COASTAL EROSION RISK ASSESSSMENT IN NEW SOUTH WALES: LIMITATIONS AND POTENTIAL FUTURE DIRECTIONS

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This paper reviews coastal erosion risk assessment practices in NSW in the context of present theory and available tools. A spatial database was developed to inform the review, in which assessment methodologies and findings gathered from Coastal Hazard Definition Studies were appended to coastline segments defined by the Smartline dataset. The database allows for the ready comparison of assessment approaches and outcomes along the NSW coast.

The techniques applied and findings of the assessment studies, and their geographical variability, are presented and discussed. This includes quantification of the various components of coastal change, including storm-induced beach erosion, periodic wave-climate driven shoreline variations, historical shoreline recession due to persistent sediment losses, and potential future responses to sea level rise. The second aspect of the paper considers the relationship between hazard assessment and risk management, including the use of probabilistic modelling techniques to quantitatively account for uncertainty in hazard likelihoods within risk management.

Some limitations identified by the review include the selection of key outcomes and model variables by assumption or rule-of-thumb, and the restricted capacity of available datasets and methods to resolve the various components of coastal change across the timescales of interest. Additional to the temporal limitations of available datasets, the sparse coverage of measurement data (both morphological change and coastal processes) that is representative of the full spectrum of coastal geomorphology in NSW remains a particular impediment to understanding regional-scale and site-specific variations in coastal erosion risk. In regard to risk assessment techniques, the limited knowledge of hazard likelihoods and the potential for change in the future has impaired the quantification of uncertainties and the communication of statistically meaningful risk. In response to these limitations, potential future directions are suggested, which may improve practice within the context of theoretical constraints and persisting uncertainties in future forcing scenarios.

Introduction

Historically, coastal erosion in New South Wales (NSW) has resulted in significant impacts to private property, public infrastructure and coastal amenity. For example, episodic beach erosion associated with extreme coastal storms, such as those experienced during the 1950s, 1970s, 1990s and 2000s resulted in the exposure and undermining of beachfront properties, damage to coastal facilities and infrastructure, and the temporary loss of beaches (Fig. 1). Furthermore, persistent and ongoing erosion associated with shoreline retreat along some coasts, has resulted in the 'permanent' loss and destabilisation of both public and private land (Fig. 1). In the future, accelerated sea level rise driven by climate change is expected to contribute to enhanced coastal erosion, by increasing storm surge levels experienced during extreme storms, and thus the reach of wave processes, and, by driving shoreline recession (Fitzgerald et al., 2008; Nicholls and Cazenave, 2010).

An established framework for managing the potential impacts of coastal hazards and climate change has been in practice in NSW for over two decades. Specifically, the NSW Coastal Policy, the Coastal Protection Act 1979, and the Coastal Protection Regulation 2011 provide the statutory framework for coastal management practices. Furthermore, the NSW Government publishes guidelines that provide minimum criteria for defining coastal hazards and assessing risks to properties and infrastructure. The NSW Coastline Management Manual (NSW Government, 1990) was the first document to define the relevant coastal processes that should be considered in hazard assessments, and describe suitable techniques for estimating the potential extents of coastal hazards. More recently, the Guidelines for Preparing Coastal Zone Management Plans (NSW Government, 2013) outlined the general approach to managing hazards in the coastal zone, through the development of Coastal Hazard Definition Studies and Coastal Zone Management Plans. It remains the responsibility of local governments to engage appropriate expertise to prepare Coastal Zone Management Plans in accordance with the present guidelines.

The ongoing coastal management reforms process provides the impetus for a detailed review of coastal erosion risk assessment practices in NSW, in the context of more recent advances in theory and available techniques. Furthermore, the reform process also presents an opportunity to align likelihood-based approaches to hazard definition with an appropriate and consistent risk management framework. Ultimately, such an approach may enable the full consideration of uncertainties in coastal forcing, processes and responses, within coastal risk management. Therefore, this paper aims to document and review coastal erosion risk assessment practices in NSW, in the context of limitations including; (1) the availability and resolution (both spatial and temporal) of process and morphology datasets, (2) uncertainties regarding future forcing scenarios (e.g. sea level rise, wave climate), and (3) theoretical impediments to a quantitative understanding of coastal change at management timescales (i.e. 10^0-10^2 years). The outcomes of this review will inform the revision of existing coastal management guidelines as part of the wider coastal management reforms process.

Figure 1 – Examples of the impacts of coastal erosion hazards in NSW, including (left) storm-induced beach erosion at Collaroy-Narrabeen Beach during 2003, and (right) shoreline retreat at Old Bar Beach during 2011.

Development of a spatial database

To inform the review of coastal erosion risk assessment practices, evidence was gathered from recent Coastal Hazard Definition Studies, which have been carried out by consulting engineers for individual local government councils. Where relevant, evidence was also gathered from earlier hazard studies carried out by consulting engineers or government agencies. The information extracted from reports included datasets, analysis techniques applied (including models), and hazard assessment findings, in terms of both the predicted responses and the extents of recommended coastal hazard areas. The information was entered into a spatial database, in which the bibliographic details and assessment data were appended to the corresponding coastal segments. The Smartline dataset (Sharples et al., 2009) was chosen as the baseline dataset for the spatial database. Use of the Smartline dataset allowed for the ready identification of NSW beaches and ensured compatibility with national-scale coastal datasets. Furthermore, because the Smartline coastline segments are defined on the basis of alongshore homogeneity in geomorphology, they were usually reconcilable with alongshore variations in assessment techniques and findings.

A first-pass assessment of potential exposure to coastal erosion in NSW (after DCC, 2009) was also carried out using the Smartline dataset, cadastral data, and the GURAS address database. The approach followed that of Kinsela and Hanslow (2013), who used GURAS to isolate and remove public and/or undeveloped address sites from the assessment process.

Quantifying the problem

To determine the most suitable approaches for managing coastal erosion risk in NSW it is essential to define the scale and distribution of the problem. This is because the most suitable approach for managing a given coastline may vary depending on regional variations in coastal geomorphology and wave climate, land ownership or tenure, and the nature of coastal development. For example, where development of the coastal zone has already occurred, a detailed and site-specific assessment may be necessary to constrain the total assets at risk for a range of relevant planning periods and potential scenarios, and identify any scope for within-site variations in coastal processes and asset exposure. On the other hand, a more conservative and less detailed approach may be suitable for Greenfield sites where development is yet to occur. For coastlines located within National Parks, natural shoreline retreat may pose minimal risk where existing facilities and infrastructure are beyond the estimated extent of future hazards.

In Figure 2, the NSW coastline has been classified into different categories that indicate the potential property exposure to coastal erosion hazards. Specifically, yellow, orange and red coastline segments identify areas in which properties are located within 220 m, 110 m and 55 m of potentially erodible sandy shorelines respectively. Attributes from the Smartline dataset were used to identify sandy shorelines that are composed of erodible materials (i.e. not known to be underlain by bedrock). Similarly, green coastline segments identify shorelines that are located within or immediately adjacent to (i.e. 110 m) National Parks. For a small number of cases in which coastline segments were identified as being immediately adjacent to properties and National Parks, the proximity to properties is shown in Figure 2. Whilst around 40% of NSW sandy beaches are protected within National Parks, Figure 2 indicates that a substantial portion of the developed coastline may be exposed to coastal erosion and shoreline recession hazards. Figure 2 also shows that whilst only 5% of potentially erodible open sandy coasts in NSW were characterised as having properties located within 55 m of the Smartline coastline (i.e. mean high water line), the distribution of these areas far exceeds the distribution of nominated 'Erosion Hot Spots'. This may be indicative of the potential for future increases in exposure to coastal erosion hazards under climate change scenarios.

Figure 3 shows the proportion of the NSW coastline for which Coastal Hazard Definition Studies have been completed, and thus for which coastal hazard extents have been estimated. 'Recent' studies, which were completed from 2008 onwards, were differentiated from 'older' studies that were completed prior to 2008, to identify areas for which hazard assessments based on recent guidelines are available. For example, whilst recent studies typically adopt future sea level rise projections derived from the IPCC fourth assessment report (Meehl et al., 2007), such as the repealed Sea Level Rise Policy Statement benchmarks (NSW Government, 2009), older studies apply a range of lower and now redundant sea level rise projections from earlier IPCC reports. Therefore, the estimated extents of future shoreline recession hazards in 'recent' studies are typically greater relative to 'older' studies, in line with future sea level rise projections from the fourth assessment report. The recently released IPCC fifth assessment report indicates a moderate increase in upper range sea level rise projections, suggesting that future hazard studies should consider sea level rise in excess of the repealed Sea Level Rise Policy Statement benchmarks.

