Methods for Probabilistic Coastal Erosion Hazard Assessment

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Abstract

Traditional methods of assessing coastal erosion hazard in Australia and New Zealand have typically applied deterministic techniques, separating and evaluating (largely) independent components before combining, often with an additional factor of safety or measurement error allowance, to produce an erosion hazard setback. Such techniques have advantages in being easily understood, interpreted and updated in the future as additional data is collected. However, the methods can result in conservative (large) values along with a limited understanding of the combined uncertainty range.

New policy documents in New Zealand guiding the sustainable use of coastal resources such as the New Zealand Coastal Policy Statement 2010 (NZCPS) advocate the use of a risk-based approach to managing coastal hazard. This requires consideration of both the likelihood and consequence of hazard occurrence. Specifically, the policy statement requires consideration of areas both ôlikelyô to be affected by hazard (i.e. focussing existing development) and areas ôpotentiallyô affected (focussing on new development). Such a requirement is at odds with traditional techniques where single values are produced with limited understanding of the likelihood of occurrence or the potential uncertainty of the prediction.

The concept of using stochastic simulation to evaluate coastal processes has been developed over the last decade. This technique uses a distribution of values for each parameter to account for expected variation, or uncertainty, rather than single values. Parameters are then combined by a monte-carlo technique to produce a probabilistic forecast of future shoreline position. To date these methods have been employed for specific locations that have high quality field data over long time periods. However, hazard assessments are invariably required for large areas, where available data is limited and a variety of coastal types are encountered: for example soft beaches, estuarine shorelines and cliff coasts. This paper presents a framework of applying the stochastic simulation technique over a range of spatial scales for a variety of coastal types. Commentary is provided on the different methods available to assess each parameter and recommendations on selection of appropriate parameter bounds given the level of certainty of parameter values. Derived distributions are compared to values obtained by traditional deterministic techniques.

Keywords: Coastal hazards, Erosion, Probability, Risk.

1. Introduction

In New Zealand a collective of legislative requirements (Resource Management Act (2004), New Zealand Building Act (2004), Local Government Act (2002) and the Civil Defence and Emergency Management Act (CDEM, 2002)) provide a statutory framework to guide the process of decision making around hazard risk and management. Within this framework effective coastal management in part requires the quantification of erosion hazards to inform robust decision making. In Australia most States also maintain strategies and policies for managing coastal hazards (refer [11]), and while the federal government has released non-statutory guidance on managing coastal hazards (Commonwealth Coastal Policy in 1995 and National Cooperative Approach to ICZM in 2006), binding legislation is yet to be produced.

Traditional methods of assessing coastal erosion hazards in Australia [11] and New Zealand [6,18; 14] have typically applied deterministic techniques, separating and evaluating discrete components of the coastal erosion issue before combining them, often with an additional factor of safety or measurement error allowance, to produce an erosion hazard distance. Such techniques have advantages in being easily understood, interpreted and updated in the future as additional data is collected. However, the methods can result in conservative (large) values, inconsistency between quantitative approaches and provide a limited understanding of the combined uncertainty range.

Deterministic approaches are increasingly inconsistent with constantly evolving policy instruments in New Zealand that guide the sustainable use of coastal resources such as the New Zealand Coastal Policy Statement 2010 (NZCPS). The NZCPS advocates the use of a risk-based approach to managing coastal hazards with both the likelihood and consequence of hazard occurrence requiring consideration. Specifically, the policy requires consideration of areas both ôlikelyô to be affected by hazard (i.e. focussing on existing development) and also areas ôpotentiallyô affected by low probability events or into the future. Such requirements are at odds with traditional techniques where only a single value is produced with limited understanding of the likelihood of occurrence or the potential uncertainty of the prediction.

Planning rules have commonly been developed without recognition of the variation of hazard likelihood across the zone and which often constrain the rights of coastal property owners. As a consequence, the width of hazard zones, and the planning rules, have been highly contested and have led to litigation in numerous instances [14]. Moving towards a risk-based approach, as endorsed by NZCPS and [16], enables the implementation of more appropriate rules based around tolerable levels of risk. However, this approach requires a thorough understanding of the likelihood and extent of hazard occurrence which is not provided for by traditional deterministic approaches.

