Coastal Hazard Lines – Last Century's Thinking

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Abstract
Coastal "hazard" lines were the tool developed in the 1970s to delineate the areas expected to be adversely affected by coastal processes and therefore became the basis for coastal zone management. Progressively the methodology for calculating the location of hazard lines became more complex with the addition of storm cut, escarpment slumping, impacts of climate change and reduced foundation capacity. While the combined effects of these required a probabilistic treatment the simplistic approach of direct addition of each element tended to be favoured. Over the last three decades the market values of coastal properties have escalated dramatically, and hence the potential economic and social impacts of hazard lines that cut through existing development resulted in scientific risk being supplanted by political risk, meaning the simplistic hazard lines of the past have outlived their credibility and hence usefulness. To now be effective and credible the methodologies for determining coastal vulnerability and management require a more sophisticated approach that focuses on risk management. Solutions must present more socially and economically useful information that provide the opportunity for governments and the community to modify either, or both, the likelihood or the consequence components of potential risk so as to achieve practical, fundable outcomes.

Keywords: Hazard lines, risk matrix, risk manipulation/management, acceptable risk, fundable outcomes.

1. Introduction

The stormy conditions in the late 1960s and early 1970s, on both sides of the Tasman, provided the post war coastal residential development boom with a reality check. As a result, the 1970s saw the introduction of the concept of coastal zone management, with coastal "hazard" lines the key management tool to define the areas vulnerable to adverse affectation by "coastal erosion". Over time it was recognised that the term "coastal erosion" needed to be replaced by "coastal recession" or "coastal accretion"; indicating the longer-term trend, and "beach fluctuations" representing the erosion and accretion cycle that resulted from the cut and fill of beaches associated with storm and fair weather responses [4]. Typically hazard lines were staged at 50 and 100 years into the future from the current date, on the basis that these represented "reasonable" planning periods. Sometimes the arbitrary dates of 2050 and 2100 are used to approximate the 50 and 100 year markers.

2. Hazard Lines

Initially these lines were based on a linear projection of historical trends, a simple, robust and readily explained concept [3]. Progressively the methodology for calculating the location of hazard lines became more complex with the addition of storm cut, escarpment slumping and reduced foundation capacity. The addition of future recession due to projected climate change introduced a new dimension.

While the combined effects of these various components really required a probabilistic treatment, the simplistic approach of direct addition of each element tended to be favoured. Hence the calculation of the future areas "potentially" impacted by coastal threat at some time in the future became:

$$HL(t) = LTR(t)+SD+SLRR(t)+ ES+ ZRFC \qquad (1)$$

Where:

HL(t) = Hazard line at time (t) in the future;

LTR(t) = average historical recession rate multiplied by (t), typically t = 50 or 100 years;

SD = storm demand - typically the 1% event added as a 100% certainty to occur at time (t);

SLRR = sea level rise recession at time (t) - often based on the high range sea level rise projection applied by the "Bruun Rule", and directly added;

ES = escarpment slumping - typically assumed to be fully applied to the storm generated escarpment at time (t);

ZRFC = zone of reduced foundation capacity - again fully applied at time (t).

Gordon [7] pointed out that the factors used in the prediction of future shoreline locations, such as the historical shoreline trend, are based on annual average rates. Given the variability that can occur from year to year (or decade to decade) in the actual rate, the likely component of historical recession applicable to determining the shoreline location at any future date, such as 2050, is best represented by a probability function. Further, historical assessments are often not corrected for the sea level rise component thereby leading to an element of double counting when the future additional recession due to sea level rise is added. The storm demand component should also be included as a probability function rather than the maximum amount being assumed to occur at the end of the period. Interestingly, and often overlooked, the storm demand component should also include consideration of the cumulative probability over the time interval being considered.

Escarpment slumping is another variable which has to date received a simplistic and conservative treatment. The contribution of escarpment slumping to potential hazard to assets depends on a range of factors. The current assumptions typically fail to take into account layering and consolidation of the escarpment, the binding effect of vegetation, the time required for the escarpment to slump and hence the beach berm and foredune recovery and therefore the effective escarpment height during the slumping process. Finally, in calculating hazard lines, the simplistic approach has been to assume that full escarpment slumping immediately follows a 1% event that is also coincident with the specific selected date such as 2050. Clearly the likelihood of this coincidence is so remote as to be hardly credible. Again, escarpment slumping is best represented by a probability function.