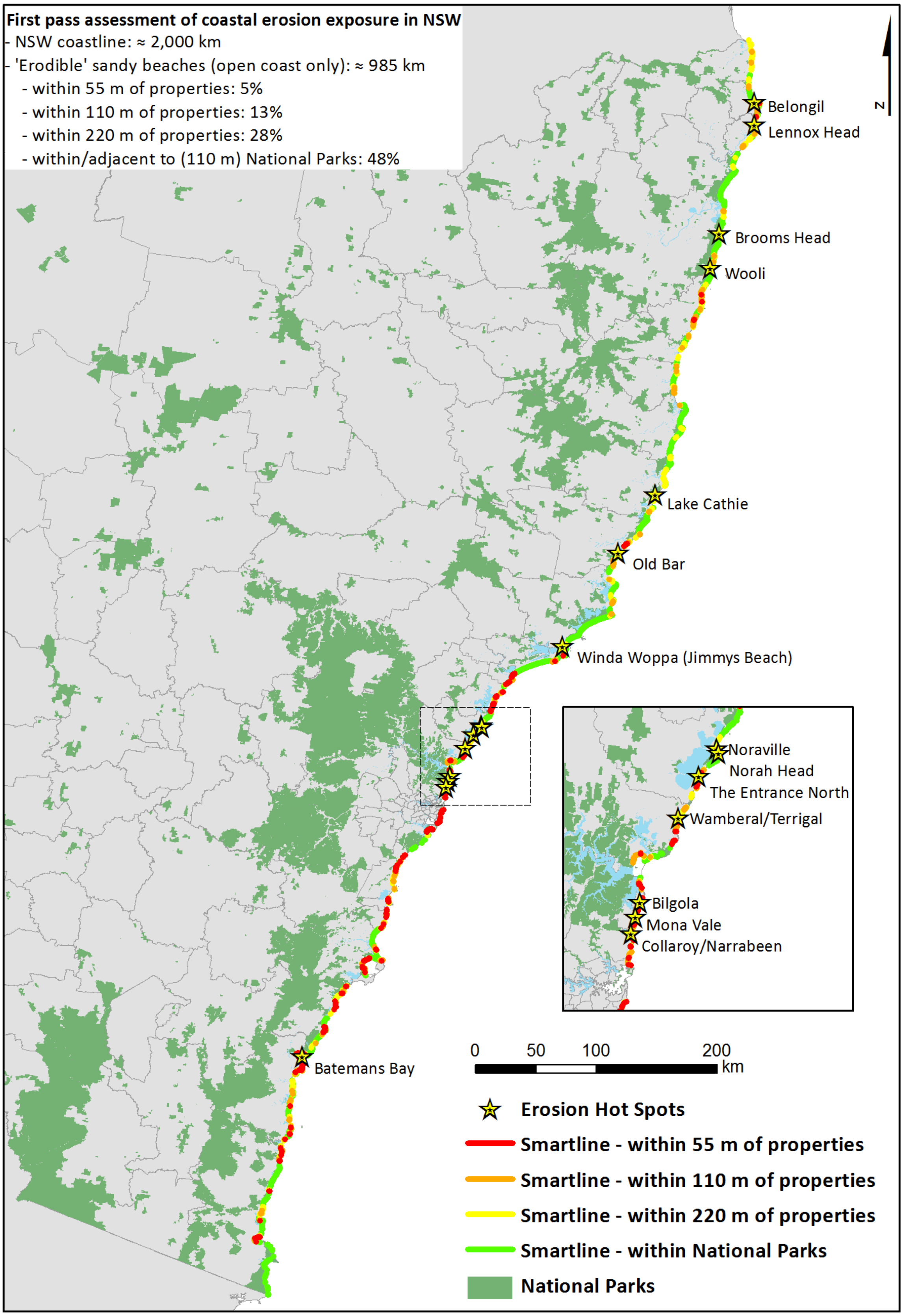

Figure 2 – Outcome of a 'first-pass' assessment of property exposure to coastal erosion hazards along the NSW coastline. Potentially erodible sandy beaches (defined using Smartline) within 220 m (yellow), 110 m (orange) and 55 m (red) of properties, and within or adjacent to National Parks (green) are shown.

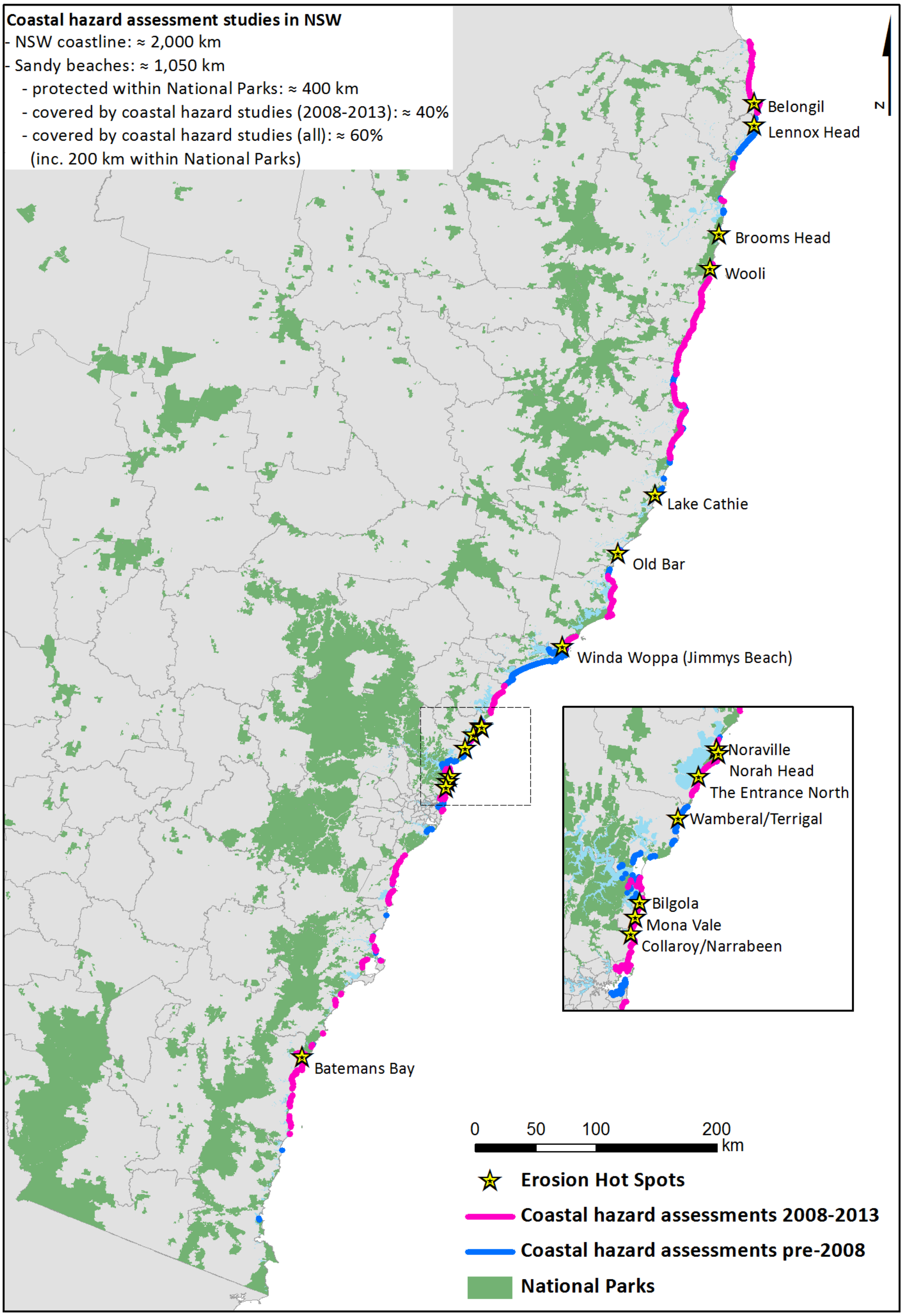

Figure 3 – Distribution of coastal hazard assessment studies carried out along the NSW coastline, including identified 'Erosion Hot Spots' and National Parks. It should be noted that at the time of preparation revised coastal hazard assessment studies were in progress for the Tweed, Byron, Eurobodalla and Bega Valley shires.

Available datasets

Present approaches to coastal erosion risk assessment in NSW should be examined in the context of the datasets and techniques available to practitioners. For example, whilst reliable and fully quantitative numerical solutions of coastal change at management timescales remain in development, the application of simpler empirical or analytical models may also be limited by the extent and resolution (spatial and temporal) of measurement records that are available to constrain the predicted responses to coastal processes. In practice, therefore, both high-magnitude low-probability coastal erosion and potential future shoreline recession are often estimated using incomplete observational records or simple behaviour rules.

Wave climate

Measurement of the NSW wave climate using wave-rider buoys (WRBs) began with the installation of the Sydney Ports Botany Bay WRB in 1971. Following a series of catastrophic storms in the 1970s, the NSW Government expanded deployments to a statewide network, including directional buoys at Byron Bay, Sydney and Batemans Bay. Recently, all remaining stations have been updated to directional buoys. Whilst data capture spans between 70-90% of total deployment times, some instruments have suffered from data omission errors during extreme storms and sensitivities to mooring locations (Shand et al., 2010). Such issues, and the limited historical extent of WRB time series, suggest that derived extreme wave climate statistics at the probabilities of interest (e.g. 100-year ARI) may under-predict wave climates in reality. For example, significant storms experienced during the 1950s, 1960s, and, in particular the 1970s, are not included in WRB measurement records. Furthermore, low-frequency high-magnitude events of particular importance to extreme beach erosion exceed the fitted extreme-value distributions, and appear to belong to a distinctly separate and sparsely sampled statistical population (Shand et al., 2010). Atmospheric reanalysis datasets (e.g. ERA-40, CFSR) provide the opportunity to improve extreme wave climate statistics, through the completion and extension of measurement records using numerical wave models (e.g. WaveWatch III). However, extreme coastal storms are often under predicted due to the imperfect representation of coastal meteorological processes, and thus thorough calibration is required to achieve wave model predictions consistent with observations.

Morphological change

A quantitative understanding of coastal variability and change requires high-frequency and long-term measurement records of coastal and nearshore morphology. Measurements are essential for establishing meaningful statistical relationships between forcing (e.g. wave climate) and coastal responses, and for the calibration and verification of predictive models. However, records are usually restricted to photogrammetric measurements derived from aerial photographs, and image quality typically restricts reliable use to about 1970 onwards. Historical field survey records from Collaroy-Narrabeen and Moruya are notable exceptions. Thus estimates of mean-trend coastal change may be subject to the influences of inter-annual to inter-decadal wave climate fluctuations (Goodwin, 2005; Harley et al., 2010). More problematic, however, is the intermittent temporal resolution of aerial photograph records – e.g. records are typically several years to a decade apart. In most cases, therefore, this impairs the capacity to establish reliable relationships between significant storms and beach erosion. Furthermore, the interpretation of such records is highly sensitive to the adopted approach (Hanslow, 2007). These limitations and the general absence of high-resolution pre- and post-storm surveys of offshore morphology severely limit the reliability of numerical modelling studies, as opportunities for model calibration and verification are limited.

Hazard assessment in practice

Storm-induced beach erosion

The ‘storm demand’ refers to the volume of sand removed from the sub-aerial beach and dunes (i.e. above 0 m AHD) in response to an individual storm or series of closely spaced storms (Gordon, 1987). The most severe beach erosion usually results from a series of closely spaced storms that feature low-frequency high-magnitude water level and wave height statistics. Although the storm demand associated with a particular event may be reliably quantified by carrying out pre- and post-storm beach surveys, the general lack of such data implies that the statistical relationship between extreme storm parameters (water level and wave height) and storm demand is poorly known. Rather, photogrammetry records represent the only measurement data of storm demand for most NSW beaches. Due to the intermittent nature of such data, and, poorly constrained rates of beach recovery that may take place over several years, during which time other erosion events may occur (Thom and Hall, 1991), reliable site-specific assessments of storm demand remain problematic. Table 1 describes the pragmatic approaches that have been applied in coastal hazard assessments throughout NSW to estimate the potential for storm-induced beach erosion.

In many cases the estimated storm demand, as derived using the techniques in Table 1, is substituted for or scaled against (i.e. relative exposure) a rule-of-thumb storm demand of 200-250m^3/m, which is regarded as a nominal value for extreme erosion on exposed NSW beaches (Gordon, 1987). This is particularly the case where the derived storm demand is significantly lower than the accepted rule-of-thumb value. However, the widely adopted rule-of-thumb storm demand has been exceeded in a number of measurement records, due to the nature of the pre-storm beach state, local influences on exposure to the wave climate, the introduction of hard structures, and rips. Thus although the rule-of-thumb storm demand volume may exceed estimates derived using the techniques described in Table 1, it is more representative of a best-estimate storm demand than an absolute maximum. That is, the techniques applied in practice are all susceptible to errors that result in the under-prediction of storm demand, and thus are unlikely to represent the full extent of the potential hazard.

