NATIONAL COASTAL CLIMATE CHANGE VULNERABILITY ASSESSMENT

Vulnerability Indices

Technical Report

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Contributors to this work

CSIR: Dr Melanie Lück-Vogel, Dr Lara Van Niekerk, Gert Wessels, John April

Stellenbosch University: Dr Andre Theron, Christiaan Theron, Jessica Eichhoff, Garth Stephenson, Zani Mouton

Nelson Mandela University: Prof Janine Adams

Department for Environment, Forestry & Fisheries: Lauren Williams

Layout and design of title page

Bjorn Rothauge (Twaai Design)

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Department of Environment, Forestry & Fisheries: Potlako Khati, Alinah Mthembu, Nenekazi Jukuda, Tshepiso Monnakgotla, Ryan Peter, Sibonelo Mbanjwa

Deutsche Gesellschaft für Internationale Zusammenarbeit – GIZ: Alexa Brown

All experts, municipal, provincial and national stakeholders consulted during this process.

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Disclaimer

The information and data used for the coastal climate change vulnerability assessment project is not intended to replace the provincial work on the establishment of coastal management line and any other adaption work but rather complement any work which has been initiated. For areas where there is no data and information, the products produced from this assessment study can be used as baseline information for decision making processes.

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1 Background and Legacy of this project

1.1 Background

The National Environmental Management: Integrated Coastal Management Act (No. 24 of 2008; hereafter referred to as the ICM Act) established the legal baseline for integrated coastal and estuarine management in South Africa. However, sustainable and integrated coastal management usually means trade-offs between different usage and benefits received from coastal ecosystem services. Further, the White Paper for Sustainable Coastal Development in South Africa, 2000 under Goal C5: makes provisions for government "to plan and manage coastal development so as to avoid increasing the incidence and severity of natural hazards and to avoid exposure of people, property and economic activities to significant risk from dynamic coastal processes". Climate change with an expected increase in storm frequency and severity, as well as projected sea level rise and population increase in the coastal zone further exacerbate the expected damage to infrastructure and the vulnerability of coastal population through coastal flooding and erosion. These projections emphasize the importance of climate and global-change geared adaptation of the coast. However, the work conducted for the development of the National Coastal Management Programme from 2015 points out that there are still significant knowledge gaps related to these factors.

Further, the DEFF has embarked on a priority project to develop the coastal climate change adaptation strategy, guided by Objective 2 of the National Climate Change Adaptation Strategy: Promote the integration of climate change adaptation response into development objectives, policy, planning and implementation.

The Department of Environment, Forestry & Fisheries (DEFF) therefore approached the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) to assist with the conduction of a national coastal climate change vulnerability assessment, building on the results and data produced by previous and current related projects and activities.

The overall objective of the project is to develop a National Coastal Spatial Vulnerability Index (CoVu Index) for South Africa's coastline and estuaries from physical hazards attributable to climate change, such as sea level rise, flooding, erosion or storm events. The majority of the required input data were to be sourced from existing projects and data sources. Critical, currently non-existing data and information were to be generated in the project. This includes extreme wave run-up for 1-in-10, 1-in-30 and 1-in-50 years storms for rocky shores at a 500m (or higher) resolution and erosion lines (for 1-in-10yr, 1-in-50yr and 1-in-100yrs) for the whole coastline, generated at an appropriate resolution (depending on elevation models) and where possible.

The CoVu Indices and their individual components for flood and erosion risk were to be embedded in a Decision Support Tool (DeST). If possible, the output data and DeST were to be integrated into existing tools or platforms, such as the Oceans and Coast information Management System (OCIMS; https://www.ocims.gov.za/) which is currently being developed for DEFF and DST, and DEFF's Coastal Viewer (https://mapservice.environment.gov.za/Coastal%20Viewer/). This intervention is important for long-term planning for climate change resilience and coastal zone management in South Africa.

Figure 1 gives an overview of the related project components, flow and outputs. **This report focusses on the technical description of the CoVu Index development.** This development was preceded by a situational assessment and various stakeholder engagements to assess the data available as input, available technologies and the skill set and data requirements on side of the users. The specific outcomes of these activities are described in the Situational Assessment Report to this project (DEA, 2019).

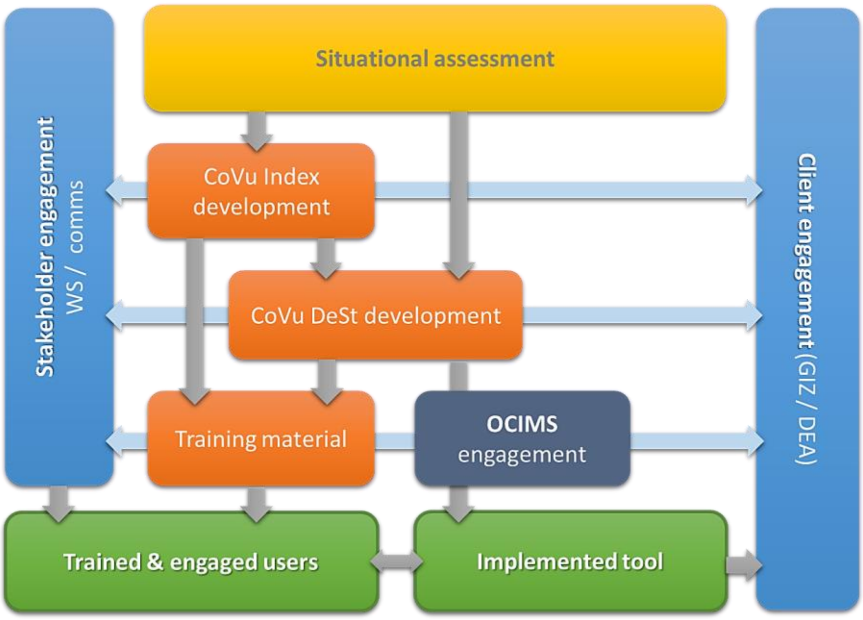

Figure 1: Schematic overview of project components, flow and outputs

The CoVu offline DeST is described in the DeST User Manual (DEFF, 2020a). Upon completion of the DeST, training workshops for key DEFF staff took place in November 2020, which will then propagate the use of the DeST and CoVu index data through a roadshow to the coastal municipalities in late 2020[1].

The envisioned outcome of this project is to provide an enhanced information base and capacity building for improved and internationally aligned sustainable coastal management and climate change adaptation in the coastal zone.

1.2 Legacy of this project

The CoVu Index development conducted in this project builds on the work conducted in the National Coastal Assessment project (NCA, 2017-2019) and the Coastal Vulnerability Index Assessment (2011-2014).

The earlier project conducted a coastal vulnerability assessment for the coast on a meso-scale, i.e. at a 500m resolution, based on Delft hydrodynamic modelling and literature based assessment methods. The assessment was conducted for all coastal areas inhabiting ports, harbours and major urban developments, i.e. for about 70% of the South African coast line. Output of the project was a modelling grid at 500m cell size with the wave run-up height for five defined storm scenarios and two future sea level rise scenarios was assigned for the nearshore, i.e. the coast line. However, while the wave height was determined, the inland inundation area in the case of these storm events was not assessed.

The NCA project aimed to assess the South African coast in terms of its physical, chemical, biological and socio-economic condition. The purpose of this geospatial desktop based assessment was to provide an interdisciplinary "status quo" of the coast as baseline for integrated management of the

[1] *As far as the Corona lockdown regulations permit.*

coast, as requested by the ICM Act (Figure 2). Intended as a baseline assessment of the current coastal condition, future climate and global change related aspects were not included.

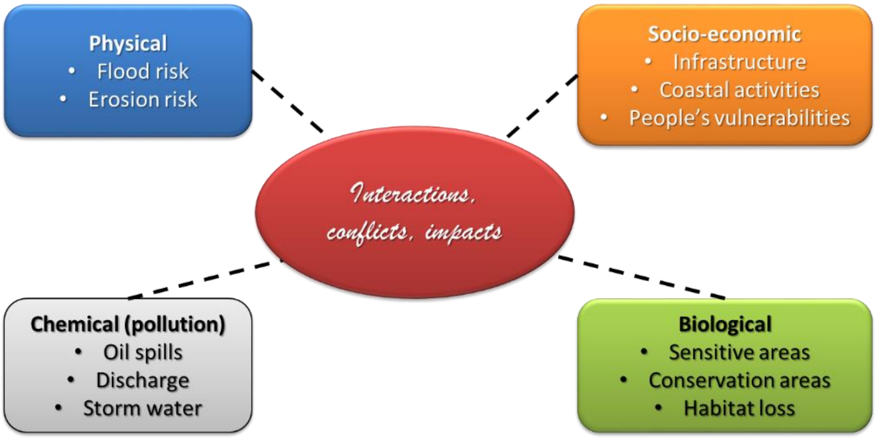

Figure 2: Schematic overview of the NCA focus areas

As this project had to be based on existing data, the physical flood and erosion assessment were conducted in a very simplistic way, based on a multi-criteria decision approach in a GIS environment. Based on seven key parameters, which were ranked using expert knowledge, a flood assessment for sandy shores and erosion assessment for rocky and sandy shores could be conducted, leading to the Physical Vulnerability Assessment version 1.0 (Figure 3). For a detailed technical description refer to the Coastal Hotspot Detection Report of the NCA project (DEFF, 2020).

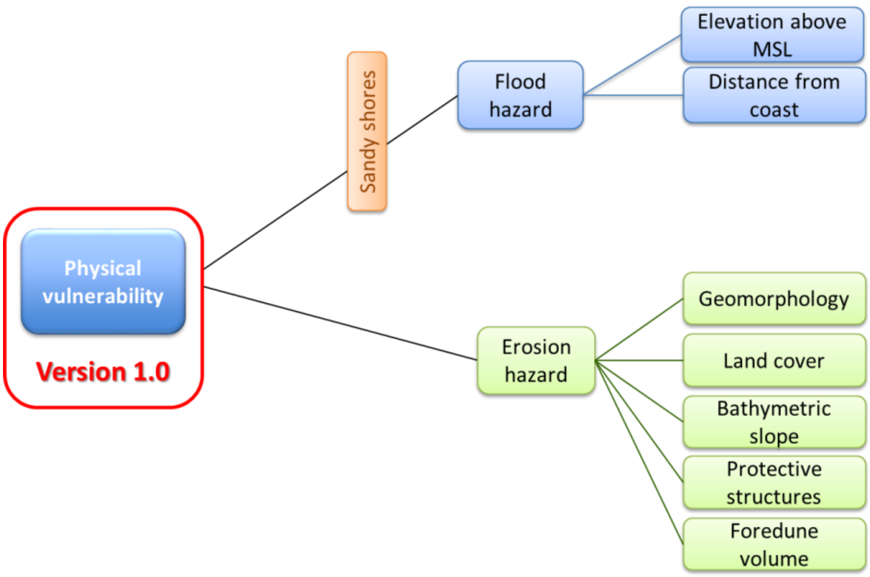

Figure 3: Coastal physical vulnerability assessment conducted in the National Coastal Assessment project.

The resulting flood and erosion layers were the first datasets which assessed the whole coast in a homogenous, methodologically consistent way that allowed for high level assessment of hotspots at risk. However, given its simplistic approach, the resulting flood and erosion layers were of limited value for actual decision making at local level. Further, given the different spatial scale and flood regime, estuaries were excluded from the NCA. With the financial aid of the GIZ, it was possible, to improve on the physical NCA layers in this project. The major aim was to include climate change, assess rocky shores with appropriate models separately from sandy shores, include wave-run up and assess estuaries in a spatially meaningful way. The result will be a physical coastal Vulnerability Index Version 2.0.

1.3 Concept of the CoVu assessment approach

The most significant change to version 1 is the distinction between short term (storm-related) coastal erosion and Sea Level Rise related coastline recession (Figure 4) in the erosion assessment. For the open shore flood assessment, the use of the Distance from coast became obsolete through the inclusion of five modelled flood scenarios and a spatially more explicit coastal inland inundation model (enhanced Bath Tub Model; Williams, 2020; Williams & Lück-Vogel, 2020).

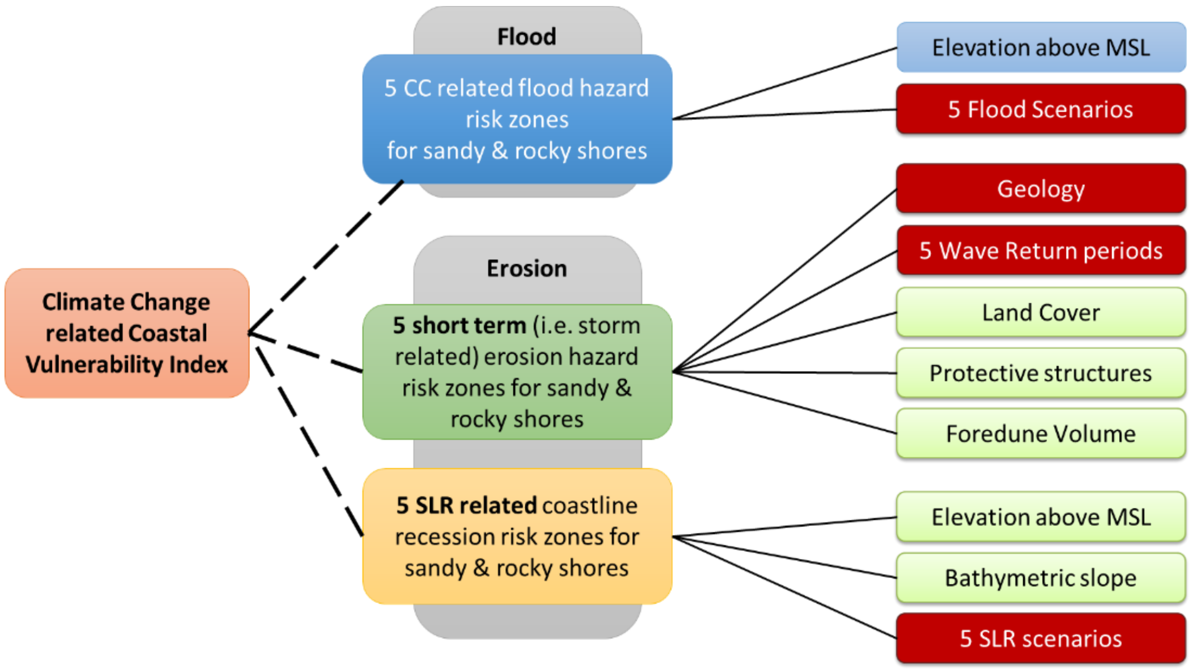

Figure 4: Coastal physical vulnerability assessment implemented in this project.

The vulnerability assessment for the estuaries is building to a large degree on existing conceptual work, such as the Estuary Ecosystem Classification (van Niekerk et al. 2020).

The technical approach for the development of the flood, short term and sea level rise related erosion indices is unpacked in the following sections. Given the different scale and mechanisms for flood and erosion in estuaries, these are described separately.

2 Key input parameters

Based on expert knowledge and past project experience, the most important environmental parameters for coastal flood and erosion assessment for this project were identified. Given their overarching importance for all indices developed, the following key parameters will be introduced in this separate section: the reference coastline used, the topographic elevation (above Mean Sea Level MSL), the assumed Sea level Rise Scenarios and the Wave Return Periods.

2.1 Reference coastline

One of the key input datasets required for this project was a reference coast line. After reviewing a number of different GIS data sets, it was decided to use the polyline vector file **National_Coast_Types.shp**, produced by Harris (2011) for this purpose. While several other spatial coastline datasets exist, this one demonstrated the closest correlation to the actual coastline when viewed against remote sensing imagery (GoogleEarth and aerial photographs). Additionally, there is an in-depth level of detail attached to it regarding the coastline type (e.g. rock cliff, boulder beach, reflective beach), which was used to inform the coastal risk assessment.

2.2 Topographic elevation

The input dataset for the inland (topographic) elevation above MSL was comprised of a number of available LiDAR datasets (Figure 5), supplemented by the Stellenbosch University Digital Elevation Model (SUDEM) where LiDAR was not available.

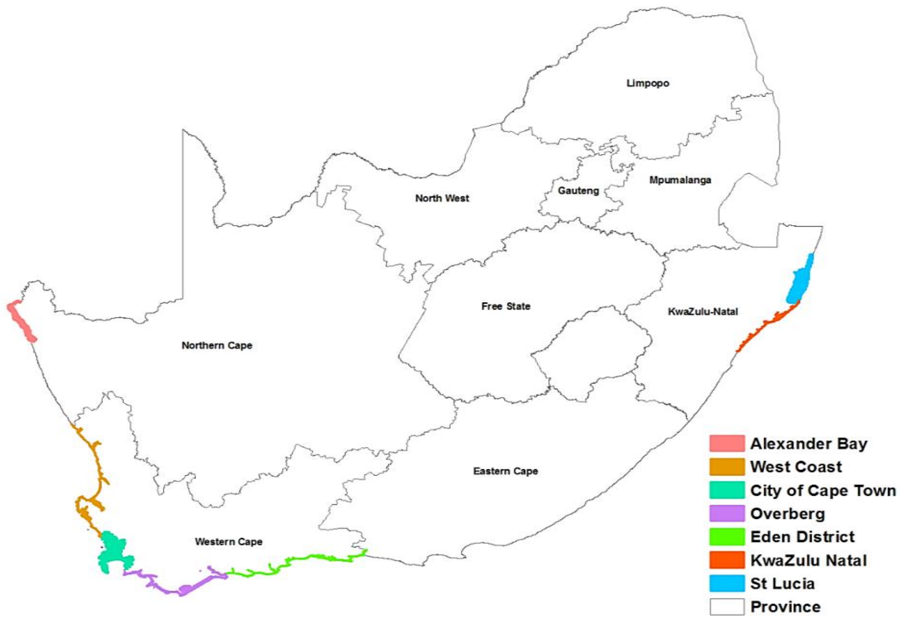

Figure 5: Areas for which LIDAR derived elevation models were used.

The LiDAR datasets were provided by ALEXCOR, Western Cape Province, City of Cape Town, KZN Province and iSimangaliso Wetland Park (usage agreements which all parties are in place). Given the variety of data sources and original purposes of use, the datasets were provided in a range of different point spacings, projections and data formats. In order to standardise the datasets, all "last return" (ground cover) elevation points were interpolated into 32-bit raster DEMs (with gaps standardised as NoData) and resampled to 5m resolution to allow for seamless fusion with the SUDEM. However, in some cases only first return data were available as input, which might cause biases in the resulting flood masks, if e.g. vegetation canopy cannot be distinguished from true elevated surface areas. While horizontal spatial detail of the original LiDAR was lost due to the downsampling, visual checks confirmed that the LiDAR-derived 5m DEMs still provided better vertical accuracy than the SUDEM.

The SUDEM was developed using a combination of algorithms and data sources. The ANUDEM (Australian National University Digital Elevation Model) algorithm was used to interpolate a DEM from corrected contours and spot heights. The resulting digital terrain model (DTM), named Level 1, was employed to identify and correct the errors (i.e. voids and spikes) in the publically-available 30m SRTM DEM. Once corrected, the SRTM DEM was fused with the Level 1 DTM using a patented algorithm which ensures that the SRTM DEM is only applied in areas with low densities of contours and spot heights (van Niekerk 2016). Although it is recognised that the SRTM DEM is not a true DTM[2], the fusion procedure reduced the effect of surface objects. To create the final coastal elevation dataset, the SUDEM was clipped to the 40m contour along the coast, and then overwritten by the downsampled LiDAR data, where available.

