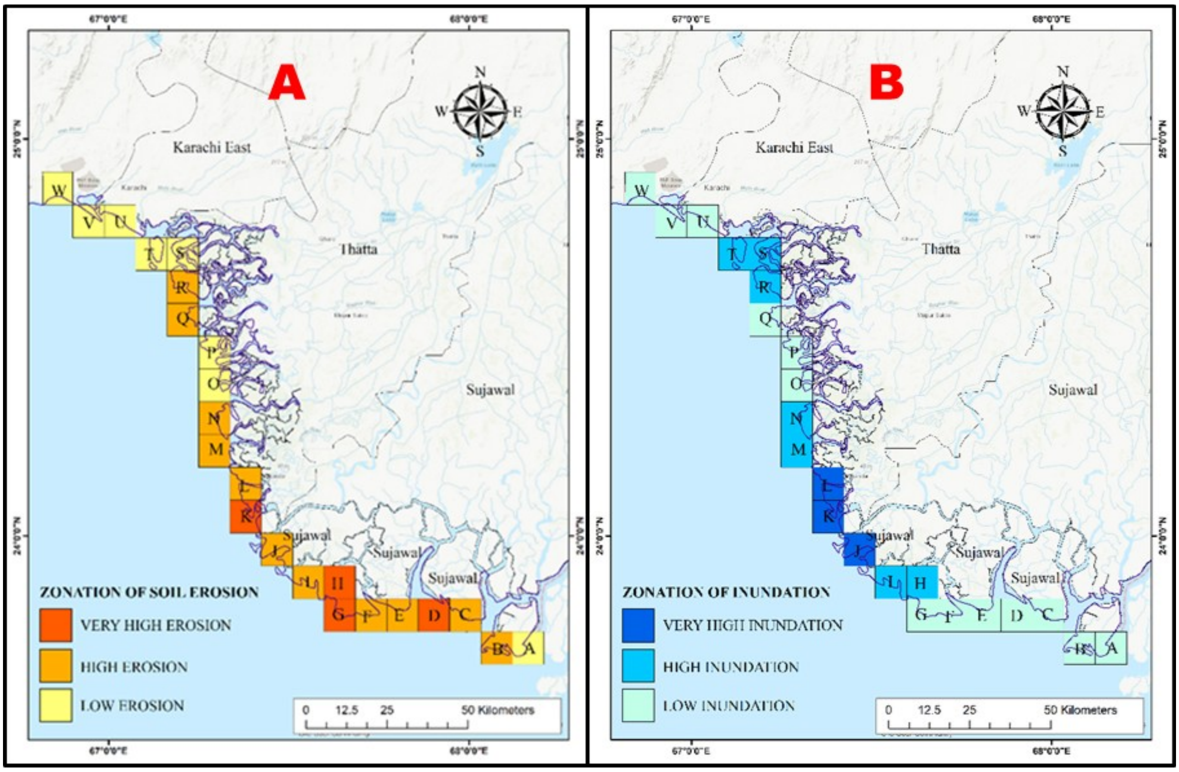


Figure 34: (A) Classified coastal Erosion and (B) Inundation across the shoreline of the study area

The total area that might be submerged if the sea level increases by 0.5 meters have been assessed using MERIT DEM. After estimating the inundated area, the zonation of inundation across the shoreline of the study area has been estimated based on the degree of risk. To adequately understand the risk from sea-level rise, inundation has been zoned, similar to erosion zones, and it ranges from very high to low (Figure 34B). As a result, the three inundation zones by indicating extremely high, high, and low inundation rates in three shades of colours. The zones with the lowest flooding (highlighted in light blue) are A, B, E, O-Q, S-W, whereas the zones with higher flooding intensity (highlighted in blue) are C, D, F-H, M, N, and the zones with the very high rate of flooding are I-M (highlighted in deep blue).

Following the evaluation of erosion and flooding using zonal identification, risk zonation can be determined by integrating erosion and inundation zones (very high, high, low). Thus, the categorized (very high to low) datasets of erosion and inundation were used to carry out the risk zonation of the research region. The same procedure of identifying risk zones have been carried out for the year 2025, 2030, 2035 and 2040. Finally, risk maps for these aforementioned years have been prepared using erosion and inundation as inputs of the model.

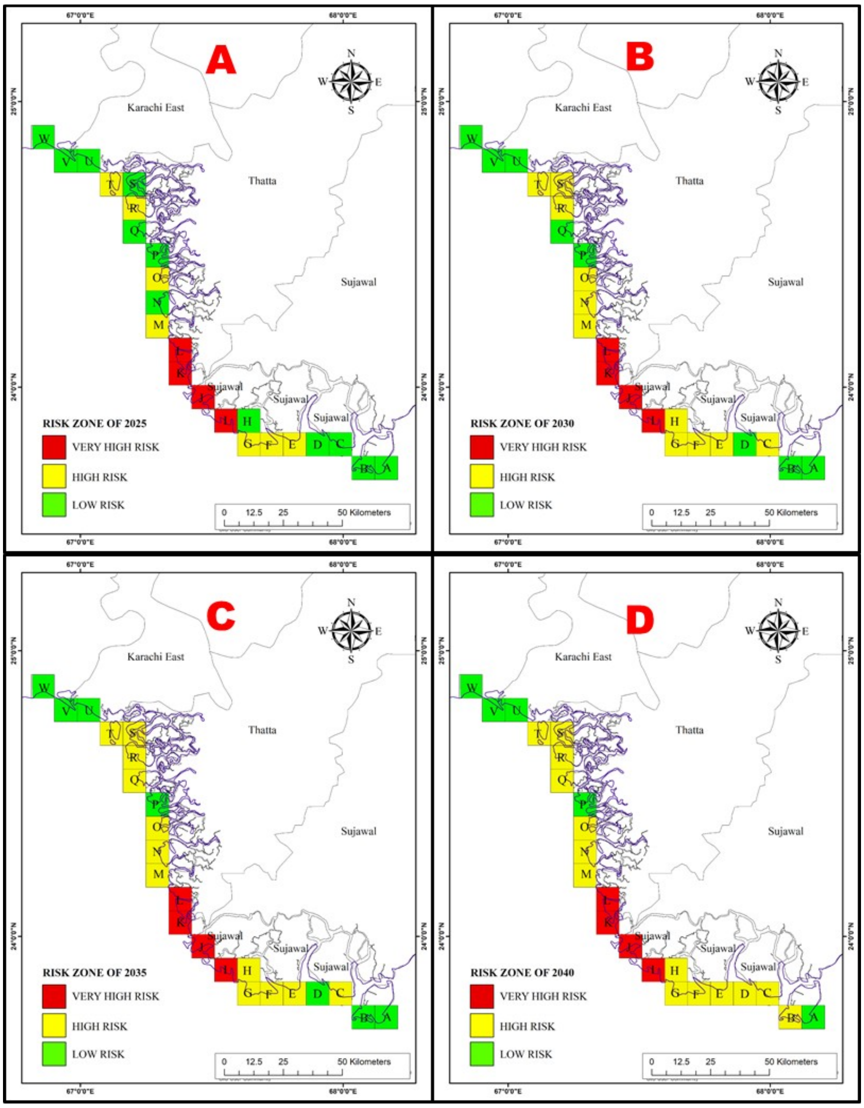


Figure 35: Risk maps for (A) 2025, (B) 2030, (C) 2035, and (D) 2040 under the sea-level rise of 0.5 m generated using predictions of erosion and inundation

If sea-level rise by 0.5 meters, the resulting inundation may result in the occurrence of risk across coastal zones of Sindh province. As a result, the risk has been assessed by categorizing it into three zones: extremely high, high, and low. The risk zonation has been evaluated in a geospatial setting using the combination of inundation and erosion zones. The final risk map (Figure 35 A, B, C and D) for the years 2025, 2030, 2035 and 2040 respectively depicts different grades of risk at different regions through the timescale. It is worth mentioning that new areas have been included as high-risk zones (such as B, C, E and T) in 2035. Also, along the Indus River estuary, the areas are always under high risk emphasizing lower elevation of that area. The three zones C, N and S have been classified as high-risk zone in 2030, whereas it was on low risk in 2025 indicating degradation with progress of time. The regions Q and D have been classified as risk zones in 2035 and 2040 respectively, depicting slow but continuous erosion in those areas.