Hence the traditional methodology became one of compounding conservatism, assuming 100% simultaneous occurrence of each element at the required time interval rather than a probabilistic representation of the shoreline location at the nominated interval. Further, whereas most of the variables in the equation were based on empirical evidence or deterministic calculation, the climate change component was constructed from projections based on scenarios. Compounding the uncertainty of the climate change component, the conversion of projected sea level rise into coastline recession was based on a very simplistic, and questionable theory. Unfortunately the climate change component, the most uncertain of the components, often became the major factor in determining the hazard line location. Gordon [7] detailed the shortcomings of each of the component variables and the unrealistic results obtained by their direct addition, demonstrating that the likelihood of the hazard line locations being realised at the nominated time intervals rendered the lines meaningless as credible, rational planning or management tools.

Interestingly, few investigators have included medium term fluctuation mechanisms such as the effects of river entrance breakouts, which can jet large volumes of sand far offshore resulting in beach erosion over many years as the entrance shoals reform by littoral drift. The sand jetted offshore eventually returns to the nearshore system and the beach recovers, however the process can take a decade and result in a shoreline fluctuation of 30 metres or more [5].

By the time the climate change component had been introduced into the calculations, the market values of coastal properties had escalated dramatically, and hence the potential economic and social impacts of hazard lines that cut through existing development resulted in scientific risk being supplanted by political risk. The mismatch of political risk timeframes with those associated with likely hazard impacts, means the simplistic hazard lines of the past had outlived their usefulness. It became important to develop a new paradigm based on an approach that would allow for assessment of the probability to which coastal property, assets and infrastructure may be vulnerable in future years. Communities needed to be empowered and equipped to make rational risk management decisions to determine their acceptable risk level for different types of developments, different design/economic lives and different management options, rather than being subjected to the overly conservative risk avoidance regime generated by the traditional "hazard line" approach.

3. Risk

Risk is defined as the product of likelihood and consequence. The challenge is in determining "likelihood" given that each of the component elements generating coastal vulnerability in reality is best described by a probability function. The vulnerability of property, assets and infrastructure can be assessed on the basis of the likelihood it will be impacted within set time periods associated with planning and/or asset/infrastructure "lives", such as 50 or 100 years, hence the potential consequences can also be evaluated as a probability function.

3.1 Development of a risk based approach

Progressively, and in recognition of the growing lack of credibility of traditional "hazard lines", new "lines" started to appear. With names like "immediate impact zone", "almost certain hazard zone", "likely impact zone", "unlikely impact zone" and "rare impact zone", there was an appearance, but not a reality, of a change to a probabilistic approach. These lines were not based on statistical methodologies, but rather subjective decisions on what components of equation 1 to include in locating the specific line. For example, the "immediate impact zone" was typically based on the storm demand term. The "likely impact zone" typically included both the storm demand and at least the historical recession, and sometimes the sea level rise projected recession. Different investigators used different approaches to determine the lines with some using the lower, mid and higher sea level rise projections to produce a set of what may have wrongly appeared to be statistically based results.

Increasingly the escarpment slumping and the zone of reduced foundation capacity tended to be separated from the pseudo statistical calculations, and simply added in at the end on the basis it was the other terms that should be considered as being potentially variable, whereas these two terms were determined by direct calculation. The reality however is that these components also feature behaviour that is best represented by probability functions.

In 2007 the Australian Geomechanics Society produced a watershed document for assessment and management of landslide risk. The methodology of the approach was based on a matrix of likelihood versus consequence [1]. The matrix provided a rational way to link outcomes for property and life to the probability of geotechnical hazards, and as a result the information required to determine the acceptable risks the society was prepared to take (see Figure 1). By 2013, investigators were experimenting with the adaption of the approach to assessment of coastal hazards. A methodology was progressively developed for establishing a probability-based outcome for the potential location of a shoreline at some date in the future, and hence the statistically likely consequences for coastal property, assets and infrastructure. The so-called "acceptable risk" [8], [9] methodology represented a significant breakthrough. The approach first requires the setting of a timeframe, which Horton argues should be 60 years for typical residential development [8]. The approach highlights the cumulative effect of frequency of occurrence over the lifetime of an asset or infrastructure. Table 1 demonstrates the cumulative probability over a 60 year lifetime; when applied to the "likelihood" descriptors recommended by the AGS [1].