2.3 Sea level rise (SLR) scenarios

In their latest special report on Ocean and Cryosphere (IPCC, 2019), the likely values for global SLR until 2100 range between 0.43m (RCP2.6) and 0.84m (RCP8.5). However, the report also states that the local SLR rates vary substantially (within ±30% of the global mean sea-level rise), partly exceeding and partly staying below the global average (IPCC, 2019). This is supported by Mather et al. (2018), who state that the recorded SLR rates on South Africa's coast are usually below the IPCC-projected rates, and that the SLR rates even vary along South Africa's west and east coast.

In essence, the exact SLR rates to be expected for South Africa's coasts are unclear. The only reliable fact is that the sea levels are in fact rising. It was therefore decided to use for this project the following SLR scenarios:

Table 1: List of SLR scenarios used in the flood and SLR related erosion assessment

SLR scenario (m)	Expected by year*	Flood risk assessment	SLR related shore line recession
0.15	2030		X
0.35	2050	X	X
0.5	2070		X
1.0	2100	X	X
2.0	2200		X

**according to projections for RCP8.5 at 50%; Kopp et al. (2017).*

These values are in line with the IPCC provided scenarios and also in line with scenarios which have been used for SLR related coastal risk assessment elsewhere in South Africa and beyond. Using these scenarios will allow for better comparability between different products. Table 1 also indicates which of the five SLR scenarios were used for the coastal flood index and the SLR-related coastal long-term erosion in this project.

[2] The SRTM DEM was developed using C-band radar technology. Objects on the ground (e.g. buildings) are consequently included in the signal, which results in a digital surface model (DSM) instead of a digital terrain model (DTM).

2.4 Bathymetry

Detailed bathymetric data for the coast as input for the wave and erosion modelling was not available for this project. The nearshore bathymetry was therefore interpolated from the 15m bathymetric contour derived from the SA Nautical Charts.

2.5 Wave modelling & return periods (for 5 extreme events)

Wave modelling and wave return periods in this project were computed using numerical modelling. Numerical modelling is a methodology to resolve mathematical equations representing physical phenomena using a time-step based algorithm. Assuming that the mathematical model is well defined, the outcome of the numerical model is entirely dependent on the input data used.

For the wave modelling the Deltares SWAN (Simulating WAves Nearshore) product was used. SWAN is part of the Deltares developed Delft3D software suite and contains all the necessary tools to set up, run and analyse the model. SWAN makes use of a spectral action balance equation to solve the waves and is driven by wave boundary conditions. A bathymetry is also required and is created in conjunction with a numerical model grid.

For this study, a model resolution of at least 200m was required. To achieve this, a nested grid approach was chosen to effectively use the majority of the computational time on the area of interest, Figure 6. To generate the bathymetry for the model, available bathymetry data were interpolated to find a water depth value at each of the computational cells as seen in Figure 7.

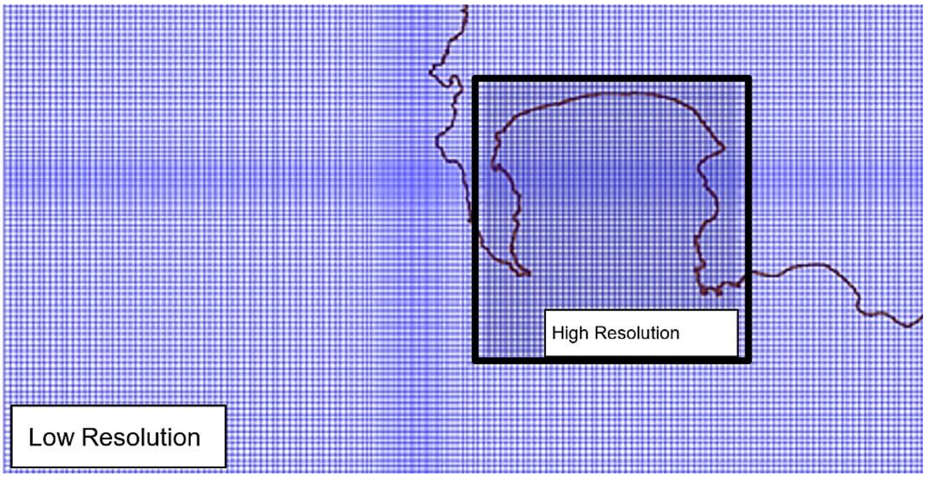

Figure 6: Example the low resolution (1 km) and high resolution (100m) computational grid used for the False Bay study

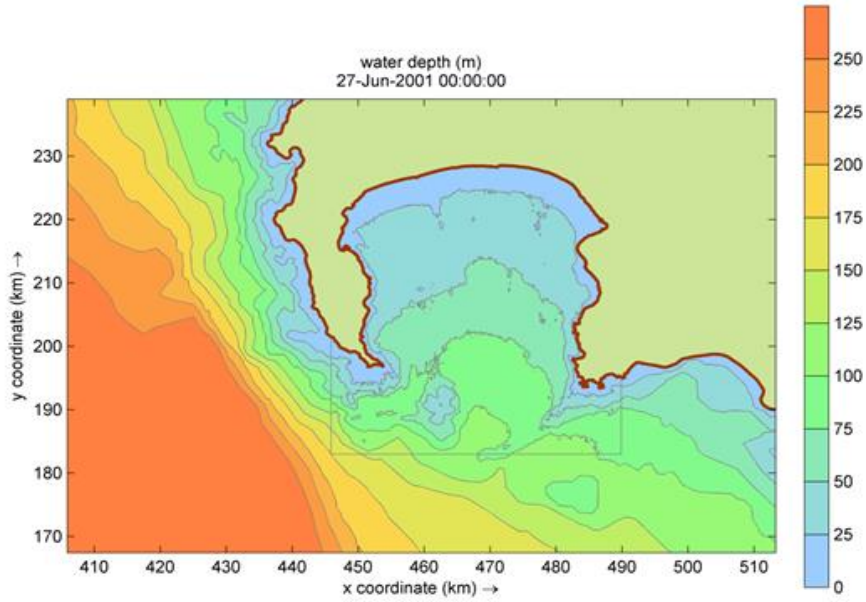

Figure 7: Bathymetry of False Bay displayed on both the 1km and 100m resolution computational grid.

To get an accurate picture of the wave climate experienced along the coastline, appropriate boundary conditions are required. This was done by analysing 15 years of the National Centre's for Environmental Prediction (NCEP) global wave model data (Figure 8). Rather than simulating all possible wave conditions, this approach provided a smaller set of realistic wave conditions specific to the area.

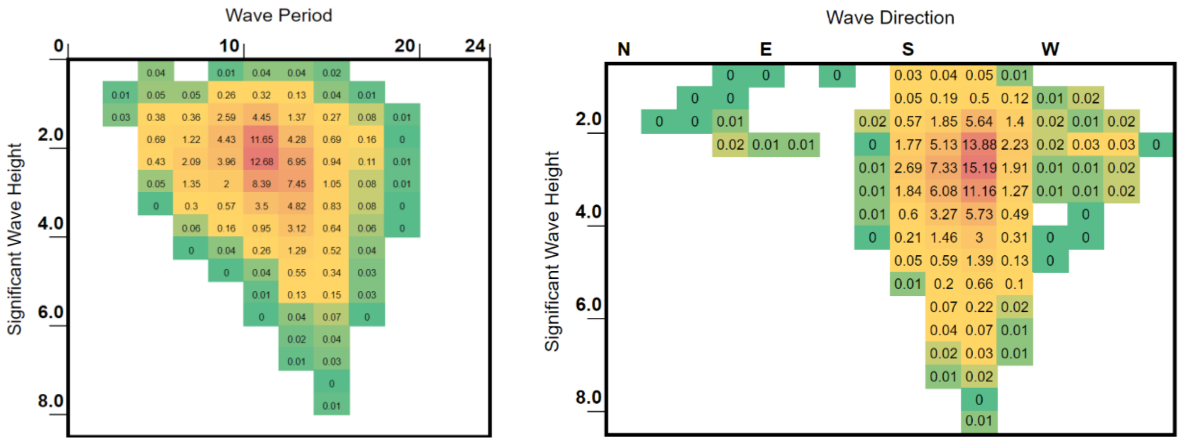

Figure 8: Analysis of 15 years of NCEP data.

With the wave data now available the wave return was calculated. This is the estimated interval between the recurrences of a specific wave height. For this calculation, it was required to get the wave output at the 15m contour, Figure 9. This lead to a database of wave output parameters at a 200m resolution on the 15 m contour for each of the conditions simulated. Before the return period was calculated at the output locations, the data were processed and the statistically improbable values were determined and excluded from the calculations. This removed all the outliers numerically introduced by the modelling process. A similar approach was followed to determine the most probable wave period and wave direction.

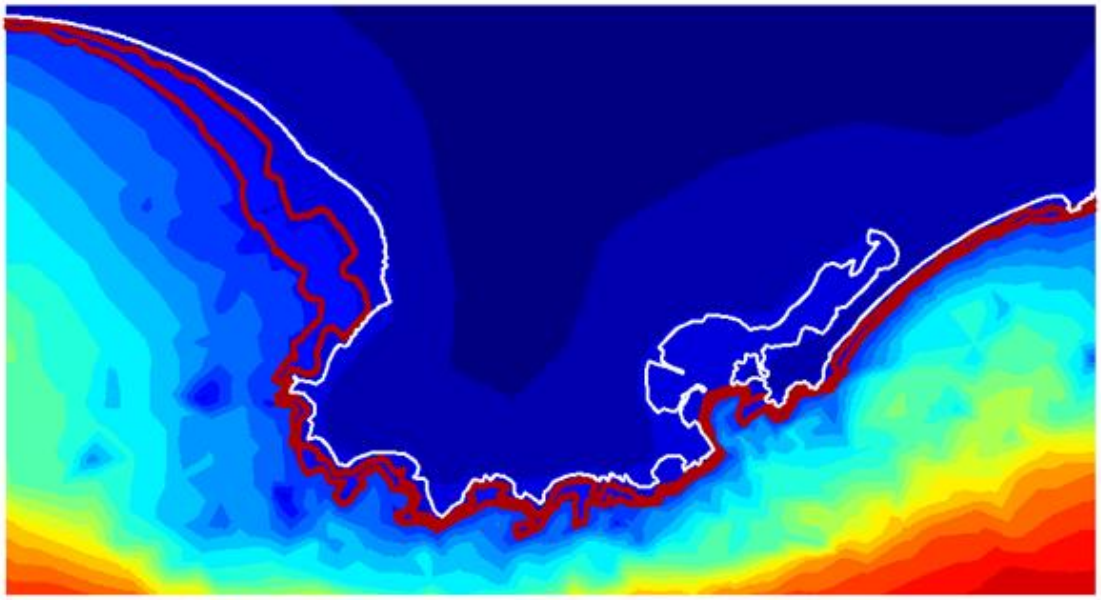

Figure 9: The 7m and 15m output locations defined for St. Helena Bay (red contours).

Finally, a peak-over-threshold method was used to select particular wave height data, and a 3-parameter Weibull distribution was fitted to the selection, Figure 10. More information on this approach can be found in the South African Coastal Vulnerability Assessment done by the CSIR for DEA (Theron et al. 2014).

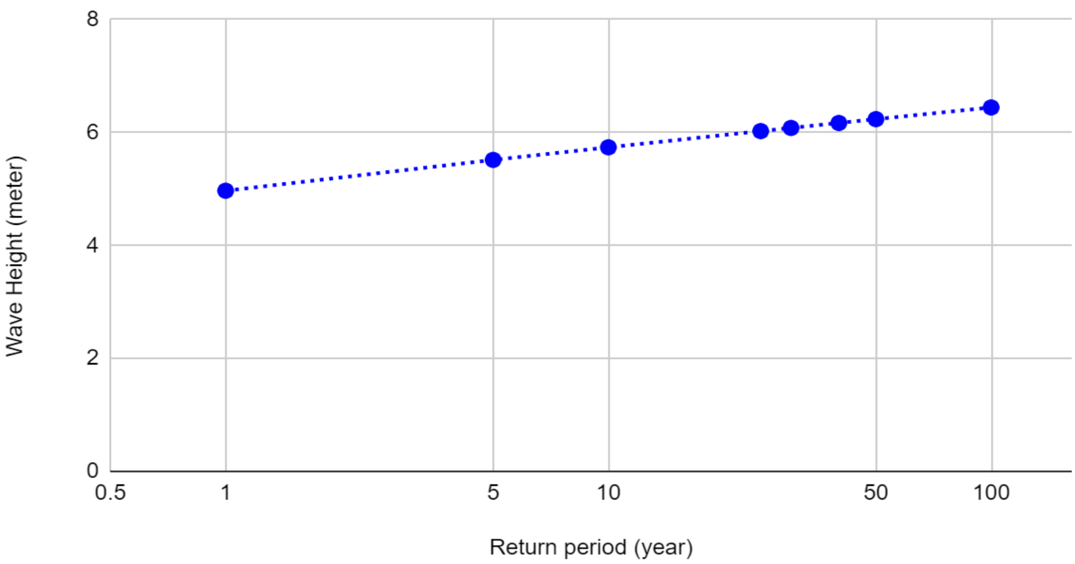

Figure 10: Example of the return period output at an output location on the False Bay coastline.

This analysis was done on 19 chosen sites along the South African coastline at a 200 m resolution (Figure 11)**Error! Reference source not found.**.

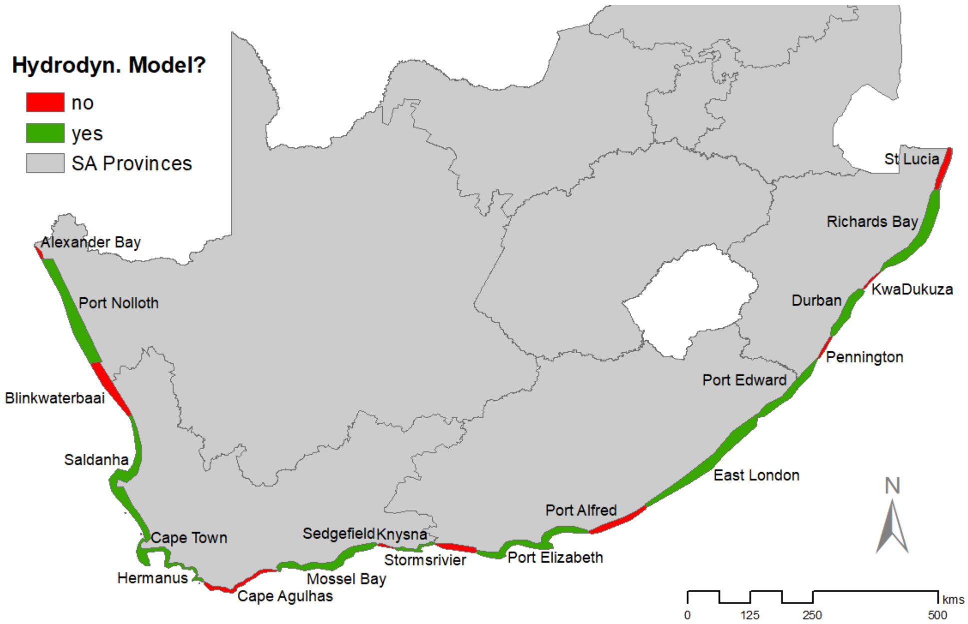

Figure 11: Overview of areas for which wave modelling data were produced

These modelling results cover about 70% of South Africa's coast. All populated areas of economic importance, including ports are covered, apart from the area between Cape Agulhas and Mossel Bay.

For the covered areas at a 200 m along-shore interval, the wave heights for the following wave return periods were extracted: 1: 1 years, 1: 10 years, 1: 30 years, 1: 50 years and 1: 100 years. These return periods were used as input for the flood risk assessment (section 3.1) and the short term (i.e. storm related) coastal erosion risk assessment (section 3.2).

2.6 Estuary Ecosystem Classification

South Africa has nearly 300 estuaries with less than 20% having detailed information available on physical processes, and even less with information on flood return periods and flood levels (< 5%). In the absence of such information, estuary ecosystem types can serve as surrogate for ecosystem processes and enable predictions of biophysical characteristics. Understanding the physical processes associated with an estuary type facilitates assessment of its resilience to natural and anthropogenic stressors. It also allows for extrapolation in data-poor environments.

However, estuaries are difficult to classify because they vary temporally in shape and size, and also encompass a gradient in conditions from riverine to marine. Human interventions and morphological changes brought about by climate and sea level fluctuations further complicate the process (van Niekerk et al. 2020). For nearly three decades, the characterisation scheme of Whitfield (1992) served as the reference framework to type South African estuaries. This scheme was recently revised through the development of an ecosystem classification scheme that explicitly incorporates biogeographical zonation, introduces new estuary types and redefines existing types based on size (Van Niekerk et al. 2020). The classification scheme recognizes an estuary as a partially enclosed permanent water body, either continuously or periodically open to the sea that extends as far as the upper limit of tidal action, salinity penetration or back-flooding under closed mouth conditions. During high catchment flows or floods an estuary can become a river mouth with no seawater entering the formerly estuarine area or, when there is little or no fluvial input, an estuary can be isolated from the sea by a sandbar and become fresh or even hypersaline (Van Niekerk et al. 2020, CSIR 1992).

The scheme divided the biogeographical regions that characterise the South African coast into four major zones; the Cool Temperate (Orange to Ratel), the Warm Temperate (Heuningnes to Mendwana), the Subtropical (Mbhashe to St Lucia) and the Tropical (uMgobezeleni to Kosi), the latter being a new addition to the estuarine biogeographical provinces. These also largely reflect South Africa's climatic zones with little rainfall/runoff along the Cool Temperate region to relative high rainfall/runoff in the Subtropical and Tropical zones.

All rivers or streams with outlets to the sea were categorised broadly as estuaries and micro-systems. Focusing on the 290 estuarine systems, these were further sub-divided into nine categories, namely Estuarine Lake, Estuarine Bay, Estuarine Lagoon, Predominantly Open, Large and Small Temporarily Closed, Large and Small Fluvially Dominated, and Arid Predominantly Closed (Figure 3, Table 14) (van Niekerk et al. 2020).

Estuarine Lakes comprise one or more typically large circular water bodies connected to the sea by a constricted inlet channel (Figure 3, Table 14). Freshwater input can be from a single or multiple large rivers, groundwater or aquifers, or multiple small waterways or streams feeding into the basin; or a combination thereof. Maximum water levels are determined by berm height, mouth state and freshwater input. Marine connectivity varies from almost permanently open to temporarily closed on annual scales. Salinities are highly variable, ranging from fresh to hypersaline because of differing freshwater input (surface and ground water), evaporation and the extent and duration of the marine connection. Mixing processes are dominated by wind and, to a lesser extent, fluvial inputs, owing to their restricted mouths and relatively large surface areas. Average tidal amplitudes are negligible (15 – 20 cm) when connected to the sea, primarily due to restricted mouth conditions. Sediment processes tend to be stable, with infilling occurring over long time scales and system resetting confined to larger flood events.