11 ECONOMIC AND SOCIAL ASSESSMENT

The coastal areas of Sindh province provide important socio-economic activities which influence the economic growth of Pakistan. Particularly, the industrial activities and manufacturing sector in Karachi profit the highest GDP of Sindh, followed by service and agricultural sectors respectively. With only 23% of the national population, the revenue from provincial economic activity accounts for 33% of the country's GDP (Congressional Research Service, 2015).

Over decades, climate change have significant direct impacts Pakistan. World Bank (2020) estimated $ 3.8 billion USD for the country's annual economic loss to cope with consequences caused by climate change. In coastal zones of the country, climate change has influenced on sea level rise and coastal erosion as evidenced in the previous section regarding a constant increase in waterlogged areas. This phenomenon has impacted on national capital losses such as physical, social, environmental, and will be continuing and threatening the economy. Thus, this section aims to estimate the economic loss in different economic archetypes based on different projected scenarios of flood caused by sea level rise and coastal erosion.

11.1 Estimation of Direct Market Loss

SLR combining with coastal erosion could impact permanent land submergence which would result in a permanent loss, and this could cause the reduction of long-term economic growth (Pycroft et al., 2016). Among various direct physical impacts caused by SLR and coastal erosion, this study considers potential land loss. The predicted future land use and land cover are used as a proxy associated with the different scenarios of sea level rise to estimate direct economic loss. Types of land use and land cover are reclassified to different economic archetypes, including commercial, industrial, and residential sectors to understand which economic activities would have effects in the future.

Direct monetary loss estimation due to coastal flood caused by SLR and coastal erosion is complicated than other temporary floods. Typically, researchers usually used GDP for modelling the economic impact (Dasgupta et al., 2009; Hallegatte, 2012), and insured losses estimation or reconstruction/replacement cost coupling with average damage ratio based on vulnerability curve to calculate the economic impact on possible financial damage caused by hazards (Mazzorana et al., 2014; Ranger et al., 2011). In the study of Hallegatte (2012), they pointed out that these loss estimations do not take into consideration of permanent land loss which is a critical effect from SLR. Also, field survey and some important information at district level are required to complete the task of loss estimation. In order to handle with data scarcity, this study consider the impacts of land losses based on land valuation as the preliminary direct loss in three districts: Thatta, Sujwal, and Karachi. In order to compute estimated losses, information of land valuation for different areas provided by the Federal Board of Revenue (FBR) of the Pakistan government is used (available on https://fbr.gov.pk/valuation-of-immovable-properties/51147/131220). The dataset provides values of land in rupee per sq.yard for unique types of land uses at district level. According to the document, the numbers represent land values based on different types of immovable properties, including residential open plot, residential built-up property, commercial open plot, commercial built-up property, industrial open plot, industrial built-up property, and apartments. The land valuation also varies with respect to area-wise categories. With the limitation of land use information derived from satellite images, some detailed information of land use is not able to capture. Hence, the averaged values of land are deployed to quantify economic loss.

11.2 Impacts and cost estimation of sea level rise and coastal erosion

The coastal areas of Sindh province provide important socio-economic activities which influence the economic growth of Pakistan. Particularly, the industrial activities and manufacturing sector in Karachi profit the highest GDP of Sindh, followed by service and agricultural sectors respectively. With only 23% of the national population, the revenue from provincial economic activity accounts for 33% of the country’s GDP (Congressional Research Service, 2015).

Over decades, climate change have significant direct impacts Pakistan. World Bank (2020) estimated $ 3.8 billion USD for the country’s annual economic loss to cope with consequences caused by climate change. In coastal zones of the country, climate change has influenced on sea level rise and coastal erosion as evidenced in the previous section regarding a constant increase in waterlogged areas. This phenomenon has impacted on national capital losses such as physical, social, environmental, and will be continuing and threatening the economy. Thus, this section aims to estimate the economic loss in different economic archetypes based on different projected scenarios of flood caused by sea level rise and coastal erosion.

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Direct monetary loss estimation due to coastal flood caused by SLR and coastal erosion is complicated than other temporary floods. Typically, researchers usually used GDP for modelling the economic impact (Dasgupta et al., 2009; Hallegatte, 2012), and insured losses estimation or reconstruction/replacement cost coupling with average damage ratio based on vulnerability curve to calculate the economic impact on possible financial damage caused by hazards (Mazzorana et al., 2014; Ranger et al., 2011). Also, field survey and some important information at district level are required to complete the task of loss estimation. In the study of Hallegatte (2012), they pointed out that these loss estimations do not take into consideration of permanent land loss which is a critical effect from SLR. Doktycz and Abkowitz (2019) suggested using damage functions which explain the relationship of hazard parameter and the resulting financial cost, for example price of land of flooded areas.

This study considers the impacts of land losses based on land valuation as the preliminary direct loss in three districts: Thatta, Sujwal, and Karachi. In order to compute estimated losses, information of land valuation for different areas provided by the Federal Board of Revenue (FBR) of the Pakistan government is used (available on https://fbr.gov.pk/valuation-of-immovable-properties/51147/131220). The dataset provides values of land in rupee per yd^2 for unique types of land use, such as residential open plot, residential built-up property, commercial open plot, commercial built-up property, industrial open plot, industrial built-up property, and apartments. The land valuation also varies with respect to area-wise categories within different districts. With the limitation of land use information derived from coarse resolution satellite images, some detailed information of land use cannot be distinguished in correspondence with types of properties in the official document, for example open plot and land with built-up properties. Therefore, land use map is reclassified to match with rearranged land valuation information. Land valuation of each property within the unique district is averaged for calculating loss estimation and converted from Rs per yd^2 to USD per yd^2 (Table 13). For agricultural area, information of land valuation was acquired from Rs 700,000 to Rs800,000 per acre (Khan, 2018). Such values are also transformed to USD per yd^2 in order to make them comparable.

Table 13: Economic values of the selected land use classes in three districts (USD per yd^2)

Karachi				**Sujawal & Thatta**			
Residential	**Commercial**	**Industrial**	**Agricultural**	**Residential**	**Industrial**	**Commercial**	**Agricultural**
213.49	553.25	76.24	2.014	7.72	3.354	21.528	2.014

Note: adapted from The Federal Board of Revenue (FBR) of the Pakistan government

In order to calculate the economic damage value, a feasible approach was created based on two parameters, including the average of land value (LV) and the possible submerged area based on land use class of each district (A_x) as shown in equation (1).

$$\text{Estimated loss} = A_x\ (m^2) * LV \quad (1)$$

In this study, the current economic values were considered for calculation (Table 14), since if future economic scenario would have included in the approach, the calculation would have been complicated and the result would be difficult to compare.

Table 14: Estimated economic losses of land use

	Flooded areas (m)	**Agricultural**	**Residential**	**Commercial**	**Industrial**
		(USD/yd^2)			
Sujawal	0.5	1,335.125	0.00	0.00	0.00
	1	2,914.50	0.00	0.00	0.00
	1.5	9,541.26	2,671,429.50	0.00	0.00
	2	47,462.25	684,194.65	0.00	0.00
Thatta	0.5	3,647.175	8.44	0.00	3.99

	1	13,660.05	2,101,686.52	0.00	3,569,517.25
	1.5	26,275.81	9,159,494.09	200,787.66	2,590,229.65
	2	62,607.17	17,313,025.53	0.00	7,408,995.57
Karachi	0.5	16.85	161.88	0.00	73.74
	1	50.53	83,962,195.90	7,888,210.06	43,402,937.82
	1.5	168.44	559,198,788.69	489,246,424.55	72,175,339.00
	2	454.77	390,183,657.56	171,583,564.24	137,960,444.13

11.4 Estimation of Direct Non-Market Losses

According to the last population census, Sindh has more than 47 million people living in the province in 2017: 16.1 million people in Karachi, 982,138 people in Thatta, and 781,967 people in Sujawal (Pakistan Bureau of Statistics, 2017b). Due to locating in hazard-prone-areas, some villages were found deluged by sea, and affected people have leaved their place relocated to other areas (Salik et al., 2015). SLR and coastal erosion have gradually and persistently forced people's displacement in the coastal area in Sindh over decades (APDC and UNDRR, 2019). International displacement monitoring center reported that the coastal communities have moved inland due to seawater intrusion and salination resulting in losses of their livelihood and land, especially losses of agricultural land and natural resources (Braam and Kumar, 2021). This study utilizes the population data created by WorldPop (100 m resolution) (2018) and superimposes with flood extends to estimate the number of affected people for each district (Figure 36). The results from trajectory analysis indicate that more than 10 thousand people would be impacted if the sea level rises up to 0.5 m, and almost 78,000 people would be forced to resettle if sea water increases to 2 m.