A factor of safety approach described by Nielsen et al. (1992) is usually applied to estimate the extent of dune slumping (i.e. the landward extension of erosion impacts due to substrate instability) following an erosion event (Fig. 4). Whilst an angle of repose for dune sand of 34° is typically assumed as the key determinant of slumping extent in that approach, uncertainties in sediment composition and grain size imply that a risk-averse approach would be to sample a range of potential angles of repose, between say 30-35°.

Current practice in estimating storm-induced beach erosion neglects to account for a change in relative dune levels under projected sea level rise scenarios. The physical reasons for this are described further in the discussion of shoreline recession due to sea level rise below. However, suffice to say here that the heights of existing coastal dunes (relative to mean sea level) will decrease by the projected sea level rise for a given scenario. Thus dune-scarp variability for a given storm demand estimated from historical observations, or model simulations based on present-day morphology, are not necessarily representative of future dune-scarp variability. This is because dune volume above mean sea level may decrease for a given sea level rise and shoreline recession. In other words, for a 1 m sea level rise scenario, present-day storm demand calculated above 0 m AHD should be implemented above 1 m AHD to calculate the hazard line for the corresponding planning period. This may be expected for coastlines undergoing shoreline retreat. Similarly, for model simulations of future storm demand a relative dune level adjustment should be made.

Figures 5 and 6 show the distribution of techniques used to estimate storm-induced erosion.

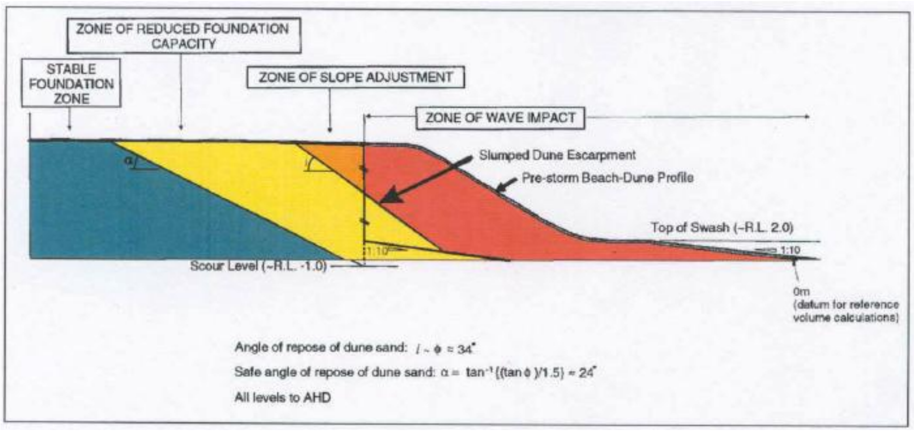

Figure 4 – Definition of hazard zones due to dune slumping and instability after Nielsen et al. (1992).

Table 1 – Range of techniques applied in practice to determine a setback allowance for storm-induced beach erosion, which is typically the most significant component of the immediate coastal erosion hazard.

Technique	**Description**	**Potential limitations**
Adopted storm demand (nearby/representative site)	Storm demand volume or setback is adopted from a previous study of a nearby or comparable site.	The adopted storm demand may not be representative or conservative for the regional setting or site characteristics.
Design storm demand (rule of thumb)	Accepted design storm demand volume (e.g. 250 m^3/m) is applied to reference beach state terrain profiles. The rule of thumb volume may be scaled based on relative exposure to wave climate.	No account for site characteristics that may enhance or moderate erosion; the typically adopted 250 m^3/m volume has been exceeded in many measurement records, due to rip activity etc.
Equivalent storm demand (photogrammetry)	Profile-area-volume (PAV) or dune-scarp migration analysis used to calculate change between aerial photographs captured either side of a significant storm. A profile correction is made to account for beach recovery between the erosion and photograph capture after Nielsen et al. (1992).	Reasonable if photographs captured immediately before and after the event (although that is not typical) as beach recovery and the likelihood of other significant erosion events increase with duration between photograph capture; photogrammetry limitations have been described by Hanslow (2007).
Most eroded beach state (photogrammetry)	PAV or dune-scarp migration analysis used to calculate difference between the most eroded beach state captured in historical records and the reference beach state.	Not necessarily representative of the largest historical storm erosion if the reference beach state is eroded relative to the pre-storm beach state associated with the captured historical erosion.
Simulated storm demand (numerical modelling)	SBEACH model used to estimate the storm demand in response to design storm wave and water level parameters (e.g. Carley and Cox, 2003; Mariani et al., 2012). Single or consecutive design storms may be simulated using an individual or multiple beach profiles.	Design storm wave and water level parameters do not necessarily reflect the design erosion event of comparable likelihood due to sequencing and other factors; general lack of measurement data restricts opportunities for model calibration and verification, and thus model predictions should be treated with caution; SBEACH predictions of erosion are generally not conservative, and do not account for factors that may enhance erosion (e.g. rip activity).
Scaled storm demand (numerical modelling)	SBEACH model used to scale a design (rule of thumb) storm demand based on relative exposure to a simulated wave climate, which is derived using a model such as SWAN. Single or consecutive design storms may be simulated using an individual or multiple beach profiles.	Exposure scaling is dependent on the nature of the model wave climate used (is it representative of all conditions?); general lack of measurement data restricts opportunities for model calibration and verification, and thus model predictions should be treated with caution; SBEACH predictions of erosion are generally not conservative, and do not account for factors that may enhance erosion (e.g. rip activity).

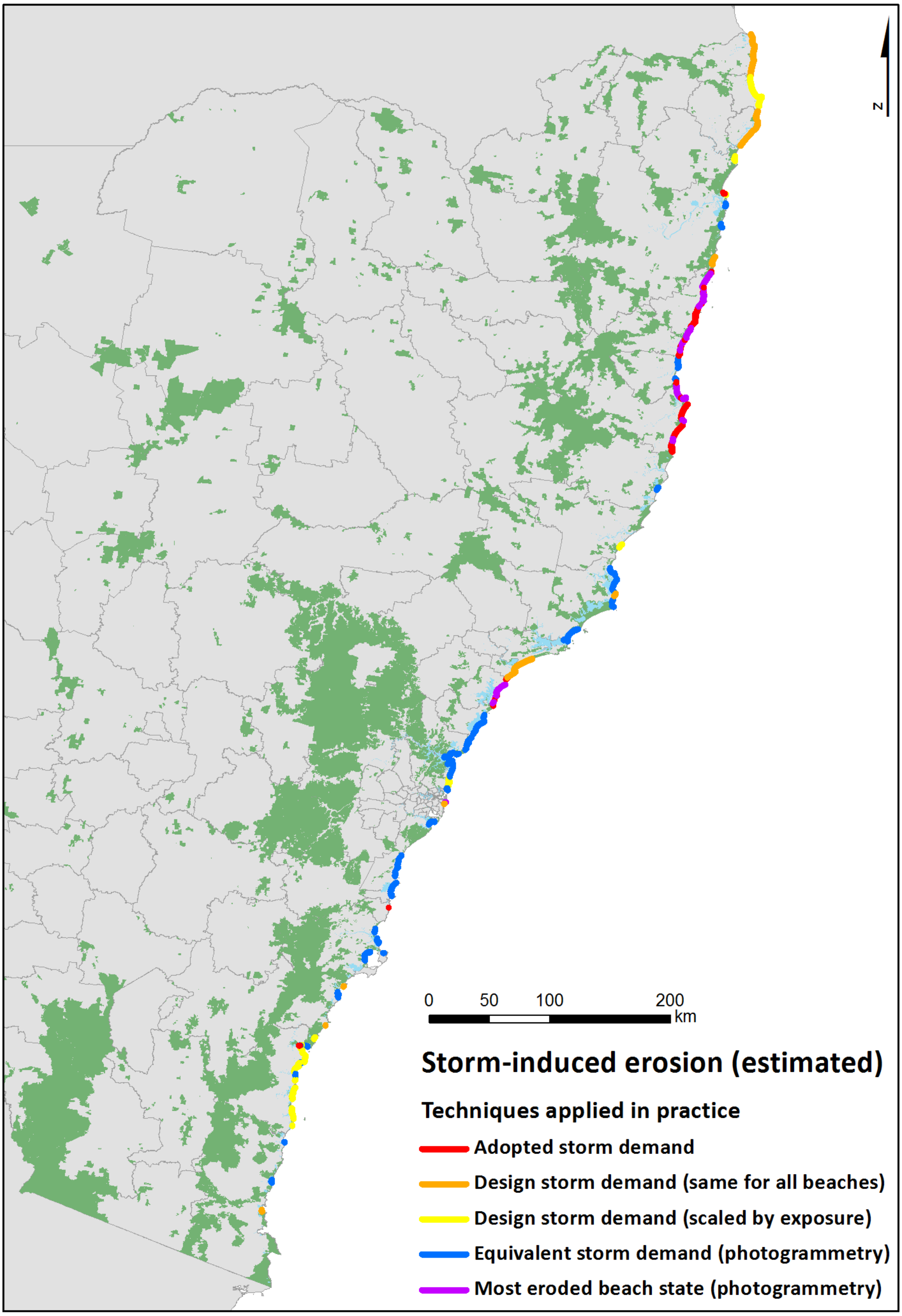

Figure 5 – Distribution of approaches applied in NSW coastal hazard studies to determine a setback allowance for storm-induced beach erosion using techniques based on beach profile data.