Estuarine Bays are permanently linked to the sea by unrestricted, deep mouths and are dominated by tidal processes, with tidal amplitude close to that of the sea. These are large systems (>1200 ha) with generally round basins where only the upper reaches experience a degree of constriction to tidal flows. As a result of relatively low river inputs they have a predominantly salinity regime in the lower and mid reaches, with freshwater mixing processes being mostly confined to the more restricted upper areas. Sediments are typically marine in origin and grain size distributions are stable over time. There are two natural occurrences of Estuarine Bays in South Africa (viz. Knysna and Durban Bay; (Figure 3, Table 14).

Estuarine Lagoon - Langebaan - has many of the characteristics of an estuary (Whitfield 2005), including calm waters that are protected from marine wave action and biota that reflect many of the species usually found in estuaries. However, despite groundwater seeps into some areas, it lacks riverine inflow and a normal estuarine salinity gradient (Table 2). Langebaan Lagoon represents a unique coastal ecosystem type (Table 4) and is recognised as an estuary because its ecological functioning includes both freshwater and marine inputs into a semi-enclosed embayment. Estuarine Lagoons, as defined here, are permanently connected to the sea and are therefore marine dominated. Tidal action is the dominant mixing process and sedimentary processes are thus generally stable. Tidal amplitude and water levels are close to those of the sea.

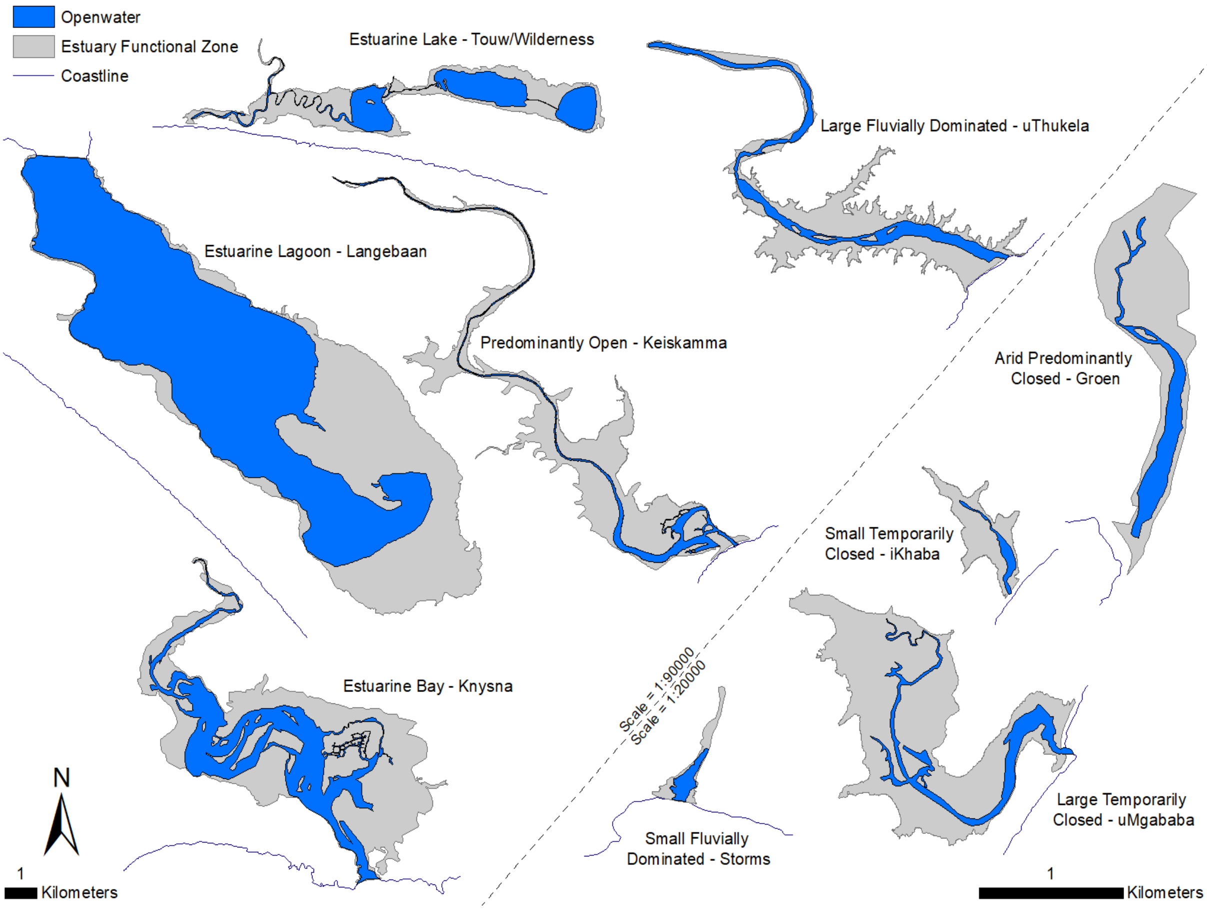

Figure 12: Revised classification of South African estuaries (Source: Van Niekerk et al. 2020a)

Predominantly Open estuaries are open to the sea for more than 90% of the time. Some are permanently open owing to perennial river flow or the presence of a large tidal prism. Tidal amplitude ranges from 0.75-1.5 m. Predominantly Open estuaries are linear systems in which mixing processes are dominated by both fluvial inputs and tidal action creating vertical and horizontal salinity gradients. Under low river flows and high summer evaporation, hypersalinity can develop in the upper reaches. The degree to which the mouth is restricted depends on the rate and volume of freshwater inflow. Some systems become severely constricted during low flow periods, decreasing the tidal amplitude and increasing the duration of the ebb tidal cycle. Regular flooding results in relatively mobile sediments. Surprisingly, their size varies considerably ranging from 10 to 7 500 ha, with smaller systems afforded a degree of protection against direct wave action by rocky headlands or subtidal reefs, which assists in maintaining an open mouth.

Large and Small Temporarily Closed Estuaries: The sizeable temporarily open/closed category of Whitfield (1992) was divided into Small and Large Temporarily Closed estuaries using a total habitat area of 15 ha (associated with ~10 ha of open water area) as the dividing threshold (Figure 3, Table 14). The division was based on differences in recorded biophysical processes and patterns. Small systems are likely to experience rapid increases and decreases freshwater runoff over a few hours making them strongly event driven. There will be little scouring following berm breaching, and a semi-closed mouth condition can easily develop owing to a small, perched, outflow channel that restricts tidal amplitude to 10 to 15 cm. There is minimal water column area during the open state. Both large and small systems tend to be linear or funnel shaped, with highly restricted inlets. Smaller systems especially tend to be 'perched' above normal tidal levels, resulting in little to no open water area during the open mouth low tide state. Water levels are dominated by the state of the mouth, with highest levels of 1 m to 2 m above mean sea level during the closed phase. Tidal ranges are very restricted, varying from 25-50 cm in Large Temporarily Closed estuaries to 15-30 cm in Small Temporarily Closed estuaries. Open phase mixing processes are dominated by fluvial input and partially by tides. When closed, wind and seepage losses through the berm play a key role. Sediment composition is largely stable, resetting mainly during floods. Salinity regimes range from almost fresh to hypersaline, which in large systems can develop during times of low flow or droughts. Small Temporarily Closed estuaries tend to be fresher in character as they have less connectivity with the sea.

Small and Large Fluvially Dominated Estuaries: Estuaries characterised as river mouths by Whitfield (1992) were divided into two categories, Small and Large Fluvially Dominated systems to distinguish between small (<15 ha), black water dominated, rocky, temperate southern coast estuaries, and large, shallow, sediment rich, freshwater dominated systems of the east and west coasts (Figure 3, Table 14). The larger systems have very high sediment turnover, often develop ebb-tidal deltas, are turbid and can close during periods of low flow, e.g. uThukela and Orange estuaries (Figure 3, Table 14). Small, sediment-starved, fluvially-dominated systems have unrestricted mouths as they usually occur along rocky shores and receive clear humic-stained water from Table Mountain Sandstone catchments. Large Fluvially Dominated estuaries tend to be constricted and can even periodically close during low flows. Fluvial processes are dominant and salinities are mostly fresh throughout the estuary for more than half the time. During peak flood conditions, outflows can influence salinities for a considerable distance offshore.

Arid Predominantly Closed Estuaries: This type comprises six small estuaries located in the Namaqua west coast region. They are linear or funnel shaped and closed on annual to decadal time scales. Salinities tend to be euhaline to hypersaline as a result of low fluvial input and high evaporation rates (Figure 3, Table 14).

Table 2: Key features and physical processes of nine estuarine ecosystem types (Source: Van Niekerk et al. 2020a)

ESTUARY TYPE	ESTUARINE AREA (ha)	% TIME OPEN TO THE SEA	GEO-MORPHOLOGY	AVERAGE TIDAL RANGE (m)	KEY DETERMINING FACTOR OF MAXIMUM WATER LEVEL	TYPICAL SALINITY RANGE	MIXING PROCESS	SEDIMENT STABILITY	MEAN ANNUAL RUNOFF ($x10^6 m^3$)
Estuarine Lake	>800	Variable	Circular with constricted inlet channel	0.1- 0.15	Mouth State	0 - 35	Wind/ riverine	Stable	20 - 650*
Estuarine Bay	> 1 000	100	Circular with unrestricted inlet	1.5 - 2.0	Tides	30 - 35 Average: 35	Tidal	Stable	40 - 80
Estuarine Lagoon	> 5 000	100	Circular with unrestricted inlet	1.5 - 2.0	Tides	35 - 36 Average: 35	Tidal	Stable	0*
Predominantly Open	10 – 7 500	90 - 100	Linear with restricted inlet	0.75 - 1.5	Tides/ Mouth State	0 - 40	Tidal/riverine	Mobile (reset by large floods)	10 – 1 790
Large Temporarily Closed	>15	>50	Linear /funnel with highly restricted inlet	0.25 - 0.5	Mouth State	0 - 60	Tidal/ riverine/ wind/seepage	Mobile (breaching and floods)	1 - 280
Small Temporarily Closed	<15	<50	Linear/funnel with highly unrestricted inlet	0.15 - 0.3	Mouth State	0 - 30	Riverine/ wind/seepage	Mobile (breaching and floods)	0.1 - 70
Large Fluvially Dominated	100 - 3 700	>90	Linear with highly restricted inlet	0.5 - 1.0	Mouth State	0 - 10	Riverine	Highly mobile (reset annually)	370 – 10 830
Small Fluvially Dominated	< 15	100	Linear with highly restricted inlet	0.5 - 1.5	Mouth State	0 - 5	Riverine	Highly mobile (reset annually)	20 - 50
Arid Predominantly Closed	10 - 500	<5	Linear/funnel with highly restricted inlet	0 (over-wash & breaching)	Mouth State	0 - 200 Average: Hypersaline	Evaporation/ seepage/wind	Stable, but reset on decadal-scales during floods	0.2 - 10

Thus, mixing processes tend to occur over long time periods and are dominated by the effects of evaporation, winds and seepage through the berm at the mouth. Occasional breaching and overwash during high sea conditions provide for marine input and connectivity. Sediment processes are generally stable on decadal time scales and are reset by large intermittent flash floods. Water levels are determined by the interplay between sand berm level, evaporation rates and seepage losses. Groundwater and inflows from local fountains replenish these losses and influence the salinity regimes of these estuaries.

Estuarine Lagoons are the rarest South African estuary type with only one member in the Cool Temperate region, followed by Estuarine Bays with two in the Subtropical and one in the Warm Temperate region. Arid Predominantly Closed estuaries are confined to six systems in the Cool Temperate region. The Large and Small Fluvially Dominated types comprise seven systems each, occurring in three and two biogeographical regions, respectively. Small Temporarily Closed (116), Large Temporarily Closed (94), and Predominantly Open (44) are the most dominant types occurring across the Cool Temperate, Warm Temperate and Subtropical biogeographical regions. Estuarine Lakes occur across all four biogeographical zones. While not numerically dominant, this type represents the largest surface area of all estuary types, with Lake St Lucia representing more than half of South Africa's estuarine surface area.

Overall, South Africa's 290 estuaries were classified into 22 estuarine ecosystem categories arising from the interplay between four biogeographical zones with nine estuary types. This represents a high diversity of estuary types, which is not unexpected considering the country's diverse climatic, oceanographic and geological drivers.

In a data-limited environment such as South Africa, classification is most often used to signify system-specific ecosystem processes and associated biotic characteristics. While not intended as an indicator of flood risk, the new estuary classification scheme was developed to reflect estuary sensitivity to flow and declining water quality (van Niekerk et al. 2019a, 2019b). Also, while not a critical consideration, using this classification scheme as basis for the flood risk assessment in this project will also ensure alignment with South African national-level biodiversity condition assessments and conservations plans.

2.7 Hydrological Flow data

No hydrological modelling (at monthly or daily time steps) or fluvial flood modelling (at hourly time steps) was done as part of this project as the focus of this study was to resolve coastal flooding as a result of sea storms and sea level rise. While it is recognised that hydrological modelling of river inputs is crucial to the accurate determination of overall flood levels in estuaries, this type of modelling is both labour and data intensive. Requiring up-to-date detail on estuarine bathymetry and topography, catchment river flow observations (i.e. from gauging station near the head of the estuary), rainfall data in catchment, and detailed information on catchment land use and water resource development. This information is not available on a national-scale for estuaries, with no information on most of the smaller systems (>60%), and should be the focus of a dedicated national project, especially focussing on estuary bathymetry and topography.

What was available for all estuaries at the national-scale was a summary of natural and present mean annual runoff (MAR) and an indication of the estuary openwater area (ha) digitised once-off for all estuaries regardless of mouth state. This data set was used as an indicator flood input into estuaries.

3 Open shore flood and erosion assessment

3.1 Coastal flood hazard risk index

Altogether for 2160 km of the coast numerically modelled wave height, period and return data, generated with Delft numerical modelling software, were available from previous projects (Figure 13 and Table 3). For the remaining 710 km of the coast, flood and erosion were modelled in a simplified way.

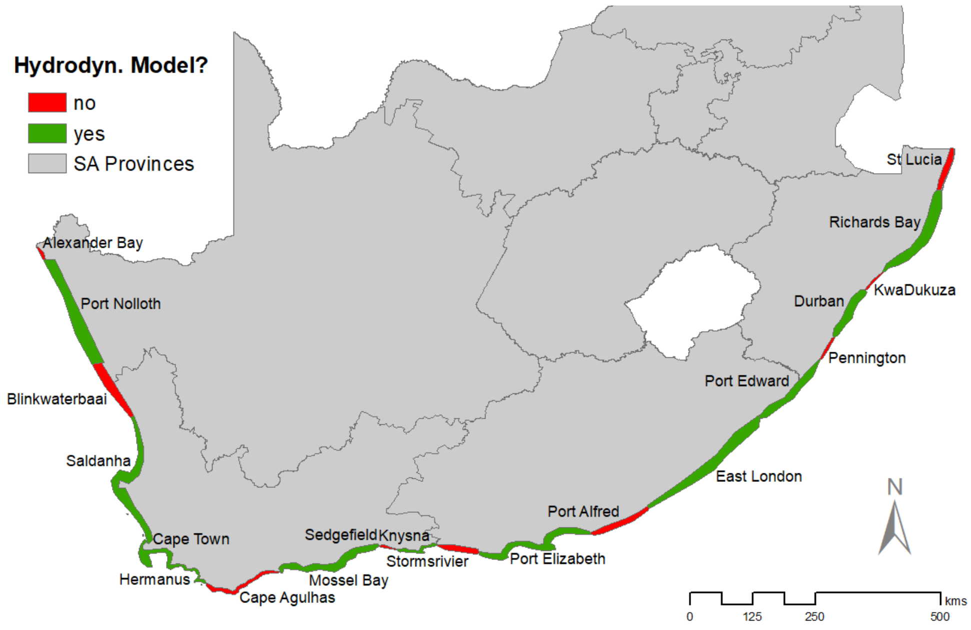

Figure 13: Overview of areas for which wave modelling data were available

Coastal flooding hazard predictions are provided for two main types of coast, which are classified as sandy or rocky coasts. The concept of the coastal flood risk assessment is illustrated in Figure 14. The prediction methods differ considerably for these 2 coastal types, as described in the following two sections.

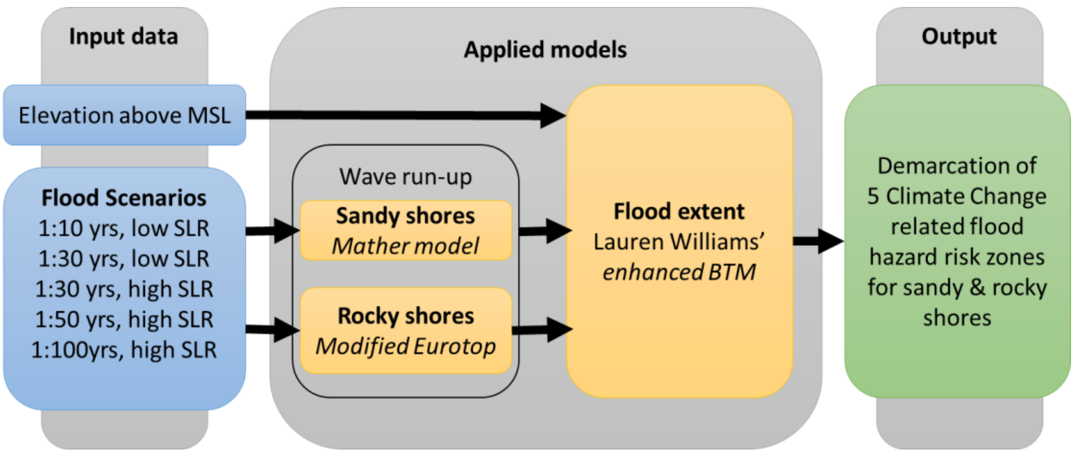

Figure 14: Concept of the coastal flood risk assessment for areas with Delft modelling.

Table 3 gives an overview for which areas Delft modelling was available. For these areas, the application of the sandy or rocky model along the coastline was based on the coast type information included in the reference coast line file *National_Coast_Types.shp*.