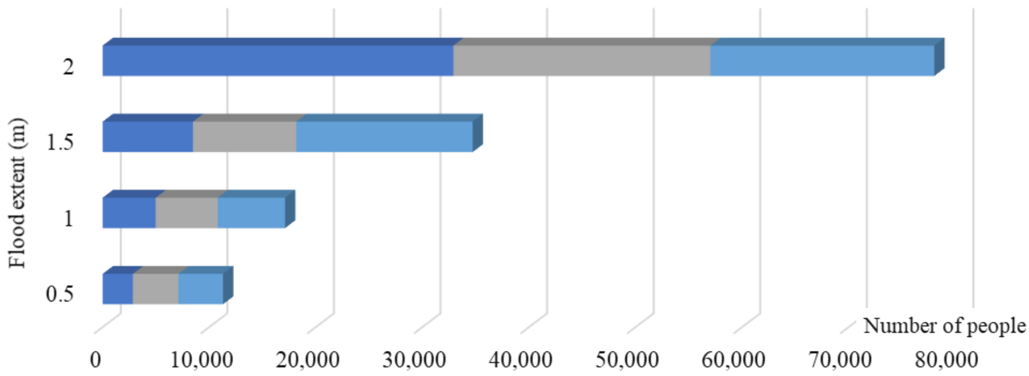


Figure 36: Number of people expected to be submerged caused by sea level rise in different flood extent scenarios

Table 15: Estimated number of affected people caused by SLR induced flood in diferent scenarios

District	Flood (m.)			
	0.5	1	1.5	2
Sujawal	2,837	4,971	8,473	32,906
Thatta	4,271	5,823	9,695	24,131
Karachi	4,186	6,316	16,550	20,994
Total	11,294	17,110	34,718	78,031

11.5 Estimation of Indirect-Market Losses

- **Indirect losses in industrial sectors**

Indirect loss of flood induced by SLR and coastal erosion come from consequences of direct impacts, for examples include business interruption, relief efforts, relocation costs, and so on. In the study area, industrial and commercial zones in Karachi have produced a massive money to stimulate the country's GDP. The port of Karachi is one of the South Asia largest seaports, and along the Karachi coast, there are two ports, a nuclear power plant, and industrial estates (MFF Pakistan, 2016). It was mentioned in the study of Memon (2016) that it will approximately cost 6 billion rupees per day if economic activities are halted by flood.

- **Indirect losses form relief efforts**

Having said that, people cannot be directly assessed as monetary value. However, referring to the report of World Bank (2015), the government of Pakistan allocates compensation budget per person affected by flood during post-disaster reconstruction period around 400 – 600 USD on average. This financial support covers reconstruction of damaged houses and livelihoods support, and the rest of the money is also used for reconstruction of critical public assets. The amount of money is considered as the direct financial cost. In order to compute such economic cost, the average budget provided by the government is deployed multiplying by the estimated number of affected people (Table 15) in different flooding scenarios, and the ranges of approximate compensation are presented in Table 16.

Table 16: Financial estimation of post-disaster expenditure (in USD)

District	Flood (m)			
	0.5	1	1.5	2
Sujawal	1,134,800-1,702,200	1,988,400 - 2,982,600	3,389,200 - 5,083,800	13,162,400 - 19,743,600
Thatta	1,708,400-2,562,600	2,329,200 - 3,493,800	3,878,000 - 5,817,000	9,652,400 - 14,478,600
Karachi	1,674,400-2,511,600	2,526,400 - 3,789,600	6,620,000 - 9,930,000	8,397,600 - 12,596,400
Total	4,517,600-6,776,400	6,844,000 - 10,266,000	13,887,200 - 20,830,800	31,212,400 - 46,818,600

- **Indirect losses in agricultural sector**

Crop loss is another major economic loss resulting from land submergence. As mentioned earlier, agricultural sector has substantially contributed to the nation’s GDP. According to literature reviews and visual interpretation of satellite images, cotton is a dominant crop in the affected areas (CIMMYT-Pakistan, 2020). Thus, the price of cotton and the average yield per acre published by Agricultural Statistics of Pakistan are applied for estimating the direct economic loss of the agricultural sector-(Pakistan Bureau of Statistics, 2017a). The average yield of cotton of the Sindh province in 2019-2020 is obtained, i.e., 28 maunds per acre, and the average price per acre was 7,000 Rs per 40 kg (Agriculture Marketing Information Service, 2020; Wagan et al., 2016). The estimated economic losses of the agriculture outputs in the flooded areas per year are presented in Table 17.

Table 17: Indirect economic losses in agricultural sector per year (USD)

District	Flood (m)	Agricultural areas (acre)	Estimated yield Losses (kg)	Estimated economic loss (USD)

Sujawal	0.5	202.626	226,941.23	516,291.30
	1	442.318	495,396.10	1,127,026.14
	1.5	1,448.035	1,621,799.54	3,689,593.94
	2	7,203.111	8,067,484.04	18,353,526.19
Thatta	0.5	553.515	619,937.02	1,410,356.73
	1	2,004.022	2,244,504.14	5,106,246.91
	1.5	3,854.838	4,317,418.56	9,822,127.22
	2	9,184.893	10,287,079.99	23,403,106.98
Karachi	0.5	2.471	2,767.58	6,296.24
	1	7.413	8,302.73	18,888.71
	1.5	24.711	27,675.76	62,962.35
	2	66.718	74,724.55	169,998.36

11.6 Intangible losses

Quantification of intangible losses is difficultly performed, because it involves many subjective nature of the variables which make it is hard to consider as monetary aspects, for example degradation of natural resources, people health, and so on (Doktycz and Abkowitz, 2019). Considering ecosystems and environmental perspectives, rising sea level and coastal erosion have changed the environmental systems which have impacted on natural capital in many aspects.

11.6.1 Natural capitals

- **Mangrove forests**

Mangrove forests provide a rich ecosystem such as natural and marine biodiversity. In coastal areas of Sindh province, mangroves have produced fuel and fodder for farm animals (MFF Pakistan, 2016). Although they are salt tolerant plants which can survive under salty soil condition in the areas where water meets the seawater, coastal erosions and deposition of sediments alter the natural processes, e.g., river flow and wave action, which decrease the development of mudflat. These changes reduce the opportunity of mangrove to grow up. Regarding the section 5.3, a significant decrease in mangrove areas has been observed over 20 years.

The Pakistan's government invested in planting mangrove trees in Sindh to lessen the provocation of salt intrusion and coastal erosion (International The News, 2020). This implementation can be considered as indirect cost, since the government have to allocate the budgets for increasing the number of mangrove areas. Having said that, such measures have built natural barriers to the coast which would save a huge budget per year in flood impacts (Menéndez et al., 2020). Moreover, mangrove restoration would boost up commercial marine species and that supports local economies. The report from Earth security (2020) stated that mangrove restoration in Pakistan led to doubled fishermen's income per year due to an increasing number of shrimp in the sea. In contrast, deterioration of mangrove forests leads to less quantity and quality of marine life.

- **Saline area**

Saltwater is one of the consequences from SLR. The sea level rise allows saltwater to enter inland and upstream into the rivers and wetlands, which jeopardize aquatic habitats and life on land. Considering effects of saltwater intrusion, increased salinity reduces the quality of freshwater supplies to the transitional zone along the coastal areas. Brackish water causes economical and health problems in the coastal regions. The accessibility of clean water for people's consumption is decreased. The salt water infiltrates to the ground water column resulting in severe impacts on the quality of drinking water and agricultural waters (Rabbani et al., 2008). The recent study found around 25 acres of farmland unproductive due to the intrusion of seawater (Lozoya et al., 2011).

Natural water in lower Sindh especially deltaic region is highly saline, especially Sujawal and Tahtta districts (Ali, 2020; Rasul et al., 2012). In agricultural zones, the saline water has posed a problem on deterioration of soil fertility, and this issue has brought challenges to farmers not to have potential crop productivities (Solangi et al., 2019). Currently, 30% of the irrigated agricultural lands suffer from salinity, particularly in the dry season cropping activities are hardly carried out because of salt visible on land surface (Shaikh, 2020). Likewise, there are correlations between fisheries and seawater intrusion. Breeding grounds for newborn shrimps and fish have been ruined. The impacts have also escalated on livestock production and business, as the number of in livestock has been decreased over years due to insufficient food and fodder (Ali, 2020; Jagirani et al., 2021).

