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COASTAL FLOODING HAZARD ASSESSMENT

WORKSTREAM 4: RESEARCH REPORT

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1 INTRODUCTION

Climate change is expected to affect the oceans' coasts in a variety of impacts. Sea levels are expected to be about 0.8 m higher by 2100 than today (see Appendix 2 for details) which will lead to flooding of low lying coastal areas, where no protective structures are in place. Increased storm frequency and intensity will affect coastal flooding through storm surges and wave run-up.

Storm surge is the increase in water level of the whole [inshore] water body if e.g. wind pushes into a bay and/or low barometric pressure results in raising of local seawater levels. **Wave run-up** occurs independent or on top of a surge, dependent on the wave height and local exposure of the coast and other factors such as slope, wave length, etc.

Further, more intense wave action is expected to have greater impact on coastal sediment dynamics, likely leading to increased rates of coastal erosion (and locally sedimentation). These predictions of an increase of coastal hazards are becoming highly relevant in the light of the following statistics:

- about 40% of the global population living within 100 km of the oceans' coasts (Millennium Ecosystem Assessment (2005) and Figure 1);
- about 40% of South Africans are living within 60 km of the oceans' coasts (DEA 2014); and
- approximately 60% of the South African economy depends on coastal natural resources and trade infrastructure such as ports.

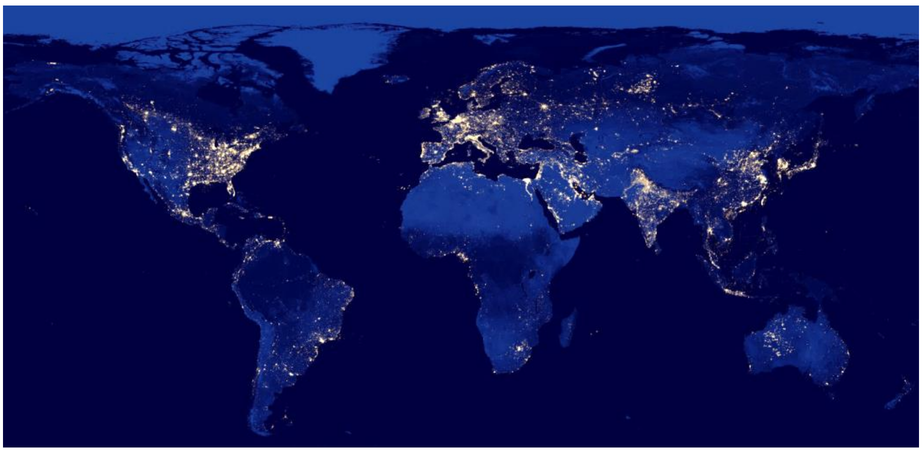

Figure 1: Indication of global population densities as derived from Landsat nightlight images.

Source: https://eoimages.gsfc.nasa.gov/images/imagerecords/79000/79765/dnb_land_ocean_ice.2012.3600x1800.jpg

These figures highlight the enormous importance of coastal environments and resources but also indicate the potential risk and vulnerability that coastal populations and assets in South Africa (and beyond) are exposed to. In order for better climate change resilience, risks and vulnerability to the coastal hazards sea level rise, storm surge flooding and wave run-up and coastal erosion need to be assessed.

At the CSIR, work relating to all three hazards has been conducted in previous projects for parts of the South African and Mozambican coast at different levels of detail and scale. The general approach followed common coastal engineering practices as applied in South Africa and internationally (e.g. Coelho and Arede, 2009).

This project aims to adopt those existing methods for better identification of coastal areas in South Africa potentially affected by coastal storm-related flooding and sea level rise as input for climate change resilience. At this stage of the project, wave run-up and coastal erosion could not be assessed. The research team has identified it as a critical element, and is including it in continued research activities. Flooding through rising water levels in the hinterland e.g. through excessive rain fall and river flooding is addressed in the research report on flooding. Potential flood risks through tsunamis do not form part of this research report.

2 METHODOLOGY

The concept for the storm surge flooding approach is largely based on the work conducted by André Theron et al. (Theron et al. 2012; Nel et al. 2011; Nel et al. 2014; Theron 2016). While those earlier works produced coastal hazard assessment indices along a one-dimensional transect along the respective coasts (see Appendix 1 for an example), in this project we conduct the hazard assessment in a two-dimensional space, i.e. assessing the coastal area perpendicular to the coastline inland.

The work described in the following section was done in collaboration between the CSIR and the Stellenbosch University's Centre for Geographical Analysis and Department for Civil Engineering.

2.1 Input data

2.1.1 Reference coastline

As coastline reference for this project the polyline vector file National_Coast_Types.shp file was used. While other coastline data exist, this particular one was chosen as it follows the coastline visual on recent remote sensing imagery, e.g. on Google Earth most closely. Other available data sets, apparently digitised at a coarser scale, did not give enough detail on rocky cliffs and highly dynamic sandy coastal areas.

2.1.2 Elevation data

Input data sources for the assessment of elevation were the 5 m Stellenbosch University Digital Elevation Model (SUDEM), and, where available, high-resolution LIDAR DEMs, downsampled to 5 m.

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 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 30 m 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[1], the fusion procedure reduces the effect of surface objects.

LIDAR data to complement the SUDEM were available for about 50% of the SA coast, as indicated in Figure 2 below.

[1] 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).