Table 3: Overview of hydrodynamic model availability as input for flood modelling

	Area Name	Province	Delft available?	app. Length (km)
1	Port Nolloth	NC	yes	228
2	Alexander Bay	NC	no	30
3	Blinkwaterbaai	NC/WC	no	125
4	Saldanha	WC	yes	308
5	Cape Town	WC	yes	213
6	Hermanus	WC	yes	83
7	Cape Agulhas	WC	no	153
8	Mossel Bay	WC	yes	250
9	Sedgefield	WC	no	31
10	Knysna	WC	yes	88
11	Stormsrivier	EC	no	72
12	Port Elizabeth	EC	yes	250
13	Port Alfred	EC	no	109
14	East London	EC	yes	265
15	Port Edward	EC/KZN	yes	159
16	Pennington	KZN	no	53
17	Durban	KZN	yes	113
18	KwaDukuza	KZN	no	49
19	Richards Bay	KZN	yes	203
20	St Lucia	KZN	no	88

3.1.1 Wave run-up for sandy coastlines

Extreme seawater levels, storm surge and wave run-up prediction are all part of determining coastal flooding elevations, which is one of the two major abiotic hazards to coastal infrastructure, and also a major focus of this project. Significant drivers of high inshore seawater levels are tides, wind setup, hydrostatic setup, wave setup and, in future, sea-level rise (SLR), which all affect the still-water level at the shoreline. South African seawater level recordings and the tidal ranges for the South African coast are summarized in Theron (2016). Extreme South African seawater levels excluding tides (thus mainly due to wind and inverse barometric setup) have been analysed for all of the South African stations (Theron et al., 2014), and the results (i.e. residuals for various return periods) are also summarized in Theron (2016). In South Africa spring tides occur every two weeks, which means that the chances of storm waves coinciding with spring high tides are relatively high. Therefore, the input water level was set at spring high in the water level calculations. In addition, the water levels also include inshore sea level increases due to other effects (mainly hydrostatic and limited wind effects). Thus, 1-in-10-year sea level residuals (surge) as determined for each coastal region are also added to the input sea level.

Wave run-up is another key parameter for storm-related flooding along the SA coast. This parameter was not available at a sufficient spatial resolution for use in the geospatial hybrid approach in the NCA. In this project, the existing coarse resolution wave run-up models were re-run at higher resolution to provide information at a scale required for the geospatial assessment. Wave run-up (i.e. flooding elevation) was modelled for 4 different storm return period cases: 1 in 10yr, 1 in 30yr, 1 in 50yr and 1 in 100yr storms. These were combined with 2 appropriate Sea-level rise (SLR) scenarios, namely SLR of: 0.35m (year ~2050) and 1m (year ~2100), giving 4x2 = 8 total flooding scenarios. Of these possible 8 scenarios, 5 were selected to simulate coastal flooding hazard zones (Table 4).

Table 4: Input parameters used for five flood scenarios

Scenario No.	Constituents
1	1 in 10 years + 0.35 m SLR
2	1 in 30 years + 0.35 m SLR
3	1 in 30 years + 1.0 m SLR
4	1 in 50 years + 1.0 m SLR
5	1 in 100 years + 1.0 m SLR

For those 5 scenarios the coastal flooding heights were calculated at each coastal point of the Wave model (i.e. at 200m intervals alongshore), then plotted using GIS technology (see section 3.1.4 below) to demarcate the respective 5 coastal flooding hazard zones. In this manner, extreme flooding values including run-up were thus determined at each coastal point, for realistic combinations of all the inshore seawater level components, as applicable to each South African coastal region.

3.1.2 Wave run-up for rocky coastlines

The "Mather" run-up model used in the NCA and also in the above methodology was designed for sandy shores. Run-up on rocky shores however differs from run up on sandy shores. In this project, the run-up risk on rocky shores was assessed using a combination of the EurOtop model (for run-up on rock structures: EurOtop, 2018) with a model that accounts for the wave climate, nearshore slope and wave transformation over the nearshore zone by calculating a reduction coefficient at each location based on the wave modelling outputs at that point. The combined run-up model also accounts for (amongst others) the inshore (modelled) wave characteristics, the roughness factor (based on the local geomorphology type), and the calculated local Irribarren number.

Besides using the run-up model developed for rocky coasts, the same procedure and scenario combinations as used for the sandy coastal areas, were applied along all SA rocky coastal areas using the same 5 flood scenarios as for sandy shores (Table 4). For those 5 scenarios the coastal flooding heights were calculated at each coastal point of the Wave model (i.e. at 200m intervals alongshore), then plotted using GIS technology (see section 3.1.4 below) to demarcate the respective 5 coastal flooding hazard zones.

3.1.3 Flood modelling for non-Delft areas

Where no Delft wave period model outputs were available (Figure 13 and Table 3), no explicit Mather coefficient could be calculated. Instead the sandy shore method was used on all areas, using a constant Mather value of 7.5m, modified only in certain areas using expert knowledge.

3.1.4 Demarcation of scenario-based flood hazard zones

For plotting the respective flood height occurring on the coast sandy and rocky shorelines inland, Williams' (2020) enhanced Bath Tub Model (eBTM) was used. This model is based on the Cost-Distance Model implemented in ArcGIS, and displays the inundated areas more reliably than a simple bathtub model (e.g. used in the OCIMS Coastal Flood Hazard Viewer), as it does not flood low-lying, but disconnected areas. This model further takes beach slope and surface roughness into account as factors influencing inland flood propagation.

As the eBTM at this stage can only be run with a static flood height, the coastline was segregated into segments of uniform direction, as the assumption was that within those segments the wave run-up would be relatively homogenous. For each of these windows, the average of the wave run-up established for the respective ten model points (200 m spaced) was extracted and used as input water height for the respective coastal segments. As surface roughness was indirectly considered in the separation of the coast into rocky and sandy shores, therefore a uniform roughness coefficient of 1 was used for the whole coast. The slope was extracted from the underlying Digital Elevation Model (section 2.2). For each of the coastal segments, the model was run five times, to generate the hazard zones for the 5 flood scenarios from Table 4. The resulting flood model results were merged. For areas of model overlap the respective local maximum value was stored, should the results for neighbouring segments differ.

3.2 Short-term coastal erosion due to storm events (waves)

During sea-storms the shoreline erodes and can (usually) recover again afterwards, typically over weeks or months. This short-term erosion (i.e. occurring in a matter of hours to days) was modelled based on extreme wave events and additional local and regional parameters (Figure 1). Approximate cross-shore horizontal erosion distances for 1: 1, 1: 10, 1: 30, 1: 50 and 1: 100 years wave events were generated for those sections of the coastline with available input data at appropriate resolution (about 200m alongshore intervals spatially continuously post-processed afterward, see section 2.5).

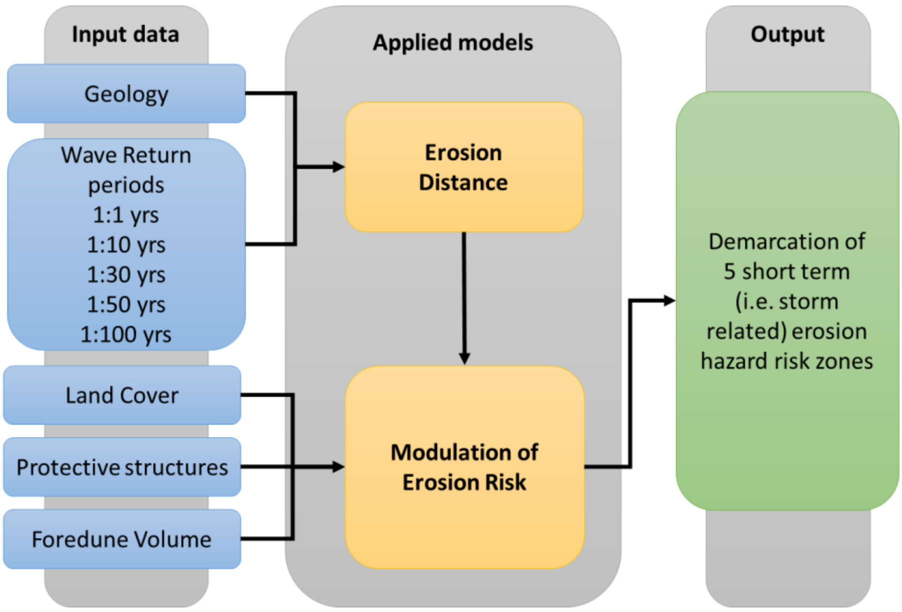

Figure 15: Schematic overview of project components, flow and outputs

3.2.1 Erosion distance

As input for the Erosion distance calculation, the attribute classes of the 1:250,000 Geological map (**RSA_geo_1k.shp**) were used. This dataset, provided by the Council for Geoscience, contains stratigraphic and lithologic information. The geology types were categorised according to their sensitivity to coastal erosion, based on expert knowledge and previous work (e.g. Theron 2016). The geology was classified up to the 40m elevation contour, albeit, storm related erosion up to that elevation is rather unlikely. The full classification scheme is provided in the Appendix. Examples of the resulting geological erosion risk classes are shown in Figure 16 and Figure 17. Using these classes and the wave return periods, an erosion distance was calculated.

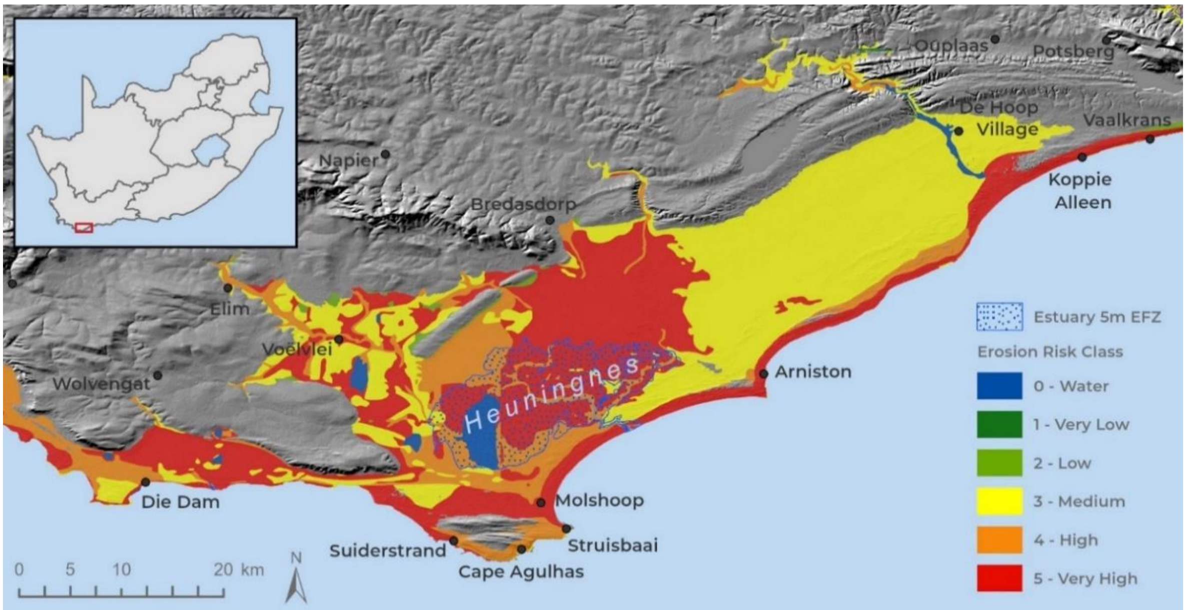

Figure 16: Geological erosion risk classes for the Cape Agulhas Region, Western Cape

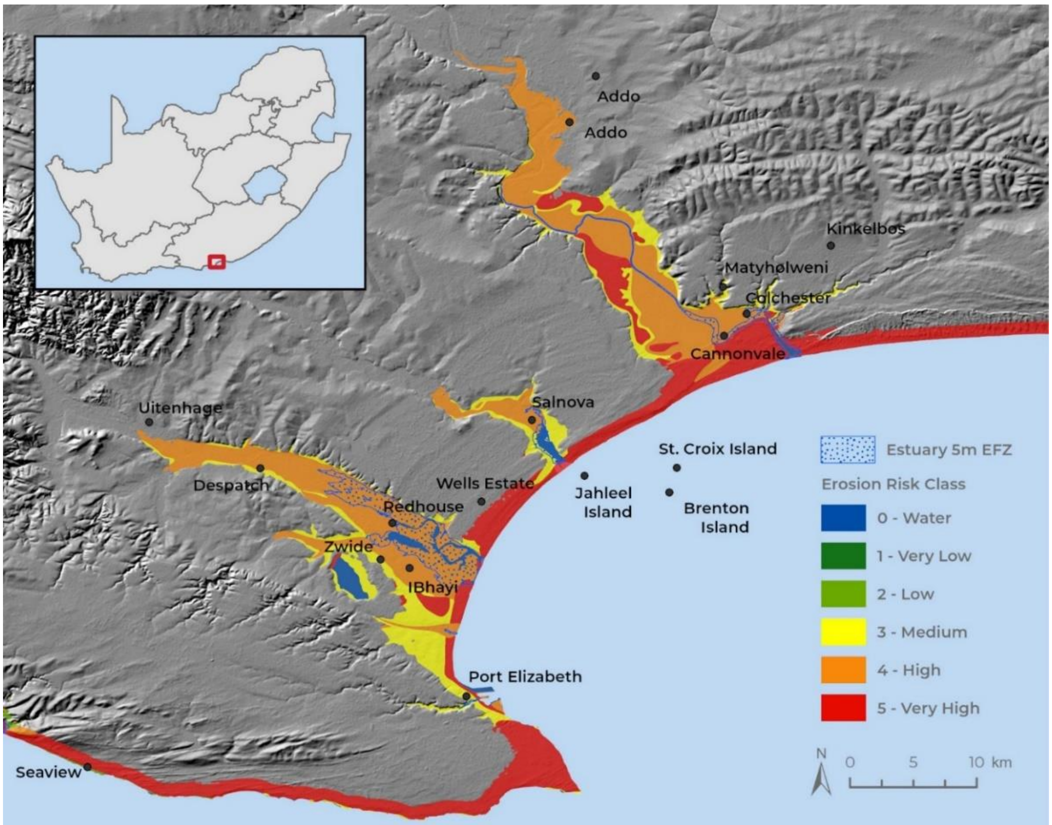

Figure 17: Geology Index for Nelson Mandel Bay Municipality in the Eastern Cape.

A parametric erosion model was employed to determine the respective erosion distances for each of the modelled local nearshore wave outputs at the selected return periods. This model also takes into account: geology erosion coefficients (derived from geology hardness classes related to the geology type from GIS for each location), wave erosion coefficients (calculated from the local wave heights relative to regional 50yr extreme wave heights), and a default regional erosion distance.

3.2.2 Modulation of erosion risk

This erosion distance was then calibrated/modulated by acknowledging the impact of actual local land cover, presence of man-made protective structures (sea walls) and foredune volume on the actual coastal erosion risk. The use of this parameters is described in the following sections.

Two significant factors are wave climate and tidal levels, which would normally also be included in comprehensive coastal risk assessments (e.g. Theron, et al., 2014). However, the present risk assessment is limited to the SA coast, and there is almost no alongshore variability in tidal extremes, and relatively little difference in extreme *offshore* wave heights around the SA coast. By including such "invariable" parameters in the overall risk assessment, the sensitivity of the other parameters is relatively reduced. In such instances, it is therefore better to exclude these virtually "invariable" parameters.

3.2.2.1 Land cover

As source for land cover and vegetation in the coastal zone, the South African Land Cover 2013/2014 (SALC 13/14) was extracted for the area from the coastline to 1km or the 40m inland contour, whichever came last. From this subset all urban classes were removed, and all remaining, non-urban classes were classified according to their sensitivity to erosion. Table 5 shows the risk/sensitivity values assigned per land cover class group (for a complete breakdown of the SALC13/14 class assignment, see Appendix 2). Examples of the resulting ground cover risk index are shown in Figure 18 and Figure 19.

Table 5: Hazard risk categories for ground cover

	Hazard Risk					
	Very Low	Low	Medium	High	Very High	Not considered
	1	2	3	4	5	0
Land Cover	**Indigenous Forest/ Thicket /Dense bush**	**Herbaceous vegetation/**	**Wetlands/ seasonal water bodies**	**Cultivated ground**	**Bare soil**	**Urbanised or industrial/ Rural urbanised**

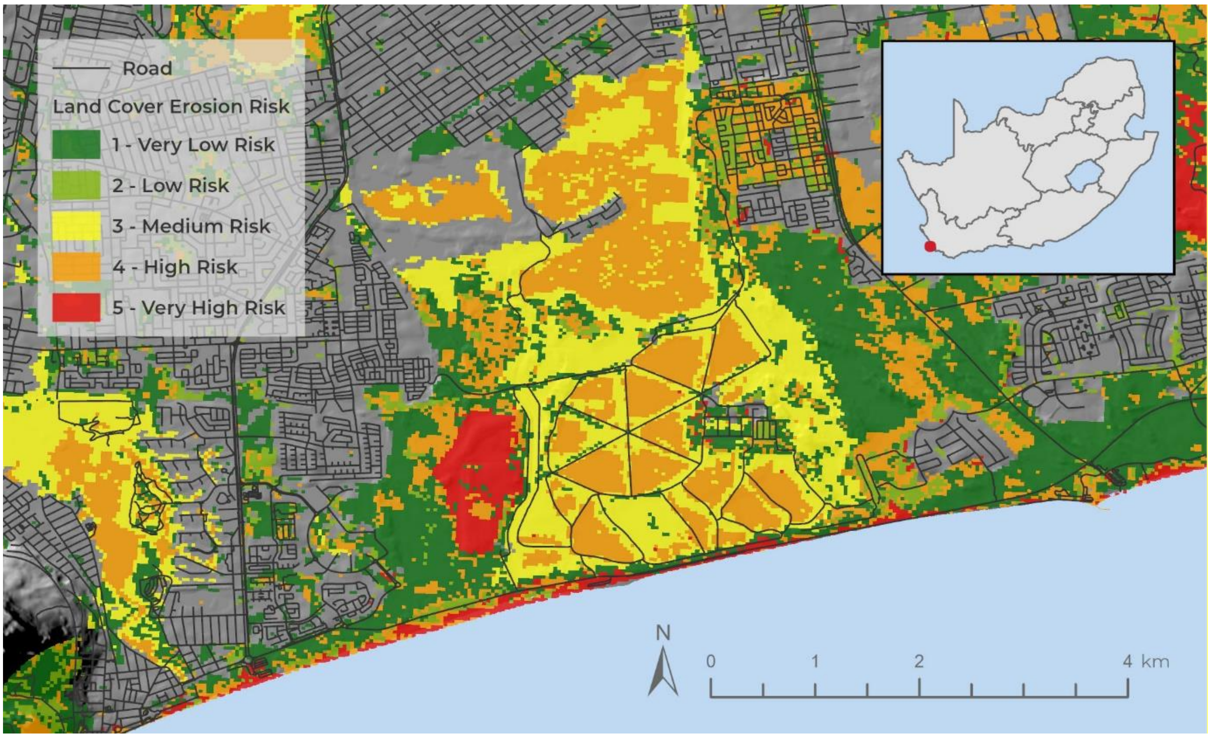

Figure 18: Land cover index for Muizenberg Beach, False Bay, Western Cape

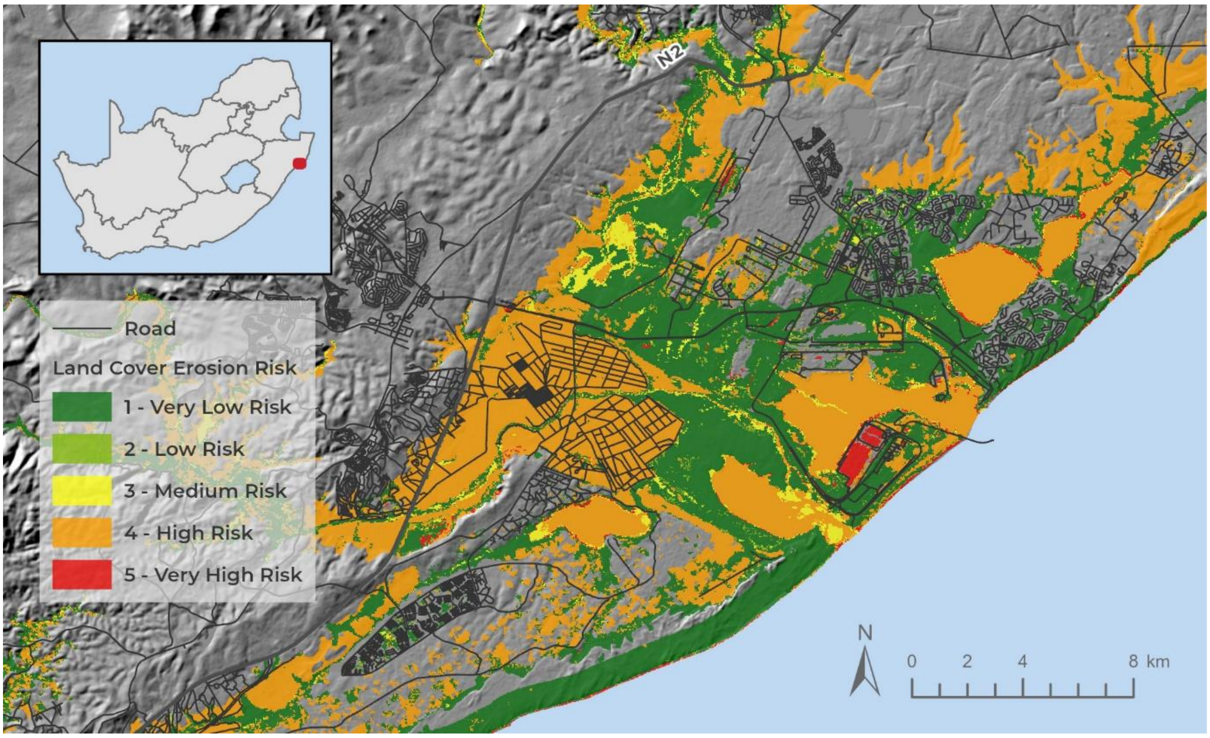

Figure 19: Land cover index for Richard's Bay, KwaZulu-Natal

3.2.2.2 Coastal protective structures

The second criterion impacting local coastal erosion hazard risk was the presence or absence of coastal protective structures. For this purpose, the layer generated in the NCA project, containing sea walls and revetments was used (DEFF, 2020).