11.6.2 Social capital

In Pakistan, 10% of the country's population are living by the seas, and rising sea level and coastal erosion have led to huge impacts on people (Ajani and van der Geest, 2021). People tend to move further inland when their lands have become permanently unproductive, because farming and fishery are the backbone of household economy (Ajani and van der Geest, 2021; Braam and Kumar, 2021). From the past, almost a million people has been forced to migrate to other areas in the search of sufficient food and livelihood. Nonetheless, affected people have lost livelihood and property; therefore, financial constraints have limited them to move to the mainland. The affected people still chose to live in rural areas, isolated and scattered settlements, which has suffered from insufficient basic infrastructures and facilities. These issues have led to poverty and illiteracy (Ajani and van der Geest, 2021; Tahir, 2020; Werner and Simmons, 2009). Moreover, seawater intrusion has degraded water quality which is a source of water-borne-diseases, e.g., malaria, cholera, and diarrhea (Babar et al., 2021; Rabbani et al., 2008).

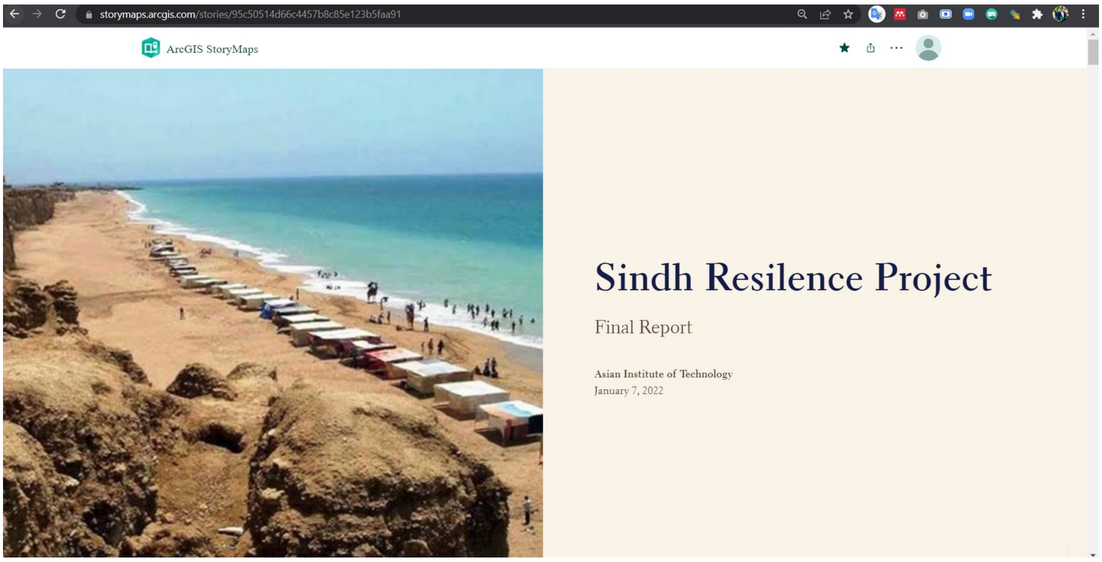
12 SAMPLE VISUALIZATION OF THE RISK PROFILE IN ESRI STORY MAP

ArcGIS story map is an open-source platform where users can easily share their final products, i.e., Maps/Graphs/Story, etc., with the world.

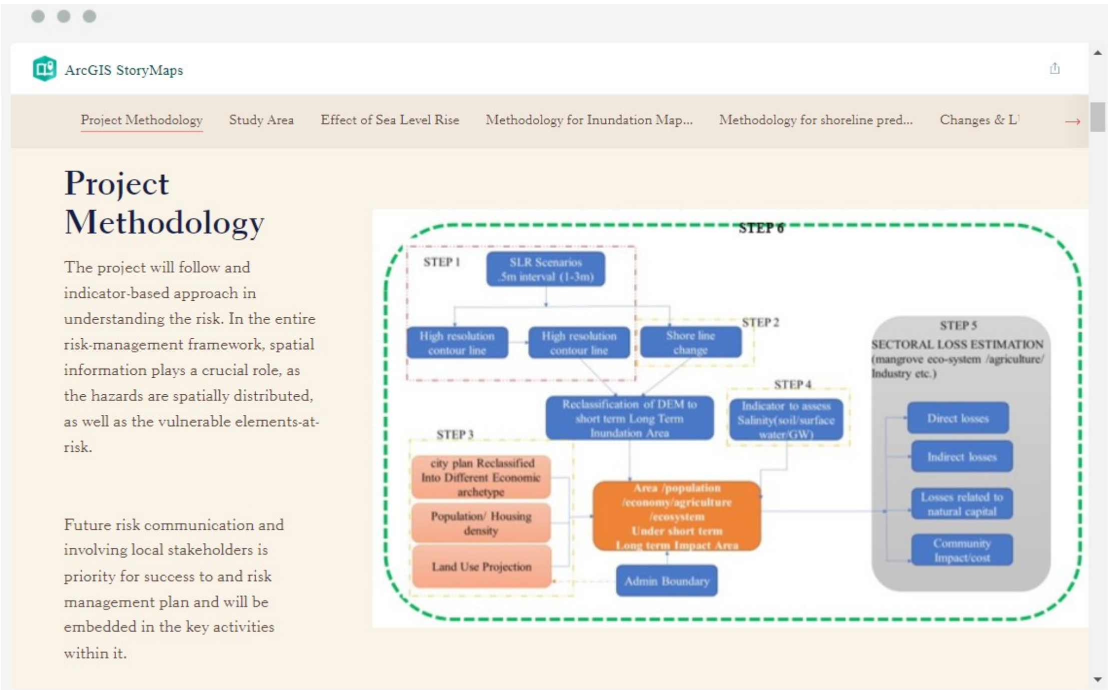
- It is a web-based application that enables us to share narrative text and other multimedia content published and shared with our URL.
- It is the latest and most versatile place-based storytelling tool.
- Stories can include maps, narrative text, lists, images, videos, embedded items, and other media.

In this current project, all of the key outputs have been published in the ArcGIS story map so that the users can easily access the maps, graphs, and stories of this project.

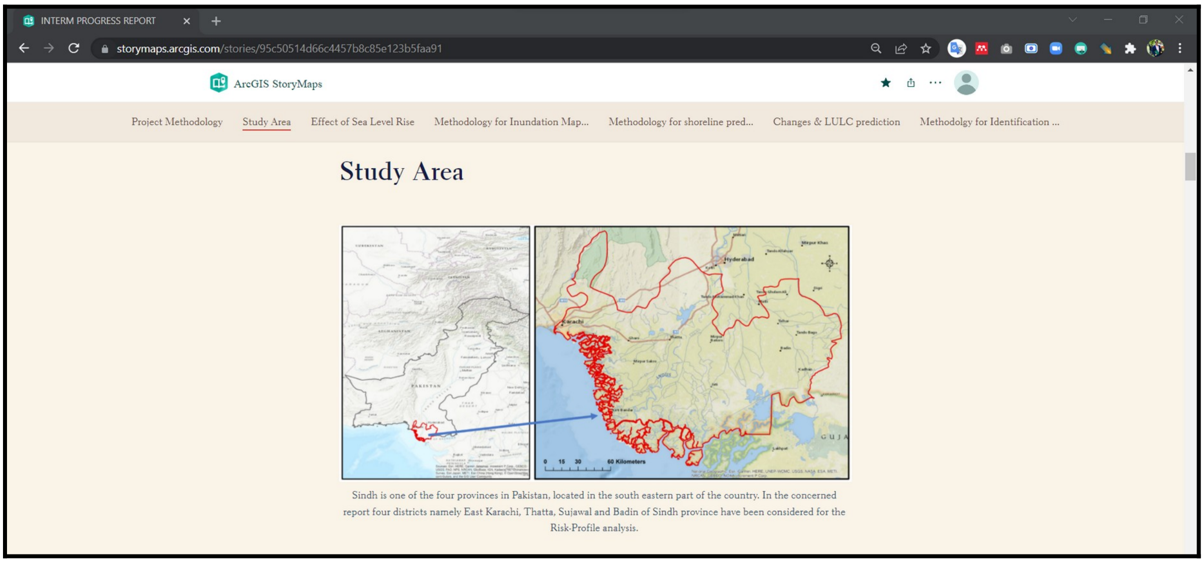
Using the ArcGIS story map, a unique page has been created for the project. It gives a glance at all the sections present in the story.