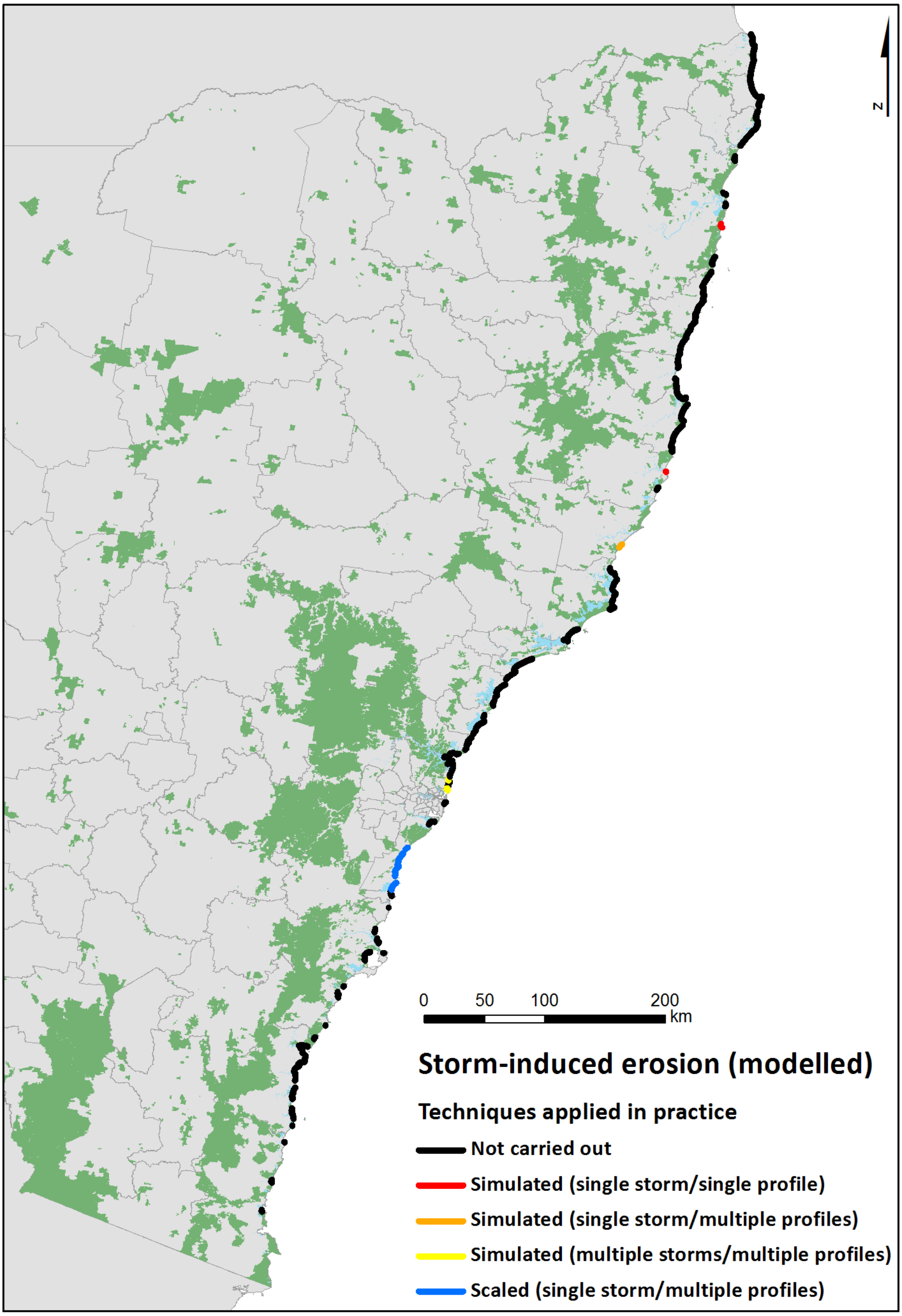

Figure 6 – Distribution of approaches applied in NSW coastal hazard studies to determine a setback allowance for storm-induced beach erosion using numerical modelling techniques (i.e. SBEACH model).

Beach rotation

A variety of approaches have been applied to estimate the potential for periodic alternating beach erosion and accretion that arises from intra-embayment variations in onshore-offshore and alongshore sand transport processes (Tab. 2). Through time, these processes contribute to a shoreline rotation trend, due to differential erosion and accretion at opposing ends of a beach compartment (Short and Trembanis, 2004). The range and distribution of approaches applied in practice (Fig. 7) reflects a generally poor understanding of the drivers, responses, and significance of beach rotation along the NSW coast. Although a strong correlation between beach rotation and wave climate variation has been demonstrated (Ranasinghe et al., 2004), contention remains regarding the relative significance of onshore-offshore and alongshore processes to beach rotation (Harley et al., 2011). Furthermore, because long-term survey data are necessary for statistical analyses, the detailed investigation of beach rotation is limited to a single beach compartment – i.e. Collaroy-Narrabeen Beach, Sydney.

Figure 6 indicates considerable variability in both the consideration and assessment of beach rotation in practice. Whilst an attempt is made to estimate potential beach rotation in many cases, the outcome is not always applied in hazard definition. Other inconsistencies that were identified during the review of current practices included that allowances for beach rotation have been applied for sites where there is no historical evidence of differential erosion – i.e. erosion and accretion trends appear to have occurred uniformly alongshore within historical records. Furthermore, in some instances the calculated allowance for beach rotation has been applied to the entire embayment shoreline, which is inconsistent with the observation that rotation trends reduce to zero in the centre of a beach compartment (Short and Trembanis, 2004). Lastly, if either approach is used with a photogrammetric assessment of storm demand or ongoing shoreline recession, there is the potential that any shoreline variability signal attributed to beach rotation may be sampled twice.

The significance of beach rotation for different compartments of the NSW coast is likely to vary with latitude, orientation and length. First, latitude determines the wave climate (and variability) that a given beach is exposed to. For example, analysis of WRB records suggests significant differences in measured wave climate along the NSW coast, due to latitudinal variation in storm climatology (Shand et al., 2010). Furthermore, coastal geomorphology and headland bypassing also vary with latitude. Second, embayment orientation influences exposure to the wave climate and relative directionality. Lastly, the requirement of differential sediment transport suggests that a minimum embayment length exists for shoreline variability due to beach rotation to become significant. Ideally, all of these aspects should be considered when assessing the potential for shoreline variability due to beach rotation.

Table 2 – Range of techniques applied in practice to determine a setback allowance for beach rotation.

Technique	Description	Potential limitations
Reference beach state (average/supposed future)	Reference beach state used for hazard definition represents average shoreline planform, or supposed future conditions (e.g. El Nino dominant) that contribute to enhanced or moderated erosion.	Average conditions do not reflect the potential for coincident medium-term erosion (beach rotation) and episodic storm-induced beach erosion; future wave climate remains uncertain.
Mean wave direction (MWD) variability	Modelling of altered incident wave direction in response to a range of supposed future deep-water wave directions. A linear shoreline planform normal to incident waves is then used to calculate potential beach rotation.	May not consider relevance of beach rotation to site of interest; maximum allowance for shoreline variability due to beach rotation is simply proportional to compartment length; future wave climate remains uncertain.
Photogrammetry	Photogrammetry analysis of historical aerial photography records carried out to identify (and measure) any past differential erosion/accretion patterns within the compartment of interest.	Frequency of aerial photograph capture is too low to allow for the isolation of beach variability at rotation frequencies (e.g. seasonal, inter-annual) with any confidence.
Shoreline Evolution Model (SEM)	Beach rotation is implicitly accounted for within shoreline evolution modelling, which is driven by a sampled model wave climate that is considered to be representative of the full spectrum of potential conditions.	Model wave climate may not provide a full description of the range of potential conditions, particularly for inter-decadal wave climate variability; storm-induced beach rotation not explicitly included in the model

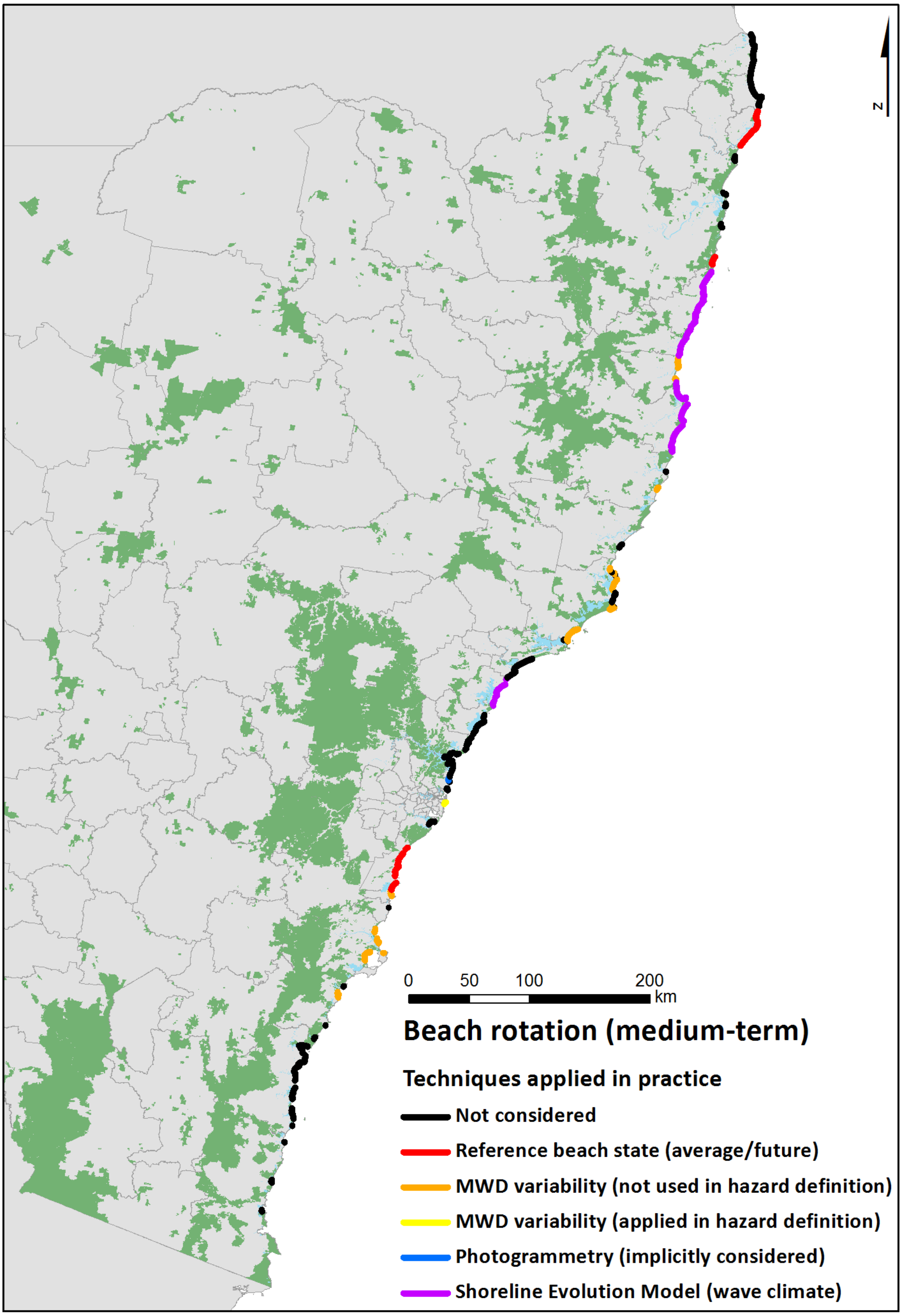

Figure 7 - Distribution of approaches applied in NSW coastal hazard studies to determine a setback allowance for beach rotation, which refers to medium-term shoreline change associated with wave climate variability.