Table 1: Likelihood of hazard line location over 60 years (adapted from: [8], in form of AGS [1])

Descriptor	Designated Annual Exceedance Probability	Designated cumulative probability of event occurring over design life of 60 years
Almost Certain	5%	95.4%
Likely	0.5%	26%
Possible	0.05%	3%
Unlikely	0.005%	0.3%
Rare	0.0005%	0.03%
Barely Credible	< 0.0005%	< 0.03%

Risk could then be determined through the matrix by charting likelihood against consequence. Although insightful, the treatment of consequences as detailed by Horton [8] was based on the AGS [1] approach that was developed for damage to buildings as a result of landslides (Table 2).

Table 2: Consequence of hazard line location (presented in [8], as adapted from the AGS [1])

Descriptor	Approximate quantum of damage (cost)	Description
Catastrophic	> 100%	Structure(s) completely destroyed and/or large scale damage
Major	40% to 100%	Extensive damage to most of structure,
Medium	10% to 40%	Moderate damage to some of structure,
Minor	1% to 10%	Limited damage to part of structure,
Insignificant	< 1%	Little damage

Landslide and flooding, including oceanic inundation, can produce a range of severity of damage to buildings that may vary from minor to total loss and are generally of a "temporary" nature; whereas coastal recession tends to result in the permanent loss of land, buildings and infrastructure. The loss of assets may be delayed where there is ongoing net recession and not full recovery after successive storm events, by constructing the assets on deep pile foundations. However, unlike landslide and flooding, the opportunity to "recover" from coastal recession is all but non-existent. "All but" because, if the allotment is long in the shore-normal direction there may be an opportunity to re-construct some form of building further landward, which in time will also come under threat and eventually lost.

While a different approach to consequences is required, the philosophy of the matrix approach provides a form of analysis and presentation that allows rational decisions to be made about the level of risk that is acceptable, or tolerable, for the circumstances and the asset type, and forms a basis for evaluating options to alter likelihood and/or consequence.

Horton proposed a simplified methodology for calculating likelihood [8] with two scenarios to define likelihood lines ("almost certain", "likely", "possible", "unlikely" and "rare"). One was based on a storm event occurring at any time over the design life, ignoring recession. The other assumed a storm event occurring in the last year of the design life, after the full magnitude of recession, with recession being the combined effect of long - term recessional trend, and the future recession projected to occur as a result of

Figure 1: Likelihood/Consequence Matrix
(Adapted from: AGS 2007)

Likelihood	Consequence				
	Catastrophic	Major	Medium	Minor	Insignificant
Almost Certain	Very High	Very High	Very High	High	Medium
Likely	Very High	Very High	High	Medium	Low
Possible	Very High	High	Medium	Medium	Very Low
Unlikely	High	Medium	Low	Low	Very Low
Rare	Medium	Low	Low	Very Low	Very Low
Barely Credible	Low	Very Low	Very Low	Very Low	Very Low

sea level rise. The estimates of recession for historical trend used the available information and divided it into "mild", "best estimate" and "severe" representing 95%, 50% and 5% probability of exceedance, based on an interpretation of the variability of the trend over the period of record. The future recession due to climate change averaged the results of 5 IPCC models and used the 5%, 50% and 95% "confidence" lines to obtain the values to be used in the analysis [8]. There was also an allowance for possible change in the shoreline orientation of the compartment as a result of climate change induced shift in wave energy flux. This was based on historical evidence of beach rotation due to semi-persistent weather conditions such as associated with El Nino [8].

The two scenarios were run. A judgment was then made as to the actual values to be used in constructing the likelihood lines [8]. The escarpment slumping was directly added at the end of the process. From consideration of the matrix outputs it was argued that for an "acceptable risk" criterion, the "unlikely" likelihood line should be used to establish the setback for new developments with conventional foundations, whereas the "likely" likelihood line should be used for new developments on piled foundations. The overall approach was an effort to provide an improved probabilistic assessment of the shoreline location in the future, but importantly it introduced the concept of risk-based assessment of vulnerability.