2. Deriving coastal erosion hazard zones

The typical components evaluated in assessing coastal hazard on beaches and cliff coasts are described below but will often vary to include additional or fewer components as relevant to that particular coastline or statutory requirement.

2.1 Non-consolidated beaches

The method for unconsolidated beach shorelines is expressed in Eqn. 1. It is applied to uniform, non-consolidated coastlines not influenced by streams, estuaries or distal spit migrations. The CEHZ is established from the cumulative effect of four main parameters (Figure 1):

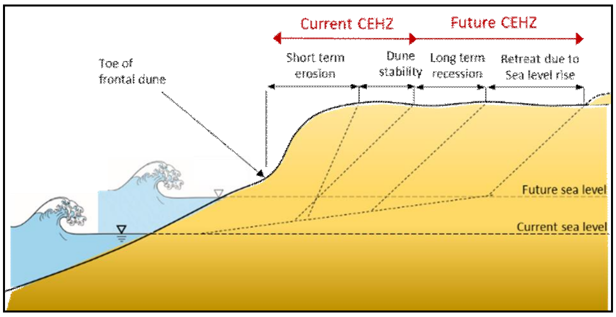

Figure 1 Definition sketch for open coast CEHZ

$$CEHZ_{Beach} = \left[ST + DS + \left(LT \times T \right) + SL \right] \times FoS \qquad (1)$$

Where: ST = short-term changes in horizontal shoreline position related to storm erosion due to singular or a cluster of storms events, DS = dune stability allowance to allow for the over-steepened dune scarp following erosion, LT = long term rate of horizontal coastline movement, T = study timeframe (years), SL = the horizontal coastline retreat due to the effects of increased mean sea level (m) and FoS = a combined or gross factor of safety/uncertainty.

2.2 Cliff coasts

The CEHZ for cliffs is typically established from the cumulative effect of the long-term erosion of the cliff material and slope instability (Figure 2) as outlined in Eqn. 2.

$$CEHZ_{Cliffs} = \left[\left(\frac{H_C}{\tan\alpha} \right) + \left(LT_H + LT_F \right) \times T \right] \times FoS \qquad (2)$$

Where: H_c = height of cliff from toe to crest, Ŭ = the characteristic stable angle of repose for that particular material, LT_H = historic long-term rate of cliff toe retreat, LT_F = potential increase in future long-term retreat due to sea level rise effects and T = timeframe (years).