Shoreline recession due to sediment budget imbalance

A historical trend of shoreline recession may be apparent in some settings due to the persistent loss of beach and dune sediments to onshore (dunes), offshore (shoreface), alongshore or estuarine sediment sinks. Photogrammetry records usually represent the only dataset of sufficient duration to investigate any underlying shoreline recession trend (Tab. 3). Where such data is not available, the longshore sediment budget may be investigated to support reasoning for or against any underlying shoreline recession trend (Fig. 8).

The interpretation of photogrammetry data has been shown to be highly sensitive to the adopted trend indicator (Hanslow, 2007). Of further concern when quantifying underlying shoreline recession trends, such records provide only intermittent snapshots in time, and thus interpreted beach volumes and feature migrations are a product of a combination of coastal responses of varying amplitudes and frequencies. For example, periodic coastline change due to wave climate variations associated with medium-term climatic phenomena (e.g. ENSO, PDO, IPO) may be inadvertently included in estimates of underlying change.

The duration and frequency of aerial photograph capture is typically insufficient to isolate the various components of coastal change with sufficient confidence to extract an absolute 'underlying trend'. In practice therefore, underlying shoreline recession is usually treated conservatively, only being considered where a consistent recession trend is apparent throughout records. Shoreline progradation trends are seldom considered in the assessment of hazards. Nonetheless, care should be taken to isolate other fluctuating components of coastal change from any identified mean trend to avoid double sampling. Whilst a range of potential shoreline recession rates are often identified during photogrammetry analysis, the best estimate or upper (conservative) estimate is usually adopted in hazard definition.

Table 3 – Range of techniques applied in practice to determine a setback allowance for shoreline recession due to a sediment budget imbalance.

Technique	**Description**	**Potential limitations**
Longshore sediment budget	The rate of sediment gain/loss from the compartment of interest is estimated, or a closed embayment identified.	The reliable quantification of longshore sediment budgets is difficult and often requires long-term survey datasets.
Dune-scarp migration (photogrammetry)	Long-term change in position of dune scarp (identified by a suitable elevation contour) is measured to estimate the rate of beach recession or progradation for the period covered by reliable aerial photographs	Estimates of long-term beach change, including the overall trend (recession or progradation), are sensitive to the trend indicator measured (Hanslow; 2007); potential for double sampling exists if photogrammetry used to assess other components of coastal change
Profile-area-volume analysis (photogrammetry)	Long-term change in beach volume (area below profiles) is measured to estimate the rate of beach recession or progradation for the period covered by reliable aerial photographs	Estimates of long-term beach change, including the overall trend (recession or progradation), are sensitive to the trend indicator measured (Hanslow; 2007); potential for double sampling exists if photogrammetry used to assess other components of coastal change
Dune-scarp migration and profile-area-volume analysis (photogrammetry)	Both dune-scarp migration and profile-area-volume analysis used to estimate long-term beach change.	Estimates of long-term beach change, including the overall trend (recession or progradation), are sensitive to the trend indicator measured (Hanslow; 2007); potential for double sampling exists if photogrammetry used to assess other components of coastal change

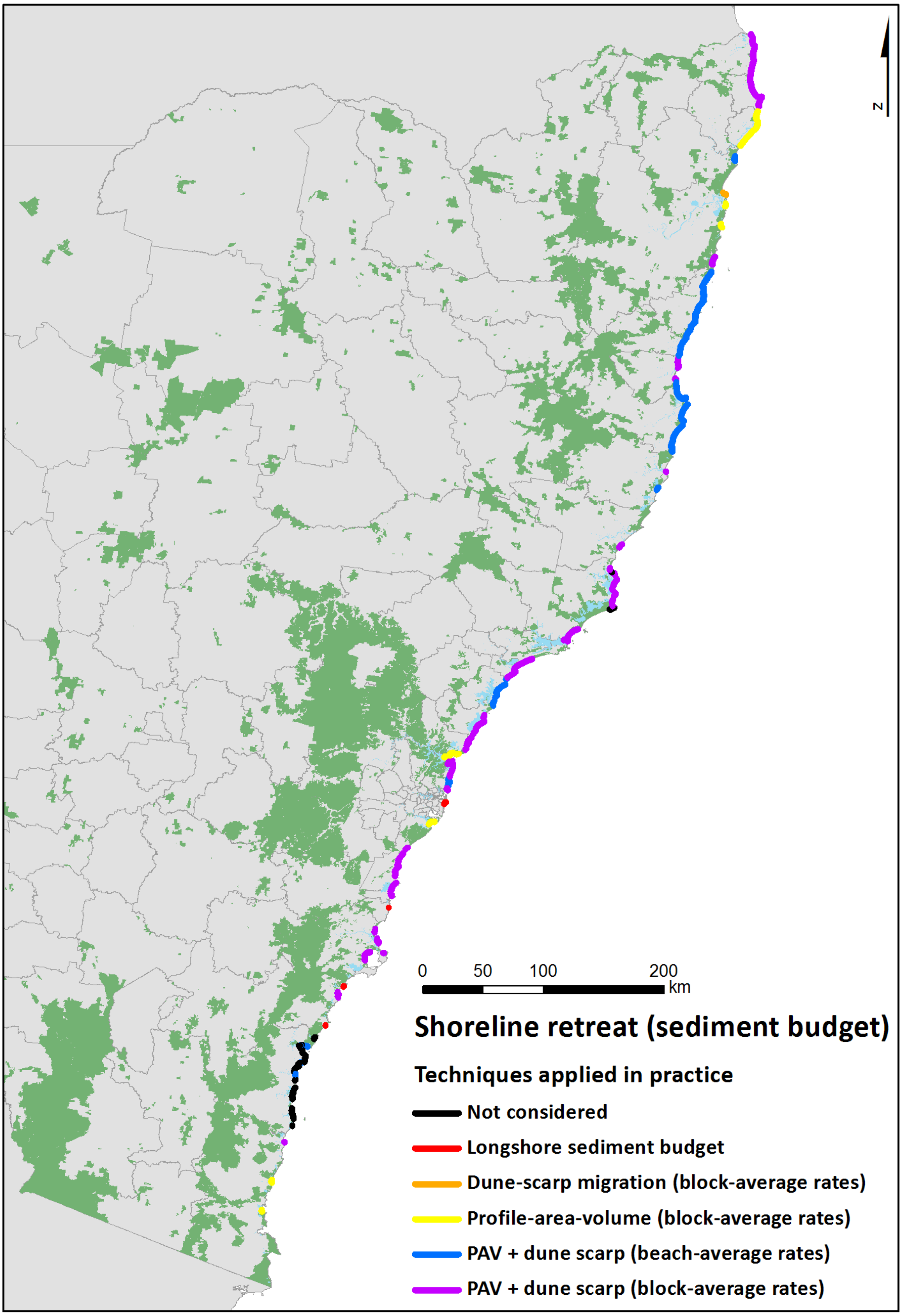

Figure 8 - Distribution of approaches applied in NSW coastal hazard studies to determine a setback allowance for shoreline recession due to a sediment budget imbalance.

Shoreline recession due to sea level rise

Potential future shoreline recession is typically estimated using the ‘Bruun rule’ (Bruun, 1962; 1983; 1988), in which predicted retreat is proportional to sea level rise and the average slope of the coastal profile, measured between the foredune and offshore limit of the active profile, or ‘closure depth’ (Tab. 4). The conceptual basis of the Bruun rule appears to be valid at geological timescales. Also, comparison with observation datasets for cases that satisfy its restrictive assumptions suggests that the general relationship is sound at management timescales (Zhang et al., 2004). However, ignoring the omission of longshore processes, the validity of the Bruun rule depends on the ability to identify the closure depth for the setting and planning period of interest, and the assumption that wave-driven sediment transport residuals beyond closure depth are insignificant. High-resolution repeat offshore surveys are often unavailable for beaches in NSW, and certainly not for the timescale of interest (c. 10^2 years). Thus as seen in Figure 9, the adopted closure depth is usually estimated using the ‘inner’ shoal zone limit (d_l) of Hallermeier (1981), although recent guidelines advise use of the deeper ‘outer’ shoal zone limit (d_i). In practice a profile slope of 1:50 may be simply assumed, or an estimate is made from low-resolution nearshore bathymetry. In some cases vastly different estimates of shoreline recession that solely derive from alongshore variation in profile slope have been considered within pocket embayments. Such findings clearly make no account for other influences (e.g. geological framework) on profile geometry, or the influence of surf zone processes on shoreline shape and stability.

Recently, an alternative model has been applied to some beaches in NSW to address some of the widely criticised limitations of the Bruun rule (Pilkey et al., 1993; Thieler et al., 2000, Ranasinghe et al., 2007). Specifically, the Shoreline Evolution Model (SEM) also considers the effects of wave climate variability on longshore transport rates, interruptions to littoral drift pathways, and onshore sand supply from beyond closure depth (Patterson, 2009; Rollason et al., 2010). The SEM considers shoreline recession due to sediment budget imbalances and sea level rise collectively. Limitations of the SEM include a generalised and time-averaged wave climate and wave transformation, uncertainty arising from use of the CERC formula to predict longshore transport rates (Thieler et al., 2000), and potentially, the use of cross-shelf sediment transport rates based on profile survey data from the Gold Coast. SEM predictions of shoreline recession appear to be roughly equivalent to the Bruun rule in swash-aligned settings (e.g. central and southern NSW). In drift-aligned settings, model predictions are sensitive to calculated longshore transport differentials, which do not appear to account for the potential effects of high frequency (i.e. event to seasonal timescales) wave climate variations and surf zone circulation on sediment redistribution within embayments. Thus model findings require some degree of interpretation, and application of the SEM to the range of coastal settings present in NSW requires further investigation.

Regardless of whether a profile or planform modelling approach is adopted, there remain a number of potential sediment sources and sinks under rising sea level scenarios, which are frequently overlooked. For example, rising sea level may be expected to generate sediment accommodation across flood-tide delta deposits, which may potentially support an increase in the sequestration of shoreface and beach sediments from the open coast (Eysink, 1990). On the other hand, where carbonate sediment is dominant, ongoing biogenic production may contribute a positive sediment supply (Mariani et al., 2013). Lastly, whilst the Bruun rule predicts an upward and landward profile response to sea level rise, an onshore supply of sediment from the lower shoreface may be maintained in settings where shoreface geometry remains shallower than the dynamic equilibrium profile (Cowell et al., 2001).