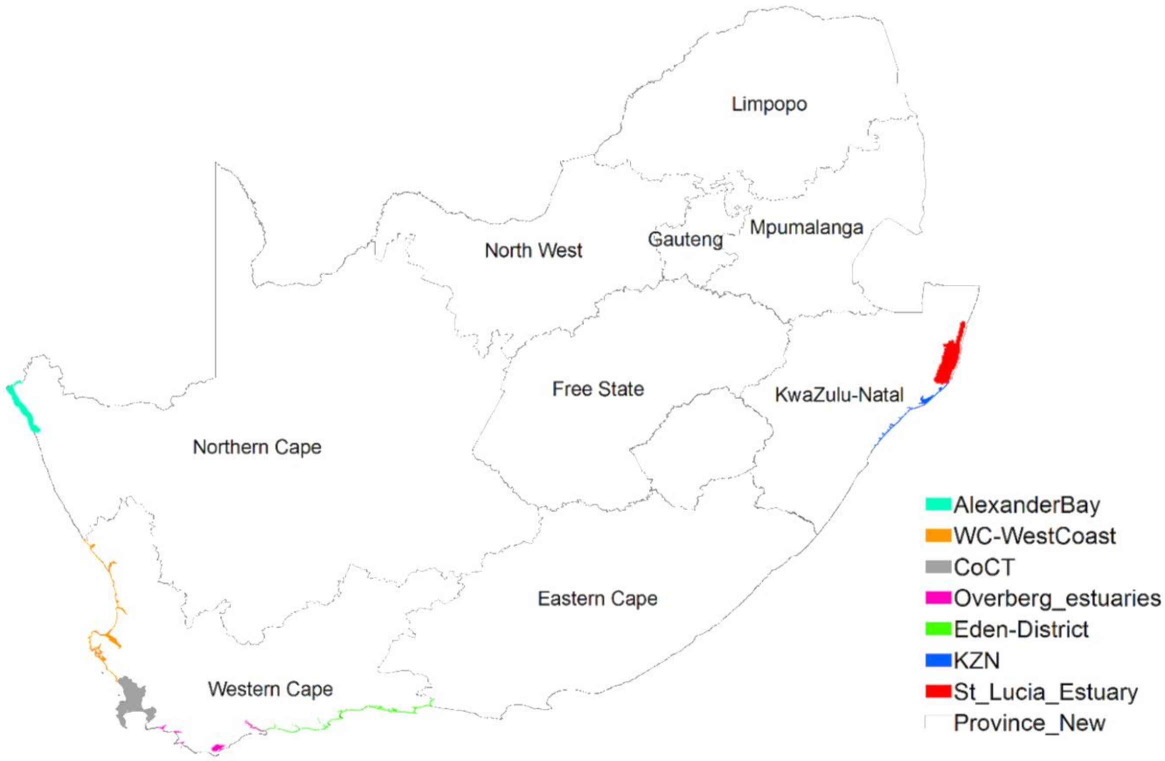

Figure 2: Areas for which LIDAR derived resampled elevation models were used

The LIDAR data used in this project were provided by ALEXCOR, Western Cape Province, City of Cape Town, KZN Province and iSimangaliso Wetland Park. With all LIDAR point data, the respective "last return" or "ground cover" information was used to generate raster DEMs. The bit-depths and NoData values of the various LIDAR DEMs were standardised, and each DEM was resampled to 5m resolution to allow for seamless fusion with the SUDEM. While horizontal spatial detail was lost due the downsampling, the LIDAR-derived 5m DEMs still provide better vertical accuracy than the SUDEM. This is due to the higher vertical accuracies of the original LIDAR point clouds when compared to the topographic maps and SRTM that form the principal base for the SUDEM. All input datasets were combined by overwriting the SUDEM with the LIDAR DEMs (where present), and the final dataset was exported in TIFF format.

2.1.3 Urban edges

The focus of the project is on populated coastal areas only, and excludes currently unpopulated rural areas. As such, datasets for formal and traditional settlements were provided by CSIR Built Environment (GB_TRD_STLMNTS_V8_EAs.shp and

GB_STLMNTS_V8_EAs_140717.shp). Figure 3 shows an example for an area in KwaZulu-Natal.

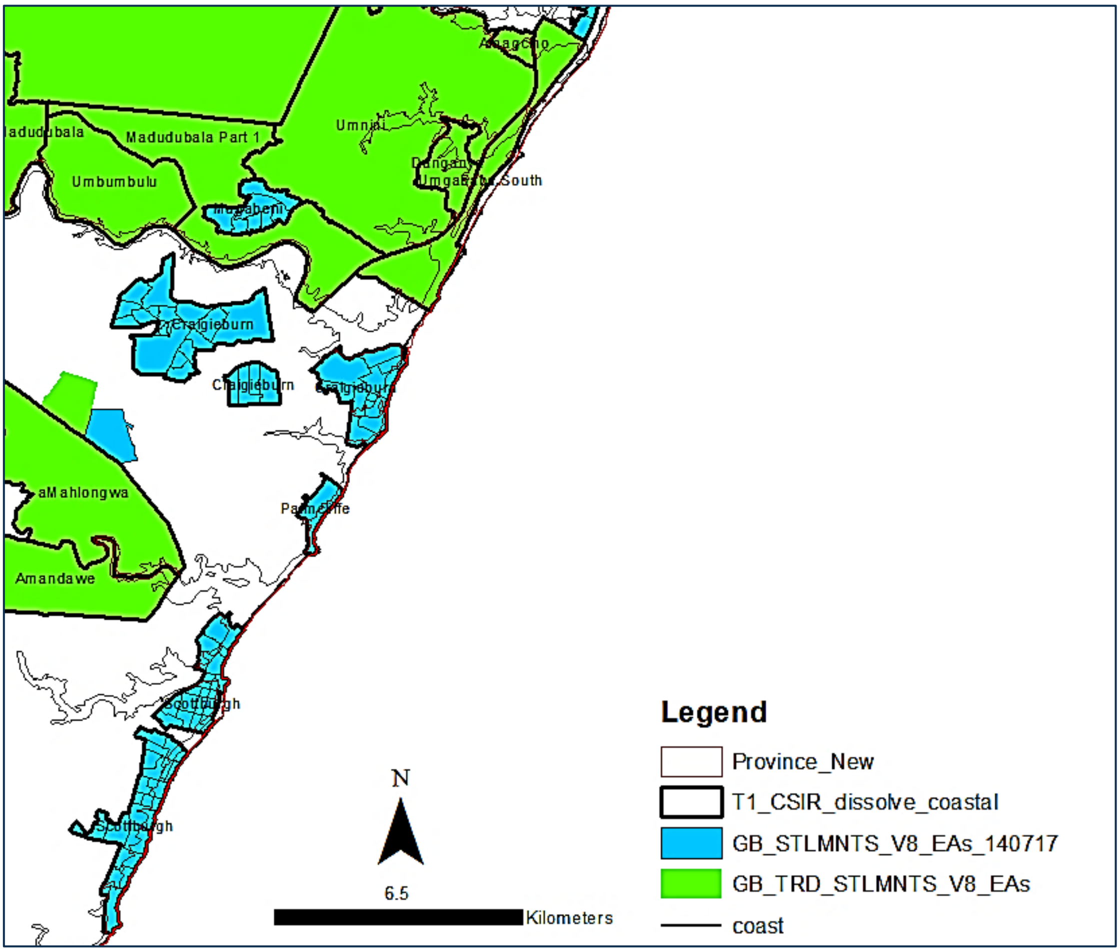

Figure 3: Example of the urban edge data sets for formal (light blue) and traditional (green) settlements for an area in KwaZulu-Natal.