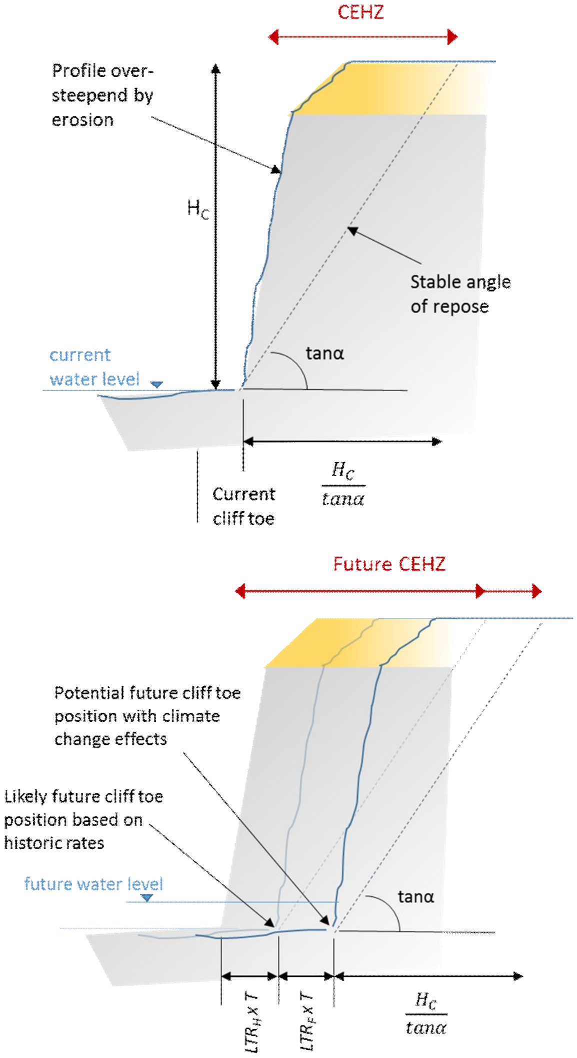

Figure 2 Definition sketch for cliff coasts CEHZ

3. Probabilistic framework

The concept of using stochastic simulation for prediction of coastal processes has been developed over the last decade [5]. This technique uses a distribution of values for each parameter to account for expected variation, or uncertainty, rather than single values. Parameters are then combined by a monte-carlo technique to produce a probabilistic forecast of the relevant process. Results have been promising in overcoming many of the issues arising from single-value deterministic predictions, however, these methods have, to date, focussed on specific locations that have high quality field data over long time periods, e.g. [20].

The methodology used in this assessment combines standard and well-tested deterministic approaches for defining coastal erosion hazard zones with the stochastic methods described above. Rather than including single values for each component and a factor for uncertainty, parameter bounds are specified for each parameter and combined by stochastic simulation. The resulting distribution is a probabilistic forecast of potential hazard zone width.

The method is based on the premise that uncertainty is inherent in individual components due to an imprecise understanding of natural processes and due to alongshore variability within individual coastal cells. Stochastic simulation allows the effect of these uncertainties to be explored simultaneously providing estimates of the combined hazard extent (i.e. the central tendency) and information on potential ranges and upper limit values. This contrasts with deterministic models which provide limited understanding of uncertainties.

The stochastic method is described in [5]. The methods used to define probability distribution functions (pdfs) for each parameter are described within each component estimation detailed below. Where pdfs are not defined empirically (i.e. based on data or model results), simple triangular distributions have been assumed with bounding (minimum and maximum) and modal parameters. These triangular distributions can be constructed with very little information yet approximate a normal distribution (Figure 3) and permit flexibility in defining range and skewed asymmetry. Where better information is available alternative distributions may be substituted i.e. for short-term erosion distances or confidence around sea level rise scenario predictions.

4. Component estimation

The derivation of distributions for individual components of erosion hazard assessment need to include the probabilistic likelihood of occurrence (where relevant), the uncertainty related to understanding of the process or data available, and the variation within the coastal cell of interest.

Methods used to evaluate these components may range from comprehensive statistical or numerical evaluation for site-specific or detailed assessments to generic or heuristic for preliminary or coarse resolution assessment. Provided the assumptions and adopted values are presented, values can be reviewed and modified as improved methods and data becomes available.

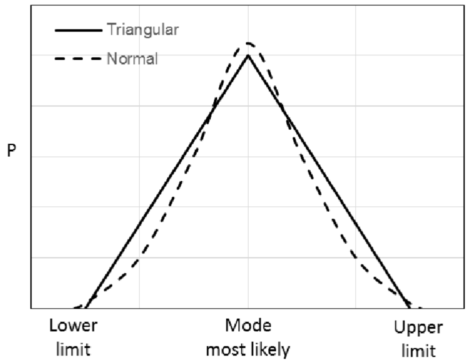

Figure 3 Example triangular and normal pdf

4.1 Short-term erosion

Short-term erosion applies to non-consolidated beach and estuary coastlines where rebuilding by wave and aeolian processes follows periods of erosion. These effects include changes in horizontal shoreline position due to storm erosion caused by singular or clusters of storms events, or seasonal fluctuations in wave climate or sediment supply and demand. Short-term erosion effects can be assessed by analysis of:

1. anecdotal evidence of past erosion distances or geomorphological signatures;
2. statistical analysis of change in shoreline position obtained from aerial photographs or beach profile analysis [18, 4] (Figure 4);
3. simple geometric models for beach response such as [9, 10];
4. assessment of storm erosion potential using semi process-based models such as Sbeach and Xbeach [11] (Figure 5).