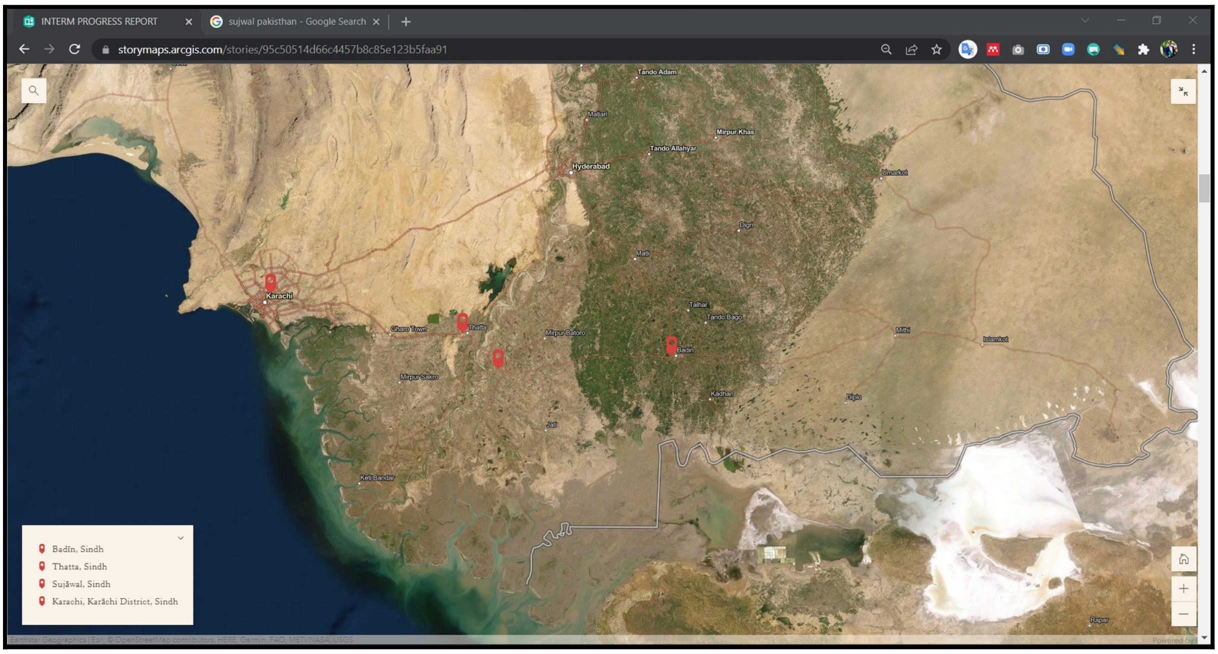
The First tab in the story map will explain the overall methodology of the project.



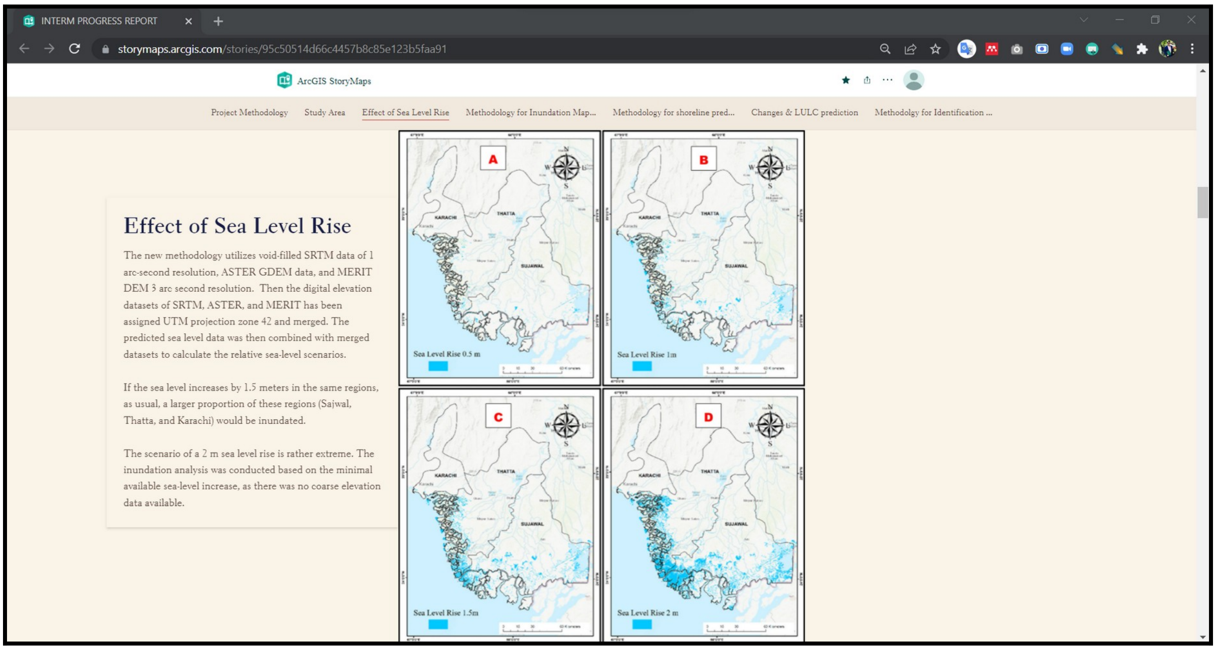
The study area map will be displayed alongside ahybrid base map with all the four district points covering the study area in the second tab.



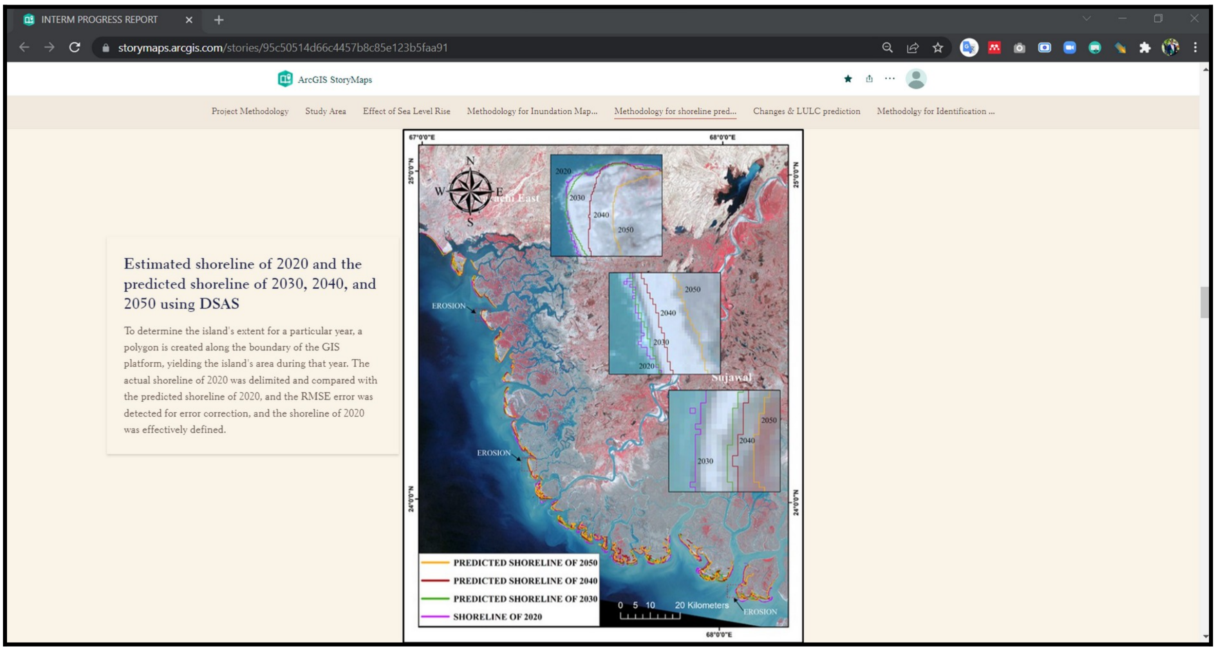
Each point in the above image represents a district present in the study area.



In the effect of the sea-level rise tab, four scenarios has been applied to see the effect of sea-level rise at different levels (0.5m, 1m, 1.5m, 2m). The scenario of a 2 m sea level rise is rather extreme. The inundation analysis was conducted based on the minimal available sea-level increase, as there was no coarse elevation data available.