2.2 Definition of the study area

Areas higher than 40 m above Mean Sea Level were generally assumed to be safe from ocean-borne flooding. The 40 m contour was thus derived from the merged DEM product (section 2.1.2) and used as inland boundary of the study area. As seaward boundary the reference coastline (section 2.1.1) was used.

Further, for this project, the focus was only on urbanised areas. Therefore the urban edges data for both, “formal” and “traditional” settlements (section 2.1.3) were used as reference for the definition of the study area. While only areas falling within this urban buffer AND below the 40 m contour are going to be assessed in this project, the processing was conducted for the entire South African coastline. Primary towns, i.e. metropoles have been excluded from the analysis, too.

2.3 Index generation

The coastal flood hazard assessment for the resulting urban study areas was based on two criteria:

a) the elevation above sea level, and
b) the distance (of the settlement) from the coast.

These input criteria were used to create individual hazard indices which were then used to generate the final overall flood hazard index. This process is described below.

2.3.1 Index for elevation above sea level

One key factor determining whether a coastal area is at risk of flooding is its elevation above sea level. The following elevation hazard risk categories were determined, based on Theron (2016).

Elevation (above mean sea-level (MSL))	**Hazard Risk Classification and Score**				
	Very low	Low	Medium	High	Very high
	1	2	3	4	5
Open coast	**>20 – 30 m**	**>10 – 20 m**	**>5 – 10 m**	**>3 – 5 m**	**0 – 3 m**

It is acknowledged that estuaries should be categorised separately, as here the risk of flooding through additional water coming down the catchment, tends to be higher. Due to the complexities of estuarine areas, for this phase of the project the estuaries were assessed using the same categories as the open coast. Refinement of the estuarine areas will be addressed at a later stage. An example for the elevation hazard index for Strand (False Bay, Cape Town) is given in Figure 4 below.

According to the scenarios provided by the IPCC-5 (2013) (see Appendix 2) the sea level is expected to rise between 0.55 m and 1.2 m globally by 2100. In the context of the elevation hazard scoring in the table above, sea level rise will impact areas falling in the category 5 – Very high hazard risk. The hazard risk in the categories 1 to 4 is mainly related to storm events related flooding.

2.3.2 Index for the distance (of the settlement) from the coast

The second criteria element for flood hazard risk was the distance of infrastructure to the shore. This criteria element is relevant for assessment of flood risk as a result of storms where extreme high sea water levels will affect areas close to the coast immediately but take time to propagate inland. The extent and magnitude of flooding of landward areas also depends on the duration and rate of overtopping of the area immediately adjacent to the sea. Low lying areas further inland consequently should have a lower hazard risk than low lying areas close to the coast. The following 'distance from coast' hazard risk categories were determined based on Theron (2016).

Distance of the infrastructure from the coast was calculated using the coastal reference file National_Coast_Types.shp through buffering in ArcGIS. An example of a distance index map is given in Figure 5.

	Hazard Risk Classification and Score				
	Very low	Low	Medium	High	Very high
	1	2	3	4	5
Distance from coast	**>1,000 m**	**>200 – 1,000 m**	**>50 – 200 m**	**>20 – 50 m**	**0 – 20 m**