4.2 Dune and cliff instability

On non-consolidated beaches, the dune stability factor delineates the area of potential risk landward of the erosion scarp by buildings and their foundations. The parameter assumes that storm erosion results in an over-steepened scarp which must adjust to a stable angle of repose for loose dune sand. The dune stability width is dependent on the height of the existing backshore and the angle of repose for loose dune sand. Uncertainty results from variation in the dune height along the coastal cell, the stable angle of loose dune sand and assumptions made around the post-storm adjustment and geotechnical stability of the over-steepened profile, e.g. [15, 4].

Along cliff shores, the stable angle of repose is dependent on a range of factors such as geological type, weathering profile, local bedding and faulting characteristics, groundwater level, overland flow paths and vegetation cover. Furthermore, if a slope comprises multiple rock types (for example a competent underlayer and weathered cover material), composite angles incorporating stable angles of repose for each material must be derived.

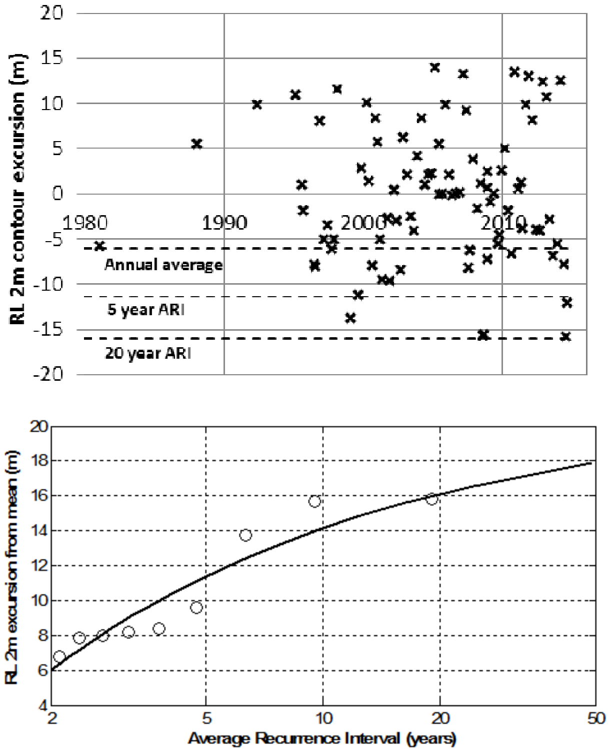

Figure 4 Example of the residual (de-trended) contour excursion from field data (upper panel) and the results of extreme value analysis (panel).

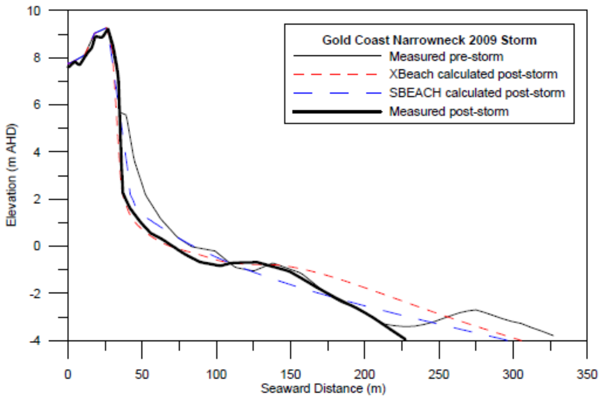

Figure 5 Example of semi-process based erosion assessment (source: [11])

4.3 Long-term trends

The long-term movement of the beach profile may be driven by changes in relative mean sea level, in coastal sediment supply (driven by volcanic and tectonic processes, changes in landuse, rivermouth dynamics etc), by anthropogenic influences or associated with long-term climatic cycles such as IPO. Erosion of cliff coasts is a one-way process with which typically has two components; a gradual recession caused by weathering and coastal processes, and episodic failures due to cliff lithology and geologic structure. Gradual recession due to weathering is a function of climatic conditions, exposure and cliff material.