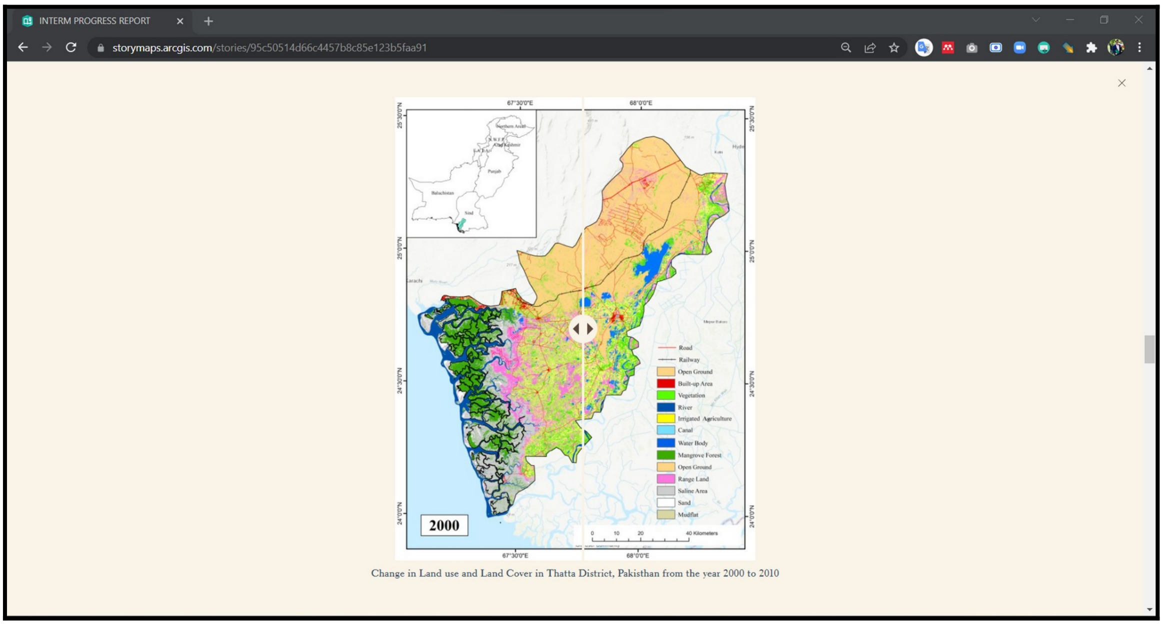


Changing coastline, estimation of erosion, and future projection of the coastlines have been made.



12.1 LULC Detection

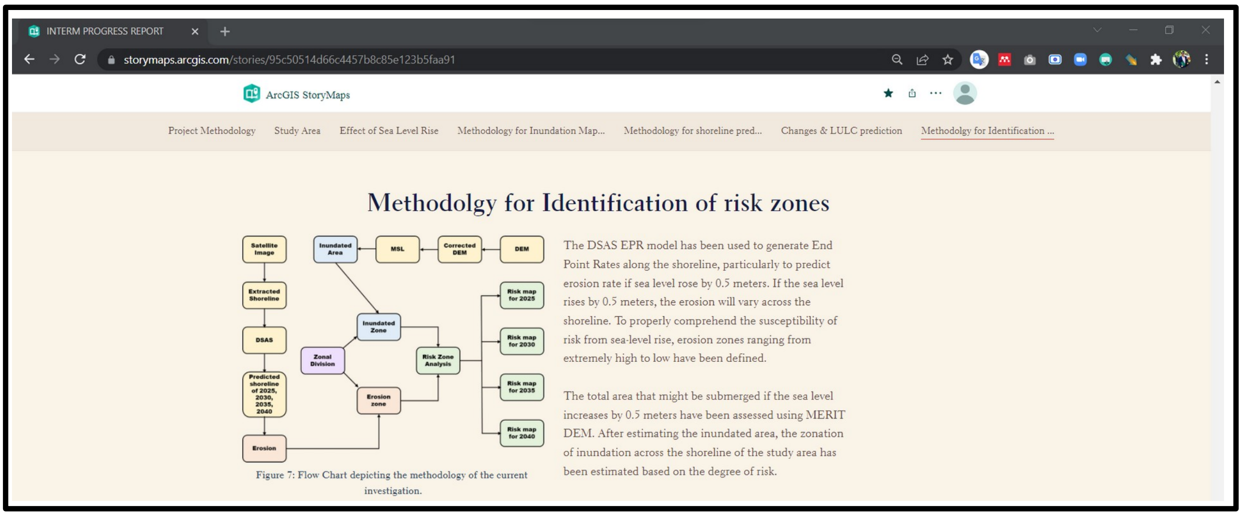
Land Use and Land Cover (LULC) change in the four districts for the past 20 years has been assessed using LANDSAT data. An object-based classification approach was taken in this research, and employing Support Vector Machine (SVM) and Random Forest (RF) algorithms, separate classes, were obtained in each district. Change detection analysis was carried out to demonstrate the apparent changes in land use for the past two decades.



Also, to compare the images more elegantly; comparison was done with two images side by side. In the LULC tab, two different timelines were compared for all four districts in the project study area.

12.2 Methodology for Identifying Risk Zones

At first, the DSAS EPR model was used to generate End Point Rates along the shoreline, particularly to predict erosion rate if sea level rose by 0.5 meters. If the sea level rises by 0.5 meters, the erosion will vary across the shoreline. Thus, it has been segmented into three zones (very high, high, and low) to indicate the range of vulnerability to risk. To properly comprehend the susceptibility of risk from sea-level rise, erosion zones ranging from extremely high to low have been defined.



The last tab can find the flowchart image, which explains the methodology followed for identifying the risk zones.

Limitations:

- A licensed version will be needed to import the work from ArcGIS to story maps.
- Sharing the data between the platforms or other web GIS platforms is impossible.
- Query building is also not available in the free version.

Hence, an extension of this existing project could be done to shift it to web GIS platforms for next-generation interactive platform creation.

13 COASTAL RISK MANAGEMENT PLAN (CRMP)

It is evident that the world's climate is changing, the magnitude of changes and the full scale of impacts remain unclear. Risk management approaches that use quantitative and/or qualitative techniques and information to describe risks are useful where there is uncertainty about the likelihood of an occurrence, and also in assessing the consequences of such an occurrence. The coastal zone is particularly vulnerable to the impacts of natural hazards such as storm surge flooding and erosion.

The firsthand risk profile of the coastal areas of Pakistan emphasizes climate induced hazards and its associated impacts. Various future scenarios also have been predicted for the sea-level rise and associated inundation. Low-lying coastal areas in Pakistan are especially vulnerable to storm-surge flooding and will experience a more significant level of flooding as a result of rising sea levels. Erosion is the process of the gradual wearing a way of land by water, wind and general weather conditions. Coastal landforms, particularly "soft" shores such as sandy, muddy, clayey and gravelly coasts are mobile and dynamic environments. As such, the normal cut-and-fill erosion cycle of shorelines will tend towards progressive erosion as a result of sea-level rise.

13.1 Purpose and Overview of CRMP

This report provides guidance for developing Risk Management Plans in the coastal zone of Pakistan. It is designed to assist with considering risks to specific assets, or discrete local areas where a number of particular assets at risk occur together, and then to identify realistic and effective options for how to respond to those risks. Climate change and sea-level rise will also exacerbate these hazards in ways that will increase damage to assets and values within the coastal zone.

The risk management approach, authorities responsible for local level planning and management of coastal zones will be able to ensure that the risks posed by climate change and associated sea-level rise are managed appropriately. Risk is generally defined as a combination of an exposure to a hazard, the likelihood of an occurrence, and a consequence of that occurrence.

In all risk management planning, it is recommended that an initial risk assessment process is undertaken to broadly identify what risks are likely in which areas. Following this initial assessment, detailed planning can be undertaken. During the development of a Risk Management Plan, guidance from relevant experts is highly recommended. Asset managers, engineers, coastal geomorphologists and sea-level rise experts will all be able to provide relevant expertise to the development of a soundly based plan.

Coastal storms, sea level rise and flooding have caused and will continue to cause significant impacts across the coastal areas of Pakistan and endanger the security of people and their livelihoods. Present macro-scale risk profile study of the three selected coastal districts of Pakistan reflects the need of holistic risk management planning and DRR interventions, which can be separated into three categories: prevention, mitigation and preparedness measures.