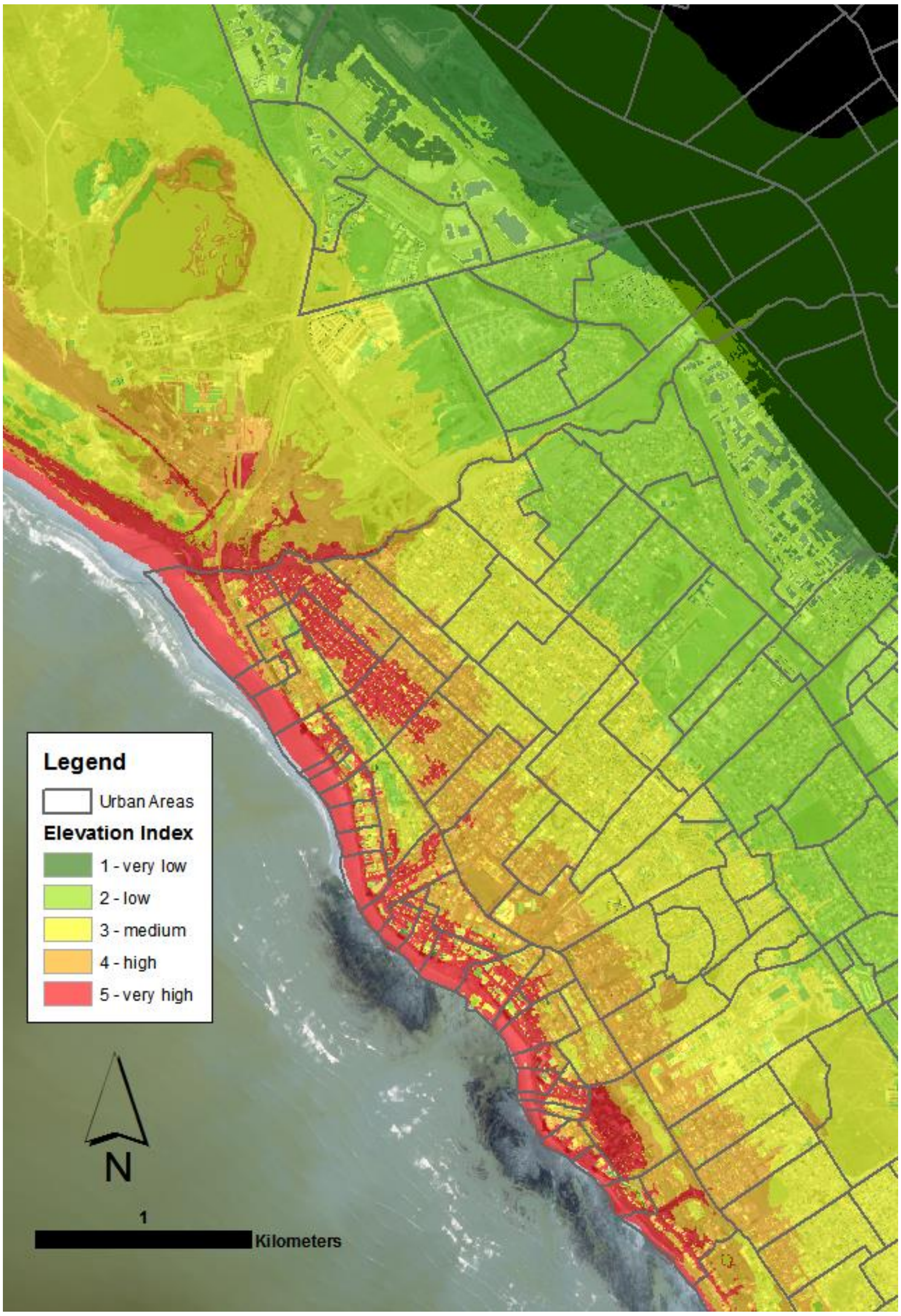

Figure 4: Elevation index for Strand (False Bay, Cape Town).

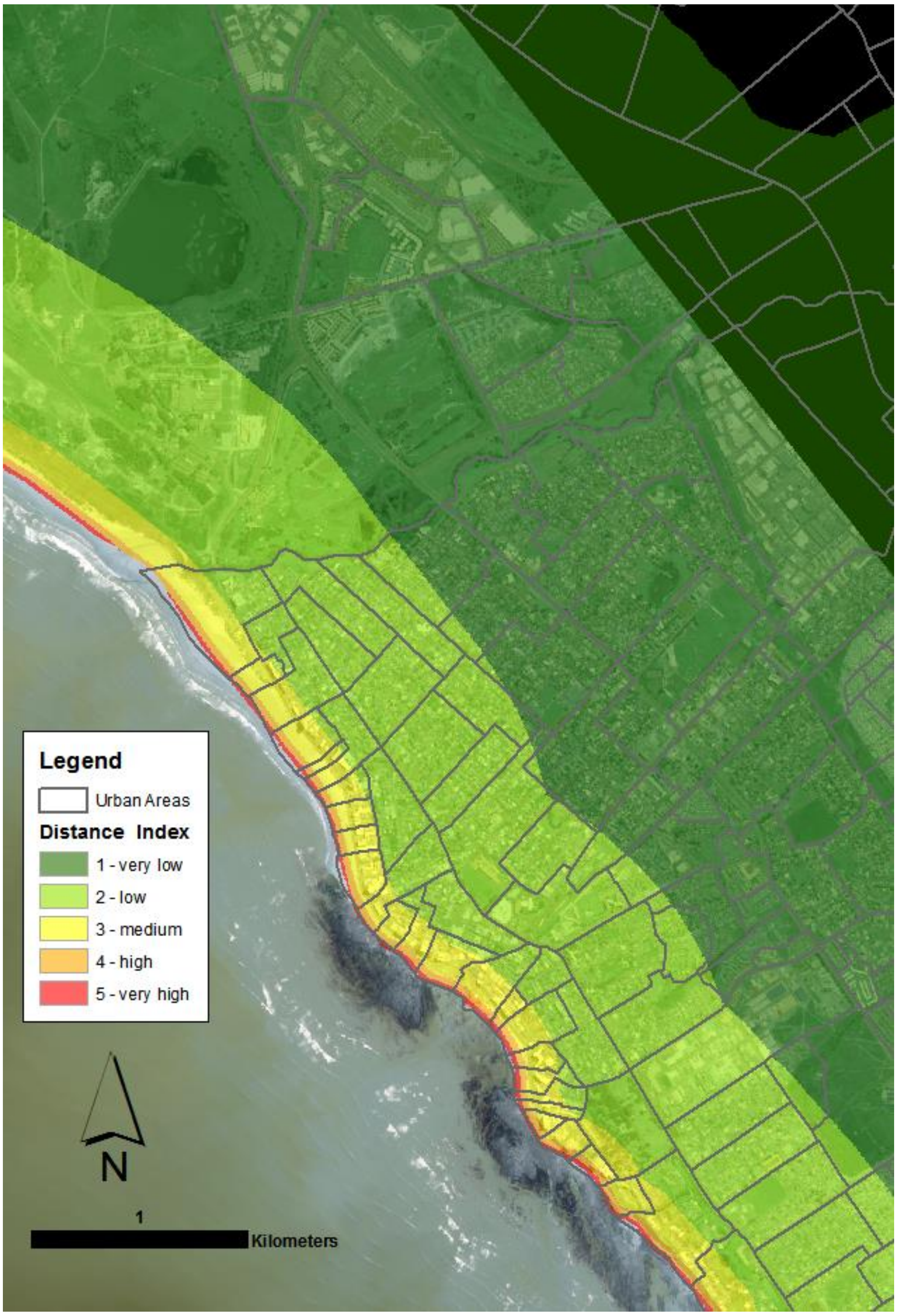

Figure 5: Distance from coast index map for Strand (False Bay, Cape Town).

2.3.3 Generation of final coastal flood hazard index

The final flood hazard index product was calculated as the average of the two individual indices. This resulted in five final flood hazard risk categories (see Figure 6):

Final Flood Hazard Risk Classification and Score				
Very low	Low	Medium	High	Very high
1	2	3	4	5