Data analysed should be long enough to differentiate multi-decadal cyclical changes from ongoing trends. Analysis could be based on long-term beach profile data, photogrammetric data or analysis of geomorphological signatures in historical aerial photographs. Uncertainty is introduced in the measurement of the adopted shoreline position, within the statistical regression model (Figure 6) and in the alongshore variation within the coastal cell. These should be accounted for when defining parameter ranges.

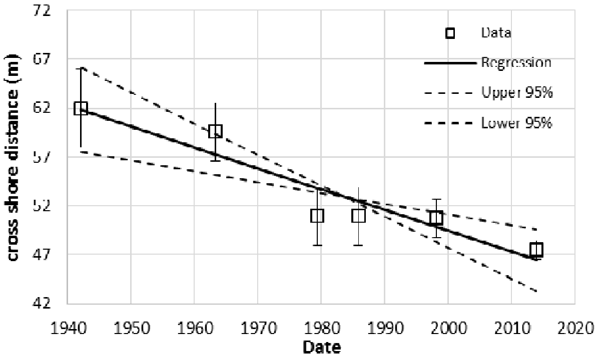

Figure 6 Example of data uncertainty and confidence intervals around long-term trends derived by regression analysis

The issue of how to take into account accretion is often challenging in deterministic assessments. FEMA advocated setting long-term trends to zero [13] arguing that this accretion hasn't yet occurred and relying on it, when processes may change in the future, is non-precautionary. This is especially important where the century/millennium record is characterised by episodic accretion. Ultimately this decision is dependent on intended usage and confidence in the understanding of the process.

4.4 Response to sea level rise

This component allows for the additional shoreline recession caused by potential increased future rates of sea level rise (SRL). Uncertainty is related to the amount of future sea level rise and the coastal response model used.

The future sea level rise should consider both local tectonic movement (though care is required separating gradual from episodic movement) and a range of SLR projections based on international [8] and/or local guidance [7]. In order to avoid double counting SLR effects, reliable estimates of historic SLR should be discounted from projections as the LT component likely already includes these effects.

As described within [17] a range of models for estimating coastal response to changes in sea level have been developed over the past 50 years ranging from simple geometric relations to more complex process-based models. If a simple Bruun-type model is adopted [2,3] then sensitivity around aspects such as the closure depth may be used to define parameter ranges.

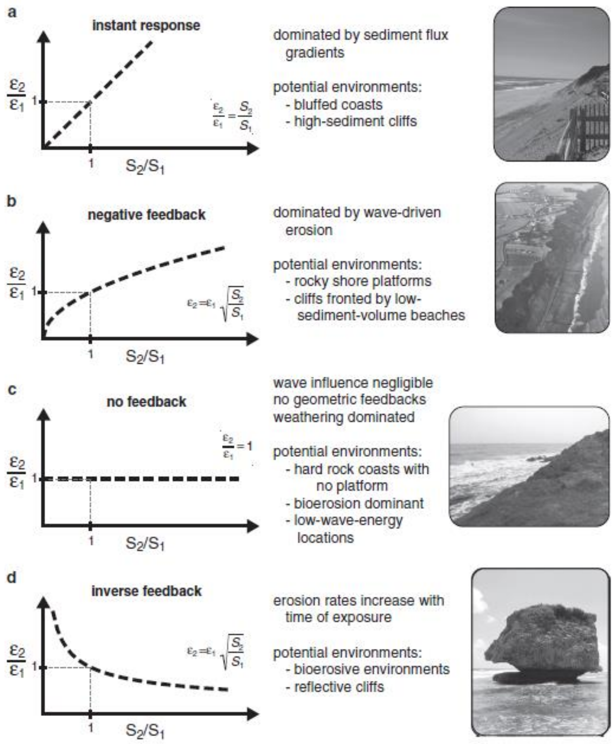

Figure 7 Possible modes of cliff response to SLR (adapted from [1])