In reality depth-diminishing wave influence across the shoreface seabed suggests that profile activity is intrinsically linked to the timescale of interest (Stive and de Vriend, 1995). Thus closure depth is expected to increase with the timescale of the problem. Therefore if observed annual closure depths are comparable to d_l, it is implicit that over centennial timescales profile activity should extend to somewhere between d_l and d_i. However, whilst d_i may be a relevant limit of annual significant cross-shore transport, full profile response over 50- to 100-year planning periods most likely ceases somewhere between d_l and d_i, with depth-diminishing rates of response persisting beyond. Thus application of the Bruun rule using d_i as closure depth may be expected to yield conservative estimates of future shoreline recession. Accordingly, use of d_l as a closure depth will most likely result in the under-prediction of potential shoreline recession. Considering uncertainty regarding timescale-dependent closure depth, the relevant depth range (i.e. d_l to d_i) should ideally be sampled using statistical methods, with increased weighting toward d_i for longer timescales (e.g. 100-year planning period).

The Bruun rule implies an upward and landward response of the coastal profile to sea level rise. At geological timescales it seems reasonable to expect that coastal processes have sufficient time to maintain relative beach and dune heights during shore-normal coastline translation (i.e. assuming a constant energy climate). However, for the rapid rates of sea level change projected over the next century, coastal change will most likely be characterized by shoreline encroachment into the existing coastal geomorphology. At geological timescales the mode of coastal change is sensitive to the average gradients of the coastal plain and continental shelf, with gentle slopes encouraging coastline translation and steep slopes shoreline encroachment (Roy et al., 1994; Cowell et al., 1995). However, that effect is likely to be less apparent during coastal response to rapid sea level change, due to the limited time available for coastal processes to maintain morphology that has evolved during thousands of years of relatively stable conditions. Observed shoreline encroachment on beaches of northern NSW (i.e. low gradient coast and shelf) that have experienced historical shoreline recession due to persistent sediment losses is evidence for this behaviour. Thus for rapid sea level rise, dune heights relative to mean sea level should be expected to become lower. This implies that estimates of future storm demand based on historical beach erosion may not be representative of future storm demand under sea level rise scenarios.

Table 4 – Range of techniques applied in practice to determine a setback allowance for shoreline recession due to sea level rise.

Technique	Description	Potential limitations
Assumed Bruun factor (Bruun rule)	Bruun rule used to estimate potential future coastal response to sea level rise, with rule-of-thumb Bruun factor adopted (i.e. typically 1:50).	No account for site geomorphology (i.e. profile shape) in Bruun rule application; inherent limitations of the Bruun rule as described by Ranasinghe et al. (2007).
'Inner' closure depth (Bruun rule)	Bruun rule used to estimate potential future coastal response to sea level rise, with adopted closure depth that is comparable to Hallermeier inner shoal zone limit (i.e. 10-15 m water depth).	Consideration of 'inner' closure depth only may under-estimate the potential for shoreline retreat; inherent limitations of the Bruun rule as described by Ranasinghe et al. (2007).
'Intermediate' closure depth (Bruun rule)	Bruun rule used to estimate potential future coastal response to sea level rise, with adopted closure depth that is comparable to the inner shelf sand boundary (i.e. 20-25 m water depth).	Consideration of 'intermediate' closure depth only may not account for the full range of potential shoreline retreat; inherent limitations of the Bruun rule as described by Ranasinghe et al. (2007).
'Outer' closure depth (Bruun rule)	Bruun rule used to estimate potential future coastal response to sea level rise, with adopted closure depth that is comparable to Hallermeier outer shoal zone limit (i.e. 30-35 m water depth).	Consideration of 'outer' closure depth only may over-estimate the potential for shoreline retreat; inherent limitations of the Bruun rule as described by Ranasinghe et al. (2007).
'Inner' closure depth (Shoreline Evolution Model)	Shoreline Evolution Model (SEM) used to estimate potential future coastal response to sea level rise, with an adopted closure depth comparable to the Hallermeier inner shoal zone limit applied (i.e. 10-15 m water depth).	Consideration of 'inner' closure depth only may under-estimate the potential for shoreline retreat; inherent limitations of the SEM including abbreviated wave climate and use of the CERC formula to calculate longshore transport rates.

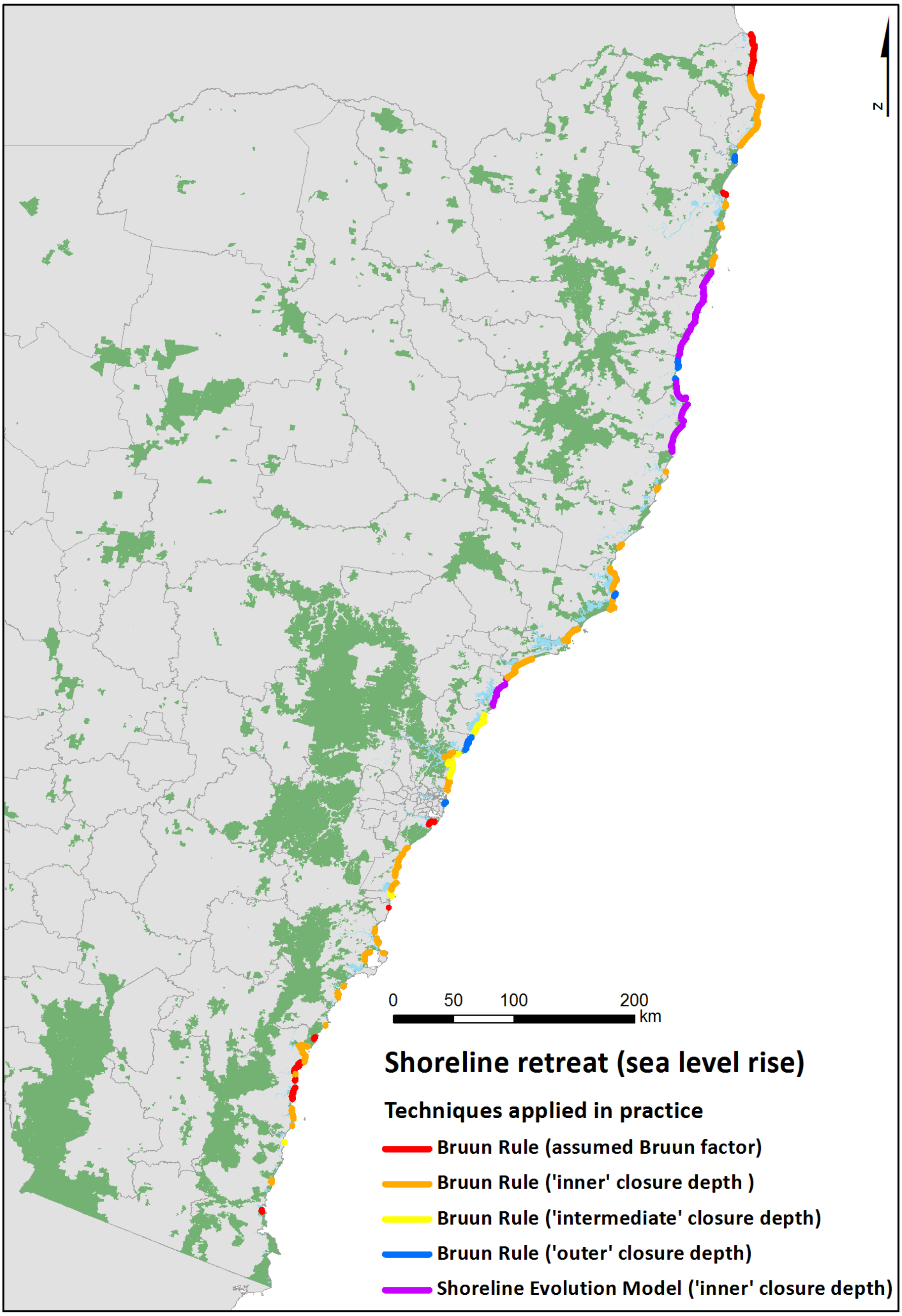

Figure 9 - Distribution of approaches applied in NSW coastal hazard studies to determine a setback allowance for shoreline recession due to future sea level rise.

Dune instability and hazard line definition

The Guidelines for Preparing Coastal Zone Management Plans (NSW Government, 2013) suggest that an allowance for reduced building foundation capacity should be considered in estimating the beach erosion hazard. Specifically, the Zone of Reduced Foundation Capacity (ZRFC) identifies the area beyond a fully adjusted erosion scarp that may be susceptible to instability. Buildings with unpiled foundations that occupy this zone may be at risk from the potentially unstable substrate. Where considered, the approach proposed by Nielsen et al. (1992), which advocates a factor of safety of 1.5 (Fig. 4), is typically adopted. Figure 10 shows the various levels of application of the Nielsen et al. (1992) method as applied in practice, which are summarised as follows:

- ZRFC is not considered in hazard definition study
- Indicative ZRFC widths are provided for a range of representative dune heights
- ZRFC is calculated for each beach using a beach-average dune height
- ZRFC is calculated for each beach profile block using block-average dune heights

Whilst the relevance of the ZRFC typically depends on the nature of the hind-dune substrate, which in many cases may be unknown, a conservative approach would be to include the ZRFC in hazard line definition unless the substrate in question is known to be composed of consolidated materials, and therefore not susceptible to dune instability.

Figure 11 shows the various approaches used to define hazard lines in practice. Specifically, proposed hazard lines may be defined at the Zone of Slope Adjustment (ZSA), which is analogous to an adjusted (i.e. slumped) dune scarp, or the more conservative ZRFC (which explicitly accounts for potential dune instability). Furthermore, the ZRFC may be calculated for the immediate hazard line only, or for all future planning periods as well. The stability zone adopted for hazard line definition generally arises from council's request. In most approaches, only best-estimate hazard lines are defined, which generally represent the sum of the best-estimate assessments of each erosion hazard component. Alternatively, where a risk management framework has been applied in the hazard assessment process, a variety of hazard lines may be defined for each planning period, which are based on qualitatively-based likelihoods of occurrence that have been defined for each erosion hazard component (e.g. almost certain, likely, unlikely, rare).