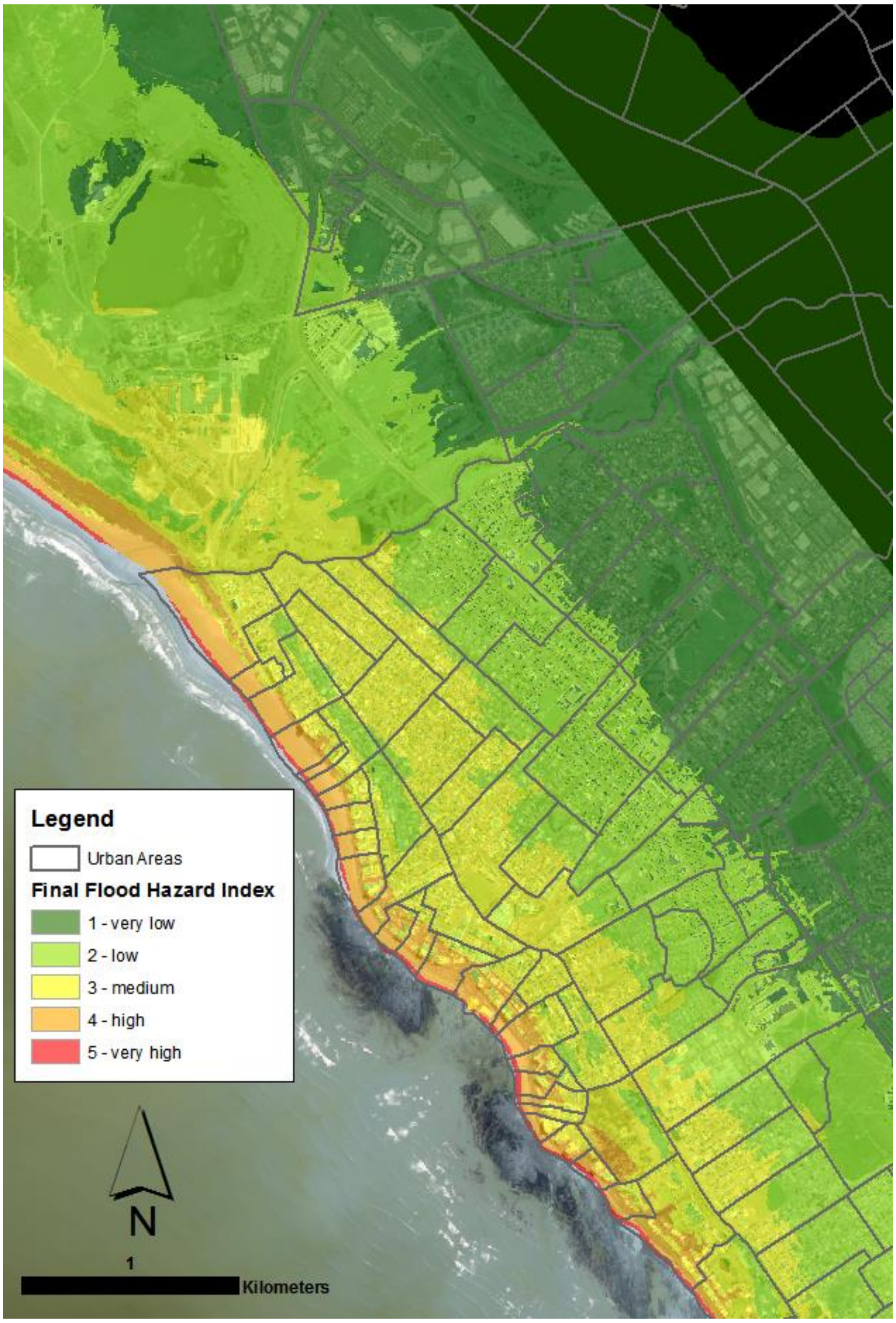

Figure 6: Final Flood Hazard Index for Strand (False Bay, Cape Town).

It was observed that the mosaicking of the different elevation datasets resulted in anomalies along the edges of the various inputs, particularly in the Northern Cape and KwaZulu-Natal. To remove these anomalies, multiple majority filters were applied in these provinces to the final flood hazard product. The results of the filtering can be seen in Figure 7 and Figure 8.

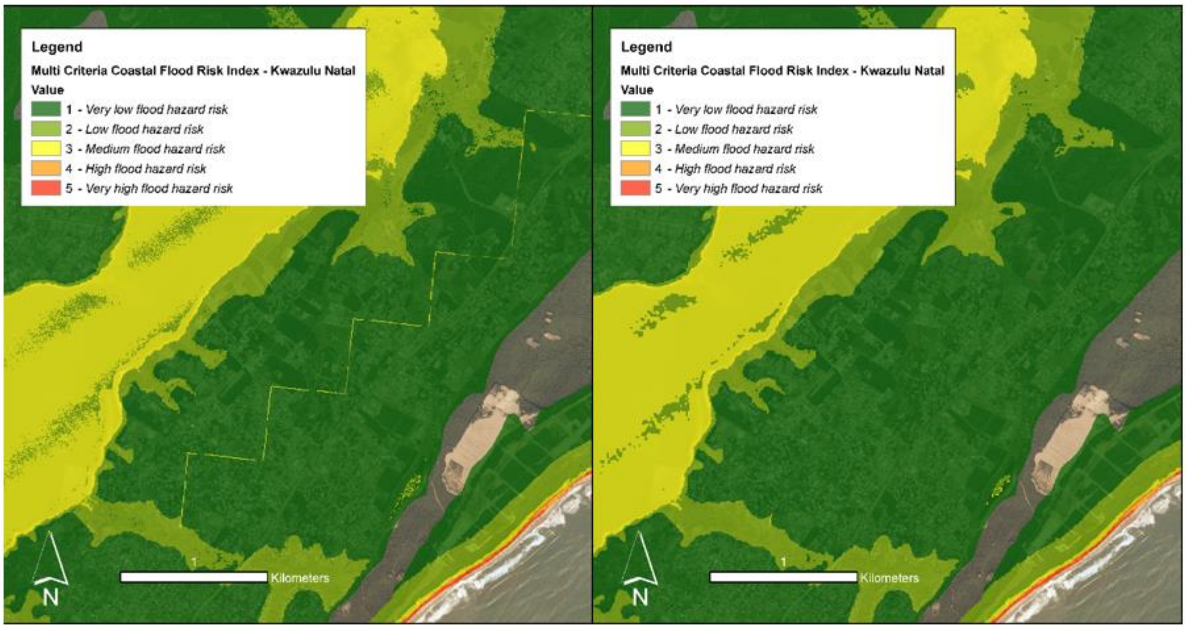

Figure 7: Multi Criteria Coastal Flood Risk Index of an area of KwaZulu-Natal displaying anomalies before and after multiple majority filters were applied.