SLR increases the amount of wave energy able to propagate over a fronting platform or beach to reach a cliff toe, removing talus more effectively and increasing the potential for hydraulic processes to affect erosion and recession. [1] propose a model by which the generalised recession rates for cliff coasts can be described by the relationship shown in Eqn 3 and Figure 7 where the coefficient m is determined by the response system ranging from no response (m=0), a damped response where a shore platform or beach form slowing the increase or an instantaneous response (m=1) where the rate of future recession is proportional to the increase in SLR.

$$LT_F = LT_H \left(\frac{SLR_F}{SLR_H} \right)^m \tag{3}$$

4.5 Parameter combination

Individual parameter distributions can be constructed empirically or using parameter bounds and simple triangular distributions as per [5]. Table 1 shows an example of generic parameter bounds used for regional assessment [19] with specific values derived for an example site at Waipu Cove, Northland.

Probability distributions constructed for each parameter are randomly sampled and the extracted values used to define a potential CEHZ distance. This process is repeated 10,000 times using a Monte Carlo technique and probability distribution of the resultant CEHZ width is forecast. The CEHZ histograms and hazard zone plot for the example site are shown in Figure 8.

Based on these assessed values, a CEHZ width derived using the ðbuilding blockôaddition using all worst case parameters would be 80m excluding any additional FoS. However, the stochastic forecast method shows a maximum combination of 77 m after 10,000 simulations. This is because of the extremely low probability of independent, upper end values occurring coincidently. The $P_{95\%}$ value is substantially lower at around 61m and the $P_{50\%}$ value of 48 m is offset towards the lower end of the distribution (min of 27 m). This skewness is caused by the high upper end sea level rise and outer closure depth combination which result in a long distribution tail. This information only becomes apparent using non-deterministic methods.

It should be noted that deterministic hazard zone assessment by experienced practitioners have not tended to use all worst case parameters but rather have used professional judgement to select combinations of parameters to achieve pragmatic hazard likelihoods. For example, the methods employed by [4] used combinations ranging from ðlikelyô to óvery unlikelyô plus a combined uncertainty term which would have resulted in a CEHZ value of 60 m for this example, or around the $P_{5\%}$.

Table 1 Example of generic parameter bounds used for regional assessment by [19] and values derived for a specific site example (*in italic*)

Parameter		Lower	Mode	Upper
ST (m)		10% AEP storm cut *-10*^{1}	1% AEP storm cut *-15*^{1}	2 x 1% AEP storm cut *-20*^{1}
DS (m)		H$_{max}$ & Ŭ$_{min}$- *-4*	H$_{mean}$ & Ŭ$_{mean}$ *-5.5*	H$_{min}$ & Ŭ$_{max}$- *-6.7*
LT (m/yr)		-95% CI of smallest trend in cell *-0.02*	Mean regression trend *-0.05*	+95% CI of largest trend in cell *-0.1*
SLR (2115) (m)		lower 95% CI value *0.45*^{2}	50% SLR value *0.77*^{2}	upper 95% SLR value *1.1*^{2}
Closure slope (-)		Slope across active beach face *0.05*	To inner Hallermeier closure depth *0.03*	To outer Hallermeier closure depth *0.025*
LT$_F$ (-)	Hard cliff	No response *m=0*	*m=0.25*	Negative feedback *m=0.5*
	Soft shore	Negative feedback *m=0.5*	*m=0.75*	Instant response *m=1*

[1] Storm cut derived using Sbeach with Synthetic Design Storms validated with profile analysis

[2] RCP8.5 scenario extrapolated to 2115 minus historic trend

5. Selection of appropriate values for planning purposes

Selection of appropriate values for planning purposes will depend on the intended use. A consequence-based risk assessment may require the use of the full likelihood range and therefore a graduated output may be required. Establishing generic planning rules require specific zones or lines so selection of the appropriate likelihood and timeframe is required.

The NZCPS refers to ólikelyô hazard areas for existing development (Policy 27) and ópotentialôfor new development (Policy 24/25). While specific values have not yet been defined, [12] presents values for likely (66-90%) and very unlikely (1-10%). Conversely, [14] defined potential as óworst caseôimplied to mean the distribution maximum or at least 1% exceedance.