The digitised structures were one-dimensional, i.e. attributable polyline shapefiles. In order to represent their protective value for the coast in a two-dimensional GIS context, perpendicular bearing lines were created at the beginning and end of each structure and extracted inland to 1km inland or the 40m topographic contour, whichever came last. Bearing lines were then manually edited to ensure an accurate representation of hazard projection inland. Once the dataset was considered accurate, the resulting polyline skeleton of bearing and buffer lines were converted to polygons and assigned hazard risk values. In this case only two hazard risk classes were assigned: a 1: very low risk for sections where protective structures were present and a 5: very high risk where no structures were present (Table 6). An example for the resulting index is shown in Figure 20.

Table 6: Coastal protection hazard risk categories

Hazard Risk		
	Very Low	Very High
	1	5
Protective structures	**Seawalls & revetments**	**No protection**

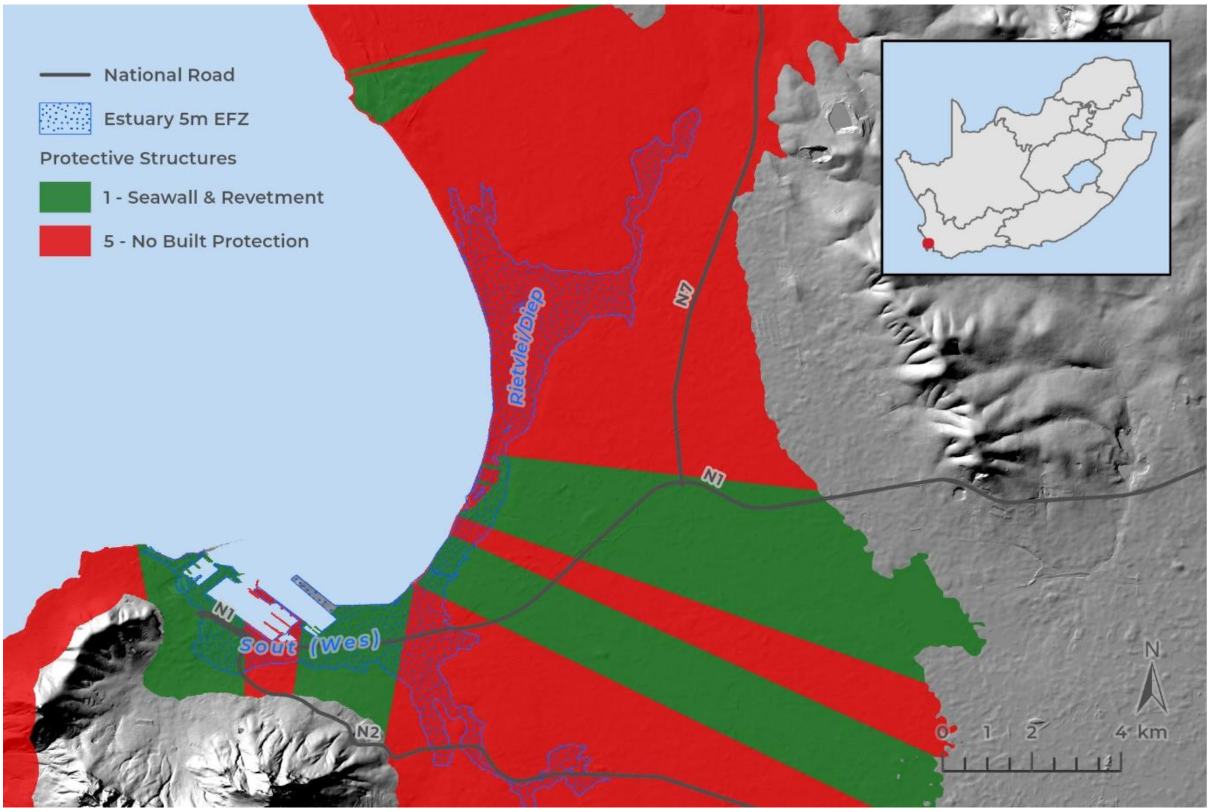

Figure 20: Example for the protective structure index for Table Bay, Cape Town, Western Cape.

3.2.2.3 Foredune volume

The third criterion modulating local coastal erosion risk was foredune and backshore volume. It is known that the volume of the foredune and backshore zone considerably contributes to its erosion buffer function. To calculate this, the coastal elevation (as derived from the fused elevation model described in section 2.2) was extracted for a 1km wide strip from the coastline inland or up to the 40m topographic contour, whichever came last. The volumes per pixel were then calculated i.t.o. effective buffer volume above a selected basis elevation. This was done by subtracting the average highest astronomical tide (HAT) value specific for each province (Table 7) from the pixel elevation. The respective HAT and datum correction values were derived from tide tables provided by the SA Navy's Hydrographers Office (SANHO).

Table 7: Original and per province HAT values

Port	HAT to Chart Datum	Difference Chart Datum to Land Levelling Datum	HAT to Land Level (and MSL)	Province	Avg. HAT per Province
Port Nolloth	2.25	-0.925	1.33	NC	1.33
Saldanha	2.03	-0.865	1.17	WC	1.30
Granger Bay (Cape Town)	2.02	-0.825	1.20	WC	
False Bay (Simon's Town)	2.09	-0.843	1.25	WC	
Hermanus	2.07	-0.788	1.28	WC	
Mossel Bay	2.44	-0.933	1.51	WC	
Knysna	2.21	-0.788	1.42	WC	
Port Elizabeth	2.12	-0.836	1.28	EC	1.32
East London	2.08	-0.716	1.36	EC	
Durban	2.3	-0.913	1.39	KZN	1.42
Richards Bay	2.47	-1.015	1.46	KZN	

For this project, we assumed that dunes would only effectively be able to act as buffers for erosion if they are still in a (semi-) natural condition (vegetated or non-vegetated). Transformed areas, i.e. urban, commercial or industrial areas, as well as permanent water bodies were identified using the SALC13/14 land cover map and subsequently masked out. For the remaining dune and backshore areas the volume for each elevation pixel (5m x 5m x (elevation – HAT)) was calculated and assigned hazard risk values (Table 8). Examples of the foredune volume index are shown in Figure 21 and Figure 22.

Table 8: Effective dune volume hazard risk categories

Hazard Risk					
	Very Low	Low	Medium	High	Very High
	1	2	3	4	5
Effective dune Volume (m^3)	**>300**	**175 – 300**	**100 - 175**	**50 - 100**	**< 50**

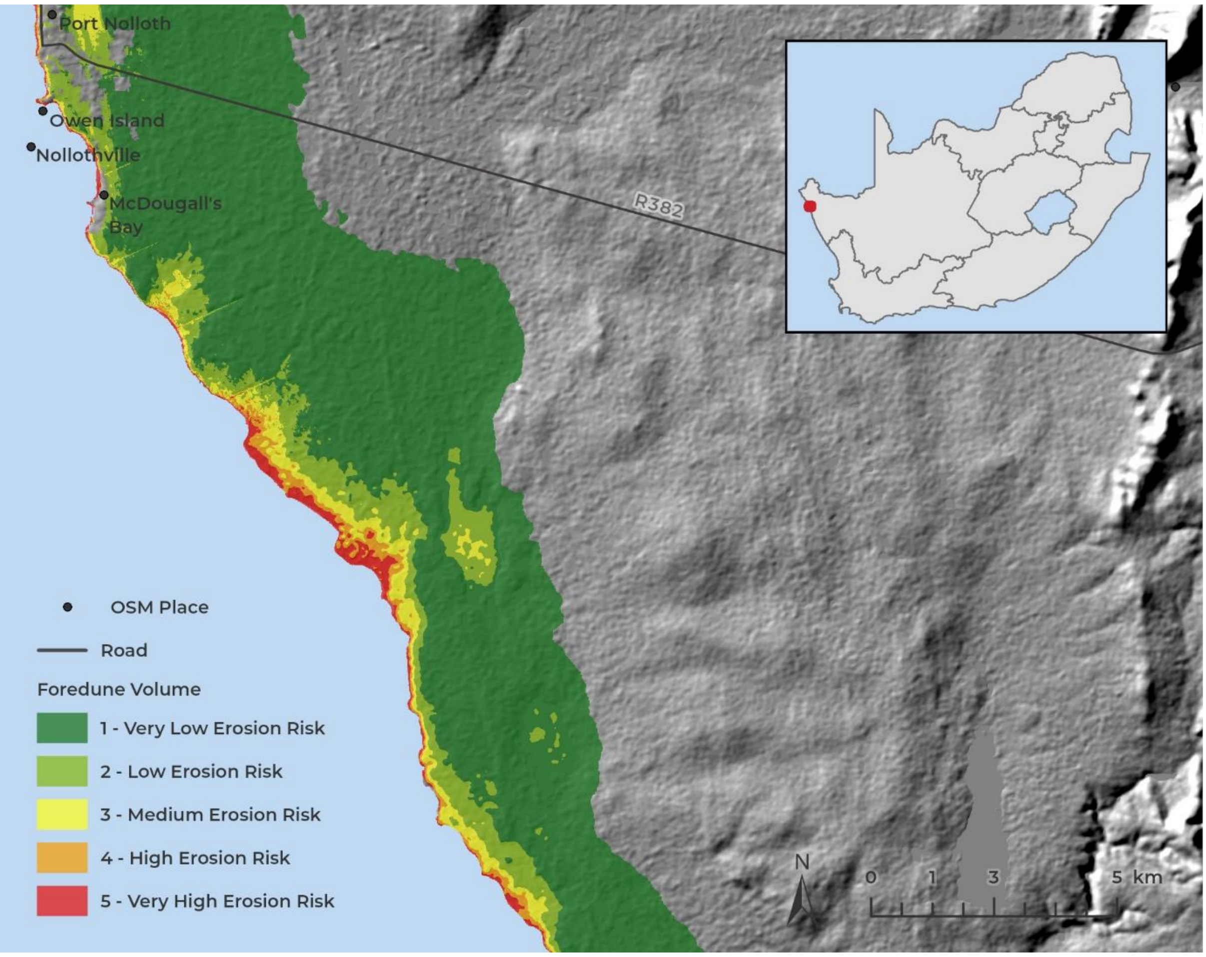

Figure 21: Effective foredune Volume Index for the area south of Port Nolloth, Northern Cape, here displayed up to the 40m topographic contour. No index values derived for urban areas.

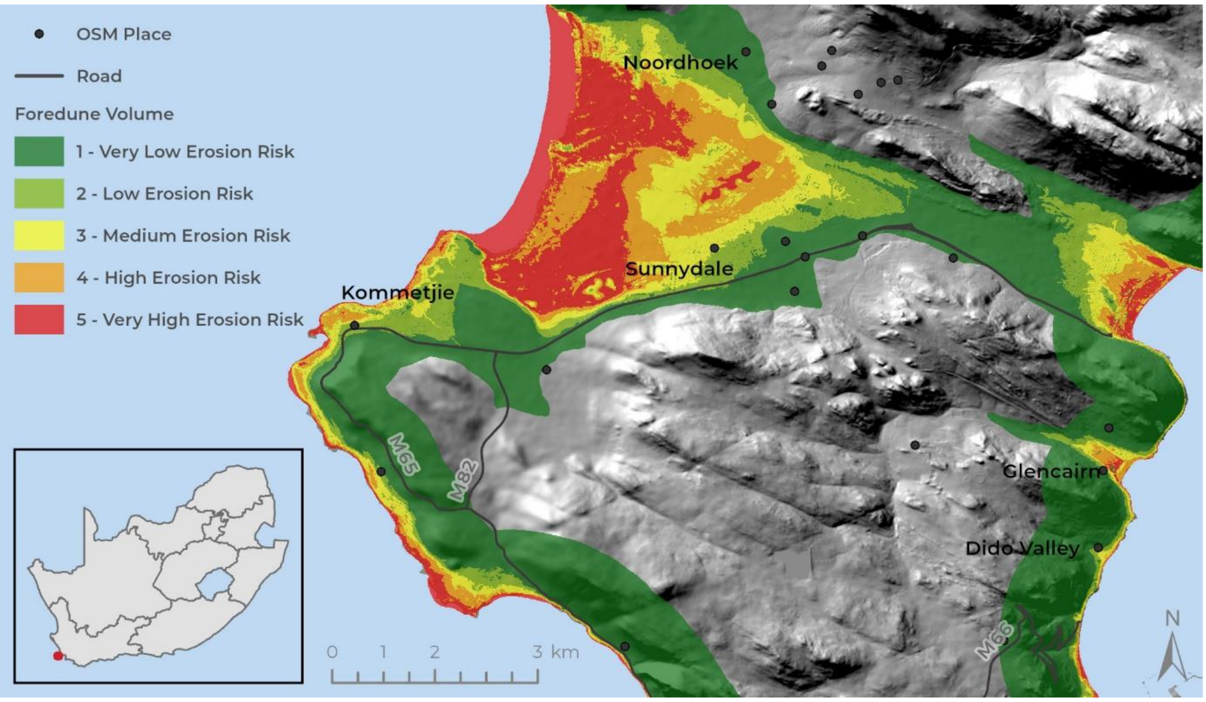

Figure 22: Effective foredune Volume Index for a section of the Cape Peninsula, Cape Town, Western Cape, here displayed up to the 40m topographic contour.

3.2.3 Erosion modelling for non-Delft areas

For areas without Delft wave return periods, the process was run with only the 4 other input parameters, i.e. Gelology, Land Cover, Coastal Protective Structures and Foredune Volume.

3.2.4 Plotting of erosion hazard zones

In order to project the derived erosion distances inland, for each of the 200m spaced assessment points along the coast, perpendicular lines inland were generated and the respective point specific distance along this line was marked. Then all points per return period event were joint to a continuous hazard line. This was done five times, once for every SLR scenario.

3.3 Long-term coastal recession due to Sea-level Rise (SLR from Climate Change)

The afore-mentioned erosion hazard/vulnerability (section 3.2) mainly relates to extreme events (sea storms), while a primary focus of this project was to also include long-term erosion/recession attributable to Sea-level rise (SLR). This is the long-term (>10yr to 200yrs) *potential* erosion (shoreline recession) due to sea-level rise, according to the Bruun Rule (Bruun, 1988). The average shoreline position will recede over time and cannot recover (unless sea levels were somehow to drop again in the very far future, which is not foreseen). This recession is independent of the short-term effects of waves and only considers the amount of SLR, the current elevation above mean sea level and the bathymetric slope (here determined to 15m water depth). Figure 23 provides a schematic overview of the technical approach taken.

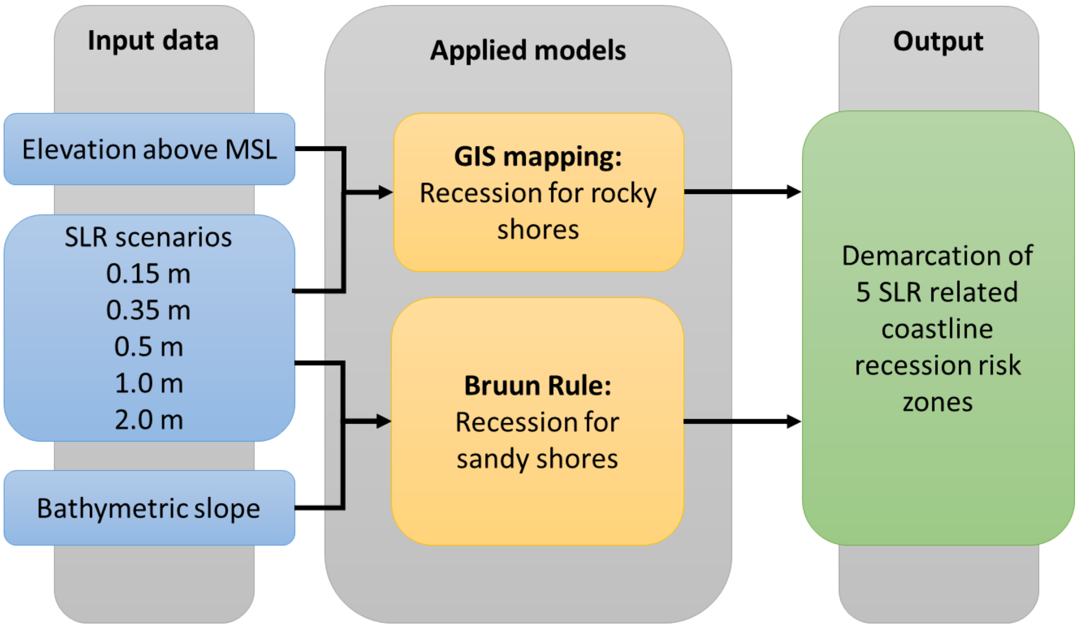

Figure 23: Schematic overview of project components, flow and outputs

Input data were the topographic elevation as described in section 2.2, the reference coastline (section 2.1), sea level rise scenarios (section 2.3) and the bathymetric 15 m contour, taken at approximately

200m spaced points alongshore. The recession/erosion potential due to SLR was thus determined for 5 SLR scenarios, namely SLR of: 0.15m (year ~2030), 0.35m (year ~2050), 0.5m (year ~2070), 1m (year ~2100) and 2m (year ~2200 according to projections for RCP8.5 at 50%; Kopp et al., 2017).