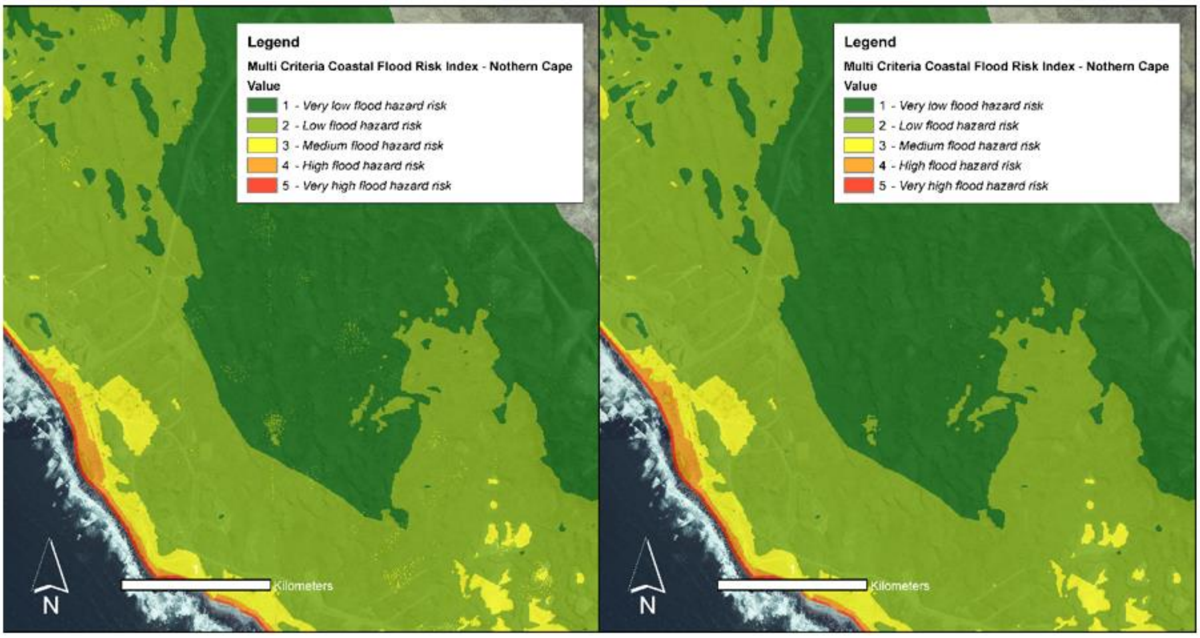

Figure 8: Multi Criteria Coastal Flood Risk Index of a section of Northern Cape displaying anomalies before and after multiple majority filters were applied.

3 DISCUSSION OF TECHNICAL CONSTRAINTS

The intended use for the final coastal flood hazard index is to inform the project team concerned with adaptation planning, local authorities, coastal managers and town planners of which areas of a development are at risk of exposure to a coastal flood hazard.

As seen in Appendix 1 (or in Theron, 2016 for more details), coastal flooding is a function of a number of impact factors. As yet, only the very tip of the iceberg has been addressed in this project (i.e. elevation and distance of the infrastructure from the coast). Reasons for this are given below.

A number of factors used in the coastal hazard assessment in Appendix 1 are directly suited to the coastal engineering approach presented there, and thought is required on how to transpose them into a 2D GIS environment. It may arise that this is not possible, and some factors may need to be omitted or substituted. However, the GIS environment provides opportunities to improve on the parameters used in the engineering approach. For example, instead of the relative protective foredune height used as proxy for the foredune volume in the engineering approach, the DEMs in the GIS environment may allow for the calculation of the actual foredune volume directly. This example has been earmarked for the next project phase.

It should be noted that the two parameters used to calculate the final flood hazard index presented here are affected by a degree of uncertainty. While elevation above sea level is well understood and can be modelled reliably, sea level rise is more complex and not yet understood well enough to be reliably predictable (see Appendix 2 or IPCC-5, 2013).

Further, there are technical issues which contribute to uncertainty. In cases where elevation is being used as stand-alone index in flood hazard approaches and products (e.g. https://ocims-dev.dhcp.meraka.csir.co.za/hazardlines/; https://coast.noaa.gov/slr/; http://www.coastalrisk.com.au/), the typical weaknesses of a "bath-tub flood model" are to be expected. This means local minima (low-lying areas disconnected from the coast) are indicated as high risk, where realistically they are at low risk of flooding. Figure 4 shows those disconnected areas in the large vlei area in the northwestern corner of the image. Furthermore, the "bath-tub" is not sensitive to physical constraints such as the time it would take flood water to actually flood a low-lying area far inshore. While the distance-to-shore index used here reduces the effect of the bathtub artefacts, it is still likely that a flood hazard risk product solely based on the elevation and distance parameters will overestimate areas at risk to some degree.

Another element of uncertainty is the dependence of the distance-from-coast index on the definition and delineation of the coastline. For example, an oversimplification of complex shorelines such as river mouths, lagoons and estuaries, can lead to the underestimation of risk. In the example given in Figure 5 and Figure 6, the distance-to-coast does not consider the river mouth, thus not accounting for areas which are likely to be flooded from the inland river (fluvial) side.

It is therefore recommended to evaluate the reliability of the final index in each area individually, before designing adaptation and resilience measures.