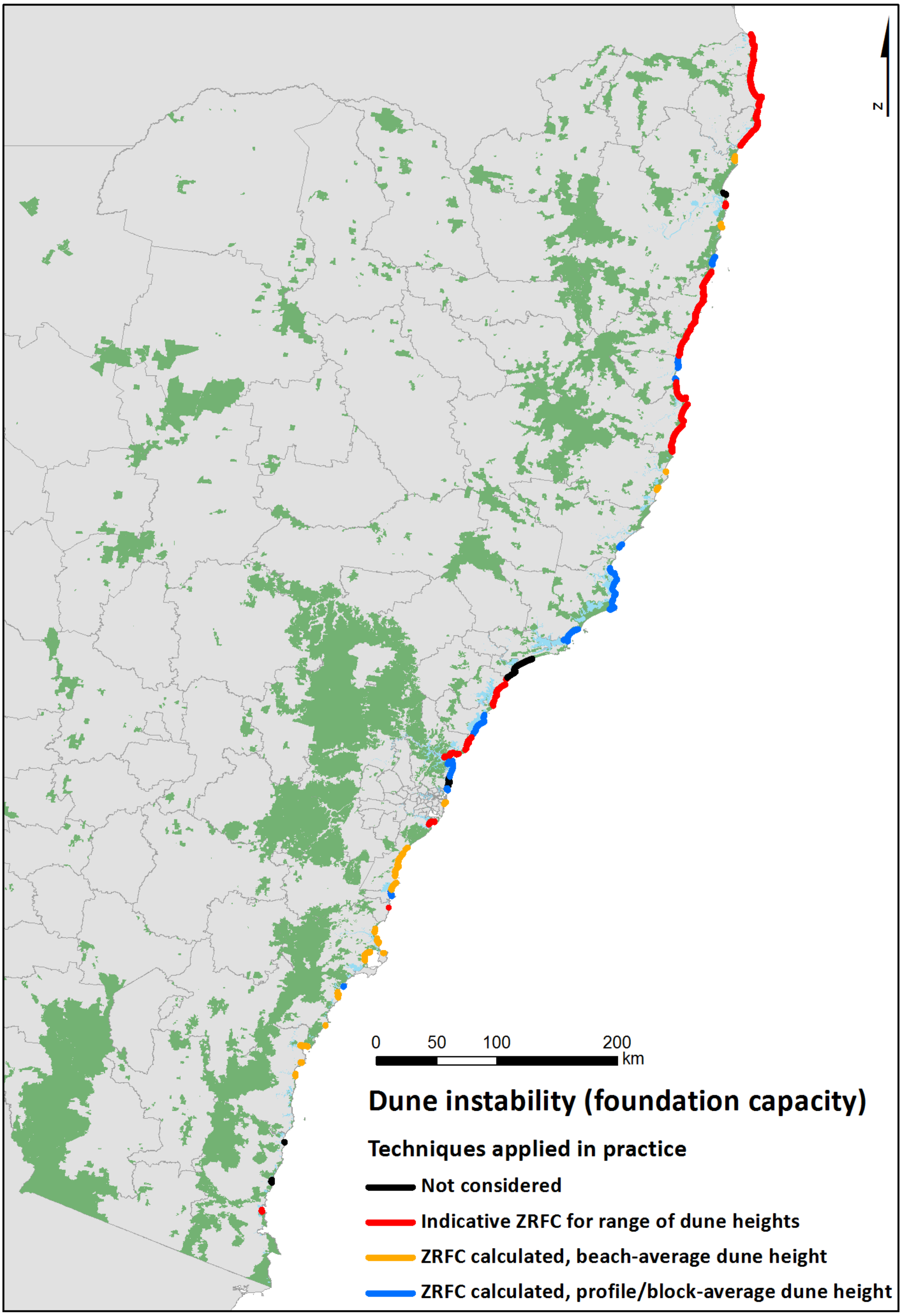

Figure 10 – Distribution of approaches applied in NSW coastal hazard studies to consider potential dune instability through identification of the zone of reduced foundation capacity (ZRFC).

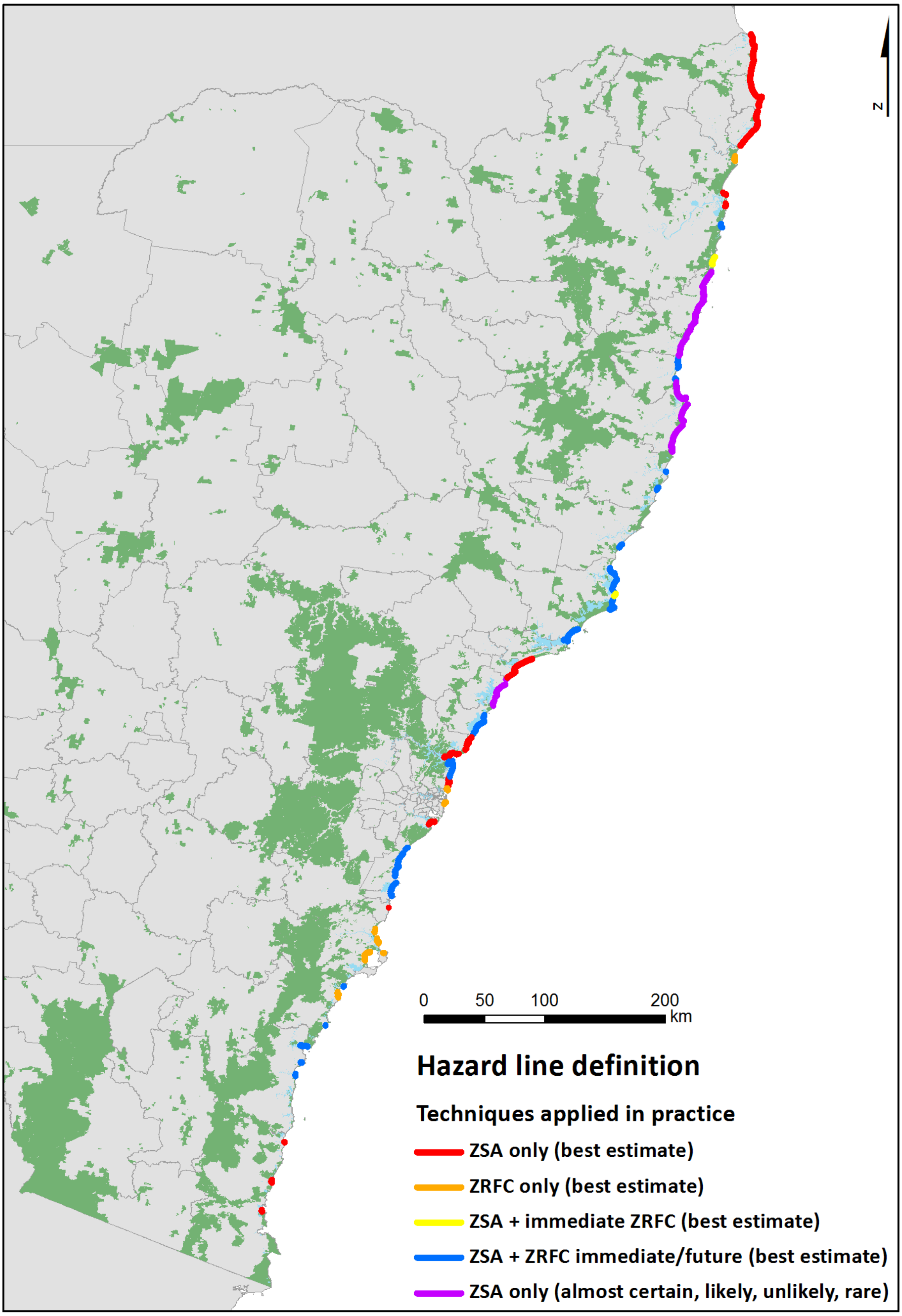

Figure 11 - Distribution of approaches applied in NSW coastal hazard studies to define coastal erosion hazard lines for immediate and future planning periods.

Hazard assessment and risk management

The pragmatic approaches to coastal erosion hazard assessment described above remain subject to the spatial and temporal limitations of measurement data, persisting theoretical impediments to the reliable prediction of coastal processes and responses at management timescales, and uncertainties regarding future forcing scenarios. Collectively these limitations imply considerable uncertainty in estimates and predictions of coastal erosion hazards, and thus derived coastal hazard lines. Whilst an appropriate and consistent risk management framework may facilitate decision making in the face of uncertainty, the benefits of such an approach remain contingent on hazard definition procedures. In particular, the definition of 'best estimate' hazard lines, as is typically carried out in practice, is not readily compatible with holistic risk management and the consideration of all likelihoods.

In practice, hazard likelihoods are considered in coastal hazard assessments in one of two ways. First, some components of coastal variability and change, such as storm demand, may be assigned statistical likelihoods of occurrence, such as an Average Recurrence Interval (ARI). However, whilst wave climate measurement records may be sufficient for reasonable statistical descriptions of extreme storm parameters (Shand et al., 2010), the probabilities associated with extreme beach erosion in response to extreme storms, and in particular clustered storms, are not known with confidence. This is due to both the relatively short timescales of historical observations (relative to the occurrence of extreme events), and, the general lack of reliable measurements of storm demand during that time. Thus exceedance probabilities that have been derived from the application of extreme value analysis to wave and water level data are not readily applicable to storm demand. Whilst beach recovery rates remain also poorly constrained, further investigation of the relationship between extreme wave and water levels, storm sequencing, and beach erosion, has been demonstrated to be possible using joint-probability statistical simulation techniques (Callaghan et al., 2008).

Second, practitioners may adopt a risk analysis framework that is based on the ISO 31000-2009 risk management guidelines and the associated Australian Standard, in which risk is defined as *risk* = *likelihood* x *consequence* (e.g. Rollason and Haines, 2011). Accordingly, such an approach requires the definition of a series of likelihood-based hazard lines for each planning period of interest, rather than a single best-estimate hazard line. Whilst this method represents a welcome move towards a formalised coastal risk management framework, care must be taken to maintain transparency in the definition of hazard likelihoods, to ensure that decision makers interpret the outcomes correctly. For example, where qualitative hazard likelihoods (e.g. likely, unlikely, rare) are derived from only the consideration of incomplete historical records, risk considers only a range of known hazards (and their consequences), not the probability of a design magnitude hazard occurring. That is, risk does not explicitly account for uncertainty associated with the probabilities of hazards of varying magnitudes, and thus the qualitative likelihoods may give a false impression of statistical probabilities of occurrence. Furthermore, the definition of hazard likelihoods based solely on the observed historical occurrence is inflexible in regard to potential future changes in forcing.

Ideally, hazard likelihoods could be expressed as statistical probabilities of exceedance, rather than qualitative likelihoods of occurrence. Such an approach would allow for the communication of quantified uncertainty within the risk management framework, and the objective assessment of risk against predefined acceptable risk thresholds. For example, uncertainties in both forcing scenarios and coastal responses could be included through the definition of variables and model parameters as probability distributions. This approach then allows for the sensitivity of coastal response to the range of uncertainty to be examined (Cowell et al., 2006; Kinsela and Cowell, 2011). Whilst the attribution of probabilities to future sea level rise may be potentially misleading without a full assessment of the likelihood of various political and societal outcomes, probabilistic approaches may be similarly robust when a range of sea level rise scenarios is considered.