13.2 Identification of the Risk Level for CRMP

The Population growth and climate change lead to increased risk in coastal areas in Pakistan. The IPCC AR5 expresses confidence in the technical feasibility of adaptation measures but indicates that these measures need to be ecosystem-based to incorporate existing ecological and natural values, as well as maximize spatial efficiency to allow for multiple uses. At the same time, adaptation to coastal hazards is influenced to a large degree by national, regional, historical, cultural, socio-economic, institutional, political and geographical factors. This presents a challenge which requires a more dynamic representation of the evolution of risk as well as approaches and metrics. As the investment level in coastal areas plays an important role in the selection and effectiveness of DRR measures, coastal development necessitates that DRR strategies are adjusted to adapt to these changes. The expectation is that DRR strategies which depend heavily on preparedness and some mitigation measures will shift to more preventive measures as the level of coastal development increases.

The Coastal Risk Management Plan (CRMP) for Pakistan proposed in this report after an initial risk profile development for sea-level rise and coastal erosion. It is important to have an understanding of the broad range of hazards, and the assets and values at risk in a coastal area of Pakistan before specific management plans are developed.

Wherever possible, risk management plans for individual assets or values should be undertaken in a manner that is consistent with the approaches taken elsewhere by the managing authority.

However, a systemic methodology needs to be co-developed through the multi-stakeholder approach for Template and Guidelines to develop a risk management plan for individual assets or local areas, with clear actions for how risks will be managed and treated into the future.

The Template for the Coastal Risk Management Plan (CRMP) should be structured to follow the National and Provincial level guidelines, frameworks and legislations of Pakistan for Disaster Risk Management, and is guided by the following simple questions:

- ✓ What is the risk?
- ✓ What is the future scenario of the risk?
- ✓ What is the impact of not treating the risk?
- ✓ Should the risk be treated?
- ✓ Which treatments to use?
- ✓ Which plan for the risk minimization will be suitable for the region?

13.3 Risk Management Process

The risk-management process is a living process, whose documents are intended to be maintained throughout design and development and the product life cycle. Risk management is a process consisting of well-defined steps that, when taken in sequence, support better decision-making by contributing to a greater insight into risks and their impacts. It includes elements such as risk identification, assessment, mitigation, elimination, and communication (Figure 37).

Following template for risk level identification will be useful for the Coastal risk management planning process as a guiding document,

Coastal Risk level	**Risk identification / Mitigation Measures**
CR1	Intolerable. Risk is unacceptable and must be reduced through extensive mitigation, prevention and adaptation activities as corrective action required. Full evaluation and investigation must be conducted to a depth sufficient to attempt to determine root cause to implement full corrective action. Field correction: If through the course of the evaluation, risk analysis, or investigation, a re-assessment of the specific risk for an element to be required.
CR2	Risk is unacceptable and should be reduced as low as reasonably practicable; technical practicability is balanced against risks/benefits. Risk is reduced through extensive effort with substantial corrective action activity as mitigation, prevention and adaptation to be performed. Evaluation must be conducted. Investigations must be performed to determine appropriate mitigation activities. Field correction: If through the course of the evaluation, risk analysis, or investigation, a re-assessment of the specific risk for an element to be required.
CR3	Risk is marginally acceptable. Technical and economic factors are balanced against risks/benefits. Risk may be reduced through reasonable corrective action activity. Evaluation must be performed. Results of the evaluation along with any other available information, such as available statistical information, will be

Coastal Risk level	Risk identification / Mitigation Measures
	used to determine if an investigation is required. Field correction: If through the course of the evaluation, risk analysis, or investigation, a broad re-assessment of the overall risk to be required.
CR4	Evaluation is performed. The event is generally acceptable. Further risk reduction, via an investigation and/or corrective action activity in terms of mitigation, prevention and adaptation, is based upon the discretion of the local / provincial govt. Include data in appropriate quality system and designated databases. Field correction: For risks not affecting community and local systems' safety, generally no further assessment is required.

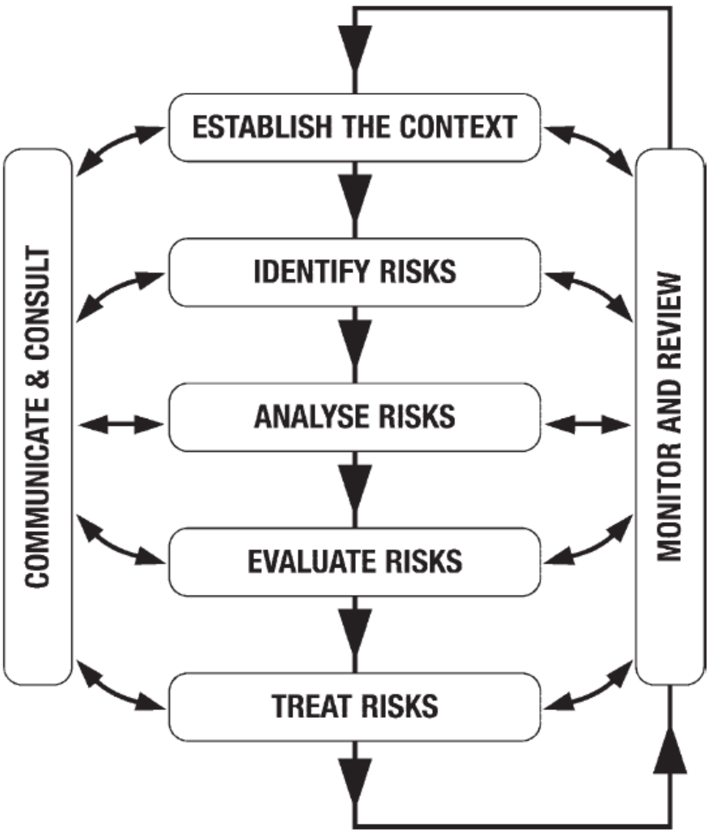


Figure 37: The Risk Management Process

(Source: Emergency Management Australia 2004 *Emergency Management in Australia: Concepts and Principles*)

13.4 Excerpts from SAARC Key Recommendations for CRMP

A. Regional Cooperation

- A common protocol should be developed at regional level addressing the coastal and marine risks for Arabian Sea countries
- Promote integrated coastal zone management strategies with regional perspectives for sustainable development of the coasts.
- Mainstreaming of coastal and marine risk reduction strategies in the coastal zone management plans;
- Engage stakeholders and secure the commitment and political support from the respective governments
- Enforce national legislation to provide an institutional and legal basis for coastal management with the regional perspectives
- Regional agreements on sharing the data along the coasts for the cyclone and storm surge warning systems along the coast.

B. Enhancing the Capacities and Effectiveness of Early Warning Systems of Coastal Hazard

- Enhance the quality of the forecast of storms, tsunami, coastal floods and storm surge in line with the best practices forecast capacities in the region and the rest of the world.
- Mapping coastal risks at provinces, districts and critical zones for proactive prevention, disaster risk assessment and policy formulation.

C. Mitigation

1) Structural and non-structural measures (shelters, Coastal Resource Management etc.)

- Sustainable and integrated land use planning to minimize exposure to various coastal hazards
- Identifying evacuation zones and protecting evacuation routes to identified safe areas
- Identifying buildings for approved vertical evacuation
- Reduce exposure of critical infrastructure to risk including possible relocation

- Sitting, design and construction of building and infrastructure considers risks from coastal hazards and protects sensitive coastal habitats
- Management of sensitive coastal resources and natural protective features to reduce risk (eg. Mangroves, coral reefs, etc)
- Redevelopment policies and systems in place to guidepost reconstruction away from high-risk areas

2) *Enforcement of construction guidelines and building codes*

- Commitment to promote best practice guidelines and adoption of model building codes
- Land use planning and building codes

D. Information sharing regionally

- Establish data infrastructure and mechanisms for information sharing on coastal risk reduction,
- Promote and encourage – (i) scientist to scientist interactions & information sharing; (ii) institution to institution partnerships, and (iii) government to government cooperation both on bilateral and regional level facilitating R&D, better operational strategies, more effective S&T products and services in support of reducing coastal risks along the coast
- Organize the working groups on risk assessment, inundation modeling and interoperable warning system issues through regional cooperation.

E. Knowledge and awareness

- Develop knowledge and awareness outreach materials
- Establish system for knowledge management and advocacy programmes
- Incorporate awareness and education about coastal hazards into school curricula at various levels in formal and non-formal (local, religious, social)
- Collect and share best practice examples
- Establish regional coastal hazard education programmes
- Promote research to support improved Mitigation, Preparation and Response addressing the coastal risks

- Case study documentation and harnessing the untapped indigenous knowledge available in coastal regions of South Asia.