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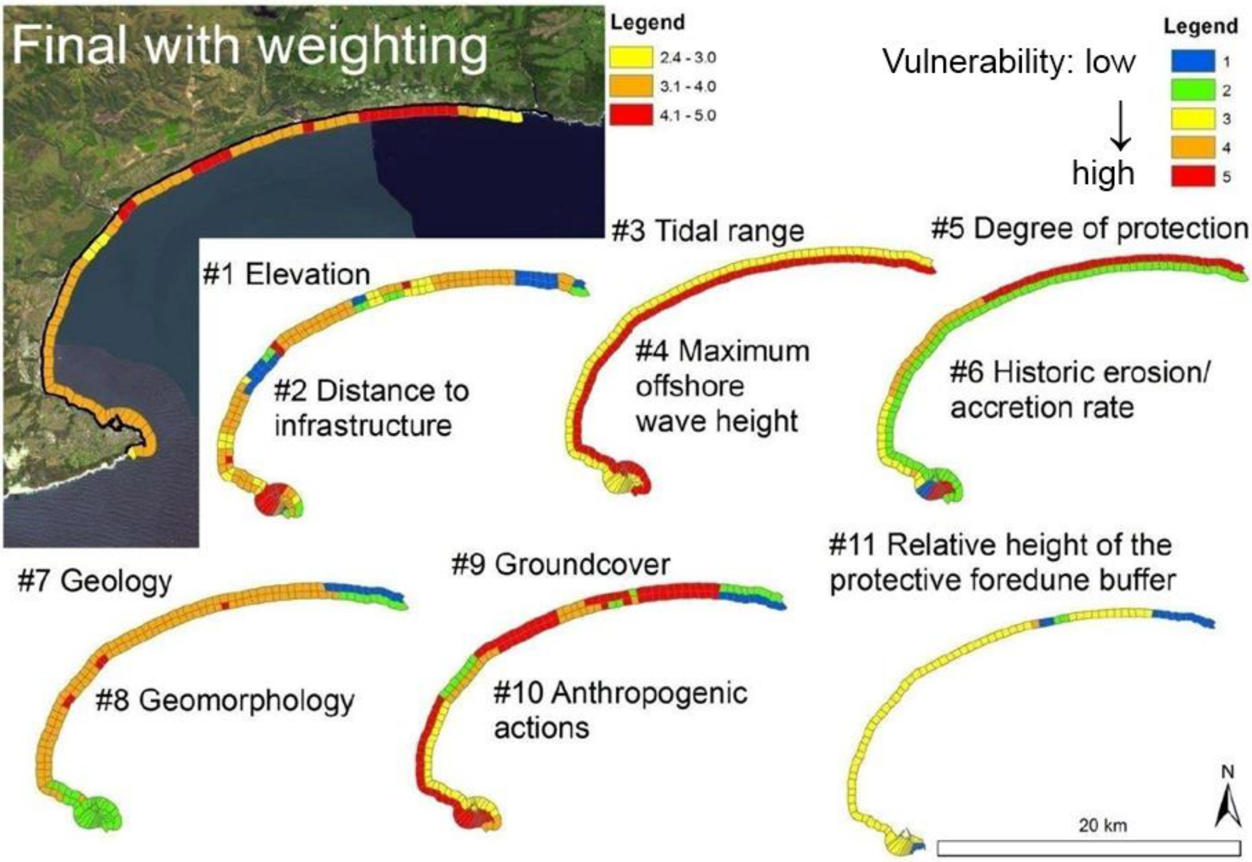
APPENDIX 1

Example of one-dimensional multi-criteria assessment of coastal hazard assessment for Mossel Bay in form of 300 meter segments along the coastline (Source: A. Theron).



APPENDIX 2

4.1 Sea level rise scenarios from IPCC

No consistent SLR scenarios modelled at a local scale are currently available for South Africa. There seems to be a tendency that sea levels are rising faster on the east coast (e.g. Mather et al. 2009), but the observation data are still too scarce for the deduction of reliable trends. It is therefore best scientific practise to rely on global SLR scenarios which are internationally accepted, such as those of the Intergovernmental Panel on Climate Change (IPCC). In the IPCC-4 report (IPCC 2007) a likely medium term SLR (by 2050) was predicted in the range of 0.35 m and a likely SLR of 1.0 m until 2100. The latest Report of the Intergovernmental Panel on Climate Change on Sea Level Rise (IPCC-5, 2013) provides updated SLR scenarios. Example predictions for various coastal locations are given in Figure 9 below. For most sites, the expected mean SLR is in the range of 0.4 - 0.7 m by 2100 and between 0.2 and 0.3 m by 2050, using 2006 as baseline.

Figure 10 below illustrates the SLR predictions from two global IPCC-5 models. Here the SLR by 2050 is expected to be at least 0.4 m, and 2100 predictions range between 0.55 and 1.25 m. It has to be noted though that the benchmark for these predictions is the pre-industrial sea level around the year 1700.

For future planning, the 1700 reference datum is of little value though. It would be more appropriate to use a recent sea level, e.g. from around 2010 as reference for future adaptation planning - which is 0.3 m above the 1700 reference already.

According to Figure 10 the residual SLR expected until 2050 would be in the range of 0.1 - 0.3 m and until 2100 between 0.25 - 0.95 m.