3.3.1 Recession for sandy shores

The long-term erosion potential due to SLR was in this way determined for all the sandy shore areas of the SA coast based on Bruun's Erosion Model (Bruun, 1988).

Other factors, not included in the Bruun Rule, e.g. landward areas that are possibly more erosion resistant or huge dunes, might mean that the Bruun Rule gives too conservative results in such areas). Based on Bruun's Rule for the 5 SLR scenarios, 5 potential recession distances were thus calculated at each coastal point, and plotted & joined alongshore by means of GIS to give the 5 coastal recession hazard zones (due to SLR). Thus, approximate long-term erosion potential lines/zones for the whole coastline were generated at appropriate resolution (spatially continuously post-processed afterward), where possible.

3.3.2 Recession for rocky shores

Along rocky shores the long-term landward transgression of the shoreline due to SLR was based on a simple slope transferal method. Sea level rise scenarios considered were the same as described before. The procedure for determining potential long-term shoreline recession due to Sea-level rise along all rocky shore areas is basically equivalent to the so-called "bathtub model" (i.e. just follows the height contours). Potential shoreline recession is therefore just determined by drawing 5 lines along the +0.15m, +0.35m, +0.5m, +1m and +2m MSL contours plotted through GIS to give 5 recession risk zones for rocky shores.

4 Estuarine flood and erosion

4.1 Estuarine flood index

Estuary flood line determinations are resource and data intensive, requiring information on estuary bathymetry/topography and river flow regimes. Estuary flood lines are also dynamic insofar that they are influenced by water resource development (e.g. dam construction), as well as catchment land-use changes (e.g. hardening of the catchment through development). While water resource development tends to decrease flood magnitude, changes in catchment permeability can increase it. Finally, localized features such as bridges, culverts and mouth structures also influence the degree to which a flood can be attenuated and related ‘back flooding’. None of this critical information is available at the national scale for all estuaries.

This project therefore developed a desktop approach for estuarine flood assessment based on available information. **However, given that the project does not entail detailed hydrological and hydrodynamic modelling, this assessment can only be used as an indicator of where more detailed flood line studies should be done in estuaries in future. This means it does do not replace the need for detailed, site-specific flood risk assessments for planned developments in the EFZ or for estuaries fed by large catchments.**

For an in-depth assessment, following the pre-screening of the estuarine area using the data produced in this project, it is recommended that detailed estuary flood line assessments be done for large catchments and urban areas following this input data and process:

- Determine bathymetry and topography of the estuary to mean sea level.
- Measure the berm height at the estuary mouth under a range of coastal conditions (e.g. winter/ summer; closed mouth conditions when system has been closed for an extended period (the longer the mouth is closed the higher the berm height).
- Determine catchment characteristics such as: area, length of river, catchment slope, land cover and land use, water resource development level and related infrastructure, climatic zone.
- Develop hourly flood hydrograph for a range of flood probabilities (1:20, 1:50 and 1:100) using measured and/or simulated data.
- Estimation of the extreme high sea water levels to establish the seaward boundary conditions in the estuary under a range a range of coastal conditions, including coastal storm with a return period of 1:10, 1:20, 1:50, 1:100.
- Estimate sea-level rise for the medium and long term.
- Route estimated flood discharges through the measured cross-section using a 1D or 2D numerical model.
- Calculate flood line from integrated results.

4.1.1 Identification of estuarine area to be assessed

The elevation boundaries and risk zonations of estuaries are largely defined by the relief, i.e. the height above mean sea level. In order to identify the boundaries of the estuarine area to be assessed in this project, the high resolution SUDEM (see section 2.2) was used. The SUDEM dataset with a horizontal resolution of 5m compromises on spatial detail (if compared to e.g. LiDAR[3]), but is consistently available for the whole coast. For the extraction of areas <20m elevation covering the estuaries from the SUDEM, an 'area of interest mask' was created, using the Coastal types coast line SHP file and the 1:50,000 topo map derived 20m elevation contour as seaward and inland boundaries respectively. In a manual approach, both lines were joined on the beach area to create closed polygons to be used as mask for each estuary. It was found however, that in some cases the 5m EFZ boundary was very close to or even crossing the 20m topographical line, which is probably due to spatial inaccuracies and the inclusion of estuarine supporting habitats (e.g. saltmarsh and swamp forest) in the EFZ delineation. However, in order to ensure that for each estuary the whole area up to the 20m contour would be extracted for the risk classification, the 20m contour was buffered by 200m before using it for the extraction of the SUDEM.

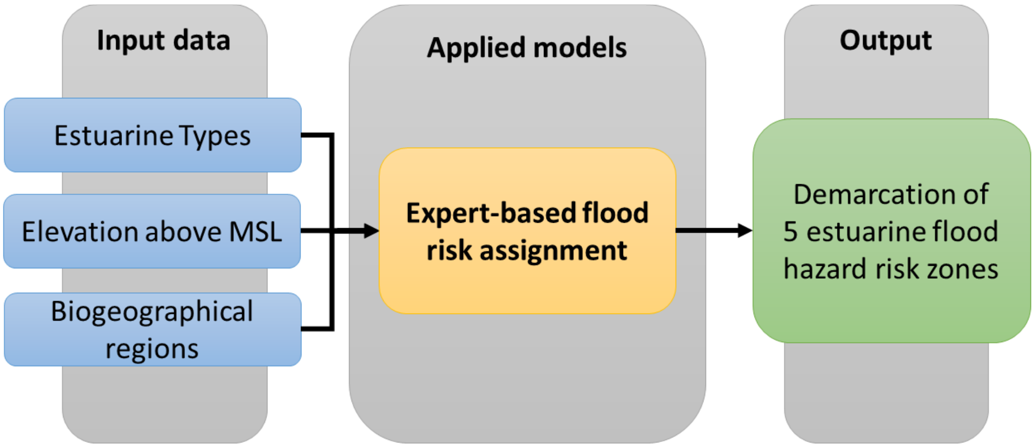

Figure 24: Schematic overview of estuarine flood risk approach

4.1.2 Creation of elevation classes

The extracted SUDEM subsets were classified into 2.5m elevation intervals, i.e. from 0.0 – 2.5m above MSL, 2.5 – 5.0m, 5.0 – 7.5m and so on. These "elevation bands" where used as baseline for the subsequent flood hazard risk classification.

For the assessment of the flood risk in estuaries, a desktop based, conceptual flood hazard risk classification scheme was developed. In this scheme the topography of the estuaries between the 0m and the 20m elevation contour was classified into 2.5m intervals. Based on expert knowledge and limited historical flood information, for each of these 2.5m intervals one out of 5 flood risk categories was assigned, ranging from 1: very low risk to 5: very high risk. See section 4.1.2 for more detail on the desktop based flood hazard risk classification process.

[3] The LiDAR data available for 50% of the coast turned out to be too inconsistent for use in the estuary assessment.

4.1.3 Desktop fluvial flood hazard risk classification scheme

Given that it is impossible to assess the flood risk for each of the 290 South African estuaries individually, it was decided to use the updated South African estuary ecosystem classification (Van Niekerk et al. 2020) as baseline. This classification categorises all estuaries according to climatic and fluvial characteristics. Table 9 provides a summary of the distribution of estuary types across the different biogeographical zones in the country.

Using the key estuary features described in Section 2.6 and information on the estuary floodplain and openwater area, mean annual runoff (MAR), regional rainfall regime and limited data and anecdotal information on flood levels, the flood hazard risk for each of the primary estuary types was determined (Table 10 to Table 18).

As for the open coast, the assigned flood hazard risk for estuaries categories range from very high to low. However, given the lack of detailed localised hydrological flood modelling, the assignment of 'low risk' in this case is problematic, as it might be misleading. While for those areas the risk of coastal and estuarine flooding might indeed be low, this assessment cannot assess the risk of localised inundation as a result of poor drainage caused by retaining walls; blocked urban drainage systems; and road/rail infrastructure. The impacts of such localised features would need site specific hydrodynamic/flood modelling. Therefore, the Low category is indicated as '*grey*' in the estuaries map to distinguish it from the ocean flooding.

Table 9: Distribution of estuarine ecosystem types across four biogeographical regions (Van Niekerk et al. 2020)

Estuary type	# of estuaries in type			
	Cool Temperate	**Warm Temperate**	**Subtropical**	**Tropical**
Estuarine Bay		1	1	
Estuarine Lagoon	1			
Estuarine Lake	4	3	4	2
Large Fluvially Dominated	1	1	5	
Large Temporarily Closed	9	40	45	
Predominantly Open	3	25	16	
Small Fluvially Dominated	1	6		
Small Temporarily Closed	8	48	60	
Arid Predominantly Closed	6			
Total	**33**	**124**	**131**	**2**

Estuarine bay systems (Knysna and Durban Bay) have very little freshwater input into a relative large surface area, i.e. relative small floods are attenuated over a large surface area resulting in very little elevation in water levels during events. This generalisation is supported by water level recorder data from Knysna and Durban Bay (e.g. Department of Water and Sanitation tidal recorder K5T001), showing very little sensitivity to freshwater input in middle and lower reaches (<10cm) and only limited increase in more constricted upper reaches. Therefore, the overall risk of fluvial flooding is very low. Table 10 provides a summary of the risk categories associated with this type of estuary. Note that not all estuary types occur in all climate regions.

Table 10: Flood hazard risk categories allocated to Estuarine Bay type estuaries

Contour level (m)	Cool Temperate	Warm Temperate	Subtropical	Tropical
0 - 2.5		Very High	Very High	
2.5 - 5.0		Medium	Medium	
5.0 - 7.5		Very Low	Very Low	
7.5 - 10.0		Very Low	Very Low	
10.0 - 12.5		Very Low	Very Low	
12.5 - 15.0		Very Low	Very Low	
15.0 - 17.5		Very Low	Very Low	
17.5 - 20		Very Low	Very Low	

There is no risk of fluvial flooding associated with Estuarine Lagoons such as Langebaan which are groundwater fed. However, there is some wave setup and build-up of equinox tides in this system.

Table 11 provides a summary of the risk categories associated with this type of estuary.

Table 11: Flood hazard risk categories allocated to Estuarine Lagoon type estuaries

Contour level (m)	Cool Temperate	Warm Temperate	Subtropical	Tropical
0 - 2.5	Very High			
2.5 - 5.0	Low			
5.0 - 7.5	Very Low			
7.5 - 10.0	Very Low			
10.0 - 12.5	Very Low			
12.5 - 15.0	Very Low			
15.0 - 17.5	Very Low			
17.5 - 20	Very Low			

Estuarine Lakes (e.g. Verloren, Swartvlei, St Lucia), similar to Estuarine bays, have low freshwater input to relative large surface areas, i.e. floods are attenuated over a large surface area. However Estuarine Lakes inlets close for months, to years, at a time causing extensive build-up of marine sediments in the mouth area (both in width and height); thereby increasing the risk of flooding significantly (Department of Water and Sanitation tidal recorder G4T004, G4T003, K3T006, W3T002, W7T003). In addition, most estuarine lakes are confined in their upper reaches often leading to significant higher upstream floods levels, especially if the mouth is closed at the time of flooding. Therefore, the overall risk of fluv ial flooding is medium at lake systems. Table 12 provides a summary of the risk categories associated with this type of estuary.

Table 12: Flood hazard risk categories allocated to Estuarine Lake type estuaries

Contour level (m)	Cool Temperate	Warm Temperate	Subtropical	Tropical
0 - 2.5	Very High	Very High	Very High	Very High
2.5 - 5.0	High	High	High	High
5.0 - 7.5	Low	Low	Low	Low
7.5 - 10.0	Very Low	Very Low	Very Low	Very Low
10.0 - 12.5	Very Low	Very Low	Very Low	Very Low
12.5 - 15.0	Very Low	Very Low	Very Low	Very Low
15.0 - 17.5	Very Low	Very Low	Very Low	Very Low
17.5 - 20	Very Low	Very Low	Very Low	Very Low

Predominantly Open estuaries (e.g. Olifants, Swartkops, uMngeni) are generally medium to large in size and fed by large catchments that generate high flood volumes. However, due to their large surface area flood inundation level are often underestimated in this type of system, for example, recent flood level studies on Groot Berg and Breede estuaries indicated that 1: 50 and 1: 100 year floods achieve levels of ~5 m MSL (flood lines available on DEFF OCIMS Coastal viewer). In addition, historical literature, e.g. Begg (1979, 1984a&b), provides also records of very high flood levels along the South African coast in this type of estuary.

It should be noted that freshwater runoff also increases notably from west to east, with related increase in flood peaks. Table 13 provides a summary of the risk categories associated with this type of estuary. The results show an increase in risk from the Cool Temperate to the Subtropical region. In addition, five Subtropical estuaries (Msikaba, Mtentu, uMthavuna, uMzimkhulu and uMkhomazi) were identified that exhibit a very high ratio of MAR to estuary storage area (size). In these systems the flood hazard risk categories were increased to reflect increased risk of flooding in these systems.

Table 13: Flood hazard risk categories allocated to Predominantly Open type estuaries

Contour level (m)	Cool Temperate	Warm Temperate	Subtropical	Subtropical **High Inflow: storage area ratio*	Tropical
0 - 2.5	Very High	Very High	Very High	Very High	
2.5 - 5.0	High	High	High	High	
5.0 - 7.5	Low	Medium	High	High	
7.5 - 10.0	Very Low	Low	Medium	Medium	
10.0 - 12.5	Very Low	Low	Low	Medium	
12.5 - 15.0	Very Low	Very Low	Very Low	Low	
15.0 - 17.5	Very Low	Very Low	Very Low	Very Low	
17.5 - 20	Very Low	Very Low	Very Low	Very Low	

Large Fluvially Dominated estuaries (e.g. Orange, uThukela, Mbashe) are characterised by high fluvial input versus relative small estuarine surface area, resulting in extremely high flood levels. Along the Warm Temperate and Subtropical regions these systems are also relatively confined and incised, thus increasing flood risk from west to east. Table 14 provides a summary of the risk categories associated with this type of estuary.

Table 14: Flood hazard risk categories allocated to Large Fluvially Dominated type estuaries

Contour level (m)	Cool Temperate	Warm Temperate	Subtropical	Tropical
0 - 2.5	Very High	Very High	Very High	
2.5 - 5.0	Very High	Very High	Very High	
5.0 - 7.5	Medium	High	High	
7.5 - 10.0	Low	High	High	
10.0 - 12.5	Very Low	High	High	
12.5 - 15.0	Very Low	Medium	Medium	
15.0 - 17.5	Very Low	Low	Low	
17.5 - 20	Very Low	Very Low	Very Low	

Small Fluvially Dominated estuaries (e.g. Steenbras, Bloukrans and Storms), are also characterised by high fluvial input versus very small estuarine surface areas, resulting in extremely high flood levels. These systems occur along the rocky Tsitsikamma coastline and are highly incised, hence the high flood risk. Table 15 provides a summary of the risk categories associated with this type of estuary.

Table 15: Flood hazard risk categories allocated to Small Fluvially Dominated type estuaries

Contour level (m)	Cool Temperate	Warm Temperate	Subtropical	Tropical
0 - 2.5	Very High	Very High		
2.5 - 5.0	Very High	Very High		
5.0 - 7.5	High	High		
7.5 - 10.0	Medium	Medium		
10.0 - 12.5	Low	Low		
12.5 - 15.0	Very Low	Very Low		
15.0 - 17.5	Very Low	Very Low		
17.5 - 20	Very Low	Very Low		

Large Temporarily Closed estuaries (e.g. Groot Brak, Seekoei, iZinkwazi) are medium to large in size with relative low runoff feeding into them. These systems all close off from the sea from time-to-time, leading to the build-up of marine sediments in the mouth area during the closed period, thus increasing risk of flooding during closed periods (Department of Water and Sanitation tidal recorder K2T004, K4H100, P4T002). Runoff increases from west to east along the coast, with resulting increase in risk from the Cool Temperate to Subtropical region. One Cool Temperate estuary, Palmiet, was identified with a very high MAR to storage ratio indicating very high flood levels in this system. Table 16 provides a summary of the risk categories associated with this type of estuary.

Table 16: Flood hazard risk categories allocated to Large Temporarily Closed type estuaries

Contour level (m)	Cool Temperate	Cool Temperate ****High Inflow: storage area ratio***	Warm Temperate	Subtropical	Tropical
0 - 2.5	Very High	Very High	Very High	Very High	
2.5 - 5.0	Very High	Very High	Very High	Very High	
5.0 - 7.5	Medium	Medium	High	High	
7.5 - 10.0	Low	Low	High	High	
10.0 - 12.5	Very Low	Low	Medium	Medium	
12.5 - 15.0	Very Low	Very Low	Low	Low	
15.0 - 17.5	Very Low	Very Low	Very Low	Very Low	
17.5 - 20	Very Low	Very Low	Very Low	Very Low	

Small Temporarily Closed estuaries (e.g. Onrus, Noetsie, Haga-haga, uVuzana) are small systems (< 15 ha) that are generally fed by small catchments. They are thus representing slightly lower flood risk categories than Large Temporarily Closed estuaries (Department of Water and Sanitation tidal recorder U7T001, K8T004; unpublished field observations). However, as these estuaries also closed for extended periods, they still represent a significant flood risk to surrounding land scape (Begg 1979, 1984a&b).

In addition, a number of estuaries was identified that display a high MAR to estuarine storage area ratio, indicating potentially higher flooding risk. Adjustments were therefore made to accommodate the increase risk at the following estuaries: Cool Temperate - Buffels (Oos); Warm Temperate - Tweekuilen, Gwaing, Matjies, Klipdrif (Oos); and Subtropical - Mkweni, uMuntongazi, uVunguza. Table 17 provides a summary of the risk categories associated with this type of estuary.

Table 17: Flood hazard risk categories allocated to Small Temporarily Closed type estuaries

Contour level (m)	Cool Temperate	Cool Temperate ****High Inflow: storage area ratio***	Warm Temperate	Warm Temperate ****High Inflow: storage area ratio***	Sub-tropical	Sub-tropical ****High Inflow: storage area ratio***	Tropical
0 - 2.5	Very High	Very High	Very High	Very High	Very High	Very High	
2.5 - 5.0	Very High	Very High	Very High	Very High	Very High	Very High	
5.0 - 7.5	Medium	Medium	Medium	High	Medium	High	
7.5 - 10.0	Low	Low	Medium	Medium	Medium	Medium	
10.0 - 12.5	Very Low	Low	Low	Low	Low	Low	
12.5 - 15.0	Very Low	Very Low	Very Low	Very Low	Very Low	Low	
15.0 - 17.5	Very Low	Very Low	Very Low	Very Low	Very Low	Very Low	
17.5 - 20	Very Low	Very Low	Very Low	Very Low	Very Low	Very Low	

Arid Predominantly Closed estuaries occur along the arid west coast of South Africa. This type of catchments tends to have very low river flow interspersed with relatively high flood peaks that occur at decadal time-scales. During the extended closed period the berms of this estuary type can build up very high (>5m MSL) and become vegetated, further increasing the risk of inundation during floods. It should also be noted that floods act as resetting events and often reconfigure the shape of this type of system, i.e. erode new openwater channels and form new sand and mud banks. Table 18 provides a summary of the risk categories associated with this type of estuary.