14 MULTI-HAZARD RISK ASSESSMENT OF COASTAL CRITICAL INFRASTRUCTURE FOR CRMP IN PAKISTAN

Several recent events have highlighted the potential catastrophic impact on critical infrastructures induced by natural hazards that pose serious consequences from health impacts. environmental degradation to economic loss due to damage to assets and business interruption. For major earthquakes, floods and tsunamis, there is a high risk of multiple and simultaneous impacts at a single infrastructure or to several infrastructures over a potentially large area. Multi-hazard risk assessment of coastal critical infrastructure is an effort to identify key risks of important infrastructure of a country that are prone to different hazards. The multi-hazard risk assessment efforts for critical infrastructure involve identification of different hazards, exposure and vulnerability parameters. The multi-hazard risk assessment approach considers different probability of occurrence and intensity from hazard to hazard (Eshrati et al., 2015).

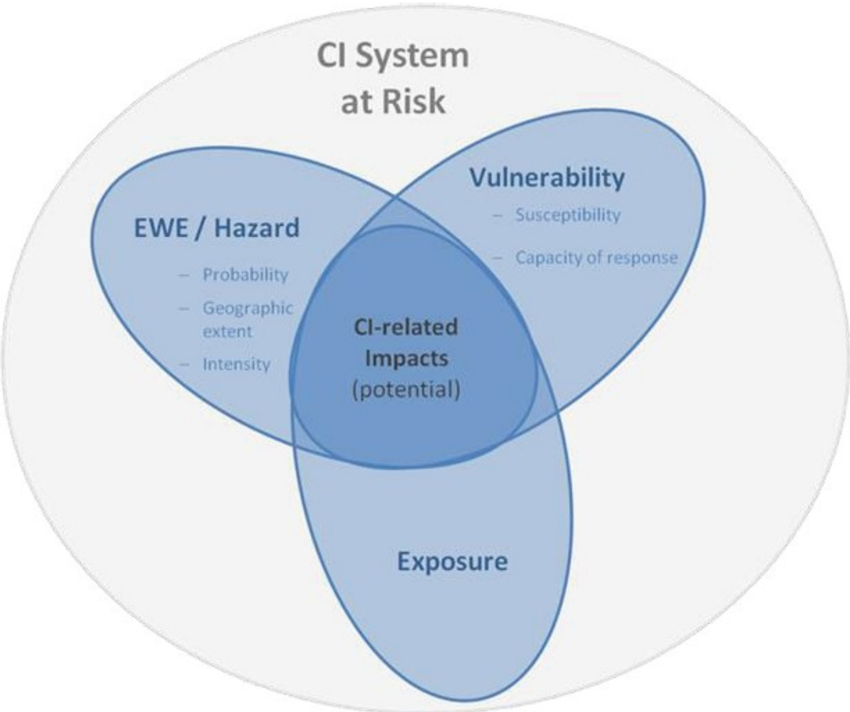


Figure 38: Figure showing critical infrastructure risk element (Source: Van Ruiten et al., 2016)

Strengthening the resilience of infrastructure systems is important for society's long-term sustainability. Critical infrastructures are vulnerable in a variety of ways such as vulnerability, complexity, connection, and interdependence of systems, inadequate capacity, management incompetence, community dependency, and ageing infrastructure are all major concerns. Interdependence causes damage cascades or domino effects, which are major disaster vulnerabilities. A disaster's effects cascade across a highly interdependent system, resulting in primary to tertiary level interventions (Figure 38).

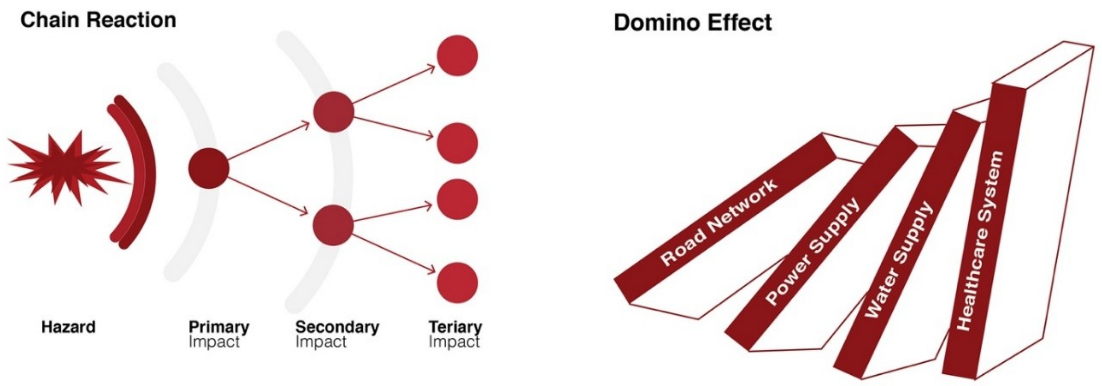


Figure 39: Complexity and Interdependence Induced Vulnerabilities in Critical Infrastructures System (Source: Azevedo de Almeida)

Coastal critical infrastructures such as ports, marinas, harbors, and airports are at risk of damage due to natural hazards and man-made disasters. In terms of function, importance, and potential for harm, the vital infrastructure along the coast is diverse. Pakistan at country level risk management plan need to consider on how to incorporate threats into siting decisions for coastal infrastructure resilience or a new coastal infrastructure as part of their planning to protect coastal critical infrastructure (Peterson, 2019). For instance, transportation infrastructure, is considered a coastal critical infrastructure due to its definite importance to society's day-to-day activities. An accessible transportation network is critical to society's and economy's continued function. Roads, highways, trains, ports, and airports are all part of a complex infrastructure that allows goods and companies to shift around (Testa et al., 2015).

15 WAY FORWARD

It was found that socio-cultural as well as historical perspectives play a critical role in the design and implementation of DRR strategies, especially on the regional level. By effectively taking socio-cultural and historical considerations into account, it is expected that DRR strategies could be significantly improved by adapting to local perceptions of risk and helping to increase understanding and acceptance of DRR measures (Martinez et al. 2014). This can be done by communicating in ways that are oriented towards local and personal values and priorities, as well as through multi-level communication and focusing on inclusiveness of all stakeholders, to enable people to make decisions that are well informed and thus leading to outcomes that are agreeable to broad group of stakeholders. Including local stakeholders as well as end users in the decision-making process also provides an opportunity to influence the risk perception (the subjective judgement that people make about the characteristics and severity of a risk (Rohrmann 2008)) of inhabitants of an area at risk as well as enable more locally responsible DRR planning and implementation.

Long-term planning and clear responsibilities facilitate successful DRR management and implementation of measures. Therefore, a re-evaluation of coastal DRR strategies is needed and a new mix of prevention, mitigation, preparedness and early response measures must be developed and new partnerships with authorities must be built to adopt and embrace them. The formulation and implementation of DRR strategies and policies are significantly influenced by political will and economic means, and that national strategies are often implemented to varying degrees at local levels. DRR responsibilities (i.e., governance level or institution) are often blurred and depend on the level of strategy formulation and implementation. At the same time, management approaches such as ICZM often correspond with national DRR implementation at local levels. As ICZM focuses on the participation of multiple stakeholders for the management of coastal zones, this suggests that participatory approaches built around local learning and action alliances between institutional actors and local societies can enable national objectives to be realized at local levels.

The use of ecosystem-based measures, potentially combined with engineered solutions, can provide win-win solutions to meet risk management objectives as well as climate adaptation and nature conservation goals. Research affirms that local problems are best dealt with by local and regional authorities and experts, and best solved using a common scientific and technological evidence base and need to be grounded in the specific historical and socio-cultural realities in order to be sustainable and accepted.

Following recommendations are being listed in line with the outcomes of current risk assessment process of Pakistan coast for sea-level rise and coastal erosion hazards and its associate impacts,

- Risk informed decision making through the effective risk governance mechanism
- Understanding the hazard potential of the coastal communities
- Pakistan Coastal Resilience Index (PCRI) development through the appropriate assessment and local level case studies would be helpful for short, medium and long-term planning and development of the coastal areas of Pakistan.
- Multi-hazard Risk Indexing of Coastal Critical Infrastructure for future investment planning
- Development of Indus River delta system risk characterization considering the natural and anthropogenic stressors
- Community-based risk information system development to improve adaptation for coastal vulnerability for near-real-time dynamic risk mapping and decision-making using cloud sourcing, Google Earth Engine and AI /ML technology.

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