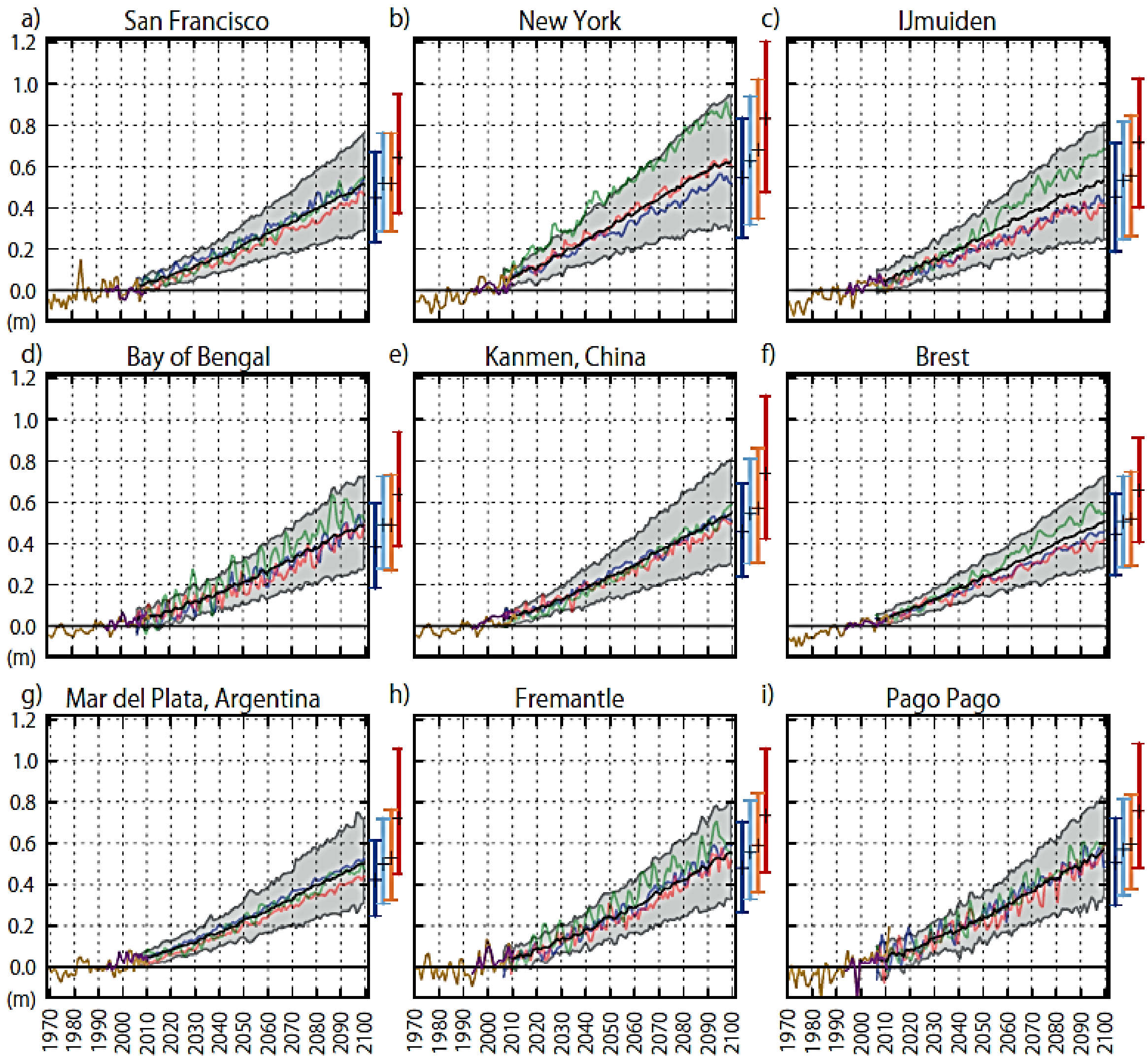


Figure 13.23 | Observed and projected relative sea level change (compare Figure 13.20) near nine representative coastal locations for which long tide-gauge measurements are available. The observed *in situ* relative sea level records from tide gauges (since 1970) are plotted in yellow, and the satellite record (since 1993) is provided as purple lines. The projected range from 21 CMIP5 RCP4.5 scenario runs (90% uncertainty) is shown by the shaded region for the period 2006–2100, with the bold line showing the ensemble mean. Coloured lines represent three individual climate model realizations drawn randomly from three different climate models used in the ensemble. Station locations of tide gauges are: (a) San Francisco: 37.8°N, 122.5°W; (b) New York: 40.7°N, 74.0°W; (c) Ijmuiden: 52.5°N, 4.6°E; (d) Haldia: 22.0°N, 88.1°E; (e) Kanmen, China: 28.1°N, 121.3°E; (f) Brest: 48.4°N, 4.5°W; (g) Mar del Plata, Argentina: 38.0°S, 57.5°W; (h) Fremantle: 32.1°S, 115.7°E; (i) Pago Pago: 14.3°S, 170.7°W. Vertical bars at the right sides of each panel represent the ensemble mean and ensemble spread (5 to 95%) of the *likely* (*medium confidence*) sea level change at each respective location at the year 2100 inferred from RCPs 2.6 (dark blue), 4.5 (light blue), 6.0 (yellow) and 8.5 (red).

Figure 9: Observed and projected relative sea level change near nine representative coastal locations.

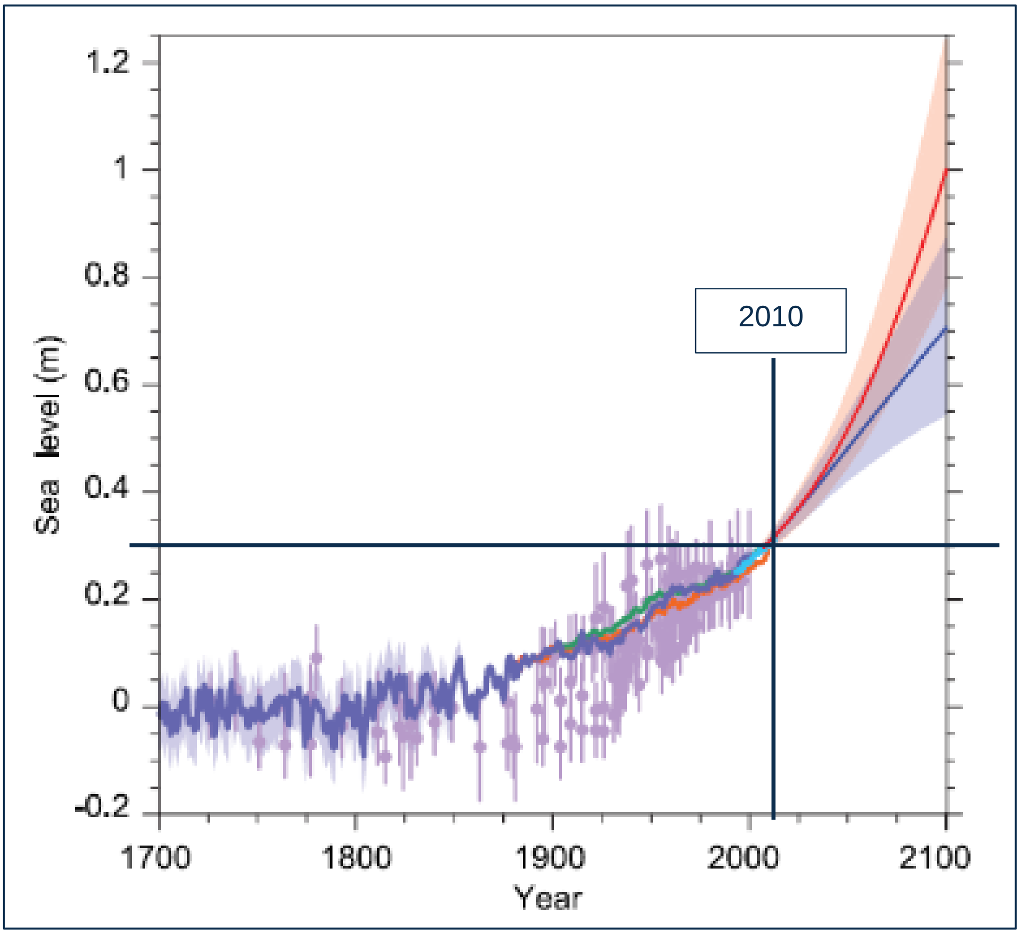


Figure 10: Compilation of paleo sea level, tide gauge data, altimeter data, and central estimates and likely ranges for projections of global mean SLR for RCP4.6 (blue) and RCP8.5 (red) scenarios, all relative to pre-industrial values. Level for year 2010 indicated by black line. Adopted from: IPCC-5 (2013), page 1204 (Church et al. 2013).