Ultimately, the adopted policies and rules should reflect the likelihood of hazard occurrence. For example, Northland Regional Council adopted a óCEHZ1ôzone as a *likely* $P_{50\%}$ at 2065 (50 years) and a *potential* óCEHZ2ôzone as $P_{5\%}$ value at 2115 (100 years) [19] with specific rules implemented for each.

6. Conclusions

As we move towards the use of risk-based approaches for managing coastal hazard both the likelihood and consequence of hazard occurrence require consideration. Traditional approaches to evaluating coastal erosion hazard provide only limited understanding of the combined likelihood of occurrence or the potential uncertainty of the prediction.

This paper has presented a framework for applying stochastic simulation techniques over a range of spatial scales for a variety of coastal types. Individual parameter distributions can be constructed empirically or using parameter bounds and simple triangular distributions. Selection of appropriate parameter values still relies on practitioner skill and experience.

Results are a stochastic forecast of hazard distance accounting for different likelihoods of occurrence, uncertainty in terms and alongshore variation. Distributions are found to be positively skewed with a long tail extending inland from the coastal edge. Adoption of a 5% exceedance value is significantly lower than the potential maximum. Planning policy and rules can then be implemented based on relevant hazard timeframes and likelihood.

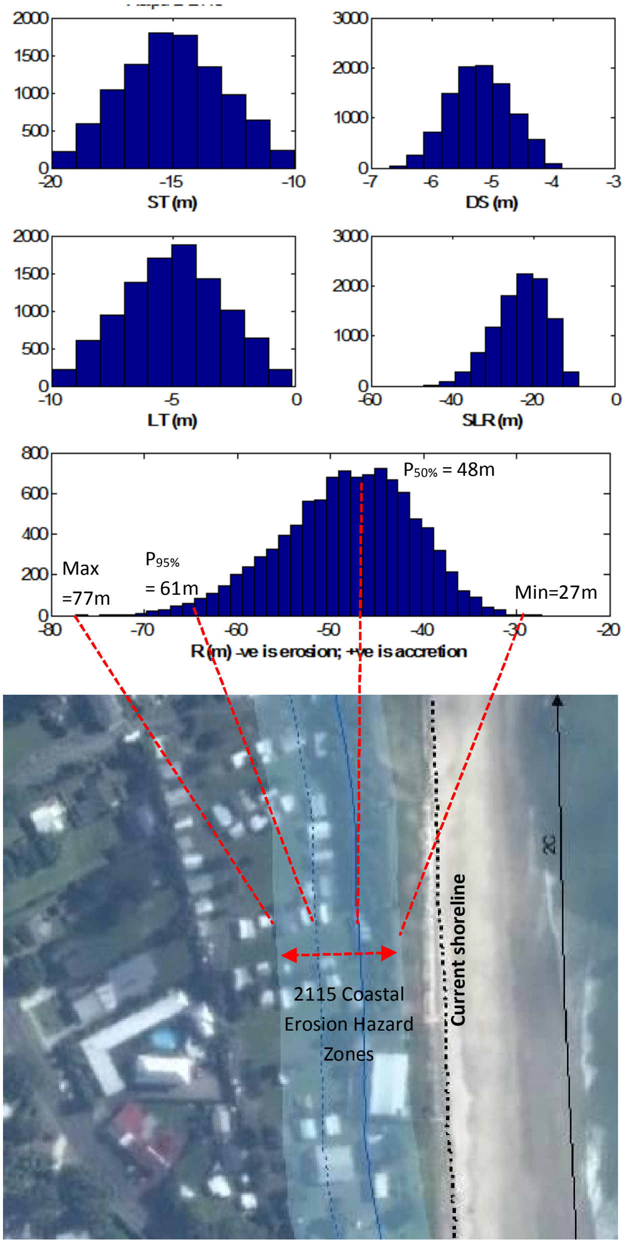

Figure 8 Sample component and CEHZ histograms with the resultant Coastal Erosion Hazard Zones width

7. Acknowledgments

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