3.2 Developments in determining likelihood

At the same time as the matrix risk-based approach was being developed, others were working towards a Monte Carlo type methodology for calculating likelihood [11]. Testing was undertaken by exploring examples of both closed and open coastal compartments; including those with lagoon entrances, climate change issues, shoreline rotation and shell degradation due to changes in acidification, so as to incorporate as many of the potential component variables that might be experienced when undertaking an assessment of future shoreline locations.

The approach was built on assigning a probability distribution for each component variable. Without more specific information on a variable, a triangular distribution was assumed (see figure 2).

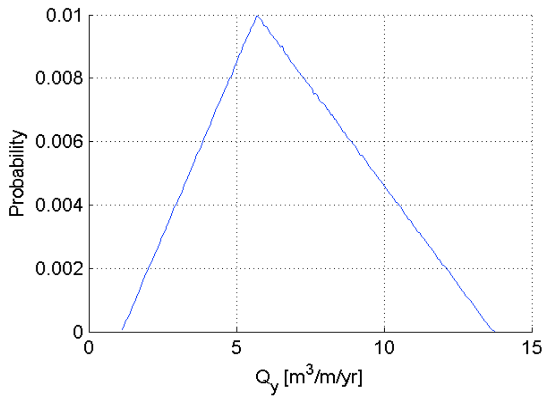

Figure 2: Example of typical parameter distribution for longshore drift (From: [11])

The distributions were defined by the modal value and "bookended" by upper and lower bounds. The values for the min/max and mode were obtained using the Delphi technique based on the opinions of 5 independent coastal engineers and scientists.

While comprising a subjective influence, it was found that there was surprisingly broad agreement between the "experts" on most variables. Where there wasn't or where there was another potential but ill-defined influence such as layers of beach rock (indurated sand), and the uncertainties of climate change impacts (see figure 3), particularly over differing time frames, sensitivity modelling was undertaken [10].

Where a variable was not considered to be part of the process in a particular embayment it was not included, for example, net longshore drift into and out of what were determined to be closed compartments, were not included. The probability distributions for the component variables were combined using a Monte Carlo algorithm, randomly selecting values from the stochastic variation of the input parameters and running10,000,000 iterations

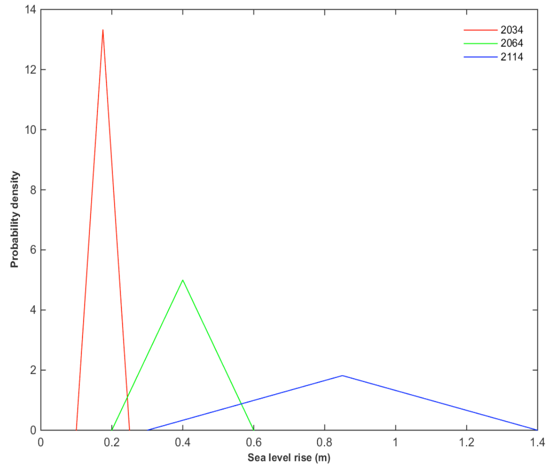

Figure 3: Sea Level rise sensitivity example (from [10])

it was possible to produce a probability distribution of future shorelines at the selected time interval. The sensitivity analysis provided additional information to assist in making informed judgements as to the final distribution to be adopted, thereby providing a greater level of confidence in the probability distribution of the future shoreline location.

This has resulted in a potentially robust and defendable methodology for calculating likelihood of vulnerability, albeit the stochastic variations of the input parameters can be better defined with greater availability of site-specific information. Further developments of the Horton "acceptable risk" methodology are discussed in [9]. Horton has now used a Monte Carlo technique to define likelihood; obtaining similar results at the 50% exceedance level as previously calculated using his original simplified technique [9].

It should also be recognised that the reliance on the Delphi technique and the quality of the outputs presupposes that those involved have the necessary expertise, experience and information.