Statistical simulation techniques may be used to quantify uncertainties in both physical processes and morphological responses by sampling the full range of potential values. In such approaches, an incomplete observation set, or range of potential values, may be used to guide the definition of probability distributions for each parameter and response. Thus uncertainty in physical processes may be explicitly defined within model inputs. Iterative application of the coastal response model (considering joint probabilities where relevant) may then generate a probability distribution of outcomes that is based on the full range of input probabilities (Cowell et al., 2006). For example, Mariani et al. (2013) present a simple method for quantifying uncertainty in future coastal behaviour, in terms of exceedance probabilities for shoreline recession, which is based on the approach of Cowell et al. (2006). Similar approaches combining process-based coastal response models and statistically-derived wave climates may be used to improve assessments of other components of coastal change, such as the immediate storm demand hazard, by addressing some limitations of available measurement datasets (e.g. Callaghan et al., 2008; Ranasinghe et al., 2012).

The use of probabilistic approaches in coastal erosion hazard assessments provides an immediate means by which to extend hazard assessment practices beyond the limitations of incomplete historical records and best-estimate predictions of future responses, thereby acknowledging the full potential for coastal variability and change in risk management using probabilistically-defined hazard likelihoods (Woodroffe et al., 2013). However, to maintain efficiency in hazard assessment practices, the level of complexity of the adopted approach could be scaled based on the perceived level of risk. That is, simple and conservative approaches may be applied where the perceived level of risk is low (e.g. undeveloped sites), whereas detailed and considered approaches could be applied to highly developed coastal areas where the risk is likely to be significant. In this way the optimal approach in terms of effectiveness and efficiency may be selected.

Suggested future directions

The spatial and temporal limitations of available process and morphology datasets represent a limiting factor on coastal erosion risk assessments in practice. However, the application of assessment techniques and the use of available datasets may be improved.

A number of potential future directions have emerged through the review of current practice. It is emphasised here that these suggestions provide a basis for future improvements to coastal erosion risk assessment, in the context of developing a comprehensive coastal risk management framework for NSW. That is, the suggested future directions in no way diminish the value of the existing knowledge base or negate accepted coastal hazard assessment studies, but identify potential avenues for the incremental advancement of existing practices.

Regarding the improvement of available measurement datasets and their potential extension using modelling techniques, the following suggestions are made for consideration:

- Existing process measurement programs (e.g. WRB wave data collection) should be continued and expanded where possible to improve confidence in available statistics and descriptions of extreme conditions.

- Process measurement datasets may be improved or extended using model datasets derived from statistical and dynamic modelling techniques. For example, statistical simulations may be used to improve wave climate descriptions derived from available wave data, whilst climate reanalysis data and dynamic wave models may be used to explore wave conditions beyond the spatial and temporal extents of measurements. These methods should be fully explored to develop consistent and statewide model datasets to inform coastal hazard assessments.

- Existing morphological change measurement programs should be continued and expanded where possible to improve our understanding of regional and site-specific responses to both modal and extreme conditions. Collaroy-Narrabeen Beach remains the only site in NSW where regular beach surveys have been carried out continuously over the period of WRB deployments. Although the dataset is an invaluable resource, addressing questions of regional- and site-scale variation in coastal erosion remains problematic. Ideally, a network of coastal reference stations that are representative of NSW settings and beach types, where nearshore processes and both onshore and offshore morphology are regularly measured, may help to address these questions.

Regarding the improvement of approaches to assessing coastal erosion hazards, including the application of available techniques and datasets, the following suggestions are made for consideration:

- A statewide geomorphology and coastal process framework could be developed to provide guidance on the identification and assessment (e.g. selection of appropriate techniques) of the processes and coastal erosion hazards that are relevant to different regions of NSW. For example, the framework could describe regional variation in wave climate, the distribution of sediment-sharing coastal cells, and the sediment transport processes active within different regions. This would ensure consistency in the decision-making criteria used to identify and assess coastal erosion hazards in NSW.

- The limitations of measurement and model datasets should be duly described where used in hazard assessments. Effort should be made to quantify uncertainty associated with assessment techniques and acknowledge error propagation through to hazard definition. For example, where photogrammetry data is used, both the error associated with the photogrammetry measurement technique and the error associated with the trend analysis approach should be described and quantified (Hanslow, 2007).

- The full range of uncertainty in historical measurements could be considered using a suitable probabilistic assessment technique (e.g. statistical simulations). For example, the full range of historical rates of shoreline recession identified using photogrammetry analysis should be considered in hazard line definition, with minimum, modal and maximum values guided by the available data (Tab. 5).

- The full range of uncertainty in future coastal processes and responses could be considered using a suitable probabilistic assessment technique (e.g. statistical simulations). For example, the full range of potential closure depths could be identified and considered in application of the Bruun rule or Shoreline Evolution Model, with minimum, modal and maximum values guided by the available data (Tab. 5).

- Potential change in the relative elevation of coastal morphology due to mean sea level rise should be accounted for in estimates of future coastal response. That is, it may not be conservative to expect that the development of coastal morphology will maintain pace with projected rapidly accelerating sea level rise.

- Coastal process and response models should be calibrated and verified using site-specific measurement data (where possible) or data collected at a representative site. Where appropriate for example, process and morphology datasets from Collaroy-Narrabeen Beach could be used to calibrate and verify a predictive model, prior to its application at a comparable site for which survey data is unreliable or absent.

Table 5 – Example of coastal erosion hazard components for which the inherent uncertainty could be included in hazard line definition, by sampling the full range of potential values, using an appropriate probabilistic technique. See Cowell et al. (2006) and Mariani et al. (2013) for examples of application.

Component	Approach	Variable	Example range	Units
Storm-induced beach erosion	Equivalent storm demand	Storm demand	$180 < S_d < 300$	m^3/m
Dune slumping	Factor of safety	Angle of repose	$30 < \alpha < 35°$	°
Beach rotation	MWD variability	Mean wave direction	$127 < \theta < 140$	°
Shoreline retreat (sediment budget)	Photogrammetry	Long-term rate of dune scarp retreat	$0.05 < x < 2$	m
Shoreline retreat (sea level rise)	Bruun rule (standard & generalised), SEM	Depth of closure	$12 < d < 35$	m
Shoreline retreat (sea level rise)	SEM, generalised profile model	Flood-tide delta aggradation rate (proportional to SLR)	$0 < Q_{FTD} < 100$	%SLR
Shoreline retreat (sea level rise)	SEM, generalised profile model	Longshore drift differential	$0 < Q_y < 20{,}000$	m^3/yr
Shoreline retreat (sea level rise)	SEM, generalised profile model	Onshore supply	$0 < Q_x < 4$	$m^3/m/yr$

Present approaches to coastal risk management do not encourage the definition of coastal erosion hazards in terms of probabilities of exceedance. Specifically, risk analysis is often considered a separate procedure, in which risk is based only on the exposure associated with best-estimate coastal erosion hazard lines. This approach implicitly considers only the risk associated with a known hazard, and does not account for the risk associated with an inaccurate or imprecise description of the hazard (i.e. uncertainty). Given the uncertainties regarding forcing scenarios and morphological responses described above, it follows that coastal erosion hazards are not yet known to sufficient levels of confidence to ignore uncertainty. However, the establishment of a comprehensive and consistent approach to coastal risk management may overcome some limitations of available hazard assessment techniques, and further support robust and transparent decision-making.

Regarding the formalisation of a standard process for coastal erosion risk management, the following suggestions are made, as factors to be considered over time to improve coastal risk management practice:

- The development and formalisation of a coastal hazard risk management framework that transcends the existing coastal hazard definition and coastal zone management plan processes. The framework would be comprehensive in scope, spanning from guidelines that outline approaches for deriving likelihood-based coastal hazard lines, to decision support criteria for selecting appropriate management responses.

- Incorporation of a process to enable the derivation of acceptable/tolerable risk thresholds based on agreed principles regarding coastal erosion hazards, for both existing and future coastal development. Such thresholds could enable objective and transparent decision making that is firmly grounded on the identified risks.

- The development of a scalable hazard assessment framework in which the complexity of the adopted approach is guided by the level of risk. For example, simple and conservative approaches could be applied to greenfield sites, whereas detailed and considered approaches could be applied to highly developed coasts.

- The derivation of likelihood-based coastal erosion hazard lines for the present day and future planning periods, in place of ‘best estimate’ hazard lines. Likelihood-based hazard lines are necessary to inform the risk analysis process, on which the improved decision-making capabilities associated with the use of a risk management framework depend.

- The definition of hazard lines in terms of statistical probabilities of exceedance rather than qualitative likelihoods of occurrence. The full scope for present and future coastal erosion hazards, and the associated uncertainties, would be identified and considered throughout the risk management process, to ensure the comprehensive nature of assessments and support objective and transparent decision-making. Where possible, statistical simulation techniques could be applied in hazard definition to incorporate uncertainties regarding forcing scenarios, processes and coastal responses.

Conclusions

This review has identified that a range of coastal erosion risk assessment practices are applied in NSW, which reflect alternative interpretations of the existing guidelines, variability in available datasets, and the absence of a standard and comprehensive framework for risk management. Theoretical constraints and uncertainties regarding future forcing scenarios (e.g. sea levels, wave climate) will persist into the future, whilst deficiencies in measurement datasets restrict our abilities to isolate the various components of coastal change at the timescales of interest. The limitations of current practice that relate to an incomplete consideration of potential responses and available assessment techniques may convey a misleading level of confidence. This emphasises the need to accurately represent confidence (uncertainty) in ways that can be understood by decision makers and communities. Improvements to coastal erosion risk assessment practices may be achieved through (1) the maintenance and expansion of both process and morphology measurement programs, (2) the development of model datasets to increase confidence in empirical relationships and statistical descriptions of observations, (3) the quantification of uncertainty in estimates of hazard extents through the use of probabilistic techniques, and (4) the communication and interpretation of uncertainty through a comprehensive and formalised risk management framework. Regardless of the limitations of available datasets and hazard assessment techniques, improving the communication of uncertainty, such as through quantified hazard likelihoods, may improve transparency in assessment findings, and facilitate robust decision-making with full consideration of the spectrum of potential outcomes.

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Disclaimer

The information and ideas presented here contribute to an ongoing review of coastal zone management practices in NSW. As such, the views presented in this paper represent those of the authors, and do not necessarily reflect the views of the Office of Environment and Heritage.

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