Table 18: Flood hazard risk categories allocated to Arid Predominantly Closed type estuaries

Contour level (m)	Cool Temperate	Warm Temperate	Subtropical	Tropical
0 - 2.5	Very High			
2.5 - 5.0	High			
5.0 - 7.5	Medium			
7.5 - 10.0	Low			
10.0 - 12.5	Very Low			
12.5 - 15.0	Very Low			
15.0 - 17.5	Very Low			
17.5 - 20	Very Low			

The above mentioned flood hazard risk categories were assigned to the geospatial datasets in the relevant elevation contour range around estuaries. Figure 25 shows the results for the Berg Rivier in the Western Cape. This assessment thus represents an inclusive/conservative approach as the flood elevation levels generally are higher in the upper reaches of estuaries. The longer the estuary, the more noticeable this effect.

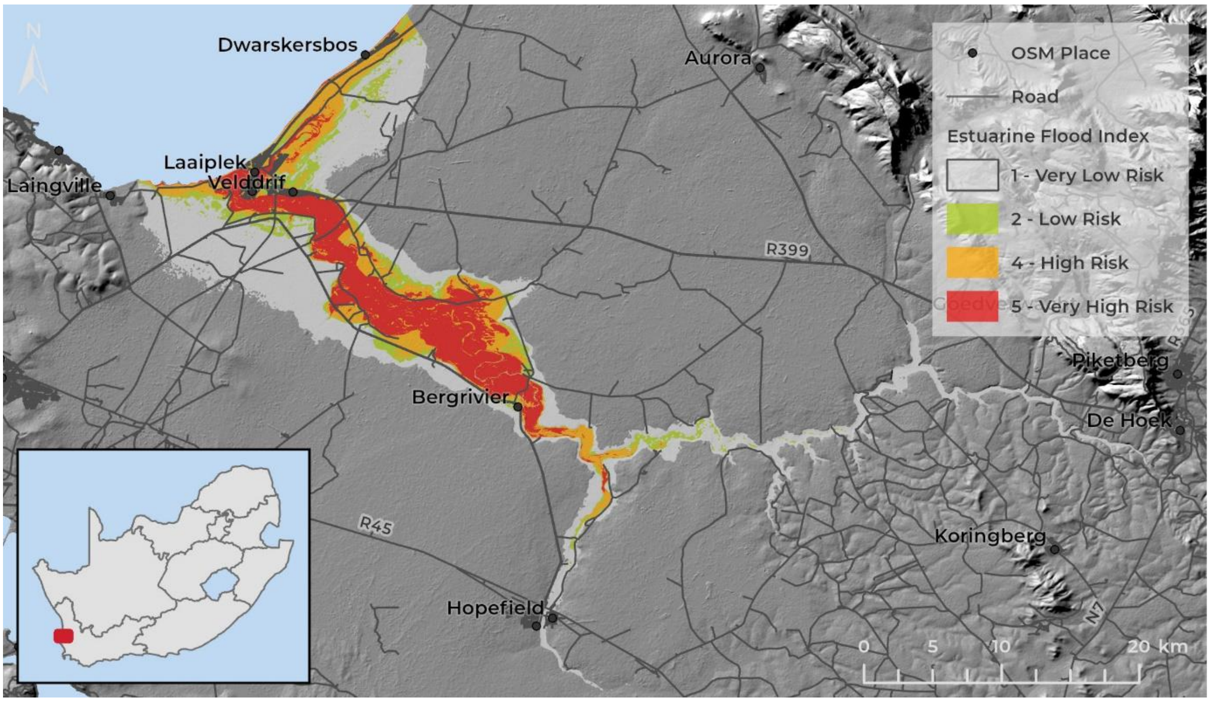

Figure 25: Example of a flood hazard risk map for the Groot Berg estuary based on the classification scheme outlined in Table 13.

4.1.4 Embedding the estuarine flood index into the coastal flood index

Following a precautionary approach, the coastal flood hazard risk index and desktop fluvial flood hazard risk index results were compared, and the highest flood value was assigned to the final raster output file.

4.2 Estuarine erosion index

In addition to applying the Coastal Erosion Index, a desktop based estuarine erosion index was designed to test sensitivity to erosion. **However, given that the project does not entail detailed hydrological and hydrodynamic modelling, this assessment should only be used as an indicator of where more detailed erosion studies should be done in estuaries in future, i.e. this work do not replace the need for detailed site specific erosion lines for planned developments in the EFZ.**

Scouring potential and erodibility of geology was the primary determining factors in estimating the erosion potential in estuaries. This was further modulated by acknowledging the impact of local land cover and bank slope on erosion risk. Figure 26 outlines the estuarine erosion assessment input parameters and processing steps.

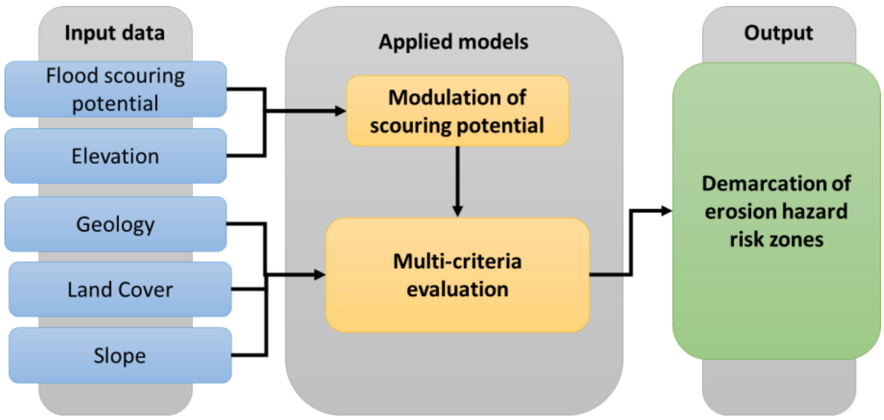

Figure 26: Schematic overview of Estuary Erosion Index components, processes and outputs

To provide an indication of flood scouring potential relative to estuary channel area, the ratio of the Mean Annual Runoff (MAR) to estuarine openwater area was used as broad indicator (Table 19). Small to medium size estuaries fed by large catchments (high ratio value), e.g. uThukela, were more likely to be subjected to extreme resetting flood events and bank erosion in comparisons with systems that receive relative little runoff to a large openwater area (low value), e.g. Verlorenvlei.

Table 19: Hazard risk categories for flood scouring potential

	Hazard Risk				
	Very Low	Low	Medium	High	Very High
	1	2	3	4	5
Conceptual	**Low MAR** **Large channel storage area**	**Low - moderate MAR** **Large - medium channel storage area**	**Moderate MAR** **Medium channel storage area**	**Moderate - high MAR** **Medium - small storage area**	**High MAR** **Small channel storage area**

MAR (m^3x10^6) / Channel volume (m^3)	0 - < 20	20 - < 50	50 - < 200	200 - < 400	400 – 10,000

Further it is acknowledged that the scouring potential is highest in the immediate flood channel and decreases with increased elevation on the estuary banks. Therefore, the 2.5m elevation classes created used as baseline for the estuarine flood risk categories (section 4.1) were reclassified for elevation (and indirectly distance from river channel) related scouring impact

Table 20: Elevation impact on scouring potential.

Hazard Risk					
	Very Low	Low	Medium	High	Very High
	1	2	3	4	5
Weighting for flood scouring potential	0.2	0.5	1	1.5	2
Elevation above MSL (m)	15 – 20	10 – 15	5 – 10	2.5 – 5.0	0 – 2.5

Similar to the coastal erosion index, the attribute classes of the 1:250,000 Geological map (RSA_geo_1k.shp) from the Council for Geoscience were used. The geology types were categorised according to their erodibility (derived from geology hardness classes assigned to geology type), based on expert knowledge and available information (see Appendix 1).

Table 21: Geology derived erosion coefficient

Geology erodibility					
	Very Low	Low	Medium	High	Very High
Erodibility[4]	1	2	3	4	5
Erosion coefficient	0.1	0.2	0.4	0.9	1

As source for land cover and vegetation in the coastal zone, the South African Land Cover 2013/2014 (SALC 13/14) was extracted for the area from the coastline the 40m inland contour. Table 22 list the risk/sensitivity values assigned per land cover class group according to their erosion sensitivity (see Appendix 2)

Table 22: Erosion hazard risk categories for ground cover

Hazard Risk						
	Very Low	Low	Medium	High	Very High	Not considered
	1	2	3	4	5	0
Land Cover	**Indigenous Forest/ Thicket /Dense bush**	**Herbaceous vegetation/**	**Wetlands/ seasonal water bodies**	**Cultivated ground**	**Bare soil**	**Urbanised or industrial/ Rural urbanised**

[4] See Appendix 1 for details

While not the primary factor, bank slope can also increase the susceptibility of estuarine banks to erode. The steeper the slope, the more likely the tendency of the banks to erode. Weighting factors were assigned that broadly aligns with the categories listed in Table 23.

Table 23: Erosion hazard risk categories for slope

	Hazard Risk				
	Very Low	Low	Medium	High	Very High
	1	2	3	4	5
Slope	**Flat e.g. mud flats**	**Gentle slope e.g. intertidal areas**	**Moderate Slope e.g. Supratidal incline**	**Steep slope e.g. banks in upper reaches**	**Very steep slope e.g. cliff face**
% Slope	0 - 1.9	2 - 9.9	10 - 29.9	30 - 69.9	>70

No detailed information was available on local protective structures in estuaries. Therefore, this parameter was not included in this index.

References

Begg, GW, 1978. The estuaries of Natal. Natal Town and Regional Planning Report 41: 657pp.

Begg, GW, 1984a. The estuaries of Natal. Part 2. Natal Town and Regional Planning Report 55: 631 pp.

Begg, GW, 1984b. The comparative ecology of Natal's smaller estuaries. Natal Town and Regional Planning Report 62: 1-182.

Bruwer et al., 2018 in: Bruwer A, van Staden M, Le Roux, A, van Niekerk, W, 2017. Disaster management in South Africa. South African Risk and Vulnerability Atlas 2nd edition.

Coelho, C, Arende, C, 2009. Methodology to classify exposure risk to wave actions in the northwest coast of Portugal. 9th International Conference on the Mediterranean Coastal Environment MEDCOAST 09. 10-14 November 2009, Sochi, Russia, p. 813–824.

CSIR, 2018. National Coastal Assessment for South Africa: Deliverable 2: Draft Baseline Report, 31 March 2018. CSIR Report No. CSIR/NRE/ECOS/ER/2018/0078/A.

CSIR GAP (Council for Scientific and Industrial Research, Geospatial Analysis Platform) 2013. Interactive regional profiler. [Online] Available from: http://www.stepsa.org/.

Department of Environmental Affairs (DEA) 2016. Review of all coastal discharges authorised prior to the Integrated Coastal Management Act (No. 24 of 2008). Draft Report for Comment (February 2016). Cape Town, South Africa.

Department of Environmental Affairs (DEA). 2018. National Coastal Assessment for South Africa: Deliverable 2: Draft Baseline Report, 31 March 2018. CSIR Report No. CSIR/NRE/ECOS/ER/2018/0078/A.

Department of Environmental Affairs (DEA). 2019. National Coastal Climate Change Vulnerability Assessment for South Africa: Deliverable 2: Situational Assessment Draft Report, 2 May 2019.

Department of Environment, Forestry & Fisheries (DEFF). 2020. National Coastal Assessment for South Africa: Deliverable 3: Hotspot Detection Report, May 2020.

Department of Environment, Forestry & Fisheries (DEFF). 2020a. National Coastal Climate Change Vulnerability Assessment: Decision Support Tool – User Manual, April 2020.

Department Rural Development and Land Reform, 2019. Draft National Spatial Development Framework. Department of Rural Development and Department Planning Monitoring and Evaluation.

EurOtop, 2018. Manual on wave overtopping of sea defences and related structures. An overtopping manual largely based on European research, but for worldwide application. Van der Meer, J.W., Allsop, N.W.H., Bruce, T., De Rouck, J., Kortenhaus, A., Pullen, T., Schüttrumpf, H., Troch, P. and Zanuttigh, B., www.overtopping-manual.com.

GESAMP (Group of Experts on the Scientific Aspects of Marine Environmental Protection), 1996. The contributions of science to integrated coastal management. GESAMP Reports and Studies No. 61. Rome, Italy: Food and Agriculture Organization of the United Nations.

Harris, LR, Bessinger, M Dayaram, A, Holness, S, Kirkman, S, Livingstone, T-C, Lombard, AT, Lück-Vogel, M, Pfaff, M, Sink, KJ, Skowno, AL, Van Niekerk, L, 2019. Advancing land-sea integration for ecologically meaningful coastal conservation and management. Biological Conservation 237, 81-89, https://doi.org/10.1016/j.biocon.2019.06.020.

Intergovernmental Panel on Climate Change (IPCC-4), 2007. Fourth Assessment Report (AR4), Synthesis Report 1-20. Cambridge: Cambridge University Press. United Kingdom. Online: www.ipcc.ch.

IPCC-5 (2013): Church, JA, Clark, PU, Cazenave, A, Gregory, JM, Jevrejeva, S, Levermann, A, Merrifield, MA, Milne, GA, Nerem, RS, Nunn, PD, Payne, AJ, Pfeffer, WT, Stammer, D, Unnikrishnan, AS, 2013: Sea Level Change. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, TF, Qin, D, Plattner, G-K, Tignor, M, Allen, SK, Boschung, J, Nauels, A, Xia, Y, Bex, V, Midgley, PM (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. Accessible online at https://www.ipcc.ch/report/ar5/.

IPCC, 2019, Summary for Policymakers. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [Pörtner, H-O, Roberts, DC, Masson-Delmotte, V, Zhai, P, Tignor, M, Poloczanska, E, Mintenbeck, K, Nicolai, M, Okem, A, Petzold, J,Rama, B, Weyer, N (eds.)]. In press. Available online at: http://report.ipcc.ch/srocc/pdf/SROCC_SPM_Approved.pdf

Kopp, RE, DeConto, RM, Bader, DA, Hay, CC, Horton, RM, Kulp, S, Oppenheimer, M, Pollard, D, Strauss, BH, 2017. Evolving Understanding of Antarctic Ice-Sheet Physics and Ambiguity in Probabilistic Sea-Level Projections, Earth's Future, 5. https://doi.org/10.1002/2017EF000663

Le Roux A, Van Huyssteen E, Van Niekerk W, Mans G, 2017. Chapter: Profiling the risks and vulnerabilities of South African Settlements. South African Risk and Vulnerability Atlas 2nd edition.

Le Roux, A, Makhanya, S, Arnold, K, Mans, G, van Tonder, L, Wools, L, 2018. The Green Book: Settlement Design Guidelines for Climate Change Adaptation in South Africa. Projecting the growth/decline of South African settlements.

Le Roux, A, van Huyssteen, E, Arnold, K, Ludick, C, 2019. Green Book. The vulnerabilities of South Africa's settlements. Pretoria: CSIR. Available at: https://pta-gis-2-web1.csir.co.za/portal/apps/GBCascade/index.html?appid=280ff54e54c145a5a765f736ac5e68f8.

Lück-Vogel, M, Le Roux, A, Ludick, C, 2019. Green Book. The impact of climate changes on coastal zones. Pretoria: CSIR. Available at: https://pta-gis-2-web1.csir.co.za/portal/apps/GBCascade/index.html?appid=0bd477eac462450c9d6e528c2d195434

The Green Book: Settlement Design Guidelines for Climate Change Adaptation in South Africa. Projecting the growth/decline of South African settlements.

Mather, A, Garland, G, Stretch, D 2018. Southern African sea levels: corrections, influences and trends. African Journal of Marine Science 31(2): 145–156.

McKelly, DH, Rogerson CM, van Huyssteen, E, Maritz, J, Ngidi, M, 2017. Spatial trends in tourism within South Africa: The expected and the surprising. In Geomatics Indaba 2017, 21-23 August 2017, Durban ICC, Durban.

Millennium Assessment 2005. Ecosystems and Human Well-being: Synthesis. Island Press, Washington, DC. https://www.millenniumassessment.org/en/Reports.html

Operation Phakisa, 2015. Small harbours – unlocking the economic potential of South Africa's Oceans. Presentation to the Small Harbours Focus Group, Operation Phakisa – Oceans Economy Review Workshop. 15 October 2015. https://www.operationphakisa.gov.za/operations/oel/Ocean%20Economy%20Lab%20Documents/5.1%20Small-Harbours_20151015_OPOE-Review-Workshop%20(1).pdf.

Pelling, M, Blackburn, S, 2013. Megacities and the Coast: Risk, Resilience and Transformation. Routledge, London & New York.

The Green Book 2018: Settlement Design Guidelines for Climate Change Adaptation in South Africa. High resolution Climate Change projection data (CSIR & IDRC, 2018).

Theron et al. (2014). MetOcean Conditions & Vulnerability - Medium resolution wave climate & run-up, South African Coastal Vulnerability Assessment, 11 September 2014.

Theron, AK, 2016. Methods for Determination of Coastal Development Setback Lines in South Africa. PhD thesis. Dissertation for the degree of Doctor of Engineering, Faculty of Civil Engineering, Stellenbosch University, pp. 391.

Van Huyssteen, E, Green, C, Songoni, Z, Maritz, J, McKelly, D, Ragoasha M, Mans, G. Under Review. Generating evidence for spatial decision-support in the context of rapidly changing urban contexts in the global South: Reflections on the development of the South African functional town typology and stepSA collaborative R&D initiative (2008-2018). Book Chapter in StepSA and Overview of Decision Support in South Africa. DST, HSRC and CSIR.

Van Huyssteen, E, Maritz, J, 2019. Functional City, Town and Settlement Typology. Available at http://stepsa.org/settlement_typology.html. Accessed 10 June 2019.

Van Niekerk, L, Adams, JB, Bate, GC, Forbes, N, Forbes, A, Huizinga, P, Lamberth, SJ, MacKay, F, Petersen, C, Taljaard, S, Weerts, S, Whitfield, AK, Wooldridge, TH, 2013. Country-wide assessment of estuary health: An approach for integrating pressures and ecosystem response in a data limited environment. Estuarine, Coastal and Shelf Science 130: 239-251.

Van Niekerk, L, Taljaard, S, Adams, JB, Fundisi, D, Huizinga, P, Lamberth, SJ, Mallory, S, Snow, GC, Turpie, JK, Whitfield, AK, Wooldridge, TH, 2015. Desktop Provisional Ecoclassification of the Temperate Estuaries of South Africa. WRC Report No K5/2187.