3.3 Developments in consequences

A "consequence" analysis for coastal recession needs to recognise that once recession has rendered an asset no longer "safe", then the entire value of the asset should be taken as "lost". It is also important to recognise, and include, the vulnerability of the infrastructure servicing the asset. If this infrastructure is damaged beyond repair or reasonable replacement, then the asset is no longer serviceable and should therefore also be considered "lost". While this may seem to simplify the "consequence" considerations of the risk matrix, this apparent simplification of "on-market" costs/losses is complicated by having to include "off-market" costs and benefits. Even the "on-market" costs/losses, such as the value of the projected property/asset/infrastructure losses, is made challenging by the downgrading of property and asset values as the potential risk imposed by recession is realised. The simplest, and the most acceptable to the affected property owners, is the value before there was "reasonable" knowledge of the threat. However, usually by the time the threat has been formally recognised, property values have already fallen, typically as the result of a severe erosion event. There is a growing tendency, as is seen in the United Kingdom and in some of the States of the USA, to assign a zero value to threatened property. The challenge is that, if the likelihood is varied, by say the construction of a competent seawall, then property values may remain at pre-threat levels or may even increase if beach nourishment is included, as is evidenced on the Queensland Gold Coast. Further work is required to develop a consistent standard and framework for on-market property valuations. Until this happens subjective judgements are required to determine what values to apply in each circumstance; an approach that is always vulnerable to challenge and emotional decision-making.

The "off-market" costs/benefits such as costs and benefits of beach amenity to the general community, or the loss of environmental assets, or the impact on commercial businesses that rely on the beach amenity, are far more challenging and subjective. As a first step it is essential that a social impact study be undertaken to determine the often multivariable and complex interrelationship between those members of the community who may lose their private assets, and the impacts of these losses, or any actions to save the assets/property, on the overall community and the beach amenity. For example, the commercial impacts on shopping centres in small coastal villages if a significant number of properties are lost or identified as being vulnerable. Or, the impacts infrastructure such as schools and hospitals, water supplies and sewerage systems, if a population in an area falls below the sustainable number for the particular infrastructure. In larger towns and cities there can be the adverse impacts on the hospitality industries if a popular "beach front" location loses its beach or has the dune system replaced by a rock revetment.

The socioeconomic and benefit cost approach has recently been applied to Old Bar on the NSW coast [2] and is currently being further developed, along with a more complex likelihood analysis, at Lake Cathie on the NSW coast, by officers of the NSW Office of Environment and Heritage [10].

Once the social impacts in a coastal region have been identified and subjectively ranked to identify the "off market" impacts, a cost/benefit study can proceed allowing the consequence region of the matrix to be populated. Initially the consequence region would be based on the "do nothing" or the base case. Hence "consequences" would grade from "catastrophic" or "major" impacts, such as the loss of entire villages as is currently being experienced on the Norfolk coast of Great Britain and in the Gulf States and East Coast Barrier Islands of the USA, to "minor" or "insignificant' consequences such as the loss of a beachside public toilet block, or a small socioeconomic disruption to a local commercial business.

The real power of the matrix approach however is that management options can be investigated by altering the likelihoods through interventions, and then re-assessing the consequences or altering the consequences through landuse planning initiatives. Hence the matrix approach provides a robust vehicle for examining changing risk profiles and the overall benefits and costs of a variety of management options.

Currently studies are being undertaken by the NSW Office of the Environment and Heritage to review international practice and develop a standard guidance for assessing both "on-market" and "off-market" cost and benefits, to provide defendable information and a consistent basis, for the necessarily subjective process (Kovac, pers.com.). While this is likely to remain a contentious and challenging area, it is vital that, for credibility, maximum use is made of available information.

4. Managing likelihood and consequence

A major benefit of the risk matrix approach is therefore that it provides a tool that allows testing of risk manipulation of either, or both, the "likelihood" and/or the "consequence" of coastal behaviour. Likelihood of shoreline recession can be altered from a "base case" of almost certain loss, as a result of no intervention, to that of loss being "barely credible" due to a comprehensive defence approach with a seawall that is competently designed, well constructed and has adequate maintenance and upgrades as required. The consequences of this change in "likelihood" include the cost of the wall and the loss of beach amenity (unless an on-going nourishment program is included), while the consequential benefits include the value of the assets saved, and/or development potential of the property landward of the wall plus the value of the infrastructure protected, and the health of the local economy.

Without altering "likelihood" it is also possible to manipulate consequence by, for example, development set backs, buildings on piled foundations or demountable (relocatable) buildings and disposable infrastructure as detailed by Gordon [6], or other landuse planning options that recognise the ambulatory nature of coastal shorelines.

5. Managing risk

Having established a "base case" (the likelihood of erosion and recession at a coastal location with its current configuration, and the associated consequences of the implied losses), the government and the community are in a position to determine the level of risk they wish to deem acceptable for the affordable management options. This may involve testing various options through the risk matrix approach to arrive at what measures need to be taken to either or both modify likelihood and/or consequence. Such an analysis helps balance risk management against ability to pay, and identifies who will be the beneficiaries, and hence who should be involved in the required funding mix to achieve the outcome.

It is useful to differentiate two regimes of risk for practical consideration and subsequent selection of management options. The first is the risk profile that should be applied to "greenfield sites" (those coastal regions that have not yet been developed and where there is not yet a community of interest). In such locations it is often possible to implement landuse controls that more readily accommodate the ambulatory and fluctuating nature of the coast, thereby allowing the coast to function naturally without unwarranted social and/or economic consequences. Hence it is feasible to reasonably establish set backs for various development types to ensure that they enjoy an acceptable risk in their economic lifetime.

For example, to illustrate the opportunities for management of greenfield sites it could be determined that: there are to be no assets, except say removable lifeguard towers, placed seaward of the 50 year 90% exceedance line; caravan parks and the like (with removable facilities and infrastructure) between the 50 year 90% and the 50 year 50% exceedance line; relocatable dwellings with disposable infrastructure [6] between the 50 year 50% and the 50 year 10% exceedance line; traditional housing, on pile foundations, between the 50 year 10% and the 50 year 1% exceedance line. Traditional housing and other development could be landward of this line; except for vital emergency infrastructure such as hospitals and airports that should be landward of the 100 year 1% line. It is emphasised that this is intended as an example only and not as a recipe; it demonstrates the flexibility in land use planning that can be rationally determined through the risk matrix approach. Further, it is important to recognise that the socio-economic consequences are the real determinate in political decision-making, not simply the economic cost/benefit outcome.

The second is "brown field areas" (regions that have already been developed, including redevelopment, in-fill development as well as management of "legacy areas" - developed areas that are under threat or may come under threat in the socioeconomic lifetime of the development), Appropriate risk management can be achieved through interventions in either the likelihood and/or the consequences. Often the "acceptable risk" becomes more of a "tolerable risk" criterion because of the limited opportunities to achieve practical and implementable solutions. Options are often limited, ranging from those associated with a defensive approach, such as physical structures and/or nourishment to alter the likelihood, to a retreat approach, which may vary from abandonment to an active "coastal adjustment package", or planned adaptive retreat, which provides opportunities for local resettlement. This may include options such as planning controls to allow relocatable buildings, so that owners can enjoy their property for as long as possible and then recover the value of the built asset. This approach allows people to remain in the same general vicinity by relocation funding or low cost alternate land; thereby encouraging owners to remain part of the local community/economy.

6. Summary

The only justifiable continued use of conventional "hazard lines" is as a "first pass" for undeveloped coastal areas in order to determine the information required for a more informed assessment. Effective and credible coastal management should be based on a more sophisticated and defendable scientific platform that is also sensitive to social and economic considerations. The risk matrix approach allows governments and communities to analyse risk, evaluate and rank options in terms of both the social and economic benefits and costs, and determine the level of vulnerability and risk they are prepared to accept and the options they can afford to fund, or the losses they are prepared to accept at each location.

Finally, it is important to recognise that community/political decision making is not necessarily a clinical, rational process, but often also involves an emotional element which, if not accounted for, can frustrate attempts to implement otherwise rational, technically feasible, and clearly viable, options to manage coastal risk. Hence, the "consequence" area of the risk matrix requires far more than just a cost/benefit approach; an understanding of the affected community, its history and the potential future outcomes for its citizens and their extended families, is essential.

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Note: The Author of this paper is the independent Chair of the NSW Coastal Panel; the panel established under the NSW Coastal Protection Act 1979. However, the views expressed in this paper are those of the Author alone, as an independent coastal researcher, and coastal zone manager.