Van Niekerk, L, Adams, JB, Lamberth, SJ, MacKay, F, Taljaard, S, Turpie, JK, Weerts, S, Raimondo, DC 2019 (eds). South African National Biodiversity Assessment 2018: Technical Report. Volume 3: Estuarine Realm. CSIR report number CSIR/SPLA/EM/EXP/2019/0062/A. South African National Biodiversity Institute, Pretoria. Report Number: http://hdl.handle.net/20.500.12143/6373.

Van Niekerk, L, Adams, JB, James, N, Lamberth, S, Mackay, F, Rajkaran, A, Turpie, J, Weerts, S, Whitfield, AK, 2020. An Estuary Ecosystem Classification that encompasses biogeography and a high diversity of types in support of protection and management. African Journal of Aquatic Science 45: 199-216.

Whitfield AK, 1992. A characterisation of southern African estuarine systems. Southern African Journal of Aquatic Sciences 12: 89-103.

Williams, LL, Lück-Vogel, M, 2020. Comparative assessment of the GIS based bathtub model and an enhanced bathtub model for coastal inundation. Journal of Coastal Conservation 24:23 https://doi.org/10.1007/s11852-020-00735-x.

Williams, LL, 2020. Developing a spatial risk profile: assessing building vulnerability to extreme coastal inundation hazard. PhD thesis, Department for Geography and Environmental Studies, Stellenbosch University, Stellenbosch, South Africa.

Appendix

Appendix 1 – Geological erosion ranking

Class	Geological Erosion Risk	Geological Description
0	N/A	Water
1	Very Low	Alaskitic granite, aplite, pegmatite
		Basic volcanic rocks (tholeiites, picrite basalts and nephelinites)
		Bimodal suite comprising mafic two-pyroxene granulites and felsic charnockites
		Calcitic and dolomitic marble plus thin quartzites
		Charnockitic, megacrystic, gneissic granite
		Coarse-grained, megacrystic, granitic biotite-garnet augen gneiss
		Coarse-grained, porphyritic granite (monzogranite / quartz monzonite)
		Coarse-grained, porphyritic, biotite-rich granite with large K-feldspar phenocrysts occurring in the Saldanha Batholith
		Contaminated, fine- to medium-grained, mesocratic granite
		Diabase
		Diorite, subordinate gabbro
		Dolerite dyke
		Equigranular biotite and quartz-feldspar gneiss, augen gneiss
		Fine-grained sandstone, siltstone
		Fine-grained, feldspathic sandstone, subordinate mudrock
		Fossiliferous glauconitic siltstone and fine-grained sandstone, conglomeratic towards the base
		Gneissic granite and granodiorite
		Granite
		Granite (generally porphyritic), minor quartz monzonite, syenite and granodiorite
		Granite, quartz-monzonite, quartz-porphyry
		Grey shale, siltstone and fine-grained sandstone
		Grey, coarse-grained, foliated, megacrystic, augen biotite granite gneiss
		Grey, fine grained biotite microgranite (ex Belmont)
		Grey, fine- to medium-grained quartz-feldspar (Â±biotite, Â±sillimanite) gneiss
		Grey, fine-grained, granodioritic gneiss
		Grey, generally fine-grained gneissic granite
		Grey, medium- to coarse-grained biotite-hornblende gneiss
		Intrusive, generally pink-weathering augenbiotite gneiss
		Layered pelitic and semipelitic paragneisses/migmatites
		Layered, medium- to coarse-grained, grey, gneissic quartz diorite, tonalite, trondhjemite and granodiorite
		Leucocratic, megacrystic granite, gneissic in places
		Light pink and grey gneissose garnet leucogranite, migmatite
		Limestone, dolomite, marble
		Mafic two-pyroxene granulite and gneiss
		Medium- to coarse-grained, pinkish grey, foliated, felspar-porphyritic biotite granite
		Megacrystic charnockite
		Mesocratic, coarse-grained, augen biotite gneiss
		Metabasaltic greenstone

Class	Geological Erosion Risk	Geological Description
		Mica and quartz schist, greywacke, thin limestone units
		Micaceous almandine-staurolite-kyanite schist, quartzite
		Network of dolerite sills, sheets and dykes, mainly intrusive into the Karoo Supergroup
		Occasional sandstone beds
		Phyllite, shale, slate, schistose "grits
		Phyllitic shale, greywacke, limestone, arenite
		Phyllitic shale, greywacke, subordinate limestone
		Pink quartz syenite, monzonite
		Pink, very coarse-grained, megacrystic granite
		Quartz schist, mica schist
2	Low	Amphibolite, talc- chlorite schist
		Banded biotite-bearing amphibolitic gneiss
		Biotite-granite gneiss
		Biotite-plagioclase gneiss
		Coarse-grained, porphyritic, biotite-rich gneissic granite
		Feldspathic arenite, quartz-mica schist, minor volcanic rocks
		Feldspathic arenite, wacke, mudrock
		Feldspathic quartzite (with lenticular conglomerate interbeds in places), calc-silicate rocks
		Feldspathic quartzite, arkose, intermediate to felsic lava and tuff
		Fine- to coarse-grained sandstone (granuly in places), subordinate mudrock
		Fine- to medium-grained, granodioritic to granitic gneiss
		Fine- to medium-grained, strongly foliated, leucocratic, granodioritic to tonalitic gneiss
		Fossiliferous limestone containing coral
		Granite, granodiorite
		Granite-gneiss
		Granitoid gneiss (intrusive)
		Greenstone with dolomite and chert lenses
		Grey biotite quartz-feldspar gneiss
		Grey, fine- to medium-grained quartz-feldspar (┬▒biotite, ┬▒sillimanite) gneiss
		Grey-green sandy tillite, sandstone and muddy tillite overlain by grey shale and siltstone and thin-bedded sandstone
		Greyiotite quartz-feldspar gneiss
		Greywacke, schist, arkose, conglomerate, impersistent limestone and quartzite
		Grey-weathering, massive or large-scale cross-bedded calcarenite and calcareous sandstone
		Limestone, dolomite
		Limestone, dolomite, partly brecciated
		Limestone, dolomite, phyllite, calcarenite
		Medium grained charnockite
		Metaquartzite (feldspathic, glassy, ferruginous), leucogneiss
		Muscovite-biotite granite gneiss
		Paragneisses, metamorphosed to granulite facies
		Phyllite, quartzite, conglomerate, arkose, greywacke
		Pink augen gneiss, equigranular gneiss, leucogneiss

Class	Geological Erosion Risk	Geological Description
		Pink-weathering, medium- to coarse-grained, equigranular biotite gneiss (with augens in places) and subordinate fine- to medium-grained biotite-poor leucocrastic gneiss
		Purple-weathering, charnockitic, coarse-grained and augen gneiss
		Quartz-feldspar gneiss (metamorphosed greywacke or feldspathic quartzite), quartz-chlorite-sericite schists (partly metabasalts?)
		Quartzite, arkose, phyllite, conglomerate
		Quartzite, quartz-sericite schist
		Quartzite, schist, phyllite
		Quartzites, schists, peltic and quartzo-feldspathic gneisses
		Quartz-muscovite-biotite-garnet+_kyanite+-staurolite schist
		Sandstone, minor siltstone and mudstone
		Sandstone, siltstone, conglomerate
		Shale, greywacke, quartzite, minor volcanic rocks
		Sheet-like intrusions consisting of foliated, equigranular to blastoporphyritic, mafic to intermediate granulites
		Silcrete
		Sillimanite-garnet-biotite and quartz-biotite-garnet gneiss
		Streaky pink quartz-feldspar gneiss and migmatite, subordinate amphibolite and calc-silicate rocks
		Tuff, amygdaloidal lava, feldspathic arenite/greywacke
3	Medium	Acid lavas (rhyolites with some dacites), minor tuffs
		Acid to intermediate volcanic (mainly pyroclastic) rocks
		Alternating fine- to very fine-grained sandstone, mudrock and rhythmite
		Arenaceous limestone (calcarenite)
		Arenaceous limestone (shelly in places), calcareous sandstone, subordinate conglomerate
		Breccia/conglomerate, greenish sandstone
		Brownish-weathering, foliated, medium- to coarse-grained biotite-bearing granite, fine-grained, biotite-poor granite
		Brownish-weathering, quartzitic sandstone, subordinate shale and siltstone
		Calcarenite and calcareous sandstone with scattered pebble and coquinite layers
		Calcareous sand/sandstone, gravel/conglomerate, shelly limestone and coquina/coquinite
		Calcareous sandstone (aeolianite) with interbedded palaeosols
		Calcareous sandstone, conglomerate, coquinite
		Calcareous sandstone, sandy limestone
		Calcrete
		Chert lenses
		Conglomerate, quartzite, arkose
		Conglomerate, sandstone, minor shale
		Conglomerate, subordinate lenticular sandstones and claystones
		Coquina, calcarenite, conglomerate
		Dark purple-grey quartz monzonite
		Diamictite (polymictic clasts, set in a poorly sorted, fine-grained matrix) with varved shale, mudstone with dropstones and fluvioglacial gravel common in the north
		Dolomite lenses
		Dolomite, partly brecciated, silicified

Class	Geological Erosion Risk	Geological Description
		Ferricrete
		Fine- to coarse-grained sandstone, shale, coal seams
		Fine- to medium-grained, dark to light grey, feldspathic sandstone, shale
		Fine-grained tuffs, thin tuffaceous sandstones
		Fixed dunes
		Foliated amphibolite and subordinate hornblendite
		Foreign country lithology not recorded
		Generally foliated amphibolitic rocks
		Generally reddish, feldspathic and micaceous sandstone with subordinate quartz arenite, mudrock, granulestone and conglomerate
		Greenish- to bluish-grey and greyish-red mudstone, subordinate sandstone
		Greenish/bluish-grey and (in the west) greyish-red mudstone, subordinate sandstone
		Grey and red mudstone, subordinate sandstone
		Grey or reddish shale and siltstone, subordinate quartzitic sandstone
		Grey shale, siltstone and sandstone
		Greywacke, phyllite, schist, limestone
		Heterogenous layered paragneisses and migmatites with a wide compositional range
		Interbedded lava and tuff
		Massive diamictite and minor ferruginous metasedimentary rocks
		Melanocratic granoblastites, gneisses, orthopyroxenite and enderbitic granolites
		Metagabbro
		Mudrock
		Mudrock, minor sandstone
		Mudrock, sandstone
		Mudrock, sandstone, minor coal seams
		Mudrock, sandstone, shelly limestone, basal conglomerate (with fossil logs)
		Mudrock, siltstone
		Mudrock, subordinate sandstone
		Mudstone (diamictite) or sandstone containing scattered pebbles, cobbles and boulders
		Mudstone, minor sandstone
		Mudstone, siltstone, subordinate sandstone
		Olivine melilitite and olivine nephelinite plugs
		Olivine norite, troctolite gabbro
		Phyllite, "grit", quartzite
		Quartzite, conglomerate / diamictite, schist
		Quartzitic sandstone, minor conglomerate and shale
		Quartzitic sandstone, phyllitic shale, subordinate small-pebble conglomerate
		Quartzitic sandstone, subordinate mudrock
		Red and greenish-grey mudstone, subordinate sandstone
		Red mudrock and interbedded sandstones
		Rhyolite
		Rhyolite plugs, domes and dykes
		Rhythmite, mudrock, minor sandstone
		Sandstone (pebbly in places), conglomerate
		Sandstone (pebbly in places), mudrock
		Sandstone, subordinate conglomerate, breccia and shale

Class	Geological Erosion Risk	Geological Description
		Schist
		Shale with thin siltstones and sandstones in the uppermost part
		Shale, sandstone, diamictite
		Shale, siltstone, quartzitic sandstone
		Shale, siltstone, subordinate sandstone
		Shale, with sandstone-rich units present towards the basin margins in the south, west and northeast and coal seams in the northeast
		Shale; thin yellow tuff and chertbeds, posphatic lenses
		Shelly limestone and sandstone
		Siltstone with shelly and concretionary layers
		Thick-bedded, medium- to coarse-grained, cross-bedded, white-weathering, quartzitic sandstone
		Thin-bedded sandstone, reddish siltstone and shale
		Thinly interlayered psammites and semipelites
		Three sandstone and three shale units
		Three shale units separated by two sandstone units
		Two-pyroxene mafic gneisses, augite amphibolites, calc-silicate rocks
		Unfoliated to weakly layered leucogranodiorite
		Variegated (reddish-brown and greenish) silty mudstone and sandstone, subordinate grey shale and sandstone
		White, siliceous, feldspathic sandstone, subordinate mudrock in places
4	High	Alluvium
		Alluvium, colluvium, eluvium
		Coarse gravels (Curlew Strand Formation)
		Consolidated to semi-consolidated aeolianite (calcarenite) calcareous sand, calcrete lenses
		Fill, reclaimed area
		Fine- to medium-grained, partly calcretized, shelly sand and (aeolian) calcarenite
		Granitic sand with calcrete and dorbank, gypsiferous in places
		Gritty sand
		High-level terrace gravel
		Quartzose sand, pelletal phosphorite, gravel, sandy silt, grey-black carbonaceous kaolinitic clay, peat
		River-terrace gravel
		Sand/sandstone, calcarenite, gravel/conglomerate
		Scree/Talus/Alluvium grading into piedmont gravel
		Semi-consolidated red sand
		Semi-consolidated to consolidated calcareous sandstone and sandy limestone with large-scale cross-bedding
		Terrace gravel
5	Very High	30 m Shoreline terrace (Honderklip Bay Member)
		60 m Shoreline terrace (Avontuur Member)
		Aeolian sand
		Alluvial gravel, sand, silt
		Ancient aeolian sand
		Brackish, calcareous soil
		Brown, loamy sand
		Calcareous and gypsiferous soil
		Dune and beach sand

Class	Geological Erosion Risk	Geological Description
		Fine- to medium-grained sand, clayey sand and silt with a lignite bed up to 2.5 m thick
		Generally unconsolidated, calcareous dune sand
		Gravel, sand, silt
		Gravelly clay
		Light-grey to red sandy soil
		Loam and sandy loam
		Marine terrace deposit
		Mottled, brown, clayey sand
		Pale red to red dune sand
		Red decalcified sand in inland dune cordons
		Red, aeolian sand
		Remobilised plume sand
		Saline soil
		Sand
		Sand, red and grey aeolian dune sand
		Shelly, aeolian sand
		Silt, sand, calc-tufa, minor gravel
		Stabilized,dune plume sand
		Unconsolidated calcareous sand (coasted dunes), minor palaeosols
		Unconsolidated dune sand
		White to flesh-coloured wind-blown sand
		White to grey dune sand
		Yellowish redistributed sand
		Young aeolian sediments; reddish, mobile, vegetated

Appendix 2 – Land cover erosion ranking

Class	Land Cover Erosion Risk	Class Name	Class Number	Group
0	N/A	Mine buildings	SAL_39	mines
		Urban sports and golf (dense tree /	SAL_57	golf and sports grounds
		Urban sports and golf (open tree / bush)	SAL_58	golf and sports grounds
		Urban sports and golf (low veg / grass)	SAL_59	golf and sports grounds
		Urban sports and golf (bare)	SAL_60	golf and sports grounds
		Urban school and sports ground	SAL_52	golf and sports grounds
		Urban commercial	SAL_42	urban
		Urban industrial	SAL_43	urban
		Urban informal (dense trees / bush)	SAL_44	urban
		Urban informal (open trees / bush)	SAL_45	urban
		Urban informal (low veg / grass)	SAL_46	urban
		Urban informal (bare)	SAL_47	urban
		Urban residential (dense trees / bush)	SAL_48	urban
		Urban residential (open trees / bush)	SAL_49	urban
		Urban residential (low veg / grass)	SAL_50	urban
		Urban residential (bare)	SAL_51	urban
		Urban smallholding (dense trees / bush)	SAL_53	urban
		Urban smallholding (open trees / bush)	SAL_54	urban
		Urban smallholding (low veg / grass)	SAL_55	urban
		Urban smallholding (bare)	SAL_56	urban
		Urban township (dense trees / bush)	SAL_61	urban
		Urban township (open trees / bush)	SAL_62	urban
		Urban township (low veg / grass)	SAL_63	urban
		Urban township (bare)	SAL_64	urban
		Urban village (dense trees / bush)	SAL_65	urban
		Urban village (open trees / bush)	SAL_66	urban

Class	Land Cover Erosion Risk	Class Name	Class Number	Group
		Urban village (low veg / grass)	SAL_67	urban
		Urban village (bare)	SAL_68	urban
		Urban built-up (dense trees / bush)	SAL_69	urban
		Urban built-up (open trees / bush)	SAL_70	urban
		Urban built-up (low veg / grass)	SAL_71	urban
		Urban built-up (bare)	SAL_72	urban
1	Very Low	Indigenous Forest	SAL_4	natural woody
		Thicket /Dense bush	SAL_5	natural woody
		Shrubland fynbos	SAL_8	natural woody
2	Low	Woodland/Open bush	SAL_6	natural woody
		Low shrubland	SAL_9	natural woody
3	Medium	Water seasonal	SAL_1	waterbodies
		Wetlands	SAL_3	wetlands
4	High	Water permanent	SAL_2	waterbodies
		Plantations / Woodlots mature	SAL_32	plantations
		Plantation / Woodlots young	SAL_33	plantations
		Plantation / Woodlots clearfelled	SAL_34	plantations
		Cultivated orchards (high)	SAL_16	agriculture
		Cultivated orchards (med)	SAL_17	agriculture
		Cultivated orchards (low)	SAL_18	agriculture
		Cultivated permanent pineapple	SAL_22	agriculture
		Cultivated vines (high)	SAL_19	agriculture
		Cultivated vines (med)	SAL_20	agriculture
		Cultivated vines (low)	SAL_21	agriculture
		Cultivated cane pivot - crop	SAL_26	agriculture
		Cultivated cane pivot - fallow	SAL_27	agriculture
		Cultivated cane commercial - crop	SAL_28	agriculture
		Cultivated cane commercial - fallow	SAL_29	agriculture

Class	Land Cover Erosion Risk	Class Name	Class Number	Group
		Cultivated cane emerging - crop	SAL_30	agriculture
		Cultivated cane emerging - fallow	SAL_31	agriculture
		Cultivated comm fields (high)	SAL_10	agriculture
		Cultivated comm fields (med)	SAL_11	agriculture
		Cultivated comm fields (low)	SAL_12	agriculture
		Cultivated comm pivots (high)	SAL_13	agriculture
		Cultivated comm pivots (med)	SAL_14	agriculture
		Cultivated comm pivots (low)	SAL_15	agriculture
		Cultivated subsistence (high)	SAL_23	agriculture
		Cultivated subsistence (med)	SAL_24	agriculture
		Cultivated subsistence (low)	SAL_25	agriculture
		Grassland	SAL_7	natural herbaceous
		Mines water seasonal	SAL_37	mines
		Mines water permanent	SAL_38	mines
5	Very High	Bare none vegetated	SAL_41	bare soil
		Erosion (donga)	SAL_40	bare soil
		Mines 1 bare	SAL_35	mines
		Mines 2 semi-bare	SAL_36	mines